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A Proposal
to the
Office of Science of the United States
Department of Energy

for the

MIT Center for Accelerator Science and Technology

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Executive Summary

Accelerators are one of the cornerstones of the scientific enterprise. From biology to medicine, from materials to metallurgy, from the fundamental structure of matter to the cosmos, accelerators provide the microscopic information that forms the basis for scientific understanding and application. Many future plans for science in this country involve construction of novel particle accelerators. For example, the Department of Energy twenty-year plan, "Facilities for the Future of Science: A Twenty-Year Outlook", which maps the future of major new facilities in the United States for basic research, depends upon progress and breakthroughs in accelerator science and technology.

A new MIT Center for Accelerator Science and Technology (CAST) is proposed and in this document initial funding from the United States Department of Energy Office of Science is requested for the years FY2006-FY2008. CAST will include many departments across the Schools of Science and Engineering at MIT with the primary purpose of conducting frontier research in accelerator science and technology. The proposed research at CAST involves both developing new types of accelerators for fundamental scientific research as well as applying accelerators to address issues of high national priority. In addition, CAST will develop a strong program to educate young people at the undergraduate, graduate, and postgraduate levels using 'hands on' instruction at the existing suite of powerful particle accelerators at MIT, among the best at any university in the country. Strong collaboration of mutual benefit with scientists from other laboratories is an essential aspect of CAST. An accelerator R&D center with physicists and engineers working closely together at a major research university would both significantly strengthen the national effort in accelerator science and enhance the research portfolio of MIT.

The research and educational programs at CAST will be led by faculty in the Departments of Physics, Nuclear Engineering, Electrical Engineering and Chemistry. In addition, senior researchers in the Laboratory for Nuclear Science and the Plasma Science and Fusion Center are playing a central role. CAST will be based at the Cambridge campus of MIT with the Bates site providing a laboratory focus for major projects and advanced accelerator R&D. The initial CAST research program is principally concentrated in three distinct but technically complementary areas:

- The development of new charged particle sources and advanced accelerator techniques required for the study of the fundamental structure of matter as pursued by the Office of Nuclear Physics. The proposed research is directly relevant to the ongoing and future programs at both the Relativistic Heavy Ion Collider (RHIC) and Continuous Electron Beam Accelerator Facility (CEBAF).
- Research on high brightness photoinjectors and related beam physics required for the next generation of light sources utilized by the Office of Basic Energy Sciences. The proposed research is directly relevant to several major facilities which are scheduled for construction, e.g. the Linac Coherent Light Source (LCLS) in FY2005 and the European X-ray Laser.
- Research on new accelerator techniques relevant to the mission of the Office of High Energy Physics. In particular, MIT scientists and engineers are participating in the international discussion to develop a plan for R&D necessary for the International Linear Collider (ILC). It is anticipated that CAST would provide a framework for MIT participation in the ILC accelerator development, which would complement the existing MIT participation in the ILC scientific and detector activities.
- Research in all of these areas will greatly profit from the educational program at CAST. The planned enrollment of 15-20 graduate students, as well as several postdoctoral associates,

will address a critical need for workforce development in accelerator science and technology especially with 'hands on' training. The students will also be involved in extensive collaboration with researchers from National Laboratories, ensuring that results from thesis research investigations will be directly applicable to important national accelerator development needs.

In each of these areas of research, MIT scientists have recently made important contributions and are playing a leadership role. Once CAST is realized, it will be essential to broaden the research program to include significant efforts in other important areas, e.g. High Energy Physics/ILC and Fusion Energy Sciences. A central and unique aspect of CAST will be interdisciplinary research; the newly developed collaboration between Bates accelerator physicists and members of the Optics and Quantum Electronics Group in the MIT Department of Electrical Engineering and Computer Science on laser seeding of an x-ray laser is a good example of this. Indeed, the projects described in this proposal were chosen particularly for the strong synergy among the different research areas: nuclear physics, high-energy physics, basic energy sciences, and plasma science.

Education will be a primary mission of the Center. MIT attracts some of the very best students in the world and has a long tradition of departmental and interdisciplinary programs. CAST will draw upon faculty across the Schools of Science and Engineering to organize and teach a core curriculum, and would aim to support 15-20 graduate students. In addition, CAST will aim to actively involve undergraduate students in the research program. Hands-on instruction using the Bates accelerator and other MIT facilities will be an essential aspect of the CAST educational curriculum. With CAST, MIT will make a significant contribution (about 3-4 Ph.D.s per year) to the national pool of young accelerator scientists and engineers, since the number of students graduating in this discipline is quite small nationally (about 15 Ph.D.s per year). The proposed CAST educational program is directly relevant to the mission of the DOE Office of Workforce Development for Teachers and Scientists.

The Bates accelerator complex is a central element in CAST. In the last fifteen years, over $50 million has been invested in completely refurbishing the linear accelerator, in construction of a state-of-the-art 1 GeV storage ring which is delivering a highly intense polarized electron beam for nuclear physics research, and in a modern control system which allows operation of the entire accelerator complex by a single person. With reasonable support and a careful transition from nuclear physics user facility to CAST, the Bates accelerator complex has a lifetime of several decades. Discussions between MIT and DOE to allow MIT to take ownership of Bates at the end of the nuclear physics user facility era are in progress. Nationally, there is a scarcity of particle beams available for accelerator R&D. CAST will make available test beams at Bates for accelerator R&D, education and detector development.

Particle accelerators are an essential part of the nation's technical infrastructure for health care, for industry and for national security. CAST can provide a unique catalyst for R&D using accelerators in the Boston area where medical institutions and high technology companies abound. While no funds are requested yet for research into these applications of particle accelerators, we envision a future that includes broad applications of accelerator technology within CAST. As examples, a collaborative effort between CAST and Massachusetts General Hospital plans to study the ability of ion beams to treat cancer tumors, and a collaboration with L-3 Communications will develop compact particle accelerators for cargo screening in the interests of national security, continuing MIT's strong history of collaboration with the private sector.

The funding requested for CAST in this proposal will have substantial leverage. The initial CAST research program proposed here is directly relevant to high priority efforts at DOE: efficient operation of both CEBAF and RHIC, the lepton-ion collider eRHIC, the advanced light source project LCLS, and the ILC. Further, a number of other related initiatives are under development which would significantly broaden the research scope of CAST. For example, discussions are in progress with Sincrotrone Trieste, Italy, concerning substantial MIT participation in design and construction of an approved seeded laser FEL at that laboratory; DARPA has requested a proposal for an inverse Compton scattering x-ray source proposed by MIT researchers; several active proposals have been submitted by MIT scientists to pursue accelerator-based techniques for cargo screening with the Department of Homeland Security. For each of these initiatives, CAST expertise and infrastructure would be essential for success.

CAST will be an MIT Center with its headquarters at the Cambridge campus. The Director will be an MIT faculty member from either the School of Science or Engineering who will report to the MIT Vice President for Research. CAST is proposed by faculty and scientists active in the research areas of Nuclear Physics, High Energy Physics, Fusion Energy Sciences and Basic Energy Sciences. Eight MIT faculty (Bertozzi, Kadak, Kaertner, Kowalski, Milner, Moncton, Nelson and Surrow) and three MIT Senior Research Scientists (Lanza, Temkin, and Tschalaer) are committed to providing the necessary leadership to initiate the CAST research and educational programs. The educational curriculum will be overseen by a committee of MIT faculty and research scientists who will report to the CAST Director. The funding requested for initial CAST activities starting in FY2006 is $6,140K. This supports 19 FTEs of research staff (all present Bates staff), 5 post-docs and 5 graduate students. In addition, it includes $1,020K of capital equipment funds and supports test beam delivery at the Bates Accelerator complex for education, R&D activities and detector development for 1500 hours per year. MIT will provide resource and salary support of the CAST directorate, administration, facility, and infrastructure. In FY2006, this would amount to $1,550K. Further, an MIT faculty search for an accelerator physicist has been launched. The proposed CAST organizational structure, as well as a plan to realize the Center, is described in Chapter 5. Chapter 6 provides detailed information on the CAST personnel, budgets and schedule for FY2006-FY2008.

The Office of Science Occasional Paper 'Accelerator Technology for the Nation' eloquently makes the case for a new national initiative in accelerator research and development. CAST directly addresses the critical areas identified in this important paper:

- CAST proposed research will directly improve the capabilities and operational performance at existing accelerators such as CEBAF and RHIC.
- CAST will create new, powerful collaborations between scientists and engineers at MIT and those at the national laboratories.
- CAST will provide unique educational opportunities and open up a new talent pool for accelerator science and technology.
- CAST will carry out advanced accelerator research which is critically important for the long-term viability of accelerator-based science.

In summary, MIT CAST will provide an outstanding national research and educational program in accelerator science and technology that is both interdisciplinary, drawing on the particular strengths of MIT, and fully integrated with the priority efforts of the DOE Office of Science.

1.0 OVERVIEW

1.1 Importance of Particle Accelerators to Scientific Research

Accelerators are instruments that deliver beams of fundamental particles (electrons, protons, ions and molecules) for collisions with fixed targets, for collision with other beams or for production of secondary beams. They can range in scale from table-top devices to the largest instruments that the human mind can imagine to construct. Accelerators are essential tools in many areas of scientific research, e.g. fundamental sub-atomic physics, condensed matter physics, materials science, life sciences, and chemistry. Further, they are also essential in many applied fields of study and applications, e.g. dating of artifacts, geological exploration, cancer treatment, weapons verification, cargo screening and even possibly radioactive waste transmutation.

The physics of accelerators typically involves determining the properties and behavior of many-body systems with $\sim 10^{10}$ particles obeying the known laws of electricity and magnetism. The intellectual focus of accelerator physics is to understand new phenomena, particularly those that enable new capabilities (e.g. higher energy, increased luminosity, high spin polarization) in the use of these instruments for scientific research and applications. Important problems of great current interest include: developing new techniques to accelerate charged particles to the highest energies; producing highly defined (in both space and time), intense multi-GeV electron beams that can deliver brilliant, coherent light in the wavelength range of 100 to 0.1 nm; developing techniques to cool high energy hadron beams to enhance the luminosity of particle colliders. More speculative, but certainly not impossible, would be to imagine shoe-box sized accelerators or even micro-accelerators. One could easily foresee many novel applications if such devices became practical. It will require intellectual and technological breakthroughs and extensive R&D to make such advanced devices a reality.

Accelerators have been at the cutting edge of nuclear and particle research for many decades. The needs of sub-atomic physics drove their evolution and development. Physicists have used them to discover fundamental particles (electron, muon, pion, tau, etc.), quarks, force carriers (gluons and electroweak bosons (W,Z)), and to measure their properties (mass, charge, spin, etc.). Our detailed knowledge of these particles and their modes of decay and interaction come from experiments using accelerators and sophisticated detectors. Notable discoveries in the US include: antiproton at UC Berkeley; tau meson and quarks at SLAC; J/Ψ at BNL and SLAC; top quark at FNAL and others. Many Nobel prizes in physics have been awarded for these discoveries. Some of our most challenging problems in particle physics today, such as the anticipated discovery of the Higgs boson and evidence for possible physics beyond the Standard Model, will require experiments that push the envelope of accelerator technology. Quarks and leptons appear to be the fundamental building blocks of matter. Is there anything else? That is a very important physics question. To understand nature at the smallest distance scales requires particle beams of the highest energies, intensity and beam quality. It will require technological advances that are not now in hand. The US currently is at the frontier of highest energy collisions; FNAL for protons on protons and BNL for heavy nuclei on heavy nuclei. In a few years these will be supplanted by the LHC at CERN, where US particle physicists will continue to play important roles in research. For the longer term, plans are underway for a linear collider with a center of mass energy of 500-1000 GeV. Collisions of electrons and positrons at these high energies will allow precision studies of the Standard Model and elucidate new physics discovered at the LHC. Accelerators will continue to drive research in nuclear and particle physics for the foreseeable future.

For over a century, x-ray diffraction and imaging has had an enormous impact on science and technology. From broken bones to angiography, modern medicine could not exist as we know it without x-rays. In materials science, chemistry and biology, the atomic structures of virtually all forms of matter, from thin films to proteins, come almost exclusively from x-ray diffraction data. Today the most important x-ray sources for these studies are based on synchrotron radiation from particle accelerators. As a result of such 'light' sources, rapid progress is now being made on determining the 3D atomic-level structure of the proteins responsible for life. The next step in the development of such accelerator-based sources is the x-ray laser - a fully coherent source of 0.1 nm wavelength light, emitted in either ultra-short femtosecond to attosecond pulses, or in longer pulses with extremely narrow spectral bandwidth. Among many of its revolutionary applications, such a facility may make the hologram of a single molecule possible, or enable a chemical reaction to be followed in detail in real time with precise identification of intermediate states.

Similarly, for over fifty years neutrons have enjoyed a unique role in determining magnetic structure, understanding the dynamics of condensed matter, and providing an essential tool for imaging large, dense objects inaccessible to x-rays. For example, almost everything we know about the atomic level structure of magnets comes from neutron scattering. Unlike x-rays, neutrons interact strongly with the magnetic moments of electrons or with the atomic nucleus, so their scattering strength differs significantly and importantly from x-ray cross-sections. As a result, the techniques of neutron scattering are an essential complement to x-rays. And, like x-rays, the most powerful sources of neutrons today come from particle accelerators. The Spallation Neutron Source (SNS), now nearing completion, is designed to advance basic neutron science to a new level. As these sources mature over the next decade, they will reveal, for example, the detailed magnetic structure of materials essential to magnetic information storage, and enable understanding of the dynamics of proteins whose structures were determined by x-rays.

Accelerators have had a long history in many other areas of basic research. Recent technological improvements have been primarily towards higher energy and currents. Smaller and more compact accelerators are often more oriented to applied science and technology than to basic science. Recent technical developments have now made possible the routine operation of small accelerators outside the research laboratory and of such a size as to permit their transport to the site of operation. The challenges for small accelerators lie in exploiting new technological approaches and advanced system engineering, providing turnkey operation, enhanced reliability, commercial availability, safe operation with non-specialist operators, cost effective operation, and, most importantly, designs that are application driven. As a further point, small accelerators can be used as test beds for new concepts in accelerator science.

Some examples of the many applications of small accelerators include:

- Nuclear material scanning for proliferation control

- Well logging – water, petroleum, geosciences
- Security and inspection
- Sterilization
- Ion implantation, material modification, and nanofabrication
- Medical isotope production
- Environmental monitoring and remediation (waste management)
- Pollution
- Compact electron accelerators for inspection and therapy
- Accelerator-based sources of both thermal and fast neutrons

The Department of Energy (DOE) provides the largest financial investment in the physical sciences and engineering and funds the majority of large scale science facilities. DOE recently released a major report, "Facilities for the Future of Science: A Twenty-Year Outlook." This report lists 28 facilities, rank ordered in priority, that the Department plans to construct. In effect, the report sets the priorities for large-scale science for the next twenty years. The proposed facilities rely very heavily on advances in accelerator science and technology.

The proposed CAST research program will support R&D directly relevant to the following advanced accelerators: Linac Coherent Light Source, 12 GeV CEBAF Upgrade, RHIC II, eRHIC, and ILC. The CAST educational program would substantially augment the number of young accelerator physicists produced nationally. Thus, the research mission of CAST is very timely and relevant to national needs.

The Office of Science Occasional Paper "Accelerator Technology for the Nation" eloquently makes the case for a new national initiative in accelerator research and development. CAST directly addresses the critical areas identified in this paper:

- CAST proposed research will directly improve the capabilities and operational performance at both CEBAF and RHIC.
- CAST will create new, powerful collaborations between MIT scientists and engineers and scientists at the national laboratories.
- CAST will provide unique educational opportunities and attract a new talent pool into accelerator science and technology.
- CAST will carry out advanced accelerator research which is critically important for the long-term viability of accelerator-based science.

The design, construction and operation of the future machines outlined in the DOE long-term planning will be very challenging technical efforts with important scientific goals. They will provide high technology job opportunities for many young accelerator physicists and engineers. Education and training of accelerator scientists and engineers have been identified as important national priority. With CAST, MIT can make an important contribution to a high national priority through research and education in the area of accelerator science and technology.

1.2 Research Opportunities in Accelerator Science and Technology

Advanced accelerator R&D over the past decade has resulted in several important breakthroughs as well as evolutionary developments. These have been exploited in the new machines that were subsequently constructed and in the upgrade of existing facilities. Some of the most significant recent developments include:

- Space charge compensation scheme for increased beam brightness.

- Increased critical currents in niobium-tin superconductors. This has had a large impact on magnet capabilities. High field final focus quadrupoles in storage rings yield greatly increased luminosities.

- Increased field strength and Q's in superconducting cavities. This is important for future heavy-ion machine design.

- Improved understanding of storage ring beam instabilities. This has yielded unprecedented brightness and beam power.

- High polarization electron guns. Beam polarizations of 80% are routine and near the maximum possible.

There are many opportunities for future research in the field of accelerator science and technology. Key areas include:

- **Theoretical Beam Physics:**

  The stability of intense charged particle beams is a major physics challenge. In linear machines, instabilities can occur due to the wakefields of electron bunches, resulting in trailing bunches being driven off axis. In circular machines, instabilities may also occur due to lattice resonances. Beam halo, the tendency of a beam to develop a set of particles at large radius, is also a serious problem in all high power accelerators.

- **Conceptual Design of Future Accelerators:**

  There is a need for scientists to carry out the detailed design of future machines, including electron, proton, heavy ion and muon accelerators. Some of these machines are already on the list of DOE planned facilities. Others are novel concepts that require detailed planning by accelerator physicists before they can be proposed.

- **Advanced Accelerator Research:**

  Improvements are required in all areas of accelerator performance in order to allow accelerators to achieve higher gradients, lower cost, higher reliability, etc. The research opportunities encompass both physics challenges and engineering challenges. Topics for research include high brightness injectors, high gradient accelerators, advanced structures with reduced wakefields, high power microwave sources, superconducting magnets, control systems, beam focusing, beam optics, lattice properties, beam diagnostics and auxiliary components such as beam switching devices.

- **Novel Accelerator Concepts:**

  Modern accelerators feed RF or microwave power into a metallic slow wave structure for coupling to the particles. This technique is limited to gradients of about 100 MeV/m for electrons and 10 MeV/m for protons. A number of novel concepts are being investigated to overcome these limitations on gradients. Laser accelerators, using vacuum, dielectric or plasma guide media, are being intensively studied both theoretically and experimentally. Two beam accelerator concepts are also under investigation. In one embodiment, a "drive" beam produces an electromagnetic field that can accelerate a following bunch. Such novel concepts are a very rich area for research in accelerator science and technology.

- **Applications:**

  Research programs in accelerator science and technology lead naturally to novel applications of accelerators. A major area of research is the x-ray laser, operating at wavelengths from the UV to the x-ray region where conventional table-top laser technology is inadequate. Seeding the electron beam with conventional lasers is needed to improve beam quality and achieve the shortest wavelengths with the highest efficiency. Accelerators also have major applications in medicine and homeland security. Major accelerators also often develop into large user facilities enabling new research.

The MIT Center for Accelerator Science and Technology is motivated in part by the desire to solidify the above-mentioned efforts as well as to broaden and deepen the scope of accelerator R&D at MIT. CAST would provide new leadership at MIT for accelerator R&D, would attract existing MIT faculty and their groups from across different Departments and Schools, would capitalize on the substantial existing accelerator infrastructure at Bates and PSFC, and would provide a unique and fertile environment in which advanced R&D could blossom and young scientists and engineers would be educated in accelerator science and technology.

There are currently many areas of research in accelerator science and technology in which CAST can play a leadership role. Here a short list of advanced R&D topics that could form an initial core of studies is presented. They represent problems that are at the cutting edge of accelerator science and technology and in which there is already faculty interest and involvement. These include:

- **High Luminosity Lepton-Ion Collider:**

  Design of a high luminosity (~10^{33} nucleon cm^{-2} s^{-1}) electron-ion collider in the center of mass energy range 30 to 100 GeV for nuclear physics is underway by MIT-LNS physicists in collaboration with MIT faculty and physicists at Brookhaven National

Laboratory, DESY in Hamburg, Germany and the Budker Institute in Novosibirsk, Russia. This next-generation facility for research into the fundamental structure of matter will study the spin structure of the nucleon, provide precise measurements of the gluon distribution in atomic nuclei, and together with new QCD predictions from lattice calculations provide a set of stringent tests of the strong interaction sector of the Standard Model.

The present design concept is based on a 10 GeV electron/positron storage ring colliding with the 250 GeV polarized proton and heavy ion beams of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The lepton beam is highly polarized and is fed from a polarized electron source using a full energy linac. The design is based on realistic parameters from the B-factories and the RHIC accelerator. The principal technical challenges are to implement electron cooling of the ion beam, to maintain high beam polarizations over a range of luminosities and to absorb high levels of synchrotron radiated power in the arcs of the lepton ring.

- **X-ray laser:**

Research and development toward a fully coherent x-ray laser is now in progress at MIT, involving Physics and Electrical Engineering and Computer Science (EECS) faculty working with MIT Bates accelerator scientists. The linear-accelerator-based technique of Self Amplified Spontaneous Emission (SASE) has been demonstrated at several laboratories worldwide, and is now the basis for the Linac Coherent Light Source (LCLS) project at SLAC and the TESLA XFEL project at DESY. This process produces intense mJ x-ray pulses of about 100 femtosecond duration with 0.1% longitudinal coherence. Such systems are not true lasers, which will eventually limit their range of scientific applications. MIT physicists and engineers are working on seeding the electron beam with a fully coherent signal using conventional lasers. Seeding has enormous advantages, since x-ray pulses can achieve the transform limit defined by the Uncertainty Principle. The fully coherent pulses can be either sub-femtosecond pulses with eV bandwidths, or extremely narrow (millivolt) bandwidth pulses with picosecond time duration. Other concomitant advantages of seeding include achieving femtosecond synchronization for pump-probe experiments and high pulse-to-pulse stability. The use of high-pulse-rate superconducting RF cavity technology will allow many tens of independently tunable x-ray beamlines (wavelength range from 200 nm to 0.1 nm). A new generation user facility is envisioned that will have spectacular scientific impact in biology, chemistry, condensed matter physics, materials science, engineering, and fundamental physics. It is clear that the x-ray laser design will demand high performance, at or beyond today's capabilities, in many exciting R&D areas. These include development of high brightness photoinjectors, seeding of the x-ray laser which demands exquisite timing precision of multiple systems, and optimized RF systems for superconducting cavity technology.

- **International Linear Collider (ILC):**

  The ILC is proposed as the next major electron accelerator for high energy physics. It is a 0.5-0.8 TeV electron – positron collider. Research opportunities exist on this machine covering all aspects of accelerator science and technology. These include research on the structures, microwave sources and microwave distribution system. They also include design of the machine itself, including the damping rings, the final focusing system and the diagnostics of the TeV beam. In particular, the ILC detector will be an integral part of the accelerator which will bring together machine and particle physicists.

- **Accelerator Research for Heavy Ion Fusion (HIF):**

  Inertial fusion energy (IFE) relies upon the DT fuel's inertia to hold it together as it is being heated and undergoing fusion. In IFE, an energetic laser or charged-particle beams are used to heat a small (~1 cm) inertial fusion target for about 10 nanoseconds. Although at present IFE is mainly studied with laser beams, it is believed that charged-particle beams, in particular Heavy Ion beams, are the most practical approach to a demonstration of IFE. In the US, HIF research is focused on the development of induction accelerators capable of delivering 5 MJ of energy of 3 to 10 GeV ions on the target in a 10 ns pulse at a repetition rate of 5 Hz. Challenges in HIF accelerator research include understanding the Heavy Ion injector, the beam quality, emittance growth in the accelerator, beam halo, beam combining and many engineering features of the accelerator. Opportunities exist both in experimental and theoretical research.

- **Low Energy Electron Accelerators**:

  Electron machines in the 5 to 50 MeV energy range have numerous research and engineering applications. Applications include isotope production, high energy x-ray imaging and tomography, aircraft security and detection, waste technologies, and the development of test beds for pulsed cold neutron sources. New areas of cross-disciplinary research include slow positron production, photon activation analysis, coherent x-ray production and materials analysis using nuclear fluorescence. The Nuclear Engineering Department is currently actively involved in this area of research.

- **Development of Compact Accelerators:**

  An important new area of research and development in accelerator science and technology is compact accelerators for a variety of applications in materials science, medicine and security. At the present time there is strong interest not only within the DOE community but also within the DOD, DHS, and NIH where size is a critical issue. These small machines can be the test beds for future development of larger and even smaller machines.

1.3 Synergy Among DOE Accelerator Programs

Many of the accelerator development efforts described here are applicable across a number of DOE programs. The topics were explicitly chosen to address common systems. For instance superconducting RF development is needed for the Jlab 12 GeV upgrade, RIA, e-cooling of RHIC, the ILC, SNS, ERLs, and an x-ray FEL user facility. These projects span the programs in nuclear physics, high energy physics, and basic energy sciences. Although designs of the final accelerator modules are likely to differ for these programs, there are many common systems such as low level RF development, power sources that are stable and efficient, and automated control systems.

Another system common to most new electron accelerators, such as LCLS, the ILC, e-cooler, and ERL, is a photoinjector, possibly polarized, using either DC or RF accelerating modules. MIT personnel have extensive experience with both polarized DC and RF photoinjectors and are actively working with other laboratories on their further development. The development of better injectors has a large impact on the total cost and performance of major accelerator projects.

Accelerator-based science relies increasingly on precise timing synchronization of beams that collide, or on overlap between multiple beams of photons and electrons. Likewise improved control and stability depends on synchronization of many RF sources spread over a large facility. MIT is a recognized leader in laser-based synchronization, and research is underway to expand this program to synchronization of RF sources and electron beams. This work is expected to produce unprecedented timing synchronization allowing, for instance, sub-ps synchronization of the 30 km long ILC, or for linac-based accelerators to achieve the mature stability of rings, or exquisitely synchronized pump-probe experiments at LCLS.

1.4 Accelerator Science and Technology at MIT

Accelerator science and technology have historic roots and a tradition at MIT that extends for more than half a century. MIT faculty, including Van de Graaff, Slater, Livingston, Demos, Osborne, Frisch and Wall played leading roles in designing, constructing and operating accelerators for research. The earliest particle accelerators at the Institute included a Van de Graaff, an S-Band linac and a synchrotron. These were soon followed by a cyclotron, the Cambridge Electron Accelerator and the Bates Linear Accelerator. Hundreds of graduate students made use of these facilities to support their thesis work. Although accelerator physics itself was not formally a component of research or of the education of students, many students and faculty spent as much or more effort on accelerator science and technology as they did on nuclear or particle physics. In the process they contributed to the advance of accelerator science and technology nationally, which subsequently led to the construction of more advanced machines elsewhere.

CAST will focus research efforts from both the School of Science and the School of Engineering. Many MIT Departments and Laboratories see the Center providing an important connection to their research activities. These include:

- Physics
- Chemistry
- Laboratory for Nuclear Science
- Plasma Science and Fusion Center
- Nuclear Engineering
- Materials Science and Engineering
- Electrical Engineering and Computer Science

At present, activities in accelerator R&D at MIT are focused principally at the Bates Linear Accelerator Center, the Plasma Science and Fusion Center, and within the Department of Nuclear Engineering. At Bates, an accelerator physics group has been principally engaged in the development and delivery of intense polarized electron beams from the South Hall Ring for the nuclear physics user program. They have also played a leadership role in the development of a conceptual design for the proposed eRHIC lepton-ion collider at Brookhaven National Laboratory. Further, in collaboration with other MIT scientists and engineers they have played a central role in the development of a conceptual design for an x-ray laser. At the PSFC, high-gradient accelerating structures relevant to the ILC are under development. In addition, experimental research on novel high-power microwave sources and theoretical study of formation and propagation of high brightness beams are in progress. In the Department of Nuclear Engineering, R&D into low energy accelerators for cargo screening is underway, as well as research on accelerator-based fast neutron brachytherapy and proton microbeams for sub-cellular and single particle irradiation of cells.

With the phase-out of the Bates nuclear physics user facility in FY2005, a unique opportunity exists to retain the Bates accelerator complex, the highly trained accelerator physics group and associated technical personnel as essential elements in CAST. Together with the facilities at the PSFC and the Nuclear Reactor Laboratory, CAST can provide access to a unique suite of particle accelerator facilities in a university setting. Students can be educated using 'hands on' experience and cutting edge accelerator R&D can take place at the university campus.

An essential aspect of CAST involves close collaboration among both physicists and engineers. While the accelerator physicist is responsible for developing the fundamental understanding of new phenomena, the engineer is essential in achieving its technical realization and system design. State-of-the-art accelerators routinely push the envelope of physics and mechanical and electrical engineering. An excellent example of this is the ongoing collaboration between Prof. Kaertner's Electrical Engineering Group and the Bates accelerator physics group on seeding of x-ray lasers.

1.4.1 Bates Linear Accelerator Center

The Bates Linear Accelerator Center, located on an 80 acre site about 25 miles northeast of MIT in Middleton, Massachusetts, is funded by the Department of Energy and operated by

MIT as a national user facility for experimental nuclear physics. The Center was built and operated by MIT faculty, scientists, engineers and students. A staff of 75 scientific and technical personnel operates and maintains the facility for over 200 users from more than 50 institutions worldwide. Bates delivers both polarized and unpolarized electron beams in the energy range 125 MeV to 1 GeV to two experimental areas. Figure 1.1 shows a schematic layout of the accelerator complex, including the 500 MeV linear accelerator, the recirculator that doubles the energy to 1 GeV, the South Hall storage ring, the energy compression system and the polarized electron source.

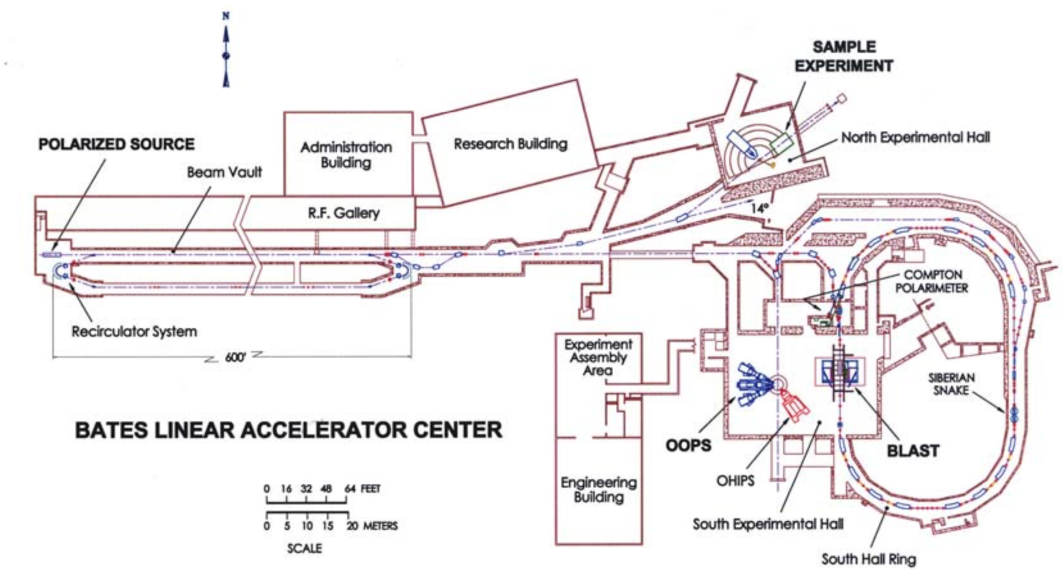


Figure 1.1: A schematic layout of the Bates accelerator complex.

Since the initiation of experiments in 1974, the Bates laboratory has carried out frontier research in nuclear physics. Bates pioneered technical developments in many areas: high duty factor accelerators, beam recirculation and energy doubling, polarized electron beams, spin manipulation, high resolution spectroscopy, large acceptance coincidence experiments and internal target physics with high energy, high intensity storage rings. Research highlights include the understanding of deformed nuclei using high resolution electron scattering in the 1970's; pioneering experiments on light nuclei in the 1980's; and the study of proton structure using parity violating electron scattering in the 1990's. At present, a central research focus at Bates is the study of the fundamental properties of the nucleon, including its shape, magnetism and charge distribution. A major new detector, the Bates Large Acceptance Spectrometer Toroid (BLAST) has been constructed and is taking data on spin-dependent electron scattering from both vector and tensor polarized deuterium at 850 MeV energy. BLAST is scheduled to take data until the end of 2004. The present understanding between DOE and MIT calls for a phase out of the nuclear physics user facility at Bates after the BLAST program is completed.

Over the last fifteen years, there has been a sustained investment by the Office of Nuclear Physics in refurbishing and upgrading the Bates accelerator complex. This has involved a complete upgrade of the linac vacuum system, a complete realignment of the linac magnetic systems, enhanced diagnostic instrumentation, upgraded klystrons and RF switches and a modern controls system, EPICS (Experimental Physics and Industrial Control System). The

South Hall Ring, constructed in 1988-92, is a state-of-the-art 1 GeV storage ring which is routinely storing 195 mA of 65% polarized electron beam for the BLAST experiment. With a reasonable level of support as outlined in this document and a careful transition from nuclear physics user facility to CAST, the Bates accelerator complex can have a lifetime of several decades.

The EPICS control system has been essential in minimizing the human resources necessary for accelerator operation to the point where the polarized electron source, linac, recirculator, South Hall Ring, and BLAST experiment is successfully controlled for extended periods of production data taking by a single operator. Figure 1.2 shows a recent screen shot from the Bates control system illustrating the automated character of beam delivery and data taking with the BLAST experiment. The BLAST experiment is similarly automated so that the BLAST data taking can be successfully carried out by a single experimenter.

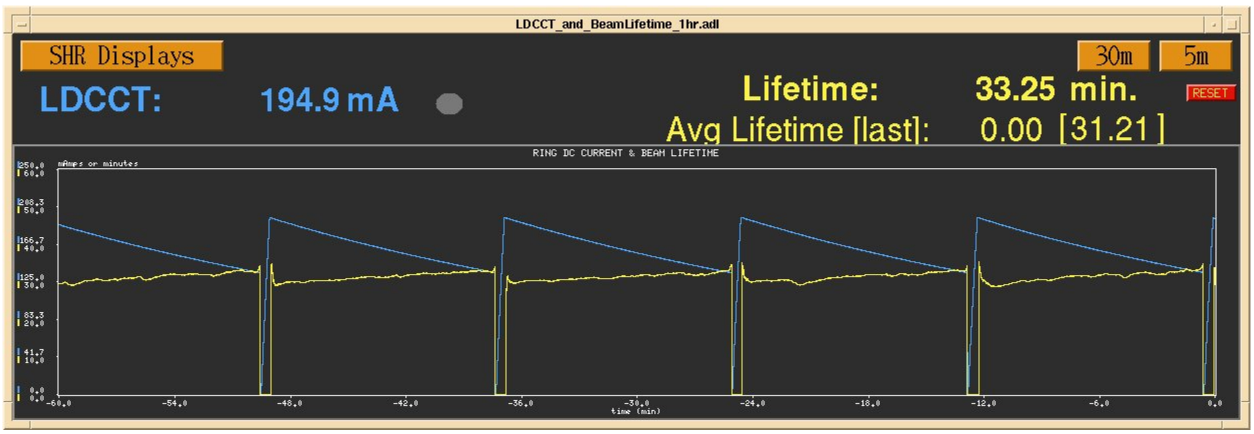


Figure 1.2: A screen shot from the EPICS control system at the Bates Linear Accelerator Center taken in December 2004. The blue (yellow) curve indicates the stored current (lifetime) in the SHR as a function of time. The instantaneous numerical values are printed on the top of the panel.

The integrated charge delivered to BLAST over more than a five month period in 2004 is shown in Figure 1.3. Figure 1.4 shows the polarization of the stored electron beam over an extended period.

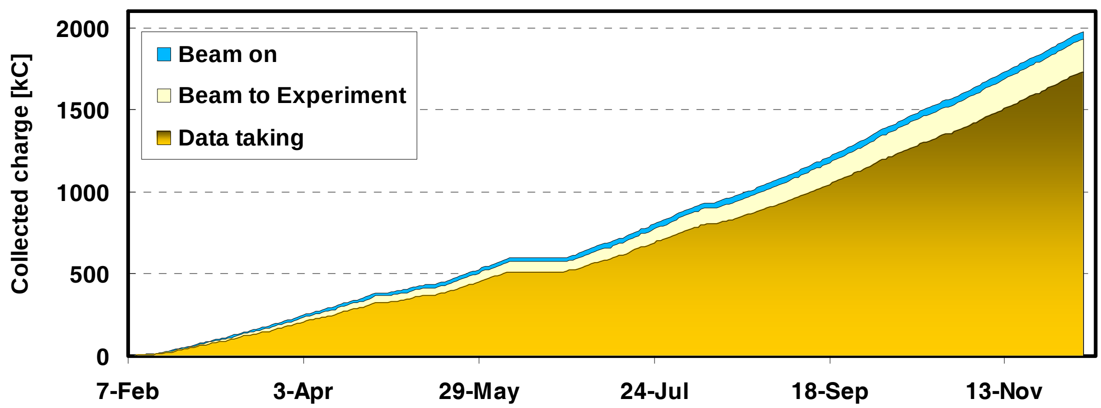


Figure 1.3: The integrated charge delivered to the BLAST experiment (shaded area) at the South Hall Ring from February to December 2004.

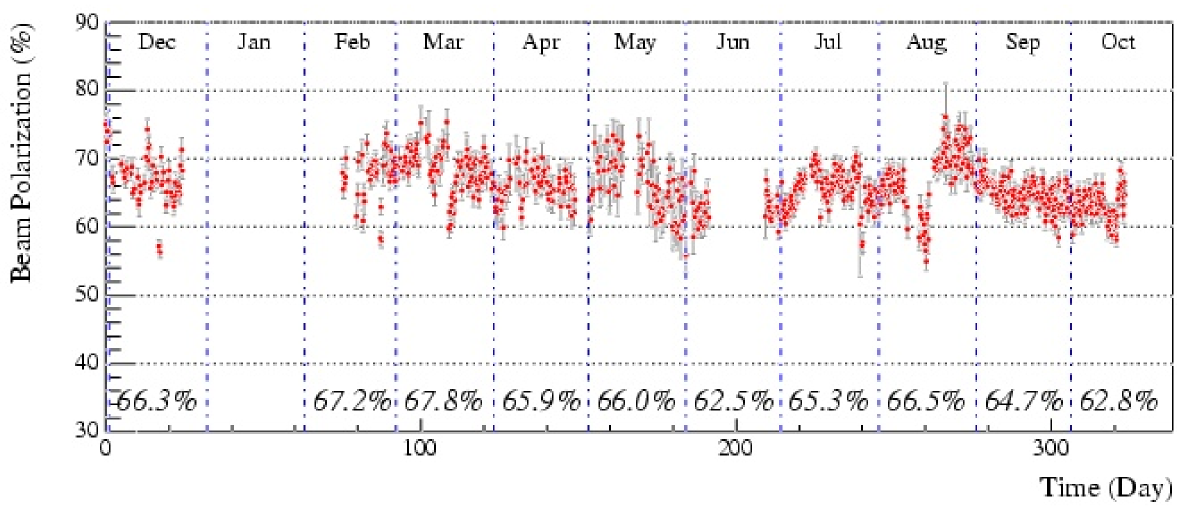


Figure 1.4: The polarization of the stored beam in the South Hall Ring for the BLAST experiment as measured with a Compton backscattering polarimeter from December 2003 to October 2004.

In the Bates linac six new modulators provide pulsed power to 12 klystrons. These innovative direct switch devices support 150 kV, 100 A pulses with rise and fall times of less than one microsecond at kHz repetition rates. The RF group at Bates designed and built this new switching circuit by combining traditional switch tubes with state-of-the-art solid-state switches recently developed by Diversified Technologies, Inc (DTI). The new circuit has greatly improved pulse stability, reliability, efficiency and ease of accelerator operation at Bates.

Based on this successful modulator development at Bates, DTI has pursued the new high-voltage solid-state switching technology in a number of applications. One such application is to replace vacuum tube modulators in the transmitter for two important U.S. Navy shipboard radar systems. In addition, missile-range instrumentation radar systems have transmitter pulse modulators which are candidates for solid-state upgrades. This new technology represents the next step forward in modern high-power transmitter and radar design.

A good example of development of beam diagnostic techniques at Bates is an on line betatron tune measurement in South Hall Ring using a "Tune Sweeper" comprised of an EPICS controlled RF oscillator. This diagnostic is an excellent on-line indicator of any slight changes in the beam betatron tunes. Maintaining a good working point is essential to the stable operation of the Bates internal target experiment with high stored beam current and high equilibrium polarization. Figure 1.5 shows a typical data set on the stability of the tune.

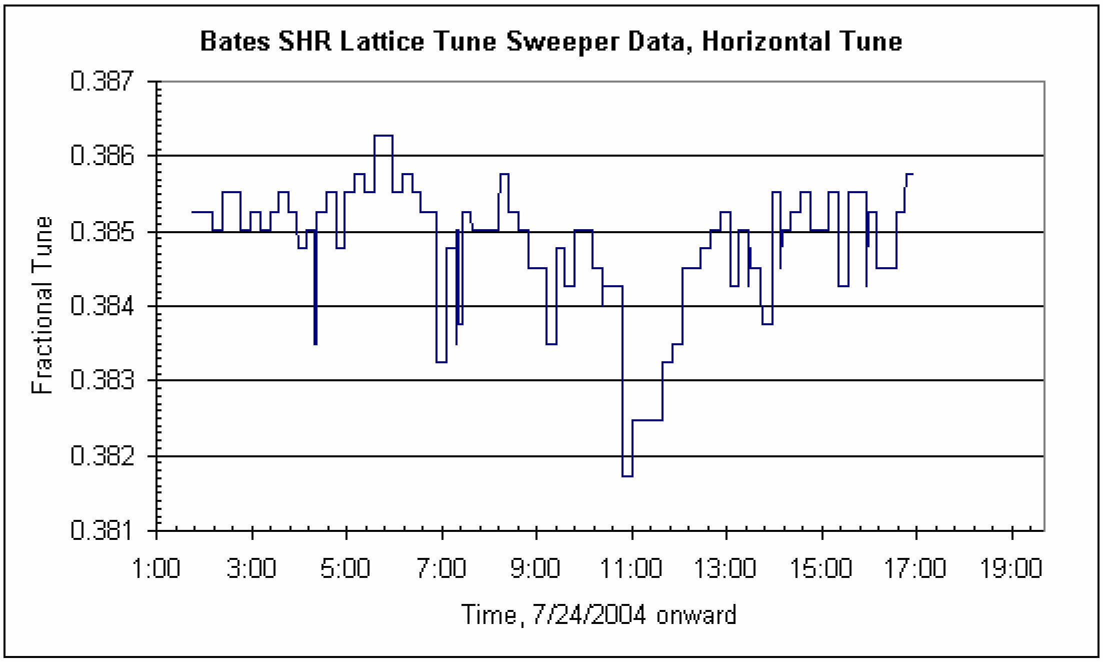


Figure 1.5: Fractional contribution to the SHR horizontal betatron tune (7.385) as a function of time. The tune is stable to 0.001

The staff at Bates has developed considerable expertise in particle accelerator R&D. Recent achievements include:

- Successful construction and operation of the 1 GeV South Hall Ring which delivers up to 195 mA of longitudinally, highly polarized electrons for internal target physics with the BLAST detector
- Successful development of a polarized electron source which has been used for parity violation studies (SAMPLE) and is used to feed the South Hall Ring
- Development of high power, fast solid-state switches for the klystrons. These are in commercial production by industry and have had significant impact on radar tracking of ballistic missiles.
- Leadership role in collaboration with BNL in the development of the design for the lepton-ion collider eRHIC.

In addition to strength in accelerator physics, Bates has a small but outstanding group of engineers and technicians with the demonstrated ability to design and construct novel instrumentation, e.g. magnetic spectrometers, polarized targets, beam instrumentation and controls systems. These highly valuable professionals are an essential element of both the Research and Engineering Laboratory and CAST.

A major impact of a university based laboratory like Bates is the ability to educate and train high quality students. Since the start of experiments in the early 1970's, over 110 Ph.D.s have written their theses on research carried out at Bates and by the end of the BLAST experiment this will have grown to over 120. These students are widely sought in industry and research laboratories. Over 25 Bates educated Ph.D.s are in academic positions worldwide. With the establishment of CAST, a similar rate of production of high quality young accelerator physicists can be anticipated. This would substantially increase the national production rate of accelerator physicists (at present about ten per year).

LNS currently has a cooperative agreement with the DOE in Nuclear Physics and High Energy Physics which includes the Bates Nuclear Physics Facility through mid FY2005. After the completion of the nuclear physics user facility program it is proposed beginning in late FY2005 that the core experimental support facilities operate as the Bates Research and Engineering Laboratory. The scientific and engineering talents and infrastructure would be utilized to support LNS research activities, especially those at JLAB and BNL and possibly those at high energy facilities as well. The Laboratory is expected to play an important technical role in launching and supporting major new MIT/LNS research projects at these and other off-campus facilities. Important efforts could include R&D in the design, construction and testing of new detector technologies.

Operation of the Laboratory will be overseen by a Manager (a senior LNS physicist) reporting to the LNS Director. The Manager will be advised by an LNS Standing Committee. The initial activities envisaged for the LNS Research and Engineering Laboratory call for a staff of approximately 15 FTE's including physicists, engineers, technicians, and support staff. Funding for capital equipment is anticipated to be associated with specific research projects.

1.4.2 Plasma Science and Fusion Center

The Plasma Science and Fusion Center has played a leading role as a university laboratory in developing the scientific and engineering aspects of magnetic confinement fusion and related plasma science and technology. One of the primary goals of the Center is to carry out research and educate scientists in advanced accelerator science and technology. The areas of research in accelerator physics include high power microwave sources (gyrotrons), novel electromagnetic structures (photonic band gap resonators), periodic focusing of high-intensity charged particle beams, the study of chaos and coherent structures in beams and the non-linear dynamics of heavy ion beams for use in fusion technology. Research is also conducted on high performance superconducting magnets for present-day and planned future accelerators. Current areas of study include:

- High gradient structures necessary for reducing the size and cost of future accelerators, such as the ILC and its upgrades. Scientists and engineers at the PSFC and their collaborators have built a 25 MeV electron accelerator demonstrating a 50 MeV/m acceleration gradient. This is the highest frequency (17 GHz) stand-alone accelerator in the world and the most powerful accelerator on the MIT campus.

- Ongoing experimental accelerator research at the PSFC also covers such areas of interest as novel high-power microwave sources; novel accelerator structures, such as the photonic bandgap structure; RF photoinjectors yielding high-brightness electron beams; diagnostics of femtosecond electron bunches; coherent radiation generation by electrons; and superconducting magnets.

- Theoretical research at the PSFC covers methods of forming and propagating intense high brightness beams. The research supports future electron machines, such as the ILC, and also the program of research on Heavy Ion accelerators for fusion energy production.

- A diagnostic neutral beam for measuring plasma parameters on the Alcator Tokamak and a charged particle accelerator for testing spectrometers used in laser fusion research at Lawrence Livermore Labs.

1.4.3 Nuclear Engineering

MIT has a number of other research programs in accelerator science and technology. In the Nuclear Engineering Department's program of Bionuclear Engineering, there is research on accelerator-based fast neutron brachytherapy and proton microbeams for sub-cellular and single particle irradiation of cells. The Center would provide a technical resource, as needed, for these smaller projects and would provide educational programs for students.

1.5 Funding of CAST

In this proposal, initial funding for CAST is requested from the Office of Science in the United States Department of Energy. This would fund a research program described in Chapter 2, as well as an educational program described in Chapter 3. CAST is proposed by faculty and senior research scientists at present carrying out research supported by Nuclear Physics (Bertozzi, Kowalski, Matthews, Milner, Surrow and Tschalaer), by High Energy Physics (Becker, Fisher, Temkin and Yamamoto), and by Basic Energy Sciences (Moncton). To further strengthen CAST additional faculty with strength particularly in accelerator physics are being sought.

