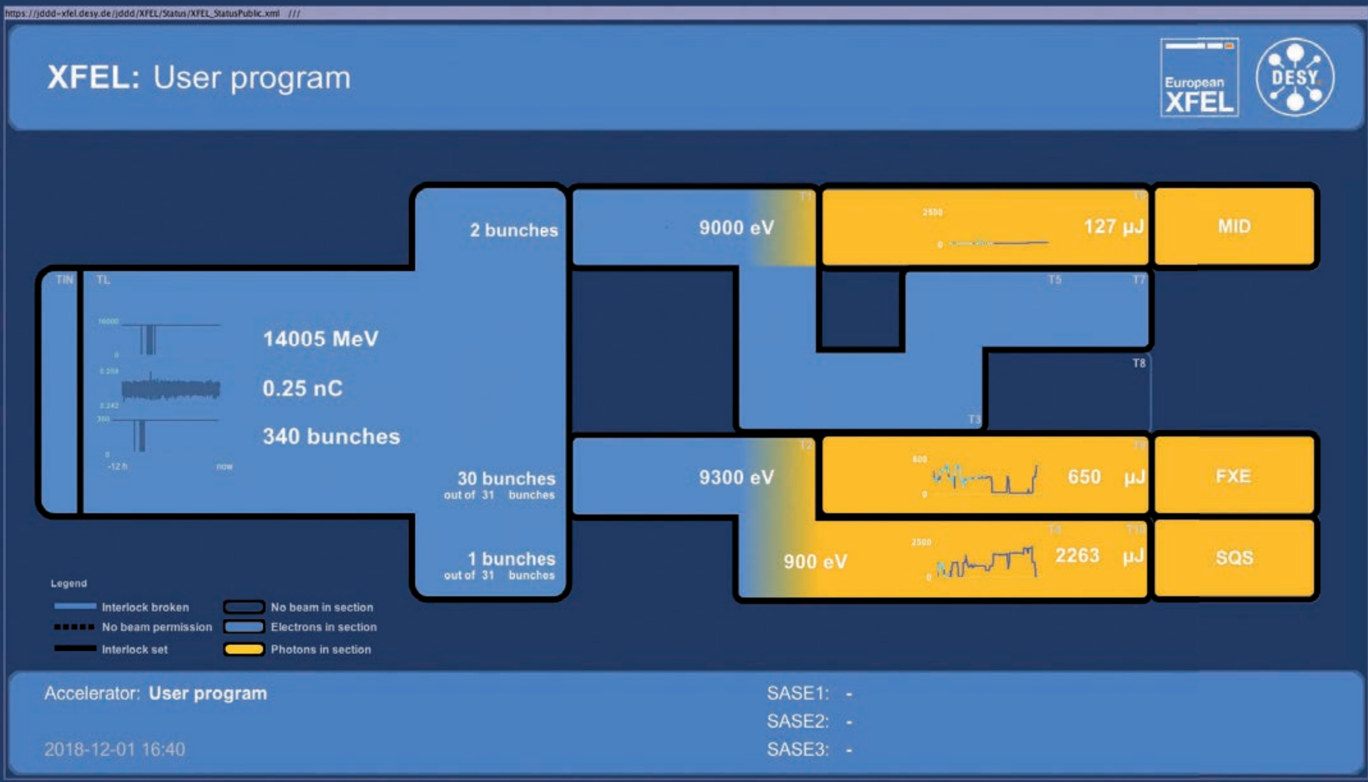

ACCELERATORS 2018.

Highlights and Annual Report

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

Cover

A world first: In December 2018, all three light sources of the European XFEL X-ray laser were operated in parallel.

ACCELERATORS 2018.

Highlights and Annual Report

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Chairman's foreword

Dear Colleagues and Friends of DESY,

Accelerators are among the most important and versatile tools used in science, benefitting a wide range of fields, from medicine and biology through physics and materials science to art history. Developing the accelerator technologies and facilities of the future is one of our core competencies, in which we have been excelling since the foundation of DESY almost 60 years ago. Accordingly, furthering accelerator development is one of the key elements of the DESY 2030 strategy.

In particular, we will upgrade our PETRA III synchrotron radiation source – one of the most brilliant storage-ring-based X-ray sources in the world – to an ultralow-emittance facility, enabling us to realise the ultimate 3D X-ray microscope. The work on the conceptual design report for PETRA IV is progressing well. Over the next two years, we will enter a preparatory test phase for the project. We must significantly strengthen the project group in terms of personnel and allocate funds for prototype development

Figure 1

Welcoming of Wim Leemans, the new director of DESY's Accelerator Division, who took over from Reinhard Brinkmann on 1 February 2019

in order to prepare a solid technical design report by the end of 2020. The preparatory phase 2019–2021 is a critical milestone and indispensable for a smooth construction phase later on. We are foreseeing considerable investments of our own in the project, but need additional financial support from the German Federal Ministry of Education and Research (BMBF).