The CAST educational program is directly relevant to the mission of the Office of Workforce Development for Teachers and Scientists but would also clearly be of great benefit across the research scope of the DOE Office of Science. It will significantly increase the number of students trained nationally in accelerator science and technology.

MIT support will be essential to provide campus space for CAST, as well as facility, infrastructure, EH&S and administrative support at the Bates site. This support is described in Chapter 5 and is costed in Chapter 6.

Chapter 6 provides a detailed justification for the funds requested starting in FY2006 to support a CAST staff of 16 FTEs (all existing Bates personnel), 5 post-docs and 5 graduate students. It also details the capital equipment funds required to initiate the CAST research program as well as the personnel and funding required to deliver test beams from the Bates accelerator for 1500 hours per year. Table 1.1 summarizes the requested CAST funding with respect to the different Program Offices within the DOE Office of Science.

Table 1.1: Summary of CAST funding request by Program Offices in the DOE Office of Science.

Funding Allocation		**FY2006**	**FY2007**	**FY2008**
Nuclear Physics	**k$**	**2606**	**2776**	**2924**
	(%)	(43)	(44)	(43)
Basic Energy Sciences	**k$**	**2215**	**2302**	**2562**
	(%)	(36)	(37)	(38)
Workforce Development	**k$**	**868**	**889**	**917**
	(%)	(14)	(14)	(14)
High Energy Physics	**k$**	**451**	**322**	**329**
	(%)	(7)	(5)	(5)
TOTAL	**k$**	**6140**	**6289**	**6732**

In Chapter 4, other accelerator research in the area of applications is described. Additional funding from other sources will be pursued to support this effort.

2.0 CAST RESEARCH PROGRAM

2.1 Introduction

In this chapter, the proposed CAST research program is described. It is shaped primarily by the major scientific interests of present MIT faculty and is matched to the expertise of the CAST scientific staff. There are two central thrusts of the initial CAST research program proposed here: accelerator R&D for nuclear physics, and accelerator R&D for advanced light sources relevant to basic energy sciences.

Accelerator R&D for Nuclear Physics

CAST scientists propose to initiate a program of accelerator R&D on high priority research in collaboration with the flagship Nuclear Physics facilities in the United States. Projects have been carefully selected which are a good match to existing MIT expertise and infrastructure.

- Polarized electron source development

The CAST polarized source research strives to attain beams with very high polarization in combination with the high peak and average currents needed for efficient operation. This research has direct benefits for nuclear physics accelerators, particularly for the nuclear physics program at Jefferson Lab, as well as for high luminosity lepton-hadron colliders like eRHIC and ELIC. In collaboration with Jefferson Lab, we are proposing research in polarized electron source development that can lead to higher beam polarization and higher beam time up on the CEBAF accelerator, resulting in an increase in the efficiency of the CEBAF operation. This will be achieved by a redesign of a newly constructed load lock gun intended for use in the CEBAF main injector and redesign and modification of the photocathode. This would permit insertion to the main injector of high quantum efficiency (QE) and high polarization photocathodes pre-qualified in the test setup, without compromising the UHV conditions of the sample photocathode and the gun chamber. This will have a major impact on the cost effectiveness of the CEBAF accelerator. New directions in polarized source development are also under consideration that can lead to new sources essential for high luminosity lepton-ion colliders.

The proposed CAST research (see Section 2.2) builds on over two decades of polarized electron source development at Bates. This work has pioneered parity violating electron scattering measurements for study of hadron structure as well as producing the world's highest intensity polarized electron beam for BLAST – 150 mA of 850 MeV 70% polarized electrons stored in the South Hall Ring [Far02, Zwa01].

Dr. Manouchehr Farkhondeh, an internationally recognized leader in the area of polarized electron sources, will coordinate the CAST polarized electron source research.

- Design and construction of a new ion source for RHIC

BNL has proposed to design and construct a new heavy ion preinjector for RHIC based on an Electron Beam Ion Source (EBIS), Radio Frequency Quadrupole (RFQ) accelerator and a short linac. The new injector is essential for an increase in the luminosity and performance of RHIC. There is a mutual interest between BNL and MIT to utilize the considerable expertise at MIT-Bates in the areas of RF technology, accelerator cavities, accelerator controls and ultra high vacuum in the design and construction of EBIS. The scientists and engineers at MIT with many years of experience in these areas are proposing, as part of CAST, to design and construct the short linac system of EBIS and the RF system for the RFQ accelerator (see Section 2.8). Dr. Jan van der Laan, an experienced accelerator physicist, will oversee the EBIS activities at MIT.

- Design of a high luminosity polarized lepton-ion collider

The proposed CAST collider beam physics research will address critical issues facing the design of future high luminosity lepton-ion colliders, especially the proposed eRHIC machine [eRH03, Far04] at BNL. MIT scientists are playing a leading role in both the development of the scientific case and the machine design in the international effort to realize a high luminosity lepton-ion collider. The detailed CAST studies (see Section 2.4) will include the lepton collider storage ring lattice, the beam polarization in lepton rings, beam-beam effects and two-stream beam instabilities in lepton-hadron colliders, spin studies for a booster synchrotron and high precision polarimetry for the lepton rings. In addition, CAST physicists will be available to carry out simulations of the RHIC polarized proton beam to optimize beam polarization and collision luminosity for the RHIC-spin program. The work will be carried out in close collaboration with Dr. Desmond Barber from DESY, Hamburg, Germany as well as physicists from Brookhaven National Laboratory.

Dr. Fuhua Wang is leading the MIT design of the high intensity lepton storage ring. Dr. Christoph Tschalaer and Physics Profs. Richard Milner and Bernd Surrow are leaders in the international effort to realize a high luminosity electron-ion collider.

Accelerator R&D for Advanced Light Sources Relevant to Basic Energy Sciences

Over the past 2 years MIT has been actively pursuing research towards an x-ray laser based on an FEL. We have joined in collaborations with ANL, LBNL, TJNAF, and DESY, and are in discussions with other labs. Recent staff additions for this effort include Dr. David Moncton, former Director of the Advanced Photon Source at ANL, and Dr. William Graves, a principal in the seeded FEL experiments carried out at BNL. In addition, Professor Franz Kaertner has focused his research on synchronization and laser issues, demonstrating extraordinary advances in timing of microwave and laser sources, and Dr. Townsend Zwart has spent several months at DESY carrying out experiments in CW superconducting RF. MIT recently hosted an ICFA Workshop on the Physics of Seeded Free Electron Lasers [ICF04] attended by leading accelerator and laser scientists from around the world.

For CAST we are proposing work in areas that will have immediate impact on current projects such as LCLS at SLAC and DESY's VUV-FEL, and also are proposing longer term work toward development of high repetition rate linacs that would be appropriate to serve a large user facility based on an FEL. Four areas of research in advanced light sources are proposed:

- Development of a high brightness photoinjector

RF photoinjectors are the focus of much interest in achieving low emittance electron beams for several applications, including x-ray FELs, energy recovery linacs, and a linear collider where it obviates the need for damping rings. The proposed photoinjector work (see Section 2.2) is synergistic in terms of manpower, expertise and infrastructure with the polarized electron source research discussed above. Dr. William Graves will lead the CAST photoinjector research.

- Development of an RF amplifier and reactive tuner for superconducting cavities

The proposed CAST research (see Section 2.3) to develop a CW RF amplifier, tuner, and controls for lightly loaded superconducting cavities is motivated by the desire to greatly reduce the power delivered to the cavity, thus substantially reducing the capital and operating costs associated with these devices. The success of this effort can have a major impact on the operation of an energy recovery linac or x-ray FEL. Dr. Townsend Zwart is leading the superconducting RF research.

- Development of femtosecond Synchronization Techniques

Timing synchronization between optical and electron beams at the femtosecond level, and distribution of clock signals over large facilities with the same precision, is increasingly important to the next generation of x-ray experiments that examine transient phenomena. A program focused on advanced methods of synchronization of lasers, RF, and electron beam is proposed in Section 2.5. Professor Franz Kaertner is leading the synchronization effort.

- Bunch Compression and High Brightness Beam Physics

A number of the most interesting problems in beam physics revolve around the production of very bright, short pulses of electrons. Topics such as emittance compensation, space-charge instabilities, microbunch instabilities, and the achievement of large compression ratios while preserving beam quality are all of current interest and likely to have large impact on the cost and performance of accelerator facilities such as LCLS. Section 2.4 addresses research and education in these areas. Dr. William Graves will coordinate the linac beam physics research.

Accelerator R&D for High Energy Physics

The third research focus of CAST will be accelerator R&D relevant for High Energy Physics. It is proposed in Section 2.6 that Dr. Richard Temkin will lead a study of coherent radiation using the Bates electron beam, which could result in new uses of radiation in beam diagnostics. In addition, Chemistry Prof. Keith Nelson has proposed a novel laser acceleration technique (see Section 2.7) which his group will study as part of the CAST research program. If successful, this technique has the potential to produce multi-MeV electron beams using a more compact accelerator. Such beams are of wide interest for accelerator applications (see Chapter 4).

At this time, the most important future accelerator project for High Energy Physics is the International Linear Collider (ILC). Section 2.10 describes the MIT participation in the ongoing planning for realization of ILC. CAST can play a significant role in the machine R&D for the ILC.

The proposed CAST research program will have the necessary components to a) provide training for undergraduate and graduate students in accelerator science, b) advance the state of the art in each area, and c) provide design concepts and detailed technical guidance for future accelerators.

The proposed CAST program in this chapter addresses high priority research in several Program Offices in the Office of Science at DOE. There are seven R&D topics proposed for CAST that are divided into Nuclear Physics (NP) and Basic Energy Sciences (BES) Program Offices and two topics that are more general, appropriate for High Energy Physics (HEP). Table 2.1 lists R&D areas, the lead MIT scientist and the relevant Program Office.

Table 2.1: Assignment of CAST R&D topics to the DOE Program Offices.

	CAST R&D Topics	**DOE Program Office**
1	Photoinjector	
	a. RF photoinjector (W. Graves)	BES
	b. Polarized source (M. Farkhondeh)	NP
2	RF amplifier and reactive tuner for SC cavities(T. Zwart)	BES+NP
3	Beam physics for x-ray lasers and storage rings	
	a. linac beam physics (W. Graves)	BES
	b. EIC beam physics (F. Wang)	NP
4	Femtosecond beam synchronization (F. Kaertner)	BES
5	EBIS for RHIC (J. van der Laan)	NP
6	Beam physics (R. Temkin)	HEP
7	Laser electron acceleration (K. Nelson)	HEP

The remainder of this chapter contains a detailed description and motivation for each of these seven R&D areas.

2.2 Photoinjector Activities

An important thrust of the CAST research program is related to the injectors which generate electron beams. Due to rapid progress in fields like laser and semiconductor technology, photoinjectors now provide an excellent versatile method of producing intense electron beams with carefully tailored properties. This versatility is reflected in the diverse pursuits of the two major CAST photoinjector initiatives described in this section: RF photoinjector research for a high-brightness linac, and polarized electron source research and development geared toward an advanced lepton-ion collider and increased beam delivery efficiencies at existing flagship accelerators like Jefferson Lab. Although the aims of these programs differ, they share the need for advanced laser systems, ultra-high vacuum technology, and state-of-the-art controls. It is clear that physical proximity of these groups and exchange of ideas will strengthen both activities, each of which is described in detail below.

2.2.1 High Brightness RF Photoinjector

A recent BESAC subcommittee report [Ric03] on the DOE 20-year facilities plan ranked research on photoinjectors (and training in accelerator design) among its highest priorities. This is because of the large impact that injector performance has on future light source performance. RF photoinjectors have emerged over the last decade as the primary choice in electron sources for accelerators requiring the brightest beams. These beams are important today for driving prototypes of the next generation of light sources based on free electron lasers (FELs) and energy recovery linacs (ERLs), which currently operate in the IR to UV spectral range. In the future they will produce hard x-rays from user facilities [LCL04, XFE03, MIT04, LUX04, BES04, CHE03], which will place a premium on both injector performance and reliability.

Photoinjectors have additional applications across many disciplines, including electron cooling of heavy ions [Ben03], as an injector for an electron-ion collider [eRH03], and as a compact source of Compton x-rays [Gib04]. With continued improvements in performance, an injector could produce beam with emittance low enough to allow construction of a Linear Collider without damping rings [Bri01], saving substantial money. Improvements in our understanding of the physics and engineering of photoinjectors, and in their delivered beam properties, will result in less expensive and higher performance accelerator facilities.

The primary purpose of the injector is to generate a very low emittance beam at the cathode, and then to accelerate that beam to relativistic energy without irreversible emittance growth. The great challenge is to control nonlinear space charge forces, which are the primary cause of emittance growth, while producing the desired pulse shape in all dimensions with adequate charge.

Despite the current good performance, there is much room for improvement, and experimental results have not reached the very high level of performance predicted by computer codes. It is recognized that the discrepancy lies in generating and measuring the desired experimental conditions [Gra01a, Ros01, Gra01b], rather than weakness in the physics of the codes. Additionally, today's photoinjectors have been designed for low repetition rates (10 – 120 Hz) whereas user facilities are likely to require very bright beams generated at rates of tens of kilohertz or higher. The high average power required by this next generation of photoinjector drives important design changes.

It should be noted that the current Bates S-band linac is one of very few facilities operating at high repetition rate (up to 1 kHz) at this frequency. As such it is capable of testing LCLS accelerator components at their full repetition rate, and to the greatest extent possible we will choose frequencies and repetition rates compatible with LCLS.

In the sections below we describe research efforts that address the physics and engineering issues required to improve the performance of existing injectors, and also work toward a next generation, high repetition rate injector. Following this two pronged approach, we propose adding an existing commercially available photoinjector [AES04] to the existing Bates linac to study beam dynamics and develop specialized instrumentation, and also pursue research into a next generation injector with improved beam characteristics and higher repetition rate.

There is substantial expertise at MIT-Bates on the relevant topics, including RF photoinjector beam dynamics and instrumentation, RF controls, and high average power sources. Members of the Optics and Quantum Electronics Group in the Electrical Engineering and Computer Science department have expertise in short-pulse solid-state laser design. In addition we are collaborating with members of the Beam Electrodynamics Group at LBL, led by John Corlett, on design and development of the high power RF cavities for the next generation injector.

An RF photoinjector consists of several components, including one or more pulsed RF cavities with a high accelerating gradient (10 – 100 MV/m) in each cell, a photocathode in the first cavity, and a drive laser to excite electrons from the photocathode. Stable high-power klystrons and modulators are required to power the RF cavities. Focusing solenoid magnets are required to match the electron beam into a post accelerator. What is critical to obtaining the best performance is a broad suite of instrumentation that can measure the properties of the laser, cathode condition, RF and magnetic fields, and the detailed phase space properties of the generated electron beam distribution. The range of disciplines covered, the small size of the systems, and the high impact of improved performance make photoinjector development well-suited to the expertise and educational goals at MIT.

Photoinjector Upgrade of Bates Linac

The Bates Center currently operates a 500 MeV S-Band linac with a polarized DC electron injector [Far02]. With the addition of an RF photoinjector and associated diagnostics this facility could test all aspects of bright electron beam physics and would make an excellent training base for MIT's initiative in accelerator science and engineering. We propose to add an S-band RF photoinjector to the existing linac.

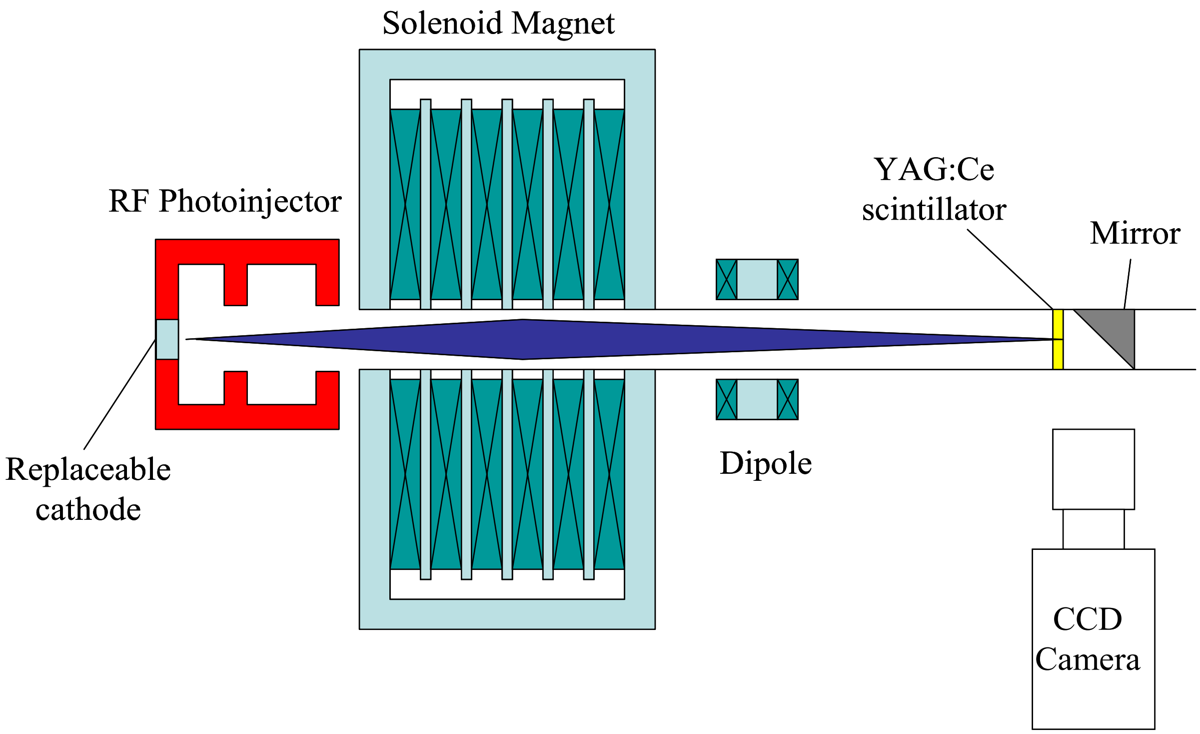


Figure 2.1: Layout of solenoid scan measurement of intrinsic emittance.

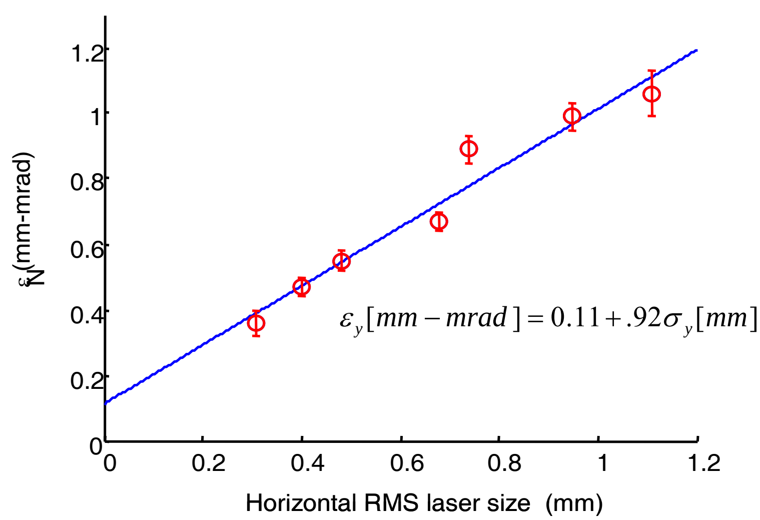


Figure 2.2: Intrinsic emittance measured at BNL [Gra01c].

Much of the required infrastructure to support the injector, including S-band RF and controls, vacuum equipment, water cooling, and radiation shielding, is already in place in the accelerator enclosure, allowing installation for a low incremental cost. The addition of a photoinjector enables a number of advanced beam studies, including:

- Photoemission, including measurement of intrinsic emittance from different cathodes
- Injector drive laser development
- Generation and measurement of shaped electron beams with sub-ps time resolution
- Femtosecond timing synchronization of electron beam and lasers
- Development of specialized diagnostics and instrumentation
- Detailed comparison of beam dynamics simulation with experiment

We describe plans for each of these topics in more detail in the following sections. Many of the experimental methods and special diagnostics have been developed by MIT personnel, including femtosecond synchronization of lasers [Sch03], high resolution YAG:Ce scintillators for imaging the electron beam [Gra97], measurements of intrinsic emittance based on the solenoid emittance scan [Gra01c], and study of the time dependent phase space properties of the beam with subpicosecond resolution [Gra01b, Dow03].

Photocathode Studies

The requirements for the cathode are that it have a high quantum efficiency, prompt and uniform emission, and low intrinsic emittance, and good lifetime in the high gradient and vacuum level of the accelerator cavity. Figure 2.1 shows the experimental setup required to measure the intrinsic emittance of a cathode [Flo97]. This measurement has been demonstrated for Cu [Gra01c], and with the illustrated layout it can be extended to many other cathode materials. The beam is accelerated in the RF cavity and then the solenoid magnetic field is scanned to produce a waist at the scintillator in the same manner as a quadrupole-scan emittance measurement. The effects of space charge, wakefields, and time-dependent RF distortions are removed for this measurement by accelerating a low charge (1 pC), short duration (1 ps) electron pulse. The sensitive YAG:Ce scintillators [Gra97] can measure the transverse profile of the low charge beam with a resolution of less than 10 μm. Results of the measurements performed at BNL are shown in Figure 2.2. We propose to extend this method to other metals of interest such as Mg, and to higher quantum efficiency semiconductor cathodes including Cs_2Te and K_2CsSb. The replaceable back plate of the injector on which the cathode is mounted enables simple exchange of plates with different cathodes.

Using this method it is possible for the first time to create "maps" of the intrinsic emittance as a function of position on the cathode surface. This is done by scanning a small laser spot across the cathode while measuring the emittance of the resulting low-charge beam. By combining these local emittance measurements with quantum efficiency measurements and microscopic study of the surface structure we can learn the details of the local photoemission properties of the surface and its dependence on field strength and surface quality.

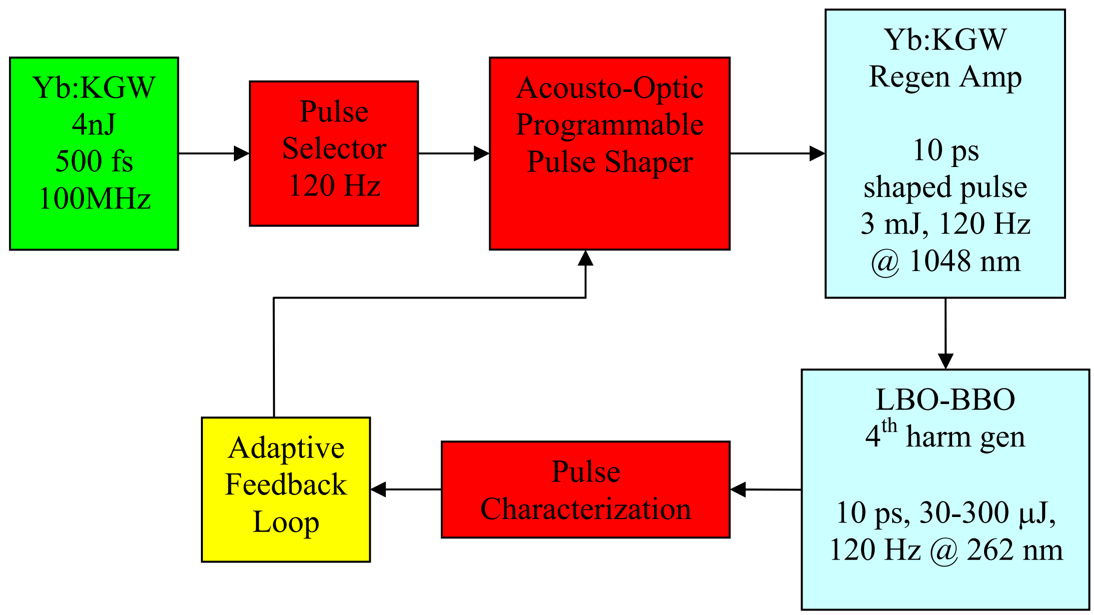


Figure 2.3: Yb:tungstate laser system for photo-injector drive laser.

Photoinjector Drive laser

Drive lasers play a primary role in determining the beam quality because the electron beam emittance is very sensitive to the shape of the pulse and to timing jitter between the laser and RF. Improvements in generating and measuring the desired pulse shapes, reliably reproducing them, and synchronizing the laser to a fraction of an RF degree are important goals that would benefit all photoinjector facilities. Our methods for synchronizing the laser and RF to tens of femtoseconds are described in Section 2.5.

Here we describe the requirements for the drive laser including the following parameters:

- Wavelength < 300 nm
- Pulse length 10-30 ps
- Rectangular pulse shape
- Super-Gaussian beam profile
- Pulse energy > 100 μJ

The proposed laser is capable of operating at the full Bates linac repetition rate of 1 kHz. This can be reduced to the LCLS repetition rate of 120 Hz for demonstration of relevant technologies. To the greatest extent possible we will make this system compatible with LCLS parameters, choosing for instance the same laser oscillator frequency and compatible timing signals.

To achieve a rectangular shaped UV-laser pulse, we must clearly start with a much shorter pulse length so that with additional pulse shaping we can achieve the required temporal pulse shape. We envision a laser system based on the newly developed diode-pumped Yb:KGW laser, for example the Spectra Physics Eclipse. This laser consists of a compact diode-pumped Yb:KGW laser that is very reliably mode-locked by a semiconductor saturable absorber mirror (SESAM) generating a pulse stream of 4 nJ, 500 fs pulses at a repetition rate near 100 MHz (see Figure 2.3).

From the emitted pulse stream, pulses are selected at a rate of up to 1 kHz. At this position we will insert a commercially available pulse shaper called Dazzler that enables arbitrary amplitude and phase shaping of the transmitted pulse. After the pulse shaping, the pulses are amplified in the Eclipse regenerative amplifier to the mJ level. The pulses are then frequency quadrupled in lithium barium borate and beta barium borate crystals to 266 nm. The pulses will then be characterized with respect to amplitude and phase and compared with the desired rectangular shaped pulses in the UV. Deviations from this ideal form will be analyzed in the following adaptive feedback loop. A corresponding signal to the pulse shaper will be sent to change the infrared pulse in such a way that the desired UV-pulse shape is achieved after frequency quadrupling.

Complete characterization of the generated UV-pulses is a non trivial task, since no nonlinear crystals are available to perform an autocorrelation measurement in the UV. Therefore, we plan to employ a single shot cross correlation of the amplified pulses with the unmodified and transform limited 500 fs IR-pulses from the oscillator, which are dumped in any case. Here we will look at the difference frequency output between the 262 nm amplified pulses and the 1048 nm, which is at 349 nm. The cross correlation will directly give the intensity profile of the rectangular shaped and therefore strongly stretched UV pulse. Since the quadrupling process can be modeled very well, a multi-dimensional state-space controller can be developed and implemented in the adaptive feedback loop to generate the rectangular shaped UV pulses with high quality.

After optimization of the temporal pulse, the final task is the spatial beam shaping to achieve a strongly super-Gaussian beam which is of major importance for the generation of a low-emittance electron beam. Since we expect to have plenty of pulse energy available at 262 nm, we want to explore several different approaches to achieve beam shaping:

- Simple reshaping of the beam using a properly sized pinhole in aluminum can be employed.

- The pulse can be propagated through a two-photon absorber, which attenuates the high peak-power center of the beam more strongly than the wings.

- A proper dielectric amplitude transmission mask can be utilized.

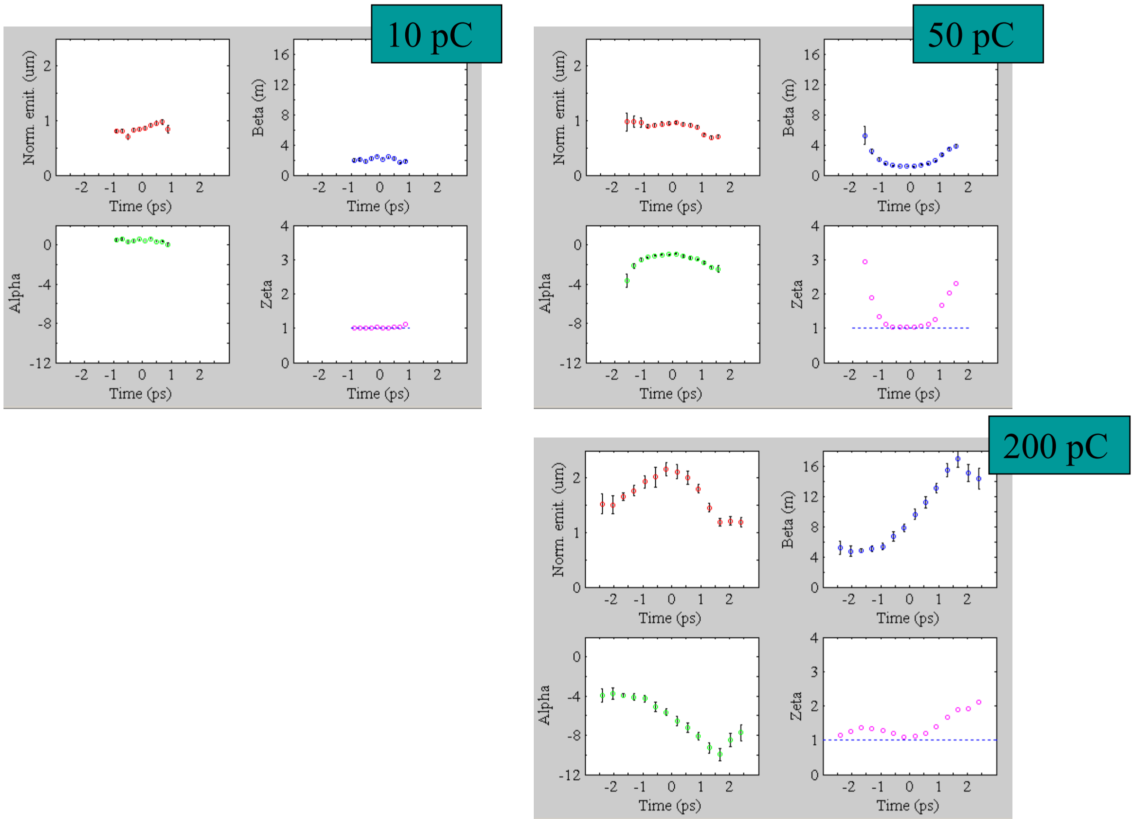


Figure 2.4: Measurements of time dependence of electron beam phase space parameters for different charge (or peak current). Resolution is ~100 fs. Complex dynamics due to space charge are observed at high current.

Generation and Measurement of Shaped Electron Beams

With programmable control of the drive laser pulse shape, we must develop techniques to measure the resulting electron beam distribution in order to optimize the laser shape. By manipulating the accelerator lattice and using the linac as a relativistic streak camera, it is possible to not only image the longitudinal distribution of the electron beam, but also to measure the subpicosecond transverse phase space properties, as shown in Figure 2.4. This allows unraveling the complex phase space shapes generated by space charge and laser nonuniformities, and acquisition of detailed information on the electron beam distribution in all dimensions. The data in Figure 2.4 were obtained at BNL's DUV-FEL. They were produced by dispersing an energy-chirped electron beam on a YAG:Ce screen and imaging it while scanning an upstream quadrupole for an emittance measurement. Because different timeslices of the beam are dispersed horizontally in the image, software can be used to reconstruct the phase space parameters for each thin slice. The resulting plots show time correlations that depend on the instantaneous current and the overall bunch shape. As the charge or current is increased, space charge effects cause both distortion of the phase ellipses in time, and larger instantaneous emittance due to nonlinear fields. We propose to use this method to systematically study the dependence of the sub-ps beam dynamics on laser pulse shaping and other parameters such as charge, accelerator gradient, cathode spot size, and lattice settings. The methods can be extended to longitudinal and transverse beam tomography, providing a complete picture of the beam's phase space. The pulse shaping and diagnostic methods are critical to generating the desired beam distributions and understanding the distortions that occur. In addition to the photoinjector, these experiments require only the addition of YAG:Ce imaging screens, at modest cost. The methods otherwise rely on the existing accelerator infrastructure.

Development of Specialized Diagnostics and Instrumentation

Members of our group have a long history of developing innovative techniques and diagnostics, from measurement of RF synchronization with resolution under 100 fs [Zol00], to laser synchronization with sub-*femtosecond* resolution [Sch03], to the high resolution YAG:Ce imaging screens [Gra97], intrinsic emittance measurements [Gra01c], and slice emittance measurement methods [Gra01b]. We propose to continue development of diagnostics in the following specialties:

- RF diagnostics for very low phase noise measurements
- RF/laser synchronization
- Electron beam transverse imaging
- Electron beam longitudinal imaging

Section 2.3.5 describes the low noise RF diagnostic development effort, and innovative methods of synchronizing external lasers to the RF master oscillator are described in detail in Section 2.5.

Measurement of bright electron beams requires high resolution transverse and longitudinal imaging methods. Although the YAG:Ce scintillators are excellent for imaging relatively low charge pulses, at high enough charge density they saturate, resulting in distortion and loss of resolution. They also intercept the beam, and are therefore destructive. Many applications, such as ERLs and high repetition rate linacs require nondestructive, high resolution diagnostics. We will investigate transverse and longitudinal imaging diagnostics including both destructive and nondestructive methods. It is important to obtain redundant measurements when developing new instrumentation, so that new devices are benchmarked against well-characterized existing devices, such as the destructive time profile measurement using rf-zero phasing and YAG:Ce screens. As a first nondestructive test we will investigate longitudinal profiling of the electron beam with femtosecond resolution by creating a coherent modulation from a seed laser in a short undulator, for example the 13 period COUR undulator currently unused at BNL. The seed signal can be derived from the injector drive laser. The optical signal from this undulator has an intrinsic time resolution due to slippage of less than 30 fs. With further investigation it may be possible to nondestructively measure the slice emittance properties also using seeding.

Comparison of Beam Dynamics Simulations with Experiment

Observed photoinjector performance decreases rapidly with increasing beam current, and the brightest electron beams have been achieved at modest current. Figure 2.4 shows evidence of this effect, which is due to space charge at low energy. Both simulation and analytical work have shown that it is possible to generate a high charge (~1 nC) electron beam while preserving the very small phase space volume of the cathode's intrinsic emittance. These simulations employ distributions that are almost perfectly uniform. Such distributions have proven difficult to generate and measure experimentally. By using the experimental methods described above we can make quantitative comparisons with simulation results, carefully measuring the experimental conditions so that there is agreement between initial and boundary conditions in both simulation and experiment. Personnel at Bates are highly experienced with the primary accelerator simulation codes PARMELA, MAD, and ELEGANT.

Next Generation Photoinjector Development

In addition to a photoinjector effort with a low repetition rate on the existing linac, we have begun research into a high repetition rate photoinjector in collaboration with the Beam Electrodynamics Group at LBNL. This injector design effort addresses the significant challenges associated with producing high quality electron beams at repetition rates up to 10 kHz. The cavity design produced by LBNL uses rounded re-entrant shapes for higher shunt impedance than the conventional pillbox design, allowing higher accelerating fields for the same wall power density. Preliminary field calculations and PARMELA simulations show good linearity of radial fields and production of a high brightness electron beam. The separate RF couplers for each cell in the multicell design allow flexibility in RF phasing between cells, which opens interesting possibilities for beam dynamics including velocity-based bunch compression and compensation of space-charge effects with RF focusing.

The development of a high repetition rate photoinjector opens new applications such as compact high-flux x-ray sources based on Compton scattering of laser light, and new linac-based FEL and ERL light source facilities. The combined effort takes advantage of the expertise in high power RF cavity design at LBNL and the MIT expertise in beam dynamics, RF sources, instrumentation, and lasers. Significant cost savings result from the combination of efforts. LBNL is currently constructing a single-cell prototype cavity that could be tested in the existing Bates accelerator vault at up to 10 kHz using the existing modulators. Although most of the infrastructure for high power tests is in place, the addition of a suitable 1.3 GHz klystron is required. Funding for this tube is not currently requested, but could be added after further study.

To develop this system we plan to conduct simulation studies of beam dynamics, investigate instrumentation for nondestructive measurement of the various phase space quantities, and study the RF power system required. The existing Bates modulators drive S-band 5.5 MW klystrons with 25 μs pulses at 600 Hz with excellent performance [Zol00]. The modulators are capable of operating for shorter durations at higher repetition rates. The table below shows operating parameters at output values of 2 MW for 5 μs at 10 kHz. These values exceed those necessary for testing the LBNL single-cell prototype. These modulators exhibit excellent amplitude stability of 2×10^{-4}, an important factor for the stable timing required.

VA-938E Klystron and Modulator Intra-Pulse Operating Conditions

Peak RF Power Output	2.0 MW
Peak Beam Voltage	100 kV
Peak Beam Current	63 A
Peak Beam Power Input	6.3 MW
BST Cathode-MA Voltage	11 kV
BST Cathode-Collector Voltage	16 kV
Peak BST Collector Dissipation	1.0 MW (500 kW/BST)
Peak SSS Dissipation	12 kW
DC Power Supply Voltage	116 kVDC

The energy values per pulse dissipated or converted to RF include the time integrals of the intra-pulse power, the energy dissipated in charging and discharging the parasitic capacitances, and the time integral of the additional klystron beam power during the pulse rise time.

Photoinjector Work Breakdown

In the first year of funding, detailed modeling and physics design of the Bates linac with an S-band photoinjector and its associated laser and diagnostics will be carried out. Following these studies, engineering design incorporating the new equipment will be done, after which procurement and construction of the new injector will proceed.

Year 1:

1. Modeling and physics design of Bates linac with photoinjector.
    a. PARMELA simulations of injector with existing linac: model set of expected experiments.
    b. Evaluate range of experiments.
    c. Determine optimum locations of new diagnostics.
    d. Begin student involvement in high brightness electron beam studies.
2. Engineering design for installation of S-band photoinjector RF cavity.
    a. Mechanical engineering support for added vacuum equipment, laser transport line, injector cavity support structure.
    b. Evaluate changes to existing RF distribution and/or purchase of injector klystron.
3. Engineering design and initial construction of photocathode drive laser.
    a. Layout of Bates laser room.
    b. Layout of laser transport line to injector cavity.
    c. Construction of laser on campus and pulse shaping tests.
4. Engineering design and initial construction of electron beam diagnostics.
    a. Design vacuum chambers and mechanical supports for YAG:Ce screens.
    b. Integrate screens and CCD cameras into control system.
5. Purchase and initiate installation of S-band photoinjector.
6. Initiate cathode studies.
    a. Seek involvement of faculty and students from Center for Materials Science and Engineering.
    b. Design experimental studies of intrinsic emittance including cathode emittance maps.
7. Design and begin installation of safety systems, RF waveguide, controls, and vacuum equipment for photoinjector.
8. Hire one postdoc.

Year 2:

1. Install photocathode drive laser at Bates
    a. Construct clean room.
    b. Build laser transport line.

    c. Install laser diagnostics.
2. Finish installation of all S-band photoinjector systems.
3. Commission S-band photoinjector and laser.
4. Modeling and analysis of photoemission from metal and semiconductor cathodes.
5. Tests of femtosecond synchronization between drive laser and RF system.
6. Studies of laser pulse shaping and diagnostics for the amplified UV output.
7. Studies of Bates modulators for driving L-band photoinjector.
8. Modeling of beam dynamics for L-band photoinjector.
9. Add one graduate student.

Year 3:

1. Electron beam studies of photoemission from metal and semiconductor cathodes.
2. Experimental studies of slice properties of electron beam including emittance, Twiss parameters, and energy spread.
3. Experiments on effects of laser pulse shaping.
4. Tests of femtosecond synchronization between drive laser, RF, and electron beam.
5. Nondestructive optical seeding measurement of slice electron beam properties.
6. Benchmarking of start-to-end simulations against beam experiments.
7. Add second graduate student.

2.2.2 Polarized Electron Injectors

Experiments with polarized electron beams have had an enormous impact on the fields of nuclear and particle physics. In all polarization experiments, the figure of merit for use of polarized beam is proportional to P^2I, with P and I denoting beam polarization and current, respectively. For flagship facilities such as the CEBAF accelerator at Jefferson Lab, there is a strong incentive to run physics experiments with the maximum beam polarization and intensity.

New developments have advanced the capabilities of polarized electron photoinjectors tremendously in the past two decades. First, research in electron spin-polarization from III-V based photoemitters made it possible to produce electron beams with low polarization of order 30% using bulk GaAs. The introduction of GaAs photocathodes with thin epitaxially grown layers pushed the polarization above 40%, albeit with reduced QE [Mar89]. The second major advancement occurred when molecular beam epitaxy (MBE) techniques were used to remove the degeneracy in $P_{3/2}$ heavy hole-light hole states in the valence band. Polarizations above 80% have been achieved through this mechanism and strained GaAs crystals are now routinely used at various nuclear and particle accelerators worldwide [Gra02, Cle02, Far02, Aul02]. However, the QE of such photocathodes is very low due to their thin active layer. In addition, basic physical processes such as depolarization effects, surface charge limit effects, and space charge phenomena often prevent these levels of performance from being achieved in a given polarized injector system. Advanced R&D efforts with dedicated test setups and experienced people are required to address these issues and explore new polarized injector technologies. For example, recently developed complex photocathodes with superlattice structure are providing beams with a high degree of polarization and QE as large as 1% using laser wavelengths lower than those of conventional high polarization structures [Kur95].

Many new developments with polarized electron beam technology have been motivated by their use in novel parity-violation experiments in nuclear scattering. These experiments, designed to measure the strange quark content of the nucleon [Has00, HAP99, JLa00a] and test the Standard Model of Particle Physics [Sou90, SLA97, JLa02], have been a significant part of the experimental programs at MIT-Bates, Jefferson Lab, SLAC, and Mainz. The asymmetries measured in parity-violation experiments are of order parts per million, and as low as a few hundred ppb (parts per billion) for more recently proposed experiments [JLa02, JLa00b]. The false asymmetries in these complex and difficult experiments often originate from the drive laser and the photocathode, making the polarized source an integral part of these experiments. The Polarized Injector Group at MIT-Bates, with two decades of pioneering research in the Bates Carbon-12 and SAMPLE experiments, has played an important part in the development of many of the techniques now in worldwide use in parity violating electron scattering [Has00, Sou90].

Another class of experiments with stringent requirements for a polarized source is those which will be performed with a future lepton-hadron collider. MIT-Bates scientists lead the design team of the electron beam for the eRHIC project. The present design for eRHIC calls for a storage ring with full-energy injection from a linac with a polarized electron source. Although the electron ring will be self-polarizing, the polarization build-up time for 5 GeV beams will be several hours, meaning that the ring must be injected with a highly polarized beam. Furthermore, use of a highly polarized source will allow operation of the storage ring in top-off mode, permitting the electron beam intensity to remain high at all times. Alternative designs, e.g. ELIC [Der04], involving a linac-ring collider, place even greater emphasis on polarized source development.

Despite the need for advancement in the area of polarized photoemission, the number of experts and facilities in this field remains limited, both within the United States and abroad. The 2002 Workshop on Polarized Electron Sources and Polarimeters, hosted by MIT-Bates, illustrated the breadth of uses for polarized electron beams in a host of areas, including imaging and materials science. The importance of this field is likely to increase in upcoming years. Still, high-performance polarized electron guns only exist at a few centers in the US, Europe, and Japan. It is crucial to pursue vigorous research programs at these existing centers of expertise. CAST can play an important role in this regard by carrying out forefront research and by training a new generation of young scientists in this challenging technology.

The Polarized Injector Group at MIT-Bates has over a decade of experience working with photoemission from GaAs-based photocathodes. The group includes three scientists working in conjunction with Bates mechanical and electrical engineers and highly trained technicians. Collectively, the group possesses a wealth of experience addressing challenges in ultra-high vacuum technology, high voltage field emission, laser systems, and combined high peak and high repetition rate photoemission from polarized electron sources. Existing infrastructure at Bates includes two distinct operational laser systems, three polarized photocathode vacuum chambers, a clean room for preparation of photocathodes and assembly of guns, and a test facility for certification of polarized guns. The efforts of this group have resulted in the routine delivery of high polarization beam (70%) from the source to the ring. For the past two years, stored currents of over 150 mA (produced by stacking 2 MA pulses from the accelerator) have been in constant use for the BLAST experiment. Figure 2.5 illustrates the Bates polarized source layout used for the SHR storage mode. The source benefits from an excellent UHV condition in the gun and the injector and the utilization of a high power diode array laser system [Tse02] matched in wavelength with a high gradient doped GaAsP photocathode [Far02].

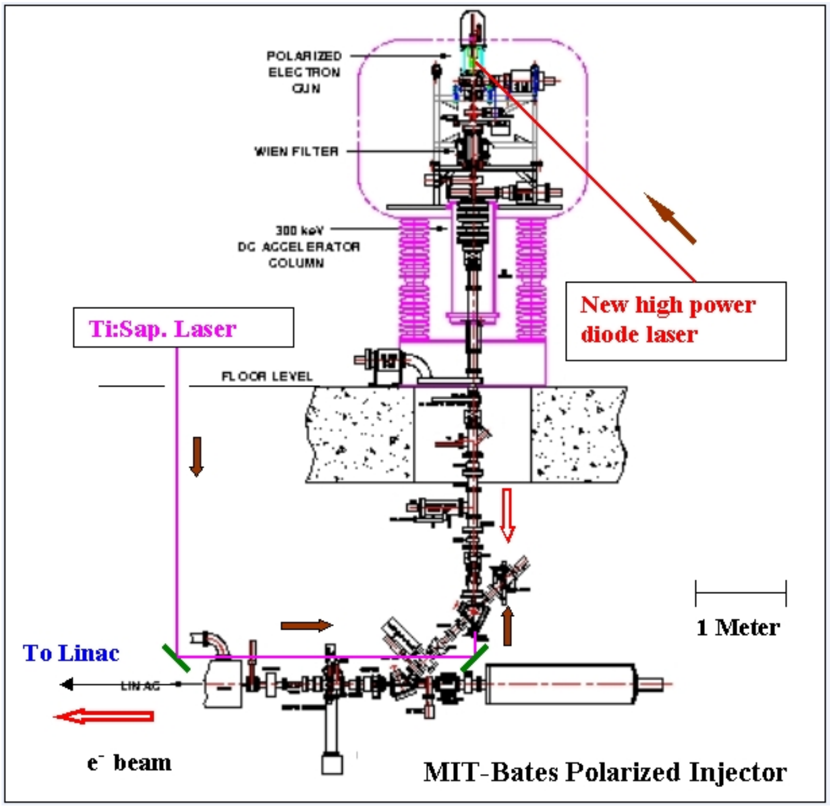


Figure 2.5: Schematic view of the MIT-Bates polarized injector configured for the high stored current operation of the SHR.

As part of CAST, the Polarized Injector Group is proposing specific R&D for FY2006-FY2008 that utilizes these strengths. The research will focus on developing a simplified test setup integrated with a load lock photogun for the main injector at Jefferson Lab as part of a collaboration with JLab on photonuclear research, challenging issues facing the polarized source for the eRHIC lepton-hadron collider, and testing photocathodes with various structures for achieving very high degree of polarization. Each of these initiatives are briefly presented here.

Design Development for Jefferson Lab Polarized Photoinjector

The polarized photoinjector is a critical component of the Continuous Electron Beam Accelerator Facility at Jefferson Lab. It is producing CW highly polarized beams for simultaneous delivery to three experimental halls for nuclear physics. The demands for higher polarization, higher average current and non-CW beams are also growing at Jefferson Lab. The most challenging requirements are from parity-violating experiments like G0 [JLa00a], Q_{Weak} [JLa02] and ^{208}Pb [JLa00b]. These challenges are made more complex when beams of distinct currents and characteristics are delivered simultaneously to three experimental halls.