The operation of the European XFEL X-ray laser is becoming a routine business. In the second half of the year, the superconducting linear accelerator that drives the X-ray laser was brought up to its nominal performance. The DESY operating team, led by Winfried Decking, mastered every physical and technical detail of the complex facility, to the benefit of the experiments on the European XFEL campus in Schenefeld. Only one year after the start of operation for users, the first successful results were published in *Nature*.

The future vision of DESY is to become the world-leading laboratory in the development of a completely new kind of high-gradient accelerators based on plasma acceleration. An important milestone was the successful application for funding of the ATHENA project, a new R&D platform on accelerator technology within the Helmholtz Association. In 2018, our focus was on the appointment of the successor to our director of the Accelerator Division, Reinhard Brinkmann. We are proud and pleased that the world's leading accelerator physicist in the field of plasma acceleration, Wim Leemans, could be convinced to leave the Lawrence Berkeley National Laboratory in the USA and join DESY. This is a great success, which will decisively strengthen the research centre and in particular the accelerator development in Hamburg.

I would like to express my gratitude to the BMBF, in particular to the chairman of our Foundation Council, Dr. Volkmar Dietz, for the great cooperation, which helped to make this challenging appointment a reality.

I thank the DESY staff and all our partners, national and international, who have contributed to the success of our research centre.

Helmut Dosch
Chairman of the DESY Board of Directors

Accelerators at DESY

Introduction

Dear Colleagues and Friends of DESY,

It is with great pleasure and honour that I report the progress that was made in 2018, under the leadership of my predecessor Reinhard Brinkmann, whom I succeeded as director of the Accelerator Division as of 1 February 2019.

For the European XFEL X-ray laser, DESY continued its responsibility for operating the 2.1 km long superconducting linear accelerator driving the free-electron laser (FEL). In 2017, the accelerator complex was swiftly commissioned and the first hard X-ray self-amplified spontaneous emission (SASE) FEL beams were provided to users at the SASE1 beamline. In 2018, the SASE1 beamline performance was further improved and user experiments commenced, operation of the second and third X-ray beamlines (SASE2 and SASE3) started, and the first operation of all three sources in parallel was demonstrated. This unique feature of simultaneous operation of three beamlines and full flexibility of pulse selection “à la carte” provides the users with tremendous options for tailoring the X-ray radiation pulses to the needs of their experiments. In July 2018, after installation and commissioning of the last two radio frequency (RF) stations of the accelerator and optimisation of all 24 stations, electrons were accelerated to the design energy of 17.5 GeV. While standard operation is typically with 300 bunches per RF pulse, i.e. 3000 bunches per second, the operating team increased the beam intensity to the full design value of 27 000 bunches per second in November. Bringing such a novel, complex facility up to its design performance in such a short time is truly an amazing achievement, and is a testimony to the expertise and dedication of all the groups of DESY’s Accelerator Division joining forces with the operating teams from European XFEL. We are looking forward to exciting new science results in the coming years!

At FLASH, the soft X-ray FEL at DESY where much of the technology underpinning the European XFEL was first developed and tested, user experiments with two undulator beamlines (FLASH1 and FLASH2) operating in parallel where successfully run. A third beamline (FLASHForward) was set up for electron-beam-driven plasma acceleration experiments. As part of the FLASH improvement programme, a new FLASH2 pump–probe laser as well as a new S-band RF cavity and new pick-ups for arrival time measurements were installed in order to push the intra-train arrival time stability below 5 fs. An online single-shot measurement of the SASE spectrum along the bunch train is now available, and single-spike lasing has become a standard technique used by many experiments. Exploration of novel lasing schemes continued, with tests of a scheme to generate two colours in one shot, the successful use of the harmonic lasing self-seeding scheme (HLSS) in an in-house user experiment and high-gain harmonic generation (HGHG) seeding established at the sFLASH seeding experiment.

At the PETRA III synchrotron radiation source, the first in-vacuum undulator for the Swedish materials science beamline was installed. After a dedicated commissioning phase, a good working point was found, enabling first experiments to be carried out on the beamline. For several weeks of the year, the weekly availability of PETRA III reached 100%. Due to three uncorrelated major faults on the DESY site in the first half of 2018, the average availability was 96.4%. Fortunately, 98.6% availability was achieved in the second half of 2018, and a similarly good figure is expected for 2019.