In large part, the success of the nuclear physics research program at Jefferson Lab depends on the performance of high polarization GaAs-based photoemission guns. It is essential that these guns provide electron beams at high current with high spin polarization for long periods of time (months) without interruption. Jefferson Lab and other institutions have been responsible for technological advances in the areas of lasers, vacuum and gun design that have improved the characteristics of polarized electron beams (e.g., higher polarization, higher current, longer photoemission gun operating lifetime), but significant advances are still possible. For CAST, we propose collaborative research on topics listed below that can enhance Jefferson Lab's ability to meet the demands of the present nuclear physics program and address the challenges of increasingly demanding future experiments. CAST R&D for the Jefferson Lab photoinjector includes:

a. Low voltage Mott polarimeter and load lock chamber systems.
b. DC photoinjector with mA currents.
c. Photoguns with cryopump vacuum technology
d. High current polarized photoinjector for future electron-ion colliders

The most important and straightforward development project is the development of a low voltage Mott polarimeter and a load lock system. This will provide the ability to insert in the CEBAF main injector the best photocathode samples, pre-qualified on the test setup, while preserving the UHV conditions of the sample. The other three areas of R&D listed above have a long term mission aimed at developing more advanced future polarized photoinjectors both for Jefferson Lab and for future high luminosity lepton-ion colliders. Each of these four areas is briefly described here.

a. Low Energy Mott polarimeter and load lock chamber systems

Only photocathodes that provide high quantum efficiency and polarization are installed at the CEBAF photoinjector. Presently, photocathode samples are pre-qualified using a 100 kV electron gun and beamline with a Mott-scattering polarimeter. Although the test stand is very useful, it suffers from disadvantages that detract from efficient operation. The photogun must be baked at 250° C each time photocathode samples are replaced, a process that takes approximately two days to complete. Furthermore, because of the high gun voltage, the test stand must be operated remotely, within a protective interlocked enclosure to prevent operators from being exposed to x-ray radiation. This necessitates relatively complicated and expensive computer control of test stand elements (lasers, optical elements, magnets, vacuum valves and viewers, Mott detectors, etc.). It would be highly advantageous for Jefferson Lab to replace this test stand with a new version containing a lower energy Mott-scattering polarimeter and a load-locked vacuum chamber.

CAST would design and build the new test stand. It would incorporate a "suitcase" vacuum apparatus that would allow transport of photocathode samples between the test stand and the newly constructed load lock photoinjector for CEBAF. Because samples would never be exposed to air, the system would eliminate the need for vacuum chamber bakeouts, greatly hastening sample evaluation. The test stand will also feature a low voltage transport beamline designed using electrostatic electron beam components and deflectors to guide the low energy polarized electron beam to the Mott chamber. The low voltage nature of the new beamline would eliminate the x-ray radiation hazard, providing greater flexibility for placement of the test stand and greatly simplified computer control.

b. DC photoinjector with milliamp current

CEBAF at Jefferson Lab relies on "synchronous photoinjection" to enhance the operating lifetime of the photogun. With this technique, electrons are extracted from the photocathode only during the portion of the RF cycle when they can be accelerated through the machine. Although this technique is beneficial to the photogun lifetime, it has disadvantages from an operational point of view. Synchronous photoinjection requires complicated lasers which emit short pulses of light (~100 ps) at the RF frequency of the accelerating cavities (one laser with 1497 MHz optical pulse repetition rate or three lasers with 499 MHz pulse repetition rate, one laser for each hall). Synchronous photoinjection also necessitates careful attention to setting, monitoring and maintaining the phase of the optical pulse train. An alternative approach using DC laser light would greatly simplify photoinjector operations. However, in using a DC light source, higher gun currents are needed because only 1/6 of the extracted DC beam will pass through the RF chopper defining the phase acceptance of the CEBAF photoinjector. To meet the demands of one endstation asking for 120 μA average beam current, 720 μA must be extracted from the photocathode. This configuration has been rejected in the past because gun vacuum limitations and existing gun designs would not provide the currents needed for operation.

Jefferson Lab and CAST propose construction of a new DC gun which includes a cathode electrode structure employing a ninety degree bend. With this structure, ionized residual gas within the gun vacuum chamber would be directed away from the photocathode surface, thus prolonging operation at milliamp gun currents (ion backbombardment is the dominant limiting factor of photogun lifetime). Such a gun would also employ inexpensive, highly reliable, maintenance-free diode lasers that can deliver high intensity light to the photocathode. Successful development of this photogun would require modeling of the cathode electrode structure and extensive beam-based tests to qualify the transverse emittance of the extracted high current beam. This area of photoinjector R&D is well suited for CAST and expertise exists in the Bates Polarized Injector Group on the design and operation of this type of quasi-DC photoinjector.

c. Photoguns with cryopump vacuum technology

Good vacuum is the central requirement for obtaining long photogun operating lifetime. A third opportunity for collaboration between CAST and Jefferson Lab is the construction of a photoemission gun that relies on cryopump technology, which is widely viewed as the means to obtain the best possible vacuum. At the moment, vacuum pressures of approximately 1×10^{-11} Torr are achieved inside CEBAF photoguns using non-evaporable getter pumps and ion pumps. Pumping speed calculations indicate that a vacuum improvement of at least two orders of magnitude could be achieved if the gun vacuum chamber were cooled to cryogenic (~ 4 K) temperature. Such an advance would greatly enhance the operating lifetime and high current capability of the existing CEBAF photoinjector.

With the existing UHV and photoemission expertise at MIT, this R&D effort will fit well under CAST. In late 1990's, the polarized source group at MIT conducted a limited number of tests on liquid nitrogen cooled photocathodes. The results showed a sharp drop in QE indicating that the photocathode surface must stay at elevated temperature while the rest of the chamber is cryopumped. We are considering a collaborative R&D effort between CAST and Jefferson Lab to design and construct a prototype cryopumped photogun at MIT. This would be tested at Jefferson Lab where liquid helium necessary for 4 K operation is readily available.

d. High current polarized photoinjector for future electron-ion colliders.

Finally, CAST and Jefferson Lab propose collaborating on the design of a high current, high polarization gun for future lepton-ion collider accelerators under development at MIT, BNL and Jefferson Lab (eRHIC and ELIC). Some of the designs under consideration include linear accelerators with tens of milliamps average beam current and beam polarization greater than 80%. These specifications greatly exceed the existing state of the art for present photoinjectors. Many obstacles must be overcome including at least the following: reduction of cathode field emission for gun voltages exceeding 500 kV, photocathode charge limit, complex laser pulse structures and power limitations, beam handling concerns at high bunch charge, and improved UHV conditions. These areas of photoinjector R&D are well suited for CAST and are essential for the successful and timely development of the lepton-ion colliders.

These collaborative R&D efforts are an excellent match to the scientific and technical expertise that exists at MIT. Bates photoinjector scientists who participated in the beam delivery to the SAMPLE parity-violating experiment can also collaborate with the Jefferson Lab photoinjector physicists in minimizing helicity-correlated false asymmetries in the beam. Requirements in this area for future JLab experiments mentioned above are extremely demanding.

Laser Development for the Polarized Injector at eRHIC

The primary design for eRHIC features a high-intensity electron storage ring. For a CW storage ring, the achievement of 0.5 A of highly polarized electrons would represent a modest technical requirement based on present state-of-the-art polarized source technology. However, because eRHIC is a collider, synchronized bunches of electrons must precisely match the time structure of the proton bunches in the RHIC ring. This presents a great challenge to the injector configuration and the polarized source design. A detailed evaluation of the eRHIC luminosity design value shows that peak currents of at least 20 mA from the source are required. The corresponding charge per bunch is 1.3 pC for bunches 70 picoseconds long produced at 28 MHz synchronous with the collider ring. This is a challenging technical requirement for a photoinjector.

Photoemission in the eRHIC polarized injector will be produced by illuminating high polarization GaAs-based photocathodes with circularly polarized laser light at 800-830 nm. For this range of wavelengths, a laser peak power of at least 50 W will be needed given the quantum efficiency of presently available photocathodes. Currently, designs based on two different types of laser systems are being considered. These two options differ in the time structure of the photoemission drive laser systems and in the electron beam line for bunching and chopping functions. The first option is based on a mode-locked diode laser [Hov98] capable of producing laser bunches synchronized with pulses in the storage ring. The advantage of this system is that neither bunching nor chopping of the photoemitted electron beam is required. The mode-locked laser is very similar in characteristics to the photoinjector mode-locked laser used for the G0 experiment in Hall C at Jefferson Lab [Gra02]. A schematic diagram of the first option based on a mode-locked laser system is shown in Figure 2.6. We propose a modest R&D program under CAST for the mode-locked laser to ensure that the power, bunch length, time stability and the time structure requirements for the eRHIC are met. This R&D program is well matched to the capabilities and experience of the Bates polarized injector physicists and engineers.

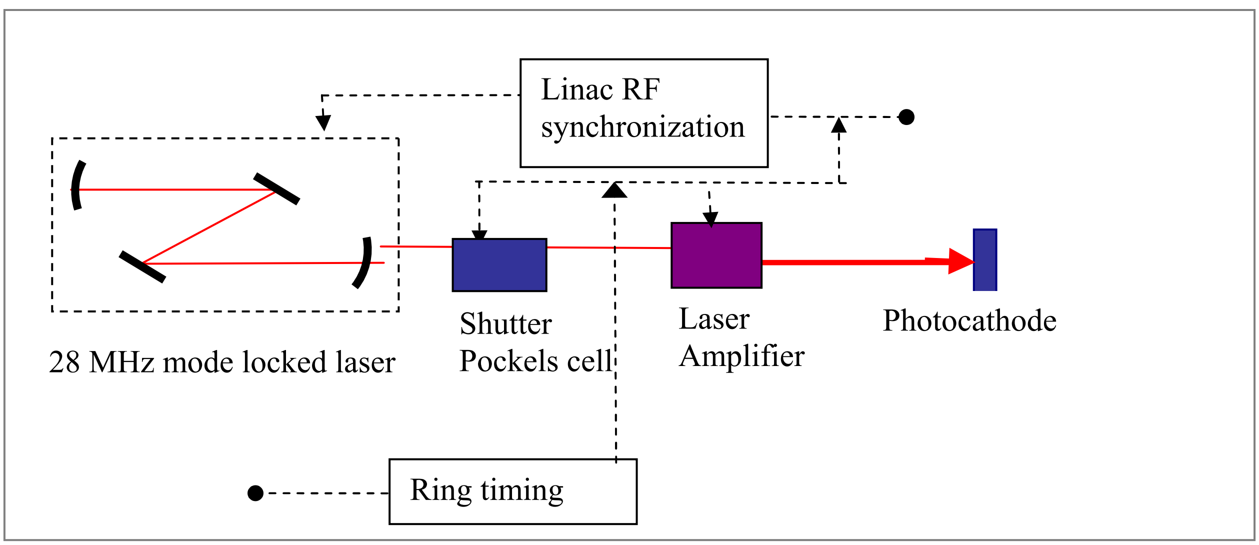


Figure 2.6: Schematic diagram of mode locked laser option for the eRHIC electron injector (Option One).

The second option relies on a high-powered DC fiber-coupled diode array laser system similar to one employed for the MIT-Bates polarized source [Tse02]. In this case, bunching and chopping elements in the linac injector are used to produce bunches synchronized with the collider ring. This option employs a commercial high power diode laser system. A schematic view of this option is shown in Figure 2.7. The laser produces DC or pulsed radiation with no microscopic structure. All RF bunch structure and synchronization is introduced to the electron beam by means of RF choppers and bunchers in the linac injector [Hai70]. We propose an R&D program for this class of lasers by combining the output of multiple identical diode lasers to achieve higher peak power and observe the electron beam characteristics on the Bates polarized test stand. The challenge of this option is to ascertain the degree to which the complex bunching and chopping of the electron beam at multiple frequencies is possible. The effort necessary to address this issue is described below.

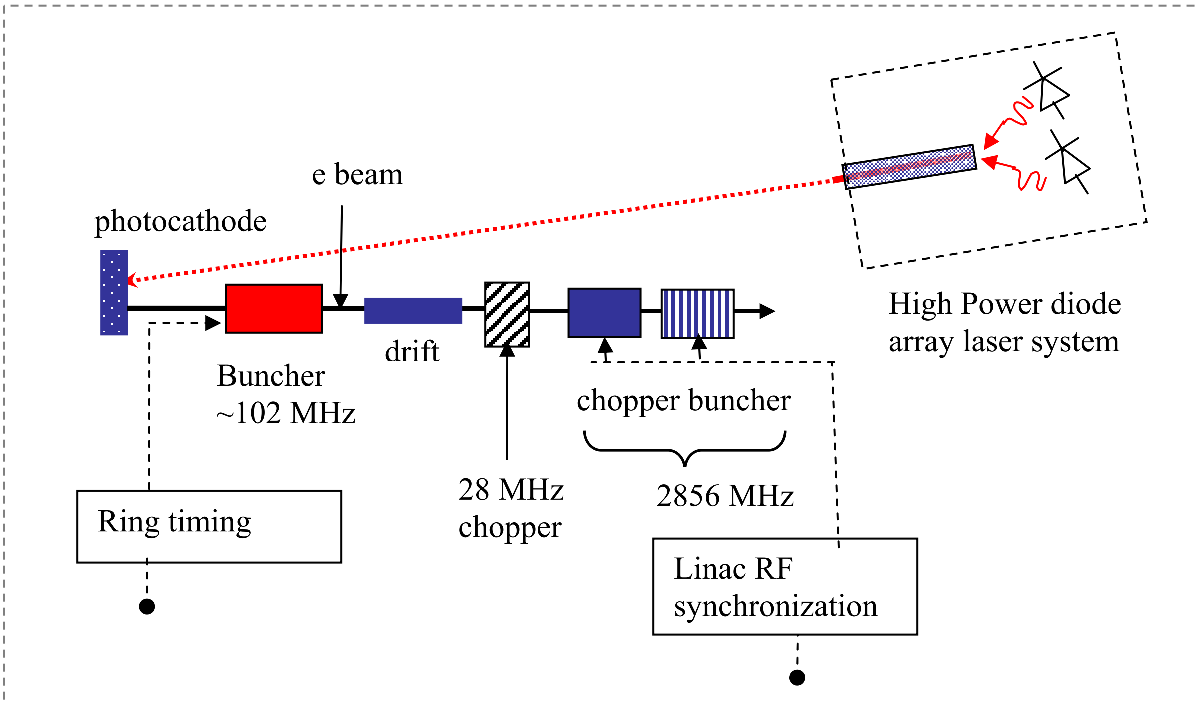


Figure 2.7: Schematic diagram of the laser and the electron beam layout for the DC fiber-coupled diode laser option for the eRHIC injector (Option Two).

Beam Dynamics Simulations for eRHIC Source

As stated above, the second option of the proposed polarized injector for eRHIC is based on a DC high power laser system and a complex electron beam bunching and chopping system. This bunching and chopping system should occur after the electrons are accelerated to a few hundred keV, but before they are fully relativistic. Similar systems exist at the S-Dalinac facility in Darmstadt [Dar04] and the ELBE accelerator in Rossendorf [ELB04]**.** The proposed setup, which features a 102 MHz buncher and a 28 MHz chopper with a 5-10 m drift in between (Figure 2.7), is expected to provide a bunching factor of 5-10 aimed at reducing the peak current requirements from the polarized source, and to provide electron bunches that are synchronous with the collider ring. The second set of chopper and buncher at 2856 MHz (or 1300 MHz) is used to prepare bunches at the linac frequency for acceleration. While the laser system is commercially available today with robust and trouble-free operational records, the chopping and bunching system described above is not straightforward and needs further study.

Specifically, the electron beam dynamics between the electron gun and the first few acceleration modules downstream of the chopping and bunching region must be modeled with advanced computer simulation codes like PARMELA [You96] and DIMAD [Ser85]. We propose to carry out these studies in FY2006 and FY2007 to determine the bunching fraction at 102 MHz, a critical parameter that would shed light on the merit of this option. In addition, beam dynamics parameters including emittance, size, velocity bunching, and bunching time stability must be understood in detail.

Photocathode R&D Using the Bates Test Facility

The polarized injector test facility [Far00] at Bates is presently used for fully characterizing and certifying polarized guns with high-polarization photocathodes prior to installation on the existing main injector. This test setup, illustrated in Figure 2.8, includes a 60 keV beam line with a removable gun assembly, Wien filter, Mott polarimeter and Faraday cup. All elements of the beam line are controlled by the EPICS control system. Photocathodes can be fully certified on this setup by measuring QE as a function of laser power to determine the surface charge limit effect [Mar02]. The test setup can also be used for measuring thermal emittance of GaAs-based photocathodes. This test facility and the three DC gun chambers at Bates can be utilized for research on novel technical issues in polarized gun technology, including surface charge limit effects on high polarization photocathodes and high peak current extractions. Both issues are of substantial importance for the JLab and eRHIC polarized injectors.

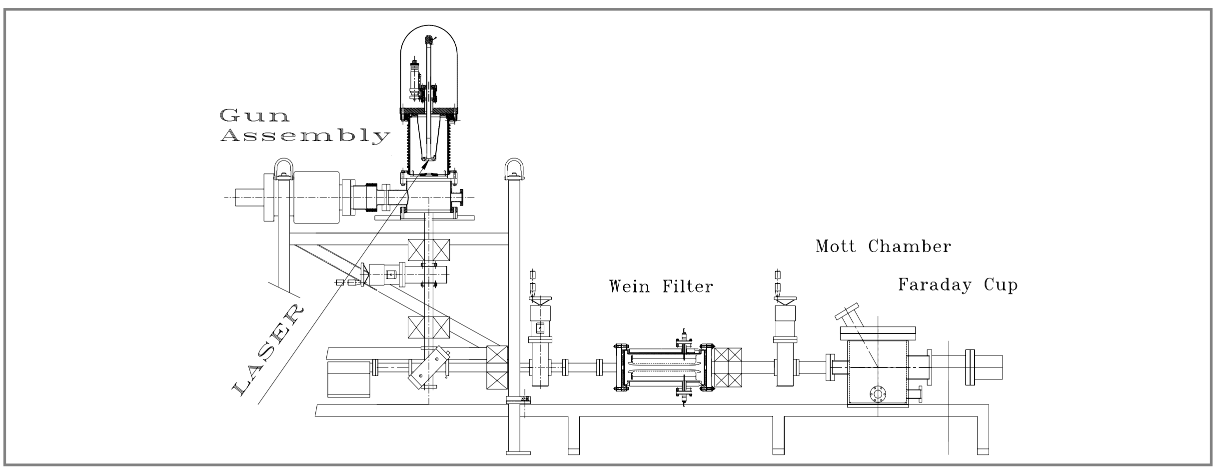


Figure 2.8: Schematic view of the polarized injector test beam facility. The gun assembly includes a UHV gun chamber, an isolation valve and a removable support stand.

The test facility can also be utilized for full evaluation and characterization of new high polarization photocathodes with different structures [Kur95]. MIT-Bates has used several suppliers for strained photocathodes including academic institutions like SLAC and St. Petersburg, and private companies like Bandwidth Semiconductor. While progress in surface science continues to yield new designs for high polarization photocathodes, the ability to certify guns under realistic operating conditions is important for accelerators and limited to a few locations. Bates can play an important role in this respect.

All of the advanced research and development in polarized source technology outlined above will be a part of CAST which can engage undergraduate and graduate students as well as postgraduate associates. The nature of this work is interdisciplinary and it is expected that students from previously unrepresented departments may become involved in this research.

Work Breakdown for CAST polarized photoinjector

CAST Work breakdown for Jefferson Lab polarized photoinjector

The following is a work plan to design and construct a low voltage test stand for Jefferson Lab, described earlier in this section as item a. In combination with the main load-lock photogun, this test stand will allow pre-qualification of photocathodes and insertion into the main photoinjector without exposing the photocathode surface to non-UHV conditions. This work breakdown does not include items b., c., and d.

<u>Year 1:</u>

1. Acquire from JLab drawings for the main load-lock photogun, test photogun setup, and the test setup beam line.
2. Begin the design work on the low voltage test stand that includes a low energy Mott polarimeter and a load-lock test chamber.
3. Start beam simulation of a low voltage beam setup using PARMELA.
4. Begin design work for a very low voltage photoemission setup with electrostatic electron beam transport line deflecting the beam into the test beam setup and the Mott polarimeter.
5. Begin design work on modification of the load-lock system of the Jefferson Lab main photoinjector
6. Begin design work for a "suitcase" transfer vessel.
7. Review all design systems with Jefferson Lab personnel.
8. Complete all technical drawings using SolidWorks.
9. Begin acquisition of parts for the approved design.

<u>Year 2:</u>

1. Begin assembly work for the low-voltage test setup photogun. Bake and UHV test the setup.
2. Begin assembly work for the low-energy Mott polarimeter.
3. Assemble and complete the transfer vessel. Bake and UHV test the vessel.
4. Complete the modifications to the load-lock chamber of the main photogun.

<u>Year 3:</u>

1. Complete the test setup assembly and the bake out to achieve UHV conditions.

2. Acquire photocathode samples, prepare and install on photogun pucks.
3. Load photocathode into the low voltage test setup and begin photoemission tests. Can use bulk GaAs photocathode for beam line certifications.
4. Commission and calibrate Mott polarimeter.
5. Transfer certified photocathodes using vessel and re-verify performance.

Work breakdown for eRHIC polarized source development

Year 1:

1. Specification and acquisition of a ~28 MHz mode-locked laser system for Option One of eRHIC injector system.
2. Design and acquire synchronization modules.
3. Acquisition of a high power diode array laser system for studying high peak current photoemission using multiple diode lasers on photocathode.
4. Setup and commencement of electron beam dynamics simulations for Option Two of the injector from the electron gun through the multiple chopper and buncher systems to the first few acceleration cavities. Simulate the bunching gain factor.

Year 2:

1. Continue testing the 28 MHz mode lock laser and evaluate the feasibility, stability and the power level against the requirement for eRHIC injector.
2. Continue photoemission tests for option two injector using multiple high power diode array laser systems and evaluate the electron beam characteristics including emittance, bunch length, peak current and charge limit effects on the photocathode. The Bates test beam setup and the three guns will be used in these tests.
3. Evaluate the merit of the two options for the eRHIC polarized injector using the results of the studies.
4. Selection of one of the options for further development.
5. Preparation of a draft report detailing the design of the polarized injector with the chosen option.

Year 3:

1. Preliminary design report of eRHIC polarized injector as part of the eRHIC 10 GeV injector/accelerator for ring-ring option.
2. Contingent upon the success of the photoemission tests with the large area photocathode gun, prepare a preliminary design report for a high average current gun for linac-ring option of eRHIC.

2.3 A RF Amplifier and Reactive Tuner for Superconducting Cavities

2.3.1 Introduction

Recent developments in the field of RF accelerators have created a demand for power amplifiers that can support very high accelerating gradients of 15-25 MV/m in superconducting structures with extremely low losses. For emerging applications with low beam loading power requirements, including energy recovery linacs (ERLs) and free electron lasers (FELs), the bulk of the generated RF power is reflected from the structure and absorbed in an external load, connected to the reflected-power port of a ferrite circulator. MIT is pursuing the design of a system that would recycle this reflected RF power while maintaining adequate phase and amplitude control of the accelerating cavities. This will greatly reduce the power needed from the RF amplifier, thus substantially reducing the capital and operating costs associated with these devices.

The intrinsic RF power required by an ERL or an FEL can be quite low. For today's state-of-the-art superconducting structures with unloaded quality factors (Q_0) in excess of 10^{10} [TES01] the power to maintain the cavity field amplitude is less than 50 W/m at gradients of 25 MV/m. For average beam currents (or imbalanced currents in the case of an ERL) of less than 10 μA, the beam power is limited to 250 W/m at a gradient of 25 MV/m. An ideal RF source coupled to a one meter cavity would therefore need to supply only 300 W to meet these demands.

Despite these low intrinsic demands, present accelerator designs call for amplifiers with power capabilities in excess of 5 kW/m [Lie03]. This additional power is necessary to compensate for small changes in the superconducting cavity geometry due to mechanical vibrations. This problem, known as microphonics, can be addressed by spoiling the cavity quality factor with a stronger coupling to the amplifier than would be necessary in the absence of the microphonic perturbation.

One strategy under development is to actively correct the cavity geometry by means of a piezo-restrictive tuner [Sim03]. This tuner adjusts the length of the cavity to compensate for the mechanical vibrations and maintain the cavity center frequency. The device must be able to correct the micron scale deformations of the cavity at frequencies between DC and a few hundred Hz.

Another approach is to make use of an external tuner to apply a corrective phase shift to the reflected RF wave and reintroduce it to the cavity structure [Kan02, Hor03]. In essence a second standing wave circuit of much lower quality factor ($Q \sim 10^3$) has been introduced into the RF system between the amplifier and the superconducting structure. The external control (phase shift) could be realized by means of low loss ferrite phase shifters similar to those presently in use at the Bates accelerator. Such phase shifters with very low insertion loss (<0.5 dB), adequate range ($d\varphi > \pm 90°$), resolution ($d\varphi < 1°$), and high power handling capability ($P_{avg} > 5$ kW), are now available commercially [Rus04]. Efforts are also underway at Fermi National Accelerator Laboratory to construct a device with similar specifications for use in tuning individual cavities of the TESLA Test Facility II Accelerator [Sim04]. Such a reactive tuner at 1.5 GHz could also prove useful in power systems for the new high gradient JLab cavities.

Bates is engaged in an effort with the TESLA collaboration to explore the optimum design of this RF amplifier/tuner circuit. For moderate power CW operation of the cavities, interesting possibilities exist for the amplifier as well. As contrasted with a klystron, the use of an Inductive Output Tube (IOT) appears to offer flexible power delivery, high AC/RF conversion efficiency and eliminates the need for expensive modulator switches. The proposed CAST effort would support the refined design and construction of this circuit. The amplifier and tuner would then be tested at one of the TESLA test labs or at a partner DOE/NSF laboratory. The successful development of this RF amplifier architecture will have a significant positive impact on the emerging technologies of ERLs and FELs based on superconducting structures.

The design and assembly of this amplifier/tuner is well matched to the present Bates RF engineering expertise. Over the past ten years the Bates RF and Controls and Instrumentation groups have improved the high power and the low level RF systems so that they are now some of the most reliable in the accelerator complex. This work has included the following systems:

- State of the art high power modulators (15 MW peak, 1% duty factor)
- RF beam energy compression system
- Digitally controlled ferrite phase shifters for each linac klystron
- Precision phase and amplitude RF instrumentation
- 50 kW CW 2856 MHz transmitter
- Single cell, 10 kW, CW, 2856 MHz standing wave cavity
- A highly stable RF synchronization between the linac and ring oscillators via a 400 m temperature stabilized optical fiber link
- Construction of FPGA controller for RF systems master timing generator
- Experimental Physics and Industrial Control System (EPICS) based control and instrumentation of all RF systems

The construction of the highly efficient amplifier/tuner set is also timely with regard to the emerging Superconducting Module Test Facility (SMTF). The SMTF goals include:

1. Operation of SRF 1.3 GHz cavities at 35 MV/m, 1% duty factor and high beam loading for an International Linear Collider (ILC)

2. CW operation of 20 MV/m, beta=1 cavities with $Q_{ext} > 3x10^7$ and Q_0 of $3x10^{10}$ for use in existing and proposed ERL, FEL and nuclear physics accelerators

3. Individual cavity resonance control with multiple cavities driven from one klystron, using fast ferrite phase shifters at both 1300 and 325 MHz

The amplifier/tuner development proposed here is very well suited to the next generation of CW, high gradient cavities which will be deployed and tested at the SMTF. Further, the requirements for the low level RF controller and RF diagnostics are common to most of the proposed SMTF RF systems. The fast ferrite phase shifters listed above in item three are very similar in their technical specifications to those proposed for use in this work in a CW reactive tuner. The proposed use of 25 kW Inductive Output Tubes (IOT's) at 1.3 GHz (see below) will provide a useful test of SRF systems at intermediate beam powers and flexible duty factors. This may be of some interest for ILC, high gradient nuclear physics and light source accelerators. If supported in a CAST framework, MIT's combination of expert physicists, engineers and talented students will be a great asset to achieving the goals of the SMTF.

2.3.2 Intrinsic RF Power Demand

The power demand for an RF cavity can be divided into two categories: power to maintain the cavity fields and power to accelerate the beam. Equation 1 shows the distribution of these power requirements:

$$P = \frac{V^2}{(r/Q)Q_{ext}} \cdot \frac{\beta+1}{4\beta} \cdot \left[(1+a+b)^2 + (2Q_{ext}\frac{\delta\omega}{\omega})^2 \right] \quad (1)$$

Here P is the power required by the RF amplifier, V is the cavity peak voltage, β is the coupling factor, *a* and *b* are factors for the beam power at two distinct phases (these terms almost cancel in the case of the ERL) and $\delta\omega$ is a measure of the frequency variation of the cavity due to uncontrolled sources. For superconducting structures where β is much greater than unity and applications with negligible beam loading equation 1 becomes

$$P = \frac{V^2}{4(r/Q)Q_{ext}} \cdot \left[1 + (2Q_{ext}\frac{\delta\omega}{\omega})^2 \right] \quad (2)$$

Note that the power requirement due to the last term in equation 2 pertaining to the frequency variation of the cavity would vanish if the RF source was able to vary its frequency to match the variation in the cavity center frequency. Clearly this is not acceptable for an accelerator where many hundreds of individual cavities must be phase locked with respect to each other. In this case additional amplifier power is required to compensate for a lower gain as the cavity frequency fluctuates about the linac center frequency.

In the case where the beam power is small, the width of the frequency variation determines the optimum coupling and thus the power demand of the cavity. Figure 2.9 shows the power demand at a beam current of 10 μA as a function of coupling factor for several values of the frequency variation width.

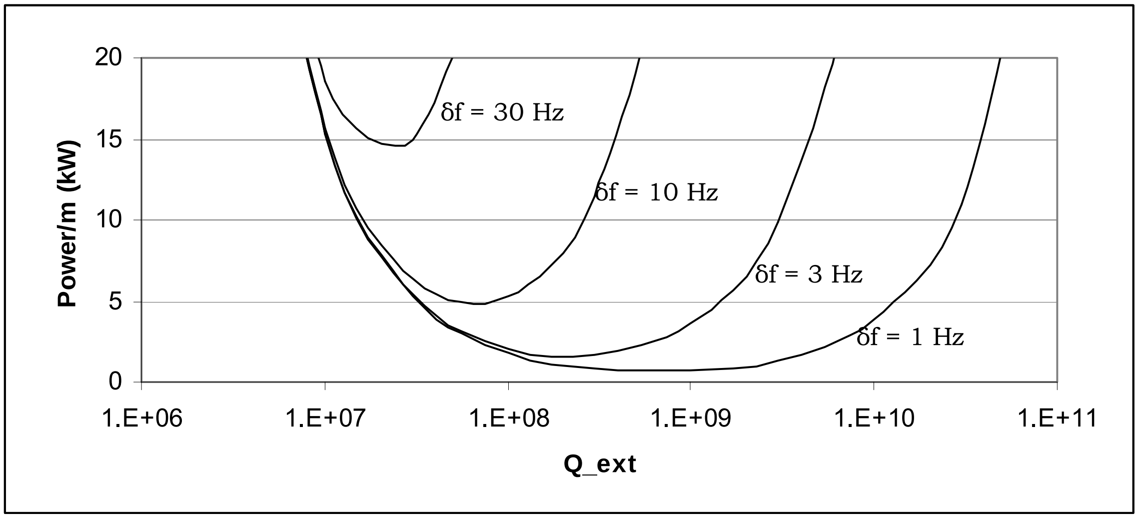


Figure 2.9: Amplifier power demand vs. external coupling (Q_{ext}) for TESLA cavities at 1.3 GHz. All curves assume a cavity voltage of 25 MV and a beam current of 10 μA.

Notice that if the frequency variation could be reduced to the level of 1 Hz the required power would be reduced to less than one kW per RF amplifier. The use of solid-state amplifiers rather than vacuum tubes might then become possible.

Accelerator facilities worldwide are aware of the potential improvement in system performance that would follow a reduction of the microphonically driven width of the cavity center frequency. Table 2.2 lists several accelerators (operating and proposed) and indicates the fraction of the power required to maintain adequate control of the cavity.

Table 2.2: Selected RF parameters for existing and proposed superconducting electron linacs. The last column shows the amount of the amplifier power that is necessary to maintain adequate phase and amplitude control of the cavity. JLAB [Hov00, Sim01], JLAB 12 GeV [Sek03], JLAB FEL ERL [Mer99], Cornell ERL [CHE02], TESLA Test Facility [TES01], BESSY [Kno04], Rossendorf [Bue02].

Facility	I_beam (mA)	Gradient (MV/m)	DF (%)	P_beam (kW/m)	Q_{ext}	Amplifier Power (kW/m)	Power for I=0 (kW/m)
JLab	0.4	7	CW	2.8	6×10^6	5/.7	2/.7
JLab -12 GeV†	0.46	19.2	CW	9	1.5×10^7	13/.7	~10/.7
JLab FEL ERL	10	12	CW	<1 ERL	2×10^7	8/.7	7/.7
Cornell ERL†	100	20	CW	<1 ERL	2.6×10^7	15	9.4
TESLA Test Facility	8	23	0.5	184	3×10^6	250	40
BESSY FEL†	0.1	15	CW	1.5	$2\text{-}8\times10^7$	15	2-8
Rossendorf	0.2-1.0	10	CW	2-10	1×10^7	10	~8

† Proposed Facility

The piezo tuner has the capability to correct for variations in the cavity geometry and initial results indicate that in some facilities microphonics can be controlled to values less than

50 Hz [Hof03]. However, the piezo device has its own mechanical resonances which may interfere with feedback performance if the self-resonance frequency overlaps with the microphonic excitation to be controlled.

2.3.3 System Architectures

Another approach to reduce the frequency variation of the system is by the introduction of an additional external oscillator of much lower Q (~1000). Corrective phase shifts can be applied to the external system which will reduce the frequency variation of the coupled system.

The standard RF amplifier and cavity configuration is shown in Figure 2.10a. We have identified several distinct RF cavity/tuner architectures that may meet the goal of $Q_{ext} > 3\times10^7$. Three of these architectures are shown schematically in the figure.

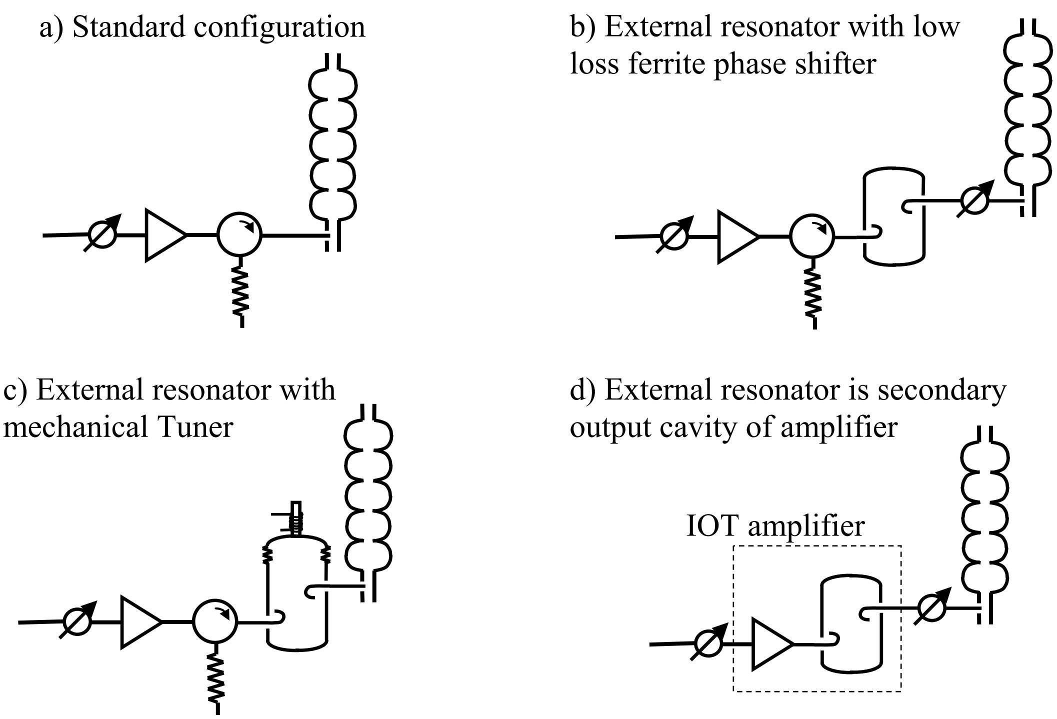


Figure 2.10: RF recycler architectures. Figure a) shows the standard configuration. Figure b) shows an intermediate "low Q" cavity between the amplifier and the SC cavity. Control is accomplished by a low loss ferrite phase shifter between the two cavities. An impedance match for the amplifier output is obtained conventionally by means of a ferrite circulator connected between amplifier output and "low Q" cavity input. Figure c) is the same topology as figure b), but here the control is realized by the mechanical tuning of the "low Q" cavity. Figure d) is also the same as b), but here the external cavity is incorporated into the structure of the amplifier. The circulator is removed. See text for details.

Figure 2.10 shows conceptually how a higher value of Q_{ext} might be reached with the introduction of an external tuner into the amplifier cavity circuit. Figure 2.10 a) shows the standard configuration where the amplifier output is delivered to the cavity through a "protected" system, including circulator and load. All reflected power from the cavity is delivered to the load port of the circulator. In Figure 2.10 b) the amplifier is still protected with a standard circulator and load, but now a warm "low Q" cavity is introduced between the circulator and the SC cavity. The amplifier will now see a Q_{ext} 2-5 times greater than in 2.10 a). Control of this coupled system could be realized with the introduction of a low loss ferrite phase shifter between the "low Q" and the SC cavity.

In Figure 2.10 c) the same "low Q" cavity has been introduced to the system, but now the control is realized through the use of a mechanical tuner. Interestingly, the stroke required for adequate system control is just proportional to the quality factor of the cavity. Therefore if a 1 μm stroke is required on a piezo-electric device operating on the SC cavity at a Q_{ext} of 3×10^6 then a 300 μm stroke would be required for an external cavity with a Q of 1×10^4. This is still a manageable range for mechanical systems at bandwidths of up to ~ 1kHz.

In Figure 2.10 d) the same architecture has been adopted as in 2.10 b). Now, however, the external cavity has been incorporated directly into the amplifier tuning structure itself. It is notable that the Inductive Output Tube (IOT) amplifier already includes such a cavity: the output cavity, either primary or secondary. In the scheme shown the control is still realized with a fast ferrite phase shifter although the amplifier cavity could in principle also include a mechanical tuner.

2.3.4 RF Amplifier Consideration

At the TESLA operating frequency of 1.3 GHz three distinct amplifier types appear to have the potential to meet the power needs of these lightly loaded SRF cavities. They are the klystron, the inductive output tube (IOT) and the solid-state power amplifier (SSPA). The power demand is likely to fall in the range of 2-15 kW per meter of accelerating structure. The exact power requirement will depend on the beam loading and the degree to which the cavity center frequency can be controlled. Table 2.3 lists some of the important features of three typical devices, one in each category.

Table 2.3: Characteristics of three 1.3 GHz amplifier types. Both klystron and IOT offer power levels in excess of 10 kW. The klystron is the more established amplifier for accelerator applications, while the IOT technology is presently in the prototype stage at frequencies in the 1-2 GHz range. SSPA's have lower power capability but may offer many system advantages in simplicity, size, cost, flexibility, and reliability and maintenance.

	Klystron	IOT	SSPA	
Model	CPI VKL-7811ST	CPI Prototype		
Power	10	20	2	kW
Efficiency - η	33	55	25-30	%
Modulator Required for Pulsed Operation	Yes	No	No	
Phase Pushing Factor	10	1	<1	%
Gain	34	23	30-50	dB
Dynamic Range w/ > 50% Max η	2	10	100	

One of the advantages of the klystron is high RF power gain. The existing klystron at 1300 MHz, which is not a particularly high-gain klystron, achieves 10 kW power output with RF drive power of 4 Watts, a power gain of 34 dB. Power gain can usually be traded for other characteristics, such as bandwidth and efficiency, by altering the RF cavity tuning strategy. Typical high-power klystron RF gain is between 40 and 50 dB. Higher gain, although relatively easy to achieve, can make a klystron susceptible to RF feedback from a DC-isolated collector to RF input, via the electron gun insulator, affecting RF phase stability or, in extreme cases, causing self-oscillation.

The klystron has low noise-like phase and amplitude modulation. The main contribution to unwanted modulation results from variation of the externally-supplied operating voltages, predominantly beam voltage. The coefficient between beam voltage and klystron phase delay, known as "phase-pushing factor" is related to the overall phase length of the tube and is typically 10 degrees per 1% change in beam voltage. Required phase deviation can then be related to required DC power supply ripple and long-term stability.

Prototype IOTs have recently become available at frequencies of interest. The EIMAC Division (San Carlos, CA) of CPI has built four devices at 1300 MHz for accelerator applications, which have demonstrated 20 kW power output, 23 dB gain and over 50% efficiency (more is expected). In addition, THALES has also developed a 1.3 GHz IOT and L3 Corp. (formerly Litton Electron Dynamics) also produce IOTs for UHF TV service and will have a prototype IOT at 1300 MHz in a few months.

IOTs are operated near Class B, approaching a conduction angle of 180 degrees, and a maximum theoretical efficiency of 78.5% ($\pi/4$). Practical UHF IOTs have demonstrated efficiency above 70%. Efficiency of an IOT operating at 1300 MHz is less than that of a lower-frequency device because of increased losses in the cavities and distortion of the cathode-current "discs" due to transit-time effects. Nevertheless, computer-simulated data shows conversion efficiency exceeding 68%, which has yet to be demonstrated in the prototypes.

Although no SSPA can compete with either a klystron or an IOT at the 15 kW output level, there are accelerator cavity-drive scenarios, involving rapid compensation of cavity de-tuning, that require amplifier power no greater than 2 kW. A 1.3 GHz SSPA at 2 kW CW is quite practical and has certain advantages, including low-voltage operation and low phase and amplitude pushing factors. At every frequency there is a "cross-over" power level above which the relative advantages of Microwave Vacuum Electron Devices (MVEDs) exceed those of SSPAs. A power level of 2 kW is probably below the "cross-over" point.

The proposed CAST effort will examine all of these amplifier types and make a selection of the most suitable for integration into the amplifier/tuner assembly. The choice of amplifier will greatly depend on several critical factors, including the expected beam power, the performance and reliability of the newly constructed IOT, and the degree to which the SRF cavity center frequency can be controlled.

2.3.5 RF Diagnostics

The successful development of this amplifier/tuner will require the use of sensitive RF diagnostics to precisely control the cavity center frequency and assess the system performance. Instrumentation and RF engineers at Bates have developed a very high resolution phase and amplitude measuring system [Che04]. This system is presently used in conjunction with a pulsed copper S-Band linac. Minor modifications to the instrumentation hardware will allow use of these diagnostics to develop the proposed RF amplifier/tuner architecture.

The Bates Phase and Amplitude Monitoring system routinely measures less than 0.25 degree phase jitter between the reference line and each of 12 high power klystrons. Half of the klystrons exhibit rms jitter of less than 0.1 degree. A portable unit was built to explore the limits of the diagnostic system's performance and was used for jitter analysis both at the Bates facility and at the Argonne National Laboratory's Advanced Photon Source. The phase signal is generated by a double-balanced mixer which multiplies uncorrelated noise outside of the required passband, thus minimizing intrinsic jitter [Kur78]. Using high levels of RF power, >17 dBm, with direct connection to the mixer additionally eliminates local RF amplifier introduced phase noise.

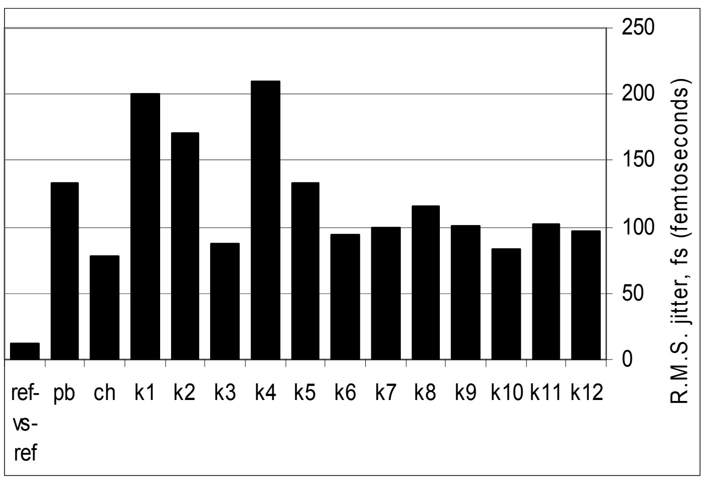


Figure 2.11: Jitter results of the Bates RF system. Shown is the rms timing (phase) jitter between directional couplers to the master oscillator amplifier (MOA) driveline distribution system and RF pick-ups from the prebuncher (pb), chopper (ch) and directional couplers to the forward power from each of 12 high power klystrons (k1-12).

Figure 2.11 shows the rms variation in the measured phase for 360 consecutive RF pulses from the Bates accelerator RF system. For this measurement the RF system was pulsed at 6 Hz with a width of 10 μs. The phase signal was measured inside a 2 us window in the center of the RF pulse. The left-most column in the figure indicates the limit of the phase detector resolution, 12 fs, as measured by comparing the reference line with itself. The performance of most of the components is better than 100 fs (0.10 degrees at 2856 MHz) of pulse-to-pulse jitter. At this time closed loop control of the phase has not been implemented at the Bates linac. In principle a control loop with a gain of 10 operating between 100 kHz and 3 MHz (well within the bandwidth of the amplifier system) could reduce this jitter to the detector resolution limit, 20 fs or 0.02 degrees.

Just this number was achieved under very different conditions at a CW superconducting accelerator. A similar mixer based phase detector was implemented at ELBE in preparation for planned FEL operation [Bue02]. Their system has achieved RF cavity phase jitter reduction to 0.022 degrees rms over the control loop's response from 10Hz to nearly 10 kHz [Bue01].

To further improve upon the phase detector resolution, one design option is to increase the phase detection slope by the use of higher frequencies. This is a viable implementation because low noise frequency multipliers, dividers, and high-order non-linear cavities are available. The required RF reference line could be a subset of the laser based synchronization detailed in Section 2.5. Table 2.4 shows the results for phase detection reference to reference jitter for 1f, 2f, and 4f of 2.856 Ghz. The column "mV / 180°" refers to the output swing for a full phase shift via a broadband trombone-type phase shifter. These results clearly show promise for further improvement of timing jitter resolution via the use of higher frequencies.

Table 2.4: High order results

GHz	mV / 180°	mV R.M.S. jitter	R.M.S. fs jitter
2.85	678	0.045	7.4
5.71	665	0.043	3.6
11.4	532.4	0.041	2.1

The Bates RF group and Instrumentation and Controls personnel are well suited to develop the diagnostics and controller circuitry necessary for the amplifier tuner circuit. This team would make good use of its expertise in the design and construction of high and low level control systems and high resolution RF diagnostics to accomplish this goal.

2.3.6 CAST Research Plan

MIT Bates has developed a three year plan to design, construct and qualify the highly efficient RF amplifier and tuner system described above. The first phase will be devoted to an analysis of the amplifier performance and engineering design. Measurements of the open loop characteristics of existing cavities will be performed. These results will be evaluated to produce a set of specifications for the amplifier tuner system which should yield an effective coupling of Q_{ext} between 3×10^7–10^8. A detailed design of the system will be completed. Important choices include selection of the amplifier and tuner and the integration of the external tuner into the cavity amplifier circuit. At this time three amplifier types appear viable: the klystron, IOT and solid-state amplifier. The klystron is the best established of the three at the frequency and the power levels that will be required. Recently developed IOT's offer moderate power levels at moderate gain, but have very high AC to RF conversion efficiency, require no external modulation and offer the possibility to incorporate the external tuner structure as an integral part of the amplifier itself. Solid-state amplifiers offer the least cost, very high reliability and require the fewest ancillary systems, but may be limited in their power capabilities. Possibilities for the external tuner include a mechanical device coupled to an external cavity of moderate Q ($\sim10^3$) which would allow microphonic correction up to a few hundred Hz, and a very low insertion loss, high average power ferrite phase shifter used to reactively control the SC cavity's center frequency.

The important steps for the development of the amplifier/tuner system are outlined below:

Year 1:

1. Perform measurements of open loop and closed loop performance of existing SRF systems. The required performance specifications for the amplifier/tuner set will be established from these measurements
2. Develop software model of amplifier, tuner and cavity systems.
3. Engineering evaluation of amplifier types, including klystron, IOT and Solid State Power amplifier.
4. Preliminary engineering design for tuner/amplifier set.
5. Preliminary engineering design of RF diagnostics and controller for amplifier/tuner set.

Year 2:

1. Demonstrate low power prototype of amplifier/tuner concept at existing SRF facility.
2. Verify accuracy of software model and amplifier/tuner principle.
3. Acquire and begin assembly of amplifier/tuner components.
4. Test amplifier/tuner system into warm dummy load emulating microphonic perturbations.
5. Qualify RF diagnostics and control circuitry

Year 3:

1. Full evaluation of amplifier/tuner system with RF diagnostics and controller at a partner SRF laboratory, possibly the proposed SMTF.

2.3.7 Summary

This amplifier tuner development is timely with respect to several factors. The effort will realize RF system efficiencies that have now become possible with the construction of extremely low loss superconducting cavities. For some accelerator designs, notably low current or ERL accelerators, this improved system efficiency translates into more than a factor of two reduction in the capital and operating costs associated with the high power RF systems. The reactive tuner could also be useful for efficient powering and control of the new high gradient structures at JLab. The proposed effort will make effective use of the considerable technical expertise and hardware infrastructure DOE has developed at the Bates Laboratory. Further, the effort will substantially support the emerging SMTF proposal with physicist, engineering and student effort.

2.4 Beam Physics

Beam physics is a broad topic encompassing much of the research in CAST. The subset of beam physics topics described in this section is largely computational and driven by Bates researchers. When appropriate and possible, aspects of the calculations may be tested experimentally using Bates facilities. The research described in this section can be grouped into the two general categories of high-brightness linacs, and high-intensity electron storage rings forming part of a high luminosity lepton-hadron collider.

2.4.1 CAST Linac Beam Physics Activities

Whether based on x-ray free electron lasers or energy recovery linacs, linear accelerators are expected to drive the next generation of light sources because of their ability to produce very bright electron pulses with very short durations of ~100 fs or less. We propose to address several primary challenges in generating these short bright beams. These topics are broadly applicable to many facilities under development. They include improvements in bunch compression, femtosecond timing of electron and external reference lasers, fast time-scale diagnostics, beam switchyard design, and start-to-end simulations of entire accelerator facilities.

The first challenge is bunch compression of relatively long pulses by high compression factors. Current designs for bunch compression aim at compression factors of 50 or less (e.g. LCLS), but there is no fundamental reason that this cannot be extended to factors of several hundred. If successful, this would have a profound impact on the beam properties because the injector could then produce a very long pulse with low peak current and hence low emittance, which is then compressed to a short high peak current pulse at high energy. Large compression ratios are not currently used because of distortions in the longitudinal electron distribution, higher order dispersion in the compression systems, and generation of coherent synchrotron radiation (CSR). The longitudinal distortions are caused by RF curvature and space charge effects at low energy. We will simulate the application of higher order harmonic RF cavities to correct the RF distortions introduced by the fundamental accelerating cavities. We will work to correct the higher order dispersion and the effects of CSR through development of compression lattices that cancel the deleterious effects of one compression section with another. Careful attention to correction of higher order dispersion has allowed terawatt tabletop lasers to achieve compression ratios greater than 1000. Similarly there are no fundamental boundaries to generating shorter, brighter electron beams through clever lattice design and longitudinal correction.

The concept of emittance correction has been extensively studied for photoinjectors, and refers to correlations that develop between, for example, the orientation of the transverse phase space ellipse and the time dimension within an electron bunch. Although each thin timeslice may have a small emittance, the projected emittance of all timeslices can be quite large if the emittance correction parameters are imperfectly realized. Complex algorithms that depend on the instantaneous current, pulse shape, and accelerating gradient have been developed that aim to remove this correlation. In practice it has been difficult to achieve good emittance correction at the high peak currents required. Furthermore, the algorithms require particular values of critical parameters such as charge, gradient, and external focusing that may not be optimal for the facility. An alternative approach is to allow the correlations to develop at low energy, and then to use RF cavities and multipole magnets at high energy to cancel the correlations. This scheme has the flexibility to address a wide range of operating conditions (variations in charge, pulse length, gradient, focusing), or even to be turned off. We will develop simulations starting at the photoinjector with realistic distributions for studying the practical implementation of emittance correction schemes that are suitable for a wide range of beam parameters.

The next generation of light sources will have the ability to produce femtosecond pulses of intense x-rays. These x-rays will often be used in pump-probe experiments where a short-pulse high power laser excites a particular time-dependent change in material properties that is then probed with the x-rays. Synchronization of the arrival time of the electron beam with the laser is a critical area of concern. Elsewhere in this proposal we address synchronization of accelerator RF with external lasers, but here we propose study of phenomena that affect the timing of the electron beam itself. These include tolerances on path length differences due to dispersion in the accelerator lattice, energy stability, self-correcting dispersion in multi-chicane compression systems, coherent energy loss due to wakes and CSR emission, and development of diagnostics that can measure electron beam timing with the required precision. Through simulation, we will develop tolerances for a representative linac design that identifies the key issues, and take steps to improve the tolerances by design of a self-correcting lattice.

One requirement for a linac-based light source to be a useful replacement for today's synchrotron rings is that they must serve many (10 or more) beamlines. To split a high repetition rate pulse train among multiple beamlines requires design of a fast switchyard that maintains the requirements of high brightness, short pulse length, and tight synchronization. We will investigate through simulation the design and tolerances of a switchyard lattice and RF switch that can service multiple isochronous beamlines.

Start-to-end simulations, which seek to model a particle beam from its emission in the injector through the entire accelerator chain to the user application, are providing valuable and unexpected insights into the complex beam physics that occurs for beams under realistic conditions. The tools for these simulations, including PARMELA at low energy, and MAD and ELEGANT at high energy, are well developed. By iterating between simulation and experiment, the simulations can be developed to give an accurate physical picture of the accelerator as built. This is valuable both for optimizing the accelerator performance and for providing insight and exceptional educational opportunities across a broad range of experimental and computational skills. We propose to model the Bates accelerator as well as others of interest, including for example the DUV-FEL at BNL. We expect to generate additional codes that are designed to integrate the experimental data with the simulations, perhaps in real-time, that integrate the simulations with controls, and that improve the exchange of data between different codes.

The linac beam physics work breakdown for FY2006-FY2008 is presented below.

<u>Year 1:</u>

1. Develop integration tools to combine codes for start-to-end simulations of high brightness linacs.
2. Apply start-to-end simulations to existing experiments at SLAC, ANL, and BNL.
3. Begin study of limits to compression ratios possible for electron beam bunch compressors.

4. Develop electron beam instrumentation for diagnosing beam slice properties and correlations among different phase space dimensions.
5. Study contributions of accelerator components and beam dynamics effects to timing jitter between electron beam and external lasers such as those used for pump/probe experiments and diagnostics.
6. Develop education program in high brightness beam physics.
7. Hire one postdoc.

<u>Year 2:</u>

1. Continue and expand upon studies initiated in year 1.
2. Compare correction of RF terms in longitudinal and transverse phase space with beam self-effects such as space-charge, wakes, and coherent synchrotron radiation.
3. Study advanced lattice design for correcting correlations among phase space dimensions. Develop a flexible emittance-correction scheme using RF and magnets that does not depend on narrow ranges of space charge forces and acceleration in the Brillouin flow regime.
4. Study "self-correcting" accelerator layouts that are able to achieve superior stability in timing and beam longitudinal performance with relaxed tolerances on RF phase and amplitude through use of multiple compressor sections and possibly higher-order RF cavities.
5. Apply studies to initial design of beamline layouts.
6. Use S-band photoinjector and Bates linac to experimentally investigate beam physics and further beam physics educational program.
7. Add one graduate student.

<u>Year 3:</u>

1. Continue and expand upon studies in previous years.
2. Apply studies to detailed accelerator design.
3. Develop experimental program in collaboration with DOE labs to test analytical and simulation studies specific to their programs.
4. Add second graduate student.

2.4.2 Lepton-Ion Collider

The scientific case for a high-energy lepton-ion collider with high luminosity to probe the fundamental structure of matter using deep inelastic scattering has been formulated in detail over the past few years. Researchers at MIT-Bates have been deeply involved in developing plans to add a new 10 GeV/c, high-intensity polarized lepton beam to the existing Relativistic Heavy Ion Collider (RHIC) complex at Brookhaven National Laboratory to produce a collider called "eRHIC". This project has been supported in the US Department of Energy Twenty-Year Science Facility Plan. The initial core of studies for a future lepton-ion collider under CAST will include research in the areas listed below. MIT scientists propose to extend their studies carried out for the eRHIC Zero Order Design Report (ZDR) to a much more extensive and deeper set of design considerations in collaboration with colleagues from BNL and DESY.

Lattice Study for Lepton Storage Rings

Lepton storage rings for the next generation of lepton-hadron colliders, such as eRHIC [Far04], will require great operational flexibility in beam energy, emittance, path length and spin manipulation to achieve the high performance required for physics experiments. For example, the peak luminosity should exceed 10^{33} nucleons $cm^{-2}s^{-1}$. These rings will also be operating under extremely demanding conditions due to the very high beam average and single bunch intensity requirements. Under CAST, these issues will be pursued with novel lattice design ideas and appropriate technical approaches based on state-of-the-art accelerator technologies.

One of the primary ring design challenges is the large range of energies over which the ring must operate. The experiments at eRHIC require an electron beam in the energy range of 5-10 GeV. The beam parameters of a lepton storage ring for a fixed lattice structure are defined by the balance of quantum excitation and damping of synchrotron radiation. In an isomagnetic storage ring, the radiation power is proportional to the fourth power of the beam energy, and the radiation damping rate is proportional to the third power of the beam energy. At high energy, the high radiation power and the high linear power density of the radiation are the major concerns for the design of vacuum and RF systems. On the other hand, at low energy, radiation damping is much weaker. This leads to a number of unfavorable results including low beam-beam limits, small emittance, and very long self-polarization time. These effects can significantly degrade overall collider performance. To solve these problems, the lattice study will investigate various optical and technical approaches, including the use of wiggler insertions or modular dipoles. Machine performance, technical feasibility, and cost effectiveness will be evaluated for each option.

Another critical issue is to maintain large beam dynamic aperture for all operating conditions. The major cause of dynamic aperture reduction is the nonlinearity of sextupole magnets needed to correct chromaticity in the ring. In collider lepton rings, the problems are significantly complicated by the large phase advance variation required in the arc for large beam emittance adjustments, and by the optics variation required at the interaction region (IR) to accommodate various collision scenarios of the lepton beams with different hadron species of different energies. The study will develop appropriate chromaticity correction schemes, with multi-family sextupoles in the arc and local correction around the IR based on theoretical analysis and numerical simulations.

Simulation code developments are essential to fulfill these tasks. The goal is to develop a fully functional, fully symplectic tracking code which can handle complicated collider optics. The code can be based on SLAC LEGO [Cai98] or KEK SAD [Hir88], for example, and should be capable of easily communicating with existing popular optical codes (like MAD [Gro91]) on an appropriate modeling deck. The codes will be developed in collaboration with SLAC and BNL.

Beam Polarization in Lepton Rings

High longitudinal polarization (~80%) of the lepton beams is required at the interaction points in the next generation of lepton-hadron colliders. To reach high luminosities, the lepton beam and hadron beam have to be matched at the Interaction Point (IP), and the beam-beam interaction will be very strong and will adversely affect the beam polarization.

The conflict between the achievement of high equilibrium beam polarization, which requires very small closed orbit deviations and small vertical beam size, and the realization of large emittance aspect ratio (perhaps 25% for matching the hadron beam at the IP) is an especially critical issue for lepton rings in high luminosity lepton-hadron colliders. The study, based on simulation and HERA machine update tests, will provide an appropriate prediction of the achievable level of equilibrium beam polarization vs. emittance aspect ratio. If the conflict proves difficult to resolve, an alternative method of using an emittance adapter [Edw01] to increase the emittance aspect ratio locally in the IR region will be considered. The study will also look into further experimental exploration of such an emittance adapter if it proves necessary.

A sophisticated spin simulation code (based on SLICKTRACK [Bar04], in progress) will be developed in which particles and their spins are tracked while photon emission is simulated approximately within a Monte-Carlo framework with non-linear orbits. Beam-beam effects on spin will also be included. The code development is essential to the above study and provides the tool to develop system specifications for beam position monitoring and orbit correction. The code will also be applicable to other special spin simulations such as the Figure-8 synchrotron suggested in the eRHIC report [Far04] and the collider ring in the JLab ELIC proposal [Der04]. Both code development and validation against experimental data from HERA and from Bates will be pursued in collaboration with the DESY Machine Physics Group.

Proton Spin Dynamics in Storage Rings

An obvious requirement for the eRHIC project is that RHIC can deliver the required high longitudinal polarization at its top energy of 250 GeV and with high beam intensity. In contrast to electrons and positrons, there is no natural polarizing process for protons such as the Sokolov-Ternov effect [Bar01]. The protons must therefore be pre-polarized at low energy in the source and the polarization must be preserved during acceleration. This would normally be an impossible task owing to the need to cross a large number of spin-orbit resonances, many of which cause depolarization. However, at low and medium energy, polarization loss can be overcome using, among other things, so-called partial Siberian Snakes. At energies above several tens of GeV full Siberian Snakes are used. These are the means by which proton polarization has been preserved in RHIC up to 100 GeV [Hua04]. However, this has still required very careful choice of betatron tunes. Since depolarizing effects tend to increase with energy, it is likely that reaching 250 GeV will require considerably more effort. So far the attainable polarization has been estimated by straightforward numerical spin-orbit tracking simulations of the acceleration process. But in the last decade a large amount of progress has been towards understanding and classifying the very high energy behavior of spins in terms of the so-called invariant spin field and the amplitude dependent spin tune. These concepts and the accompanying numerical tools, as embodied in the computer code SPRINT [Ros04], allow far deeper insights into the behavior of spins at high energy than was possible in the past. For example, before undertaking a time-consuming simulation of acceleration, it is possible to calculate the permissible maximum equilibrium polarization directly at the targeted energy.

Many other examples can be given, but suffice it to say that in the light of the eRHIC project, CAST should establish a long term commitment to the theory and phenomenology of spin dynamics of very high energy protons, deuterons and helium 3, thereby complementing and assisting the practical efforts of the RHIC team in the specific case of RHIC.

A first step would be to include necessary extra facilities in SPRINT in collaboration with its authors at the Deutsches Elektronen-Synchrotron Laboratory (DESY) in Germany and then to install it at MIT. This would form an ideal topic for a Ph.D. student. Collaboration with one of the authors, namely Professor G.H. Hoffstaetter, of Cornell University would also be desirable.

Beam-Beam Effects in Lepton–Hadron Colliders.

Beam-beam interactions are one of the most fundamental luminosity limitations for storage ring colliders. For future high luminosity colliders, the beam-beam limits for both lepton and hadron beams will be reached. This is different from the only existing lepton-hadron collider, HERA, where lepton beam current is limited by available RF power and therefore the beam-beam tune shift for the hadron beam is not a hard limit.

A lepton-hadron collider with rings of unequal circumference presents another unique beam-beam issue, which must be addressed in the early stages of the collider design. The purpose of having unequal circumferences for the collider rings is to separate the lepton and hadron rings so that the lepton ring design can be optimized. This feature improves collider performance and also provides substantial cost savings. However, previous studies [Hir89, Ale90] have suggested that the performance of such a geometrically asymmetric collider can be compromised by coherent beam-beam interaction limit. The geometrically asymmetric collider also has more complicated collision patterns. For example, in eRHIC, the ideal collision pattern is one lepton beam bunch colliding with three different proton bunches consecutively. But in the case of missing ion bunches, one lepton bunch could collide with just one or two ion beam bunches in three turns. Furthermore, the lepton beam can be an electron beam or a positron beam. The beam-beam effects for each of these collision scenarios can be quite different [Shi04].

In a dedicated eRHIC single IP mode, there is a possibility to further increase the collider luminosity by having higher electron bunch current. It depends on the magnitude of the ion beam-beam limit. An accurate prediction of the ion beam beam-beam limits by both simulation and extrapolation of the RHIC experimental results will provide solid ground for machine performance expectations and the electron ring system specifications. The study will address these issues, which will have a great impact on how the collider is designed and operated.

For the lepton-ion colliders studied here, the strong-strong model is more appropriate for beam-beam simulations. There are several strong-strong beam-beam simulations codes [Zim03].

However, to do simulations for the future lepton-ion colliders, and to address the unique and complicated situations mentioned above, more software development is required. This study will develop a fully self-consistent tracking code based on the particle-in-cell method. The code will be applicable to either hadron-hadron colliders or lepton-hadron colliders with multiple interaction points. The code will be able to deal with complicated collision patterns of asymmetric circumference rings. Code validation against experimental measurements at HERA, RHIC, and the SLAC B-factory are expected. The work will be performed in collaboration with physicists at BNL, University of Kansas, DESY and SLAC.

Two-stream Beam Instabilities in High Intensity Lepton-Hadron Colliders

The next generation of lepton-hadron colliders requires very high intensity electron and positron beams. The two-stream instabilities, such as fast beam-ion instability in an electron beam and the electron cloud effects in the positron beam, may significantly limit the machine performance. Due to the high critical photon energy and high synchrotron radiation linear density, the electron cloud effects in eRHIC are different from those in existing collider machines. Studies through analytical approaches, numerical simulations and beam experiments are needed to understand the physics and to develop solutions [Rum03].

A realistic simulation of the electron cloud accounting for the antechamber shape will be very helpful to understand the effects. The growth rate of ion instability for electrons needs to be studied carefully, especially for low energy operation. Given the high bunch current in the eRHIC lepton ring, the single bunch instabilities are estimated to be significant and need to be investigated with appropriate models. The results from the above studies will be very important in defining the vacuum chamber design and the parameters of feedback systems.

Spin Studies for a Figure-8 Synchrotron

A Figure-8 synchrotron can be used as an electron injector for a next generation electron-ion collider ring [Far04]. In this machine, a 500 MeV electron or positron beam is injected into the synchrotron, ramped up to 5-10 GeV, and then injected into the lepton storage ring. Due to the two opposing 270 degree arcs in this geometry, the forward spin precession in one arc is cancelled by that in the other arc. Hence, the net spin precession is zero, independent of the beam energy, and no spin resonances are crossed during the ramping process. This means that the storage ring can have a large bending radius, limiting the power losses in the dipoles. The large bend radius will also result in relatively long depolarization times, which improves the prospects for spin flipping in the lepton ring with minimal loss of polarization. Due to the polarized injected beam and the possibility for topping off, the maximum possible luminosity is achieved.

The topology is similar to that proposed for usage with an energy recovery linac in the JLab ELIC proposal [Der04]. Here the Figure-8 is the "storage" ring in which the electrons are circulating for ~100 turns, in order to ease the requirements for the high brightness polarized source and the ERL.

Although the topology is similar, the beam parameters are quite different. For the injector synchrotron the current is low (~1 mA) but polarization has to be maintained during the ramping process (1000 turns). The current in the storage ring for the ERL is high (1 A) and polarization has to be maintained for ~100 turns; then the beam is transported back into the ERL for deceleration and energy recovery.

Detailed simulation of the polarization behavior both at a fixed energy and during the ramping process is critical to assess the achievable polarization. Where the net spin precession is zero, there is no driving force to maintain the polarization, which means that instabilities can have a huge impact on the polarization. Development of the previously mentioned Monte Carlo non-linear spin tracking code [Bar04] is essential.

High Precision Polarimetry for Lepton Storage Rings

The next generation of colliders will feature polarized beams of unprecedented intensity. Designs for various facilities have been considered featuring beams with intensities up to 1 A and energies spanning a range from 2 GeV to 25 GeV [Far04, Der04]. Any such machine would require very good polarimeters for circulating beams; techniques for measuring the polarization of stored beams in a nondestructive manner must be developed. Many experts in this field believe that the Compton scattering technique presently in use for polarization measurements at a number of high-energy facilities [Bar93, Knu97, Woo96] can also be applied for a high-intensity collider [BNL02, Lor03], but certain technical challenges exist.

MIT-Bates is in a strong position to contribute to the development of next generation techniques for stored beam polarimetry. The South Hall Ring (SHR) already contains a longitudinal Compton polarimeter [Fra03], which has operated at beam intensities up to 200 mA during the BLAST experiment and has been simulated with detailed Monte Carlo. Higher intensities have been achieved in the SHR and could be explored with a modest amount of beam time. Additionally, for Compton polarimetry, many challenges arise specifically at low energies due to the falling energy and analyzing power of scattered gamma rays [Pas98]. Bates is well suited to explore phenomena at energies below those of the electron-ion collider. With equipment existing at the lab, it may be possible to add the ability to measure transverse components of the stored beam polarization and a feasibility study for this project is underway.

A second thrust of the polarimetry program will be to study the possibility of extracting the beam polarization from energy deposition in an RF cavity due to the Stern-Gerlach effect. This effect has been predicted to be measurable with a stored beam [Con04], but has never been successfully demonstrated. If successful, it would provide an alternative and very efficient method for measuring beam polarization in a storage ring. Scientists at Brookhaven National Laboratory are pursuing this approach and are preparing a prototype RF cavity. The MIT-Bates South Hall Ring would provide an excellent facility for testing this approach. With a calibrated Compton polarimeter, highly polarized beam, and existing spin flipper, tests of a prototype cavity can be carried out with a modest amount of beam time. Technical support and a small amount of capital are required to support installation of the RF cavity in SHR.

The polarimetry program clearly complements other areas, such as the development of highly polarized beams. Tests of other electron beam polarization phenomena can also be carried out using the ring's existing polarization infrastructure.

The work breakdown for the CAST lepton-ion collider beam physics R&D is presented below.

<u>Year 1:</u>

1. Lattice:
   IR region local chromaticity correction scheme development. Orbit correction schemes. Dynamic aperture tracking with errors. Tracking code development.
2. Beam polarization:
   Spin simulation code development, experimental verification with HERA machine studies.
3. Beam-beam:
   Strong-strong beam-beam tracking to have initial beam-beam limit predications on eRHIC collider performance and preliminary beam-beam related parameter specifications for the lepton ring.
4. Instability:
   Electron cloud effect and fast beam-ion instability study. Analytical modeling.

5. Figure-8 synchrotron:
   Spin simulations for the synchrotron operation.
6. Polarimetry:
   Transverse polarimeter: Detector and software development
   Hire one postdoc later in the year.

<u>Year 2:</u>

1. Lattice:
   Feasibility (optics, engineering etc.) studies on various lower energy radiation enhancement plans. Feasibility studies on large particle path length adjustment schemes. Beam coupling control.
2. Beam polarization:
   Spin simulations in the lepton ring to predict equilibrium polarization level under high luminosity operation scenarios. Study of lepton beam emittance ratio adjustment measures which preserve high polarization level.
3. Beam-beam:
   Simulation studies on hadron ring beam-beam limits and multi-collision scenario, experimental verifications with RHIC operation experiences.
   Low energy operation simulations.
4. Instability:
   Beam instability study in conjunction with RF system specifications and vacuum chamber design.
5. Figure-8 synchrotron:
   Feasibility study (lattice, cost etc.) on a Figure-8 synchrotron as a full energy, polarized electron beam injector for the collider lepton ring.
6. Polarimetry:
   Transverse polarimeter experiment in South Hall Ring.
   RF cavity polarimeter preparation: RF cavity installation.

Year 3:

1. Lattice:
   Full operating range dynamic aperture tracking. Optimization of lepton ring lattice for the eRHIC collider,
2. Beam polarization:
   Code development including beam-beam interactions.
   Recommend measures to be taken and relevant machine design specifications to achieve high (>70%) polarization level.
3. Beam-beam:
   Finalize lepton beam parameter specifications of the lepton beam based on full operating range beam-beam simulation and machine operating experiences.
4. Instability:
   Lepton beam instability study based on detailed multi-particle tracking simulations under high bunch intensity and average current operation conditions. Feedback system considerations.
5. Figure-8 synchrotron:
   Final report on the feasibility of a Figure-8 synchrotron as the lepton ring injector.
6. Polarimetry:
   RF cavity polarimeter experiment in South Hall Ring.

2.5 Femtosecond Timing Distribution and Synchronization

Precise timing distribution and synchronization of multiple laser sources with each other, with the electron beam, and with various RF-sources is a major challenge in advanced accelerator facilities. The timing requirements are particularly tight, at the level of a few femtoseconds, and even sub-femtosecond in the future for seeded FEL-facilities such as the proposed MIT x-ray laser.

Professor Kaertner, the leader of this effort, has an extensive background in research on precise timing of microwave and laser devices. His interests have included modeling and simulation of the nonlinear dynamics of microwave devices and circuits, noise in microwave oscillators, and quantum noise with special emphasis on squeezed state generation using the fiber nonlinearity. The algorithm he developed for determining the noise spectrum of oscillators is widely used in today's commercial microwave circuit simulation tools. His current interests are focused on ultrashort pulse generation in the few-cycle regime and its applications such as large scale femtosecond timing distribution in accelerator and free electron laser facilities. He has served on the program committees of CLEO Europe and CLEO US since 1998, Advanced Solid-State Photonics Conference ASSP since 2001, and the Conference on Fluctuations and Noise in 2003. He was the program chair of the Annual Meeting of the Laser and Electro-Optics Society of the IEEE in 2002 and general chair in 2004.

We envision developments to take place in multiple directions in the next decade depending on the specific needs of various accelerator technologies. Therefore, we believe that it is important to conduct research on, and train scientists to develop expert knowledge of, a workable scheme for large scale optical timing distribution and synchronization. This effort should ideally be of a modular structure and easily adaptable. To this end the following capabilities have to be developed:

- **A precise master clock:** An optical master-clock, *i.e.* a mode-locked laser whose repetition rate is locked with sub-femtosecond timing jitter to a frequency standard with stability and accuracy comparable to an atomic clock, and eventually to an optical atomic clock, which is an emerging technology.
- **Means to transmit the clock signal:** Timing-stabilized fiber links that transport the master clock signal to different locations with minimum added jitter.
- **Means to lock other lasers to the clock signal:** Locking of local lasers, such as pump/probe lasers to the pulse stream with femtosecond timing jitter.
- **Means to lock the electron beam and RF components to the clock signal:** Regeneration of RF-signals or synchronization of local RF-sources to the optical pulse stream emerging from the fiber links.

Figure 2.12 shows how such a timing and synchronization system could be deployed in the proposed MIT-X-ray Laser Facility.

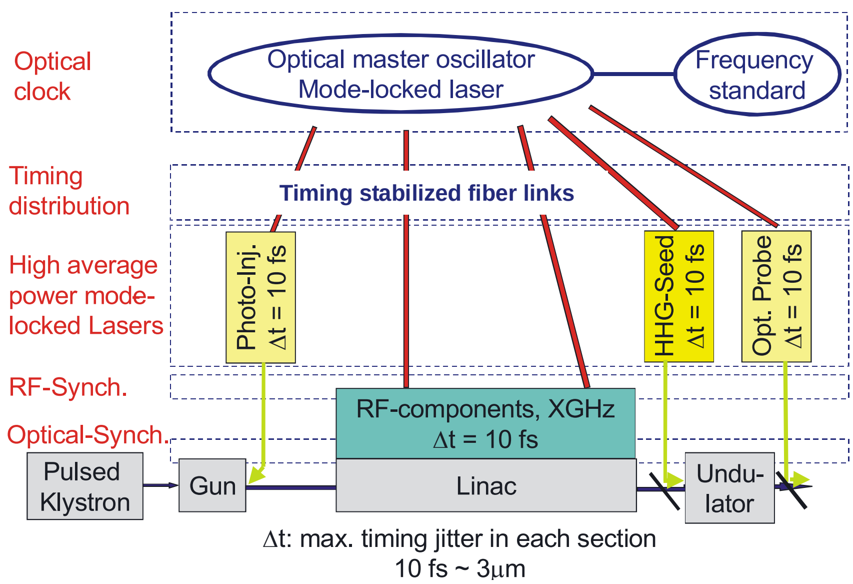


Figure 2.12: Schematic outline of the timing and synchronization system for the proposed MIT-X-ray laser.

Below we outline a specific scheme which forms the starting point of such a development effort. At a minimum, a typical facility will comprise a photoinjector laser, various RF-components to be synchronized, and lasers for the photoinjector, for driving the seed sources and as the source for pump/probe measurements. All of these sources can be connected to the master clock with timing-stabilized fiber links in a star geometry. The proposed scheme and geometry builds on modular components and can be easily expanded in the future (Figure 2.12).

The four key requirements outlined above are addressed in more detail in the following sections. We also describe results that have been already achieved, or are in progress.

Master Clock Laser for the Facility

A passively modelocked fiber laser will be used as the master clock laser and its repetition rate will be locked to an ultra-stable microwave oscillator. The use of a fiber laser has several advantages: (i) fiber lasers are compact devices which are nearly free of misalignment and exhibit excellent long-term stability, (ii) the wavelength of operation for an Er-doped fiber laser is 1.55 μm where a larger variety of low-loss, low-cost fibers with different dispersion properties exist, along with various highly-developed components, such as modulators, couplers, and detectors. Furthermore, the output of a fiber laser can be easily amplified in integrated, in-line fiber amplifiers. Thus, by the addition of fiber amplifiers, an adequate signal level can be maintained, regardless of the number of fiber links used.

Master Microwave Oscillator

Microwave oscillators with extremely low noise are available as mature commercial products. We plan to use the Sapphire Loaded Cavity Oscillator from Poseidon Scientific Instruments, Pty. Ltd. This compact device can be operated at output frequencies in the range of 8 GHz to 12 GHz with output powers of ~13 dBm. Importantly, the oscillator is extremely quiet, with noise characteristics corresponding to a timing jitter of 6 fs (from 10 Hz to 10 MHz). Therefore, at the moment, there is no immediate need for a development effort for the master microwave oscillator.

Master Fiber Laser

A stretched-pulse Er-fiber laser providing 100-300 fs pulses with 50-100 mW of average power at ~50 MHz repetition rate will be used (Figure 2.13). The stretched-pulse Er-fiber laser has been developed in the MIT Optics Group [Len95].

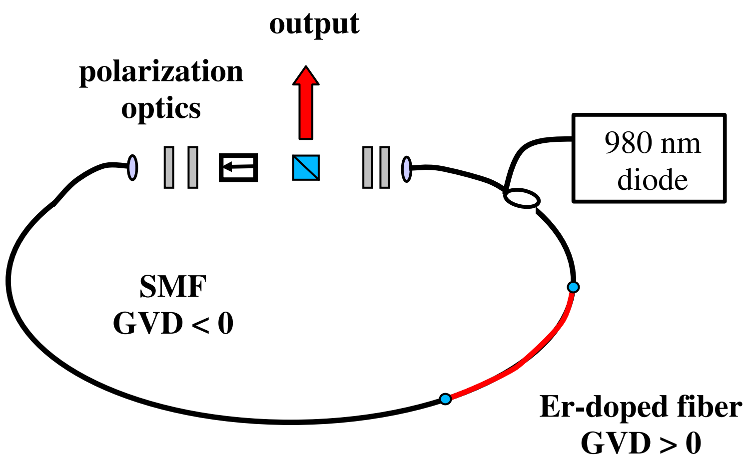


Figure 2.13: Schematics of the stretched-pulse fiber laser.

The stretched-pulse fiber laser implements the concept of dispersion management used in telecommunication fiber links. The continuous stretching and compression of the pulse within the cavity reduces the nonlinear effects, as a result 1 nJ, 100 fs pulses can routinely be obtained. Typical repetition rates are in the range of 30-50 MHz.

Synchronization of the Master Laser to the Microwave Oscillator

Leo Hollberg found in his work on optical clocks that direct photo-detection of an optical pulse stream adds excess phase noise not present in the original pulse stream [Hol03]. To avoid this phase noise, which deteriorates frequency measurements, one has to look for alternative methods to derive an RF-signal from a pulse stream or to lock a pulse stream reliably and stably on the long term to an RF-signal with femtosecond precision. The general idea for suppression of excess noise due to the photo-detection process is visualized in Figure 2.14. While still in the optical domain, the timing information is transferred into an intensity imbalance between two beams by sending the pulse train through a pair of amplitude modulators. The modulators are driven by the output signal from a voltage controlled oscillator (VCO) with 180° phase difference. The intensity difference is detected with a balanced detector and this signal controls the input to the VCO via a loop filter. Thus, the problem of photo-detector nonlinearities on the electronic side is shifted to the realization of amplitude modulators with drift-free bias points on the optical side.

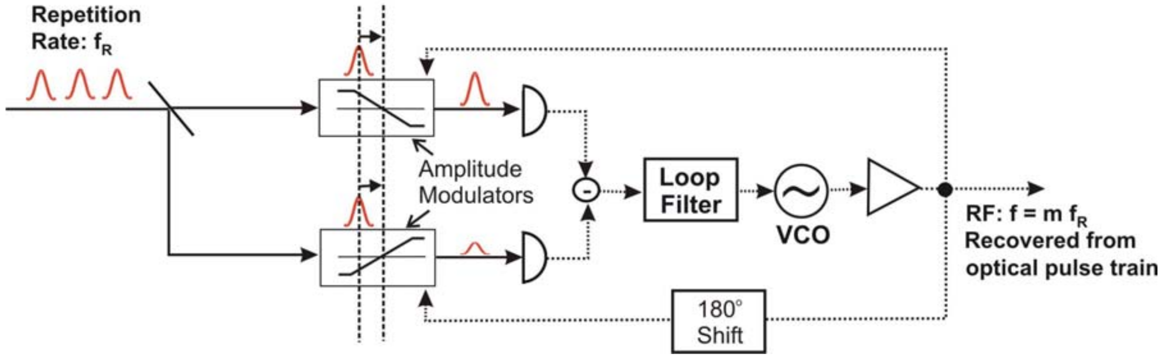


Figure 2.14: Schematic setup for RF-signal extraction from an optical pulse train. Every multiple of the repetition rate can be extracted.

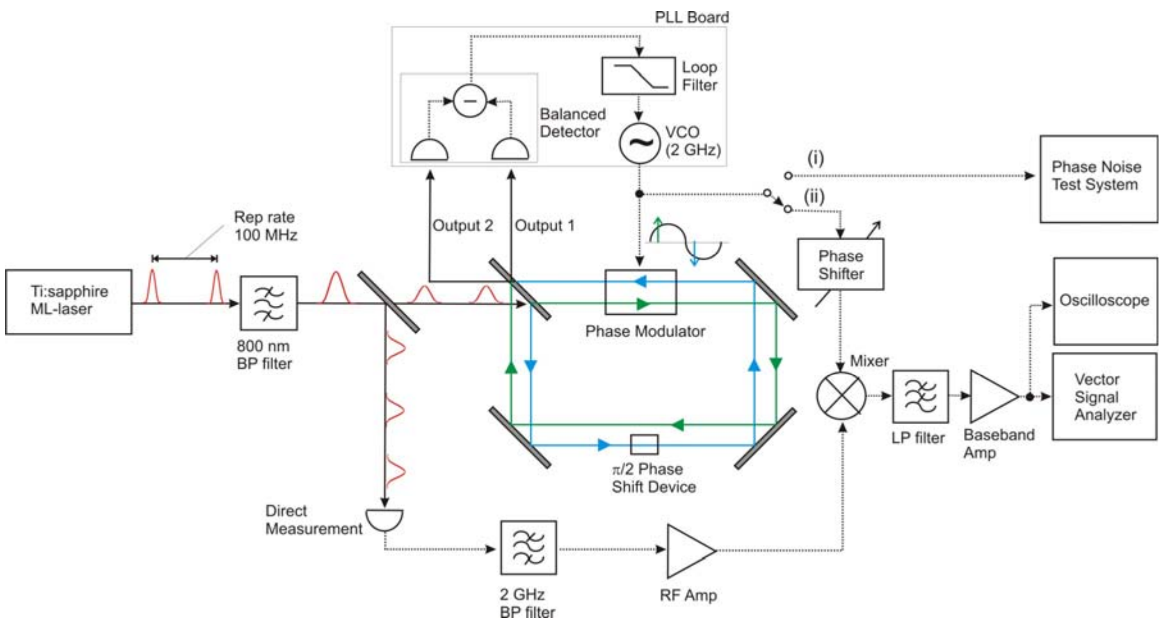


Figure 2.15: Extraction of a 2 GHz signal from a 100 MHz repetition rate Ti:Sapphire laser. The VCO output is characterized (i) by a commercial phase noise test system and (ii) by mixing in quadrature with the 2 GHz component of the directly detected signal. The resulting signal is measured with a vector signal analyzer. The normalization constant for calibration to the RF-phase is measured independently with an oscilloscope.

The 180° out-of-phase amplitude modulators can be realized in a simple Mach-Zehnder interferometer with a phase modulator placed in one arm. However, this scheme will suffer from the phase drifts in the interferometer arms due to temperature fluctuations, air currents, and mirror vibrations. To remove these problems, the interferometer can be implemented in a Sagnac-loop configuration. Figure 2.15 shows the synchronization scheme with the measurement set-up. A 100 MHz repetition rate Ti:sapphire mode-locked laser is used as the pulse source. After passing a bandpass filter at 800 nm to limit the pulsewidth to about 100 fs, the input optical pulse train is sent into the Sagnac-loop. A resonant phase modulator at 2 GHz is positioned in the Sagnac-loop in such a way that the optical delay between counter propagating pulses at the phase modulator is set to half of the RF-signal period, i.e. 0.5 ns for the current 2 GHz VCO. This assures that the two pulses experience opposite phase modulation. The output beams are detected by a balanced detector which drives the VCO after proper filtering. For a stable and drift-free biasing of the interferometer, a quarter-wave plate is inserted in one of the beams using a thin-film coating covering only half of the substrate.

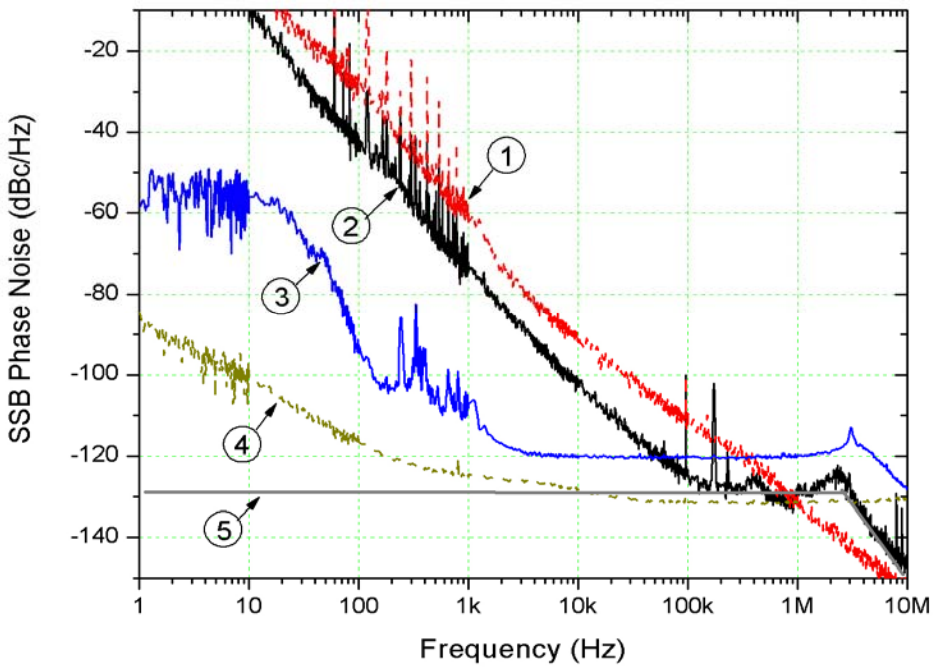


Figure 2.16: Measured single-sideband phase noise of (1) the free-running VCO and (2) the locked VCO using a commercial phase noise measurement system. Curve (3) shows the measured single-sideband phase noise between extracted RF-signal and the 20th harmonic of directly detected pulse train using a mixer and vector signal analyzer. Curve (4) shows the noise floor of the vector signal analyzer. Curve (5) shows the estimated phase noise level of extracted RF-signal from result of curve (2).

The phase noise of the RF-output signal from the VCO is characterized in two ways: (i) it is characterized by a commercial phase noise measurement setup PN9000 from Aeroflex; (ii) the output signal of the VCO is mixed in quadrature with the 2 GHz component of the directly detected pulse train, which measures the relative phase noise between the optical pulse train and the extracted RF-signal. The measured single-sideband phase noise spectra from 1 Hz to 10 MHz are shown in Figure 2.16. Curve (1) shows the phase noise spectrum of the free-running VCO measured with the Aeroflex phase noise measurement system. Curve (2) shows the phase noise measured by the same method when the system is locked. The locking is clearly visible in the spectrum covering the range of 100 kHz to 10 MHz. At lower frequencies, the phase noise of the Ti:sapphire pulse train dominates.

Following the proof-of-principle experiment, work is under way in our laboratory to implement this scheme at 1550 nm based on fibers (Figure 2.17). In addition to the availability of a large variety of components at this wavelength and matching the wavelength of the master laser, the use of fibers should decrease low-frequency noise drastically: the main source of noise below 1 kHz appears to be due to mechanical vibrations and other instabilities in the free-space interferometer.

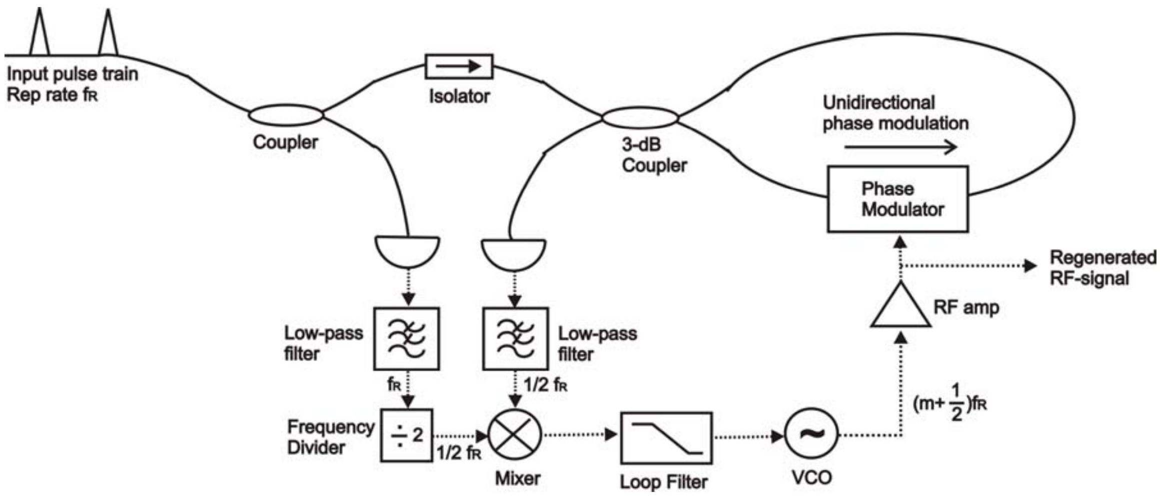


Figure 2.17: RF-laser synchronization scheme with fiber Sagnac loop.

Overall, this system can be scaled to 1 fs timing jitter between the RF-signal and the optical pulse train. The synchronization is robust and insensitive to environmental changes that impact microwave cables and temperature drifts because the timing transfer occurs in the optical domain.

Distribution of the Master Clock Signal over Timing-Stabilized Fiber Links

The second challenge is the transfer of the master clock signal over large distances that the proposed facility spans. It is necessary to distribute the clock-signal with femtosecond accuracy to multiple locations which can be several hundred meters away. To this end, we will construct a timing-stabilized fiber link and first experiments are under way.

The fiber link length will be actively controlled to ensure a fixed time of flight between two locations to be synchronized. We expect the leading contribution to length variations to arise from thermal and mechanical effects which occur with frequencies under 1 MHz. A rough estimate of these length variations can be obtained by the expected length change due to thermal fluctuations and based on the thermal expansion coefficient of fiber (~ 2 10^{-7}/°C) [Lee89]. The fiber link will be maintained at a constant temperature within 1°C with a temperature stabilized fiber link. This fiber is commercially available and deployed at many similar facilities. The corresponding length variation in a 300 m-long fiber link would be approximately 60 μm, corresponding to a timing jitter of ~300 fs. Fortunately, these changes occur on a time scale of milliseconds, and one can implement active stabilization schemes to compensate for these length variations.

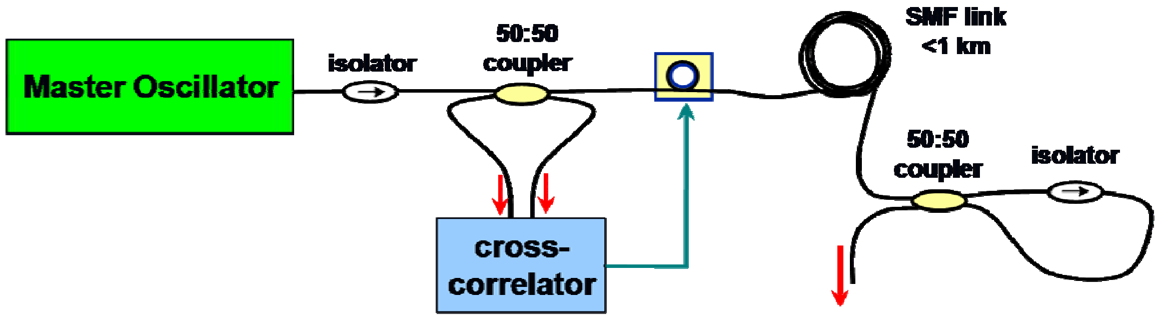


Figure 2.18: Schematics of the timing distribution over an actively-stabilized fiber link.

We briefly describe implementation of this approach with an in-line fiber stretcher. The experimental setup is illustrated in Figure 2.18. Pulses from the master oscillator are coupled into single-mode fiber which is connected to a fiber-based splitter. An isolator is placed in between to prevent back-reflected light from disrupting mode-locked operation of the oscillator. One port of the coupler is connected to the fiber stretcher which then connects to the fiber link. The other port channels a fraction (we assume 50%) of the pulse toward a cross-correlator. At the end of the link, a portion of the pulse is reflected back through a fiber loop, traversing the same path, including the fiber stretcher. Part of it is routed toward the cross-correlator where it overlaps with another pulse produced by the oscillator, nearly 100 roundtrips later. The cross-correlator generates an error signal proportional to the temporal mismatch of the two pulses. The error signal from the cross-correlator is fed into the fiber stretcher, forming a feedback loop. Since the pulse traverses the same physical path during either direction of propagation, ensuring temporal overlap of the oscillator pulses with the returning pulse also ensures that the time of flight to the end of the fiber link is maintained. The cross-correlator is analogous to the one described in the section on synchronization of different modelocked lasers.

Synchronization of Modelocked Lasers with the Master Laser

Once the repetition rate signal of the master clock laser can be accurately transmitted over the timing-stabilized fiber link, the problem of synchronizing different lasers reduces to that of locking two independent lasers that are physically adjacent to each other. Basically, the scheme described above for locking a modelocked laser to a microwave oscillator can be used, after replacing the microwave oscillator with the modelocked laser to be locked to. The underlying physics remains unchanged. The experimental setup is illustrated in Figure 2.19.