Much progress was made in the design studies for an upgrade of PETRA III towards an ultralow-emittance storage ring (PETRA IV). In particular, a reference lattice was developed that enables a natural emittance of 10 pm rad horizontally and 12 pm rad when taking collective effects into account. The results of the studies and the scientific and technical aspects of PETRA IV were published in September 2018 in the *Journal of Synchrotron Radiation*. The conceptual design report (CDR) will be completed and presented to the DESY Photon Science Committee (PSC) and Machine Advisory Committee (MAC) in autumn 2019.

The DESY 2030 strategy underlines the importance of increased R&D activities in accelerator development, as it is indispensable for securing the lab's future. Superconducting RF technology remains a key topic in which DESY already plays a world-leading role. Research into continuous-wave (CW) operation, including development of a CW RF electron source and optimisation of accelerator modules, will be of special significance for the enhancement of the European XFEL. In 2018, studies continued on amplitude and phase stability during CW operation of a standard European XFEL accelerator module.

DESY is also conducting research into novel accelerator concepts, especially plasma wakefield acceleration, where major progress was made in 2018. After generating first X-rays in an undulator in 2017, the laser-driven plasma acceleration experiment LUX, led by Universität Hamburg, was tuned to provide more stable and reliable electron beams and gain a deep understanding of the origins of fluctuations. The second major experimental infrastructure, FLASHForward, generated a wakefield with a field strength of more than 12 GV/m in a plasma using an electron beam from FLASH, confirming that FLASH beams can produce very strong accelerating fields in plasma with gradients more than two orders of magnitude larger than those in conventional accelerator cavities. At the PITZ photoinjector test facility at DESY in Zeuthen, the self-modulation of long particle bunches in a plasma was clearly demonstrated for the first time, as was the generation of world-record transformer ratios – the ratio between acceleration of the witness beam and deceleration of the driver beam – in a plasma. As part of the EU-funded EuPRAXIA design study with 42 institutes under DESY coordination, the possible design of a future European multi-GeV laser plasma accelerator was further elaborated. The ATHENA infrastructure, a new R&D platform focusing on accelerator technologies that draws on the resources of the six Helmholtz centres involved in accelerator physics, received funding. Construction of the SINBAD accelerator R&D infrastructure at DESY, which is embedded in ATHENA, and the integrated accelerator and application laboratory of the EU-funded AXSIS experiment for THz-driven acceleration made progress.

We also celebrated the achievements of Hans Weise and Andreas Maier, who received prestigious awards from the German Physical Society (Deutsche Physikalische Gesellschaft, DPG). Technology transfer got a major boost through the opening of the MicroTCA Technology lab, a Helmholtz Innovation Lab where our scientific expertise is applied to the needs of industry.

Building on all these successes, together with the outstanding DESY staff and its partners, we are looking forward to further enhancing the lab and its future as one of the most advanced and versatile accelerator centres in the world. We will continue to work on providing the highest-quality particle and photon beams to our users, invest into upgrades of our current infrastructure, develop key technologies to further enhance the capabilities of today's facilities, and secure a future for accelerator-based science through innovative concepts and bold initiatives. We will also focus on recruiting and retaining a diverse workforce to carry us into the next decades. It will be an exciting year 2019!

Wim Leemans
Director of the Accelerator Division

News and events

News and events

A busy year 2018

February

Second X-ray light source at European XFEL operational

In February, the second X-ray light source was taken into operation at the European XFEL X-ray laser – the largest and most powerful X-ray free-electron laser in the world. The SASE3 undulator, which is located a few hundred metres downstream of the first light source, SASE1, successfully produced X-ray laser flashes that will later be delivered to two experimental stations. As the main shareholder of European XFEL, DESY is responsible for the operation of the facility's superconducting linear accelerator, which provides the electrons generating the X-ray laser flashes in the undulators.

The undulators of the SASE3 beamline, the second X-ray light source to take up operation at the European XFEL X-ray laser

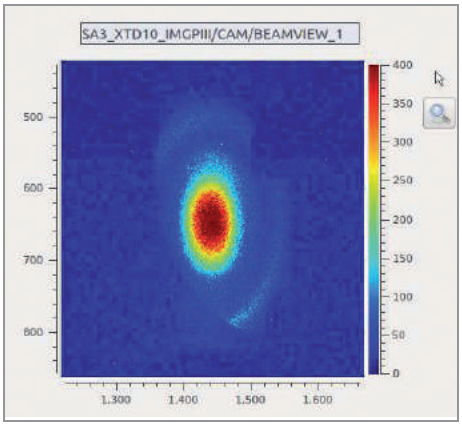
European XFEL Managing Director Robert Feidenhans'l said: "The construction and commissioning of the new light source are complex processes, for which we and our DESY colleagues have been preparing intensely for these last weeks and months. We are very happy that the commissioning of this second light source SASE3 has also run so smoothly, and that both sources, SASE1 and SASE3, produce light simultaneously. For this I would like to thank all those involved, in particular the accelerator team from DESY."