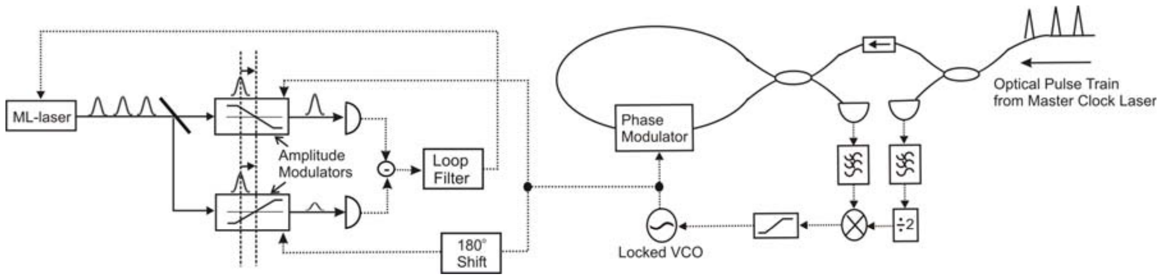


Figure 2.19: Experimental setup for locking a modelocked laser to the optical pulse train transmitted over the timing-stabilized fiber link.

This approach builds on a scheme invented and demonstrated in our group for synchronization of independent lasers to attosecond level [Sch03]. An important difference is our newly-developed scheme does not require precise alignment of an optical cross-correlator.

Synchronization of the RF-Components with the Master Laser

The master clock signal will be delivered to the RF-components that need to be synchronized, reducing the problem to that of locking an RF-component to the master clock signal. This task is the inverse of locking the master clock to the microwave oscillator and after some modification to the scheme described in Section 2.5, no separate development is needed.

The CAST R&D Electron beam synchronization work breakdown for FY2006-FY2008 is presented below:

Year 1:

1. Development of very low noise master oscillator for large scale timing distribution: Build Er-Yb:glass laser, Er-Yb:fiber lasers with different pulse shaping processes
2. High resolution phase noise characterization of master oscillator.
3. Test of noise performance of the master laser in an accelerator environment, i.e. under strong electromagnetic perturbations.

Year 2:

1. Systematically study and decide on which laser technology has the best noise performance to achieve femtosecond timing distribution over at least 500 m.
2. Develop femtosecond RF-Laser synchronization
3. Develop femtosecond Laser-Laser synchronization
4. Integration with fiber technology
5. Test of synchronization electronics in an accelerator environment

Year 3:

1. Development of timing stabilized fiber link with all fiber components
2. Timing jitter measurements over timing stabilized links

3. Timing jitter measurements between synchronized RF-RF, Laser-Laser and Laser to RF systems
4. e-beam timing measurements
5. Overall system test in accelerator environment

2.6 Coherent Radiation Generation by Relativistic Electron Beams

2.6.1 Introduction

Relativistic electron beams are powerful sources of coherent and incoherent radiation at wavelengths spanning the microwave, millimeter wave, infrared, visible, and x-ray regions. Radiation from synchrotron storage rings is employed by thousands of users because of its wide spectral coverage at useful power levels. Linear accelerators offer the potential for achieving higher brightness outputs at very short wavelengths, including the x-ray region.

We propose to study coherent and incoherent radiation using the 500 MeV electron beam available at the Bates accelerator facility. Our motivation is two-fold. First, we wish to understand the physics of novel radiation sources based on relativistic electron beams, such as Smith-Purcell radiation from gratings and from Photonic Bandgap Structures. Second, we wish to evaluate the radiation as a diagnostic of the electron beam quality and bunch length. The proposed research would be a valuable addition to the proposed research program at Bates. It would be carried out with the existing linac beam line and would take advantage of the high beam energy and high average power of the linac, relative to sources available on the MIT campus. It would also benefit from the excellent diagnostics and facilities available for the linac at Bates.

Smith-Purcell Radiation

An electron passing close to the surface of a metal diffraction grating as in Figure 2.20 emits Smith-Purcell radiation [Smi53].

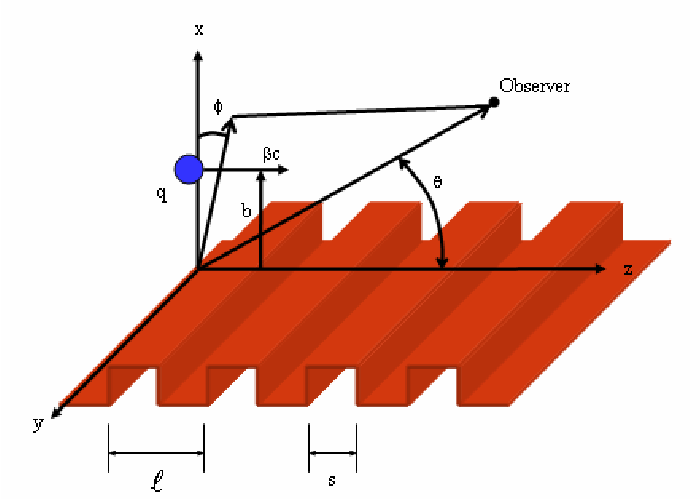


Figure 2.20: Schematic of an electron bunch, q, passing over a grating of period *l*, with an impact parameter b.

Radiation is emitted according to the well-known relation:

$$\lambda_n = \frac{\lambda}{n}\left(\frac{1}{\beta} - \cos\theta\right) \tag{1}$$

where *l* is the grating period, θ is the emission angle with respect to the propagation direction, n is the diffraction order, and β is the velocity of the electron bunch normalized to the speed of light.

The angular distribution of power radiated by the electrons is given by [Woo95]:

$$\frac{dP}{d\Omega} = N_g \frac{eIn^2\beta^3}{2\lambda\varepsilon_o}\left(1 + N_e e^{-k^2\sigma^2\cos^2\theta}\right)\left(\frac{\sin^2\theta}{(1-\beta\cos\theta)^3}\right)\left|R_n^2\right|\exp\left(\frac{-4\pi|n|b}{\gamma\lambda(1-\beta\cos(\theta))}\right) \tag{2}$$

where N_g is the number of grating periods, I is the beam current, N_e is the number of electrons in the bunch, ε_o is the permittivity of free space, b is the height of the bunch above the grating, k is the wave vector, σ is the bunch length, and R_n^2 is the grating efficiency factor.

For radiation at wavelengths shorter than the bunch length, the radiation is incoherent. However, at wavelengths longer than the bunch length the radiation is coherent and the temporal coherence of the electron bunch enhances the intensity of the radiation. In general, the coherence term is (1 + $N_e F$), where F is the form factor given by the Fourier transform of the bunch distribution. For Equation 2 a Gaussian distribution has been assumed giving a coherence term:

$$1 + N_e e^{-k^2\sigma^2\cos^2\theta} \tag{3}$$

The first term in Equation 3 corresponds to the incoherent portion of the radiation and the second term the coherent portion.

Using the Smith-Purcell relationship, Equation 2 can be rewritten as a function of frequency giving:

$$\frac{dP}{d\phi df} = \frac{eIL\beta^3}{2\varepsilon_o c^2} f \left| R_n^2 \right| \left(1 + N_e e^{-\left(\frac{2\pi f}{c}\right)^2 \sigma^2 \cos^2\theta} \right) \sin^2\theta \exp\left(\frac{-4\pi bf}{\gamma\beta c} \right) \quad (4)$$

Equation 4 is plotted in Figure 2.21 for I = 100A, $\gamma = 40$, $\sigma = 60\text{x}10^{-6}$ m, b = 10^{-4} m, $\theta = 40°$. The emitted radiation will be in the 0.5 – 1 THz regime. In the forward direction, the emitted frequency is Doppler upshifted by γ^2, where γ is the relativistic factor $(1-\beta^2)^{-1/2}$:

$$\lambda_n = \frac{\lambda}{n}\frac{1}{2\gamma^2}$$

This upshift could be utilized, as in a free electron laser, to create very short wavelength radiation, well into the x-ray region. However, this radiation is weak unless the electron beam is prebunched.

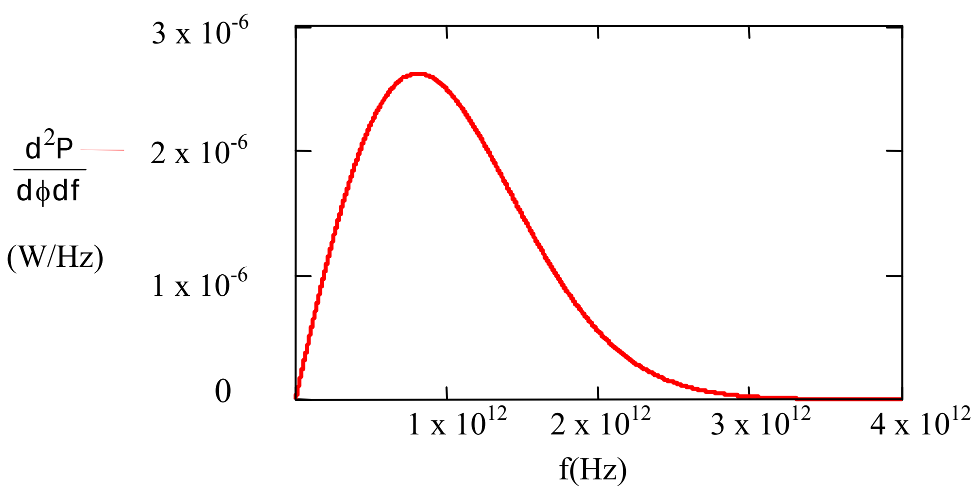


Figure 2.21: Plot of radiated power as a function of frequency**.**

Experimental Research at MIT Plasma Science and Fusion Center

At the MIT Plasma Science and Fusion Center, we are currently conducting research on Smith-Purcell radiation from short bunches produced by a 15 MeV electron accelerator built by Haimson Research Corp. An AutoCAD drawing of the experimental beamline is shown in Figure 2.22. The Smith-Purcell experimental chamber has been placed ~1 m downstream of the accelerator to allow for the use of a focusing solenoid and steering coils [Kor01a, Kor03].

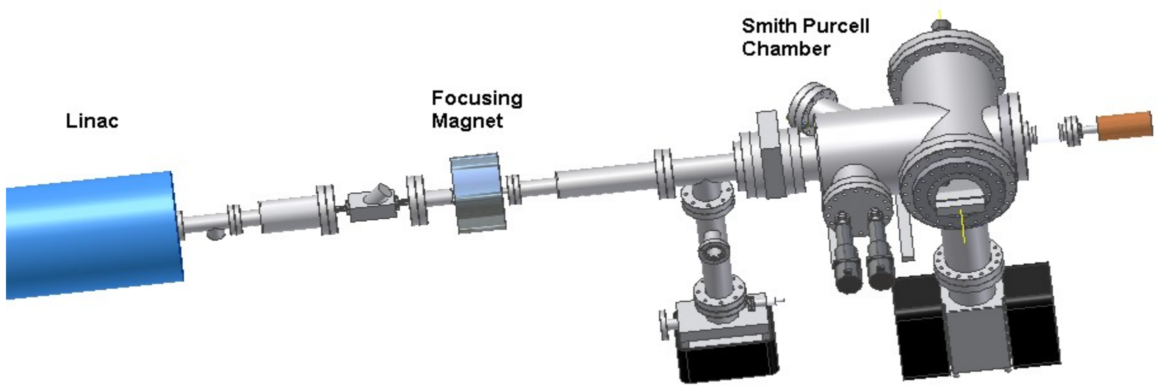


Figure 2.22: Schematic of the Smith-Purcell experimental beamline.

For this experiment, the grating parameters were optimized according to the procedure in [Tro00]. The bunch length is 60 μm (200 fs). This gives an optimum centroid impact parameter

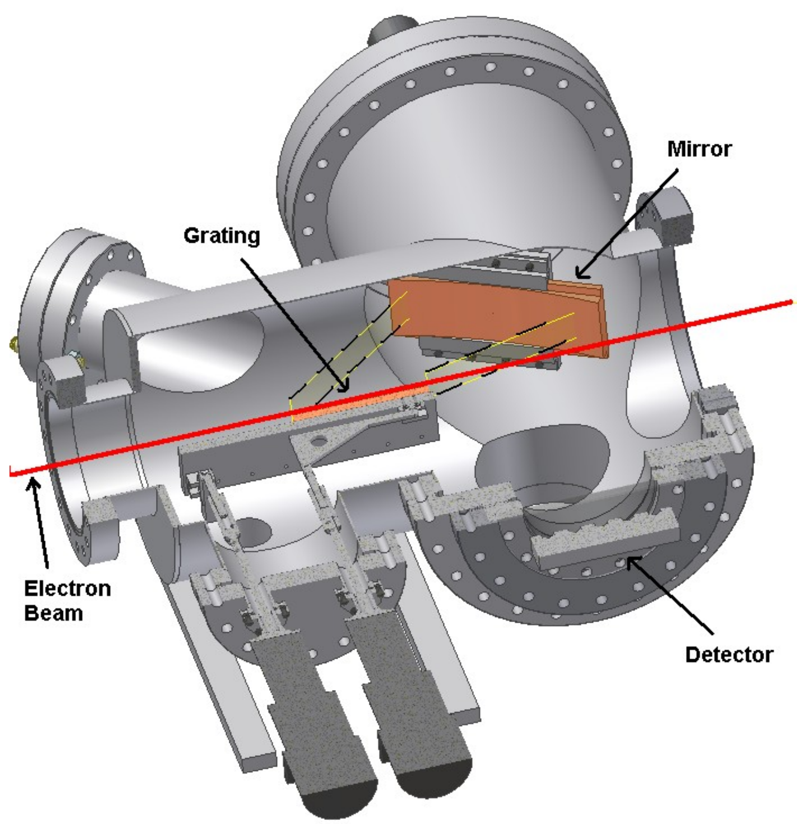


Figure 2.23: Cutaway drawing of the Smith-Purcell experimental chamber. The dashed lines represent the emitted radiation.

of b=λγ/2π=330μm. The optimum waist diameter is FWHM = $b4\sqrt{\ln 2}$ = 1mm. This is close to the current beam diameter; however, a focusing solenoid has been included in the beamline as a safety factor. The optimum grating period for 60 μm is l = λγ = 2.1 mm. A blaze angle of 10° was chosen to optimize the grating for 60 μm and an overall length of 10 cm (N_g = 47) to minimize the collection angle. A schematic of the Smith-Purcell diagnostic chamber is shown in Figure 2.23. The essential components of the diagnostic include the grating, a mirror to capture and focus the radiation, a window through which the radiation passes out of the vacuum chamber, and a detector.

Research so far, led by graduate student Stephen Korbly, has produced verification of the Smith-Purcell resonance condition, Equation 1, as shown in Figure 2.24. Furthermore, the intensity vs. angle has yielded good agreement between theory and experiment for the bunch length, which was about 150 μm or 0.5 ps for the case shown in Figure 2.25.

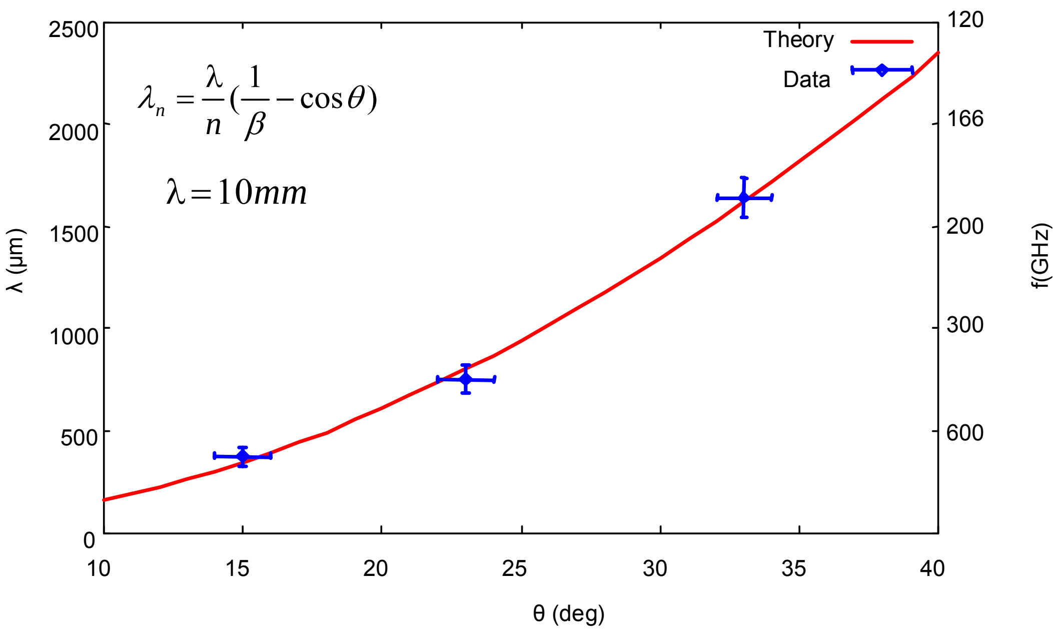


Figure 2.24: Experimental emission wavelength vs. theory.

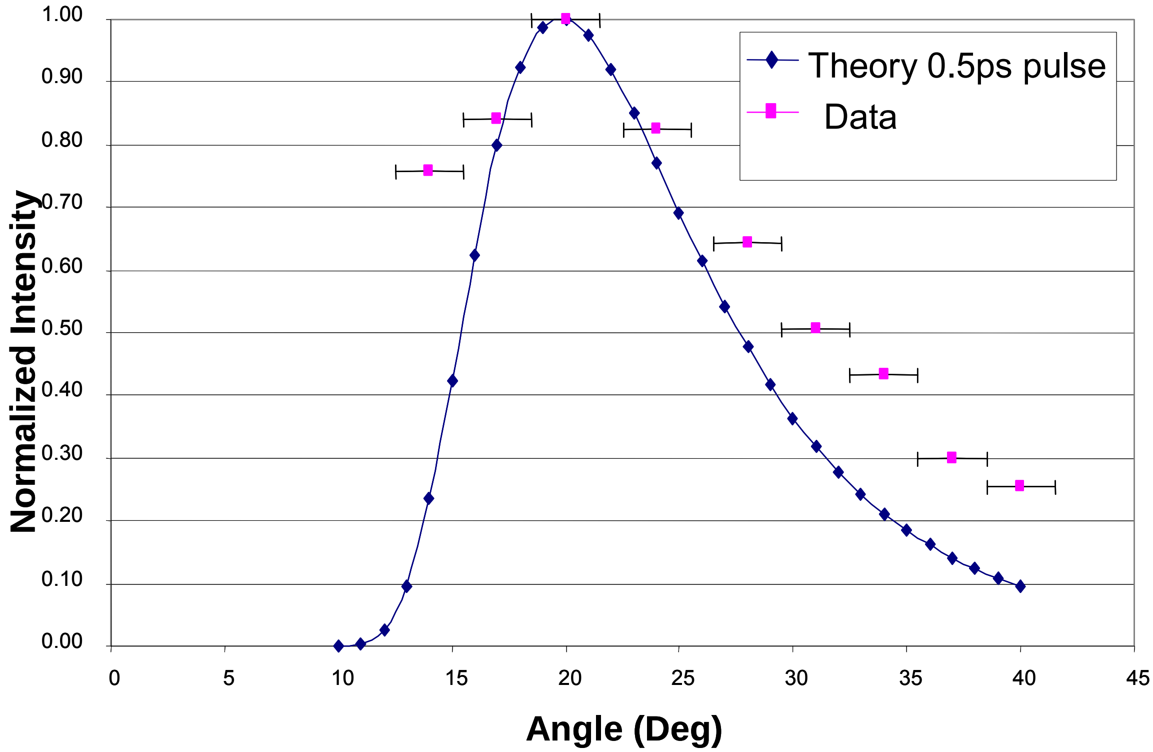


Figure 2.25: Experiment intensity vs. angle for Smith-Purcell radiation.

Proposed Research on Radiation Generation at the Bates Facility

We propose to investigate coherent and incoherent radiation generation from the Bates Linac electron beam.

Smith-Purcell Radiation from a 500 MeV Electron Beam

We propose to study the Smith-Purcell radiation using the 500 MeV electron beam at Bates. This program would complement our ongoing effort with a 15 MeV accelerator by providing tests of the Smith-Purcell theory at higher beam power and energy than is presently available. The research facility would consist of an experimental system similar to the one shown in Figure 2.25. Such a system could be set up for use with the existing 500 MeV linac at Bates.

We have been conducting theoretical research on Smith-Purcell radiation using a finite difference, time-domain (FDTD) code, written by Dr. Amit Kesar, a postdoc at MIT. A typical result is shown in Figure 2.26.

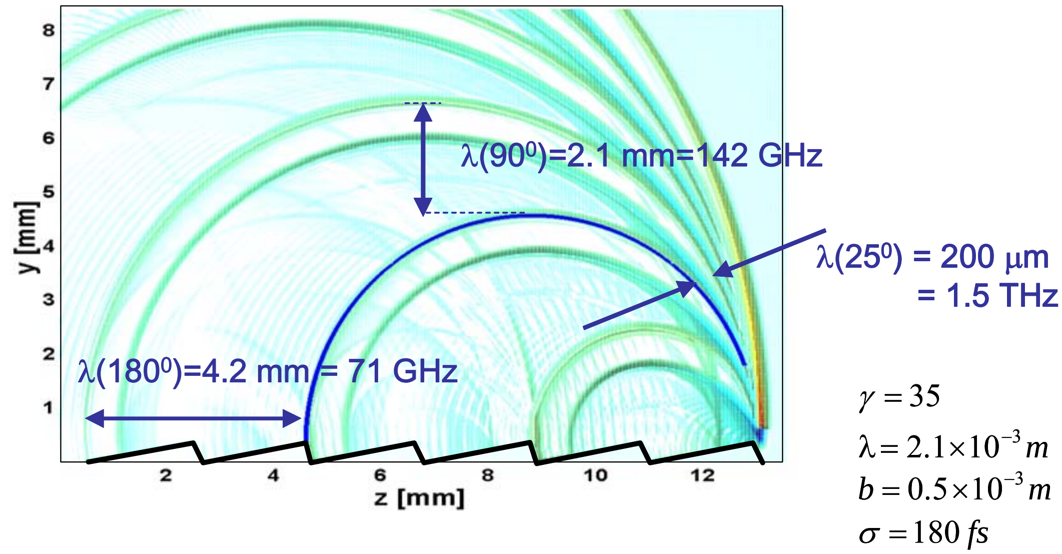


Figure 2.26: Result of FDTD code run for coherent Smith-Purcell radiation.

Several new results have emerged from these studies. These studies indicate that it would be useful to investigate the absolute value of the Smith-Purcell radiation. Different theoretical formalisms, such as the image charge model vs. the FDTD model, predict significantly different absolute intensities.

A second area of interesting research is verification of the coherent nature of the radiation. In our present experiments, we observe coherence form pulse to pulse; so that the radiation forms a train of coherent bunches. The resulting radiation is all obtained at harmonics of the accelerator frequency. We would like to verify this coherent nature of the long wavelength radiation by testing the Smith-Purcell radiation on an accelerator with a different accelerator frequency.

Recently, the Smith-Purcell radiation from a photonic bandgap structure was measured by a group at Tohoku Univ. in Japan [Yam04]. Since a photonic structure limits the radiation frequencies, as described in the next section, the results can be very interesting and potentially useful. We propose to also investigate such radiation phenomena.

Studies of Wakefields in Photonic Bandgap Accelerating Structures

The MIT Plasma Science and Fusion Center is investigating a new type of accelerator structure, a photonic bandgap (PBG) structure. A remarkable property of the PBG structure is its ability to reflect waves in a certain range of frequencies (called global bandgaps) while allowing other frequencies to pass through. A defect in a 2D periodic structure forms a PBG cavity in which a mode with a frequency inside the global bandgap can be confined under certain conditions. Unlike in a conventional pillbox cavity, only the modes with frequencies within the bandgap can be confined in a PBG cavity. The objective is to design a PBG cavity that supports the accelerating mode but does not support any high order modes that would be excited by wakefields in an accelerator. An extensive investigation of PBG cavities for accelerator applications is underway in our research program at the MIT Plasma Science and Fusion Center (PSFC) [Smi01, Smi02]. We aim to demonstrate a PBG accelerator with reduced wakefields. We began our investigation by studying PBG cavities and plan to continue with building and testing a 2π/3 PBG accelerator structure at the frequency of 17.137 GHz. The PBG 17 GHz accelerator structure contains six cells coupled through the beam holes and the input and output waveguides (see Figure 2.27). As shown in Figure 2.28, the operating TM_{01} mode is confined in the defect in the metal rod lattice whereas the dipole mode TM_{11}, which would cause deflection of the electron beam, is not confined. Therefore, coupling to the electron bunch is weak for the dipole mode in the PBG cavity and deflection is negligible. This makes the PBG accelerator structure advantageous for future accelerators.

The PBG accelerator structure will be tested at PSFC-MIT on the Haimson Research Corporation linear accelerator. A klystron pulsed power of 2 MW maximum will be available to feed the PBG structure. The acceleration of bunches with the initial energy of 8 MeV in the PBG structure will be measured. The deflection of bunches due to dipole mode wakefields cannot be measured at PSFC-MIT. We propose testing of PBG structures on the Bates Linear Accelerator. The better quality of the beam and the precise diagnostics of the beam at Bates will allow us to measure the deflection of the beam due to excitation of the dipole TM_{11} mode, or other high order wakefield modes. We can also estimate the wakefields by measuring the microwave frequencies generated in the structure by the passage of the electron beam through it. We hope to demonstrate that the wakefield modes generated in the structure are extremely small, as predicted by theory.

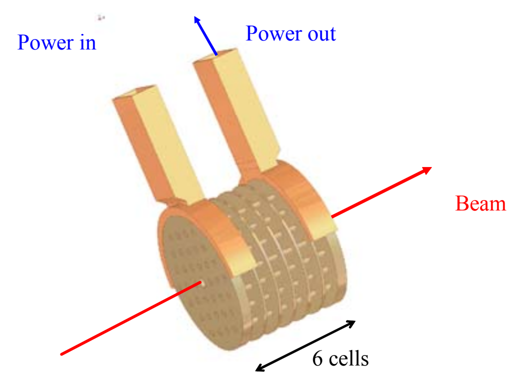


Figure 2.27: Schematic drawing of a six cell, photonic bandgap accelerator structure.

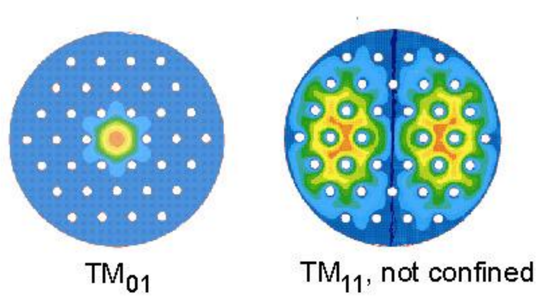


Figure 2.28: Modes of a PBG resonator with *a/b=0.15*. TM_{01} mode is confined, TM_{11} mode is not confined.

The beam physics work breakdown is presented for FY2006-FY2008.:

Year 1:

1. Calculate expected Smith-Purcell radiation from a grating using the 500 MeV electron beam at Bates.
2. Design Experimental chamber for the Smith-Purcell Experiment.
3. Procure long lead time parts for the Smith-Purcell experiment.
4. Calculate wakefields expected form tests of a Photonic Bandgap (PBG) Cavity at the Bates facility.
5. Design a chamber and diagnostics for the test of a PBG structure at Bates.
6. Procure long lead time items for the PBG experiment.

Year 2:

1. Install the Smith-Purcell experimental chamber at Bates.
2. Take first experimental data on the Smith-Purcell experiment.
3. Install the PBG experimental chamber at Bates.
4. Take first experimental data on wakefields in the PBG structure.

Year 3:

1. Finish first set of Smith-Purcell experiments. Publish the results.
2. Finish first set of PBG wakefield experiments. Publish the results.
3. Plan innovative new experiments based on the results of these experiments.

2.7 Electron Acceleration with Spatiotemporally Shaped Light Fields

With the advent of high intensity lasers, various schemes to accelerate electrons to extremely relativistic energies within relatively short distances have been discussed and tried. The majority of these rely on generation of a longitudinal field, for example by using two counterpropagating laser fields or by generating plasma waves [Taj70]. Naturally, one would like to make use of the transverse field directly rather than employing complicated schemes to partially convert the transverse field into a longitudinal field. However, if a free electron interacts with the transverse field of an electromagnetic plane wave, the net momentum transfer from the field to the electron after the laser pulse has gone by is zero. The reason for this is that the electron experiences alternating positive and negative field strengths as the laser pulse moves by. Thus the electron is made to oscillate back and forth with increasing and then decreasing amplitude. As the pulse leaves, the electron is left essentially at rest.

It now appears possible that with properly tailored light fields, the transverse field components (which represent the great preponderance of the optical energy) can indeed give rise to net electron acceleration. Analytical calculations and numerical simulations indicate that the field can be spatiotemporally shaped such that electrons that are accelerated in a particular half-cycle of the field are continuously delivered to *the same half-cycle* as it arrives at contiguous spatial locations. The electric and magnetic field components of this half-cycle drive the electrons "up and away", ultimately out of the laser beam, because the electrons never encounter any part of the light field with opposite polarity. The approach is illustrated schematically in Figure 2.29.

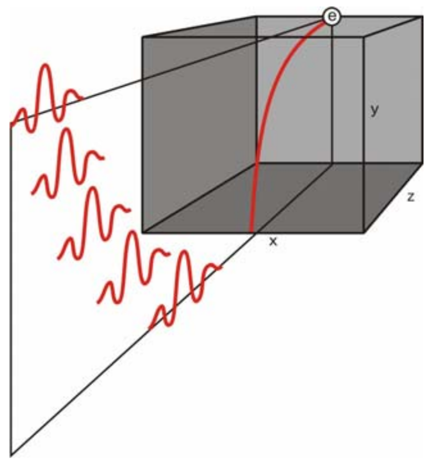


Figure 2.29: Electron acceleration scheme. The waveform is shaped such that the positive lobe of the field always coincides with the position of the electron.

Calculations and simulations indicate that spatiotemporally shaped light fields of relatively low intensity, on the order of 10^{11} Watts/cm^2, can accelerate electrons to MeV energies. Higher light intensities may be able to drive far higher energies. Different spatiotemporally shaped optical waveforms may be used to induce controlled electron trajectories with wide-ranging objectives including coherent emission at selected wavelengths.

The calculations are motivated by the recent development of spatiotemporal femtosecond pulse shaping and its use for generation of complex light fields that have enabled coherent control over propagating lattice vibrational excitations in crystalline solids [Feu03]. A spatiotemporal pulse shaper may be used to irradiate a sample with different time-dependent optical waveforms at different locations [Vau04], thereby enabling the manipulation of propagating responses. However, spatiotemporal pulse shaping has not been used yet for acceleration or manipulation of charged particles.

Our preliminary calculations show that the electron is effectively accelerated in a direction that is determined by the combined force of the transverse electric and the magnetic field components. In order to calculate the optimal spatiotemporally shaped waveform, we have solved the relativistic equations of motion for an electron in an electromagnetic field. For light propagating in the *z*-direction with the electric field *y*-polarized, the motion of the electron is confined to the *y*-*z* plane. The pulse delay as a function of *y* is given as $\Delta t(y) = t(y) - \frac{z(y)}{c}$ and the corresponding electric field as $E(x, y, t) = E_1(x) E_2\left[y, t + \Delta t(y)\right]$. We assume a constant field $E(y) = E_0$ that is switched on at *t* = 0 and switched off at some later time. We then obtain the relatively simple expression for the pulse delay as a function of the vertical coordinate, $\Delta t = \left(2 m_0 y / e E_0\right)^{1/2}$, where m_0 is the electron rest mass and *e* the elementary charge. Figure

2.30(a) shows the trajectory of an electron in a spatiotemporally shaped field that is always maximal and constant at the position of the electron, and Figure 2.30(b) displays the pulse delay in that case.

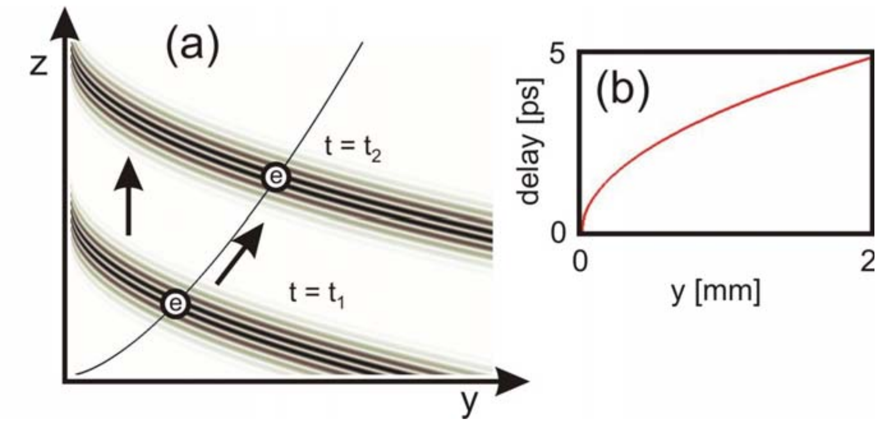


Figure 2.30: (a) Electron trajectory in the presence of the spatiotemporally shaped waveform at two times. (b) Pulse delay as a function of *y*.

Note that the result for the pulse delay is identical to that obtained by a purely non-relativistic approach. The relativistic part, in particular the magnetic field contribution to the trajectory, cancels out for the assumption of a constant field.

As the field strength is increased, the time and distance required to accelerate the electron to a given final energy necessarily decrease. From our analysis we conclude that the upper limit of the field strength is dominated by the spatial resolution of the spatiotemporally shaped waveform rather than by radiation damping effects. Assuming a field strength of 10^9 V/m, which corresponds to a light intensity of $1.33 \text{x} 10^{11}$ W/cm^2, the final total energy may be as high as 2.34 MeV. In this case the electron is accelerated for 10 ps over a distance of 1.8 mm, parameters readily achievable in many laboratories. Inspecting Figure 2.30(a) shows that good spatial resolution is only necessary during the initial phase of acceleration when the spatiotemporal waveform is curved; as the electron attains higher kinetic energies, the pulse shape tends toward an approximately linear slope. Therefore the limitation on going to higher field strengths is set entirely by the early stages of acceleration. An efficient realization of this scheme will involve an amplitude modulation that incorporates lower field strengths during the initial acceleration and builds to higher fields. It is possible that considerably higher electron energies than those calculated in our example above can be realized. Above all, it should be appreciated that the optical pulse intensities needed to reach a given energy are far lower than those required by conventional schemes involving longitudinal field components. Thus the possibility is opened up for the use of turnkey, modest-power, high repetition-rate laser systems for a wide range of fundamental and practical applications.

We have calculated the spatiotemporal pulse shaping parameters needed in order to generate a shaped field that is close to ideal. We also have also investigated practical elements of the pulse shaping apparatus including the pixilated nature of the spatial light modulator used. We conclude that practical generation of spatiotemporally shaped fields that are suitable for electron acceleration should be straightforward using our existing pulse shaping technology. We also have explored the stability of our approach with respect to both the initial conditions of the electron and to noise in the incident optical field delivered by the laser system. The results indicate that robust and effective electron acceleration should be possible.

We propose to conduct additional calculations, accounting for the full electromagnetic field as generated at the pulse shaper and propagated through the sample, and accounting for the many electrons in a chamber with specified gas pressure. We propose parallel experimental tests of our calculated results. These will require the construction of a vacuum chamber with electron diagnostics and appropriate radiation shielding, and assembly of an optical system for generation of the spatiotemporally shaped waveforms and delivery of the waveforms to the sample. The chamber and diagnostics will be modeled closely after a system currently in use at the MIT Plasma Fusion Center [Bro01]. The optical system will consist of a dedicated spatiotemporal pulse shaper and associated optics, but it will make use of the amplified output of an existing kHz repetition rate Ti:sapphire laser system.

The work breakdown for the electron acceleration with shaped light filed is presented below:

Year 1:

1. More complete modeling of the spatiotemporally shaped optical waveforms that should be used for electron acceleration.
2. Modeling of the spatiotemporal pulse shaping requirements so that we can really make the waveforms of interest.
3. Preliminary experimental work on making and characterizing the waveforms.

Year 2:

1. Complete experimental work on making and characterizing the waveforms needed for electron acceleration
2. Construction of electron acceleration chamber
3. Preliminary attempts at electron acceleration and characterization of accelerated electrons

Year 3:

1. Use of genetic algorithm for iterative optimization of shaped waveform for electron acceleration and control
2. Experiments on electron acceleration and control using the genetic algorithm, and characterization of the electrons

2.8 Electron Beam Ion Source for RHIC

A new heavy ion pre-injector for RHIC based on an Electron Beam Ion Source (EBIS) has been proposed at BNL to replace the present pre-injector. The new pre-injector will be a reliable, low maintenance linac-based facility. Linac-based pre-injectors are used at most accelerator and collider facilities with the exception of RHIC, where the required gold beam intensities could only be met with a tandem located about 1 km away from the AGS.

EBIS will produce high charge state ions directly eliminating the need for the two stripping foils presently used with the BNL tandem. Unstable stripping efficiencies of these foils are a significant source of luminosity degradation in RHIC. The high reliability and flexibility of the new linac-based pre-injector will lead to increased integrated luminosity of RHIC and is an essential component for the long-term success of the RHIC facility. This new pre-injector also has the potential for significant future intensity increase and can produce heavy ion beams of all species including uranium beams, and could also be used to produce polarized ^{3}He beams. These capabilities will be critical to the future luminosity upgrades and electron-ion collisions in RHIC (eRHIC project).

The new facility will consist of an electron beam ion source, followed by a Radio Frequency Quadrupole (RFQ) accelerator, and a short linac. Here, a collaboration between BNL and MIT-Bates on the design and construction of EBIS is proposed. The MIT involvement in this project will focus on the linac, including building RF power sources and low level RF systems. EBIS is a line item in the BNL projected budget with Mission Need (CD0) having been approved. It is expected that funding for the EBIS project will begin in FY2006, making it very timely as a development and construction project for CAST. The scale and the technical scope of the Interdigital-H (IH) linac for EBIS are well matched with the anticipated technical expertise and infrastructure available at Bates in FY2006-FY2008. MIT scientists and engineers will collaborate with scientists and engineers at BNL to ensure timely delivery of the system to BNL for installation. The personnel cost estimates for this project are presented in Chapter 6.

Linac

At the present time, the main baseline option for the linac is a room temperature cavity similar to cavities used at CERN and GSI. The investigation of Linac options, operating at 101.28 MHz, may be expanded beyond the baseline structure, the IH single-cavity design (fixed output velocity for different q/m, by means of variable voltage gradient). It is anticipated that MIT will review the merits of the existing baseline design, modify if necessary and complete the design and specification for construction. The actual manufacturing process will be contracted out to industry with close supervision by MIT engineers.

Dr. J. van der Laan, an MIT accelerator physicist, will oversee the beam simulation and the design and specification work for the cavity. Mr. Ernie Ihloff, a mechanical engineer, will oversee the bidding, vendor selection and the manufacturing process for the cavity.

RF Systems

The overall RF system will require five RF power sources at 101.28 MHz. Two of them must produce 350 kW peak-power pulses of 1 millisecond duration, at a rate of 10 pulses/second, for the Radio-Frequency Quadrupole (RFQ) and the Linac (based on the IH structure) The other three are medium-power amplifiers, producing 4 kW RF input to the bunchers.

To produce 350 kW peak power at 1% duty factor and 101.28 MHz, conventional radial-beam tetrode Vacuum Electron Devices (VEDs) are commercially available. The Inductive

Output Tube (IOT), although primarily useful at UHF, is also worthy of consideration. They require external input and output resonators; typically of coaxial or radial geometry (the internal wave-space of the tetrodes is coaxial in nature, whereas IOTs have planar geometry).

Often these VEDs are capable of operating with continuously-applied electrode voltages, with output RF wave-shape determined by the envelope of the RF drive, obviating high-level pulse modulation. Relatively large capacitive energy storage is required in order to support pulses of 1 millisecond duration. The VEDs must be protected from the transport of stored electrical charge through an internal arc by an electronic "crowbar", which diverts charge from the VED internal arc. Recent advances in solid-state technology, however, have made available series-connected, high-speed opening switches, operating in less than 1 microsecond, in conjunction with inductive di/dt limiters, to limit charge-transport to milli-Coulombs. At the 4 kW RF level, solid-state power amplifiers are readily available from domestic sources, and are preferred.

As described above, at this time there are several technical choices that may fulfill the requirements of the project. More studies are needed to identify the best solution.

MIT will be involved in:

- Investigation of design choices
- RF systems engineering and manufacturing
- Beam physics studies
- Mechanical and vacuum engineering

The RF group at MIT-Bates has substantial expertise and experience in design and assembly of RF systems comparable in scope and complexity to that proposed for EBIS. The controls and EE group at MIT-Bates is well suited for successfully accomplishing the controls requirements and instrumentations for this project. Participating accelerator physicists and engineers from MIT-Bates will include E. Ihloff, J. van der Laan, D. Wang and A. Zolfaghari.

CAST Work Breakdown for EBIS

The CAST work breakdown for EBIS for FY2005-FY2008 is outlined below. It lists the work plan including the RF systems for the RFQ and the IH-linac, the Linac and the beam transport line from EBIS to the RHIC injection point.

<u>Year 1:</u>

2. Complete the RF design, fix choices and specifications.
3. Engineering the transmitter, and start constructing.
4. Beam dynamics studies for alternative options for the linac.
5. Linac simulations, resulting in specifications for the energy range for higher q/m ions.

Year 2:

1. Constructing RF systems, ordering parts, assembling and testing.
2. Linac beam optics simulations (Parmela, LORAS).
3. Freeze design options for the Linac.
4. Beam Switch Yard optics simulations, (MAD, Parmela).
5. Cavity design specifications.
6. Bidding process for outsourcing the construction of the Linac cavity.
7. RF system testing.

Year 3:

1. Acceptance tests for RF system, including controls.
2. Integrated RF control system for RFQ and Linac.
3. Ordering magnets, vacuum equipments, for Linac and BSY.
4. Engineering diagnostic systems.
5. Test installation for the Linac.

Year 4:

1. Acceptance tests for Linac.
2. System integration at BNL.
3. Acceptance tests RF system for RFQ.
4. Acceptance tests Linac and Beam Switch Yard.

2.9 Terahertz Coherent Synchrotron Radiation

2.9.1 Introduction

The frequency region of the electromagnetic spectrum from 0.3 to 20 THz (10-600cm^{-1}, or 1mm-15 μm wavelength) is a frontier research area in physics, chemistry, biology, material science, and medicine. There have been quite a number of workshops focused on scientific applications of THz and infrared radiation in recent years, for example the series of "International Workshop on Infrared Microscopy and Spectroscopy" (WIRMS) [Dum01, Mar03]. In particular, the "DOE-NSF-NIH Workshop on Opportunities in THz Science" held in February 2004 [She04] presents a very broad and detailed discussion of THz radiation applications in science, and on source development as well. THz radiation also has potential applications in engineering, defense and homeland security [Sie02] [TDS04]. Sources of high quality radiation in this area have been scarce, but this gap has begun to be filled by a wide range of new technologies in the last decade.

The recent development of electron accelerator-based sources has demonstrated the generation of high peak and high average power broadband THz light via coherent synchrotron radiation (CSR) [Nei04, Abo02]. These sources will stimulate new areas of research investigation and scientific opportunities. For example, the high average power and broad spectrum from the accelerator-based sources are useful for linear spectroscopy and imaging of "difficult" samples, such as near-field microscopy, samples in extreme conditions, video-rate THz imaging, etc. For ultrafast science, the broad-band pulses in the far-infrared can probe atomic, molecular and solid-state process on time scales from a fraction of a picosecond to a nanosecond. The ultra-fast time-domain experiments are usually performed using the "pump-probe" technique. Requirements for time-domain experiments include: tunable THz pulses; ultrafast (50fs) with synchronized pulses (50fs) from mid-infrared to x-ray frequencies; the ability to shape the THz pulse; high repetition rate for improved S/N in spectroscopy experiments. In the area of high-field physics, the amplitude of the applied electric or magnetic field should greatly exceed the internal field in the system of interest. Requirements from experiments include: High electric fields (10-100 kV to >1MV/cm), arbitrarily shaped THz pulses, high repetition rate for nonlinear spectroscopy, etc.

The MIT CAST terahertz research will be primarily focused on coherent synchrotron radiation (CSR) sources using electron storage rings. Research will be pursued on the existing Bates South Hall Ring (SHR) which is equipped with a unique 2.856 GHz RF system. The SHR can be used to test existing CSR models and to investigate novel ideas for CSR production. The present SHR lattice used for nuclear physics operation has a bunch length of order 20 ps, not suitable for CSR. However, the design of the SHR permits low momentum compaction (LMC) lattices that can support short bunch lengths of order of 1-2 ps. These lattices combined with the high frequency rf system can provide brilliant broadband THz CSR. The CSR could be up to 10^7 times more powerful than the normal, incoherent synchrotron radiation. Critical upgrades of the ring and development of the source optical systems will enable the SHR to produce unprecedented power levels of THz radiation from a ring based source. The CAST research could lead to a mature plan for an optimal SHR upgrade. The results of the proposed R&D at Bates would be applicable to upgrades of other storage ring synchrotron radiation sources and to future dedicated ring-based THz sources. Storage ring THz sources are complementary to those based on the Energy Recover Linac (ERL), such as at Jefferson Laboratory.

It should be kept in mind that many scientific experiments and applications with THz radiation will be enabled or optimized only by using a source with a particular set of specifications. The capacity to serve multiple beam lines simultaneously is a particular strength of a storage ring source, due to its many orbit bends and stable, low radiation level operation. Such beam lines can be built in close proximity to the ring and can be developed individually to meet the needs of specific applications. CAST research of the THz source will address issues related to multi-user sources. Our ultimate goal is to promote and facilitate scientific applications and technical development in this field.

The CAST THz source research provides a wide and rich research program for accelerator science and technology education. For details, see Section 3.3 of this document.

2.9.2 Electron Storage Ring THz Source Research

CSR occurs when the synchrotron radiation emitted from a bunch of relativistic electrons is in phase. This happens when the radiation wavelength is comparable to or longer than the bunch length. The synchrotron radiation power spectrum is

$$\frac{dP}{d\lambda} = \frac{dp}{d\lambda}[N + N(N-1)g(\lambda)] \tag{1}$$

In Eq. 1, λ is the wavelength of the radiation and p represents the single electron emitted power, N is the number of electrons per bunch, and g is a form factor (the square of the Fourier transform of the normalized bunch distribution). The CSR power is proportional to the square of the number of particles per bunch. The radiation is suppressed above the vacuum chamber cutoff wavelength.

A model describing stable CSR in a storage ring [San04b] has been developed based on theoretical analysis [Ban96, Mur97, Stu02] and experimental results [Abo03, Byr02]. It provides a practical measure of the characteristics of a storage ring THz source. In a storage ring, the equilibrium bunch distribution is determined by the balance of quantum excitation and synchrotron damping in the presence of the SR wake field and other beam phenomena. For a steady-state CSR source, the bunch intensity limit can be approximated by:

$$N = A\frac{f_{rf}V_{rf}\sigma_z^{7/3}}{R^{1/3}}F\ , \tag{2}$$

where A= 1.66941 [MKS units], f_{rf} and V_{rf} are the frequency and gap voltage of the RF system respectively, R is the bending radius, σ_z is the natural bunch length and F is the numerical integral of the bunch equilibrium distribution from the dimensionless Haïssinaki equation. The maximum F value used is about 5 to 7.

The potential limits of a steady-state (or ultra-stable mode) CSR source are clearly determined by the parameter limits of the ring technical systems, i.e. the ring RF, magnets, and vacuum system.

To achieve very high field, ultrafast pulses and laser imprint THz pulse shapes, other techniques will be implemented. These include femtosecond laser slicing and external optical pulse stacking, etc. An optimized electron storage ring-based coherent THz source is anticipated to have the following broadband THz radiation characteristics and operation merits:

- High repetition rate up to a GHz and average power ~ 1 kW with E field up to a few hundred kV/cm
- A MHz repetition rate, ~ 1 MV/cm field with pulse stacking cavity
- Ultra fast pulses (~50fs), arbitrarily shaped THz pulses; high fields up to 1 MV/cm, kHz repetition rate with femtosecond laser slicing

The CIRCE ring design proposed by LBNL [Byr04a] is an excellent example of an optimized dedicated THz source ring design. The CIRCE ring is a compact low energy electron ring, operating at 0.6 GeV, with an RF system of 1.5 GHz, and bending field of 1.3 T. The performance of the SHR THz source with upgrades would be similar to the design performance of the CIRCE source. The higher RF frequency of the SHR could have an edge on radiation intensity in stable CSR operation which is the subject of interest. In addition, the long circumference of the SHR provides the needed flexibilities for various tests.

Although the MIT Bates SHR was designed as a storage and pulse stretcher ring for nuclear physics, it has a number of design features quite amenable to THz source development, including the following:

- A unique 2.856 GHz RF system
- Very flexible optical structure and capabilities for nonlinear dynamics control. It is feasible for low momentum compaction lattices and other special lattice adjustments [Wan01].
- Large magnet gap (7.62cm)
- Long straight sections available for insertion devices (see Figure 2.33)
- On-energy injection (0.2-1 GeV), continuous top-off operation
- Ample floor space available for IR beam lines (Figure 2.33)

The higher RF frequency is advantageous for producing short electron bunch lengths and for higher bunch current thresholds for ultra-stable CSR operation. The system has been in operation for 10 years. A maximum stored current of 0.3 A has been reached and this does not represent a real limit for either total or single bunch current. At the present, it is expected that the achievable CSR radiation power and spectrum from the SHR is comparable to BESSY II, the only electron storage ring which has regularly produced THz CSR [Sin04] in the world. The SHR THz radiation parameters for the present machine and possible upgrades are listed in Table 2.5. Figure 2.31 shows the relevant power spectrum. Figure 2.32 gives the spectrum of the radiation energy per pulse which is of particular interest for high field applications.

The near term (1-3 years) research projects are:

a) <u>SHR low momentum compaction lattice and stable CSR radiation generation</u>

To generate CSR, the beam bunch length has to be shorter than the radiation wavelength. This is usually done by tuning the ring lattice to low momentum compaction (α) optics. In a linear optics model, the bunch length is proportional to $|\alpha|^{1/2}$. However, as α approaches zero, higher order terms in α (with respect to momentum deviations) become important. There are also many single particle dynamics issues and collective effects related to bunch lengthening and instabilities. Several low α lattices will be tested and the nonlinear dynamic issues will be studied. The goal is to set optimal operation conditions for different stable or bursting CSR production modes.

b) <u>Bunch length measurement and THz radiation analysis</u>

Pico-second and sub-ps bunch length measurement. A bunch length longer than 1.5 ps can be measured with a streak camera. Sub-ps bunch length will be measured by analyzing the THz

CSR power spectrum [Kun04]. A CSR detection system will be set up to analyze the radiation in time and frequency domain.

c) <u>2.856 GHz bunch – bunch filling</u>

Bunch-bunch filling is a necessity due to the needs of various operating modes. For the ultra-stable CSR mode, equal intensity for bunches and top-off injection is required for stable radiation and beam efficiency. For very high bunch intensity operation, one needs to fill less bunch numbers with desired bunch spacing, to lower total storage current. The development will include laser gun, timing and synchronization, control and few GHz beam diagnostics. Although bunch-bunch filling has been practiced in many light source and collider rings, bunch-bunch filling at 2.856 GHz, and beam diagnostics and control at the same frequency in the ring are challenging tasks.

If the initial R&D program proposed here indicates that the SHR can be a powerful source of THz radiation, a subsequent program of research could be pursued. The following are possible long term research projects which will be subject to funding. They are part of a possible optimal SHR upgrade plan. The studies necessary for the development of a compact accelerator-based THz source are also described here.

a) <u>External Pulse Stacking Cavity</u>

This is an effective way to convert THz radiation of high average kW power at GHz frequency to very high peak power at MHz frequency (high field ~1-10MV/cm) [Smi97]. The high Q cavity and fast cavity energy extraction switch could be challenging. The goal is to stack 100-1000 pulses to a single pulse. Both the high Q cavity and fast pulse switch study can start early with the present 3 GHz repetition THz radiation from the SHR.

b) <u>Superconducting 2.856 GHz RF cavity</u>

To take full advantage of the 2.856 GHz RF system for shorter wavelength and high power CSR, a superconducting RF cavity is required to apply higher gap voltage. The present cavity gap voltage is limited by cooling. This upgrade will permit 10 times higher bunch intensity (100 times higher peak power) in the ultra-stable CSR operation mode. Suppressing high-order modes and achieving 1.5 MV total RF gap voltages are the critical design issues. The existing 50 kW, CW, RF power source of the SHR has enough capacity to support the superconducting cavity operation.

c) <u>Femtosecond laser slicing</u>

Femtosecond laser slicing has been demonstrated at ALS [By04b]. An external high power femtosecond laser to realize the slicing and a wiggler providing the magnet field for energy modulation are the two major pieces of equipment required. The laser intensity pattern will be imprinted onto the electron beam profile which then radiates it as a high-intensity THz E-field pattern. As the bunch intensity is high and the sliced section of the electron beam is short, the E-field of the CSR radiation from this slice of the electron bunch can reach gradients of the order of 1 MV/cm. Research activities would include exploring and resolving technical issues to realize the desired laser pulse shaped ultra fast and high field radiation.

e) Radiation ports and beam lines

The study includes: optimal bending magnet design (bending radius, magnet gap), large acceptance vacuum chamber and test lines. The present SHR dipole bending radius is 9.144m. Some of these dipoles could be replaced by short dipoles as needed.

f) Strong RF focusing for short electron bunches

The idea is to allow long bunch lengths in most of the ring to have very high bunch intensity and to realize very short bunches at one location to generate high peak CSR. This novel idea originated from an e+e- collider study [Gal03]. This could be tested with the 1.5 MV RF gap voltage in place.

g) Compact accelerated based THz sources

Compact high power THz sources are not only interesting for scientific and medical applications but could play a part in defense and homeland security applications. Feasibility, optimization of compact storage ring, energy recovery linac (ERL) or linac based sources and their applications will be the study subjects. The CAST proposal includes many critical accelerator component and beam physics developments, like photoinjector, high intensity short bunch electron beam study etc. The compact THz source study will benefit greatly from these developments.

CAST THz source development will be carried out in close collaboration with NSLS (BNL), ALS (LBL), and the FEL facility (Jefferson Lab). CAST will hold regular workshops focusing on scientific applications and plans for source development.

Table 2.5: SHR THz source performance parameters for the expected LMC lattice operation, and those anticipated after upgrades. The bunch length can be adjusted for different operating modes.

SHR	Band Width	Pulse width	Rep Rate	Average Power	Pulse Energy	Peak E-field
Present lattice	-	~20 ps	-	-	-	
LMC lattice	~1 THz	~1-2ps	2.86 GHz	~Watts	~nJoules	~ 1-10kV/cm
Ultra-stable Anticipated	~1THz	~1-2ps	2.86 GHz	100W to kW	~100nJoules	~100kV/cm
High Peak Power (With Stacking cavity) Anticipated	~1THz	~1-2ps	~MHz	100W to kW	~10μJoules	~MV/cm
High field, short pulse (Slicing) Anticipated	~20THz	~50 fs	~100kHz	~Watts	~ μJoules	~MV/cm

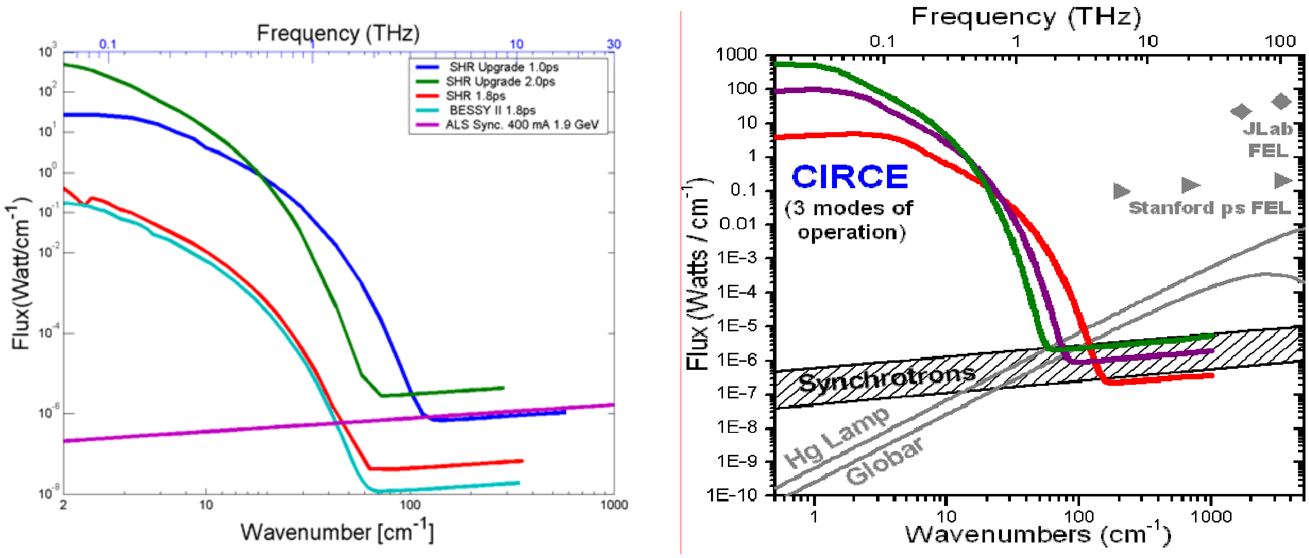


Figure 2.31: THz radiation power spectrum: SHR, CIRCE and BESSY II.

Table 2.6: Parameters of facilities in Figure 2.31.

Ring	E (GeV)	R (m)	f_{rf} (MHz)	V_{rf} (kV)	L (m)	Hor.Accep. (mrad/port)	Bunch length σ(ps)	F equ. (2)
SHR	0.6	9.144	2856	140	190.205	60	1.8	5.41
SHR-upgrade	0.6	1.335	2856	1500	190.02	300	1,2	5.41
CIRCE	0.6	1.335	1500	1300	66	300	1,2,3	7.48
BESSY II	1.19	4.361	500	1300	240	60	1.8	5.41
ALS	1.9	4.957	476	400	196.8	60		

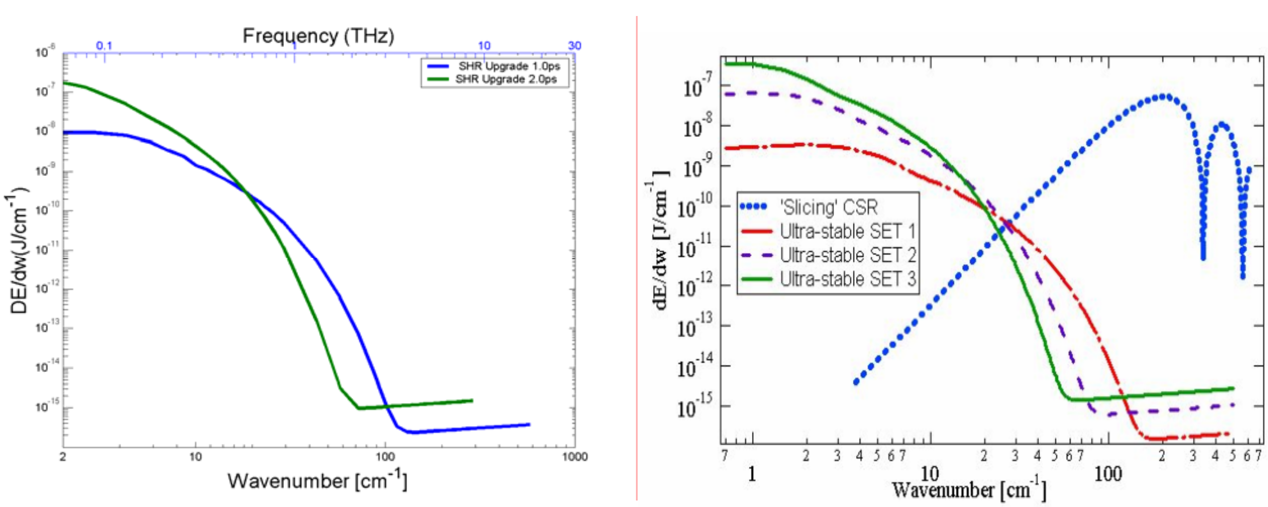


Figure 2.32: CSR Radiation Energy Spectrum (per pulse). The SHR spectrum and CIRCE ultra-stable sets are for pulses directly from the ring. SHR future 'slicing' is similar to CIRCE calculations.

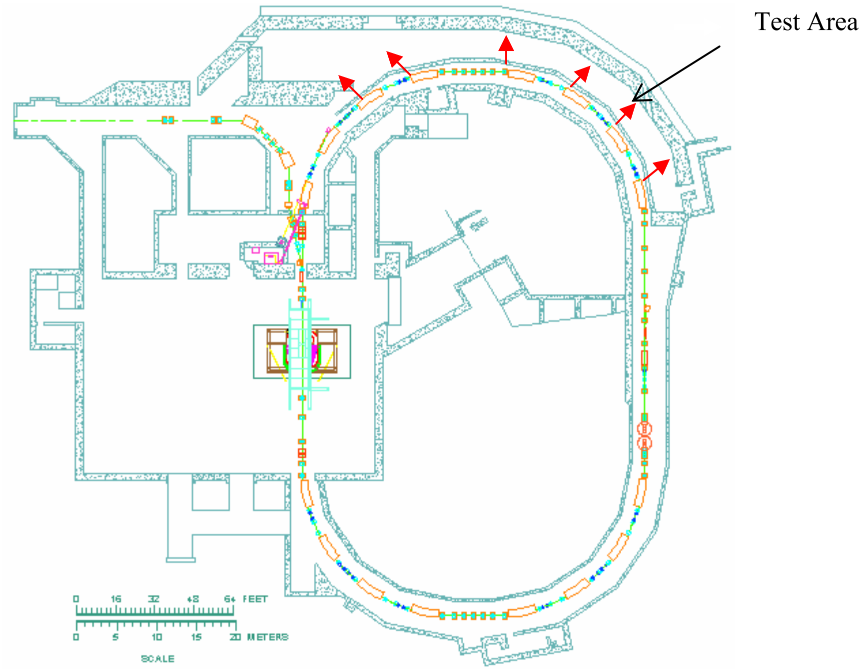


Figure 2.33: SHR THz source test area with possible beam lines.

CAST Work breakdown for THz CSR source

The CAST THz source research work breakdown for FY2006-FY2008 is outlined below:

<u>Year 1:</u>

1. SHR Low momentum compaction lattice development.
2. Establish an accessible test area in the SHR tunnel.
3. Bunch length measurement of ps bunches.
4. THz radiation power measurement.

<u>Year 2:</u>

1. Ring THz production optimization study (ring parameters, energy, bunch length etc.).
2. Test beam line design and installation.
3. THz radiation analysis, sub-ps bunch measurement.
4. 2.856 GHz ring bunch-bunch filling study.
5. Pulse stacking cavity design study.

<u>Year 3:</u>

1. 2.856 GHz ring bunch-bunch filling test.
2. First stage Pulse stacking cavity system setup and test.
3. Superconducting RF cavity design study.
4. Femtosecond laser slicing system design study.

2.10 International Linear Collider

Under the framework of the CAST program, MIT looks forward to significant participation in the R&D effort required for the International Linear Collider (ILC). This will complement the ongoing MIT efforts in development of the scientific case and detector development relevant to the ILC. While explicit funding has not been requested for ILC activities in this proposal, many of the areas of R&D proposed in this document advance technologies that will be needed for the ILC.

In particular, the work directly related to the ILC in this proposal includes:

Studies of photoinjector cathode properties	Section 2.2
Polarized electron injector systems	Section 2.2
Photoinjector beam physics modeling	Section 2.2
Photoinjector laser systems	Section 2.2
Master oscillator distribution systems	Section 2.5
Reactive tuners	Section 2.3
Low level RF controllers	Section 2.3
Precision RF phase and amplitude detectors	Section 2.3
Electron beam diagnostics	Section 2.6

Furthermore, the core competency that DOE has developed at Bates in both personnel and hardware is in the area of electron accelerators. DOE has also invested in advanced accelerator research at MIT by R. Temkin and collaborators and students. The expertise developed in these groups encompasses many other critical ILC systems which would be advanced by the CAST program at MIT.

The ability to collide polarized lepton beams in the ILC would greatly enhance its physics reach. Bates has expertise in many of the relevant systems. These include polarized electron sources, polarized beam transport systems, electron polarimetry and polarizing storage (damping) rings which may be necessary to produce polarized positrons. Furthermore, self-polarizing lepton rings are one of the systems under consideration for eRHIC, a collider which would be studied in the CAST program.

The present ILC designs call for the use of RF photoinjectors for the electron source. This is an area where MIT has particular expertise. High brightness sources may obviate the need for expensive electron damping rings. ILC photocathode materials need to provide sufficient QE and longevity to reliably serve the collider needs. Successful integration of photocathodes producing polarized electrons (see above) into RF structures has not yet been accomplished. The CAST program at MIT will advance all these technologies.

As currently conceived, the ILC will require highly efficient 10 MW klystrons powered by ~13 MW modulators. In the past five years Bates has re-engineered its 10 MW direct switch modulators to include a solid state controlled mod-anode switch tube. These improved modulators have resulted in dramatic increases in transmitter stability and reliability. Scaled versions of the 100A, 20 kV mod-anode solid state switch and engineering designs which recover the switching charge could be of great benefit to the ILC project. Bates engineers have interest in contributing to the design of the ILC modulator. It is anticipated that these modulator systems would be tested at the newly proposed Superconducting Module Test Facility (SMTF).

One of the central motivations for the creation of a SMTF is to advance the readiness of systems for the ILC. The reactive tuner and amplifier set for lightly loaded cavities (Section 2.3) was conceived as a highly efficient power source for moderate current and energy recovery linacs. While the beam power requirements of the ILC are much greater than those available from this amplifier system, many of the system components are common to ILC. These include the low level FPGA based RF controllers, application software and fast ferrite phase shifters. A likely choice for the high level controls system of the SMTF is the ExPerimental and Industrial Controls System (EPICS). If this choice is adopted, MIT engineers and students would be able to make substantive contributions to its development. Under CAST, MIT would support the development of these systems not only for the amplifier tuner set proposed here, but also for the ILC systems of SMTF.

The initial tests of RF control, both conventional amplitude/phase as well as reactive tuning, of Lotentz detuned superconducting structures are planned at Jefferson Lab's accelerator systems, especially the FEL energy recovering linacs, as per a mutual collaboration agreement. Jefferson Lab is also a leading member of the SMTF at Fermilab and with the first high gradient module fabricated and installed in the SMTF, these initial tests can be further extended in a realistic ILC-setting with high power.

MIT is well positioned to develop the Master Oscillator and reference timing systems for the SMTF. The Ultrafast Laser group in the Department of Electrical Engineering and Computer Science is constructing ultra-low noise optically based RF distribution systems. These will be necessary for accelerators requiring the most precise timing, notably seeded FEL's. This technology is also very well suited to the low loss distribution that will be required in an ILC whose present length is projected to be in excess of 30 km.

MIT engineers and physicists also have expertise and capability in the fundamental accelerator systems required for ILC. These include vacuum systems, magnet design, optical beamline design, instrumentation and control systems. Under CAST it is anticipated that these engineers and physicists would contribute to the design and construction of research and prototype systems for the ILC. Under the Research and Engineering Laboratory (RLE) this framework has already been adopted to apply MIT resources in support of the National Laboratory programs.

In addition to their use in ILC, the technologies described above are compelling research topics in their own right. These projects will attract the interest of a significant number of MIT graduate students whose caliber is among the finest in the country. These ILC research topics span many disciplines including physics, electrical engineering, computer science, laser science, digital systems and mechanical engineering. Under the guidance of a MIT advisor and a sponsor at one of the national laboratories, students would complete either Masters or Ph.D. degrees in accelerator technologies in support of the ILC. Some of this research would be done at MIT and some would be done at the national laboratories. A CAST program at MIT will serve to both develop the technologies necessary for the ILC and to educate the scientists and engineers who will be required to lead the project in the coming years.

It is anticipated that the establishment of CAST can provide a significant source of R&D activities, technical manpower and a source of young accelerator physicists for the ILC. While it is premature at this time to propose a detailed research program, MIT scientists and engineers are actively engaged in developing the national and international consensus essential to the success of this ambitious endeavor. It is anticipated that at a future date a detailed proposal for additional resources for CAST to participate in the ILC will be submitted.

3.0 CAST EDUCATIONAL PROGRAM

3.1 Overview

Undergraduate, graduate and post-graduate education is one of the main missions of CAST. A rigorous educational curriculum in accelerator science and technology will be developed and overseen by a CAST Educational Committee consisting of MIT faculty and research scientists from the Departments of Physics, Electrical Engineering and Nuclear Engineering. The CAST educational curriculum would be developed so that the first graduate students could begin in Fall 2006. Over a number of years the graduate student enrollment would be increased to attain an asymptotic number of 15-20 students. All formal teaching activities will occur on the Cambridge campus. This will include all lectures and seminars. Note that MIT has a long tradition of interdepartmental and interdisciplinary programs in which graduate degrees may be obtained, e.g. the Center for Transportation and Logistics, and the Ph.D. program in Computational and Systems Biology.

At the undergraduate level, CAST will provide new opportunities to broaden the MIT educational experience. For example, accelerator based experiments using the Bates complex could be incorporated into the laboratory curriculum. This would provide MIT undergraduates with a unique opportunity to experience experimentation on a scale larger than that in the typical campus laboratory. The proposed CAST research program would be a rich source of projects for the Undergraduate Research Opportunities Program (UROP). In this way, MIT undergraduate students could be introduced to the exciting field of accelerator science and technology.

A central aspect of CAST graduate and postgraduate education will involve research carried out under the supervision of MIT faculty and senior scientists. The graduate students will be admitted to MIT through the Departments. The CAST research program described in Chapter 2 abounds with excellent opportunities for student research projects. The graduate students will be required to pass a Specialty Examination in Accelerator Science and Technology and the Ph.D. thesis will be reviewed by oral examination by a special thesis committee. The CAST Educational Committee will oversee these important examinations.

A unique aspect of the educational program at CAST will be to develop a comprehensive and novel accelerator-based laboratory curriculum around the existing accelerator complex at Bates. This program would put an emphasis on providing unique opportunities for students to acquire direct 'hands on' experience in the operation, control and manipulation of accelerators. Thus, it is proposed to make the Bates accelerator complex available for about six weeks per year for education and training of students. In addition, the accelerator could be used for research activities during this period. This would allow for an intensive period of student training as well as opportunities for accelerator physics experiments. It is estimated that these 1500 hours of machine up time per year would require about 3 FTEs of support as well as capital investment of about $60,000 per year to maintain the equipment. This relatively low cost assumes retention of key Bates staff with the corporate memory on technical knowledge and long experience with maintenance. The operating costs (electricity plus consumables) are estimated at $300,000 per year. Utilizing the Bates accelerator complex in this way provides a very different and complementary educational experience for students of accelerator physics and capitalizes on decades of investment by the Office of Science.

The CAST accelerator-based laboratory would be organized and scheduled so that students from outside MIT could take also advantage of this unique opportunity. In particular, it would be desirable to incorporate it into the United States Particle Accelerator School (USPAS). This could begin in summer 2006.

3.2 Course curriculum

An essential component of the CAST education program will be the course curriculum. It must be designed to be relevant to current problems in accelerator physics as well as challenging and interesting to the students. We offer an initial outline of courses below, but anticipate that the program will be developed in more detail in the near future. Such a curriculum in accelerator science and technology will be developed and overseen by the faculty involved from the different MIT Departments. A major part of the curriculum will include the high level graduate courses that currently exist in physics, mathematics and engineering. The educational content of the specialty courses should include strong components of physics and engineering. A possible curriculum of new core courses might include:

- Introduction to Beam Physics
    - Review of basic electrodynamics
    - Magnetic guide fields in accelerators
    - Particle trajectory equations
    - Periodic systems
    - Emittance and beam parameters
    - Linear accelerator dynamics
    - Lattice design
    - Deviations from an ideal lattice
    - Longitudinal dynamics
    - Synchrotron radiation
- Introduction to Accelerator Technology
    - Survey of technologies
    - RF generation and measurement
    - Beam instrumentation
    - Vacuum technologies
    - Shielding and interlock systems
    - Magnet types and design
    - Superconducting technologies
- Collective Effects in Particle Beams
    - Tune shifts and tune spreads
    - Space charge oscillations
    - Beam-beam interaction
    - Wakefields

    - Transverse and longitudinal impedances
    - Instabilities
    - Coherent synchrotron radiation
- Computational Beam Physics
    - Particle movers
    - Introduction to codes: MAD, Elegant, Parmela
    - Self-consistent collective effects
    - Beam radiation
    - Finite difference and finite element algorithms
- Accelerator Physics Laboratory
    - Hands-on work at Bates accelerator facility
- Physics of Storage Rings and Colliders
- Physics of Synchrotron Light Sources, ERLs and FELs

These could be supplemented by other courses given less frequently such as:

- Linear Collider Physics
- X-ray Free Electron Lasers
- Intense Particle Beams
- Industrial and Medical Applications of Accelerators
- Lie-Algebra and Symplectic Mapping
- RF and Microwave Engineering for Accelerators
- Superconducting RF Systems
- Charged Particle Beam Diagnostics and Instrumentation
- Control Systems for Large Facilities
- Laser and Electron Beam Interactions
- Photoinjector Beam Dynamics
- Ultra High Vacuum Methods and Technologies
- Accelerator Magnet Design
- Superconducting Magnet Design

It is anticipated that a significant number of the specialty courses would be taught by Visiting and Adjunct Scientists from the major accelerator laboratories around the world associated with CAST.

3.3 Accelerator-Based Educational Laboratory

We propose to develop an educational program in the basic principles of accelerator physics at both the undergraduate and graduate levels utilizing experimentation at the accelerator complex at Bates. This would include demonstrations and experiments on the following basic topics:

- Charged particle optics
- Charged particle beam diagnostics
- RF acceleration
- Accelerator control systems
- Polarized beam production and manipulation
- Principles of storage rings
- Principles of vacuum systems.

We also propose to work closely with the educational coordinators of the Departments of Physics, Electrical Engineering, and Nuclear Engineering to integrate the Bates-based educational program into the core curriculum in Accelerator Science and Technology.

The experimental component of the CAST educational program will utilize the existing accelerator facility at MIT-Bates to carry out small-scale experiments involving students. MIT-Bates facilities include a polarized injector, a linear accelerator and recirculator which accelerate electrons to energies up to 1 GeV, and the South Hall Ring (SHR), which stores intense beams of polarized electrons. We propose to add an RF photoinjector to the existing facility for the generation of high-brightness, short-pulse beams. The lab employs highly trained personnel who can offer instruction and guidance to students in the use of these facilities.

We envision that the full accelerator and storage ring will operate for approximately 6 weeks per year for activities related to CAST. A program for use of the machine is preliminary and will be shaped by the content of the accelerator physics curriculum. However, in light of the cost of operating the accelerator, it is important to optimize the use of available beam time. This can be accomplished by interweaving beam use for two complementary purposes: student laboratory classes and student-driven original research.

An essential component of the CAST program will be a laboratory course on accelerator physics and operations suitable for students taking advanced electricity and magnetism with some experimental experience. Working with Bates staff, students would gain practical experience by tuning the machine and carrying out measurements demonstrating important physical principles. Experiments would include measurements performed previously in support of the Bates nuclear physics program and student projects to improve the capabilities of the accelerator. A subset of topics, which can be investigated in laboratory experiments using existing equipment at Bates, is listed below.

- Magnetic guide fields
  - Steering
  - Lenses
- RF acceleration
  - Bunching
  - Phase matching and synchronization
- Photoemission
  - Laser systems
  - Photocathode properties

Low energy beams

- Beam diagnostics
  - Beam position monitors
  - Synchrotron radiation
  - Feedback systems
- Stored beam dynamics
  - Injection techniques and damping
  - Periodic motion
  - Measurement of lattice parameters
- Polarization dynamics
  - Polarimetry techniques
  - Spin in magnetic fields
  - Spin manipulation of stored beams

A second component of the educational program would involve original research in accelerator and beam physics. During this time, experiments on a range of topics will be performed by individuals or small groups of students working in collaboration with scientists from Bates. Typically, these students would be at the graduate level, but the UROP program also provides a proven mechanism for involving advanced undergraduates in this type of research project. We anticipate that this program will attract scientists from collaborating institutions, providing valuable interactions for students. Typical experiments would require modest beam time of the order of a few days. Some possible areas of study are outlined below, several of which are also discussed in Section 2.4.

- Ion trapping and fast beam-ion stability
- High intensity stored beam operation
- Non-linear spin resonance effects on stored beam polarization
- Radiative polarization for stored beams
- Polarimetry techniques for stored beams and low-energy beams

The remainder of this section discusses a selected set of tractable measurements which can be performed with existing Bates facilities (introduced in Section 1.3). Many measurements involving the injector and front end of the accelerator do not necessarily require full-scale operation of the facility and can be performed in a cost-effective manner on a flexible time scale suitable for a laboratory course. Measurements involving the South Hall Ring (SHR) require full-scale operation of all components of the machine and will be restricted to the times defined for machine operation. However, the SHR presents a number of unique opportunities for graduate-level students with a strong interest in beam physics.

Injector

Since operation of the Bates injector is substantially less complicated and costly than operation of the full facility, use of the low-energy beamlines at the front end of the accelerator can provide a cost-effective means of acquainting students with accelerator operation. Furthermore, safety issues associated with beams at low energy can be managed more readily than at high energy, making low energy beams an appropriate starting point for training inexperienced operators. Low energy beams are relatively insensitive to small changes in operating conditions and can provide clear illustrations of many fundamental principles.

The polarized injector [Far03], which will maintain an active research program described in Section 2.2, includes two unique laser systems and a complete 300 kV electrostatic accelerator and beamline. The injector beamline employs the EPICS control system, and is instrumented with a wide range of diagnostics. Principles of charged particle optics (magnetic steering and focusing) can be taught with experiments in this beamline. The polarized injector can also be used to teach principles of photoemission, including the link between laser properties and properties of the emitted electron beam. Experiments illustrating pulse shaping, and the link between quantum efficiency and degree of polarization can be performed.

In addition, we propose to replace the unused inline thermionic injector with a commercially available S-band photoinjector. The installation of this photoinjector in combination with the 450 MeV linac allows study of many advanced areas of beam physics as described in detail in Section 2.2. Examples are space-charge induced microbunching, thermal emittance measurements, slice emittance measurements, and photocathode drive laser shaping. These are important issues at many US accelerator facilities and are likely to be rich sources of thesis topics.

Another large class of measurements can be performed after energizing the first of the linac's RF transmitters. Techniques for RF acceleration, such as bunching and chopping of beams can be demonstrated by sending electrons through the first RF cavity into the linear accelerator's input chicane. A 20 MeV transmission polarimeter [Zwa03] resides in this location and can be used for measurements if the electrons are polarized. Measurements using the polarized injector Wien filter can be made to demonstrate principles of spin precession in a magnetic field. The linac and injector can also be used in conjunction to demonstrate principles of feedback systems. During the 1990's and up through 2002, Bates carried out a series of state-of-the-art experiments on parity violation in electron scattering [Mue97, Spa00]. These experiments required extremely strict beam conditions and led to the development of a number of feedback techniques for minimization of helicity correlations in beam positions to a level below 100 nm [Ave99]. Such techniques remain important in next-generation parity-violation experiments and could be incorporated into student laboratory projects.

South Hall Ring Beam Dynamics

The South Hall Ring (SHR) provides a rich facility for storing intense highly energetic beams of polarized electrons. Topics for study using the ring include stored beam properties and dynamics, beam instabilities, and beam diagnostics. Techniques for measuring beam properties such as position, size, and profile, are in regular use and can provide good demonstrations of noninvasive beam diagnostics. Measurements of storage ring lattice parameters, such as betatron tune, also illustrate particle dynamics in electromagnetic fields. These measurements can be included as part of the curriculum for an accelerator physics laboratory.

Physicists at Bates use sophisticated models for beam-based accelerator and storage ring modeling and control. Such models can be applied to develop new tunes for the SHR, a project which could be carried out by students. The development of a low-emittance lattice for previously unexplored stored beam energies above 900 MeV would be of particular interest. New lattice designs and modifications can be empirically tested using the SHR for beams over a wide range of energies. In addition, the SHR can function as a synchrotron. Improvement of the ramping capability for polarized beams would open the possibility of many measurements involving energy dependence of beam properties. Ramping will be an important topic for a ring-based design of a future electron-ion collider.

The SHR is an excellent laboratory for studying the behavior of very intense beams, an essential topic for next generation facilities like a collider or light source. Over 300 mA has been observed in the SHR, and in the absence of experimental constraints, a program to explore very high current operation can be set up. Studies of ion trapping issues such as fast beam-ion instability can be carried out [Tsc00]. Physicists at Bates have succeeded in improving parameters such as beam current and lifetime by experimenting with gap structures in the normally continuous beam to allow for ion clearing. Such studies could be continued by students with an interest in beam physics.

The SHR is especially well suited for studying polarization dynamics of stored beams, an area of substantial importance in the design of a next-generation electron-ion collider. While this field has a rich history at various facilities [Mon84], the decommissioning of the Cooler Ring at the Indiana University Cyclotron Facility and the Amsterdam Pulse Stretcher Ring (AmPS) at NIKHEF have left the South Hall Ring as the only small-scale facility at which such studies are possible. The SHR features a powerful combination of tools for polarization studies including a full-strength Siberian Snake [Der76], longitudinal Compton polarimeter [Fra03], and highly efficient radio-frequency spin flipper [Mor02]. Students and young researchers have already made important contributions to the design and commissioning of each of these devices. Many measurements demonstrating important physical principles can be performed in less than one day. These include techniques for measuring stored beam polarization, and polarization measurements as a function of injection properties and energy. Demonstration of adiabatic spin reversal by an RF magnetic field, mapping of RF resonances induced by spin flipper, and calibration of the Siberian Snake using spin tune measurements all can be done in an efficient manner in the SHR.

Additionally, the SHR can also be a valuable tool for original research in polarization dynamics. Specific topics of study would include resonant behavior of polarization in storage rings and depolarization mechanisms for stored beams. Preliminary data from the SHR at 850 MeV, shown in Figure 3.1, have mapped the beam polarization as a function of storage time. Experts from other international institutions, including DESY and the Budker Institute in Novosibirsk, have created models of spin transport which they have applied to SHR beams. These models, which offer predictions for the SHR polarization lifetime and equilibrium value, are based on formalism for polarization in a ring derived by Derbenev and Kondratenko [Der73]. KP However, some implications of this formalism, such as the prediction of a kinetic polarization mechanism for self-polarization of a beam [Jag97], are difficult to verify and have not been experimentally confirmed to any high degree. Accurate measurements in the SHR and detailed comparisons to simulations could provide an important test of this formalism, which is at the heart of designs for a self-polarizing electron-ion collider.

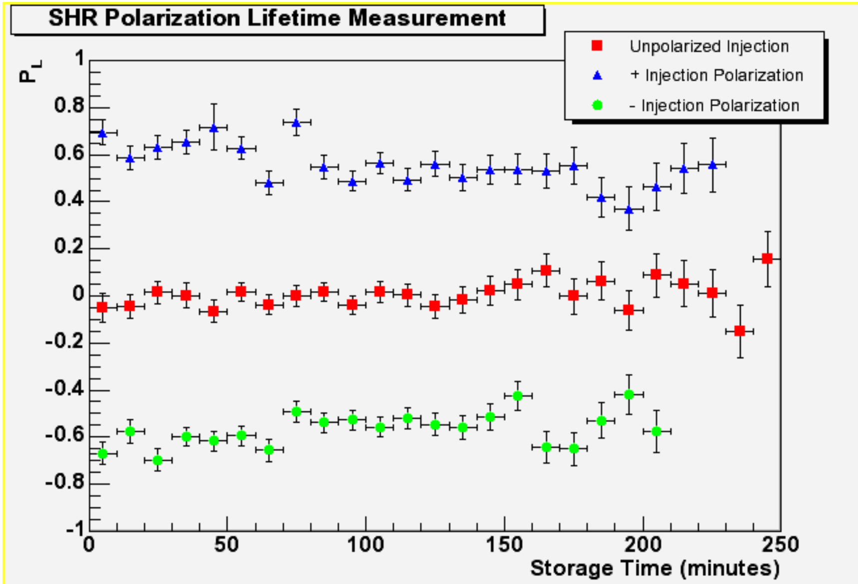


Figure 3.1: SHR preliminary polarization data at 850 MeV versus storage time acquired in November 2003. The data are indicative of the type of measurement which can be performed during an experiment of 1-2 days duration.

Investigations of resonant behavior have also been initiated at Bates during the nuclear physics program. Preliminary data from the SHR have shown sensitivity of the beam polarization to beam tune and size. This effect was unexpected in the presence of a full Snake although circumstantial evidence had also been seen at the AmPS Ring [Pas00]. It has been attributed to tune spreading. While the existing data are somewhat sparse, indications of non-linear spin resonances have been observed, a possibility which would require theoretical interpretation. A more complete map of SHR polarization as a function of betatron tune and injection current could lead to an improved understanding of resonant behavior in storage rings.

While a great deal of accelerator physics can be done with existing SHR infrastructure, operation of the ring with a highly polarized beam offers an opportunity for development of new equipment and corresponding research. For example, the SHR would provide an excellent laboratory for testing new types of polarimeters. Two such projects, discussed in more detail in Section 2.4, are the development of a transverse Compton polarimeter for a low-energy storage ring and a test of a prototype RF cavity polarimeter [Con04] based on the Stern-Gerlach interaction. Researchers at Brookhaven National Laboratory are interested in the latter initiative for the RHIC program and are developing a suitable prototype RF cavity. Each device could be installed in SHR for tests with modest capital investment and technical support. Such projects would be excellent opportunities for thesis projects for graduate students.

Two projects requiring more substantial investment, but of importance for the electron-ion collider, have also been considered. Both would offer excellent opportunities for advanced students in beam physics. One of these initiatives, a test to develop a beam with high polarization and a large aspect ratio, has important implications for the design of the eRHIC electron storage ring. It would require some development of a laser-backscattering beam profile monitor in addition to the proposed transverse polarimeter. The second idea consists of installing a set of wiggler magnets in the eastern straight section of the SHR as a novel means of producing a polarized beam in a low-energy electron ring. Calculations have suggested that polarization approaching 50% would be achievable [Kor01b], a number which could be easily measured. Such plans would most likely be contingent on revival of a self-polarizing ring design for a next-generation collider.

Finally, the SHR features a very intense beam which could in principle be used for synchrotron radiation research. A number of vacuum ports are available for looking at synchrotron light. Presently, the light is used purely for beam diagnostic purposes, but other possibilities could be considered. An example of such an initiative is discussed in detail below. High current operation could also complement research projects involving detector development for harsh environments, a topic which is being pursued in the Research and Engineering Laboratory, a parallel initiative at MIT-Bates.

SHR Coherent Terahertz Synchrotron Radiation Source

The construction of a Coherent Terahertz Synchrotron Radiation (CTSR) Source provides an example of a cutting-edge project laden with opportunities for Ph.D. students in accelerator physics. It is feasible to consider because certain unique technical features of the Bates SHR storage ring make it possible and cost-effective. It will provide a wide range of advanced research and educational opportunities for accelerator science and could appeal to users from other scientific disciplines.

The terahertz radiation frequency has been a traditionally difficult region of the electromagnetic spectrum to access. Only in recent decades has this frequency regime become scientifically available with broadband sources of moderate intensity. However, recently a coherent synchrotron source with much higher power was demonstrated [Abo02]. It was quickly applied to a problem in materials science [Sin04]. This type of radiation source opens promising new opportunities for research and applications in life sciences, materials science, imaging, instrumentation, and communication sciences. Attractive features of a steady-state far-infrared coherent synchrotron radiation generated from a storage ring include very high flux, broadband frequency range, and the stability of the source. For these reasons, a dedicated infrared synchrotron radiation source is now being proposed by the IR ring team at the Advanced Light Source [San04a].

The key technical challenge of such a dedicated ring is the realization of a very short equilibrium electron bunch length of the order of one millimeter. Because the Bates SHR is equipped with a unique high frequency (2856 MHz) RF system and a very flexible lattice structure, such bunch lengths can be realized with modest effort [Wan01]. Measurements could begin at that time on any of several synchrotron vacuum ports. With two additional modifications, the SHR CTSR source parameters would be comparable with the design parameters of the ALS CIRCE source. These modifications include the installation of additional RF cavities (retaining the existing RF power system) and the replacement of the 3-m long dipole with the CTSR port with three short dipoles of shorter bending radius. The SHR also provides long straight sections, where radiation wigglers can be inserted for femtosecond laser slicing operations.

A rich accelerator science educational research program is possible if the SHR is operated as a CTSR source. Topics of study would include very short beam bunch measurement, lattice modifications and bunch length minimization, bunch-to-bunch filling from the injector (for high bunch intensity but moderate total current), CSR simulation and measurement, RF system upgrade (possibly to superconducting cavities), magnet and insertion devices, etc. Furthermore, additional educational and research opportunities could eventually be provided for other scientific disciplines if the CTSR source performs at a high level.

The initial cost of this project for machine modifications will be very moderate as costs can be staged in an incremental manner. Development could begin immediately with adjustments to the ring lattice. Some new beam instrumentation for millimeter bunch length measurements would be required, but for initial proof-of-principle tests this can be provided by outside collaborators. On a gradual time scale, short bending radius dipoles and additional RF cavities can be added when needed. Much of the hardware needed for such upgrades, including additional power supplies for magnets, already exists at Bates. Furthermore, because detection apparatus and targets should be located as close as possible to the infrared source, no extra floor space would be expected to be required for experiments, beyond what exists in the SHR tunnel. Beam lines design and construction will be addressed separately from the machine modifications.

4.0 CAST APPLICATIONS ACTIVITIES

4.1 Accelerators for Applications to Homeland Security

The world requires multiple technologies to thwart the efforts of terrorists seeking to disrupt political stability by interrupting commerce. The USA is particularly vulnerable because of its open society and thousands of miles of borders largely open to commerce from the sea, air and roadways. Commerce is the lifeblood of the USA and a serious disruption could destabilize the economy and the political stability of many other countries of the world. The problem is an enormous one. More than nine million sea containers enter our 350 ports each year. An even greater number of air cargo containers travel our airways and even more trucks stream across the borders with Canada and Mexico. The cost of shipping a seagoing container from a foreign port to a destination in the USA is small and delivery is almost certain. They are an almost perfect delivery system for weapons. Each 40 foot container can deliver 80 tons of explosive or lethal poison or a weapon of mass destruction. It was estimated in a study by Booz Allen Hamilton that a dirty bomb in Chicago would cause at least a 65 billion dollar loss to US commerce.

To prevent such a catastrophe, techniques of non-intrusive inspection are required. Opening each container for inspection is prohibitive in time and cost and would paralyze the commerce system. The inspection systems require speed, and the ability to identify a threat without disrupting the commercial flow. The most prevalent systems in existence make use of x-ray transmission. These systems are very deficient because they are not able to distinguish between shadows cast by rice, for example, and an explosive. There are other promising techniques under development that can identify specific elements and isotopes via specific nuclear reactions. These techniques generally require spectroscopic information gathered with speed and precision and place a great premium on the duty ratio of the accelerators that produce the reacting particles. In this section, techniques under development by MIT scientists (Nuclear Fluorescence Imaging by W. Bertozzi and Neutron Resonance Radiography and Detection of Fissile Material using Low Energy Neutron Interrogation by R. Lanza) are described.

4.1.1 Nuclear Resonance Fluorescence Detection Technique

One of the techniques to identify elements and isotopes in containers is the use of nuclear resonance fluorescence. It requires an electron accelerator that is compact, has a duty ratio of about 100% and that provides beams of up to about 10 mA. The machine should be capable of providing more than one beam and have an energy variable between fixed points of about 3, 6 and 8.3 MeV. The top energy is set by the need to detect oxygen yet avoid the production of neutrons as background and also avoid the production of radioactivity. The energy variability should be accomplished very quickly, in a fraction of a second. These requirements are the result of the need to scan a 40 foot container in times that are less than a minute. Another requirement is the ability to detect any element that poses a danger (such as uranium) or those that form the basis of peroxide explosives or fertilizer or military explosives. Poisons, drugs and other contraband are part of the arsenal of terrorists that must be detected with very high detection efficiency and low false alarms.

The commercial world presently produces electron accelerators that are used for medical purposes and x-ray radiography. They are also used for the sterilization of sewage, letters and medical supplies, among other things. Because only the delivered beam power and energy is of importance, the linear electron accelerators used in these applications generally operate with a 1/1000 duty ratio. There is one electron accelerator that is commercially available that produces a duty ratio of 100%, the IBA Rhodotron. While it can be modified to serve the needs of nuclear resonance fluorescence, it suffers from a large size and footprint. It is also expensive in its present manifestation.

The technology already exists to make a 100% duty electron accelerator, in the elements of RF power sources, accelerator cavity design, magnetic elements and technical understanding. For example, there are 250 kW CW klystrons at 800 MHz that can be utilized. Ferrite magnets can be used for fast switching of multiple beams. The expense and size of the electron accelerator are important quantities that must be reduced as much as possible. Size is important since the expense of the housing and shielding of the accelerator can be considerable. A microtron is one possible configuration. A linear accelerator and hybrid varieties employing recirculation can also be explored to minimize size and costs.

One goal of these designs needs to be reliability. The inspection systems need to function reliably and be online 24/7 for months at a time. This is determined by the economic needs of an industry that operates on very small margins. Ships with thousands of containers need to be loaded and unloaded in as small a time as possible. The new inspections must not alter the customary economics of the industry.

Potentially, hundreds and perhaps thousands of these systems are needed, each with an electron accelerator. Nuclear resonance fluorescence can detect any isotope in the containers and in the energy range considered it is the most penetrating non-intrusive probe that can be made. It will be a very important tool in the arsenal to detect dangerous cargoes, but the proper accelerator is an important element in its operational success.

4.1.2 Neutron Resonance Radiography for Elemental Imaging

The central problem in the use of non-intrusive techniques for the detection of explosives or contraband is to devise a reliable method for determining both the composition and the shape of materials in a container. X-ray techniques based on either simple transmission measurements or on high-speed computerized tomography do not detect explosives; rather, they make it possible to distinguish volumes of different apparent densities and attempt to use this and shape to generate a detection signature. Unfortunately, while it is true that many explosives have e.g. a density of ~1.5 g/cc, it is not true that all materials with density ~1.5 are explosives. The result, both from the point of view of physics and practical experience in airports, is that such systems are plagued by high false alarm rates.

We have developed a new method for detecting materials, based on Neutron Resonance Radiography (NRR). This technique is capable of good spatial resolution (~ 3 mm) and penetration of heavy objects, as well as of determination of elemental composition. Element specific resonances in total neutron attenuation cross-sections, which are in the 1 to 8 MeV range, are exploited to enhance the contrast for imaging elements such as carbon, oxygen, nitrogen and others. This contrast enhancement mechanism is then used to produce elementally resolved images of objects under inspection and thus to identify the material composition of the object. Similar methods have been commercially developed by the minerals industry for on-line detection of diamonds in dense Kimberlite rock matrices. An NRR system may be scaled in size for the objects under inspection, ranging from baggage to cargo. LLNL has used fast neutron radiography for imaging very dense (~300 g/cm^2 areal density) objects as part on an ongoing DOE stockpile stewardship program.

We have performed a series of experiments demonstrating the principle and have made detailed computer simulations of imaging using Monte Carlo methods. Based on this, we have designed a system using a small, fixed energy, commercial RFQ accelerator for a neutron source and a high-resolution scintillation camera for imaging.

Other groups have used similar principles based on neutron time-of-flight (TOF), and also applied them to non-destructive inspection for the detection of explosives and other contraband in baggage and cargo. Our method does not use time of flight to determine neutron energy and thus does not require a pulsed (~ns) neutron source with a relatively long flight path, and thus can be made more compact than these systems. As has been shown by the LLNL work, part of the shorter path can be exploited to reduce scattering in the images as well and thus to improve contrast. Further, since the detector is only a simple integrating imager, it is possible to obtain considerably better spatial resolution (~ 3 mm) as compared to detectors in which each pixel must be instrumented, limiting individual pixel resolution to 3 cm or more. The proposed neutron source used as part of the imaging system is normally pulsed with microsecond pulse widths rather than nanoseconds and we are able to detect the presence of nuclear material using the same system by detecting fission neutrons between pulses. Table 4.1 shows a comparison of existing technologies as compared to NRR.

Table 4.1: Comparison of existing technologies as compared to NRR.

Method	Element Identification	Spatial Resolution	COTS* Sources	Detection of SNM	Trucks/Cargo Inspection
NRR	YES	3- 5 mm	YES	YES	YES
PFNA**	YES	5 cm	NO	NO	YES
x-ray	NO	1 cm	YES	NO	YES
Backscatter	Low Z only near surface	1 cm	YES	NO	Near surface only
Tomography	NO	3 mm	YES	NO	NO

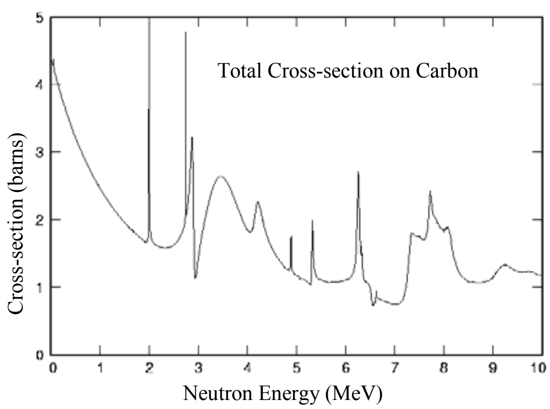
*COTS =Commercial Off-The-Shelf

** PFNA = Pulsed Fast Neutron Analysis

Fast neutron radiography with neutron energies of more than 1 MeV opens up a new range of possibilities for non-destructive inspection. One aspect of high-energy neutron radiography is the inspection of objects in the presence of lighter elements. An example of this is in the inspection of such objects as airline luggage or cargo containers. Since most of these objects contain a large amount of hydrogenous material such as plastics, thermal neutrons are essentially unusable since such an environment so rapidly moderates them and backscattered x-rays return little useful information. When high-energy neutrons are used for radiography, they are generated by small accelerators without any moderation and, as a result, the beam is kinematically collimated and has a small spot size, making it a more efficient system from the point of view of the neutronics while also improving the spatial resolution. In practical cases, shielding is a major concern and this geometrical collimation is an important factor in reducing the size of the shielding required for radiation protection. MIT has an ongoing collaboration for the development of fast neutron radiography in the DOE stockpile stewardship program and has been active in accelerator-based sources and in high-resolution fast neutron imagers. Neutron resonance radiography was originally developed for these programs and they remain significant potential users.

Neutron Resonance Radiography (NRR) utilizes the element specific resonances in total neutron attenuation cross-sections which are in the 1 to 8 MeV range and which are exploited to enhance the contrast for imaging light elements such as carbon, oxygen and nitrogen. The goal of this work is to utilize this contrast enhancement mechanism to produce elementally resolved images of objects under inspection.

The basic idea of fast neutron resonance radiography (NRR) is shown in Figure 4.1. With a mono-energetic neutron source, we can map one element at a time. We look for an energy region with a resonance peak/valley for one element while the cross sections of other elements are flat over the same energy range. For example, we might choose the sharp resonance peak at 2.077 MeV for carbon. A radiographic image is taken on-resonance, and another taken off-resonance. The difference of the two images gives a 2-D map of the corresponding element. If only carbon is to be imaged, the broad peak in the 7 to 8 MeV range is more useful since the width of the peak is so much larger.



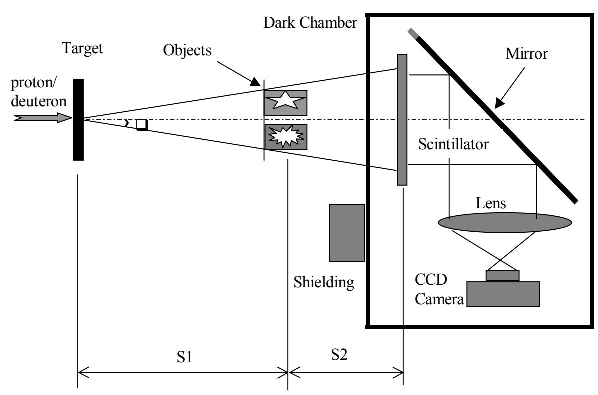


Figure 4.1: Resonance radiography with a single peak.

Figure 4.2: Fast neutron radiography hardware.

Fast neutron resonance radiography with single peaks has low sensitivity when multiple elements are to be detected and faces some difficulties with respect to sensitivity and practicality. We have developed a straightforward method to use neutrons of wide energy spectrum and to exploit the broad resonance features of elements of interest which does not require changes in the accelerator energy and only requires moving the object around the target as shown in the quad chart.

A radiographic image is a 2-D map of projected attenuation and can also be thought of as a 2-D map of the sum of the contents of all existing elements, weighted by their attenuation coefficients. For each pixel in the image, there exists a linear equation stating that the total attenuation equals the weighted sum of projected elemental contents. When we take another radiographic image with a different energy spectrum, the resulting linear equations have different attenuation coefficients (weighting factors or attenuation coefficients) and total attenuation, but have the same projected contents, as the object is the same. In principle, when there are more equations than the number of existing elements, the set of linear equations can be solved as a definite least-squares solution for the projected elemental contents. The images below in Figure 4.3 show some simulations of this process for a small suitcase loaded with a variety of contraband materials (the "terrorist's overnight bag") and the resulting fast neutron images separated by elements.

A central part of this technique is the development of compact neutron sources which can be reliably operated in an industrial environment and which can produce intense small (~ mm) sources of fast neutrons. To develop these sources requires not only accelerator development, but also the development of new target concepts such as windowless gas targets and improved fast neutron imaging and detection methods, all of which fit into the overall CAST program.

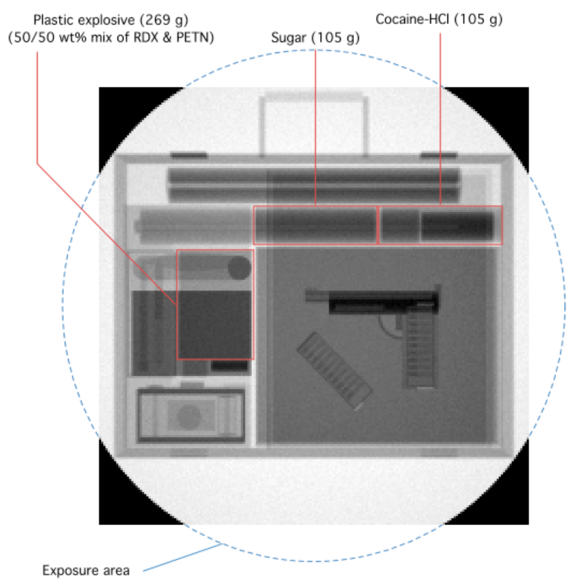


Figure 4.3: Arrangement of items in suitcase showing various contraband materials.

4.1.3 Detection of Fissile Material Using Low Energy Neutron Interrogation

The major distinguishing property of weapons related materials, (special nuclear material (SNM)), is its nuclear property of undergoing fission either spontaneously or under the bombardment of neutrons or photons. In order to distinguish fissile materials from non-fissile materials, it is necessary to demonstrate that the material undergoes fission and not that it is merely dense. We make this point initially to make clear that any detection system must have both sensitivity and specificity; detection of density lacks specificity and will result in a large number of false alarms. This limits the usefulness of such detection systems since essentially all dense materials are non-fissile and thus almost all of the alarms of such a non-specific nature will be false alarms.

We have examined a detection system for fissile materials based on the use of low energy neutrons of ~100 keV energy in place of the more conventional use of 14 MeV neutrons or of 6 to 10 MeV photons from linacs.

The advantages of this system are:

- Detects only SNM fissile materials, not depleted uranium or others
- Ability to penetrate cargo to induce fission
- Compact, transportable system
- Low energy, kinematically collimated neutron source provides efficient use of neutron output and minimizes shielding requirements
- Typical detection times for 5 kg SNM in heavily loaded cargo container will be several seconds

The method of probing for fissile materials typically is based on the use of 14 MeV neutrons produced by sealed D-T neutron generators. However, from the figure below, we see that non-SNM such as 238U is also an abundant source of fission neutrons and thus may give a

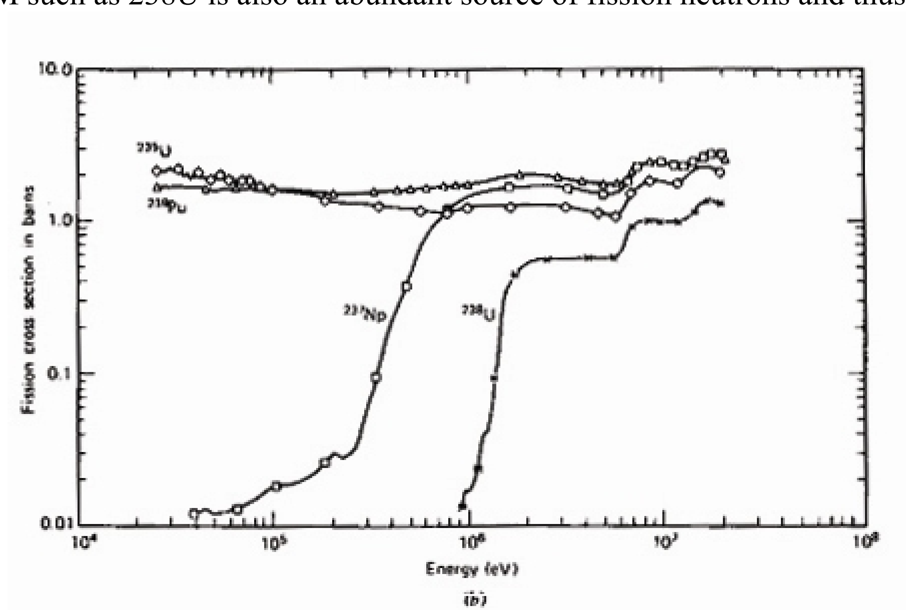


Figure 4.4: Fission cross-sections for various nuclear materials.

false alarm. A more precise and less ambiguous indication of SNM, i.e. 235U or 239Pu, can be obtained if the object is probed with low- energy neutrons, below 100 keV. In this case, the presence of fissile material is unambiguously indicated by the presence of either fission neutrons or gamma rays, since only SNM will undergo fission at these low energies. Although we will discuss fissile neutrons as the detected radiation, we will also consider gamma ray detection resulting from fission as an important, perhaps more important, way of detecting the presence of fission. (See for example the report "Detection of special nuclear material in cargo containers using neutron interrogation", UCRL-ID-155315.)

A direct way to produce large numbers of neutrons at these energies is to use a small proton accelerator to produce neutrons through the reaction $^7Li\ (p,n)^7Be$ which has a threshold of 1.88 MeV. A similar approach to neutron production at low energies was shown in the MIT Nuclear Engineering Department Ph.D. thesis of Chad Lee in 1995. If we operate the accelerator just above this threshold, we will produce low energy neutrons, and the neutrons are produced in the forward direction, further reducing shielding requirements as compared to the isotropic output of D-T generators.

There is not a significant difference in penetration between 14 MeV and 100 keV neutrons. The dominant process in neutron interactions is scattering or moderation, which lowers the energy of neutrons to the point where they are either captured or lost. However, this is a process which is inherently logarithmic in nature and on this scale there is not a significant difference between 14 MeV and 0.1 MeV. The mean number of scatters from a material with atomic weight A required to reduce a neutron energy from some initial value E_0 to an energy E' is:

$$n = \frac{u}{\xi} = \frac{1}{\xi} \ln \frac{E_0}{E'}$$

$$\xi = 1 + \frac{(A-1)^2}{2A} \ln \frac{A-1}{A+1}$$

For almost any material beyond carbon (A=12) the number of scatters is very large and penetration is large until the neutron is captured or produces a fission. Obviously for hydrogen (A=1), moderation is most rapid; however, even in this case it takes only on average 5 scatters to go from 14 MeV to 100 keV, so the apparent advantages of higher energy are soon lost. These estimates have been confirmed by more detailed MCNP calculations at LLNL.

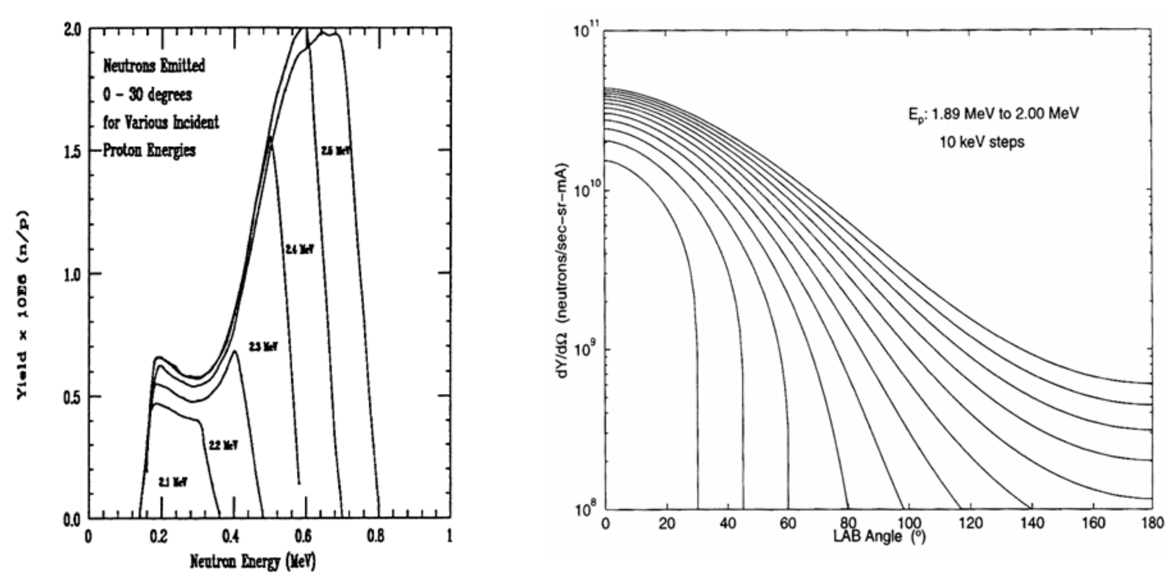


Figure 4.5: Kinematics of neutron production.

When compared to the usual 14 MeV source, the following advantages are present:

Kinematic collimation of the low energy neutrons in the forward direction as compared to the isotropic distribution of the means that a much larger fraction of the low energy neutrons are directed into the container. For the low energy process, just above threshold, essentially all neutrons are within ±30° while for the 14 MeV source, only 6% of the neutrons are emitted in such a cone. This means that far fewer source neutrons are required, considerably reducing the shielding requirements.

No fissions are induced in materials such as 238U and as a result, the presence of fission neutrons is an unambiguous indicator of SNM since it is only these materials that fission with low energy neutrons.

As compared to alternative approaches using isotropic 2.5 MeV neutrons or 14 MeV neutrons, LLNL has computed the relative time required for detection to three sigma for a 3 m sphere of various loading materials, see Table 4.2. The model assumed 5 kg of material and 1000 cm^2 of 10% efficient neutron detector. The most significant point is the vast improvement possible with the 60 keV source, especially when the requirements for shielding of isotropic sources is considered.

Table 4.2: Relative Times of detection for 3σ confidence threshold of 5 kg material in 3m spherical container filled various materials.

	Water	Al	Fe	Pb
60 keV (directional)	1.0×10^{6}	3.0×10^{-1}	2.0×10^{-1}	1.5×10^{-1}
2.5 MeV (isotropic)	2.6×10^{10}	2.1×10^{3}	6.2×10^{3}	5.7×10^{3}
14.1 MeV (isotropic)	4.6×10^{9}	$3.1\text{-}8\times10^{3}$	8.7×10^{3}	5.8×10^{3}

The challenge here is in the development of compact low energy neutron sources. The accelerator of choice would appear to be a small proton RFQ operating just above threshold. Another challenge will be in the development of new types of neutron detectors which are both fast and are also essentially gamma-blind.

4.1.4 Environmental Applications of Compact Electron LINACS

An interesting application of small electron accelerators is in the detection of elements through photonuclear resonance excitation. Applications include the detection of contaminants in soil and the analysis of mineral ores before further processing. We have investigated these in the past (Chichester, Ph.D. thesis, Nuclear Engineering 2000) and have concluded that techniques such as this could provide for rapid analysis in the field, provided that reliable, compact, and field deployable linacs of 6 to 9 MeV can be developed. The ability to rapidly analyze material in the field could lead to significant impact in environmental cleanup for chemical waste. Measurement of ore properties prior to extensive mining also reduces costs not only of the mining operation, but also of the subsequent environmental cleanup, since less material need be processed if ores are pre-selected for quality.

Photonuclear resonance excitation refers to a variety of photonuclear interaction processes that lead to the excitation of a nucleus from some initial state to a higher energy nuclear state. Typical excited nuclear state lifetimes are short, ranging from nanoseconds to femtoseconds or less; however, some isotopes have unusually long-lived excited nuclear energy states, or isomers. We have examined the feasibility of using bremsstrahlung irradiation sources to produce isomers for industrial applications. In contrast with charged particle based isomer production, the use of high energy photons allows for the irradiation and production of isomers in bulk materials. The commercial availability of reliable, high power industrial electron accelerators means that isomer activities sufficient for industrial applications may be achieved using bremsstrahlung, in contrast with neutron based approaches where suitable neutron sources of sufficient intensity for these applications are lacking.

In order to design a system for creating nuclear isomers using photons, the resonant photon absorption isomeric excitation cross section must be known. Unlike neutron absorption and scattering cross sections, comparatively little information exists for photon isomeric excitation. To address this, a theoretical model based upon statistical probability distributions of nuclear energy levels has been developed for calculating photon excitation cross sections at energies below neutron and proton binding energies; this is the ideal region of operation for most applications in order to minimize long term activation of materials. Isomeric excitation cross sections calculated using this technique have been compared with experimentally measured values and are found to agree to within a factor of two or better. Using this, a general transition equation suitable for both nuclear resonance fluorescence and isomer excitation has been developed for calculating nuclear level distribution probabilities for materials undergoing photon irradiation.

Some preliminary experiments have been carried out at Bates using an industrial 6 MeV electron accelerator to identify obstacles related to nuclear resonance fluorescence measurements as well as measurements of the decay of short-lived isomers using scintillators in the vicinity of high intensity bremsstrahlung sources. Use of a fast switching gating circuit in combination with a pulsed accelerator was found to be a satisfactory solution for dealing with problems related to the performance of a detector's photomultiplier tube as a result of exposure to scattered radiation during the beam pulse.

Calculations have been carried out to assess the performance characteristics which could be expected from industrial photonuclear resonance excitation systems, based upon a 10 MeV electron accelerator. For simple isomer production, specific activities on the order of 1 mCi/g/mA can be expected for irradiation periods sufficiently long for equilibrium to be reached. For the analysis of arsenic concentrations in environmental samples, sensitivities of 1 ± 0.1 ppm could be achieved using accelerator currents of 50 – 100 microA with irradiation times of a few minutes or less. A system designed to analyze ore traveling along a conveyor belt could be used to sort gold ore based upon a lower grade cutoff of 5 ppm using an accelerator of 10 mA with a processing volume exceeding 100 tons of ore per hour.

4.2 Accelerators for Medicine

The connection between accelerator and nuclear science and medicine has a long and successful history from the use of gamma radiation by Roengten, to application of the Van deGraaff and linacs. In fact, the application of the Van de Graaff to medicine came about as a result of a lecture by a Massachusetts General Hospital physician at the Massachusetts Institute of Technology. It is in this tradition of important contributions to society that we address this aspect of Accelerator Science R&D.

The use of accelerators in medicine has evolved from x-ray generators to the present time where the need for heavy ions with 100's of MeV/nucleon are required for an effective form of cancer therapy. The first such facility built within the National Institute of Radiological Sciences in Chiba, Japan is shown in the figure below.

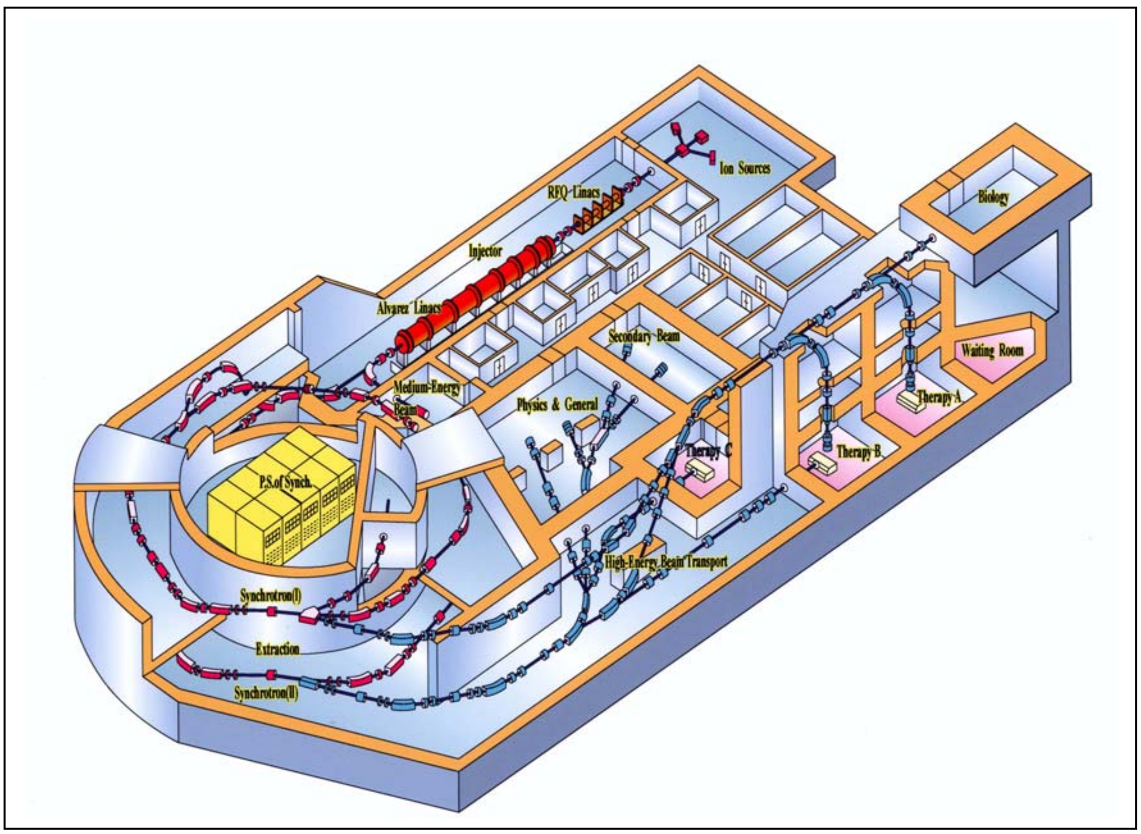


Figure 4.6: Heavy Ion Medical Accelerator (HIMAC) located at NIRS in Chiba, Japan.

This large football field size facility, while very effective clinically, cannot be easily adapted to more general use and in fact be considered for use in a hospital-based facility. It was previously considered impractical to consider building a linac for use in a hospital, and more recently the concept of building and operating a proton accelerator in a hospital was thought to be beyond reach.

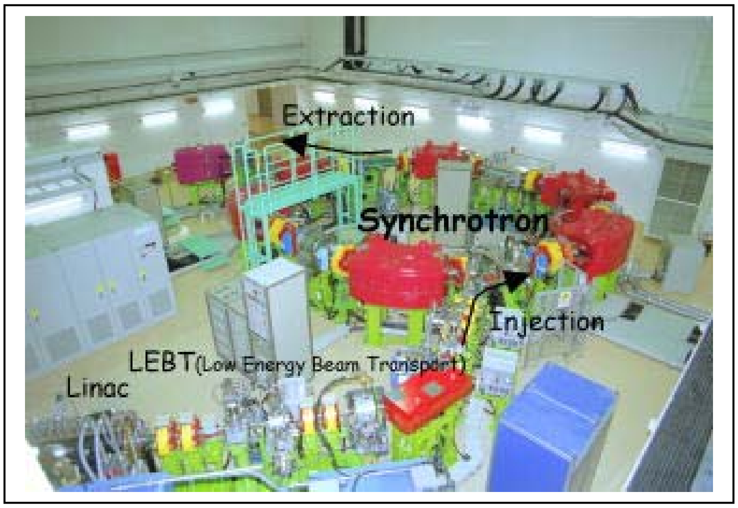
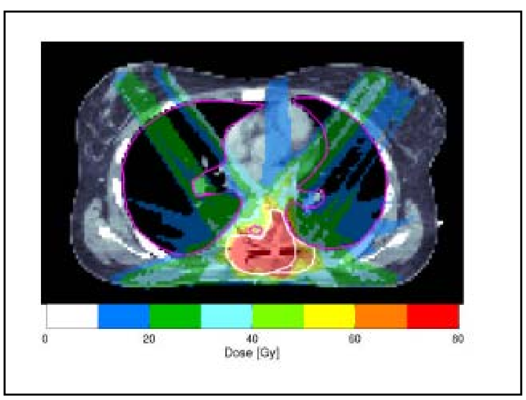


Figure 4.7: The medical synchrotron installed in the Tsukuba Proton Treatment facility of Japan. The requirements of these accelerators for the appropriate medical treatments are very stringent, and there is a significant amount of development needed to optimize their size and operability for use in a clinical environment.

Ultimately it is desired to produce a beam in the most conformal treatment possible with little if any dose reaching a healthy structure. The best way to achieve this to date is through the use of Intensity Modulation Therapy. This modality has been developed in the past few years. The figures below compare a dose distribution from an IMXT (Intensity Modulated X-ray Treatment) and an IMPT (Intensity Modulated Proton Treatment Plan). Due to the superior physical dose distribution of protons and ions compared with photons, their dose distribution will always be better. The issue of the clinical importance, depending upon the treatment site is the subject of ongoing studies.



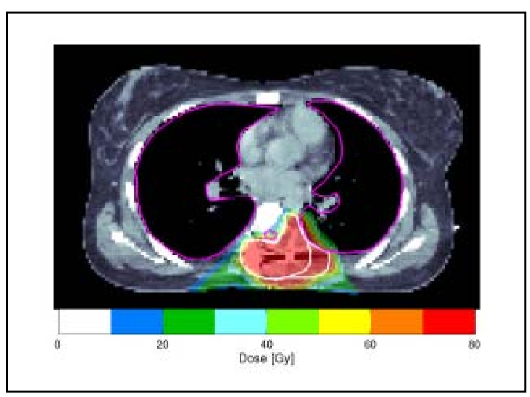


Figure 4.8: Color wash dose distributions of IMXT and IMPT treatment plans.

In order to deliver an ion beam of sufficient dose and depth in an intensity modulated fashion, quickly enough to take into account the effects of moving organs, the beam properties must be optimized. A beam must be delivered with a controllable intensity distribution as a function of time. The intensity must be able to be modified from 100% to 0% on a time scale quicker than 100μsec. This beam must be delivered with an appropriate beam size and distribution through a complex rotating gantry structure with spectrometer-like beam optics requirements. At present, there has been experimental work in the delivery of IMPT beams with methods that compromise the dose delivery due to limitation in the accelerator parameters. Cyclotrons can deliver a CW beam, and with proper feedback, sufficient intensity control, however the beam range is limited due to the size and cost of the cyclotron and while they can be useful for protons up to 230-250 MeV, they cannot be used for heavy ion acceleration. Synchrotrons suffer from extraction non-uniformity and limitations in stored intensity, especially those designs that are compact enough for commercial or hospital use. Beam delivery gantries have not been optimized optically and geometrically for scanning beams in a hospital environment. Finally the overall operation of the system must be extremely reliable and capable of being maintained by a small staff. While a hospital environment is a place for fully automated machines, it is not the appropriate place for artistic machine operators. The operation of these machines needs to be automated with appropriate design and diagnostics so that the performance can be maintained daily. Such a machine has yet to be designed and while has not been a priority in a National Laboratory environment with continually evolving operating parameters, it is a major priority in a hospital based environment.

There is a clear need for advanced research in the design and implementation of accelerators for Particle Therapy that can be fully automated and operate smoothly with better than 98% availability. In the past five years, the number of proton facilities has doubled and ion facilities are under construction. This field has become important for patient treatment and immediate advances will make a difference for the next 10 facilities that will be built in the next few years.

CAST can become an important contributor to this field. Considering the close ties between MIT and MGH, the clinical input is available to work with accelerator physics experts to help realize the appropriate designs. Combining this with the support of funding agencies and/or industry, prototypes can be built, for test and possible direct use in planned clinical facilities. The infrastructure that exists at the MIT-Bates accelerator center is well suited for such activities.

4.3 Test Beam User Facility at MIT-Bates Laboratory

4.3.1 Future Detector R&D Efforts

Future experimental projects in nuclear and particle physics will require the design and development of new detector systems. Such systems will also be crucial for the growing areas of particle astrophysics and medical physics. The availability of a test- beam facility would be an invaluable asset in studying, testing, and calibrating such systems.

An immediate example is the development of micro-pattern detectors using Gas-Electron-Multiplier (GEM) detectors. The Gas Research and Development Task (Task G within the MIT Laboratory of Nuclear Science) has undertaken the study of GEM's as a new method to read out a Time Projection Chamber (TPC). GEM's offer unique characteristics that make them desirable in a high intensity environment such as the Large Hadron Collider. Also, triple-GEM tracking detectors are under strong consideration for the STAR tracking upgrade and will likely be an important part of a future eRHIC detector at Brookhaven National Laboratory. Within LNS, the Research and Engineering Group will provide the necessary infrastructure to pursue the design and development of new detector systems. However, the availability of a test-beam facility is crucial to test various technologies for feasibility and to optimize their performance during the detector R&D phase. Characterization and calibration of the final detector could also be performed with a test-beam facility.

There is presently a national shortage of test-beam facilities in the United States. Brookhaven National Laboratory has traditionally provided the nuclear and particle physics community with test beam for detector research and development, but the B2 beam line that played a crucial role in the R&D and construction phase of the current RHIC detectors is no longer available. Many of the small-scale facilities at which such studies were possible in the past are no longer in operation. Some large laboratories do offer parasitic beams for detector tests, but availability is limited and resources are often subordinated to the needs of other programs.

MIT-Bates is in a unique position to help in filling this gap. The accelerator produces a very versatile beam, which can be tailored to the specific needs of a detector testing program. A test-beam facility at MIT-Bates, in combination with the Research and Engineering group at LNS, would ensure a leading role for MIT-Bates in detector developments such as the RHIC detector upgrade, new eRHIC detectors, and future detector systems. Such a facility would provide an ideal learning environment for undergraduate and graduate students, and a stimulating research facility at the forefront of detector R&D and construction efforts. As such, it will attract and retain the best young people and research associates with an active and exciting research program. Furthermore, the inclusion of this facility within the Center for Accelerator Science and Technology would produce a symbiotic relationship between accelerator scientists and particle physicists. This is a unique opportunity for the MIT-Bates Laboratory within the US nuclear and particle physics community.

This section will provide an overview of potential U.S. test-beam facilities, followed by a description of the MIT-Bates accelerator. The basic requirements for a test- beam facility at MIT-Bates are presented at the end.

4.3.2 Comments on US Test-Beam Facilities

A brief review of potential US test-beam facilities will be provided with emphasis on some of the foreseen requests. Although facilities outside the US are not discussed, it should be noted that many of the candidates are undergoing upgrades and will be unavailable to a large extent for test beams over the next ten years. Such facilities include CERN (after 2004) and

KEK (2004-2005). Similarly, usage of the Jefferson Laboratory for test-beam purposes is likely to be unfeasible by the end of the current decade and is not included here.

Fermi National Accelerator Laboratory

The main injector at FNAL provides simultaneous running of colliding and other fixed target programs. FNAL is constructing a dedicated test beam facility, the Meson Test Beam Facility (MTBF) on the MTest beam line. MTBF uses a 120 GeV proton beam from the Main Injector as the primary beam providing particle energies in the range of 5-120 GeV at a rate of less than 1MHz.

Several test-beam activities related to the BTeV program have been either approved for running or are under consideration. Additional usage at this facility will depend on how it could be accommodated into the foreseen BTeV test-beam program. A request would have to be made to the Technical Division, the Particle Physics Division and the Computing Division to seek support for a specific test-beam program.

Stanford Linear Accelerator Center

The "End Station A" beam line can be operated parasitically to the PEP operation for BaBar. This test beam at SLAC has a repetition rate of 10 Hz and can provide positrons in the energy range of 1-45 GeV, gammas from positron bremsstrahlung, and pions and protons produced in a beryllium target. A request would have to be made to the SLAC management to conduct a test-beam program.

Brookhaven National Laboratory

BNL has a long history of providing a test-beam facility to the nuclear and particle physics community. However, the B2 beam line, which was heavily used during the RHIC detector R&D and construction phase, is no longer available. The CAD department, in fact, would welcome the availability of other test-beam facilities for the RHIC detector upgrade program.

It is expected that the FNAL and SLAC test beam facilities will receive numerous requests for detector R&D related to the International Linear Collider. Without the BNL test-beam area, the RHIC upgrade program will have to compete with these requests if no other test-beam facility is made available.

MIT-Bates is therefore in a unique position to fill this gap. In combination with the Research and Engineering group at LNS, a dedicated test-beam facility would allow enormous flexibility for current and future detector efforts.

4.3.3 Brief Overview of the MIT-Bates Linear Accelerator Center

The MIT-Bates accelerator facility is shown schematically in Figure 4.4. The linear accelerator and recirculator are used to produce beams of polarized electrons to energies ranging from 100 MeV to 1 GeV with an energy resolution of 1 part in 10^4. Beams from the accelerator can be directed to external beamlines or injected into the South Hall Ring. Both modes could be of interest for detector testing.

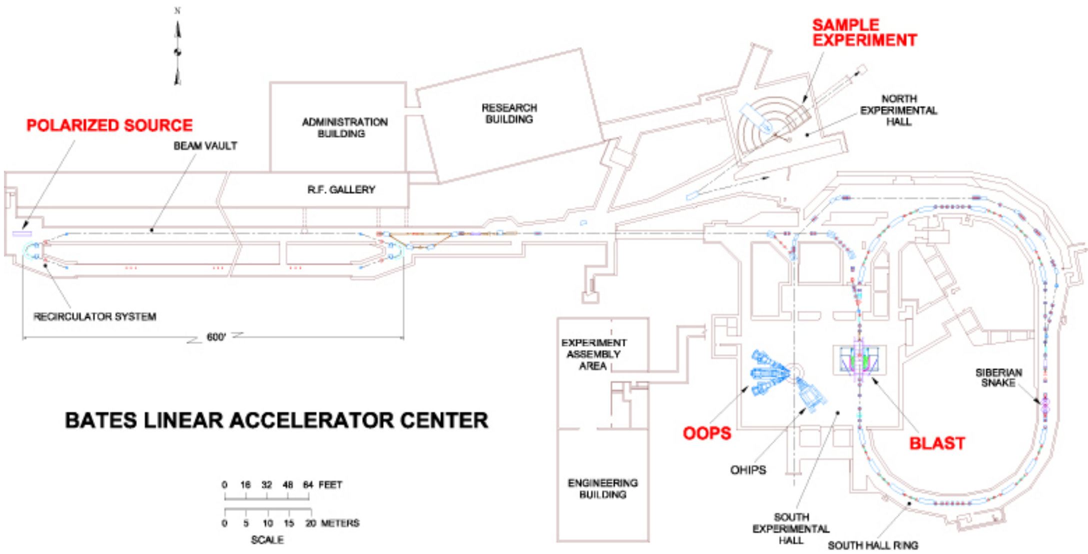


Figure 4.4: Layout of the MIT-Bates Linear Accelerator Center.

The most likely location for an external test beamline is the North Hall, where the SAMPLE experiment was formerly conducted. This location would minimize conflicts with other components of the CAST program. When running in pulsed mode repetition rates of at least 600 Hz are possible. Both of the existing experimental halls contain substantial floor space, modern radiation safety systems, and scattering chambers in which targets could be mounted. Either location could be outfitted for GEM detector testing.

The South Hall Ring may also be useful for tests of certain types of detectors and beam instrumentation. It operates in a storage mode in which the accelerator provides pulses at a rate of approximately 10 Hz. It is capable of storing currents in excess of 200 mA. The ring has a fully functioning gas feed system for thin internal targets. It has operated very reliably since 2002 for experiments using the BLAST detector. The SHR could be useful for testing detectors of low-energy charged particles, which would range out in an external target.

4.3.4 Basic Requirements for the Beamline Setup

Any test-beam facility must provide the infrastructure to carry out a general program. This would include the following items:

- Outside access to ease the transportation to and from the test-beam area
- Crane support for handling large detector packages
- Counting area with space for rack-mounted readout electronics, desk space and cable connections to the test-beam area
- System for triggering data acquisition system
- Chilled water supply
- Air cooling system
- Clean and dry air supply
- Supply of commonly used gases such as Ar-CO_2
- Beam position monitor
- Translation tables to scan position and impact angle on the test apparatus
- Production targets, possibly with momentum analyzing magnets, if the primary beam is not used directly

Technical and research support from the Research and Engineering Laboratory at LNS would be crucial in the preparation and operation of such a test-beam facility. Bates retains a skilled work force accustomed to satisfying these types of requirements from the lab's years of operation as a nuclear physics user facility.

It is anticipated that detailed design and development of a test beam line will proceed on a time scale determined by the needs of the GEM detector program. Funds are not requested for the test-beam program within this proposal. However, continued operation of the Bates accelerator for the CAST program will allow this program to remain viable and to pursue external sources of funding. It will be possible to carry out some detector tests parasitically with other aspects of the CAST program.

5.0 CENTER FOR ACCELERATOR SCIENCE AND TECHNOLOGY (CAST)

5.1 Organization and Structure

CAST will be an MIT Center with its headquarters at the Cambridge campus. The CAST Director will be a senior tenured MIT faculty member in the School of Science or the School of Engineering. The Director will report to the MIT Vice President for Research. The management structure proposed for CAST is analogous to that of many other Centers and Laboratories now at the Institute.

We propose that the Center staff be organized into two divisions: a Research Division which includes the accelerator physicists and an Engineering Division which includes engineers and technical support personnel. CAST staff will support operation of the accelerator facilities at Bates for education and advanced accelerator R&D. CAST-sponsored research will be carried out both at Bates and at other on-campus locations. The accelerator physics group and a number of technical personnel at Bates will become part of CAST. It is essential that there be a synergy of activities at the Bates site carried out by CAST and the proposed LNS Bates Research and Engineering Laboratory.

A CAST Advisory Board will be formed. Members will include MIT faculty representing the broad Departmental interests, and National Laboratory partners or affiliates (e.g. ANL, BNL, JLab, ORNL) with strong interest and overlap with both research and education at the Center. The Board will provide the CAST Director with general advice on research opportunities and directions, funding and staffing.

There will likely be a variety of research arrangements between CAST and individual faculty. Some faculty may choose to do most of their research through CAST. Others may do only some of their work there. Some CAST supported research can be based at satellite locations on campus, e.g. PSFC and at other places. An important objective for CAST will be to attract and concentrate the varied accelerator interests at MIT, provide a focal point for intellectual exchange of ideas and interests and to promote increased research funding in this area of science.

There is a potential for involving other local universities in CAST. Boston University currently has a strong interest in computational electrodynamics, non-linear dynamics, lasers and photonics and other closely related areas. There is interest at BU in exploring a possible association and collaboration with CAST.

CAST could operate as a "user" facility, similar to the current operation of Bates. Access to research facilities at CAST would be open to all MIT faculty, National Laboratory partners and affiliates and other qualified scientists.

If the DOE Office of Nuclear Physics is given the lead responsibility for funding operations, LNS contract administration for CAST may be the most efficient approach, and the scale of the proposed Bates Research and Engineering Laboratory will influence how the Bates site is best managed and used for multiple synergistic purposes.

5.2 Realization Plan

Realizing a new MIT Center for Accelerator Science and Technology will require a series of important milestones as follows:

- New faculty search initiated
- CAST funding approved
- CAST advisory board formed
- CAST educational committee formed
- MIT takes ownership of Bates accelerator complex
- CAST Director appointed
- CAST research program gets underway
- MIT committee to develop CAST curriculum formed
- First CAST graduate students in Fall 2006
- CAST laboratory course begins in Summer 2006
- CAST collaboration with other institutions gets underway

5.3 The Bates Accelerator Complex: transition from user facility to CAST

In 2005, the Bates Linear Accelerator Center will cease as a nuclear physics user facility. Decontamination and decommissioning (D&D) activities are in the planning phase by a joint DOE-MIT group and will get underway at the Bates site in FY2005. The initial focus is on clean-up of the experimental areas.

At the present time, it is planned that the complete Bates accelerator complex, including the electron injectors, linac, recirculator, and South Hall storage ring will be mothballed until a decision is made on CAST. Mothballing the accelerator and beam delivery system after terminating the user laboratory operation of Bates is restricted to a final maintenance cycle and transition to a stand-by state where minimal cooling water flow is maintained as well as fore vacuum pressure in the recirculator and beam switch yard using dry pumps and high vacuum pressure in the injector, linac, and SHR using vac-ion pumps. The EPICS control system will be kept operating to monitor these systems but all other beam line and accelerator components will be shut off.

Once CAST is funded, it is planned to complete some accelerator upgrades and documentation in order to facilitate quick start-ups for CAST, minimal spare inventories, and ease of operation by personnel with limited training.

The linac RF transmitter #5 is to be converted to solid-state switching as have all other transmitters to enhance reliability and eliminate the need for keeping separate, outdated spares for one last transmitter and relying on corporate memory for this technology. A new transmitter remote control interface which is being tested on transmitter #3 is to be installed on all transmitters to enable full transmitter control and reset from the Central Control Room. Furthermore, standard operating procedures (SOP) need to be completed and documented suitable for operators less familiar with the accelerator and beam lines, including complete startup procedures and trouble shooting guides. Maintenance procedures and spare inventories need to be completed to reduce reliance on corporate memory of the reduced staff.

Components and hardware needed for these upgrades are essentially all in house. An estimated 2 to3 man-years are needed to complete these preparations which will be covered by accelerator operations staff during FY2006.

5.4 Beam Delivery from Bates Accelerator for CAST

Within this proposal, sufficient funding has been requested to operate the Bates accelerator at full strength for 1500 hours per year. In practice, this will sustain a combination of research and educational programs ranging from use of low-energy beams in the injector to full-scale operation of the Bates Linear Accelerator and South Hall Ring. A summary of programs requiring beam from the accelerator is provided in Table 5.1. Each of these programs has been described in previous sections of this document. The table summarizes the facility requirements for each program, including the injection beamline, the scale of linac operation, and whether the storage ring would be required.

Table 5.1: A summary of CAST programs requiring beam from the accelerator. Also listed are the facility requirements for each program.

Type	Program (Section)	Injector	Scale of Linac operation	SHR requirements	Exp. Hall
Research	RF Photoinjector (2.2.1)	RF gun	Partial	None	None
	Coherent radiation studies (2.6)	RF	Full	None	North
	eRHIC beam physics (2.2.2, 2.4)	Polarized	Full + recirculator	Yes + Siberian Snakes	SHR only
	Terahertz radiation (2.9)	Polarized	Full + recirculator	Yes	SHR only
	Test Beams (4.3)	Polarized	Full	Possibly	As required
Education	Student Laboratories (3.3)	Polarized, RF	Partial	Not required	None
	Seminars, Student Research (3.3)	Polarized, RF	Full	Yes	SHR only

As shown in Table 5.1, certain programs will involve limited operation of the machine. These programs include use of only the injector and possibly a few transmitters. This type of operation can be carried out in a cost-effective manner on a flexible time scale. Such a schedule is desirable from the standpoint of encouraging educational programs during the semester, such as undergraduate laboratories. It is also well suited to developing projects such as an RF photoinjector.

Other types of programs involve operation of the linear accelerator at levels close to full scale. In some cases, the recirculator and South Hall Ring are also required. These programs must be carried out during a dedicated running period. It is envisioned that such running would take place once per year to minimize overhead from machine startup time.

Although it is difficult to anticipate accurately the beam time requirements for each program, Table 5.2 provides an initial estimate of the amount of beam time needed for the major research and educational programs on a yearly basis.

Table 5.2: An estimate of the amount of beam time (in hours) needed for the major research and educational programs for CAST on a yearly basis.

Operation Type	Program	Year 1	Year 2	Year 3	Comments
Partial	Student Laboratories	400	250	250	
	eRHIC physics	100	0	0	Polarized injector tests
	RF photoinjector	0	250	250	
	Subtotal	500	500	500	
Dedicated	Startup and General Machine Tuning	250	250	250	
	Seminars and Student Research	250	250	250	Educational programs for MIT, USPAS students
	Coherent radiation	0	200	200	
	THz radiation	250	200	200	
	eRHIC beam physics	250	100	100	
	Test Beams		Concurrently		
	Subtotal	1000	1000	1000	
Summary	**Grand Total**	1500	1500	1500	

The needs of the educational programs are expected to be relatively constant from year to year, although they may rise during years in which the U.S. Particle Accelerator School is hosted locally. Some additional development time is budgeted for the initial year to launch the student laboratory programs. The time estimates for the research programs are based on present readiness to proceed, expected development time, and scope of the program. Programs for which beam time is allocated in Year 1 can be initiated with existing machine hardware. However, as stated in Section 5.3, some necessary accelerator upgrades and documentations will be completed in FY2006 to facilitate the start up and general machine tuning with the planned reduced personnel. This includes the upgrade of the linac RF transmitter #5 to solid-state switching that was performed on all other transmitters for enhanced reliability.

In certain cases, it may be possible to operate programs concurrently. For example, the availability of parasitic test beams would greatly assist current detector development efforts (e.g. the RHIC collider program) and benefit future R&D for projects, such as eRHIC or the ILC. Such a facility will be developed and tailored to individual requirements. Requests and possibly additional funding from the Nuclear and Particle Physics community will be needed to specify details of this test beam facility.

For the "dedicated" full-scale accelerator complex running listed in Table 5.2, we envision a total of approximately six weeks of full-scale accelerator operation, including the initial run-up time. This level of dedicated operation is appropriate and consistent with the levels of personnel and funding requested in this proposal. The partial operation tallies correspond to the approximate number of hours for which the machine would be utilized for educational and research purposes during other parts of the year. The total funding request necessary for the manpower and electricity for this operation is presented in Section 6.3.

5.5 Qualifications of MIT Personnel

The proposed CAST research and education program will be carried out by a staff of 8 physicists, 5 engineers and 3 technicians. The 8 physicists are presently employed at Bates and their careers and areas of expertise are briefly summarized below.

Physicists

Dr. Manouchehr Farkhondeh: Dr. Farkhondeh received his Ph.D. in experimental nuclear physics from MIT. After his postdoctoral work at University of Virginia and MIT, he joined the Bates staff in 1990. Dr. Farkhondeh worked on the design and construction of the South hall Ring. He then joined the polarized source group and soon assumed the leadership of the group to provide the demanding high quality polarized beam for the parity-violating SAMPLE experiment. As a Principal Research Scientist, he has been the Division Head of both the Accelerator Division and Physics Division at Bates since 2000. He is the member of the Bates eRHIC design team focusing on the polarized injector, and one of the two editors of the eRHIC ZDR. He has extensive experience in a wide range of fields including laser science, photoinjectors, experimental nuclear physics, survey & alignment, cryogenic targets and accelerator physics. Dr. Farkhondeh is also an adjunct lecturer at Merrimack College in North Andover, Mass since 1988.

Dr. Wilbur Franklin: Dr. Franklin received his Ph.D. in Physics from Indiana University. He came to MIT in 1999 as a postdoctoral associate in nuclear physics and joined the Bates staff in 2001. Dr. Franklin is a Research Scientist working in the Polarized Source and Targets Group at Bates. He supervised development of the Compton polarimeter for the Bates South Hall Ring. He has also played important roles in laser development for the polarized source and in commissioning the South Hall Ring's adiabatic spin flipper. He is a member of the Bates eRHIC design team with a focus on polarimetry.

Dr. William Graves: Dr. Graves received his Ph.D. degree in Physics at the University of Wisconsin. He then became a staff scientist in the NSLS Division, BNL, where he studied accelerator physics, instrumentation and beam experiments in the high performance free electron laser facility DUV-FEL, where the first high-gain high-harmonic (HGHG) FEL was produced. Dr. Graves is now the leading accelerator physicist in X-ray Free Electron Laser (FEL) studies at MIT.

Dr. Evgeni Tsentalovich: Dr. Tsentalovich is a Research Scientist who heads the Polarized Source and Targets Group at MIT-Bates. He received a Ph.D. in Physics from the Budker Institute in Novsosibirsk. Dr. Tsentalovich has been at Bates for over ten years and has played a major role in all aspects of polarized source development to meet the needs of parity-violation and storage ring experiments for the nuclear physics program. He supervises the certification of polarized electron guns in the MIT-Bates Test Beam Setup. More recently, he has led the development of the Bates Atomic Beam Source, a polarized hydrogen and deuterium target for the BLAST experiment. He has extensive experience in a wide range of fields including laser science, nuclear physics, and accelerator physics.

Dr. Jan van der Laan: Dr. van der Laan received his Ph.D. degree in Physics at University of Amsterdam, the Netherlands. He was a research physicist at NIKHEF, Holland and DESY, Germany before he joined the staff at MIT-Bates in 2001. He worked in accelerator design and commissioning of AGOR and AmPS Holland, and HERA in Germany; the commissioning of the South Hall Ring at MIT-Bates for the BLAST experiment; and the eRHIC and XFEL design studies. His experience also extends to accelerator control systems. Currently he is in charge of coordinating the MIT participation in the EBIS project for RHIC in BNL.

Dr. Dong Wang: Dr. Wang received his Ph.D. degree in Physics at the Chinese Academy of Sciences, Beijing, China. He has worked on accelerator physics studies in several high energy electron-positron collider machines: BEPC (Beijing, China), LEP (CERN, Switzerland) and CESR (Ithaca, NY). He is now a key person in the eRHIC lepton ring design effort at MIT-Bates. He also worked on the electron-cooling project for RHIC at BNL and accelerator physics studies for new XFEL facilities.

Dr. Fuhua Wang: Dr. Wang received both undergraduate and graduate degrees in Physics at the University of Science and Technology of China, Beijing, China. He was employed as an accelerator physicist at Hefei Synchrotron Light Source in China, and Frascati in Italy as well as the Superconducting-Super Collider (SSC) before he joined the staff at MIT-Bates in 1994. Since then, Dr. Wang has played a major role in the commissioning of the South Hall Ring for the BLAST experiment and in the design of the electron-ion collider.

Dr. Townsend Zwart: Dr. Zwart is a Research Scientist who originally came to MIT-Bates as a graduate student in nuclear physics with a strong interest in accelerators and beam polarization. After earning his Ph.D. from Boston University, he joined the Bates staff in 1997 as a member of the Polarized Injector Group. In 2000, he became leader of the Bates Controls Group. Dr. Zwart played a key role on the development of spin polarization in the SHR and in particular the Compton polarimeter. In addition to his responsibilities for overseeing the development of the lab's instrumentation, he is playing a leading role in the design of an x-ray laser. He has also played a crucial part in formulating many aspects of the eRHIC design. In 2004, he spent three months at DESY working with the TESLA low-level RF group.

Engineers

The careers and expertise of the leading engineers in CAST are briefly summarized below.

Robert Abruzzio: Mr. Abruzzio is an electrical engineer with over twenty years experience with analog and digital design, maintenance of linear and switching power supplies up to 1.5 MW, power supply interface design, printed circuit board design, and database design using EPICS (Experimental Physics and Industrial Control System Software). He recently designed power supply controls circuitry which vastly improved the current stability of the Bates SHR power supplies.

Ernest Ihloff: Mr. Ihloff is a mechanical engineer with twenty years of experience at Analog Devices Inc. and MIT Bates. He has been a principal engineer on liquid cryogenic targets, construction of the South Hall Ring, the polarized electron source and the polarized hydrogen/deuterium target for the BLAST experiment. He has extensive experience in vacuum, cryogenics, fabrication, RF, and magnet design.

Abbasali Zolfaghari: Mr. Zolfaghari has over 30 years experience in the field of accelerator technology and RF-engineering. Experience includes responsibility for the calculation, design and development of the RF system for the MIT-Bates South Hall Ring (SHR), Double Ring Storage Ring at DESY-Germany (Doris), for the Positron-Electron-Tandem-Ring (PETRA), and for the Hadron-Electron Ring Accelerator (HERA). Responsibilities included development of RF-cavity resonators, microwave components, fiber optic electronics and rf control system; also, research, design, and development of microwave equipment for use in the National Aeronautics and Space Administration (NASA) space shuttle.

5.6 MIT Commitment to CAST

MIT's commitment to CAST includes:

- MIT takes ownership of Bates accelerator complex
- Salary support for Director, Associate Director and administrative support
- Infrastructure support for Bates site (~4 FTEs)
- Space for Cambridge headquarters
- Facility support for Bates site (power and utilities), including radiation protection for machine operation (~4 FTEs)
- Searching for and hiring new faculty
- Educating and training students
- Visiting/adjunct appointments for collaboration with scientists from other labs

5.7 Synergy with LNS R&E Laboratory

Beginning in late FY2005, LNS proposes to initiate a Research and Engineering Laboratory to support the research activities of MIT faculty. A proposal was submitted to the Department of Energy as part of the ongoing Cooperative Agreement to seek funds to support 13 FTEs in FY2006 and FY2007. This proposal was reviewed in summer 2004. Action on this proposal has been delayed due to delay in approval of FY2005 Department of Energy appropriation. The initial activities of the LNS R&E Lab are focused mainly on the Q_{weak} experiment to test the Standard Model at Jefferson Laboratory and the STAR experiment at BNL to study the spin structure of the nucleon as part of the RHIC-spin program.

It is expected that if both the R&E Lab and CAST are funded that there will be significant overlap between these two activities at the Bates site. For example, development of a polarized ^3He ion source for RHIC using the new EBIS source is proposed as part of the R&E Lab. Under CAST, a significant participation by Bates in the design and construction of EBIS is proposed. Significant overlap between these activities is anticipated.

The considerable expertise of the R&E staff will likely be important for specific R&D projects in CAST and vice-versa. In particular, the corporate memory (developed over decades) necessary to operate the Bates accelerator complex is distributed among the staff both in CAST and in the R&E Lab.

5.8 Collaboration with other Institutions

Collaborations of mutual benefit with other laboratories, industrial companies, and the United States Particle Accelerator School will be essential to the success of CAST. Discussions with these other institutions have been initiated and in all cases a strong basis for collaboration has been identified. The nature of these collaborations is summarized below:

Argonne National Laboratory

The collaboration between MIT and ANL has focused on timing synchronization between multiple RF sources and multiple lasers. This collaboration draws upon the laser and accelerator expertise at MIT to improve the performance of the existing laser/accelerator facilities at ANL and to explore R&D toward improved performance of future light sources, where timing at the femtosecond level is critical for study of dynamical processes.

In the spring of 2004 we performed initial measurements using microwave mixers on the linac at the Advanced Photon Source to determine the relative RF phase synchronization between the RF master oscillator and each klystron, and also the relative phase jitter of each klystron's output with the others. We plan to improve upon these measurements by developing microwave circuits for this explicit purpose, and to again test them at ANL. We are also studying the direct measurement of beam timing (rather than RF) jitter using microwave and beam-based methods, and the development of feedback loops to stabilize the low-level RF system. This work is partially funded by a Laboratory Directed R&D (LDRD) program at ANL.

A separate LDRD at ANL will fund a postdoc to study femtosecond synchronization techniques and distribution of timing signals in the Ultrafast Laser Group at MIT under Professor Franz Kaertner. The systems developed will be applied to the Terawatt Ultrafast High Field Facility and the LEUTL facility at ANL.

Brookhaven National Laboratory

Since 2000, there has been a strong collaboration between BNL and MIT on the development of the scientific case and accelerator design for a high luminosity lepton-ion collider to study the fundamental partonic structure of matter. In particular, physicists from MIT-Bates and the Collider Accelerator Department at BNL have worked closely on the design of a machine which would utilize the existing, powerful Relativistic Heavy Ion Collider (RHIC) as the basis for the ion beam. This design is known as eRHIC. In March 2004, this effort culminated in the production of a Zero Order Design Report (ZDR) where the Bates team played the lead role in the design of the electron beam for eRHIC. It is proposed that this leading role by MIT in the realization of the electron beam for eRHIC be continued under CAST (see Section 2.4).

In addition, CAST proposes a significant participation in the design and construction of the EBIS source for RHIC (see Section 2.8). It should be noted that development of a polarized ^{3}He ion source for RHIC using EBIS is planned at the Bates site under the LNS R&E Laboratory.

BNL is a leader in the delivery and development of intense photon beams for research. CAST has a significant research thrust in the area of advanced light sources. It is anticipated that there will be effort of mutual interest and benefit in this area also.

DESY (Deutsches Elektronen-Synchrotron) Hamburg, Germany

In January 2004, MIT became a member of the DESY "TESLA" collaboration, a cooperative R&D collaboration supporting both the proposed TESLA collider project and the European XFEL project. MIT interest in this collaboration is primarily driven by our interest in the XFEL project. As the attached letter from DESY Director Albrecht Wagner indicates, DESY is strongly supportive of our involvement in this activity because we bring unique expertise in laser timing and synchronization, as well as laser seeding technology.

This collaboration is highly relevant to DOE interests in that it would enable more rapid progress implementing laser seeding at the SLAC LCLS project, and eventually at a US user facility comparable to the European XFEL. The collaboration offers us the opportunity to develop and implement prototype technology on the VUV test facility (so-called TTF2) currently preparing to operate at 1 GeV at DESY and to influence the design of the European XFEL project with respect to achieving full longitudinal coherence with laser seeding methods. These activities are an important part of the proposed CAST center at MIT.

The DESY-MIT collaboration would also be an avenue for US access to the European XFEL for science requiring the higher peak brilliance of the x-ray laser beam obtained by laser seeding. Experiments exploiting the x-ray laser beam inevitably exploit the beam's short pulses and/or high energy resolution. With laser seeding the beam's energy bandwidth and time duration are reduced to the limit allowed by the Uncertainty Principle, permitting experiments which will go beyond those currently envisioned for LCLS.

In addition, DESY is the site of the world's only high energy lepton-ion collider, HERA. There has been ongoing collaboration between MIT and Dr. Desmond Barber on the design of eRHIC. This will continue under CAST.

Lawrence Berkeley National Laboratory

MIT and LBNL have been collaborating since early 2003 on accelerator and FEL topics of joint interest. Initially this has included development of a high repetition rate photoinjector and studies of harmonic generation cascade FELs. The attached letter from William Barletta, Director of the Accelerator and Fusion Research Division of LBNL describes LBNL's support.

This research is aligned with DOE's needs to develop new x-ray user facilities generating the brightest beams for its user community. In order to support a large number of users, it is important that future light sources, whether based on an ERL or FEL, attain high repetition rates serving many beamlines. All photoinjectors to date have operated at a few tens of Hertz or less. Our collaborative effort is aimed at developing an injector that will reach 10 kHz or higher, supplying kilohertz pulse rates to many beamlines. It leverages the significant investment in existing kilohertz RF power and accelerator infrastructure present at Bates Laboratory. This effort would be expanded and become a significant part of the CAST center.

The other major part of the collaboration has been the development of the physics of harmonic cascade FELs, where an XUV seed pulse is frequency-multiplied to the hard x-ray range and amplified to millijoule levels. This work has resulted in publications and significant enhancements to the code GINGER, one of the primary design tools for LCLS and other x-ray FELs.

Thomas Jefferson National Accelerator Facility

The polarized source groups at Jefferson Lab and MIT-Bates have been collaborating in recent years in many areas related to the development of polarized sources and beams. These areas spans from UHV techniques and hardware to high polarization photocathodes, test beam developments, low energy beam polarimetry, lasers and in taming helicity correlated false asymmetries persistent in parity violating experiments at both labs.

There is a renewed interest to expand this collaboration aimed at maximizing the beam uptime and achieving highest possible polarization with the Jefferson Lab main polarized source. The detail of this collaborative effort is described in detail in Section 2.2.2. The thrust of this new collaboration is to utilize the technical and photoinjector expertise at MIT to design and construct a simplified test beam setup for Jefferson Lab that permits rapid tests of photocathode samples that subsequently can be inserted into the load lock photogun in the tunnel all in UHV environment. In addition, surface physics groups at the MIT campus with analytical capabilities will be identified and contacted to perform surface analysis of photocathode for Jefferson Lab. The surface characterization of samples will be crucial for understanding the criteria for sample sections that yield the highest figure of merit for Jefferson Lab. Other areas of collaboration include polarized source development for future lepton-ion colliders that are the focus of interests at BNL Jefferson Lab and MIT. We are also proposing to collaborate with the Jefferson Lab for cold test of the RF recycler R&D project described in Section 2.3.

Sincrotrone Trieste

MIT and its collaborators are proposing to join with Sincrotrone Trieste in the construction of a seeded, fully coherent XUV Free Electron Laser (FEL) at Sincrotrone Trieste. This project has already received the majority of its funding from Italian and European sources. The proposed topics of collaboration include laser and accelerator development, FEL studies, and design of an innovative XUV beamline.

Personnel from Bates Laboratory would be involved in design, fabrication and installation of essential linac systems (e.g. RF, magnets, vacuum equipment), design specifications for the overall FEL performance carried out in collaboration with LBNL, and development of a variety of electron and photon beam diagnostics. The MIT Ultrafast Laser Group in the Department of Electrical Engineering and Computer Science has offered to provide expertise for the specification and construction of specialty components necessary for successful implementation of laser technologies including: sub-picosecond timing and synchronization (also with LBNL); short-pulse and narrow bandwidth laser seeding; and development of the photocathode laser.

Researchers from MIT and collaborators from Boston University, Princeton, Stony Brook University, the University of Hamburg, and the University of Uppsala, have offered to work towards securing US and European funding for and implementing a millivolt resolution inelastic light scattering facility with incident energies from 20 eV to 200 eV for the forefront study of structural, electronic, and magnetic dynamics of condensed matter. Such an instrument will take full advantage of the seeding technologies, which produce transform-limited beams with milli-joule pulse energies at millivolt bandwidths, to outperform current and planned instruments at third generation synchrotrons by many orders of magnitude. The U.S. funding for this instrument is being sought from the National Science Foundation.

Finally, as a leading educational institution, MIT will seek to involve students in all aspects of the project. We see opportunities for undergraduate and graduate thesis work across a range of fields from mechanical and electrical engineering to condensed matter physics and chemistry.

United States Particle Accelerator School (USPAS)

USPAS plays a central role in the education of young accelerator physicists in the United States. It coordinates regular schools which are held at different universities and laboratories around the country. In 1995 a very successful school was held at the Bates Linear Accelerator Center where the students had the rare possibility to work with the beam. It is planned to develop the CAST educational program in close consultation with USPAS and to arrange to make the `hands on' accelerator laboratory available to the USPAS program. If CAST is initiated in a timely way, the first laboratory school could be held as early as summer 2006.

5.9 Environment, Health and Safety (EH&S) at Bates under CAST

Under CAST, environment, health and safety of the Bates accelerator complex and research facilities (located 25 miles from the Cambridge MIT campus) will require oversight. It is proposed to continue the effective structure which has worked so well for over three decades, with a reduced staff of 4 FTEs supported by MIT.

The Radiation Protection Program at Bates (Bates RPP) is a division of the MIT Environment Health and Safety Office (EHS) operated under the direction of the Environmental Programs Office (EPO). Bates RPP provides independent oversight of all radiological safety (Ionizing and non-Ionizing) areas related to the operation of the Bates Laboratory and coordinates the delivery and implementation of additional EHS program requirements involving: Industrial Hygiene, Environmental Management, Safety and Biosafety.

The Radiation Safety Office, directed by the MIT Radiation Protection Committee, provides independent oversight of Bates Accelerator operation. Specific responsibilities include: shielding design reviews, review/approval of all proposed and on-going experimental protocols, personnel monitoring, worker training, area surveys, environmental monitoring, waste disposal, management of facility interlocks, instrument calibration and emergency response. Bates RPP personnel are assigned to each operating shift. Bates RPP management includes a Masters-trained ABHP certified Radiation Protection Officer, and a Masters-trained Asst. Officer.

As a division of EHS, Bates RPP is responsible for coordinating and providing assistance with implementing key elements of the MIT-EHS management system. This involves integrating service across the areas of Industrial Hygiene, Environmental Management, Safety and Biosafety. Examples of specific responsibilities at Bates include: worker registration and training, conducting routine facility-wide inspections, central registration of all areas and activities, oversight of spill prevention program, assisting with the management of hazardous waste, assisting with the management of the hot work/lock-out/fire-safety/emergency response/confined space programs and serving as a member of the Lab Safety Committee.

5.10 Administration

The CAST Director and administrative staff will be responsible for the general administration of all CAST programs. This includes all administrative, fiscal, and personnel functions. The CAST Directorate will work closely with the Office of Sponsored Programs and the DOE to fulfill all contractual obligations and will manage the Laboratory in accordance with the accepted policies and procedures of the Massachusetts Institute of Technology. It is estimated that the administrative costs will be approximately 8 percent of the modified total direct costs.

Responsibilities of the Director include:

- Coordinate and process the Center's annual summary of research and budget proposal to the U.S. Department of Energy for all projects
- Coordinate and process the Center's annual Report to the President of MIT
- Coordinate and process the Center's Five Year Plan submitted to the Vice President for Research's Office
- Space planning and changes
- Review and process all proposals for research funding
- Record and issue keys for all CAST space

The CAST administration will include a Personnel Officer who will provide a full range of services to both employees and supervisors within CAST. These will include the administration of policies and procedures, salary administration, visa processing, staff hiring, policy interpretation, and conflict resolution. The Personnel Officer complies with MIT Policies and Procedures regarding personnel practices and coordinates with the MIT Personnel Office and, in certain instances, the Office of Labor Relations, for all hiring, terminations, and disciplinary actions. The Officer will work closely with the MIT International Scholars Office processing visa requests for foreign visitors and employees in compliance with U.S. Immigration and Naturalization laws. Types of visas include J-1, H-1, B, and permanent resident. This office is also responsible for Affirmative Action/Equal Opportunity statistical reports including numbers of under-represented minorities and women employed by the laboratory, and realistic goals for the future hiring in those areas.

The CAST administration will include a Fiscal Officer who will be responsible for accurate tracking of all CAST related financial activities and for the production and delivery of financial statements and reports that accurately reflect the financial condition of the Laboratory. The Fiscal Officer will manage all budgeting and accounting services research groups and the administrative staff. These activities include:

- Preparation of the preliminary, revised and supplemental budgets
- Review/process requisitions for delivery to either purchasing or subcontracting services
- Approve invoices for payment

- Process staff, student, hourly and support staff payrolls
- Produce monthly salary reports for group leaders in accordance with MIT Audit
- Track funding/expenses to ensure compliance with DOE guidelines
- Provide monthly reports and financial status to the CAST Director concerning the status of all CAST accounts
- Assist in the preparation of details pertinent to fiscal projections and planning
- Help monitor operational, compliance, financial, and strategic factors in the fiscal operations

All the administrative services required for CAST have been provided to Bates throughout its lifetime as a nuclear physics user facility by the LNS Headquarters funded by the Cooperative Agreement. A similar arrangement, whereby these administrative services could be performed jointly with LNS, could be continued with CAST.

6.0 PERSONNEL AND BUDGET

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6.0 CURRICULUM VITAE OF CAST SCIENTISTS

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7.0 Appendix

7.1 Letters of support

ALICE P. GAST
VICE PRESIDENT FOR RESEARCH
AND ASSOCIATE PROVOST
ROBERT T. HASLAM PROFESSOR
OF CHEMICAL ENGINEERING

77 Massachusetts Avenue, 3-240
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December 20, 2004

Dr. Raymond Orbach
Director
Office of Science
United States Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dear Dr. Orbach:

We are pleased to enthusiastically support the MIT proposal for an interdisciplinary Center for Accelerator Science and Technology. MIT aspires, as always, to contribute to critical national needs and the CAST proposal is offered as a thoughtful response to the need for an accelerator technology initiative as identified in the recently released Office of Science Strategic Plan. Exploration of the scientific frontiers in the coming decades will require new particle accelerators which can only be realized by a sustained and broad national R&D program. We view CAST as a long term partnership between MIT and the Office of Science to address this national priority.

The interdisciplinary character of CAST draws on the considerable expertise in the area of particle accelerators across the MIT Schools of Science and Engineering. We believe that the tremendous depth and breadth of researchers at MIT make it uniquely suited to carry out its mission. Remarkably, many of the key challenges faced by the next generation of accelerators share broad similarities, even though they apply to very different applications. The synergy among the CAST researchers, as well as the synergy among the technologies, will drive a research program with broad and powerful impact.

CAST will provide new and exciting research and educational opportunities for the students, faculty, and staff of MIT. The suite of particle accelerators on the MIT campus is unique among U.S. universities and CAST will open up the excitement of research activities in accelerator R&D to MIT students. In particular, MIT looks forward to working with the Office of Science to develop unique educational opportunities at the Bates Linear Accelerator Center for training the coming generations of young accelerator scientists.

Collaboration with scientists at the DOE National Laboratories will be essential to the success of CAST. The initial CAST research program has been carefully developed to address high priority issues for the Office of Science. Among these are the 12 GeV Upgrade at Jefferson Lab, the development of the electron-ion collider and the International Linear Collider, and the development of high brightness light sources. I am gratified by the strong interest in CAST already expressed from researchers at the National Laboratories. I am also pleased to note the considerable support for CAST expressed by leaders in the particle accelerator community in the letters contained in the Appendix to the proposal.

The MIT commitment to the CAST proposal is strong. I note that

- 8 MIT faculty and 3 MIT Senior Research Scientists are conmiitted to providing leadership for CAST. This exceptional team draws upon remarkable strengths across multiple departments, laboratories and schools.
- There is a search for new accelerator physics faculty underway.
- MIT is committed to developing of an educational program in accelerator science and technology.
- Subject to further negotiations with DOE, MIT is prepared to take ownership of the Bates accelerator and buildings, if CAST is funded.
- MIT will support the CAST facility's infrastructure, including the CAST Director, a CAST Administrator, and 2.5 FIE's of CAST support staff.
- MIT will continue to provide Environment Health & Safety oversight of the Bates accelerator complex (4 FTEs).

I very much look forward to what I hope will be a positive response to our proposal for MIT to establish a Center for Accelerator Science and Technology.

Sincerely,

Alice P. Gast

Alice P. Gast
Vice President for Research and
Associate Provost

communications
Security & Detection Systems
10 Commerce Way
Woburn, MA 01801
781-939-3800 Fax: 781-939-3996

May 24, 2004

Dr. Richard Milner
Director of MIT - Bates Laboratory
21 Manning Ave. – P.O. Box 846
Middleton, MA 01949-286

Dear Richard,

This letter is written to confirm our interest in developing a partnership with the Bates Facility in order to further some research aims that may be critical to L-3's business development plans in the next several years. In previous discussions we have proposed two areas of work, but in fact believe there may be additional areas of collaboration. The two subjects that have already been outlined are:

1. Joint development effort in the area of "special nuclear materials" detection. Specifically the development of energy resolved gamma and neutron detectors suitable for various mobile portal inspection applications. Also, use of the Bates facility for live testing of nuclear detectors with radioisotopes such as Cs137 and Co60 and fissile materials.

2. Use of a radiation protected area for testing and development of multi MeV mobile x-ray systems that are marketed by L-3 for the inspection of trucks and cargo containers.

Some new areas of work that are becoming interesting in light of initiatives from the Transportation Security Agency (TSA) would include:

1. Development of a dual energy x-ray source with source energies of 4 and 8 MeV.
2. Development of a high current (50-100 mA) x-ray source at 160 KeV.
3. Development of a high spatial resolution neutron detector in the 4 MeV range.

This is a very brief list of some important research topics and will be further refined as we better understand the TSA's objectives.

Sincerely,

William F. Aitkenhead, Ph.D.
Senior Scientist, L-3 Security and Detection Systems

ACCELERATOR & FUSION RESEARCH DIVISION

February 13, 2003

David E. Moncton
Physics Department 13-2038, Massachusetts Institute of Technology
Cambridge, MA 02139-4307

Dear David,

I am writing to confirm our intention to collaborate with MIT on the development of technologies related to X-ray FELs. As you know, at LBL we have had a longstanding interest in high-brightness, short-pulse X-ray source development. Recently we have developed a concept for a new machine based on a recirculating superconducting linac. Many of the R&D challenges we face are similar to those encountered in the proposed MIT-Bates X-ray laser, such as production of a high quality electron beam from a photoinjector and development of seeded, fully coherent XUV output.

Each of our institutions has expertise in complementary areas. It is of utmost importance to use our R&D resources in the most cost effective way. Therefore we are pleased to collaborate in the following key areas:

1. Perform simulation studies of photoinjectors capable of producing short electron pulses with submicron emittance at kilohertz repetition rates. The Beam Electrodynamics Group led by John Corlett will participate in RF cavity design and beam dynamics simulations with accelerator scientists from MIT-Bates under the direction of William Graves. The goal is to generate photoinjector designs that can be built for each laboratory's proposed X-ray sources.
2.
3. Study the generation of fully coherent XUV pulses by laser seeding of a FEL. Simulation studies using the GINGER code under the direction of William Fawley of LBL and William Graves of MIT-Bates will examine seeding concepts including chirped pulse amplification and cascaded high gain harmonic generation. The goal of the studies is to understand the XUV source performance for different seeding approaches.

The costs associated with the collaboration consist of travel by the participants, and time spent on the studies, which will be funded by the employing institutions. There are no equipment costs.

Sincerely,

William Barletta

Dr. William A. Barletta
Director, Accelerator & Fusion Research Division
E. O. Lawrence Berkeley National Laboratory
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Deutsches Elektronen-Synchrotron DESY
Member of the Helmholtz-Association

Chairman of the Board of Directors

Hamburg

Dr. David E. Moncton
MIT Nuclear Reactor Laboratory
138 Albany St. NW12-204
Cambridge, MA 02139
USA

28 June 2004

Dear David:

The TESLA Collaboration is pleased to welcome the MIT x-ray laser group as a new member, bringing strong capabilities in accelerator science and laser technology as well as highly regarded experimental expertise. The exciting technology under development at MIT will allow lasers to be synchronized to the accuracy of less than 10 fs, as well as enabling production of synchronized RF drive fields or electron beam acceleration with low timing jitter. This synchronization will have a major impact on the science possible with the XFEL, since many experiments will involve timing between pump and probe pulses of various kinds.

These technologies and expertise are of immediate interest to us, and your group can make a unique contribution to the European XFEL project in this regard. Due to rapidly growing world-wide interest in x-ray lasers we think your proposed R&D program is of exceptional value. Because of our strong interest in this technology we will work closely with you to make resources available at DESY for the R&D collaboration, to insure that the results we achieve together will greatly exceed what either of us could have accomplished independently.

The specific issues that we would like you to address in the near term are those we discussed at the January, 2004 TESLA collaboration meeting: implement your proposed optical clock and fiberoptic distribution system, measure and analyze the timing jitter contributions of the existing laser and RF systems, and develop low level electronics for stable accelerator phase and gradient. We expect you to suggest additions and modifications to the existing systems with the goal of synchronizing the FEL output to external lasers with jitter of less than 100 fs. The timing controls should address both fast timing jitter (above 1 kHz) and slow thermal or mechanical drifts.

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phone: + 49 40 8998-3000/ -2408
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We also understand your interest in achieving beams with full longitudinal coherence by seeding the electron with a high power short wavelength laser source to overcome the noise associated with the Self-Amplified Spontaneous Emission (SASE) process. It is clear that the science potential for such coherent sources will be most attractive. Thus, DESY supports laser seeding to be among the long-term goals of the European XFEL Facility. It will require a robust R&D effort in order to succeed. If successful, such a program could be the basis for a new generation of beamlines and experimental methods in the future XFEL facility. We would very much welcome working together toward this goal as well.

With best regards

Albrecht Wagner

Prof. Dr. Albrecht Wagner

Cc: Prof. Dr. Jochen Schneider

Thomas Jefferson National Accelerator Facility

Operated by the Southeastern Universities Research Association for the U. S. Department of Energy

Prof./Dr. Swapan Chattopadhyay
Special Scientist and
Associate Director, Accelerators

December 30, 2004

Dr. Raymond Orbach
Director, Office of Science
US Department of Energy

Ref: Support letter for MIT Center for Accelerator Science and Technology

Dear Dr. Orbach,

I am writing to you in support of the proposal submitted to your office by MIT towards the creation and funding of the Center for Accelerator Science and Technology (CAST). Indeed it is a rare opportunity and privilege for the scientific community to have a world- renowned research and educational institution such as MIT show interest and dedication in promoting the physics and technology of beams – a critically needed effort in the field today.

As you are aware, this field is at the core of more than a third of the total number of facilities envisioned in the Department of Energy's Twenty Year Facilities Road Map and yet the education and training of young scientists in this field lag the demand in the US threatening the quality of this scientific enterprise towards mediocrity. Over the years, inspite of significant efforts by the APS Division of Physics of Beams and its Education Committee (of which I was the Chair for many years) and the US Particle Accelerator School supported by the national laboratories (in which I serve currently as a Board member), few universities in the US have picked up the cause. Currently, undergraduate and graduate education in accelerator science and technology is limited in varying degrees to a handful of schools but none so elaborate and comprehensive as proposed in this proposal.

I have been familiar with the MIT microwave, plasma and accelerator facilities for many years since early 1980s when I collaborated with Prof. Ron Davidson and Prof. George Bekefi on plasma physics, microwave Free Electron Lasers, nonneutral plasmas and fusion concepts, with Prof. Jonathan Wurtele, Prof. Richard Temkins and Prof. Stan Kowalski on high frequency microwaves and accelerators and later in early nineties on various accelerator concepts when I was leading the Center for Beam Physics at Berkeley. At that time I helped create a collaboration between Berkeley and MIT in advanced accelerator concepts with modest support from the DOE High Energy Physics Division (funded by the Advanced Technology branch headed by Dr. David Sutter).

The MIT Bates accelerator facility had nurtured core competency in the science and technology of polarized electron sources, a competency that will be retained in the proposed center after the current nuclear physics program comes to an end. This group is in active collaboration with Jefferson lab and will be essential in helping the community develop very high polarization (>95%), high quantum efficiency (a few %) photocathodes via vigorous R&D on specially prepared semiconductor layered surfaces. Such samples could be surface analyzed in many of MIT's fine labs and tested at Jefferson lab for their ultimate performance. Such polarized electron guns will be crucial for future electron-ion colliders as well as electron – positron colliders at high energy. Today, only SLAC, Jefferson lab and MIT hold the competency together in the US, requiring a much needed boost.

MIT has also been in collaboration with BNL and Jlab in developing ideas and designs for high luminosity electron-ion colliders and playing the role of a catalyst in accelerating the pace of establishing feasibility of such a collider in the next decade. The tremendous motivation of the nuclear and particle physicists at MIT supporting intellectually the enterprise of accelerators towards the envisoned collider program is surely going to be a great advantage in recruiting young talent in the service of science for decades to come.

But MIT today has grown beyond plasma, microwave and nuclear physics to include in its scope of work many tasks that directly support future novel light sources. There already exists world renowned visible short pulse laser expertise at MIT. There also exists in the electrical engineering department world renowned expertise in control theory, phase synchronization techniques and various microwave skills all of which will be crucial in developing ultrafast light sources of various colors and degrees of coherence. Senior expertise in light source users base and recently recruited junior expertise in high brightness electron injectors complement this team. This combination of core competencies and expertise has broadened MIT's horizon even further, in critical forefront research that directly benefits not only the nuclear physics enterprise , but also basic sciences enterprise of DOE: high brightness photocathode guns, seeded FELs, short pulse X-ray FELs, etc., all eventually benefiting the community of scientists in training a new generation equipped with the necessary background to harness these new devices.

We at Jefferson Lab have established direct collaboration with MIT on polarized source development and on development of design of a future electron ion colliders. We also are in the process of establishing a mutual graduate research program in thesis work in accelerators and FELs with mentors from both institutions and have plans to grow into collaborative areas of microwave superconductivity and Energy Recovering Linacs. Being one of the strongest institutions in SURA that manages Jlab, the accelerator-specific MIT-Jlab collaboration will have special value and strength for the entire community.

The investigators engaged in this proposal are the finest in the field, many established with international stature . The proposal has support from the highest levels of MIT administration. I have no hesitation in my expectations and have full confidence in the MIT CAST delivering the deliverables expounded in the proposal in a timely fashion and being productive for multiple divisions within the DOE's Office of Science. I leave it to your judgment, capacity and possibly to the recommendation of a properly conducted peer review to determine the level of support, but any support you can provide in establishing the Center in spirit will be important symbolically and will be worth your effort in this lean high-value-added activity at a top internationally recognized institution of unique quality.The facility can be expected to launch tens of unique special experiments a year, publish multiple dozens of high quality refereed publications per year on the average and graduate a few Ph.Ds per year in the field thus adding to the critical mass needed for the future of accelerator-driven science – and all this with a modest budget of a few million dollars a year.

I support the submitted proposal without any reservation and with the highest confidence I can gather. I ask that you give it your sincere attention and consideration it deserves.

With regards,

Swapan Chattopadhyay
Special Scientist and Associate Director
Jefferson Lab
and
Adjunct Faculty
Jefferson Lab Professor of Physics
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H E L M U T   W I E D E M A N N
P R O F E S S O R   O F   P H Y S I C S
A P P L I E D   P H Y S I C S   D E P T . A N D   S L A C / S S R L
S T A N F O R D   U N I V E R S I T Y

December 30, 2004

Dr. R. Orbach
Director, DOE Office of Science
Department of Energy
Germantown

Dear Dr. Orbach:

I am writing to you in support of CAST, the proposal to establish the MIT Center for Accelerator Science and Technology. As the director of the US Particle Accelerator School, I am especially supportive due to the inclusion of a significant educational segment in accelerator physics. In this country, we have not only a great need for education and training in accelerator physics, but also great interest by staff from national laboratories and by university graduate students. With DOE support, we organize two schools per year, each time at a different university and offer 12 to 13 courses for which the hosting university provides regular credit to enrolled students. Each school attracts about 140 to 150 students, split about 50/50 between students from labs and universities.

One of our shortcomings is the only sporadic access to real, live accelerators by students. Theoretical understanding of accelerator physics is essential, but practical training is also necessary to fully understand the intricacies of an accelerator. Access to existing accelerator facilities is generally not available because of heavy use and/or high costs. The MIT CAST proposal based on the Bates accelerator system would be a formidable opportunity for practical training in accelerator physics. It provides access to both a linear as well as a circular accelerator. For USPAS, the existence of such a facility would create an opportunity to offer annually practical training courses in support of our regular curriculum. Since Bates is a functioning laboratory, it has the infrastructure and a variety of accelerators and components to pursue training, development and testing of new ideas. The USPAS community and supporting institutions would greatly benefit from such an opportunity. I recommend strongly your support for the CAST proposal.

Sincerely,

Helmut Wiedemann

USPAS Director

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August 6, 2004

Prof. Richard Milner
Department of Physics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

Dear Professor Milner,

Thank you for sending your proposal for an "MIT Center for Accelerator Science and Technology" (CAST). I have thought for a number of years that such a concept made sense for MIT because of its long association with the Bates Laboratory and the national need for training new accelerator scientists and engineers. I believe the CAST Proposal is well conceived and will help meet this national need that has grown while the supply of such people dwindled.

The accelerator science research and development areas proposed are those for which MIT is well positioned. The plan for making cost-effective use of the Bates facility after its de-commissioning for nuclear physics research has much to recommend it, especially the ability to re-direct a cadre of skilled accelerator scientists from Bates to CAST.

Brookhaven, with its focus on operation of and R&D on a variety of forefront accelerators, has a particular interest in many of the areas of focus of CAST. MIT is already collaborating with BNL on important accelerator R&D for our proposed future RHIC II and eRHIC facilities; consequently, BNL expects to benefit from much of the proposed research work planned for CAST. The proposed work on photoinjectors and various beam physics issues are also relevant to other accelerator activities at BNL.

Perhaps even more importantly there is a national need for training the next generation of accelerator experts.

Sincerely,

Peter D. Bond
Interim Deputy Laboratory Director
for Science and Technology

Deutsches Elektronen-Synchrotron DESY
in der Helmholtz-Gemeinschaft

Notkestrasse 85, 22603 Hamburg, Germany.

Hamburg

Desmond P. Barber, Accelerator Division.

Prof. Richard Milner, Director,
The MIT-Bates Linear Accelerator Center,
P. O. Box 846,
Middleton, MA 01949,
U.S.A.

Re: Center for Accelerator Science and Technology (CAST) at MIT.

Dear Professor Milner,

I am writing to you to express my personal support for MIT's proposal to establish the Center for Accelerator Science and Technology (CAST) whereby undergraduate and postgraduate courses in accelerator physics would be offered and the accelerators at the MIT-Bates Linear Accelerator Center would provide facilities to evaluate new techniques and concepts, and hands-on experience for students.

I lead the effort here at DESY in Germany towards the attainment of high electron/positron ($e^{\pm}$) spin polarisation in the $e^{\pm}$ - proton collider HERA. HERA is the first and only storage ring to demonstrate longitudinal $e^{\pm}$ polarisation at high energy. We also have a strong interest in proton and deuteron polarisation at very high energy and have made seminal contributions to the understanding of spin dynamics for the former. An impression of our work can be found at my WWW page: http://www.desy.de/_mpybar.

Accelerator physics provides a perfect example of the amalgamation of applied physics, theoretical physics, applied mathematics, computational physics and creative engineering. It presents difficult problems which demand solutions using well established physical laws. It contrast to some branches of theoretical physics, theoretical accelerator physics leaves no room for "subverting the basic equations until they are solvable": accelerators are expensive and they must work.

Although the U.S. Particle Accelerator School and various European Accelerator Schools provide short concentrated general and specialist courses to undergraduates and others, there are few programmes for teaching at a more leisurely pace at universities. Students do not therefore have the opportunity to delve deeper under the guidance of long term mentors. Moreover, most universities have no accelerator facilities.

There are also problems with some aspects of the "culture". By this I mean that it is not uncommon to be confronted with papers by newly trained young people from which it is clear that they do not have a proper grasp of their material. Either their education was inadequate or they simply have not been taught to invest in rigour and a deeper understanding. The field of spin polarisation continues to provide examples of this. If this turns out to be a general trend, it will not auger well for the future of accelerator physics with the large and complex projects that are now under consideration.

There is therefore a clear need for a high quality programme of education in all aspects of accelerator physics at a major university. And of course, MIT with the MIT-Bates laboratory and with its ethos of combining high academic standards with hands-on applications is perfectly positioned to develop such a programme and take a leading role. It would be unfortunate if the opportunity were missed.

But such a programme also needs high quality students. However, while students are naturally attracted to high energy particle physics, some are unaware that they could use their talents more effectively in the underlying discipline that makes research in high energy particle physics possible, namely accelerator physics. Thus explicit steps should be taken by teachers to highlight the intellectual challenges of accelerator physics. Moreover, students should be sought among the mathematicians, the computer specialists and the engineers. Teachers, both in the Physics Department and in other departments should be made aware that accelerator physics can provide a multitude of examples to illustrate aspects of their courses. For example, the problem of maintaining a high energy proton beam in a storage ring provides a perfect example of the efficacy, or otherwise, of canonical perturbation theory in classical mechanics. The need for more economical means of acceleration leading to ever higher energies provides a "playground" for students interested in superconductivity and plasmas. The start-to-end simulation of all the beam and radiation-dynamical processes for a very high energy $e^{\pm}$ linac or for a state of the art free electron laser could occupy a whole band of students. The problem of formulating and then obtaining solutions for phase space densities in multidimensional stochastic systems, continues to frustrate the experts and introduces students to Monte-Carlo simulations and numerical solution of diffusion equations.

As already indicated, students at MIT would also have the advantage of access to the MIT-Bates laboratory where they would be faced with realistic problems and be able to gain practical experience. But the MIT-Bates laboratory has an essential role to play it its own right. In particular, scientists at the MIT-Bates laboratory have been the leading force in the proposal for eRHIC, namely the extension of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) so that collisions of high energy polarised protons with polarized $e^{\pm}$ could be studied.

The South Hall Ring (SHR) at Bates is a very well engineered device and a major "plus point" is that spin polarisation has been a central aspect of work at the MIT-Bates laboratory for many years. Thus the SHR would be particularly useful for addressing topics affecting the design the electron ring for the eRHIC project. For example unimpeded experiments in the SHR could be used to test the reliability of the computer programs for numerical simulations of particle and spin behaviour that are needed for eRHIC. Topics of particular interest are the maintenance of polarisation near to the "coupling resonances" that might be needed to match the electron beam size to the size of the proton beam, the maintenance of polarisation while accelerating, and resonant spin flip at the highest available energy where the effects of spin decoherence cannot be neglected. The SHR is also in a perfect and *unique* position to verify the existence of an exotic and non-trivial self polarisation mechanism known as 'kinetic polarisation". So far, there have KP been no unambiguous observations of kinetic polarisation but a demonstration of its existence would amount to inserting the key stone in the story of radiative polarisation. Kinetic polarisation is not only of interest to theorists. In particular, in rings with dipole spin rotators like HERA, kinetic polarisation, if it exists, can cause a significant limitation on the precision with which polarimeters can be calibrated. because the simple tau_p, tau_d formula neglects the KP.

In summary, the establishment of CAST at MIT would do a great service to the field. It would also be in the best traditions of MIT: it should not be forgotten that MIT had its own cyclotron on Vassar Street and was a partner with Harvard University in the Cambridge Electron Accelerator (CEA). Moreover, some of the earliest ideas on linear and circular acceleration came from Julian Schwinger while he was at the MIT Radiation Laboratory. For example, he proposed using microwave cavities for linear and circular acceleration and worked on the theory of particle motion in betatrons and on synchrotron radiation! The excellent performance of the SHR and the design work for eRHIC continue this tradition today.

Yours sincerely,

Desmond Barber

September 15 2004

David E. Moncton
Physics Department 13-2038
Massachusetts Institute of Technology
Cambridge, MA 02139-4307

Dear David:

I am writing this letter to voice my support for the proposal to create a Center for Accelerator Science and Technology at MIT. I am convinced that every area of US research in the physical and life sciences would benefit from the investment in accelerator science and technology represented by this Center.

I am sure you have noticed that, of the 28 priorities listed in the Department of Energy 20-Year Roadmap, 14-15 (depending on how you count an electron microscope) are accelerators or upgrades to facilities surrounding accelerators. To me, this demonstrates the fact that support of research in accelerator science and technology, and the education of experts in these disciplines, should be recognized as a key element in U.S. science policy with significance beyond any one facility.

As Director of the Linac Coherent Light Source Project at SLAC, I can afford only a few quick peeks at the far end of the 20-Year Roadmap. I am assembling a plan for collaboration with Lawrence Berkeley Laboratory on issues related to LCLS timing systems. As you know, John Corlett is already working on timing and low-level RF control in correspondence with MIT's Bill Graves and Franz Kaertner. These are issues of considerable importance to the LCLS Project, and I expect that LBNL and LCLS will benefit interaction with these co-authors of the CAST proposal.

I hope that the CAST proposal is successful.

Sincerely,

John Galayda

John N. Galayda
Director, Linac Coherent Light Source Project

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BERKELEY ACQUISITION TEAM
OFFICE OF THE VICE PRESIDENT –
LABORATORY MANAGEMENT

OFFICE OF THE PRESIDENT
1111 Franklin Street, 5th Floor
Oakland, California 94607-5200

September 27, 2004

Asst. Sec. Raymond Orbach,
Director, Office of Science,
United States Department of Energy
Washington, DC

Dear Dr. Orbach,

As Chairman of the Board of Governors of the United States Particle Accelerator School (USPAS), I write to bring to your attention an opportunity to increase the scope of education in accelerator science and technology in the United States. USPAS regularly conducts for-credit classes covering a wide range of topics twice per year at renowned universities throughout the US. USPAS offers a Masters Degree program in Accelerator Science through Indiana University. While such courses and classes, dating back from 1980, have offered effective theoretical and computational training to a cadre of accelerator scientists, equivalent experimental training is needed to complete the training package. While USPAS offers microwave and microelectronics lab classes on a regular basis, the experience of hands-on operation of an experimental accelerator facility has been extremely limited.

With the phase-out of the Nuclear Physics user program at Bates in FY2005, the Massachusetts Institute of Technology has proposed a substantial new initiative, the MIT Center for Accelerator Science and Technology (CAST). A central element of CAST is the use of the Bates Linear Accelerator complex as a unique 'hands-on' educational laboratory in the fundamental principles and practices of accelerator science and technology. A CAST based school made available through USPAS would be of great benefit in training young accelerator scientists. The Board has encouraged the USPAS Director and the Bates Director to work towards initiating such a collaborative effort in 2006.

The USPAS Board of Governors strongly resonates with DOE's concerns about training the next generation of accelerator scientists in the US. USPAS is dedicated to precisely this mission. We urge the Office of Science to expand its support of educational programs in accelerator science and technology and to give serious consideration to the opportunity offered by the use of the Bates facility.

Sincerely,

William Barletta
Chair, Board of Governors
United States Particle Accelerator School

SINCROTRONE TRIESTE
SOCIETÀ CONSORTILE PER AZIONI

November 15, 2004

Professor David E. Moncton
Director, M.I.T. Nuclear Reactor Laboratory
Massachusetts Institute of Technology
138 Albany Street
Bldg. NW 12-204
Cambridge, MA 02139
USA

Dear David,

We are writing to indicate our high regard for expertise represented by the M.I.T. collaboration over the wide variety of science and technology relevant to implementing and utilizing x-ray free-electron lasers. Your strong interest in our FERMI project and particularly the proposal to contribute U.S. funding for an instrument for inelastic scattering is extremely attractive to us. With the characteristics of the photon beam expected from FERMI, inelastic scattering will achieve performance levels and research impact far beyond today's third generation synchrotron sources. We want to express our commitment to move quickly to decide whether we can accommodate this instrument in our plans, and work cooperatively with you and the Italian and U.S. funding agencies to make this instrument a reality.

Sincerely

Alfonso Franciosi

Professor Alfonso Franciosi
Chief Executive Officer

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