SASE3 will provide X-ray laser light for two experimental stations. The Small Quantum Systems (SQS) instrument is specialised for the study of fundamental processes such as how chemical bonds break in molecules, or what happens on the atomic level when materials absorb many photons at the same time. The Spectroscopy and Coherent Scattering (SCS) instrument will focus on the investigation of fast changes in material properties, such as within magnetic materials, materials that withstand extreme temperatures, superconducting materials and also biological samples.

SASE3 is one of currently three undulator systems at the European XFEL. SASE1 produced the first-ever X-ray laser light at the facility in May 2017. Then SASE3 followed on schedule, with SASE2 due to start up a few months later. SASE1 and SASE2 are 200 m long, very similar in their construction and generate extremely short-wavelength X-rays. SASE3, which is located behind SASE1, is, at 120 m, somewhat shorter and produces longer-wavelength X-rays.

At the first lasing, SASE3 generated X-ray flashes with a wavelength of 1.4 nm (900 eV), about 600 times shorter than that of visible light. The start-up of operation began with 20 pulses per second; this will later be increased to 27 000.

As a world first, the electrons from the linear accelerator are first used to generate X-ray laser light in SASE1 and then again in SASE3 a few hundred metres further downstream. The undulators thus produce X-ray beams for different experimental stations at the same time. This simultaneous operation of several light sources and their respective experimental stations is a unique characteristic of the European XFEL and of particular importance because of the high global demand for experiment time.



A spot on the monitor indicates the first laser light of SASE3.

March

DPG awards for Hans Weise and Andreas Meier

The DESY accelerator physicists Hans Weise and Andreas Maier were honoured for their outstanding achievements at the Spring Meeting of the German Physical Society (Deutsche Physikalische Gesellschaft, DPG). The DPG working group on accelerator physics awarded Andreas Maier the DPG Young Scientist Prize for Accelerator Physics and, together with Physikalischer Verein Frankfurt, Hans Weise the Horst Klein Research Prize for Outstanding Scientists in the Field of Accelerator Physics.

Hans Weise

Hans Weise, a leading scientist at DESY, coordinated the international consortium that built the world's longest superconducting linear accelerator for the European XFEL X-ray laser. He was awarded the Horst Klein Prize "in recognition of his outstanding scientific achievements in developing superconducting accelerator technologies for linear accelerators and free-electron lasers".

Before the construction of the European XFEL accelerator, Weise played a key role in setting up and operating the TESLA test accelerator at DESY, which gave rise to the free-electron laser FLASH, the prototype for the ten times larger European XFEL. After more than 20 years of continuous research and development work at DESY, the European XFEL was successfully taken into operation in September 2017. According to the prize committee, "Hans Weise's work sets worldwide standards for the development of superconducting linear accelerators for free-electron lasers, which have made possible numerous novel scientific experiments and are therefore very important for other areas of physics, too".

Andreas R. Maier

Andreas Maier is an accelerator physicist at Universität Hamburg. In the context of the LAOLA collaboration between DESY and the university, he is in charge of the LUX facility on the DESY site for research into plasma acceleration. The new technology enables significantly higher accelerating fields and can thus open up new applications.

Maier received the Young Scientist Prize "in recognition of his outstanding scientific achievements during his doctoral research and initial research phase, in developing laser-driven wakefield acceleration in plasmas," stated the committee. "His research deals with pioneering and innovative ideas for the further improvement of this accelerator technology and aims to realise for the first time a free-electron laser that uses laser-plasma accelerated electrons." In particular, the committee emphasised that Maier's setup displays a long-term stability and reliability never before achieved in such accelerators. "His activities lead us to expect further outstanding research results in the near future."

April

MicroTCA Technology Lab opens at DESY

The MicroTCA Technology Lab – an excellent example of technology transfer from fundamental research to broader practical applications – opened at DESY in April. Set up as a Helmholtz Innovation Lab, the facility is working on a versatile, precise and extremely reliable communications technology that can be used not only in particle accelerators but also in industrial automation settings, for example. “The MicroTCA Technology Lab at DESY shows how much science and industry can learn and profit from one another,” said DESY’s Chief Technology Officer Arik Willner at the opening.

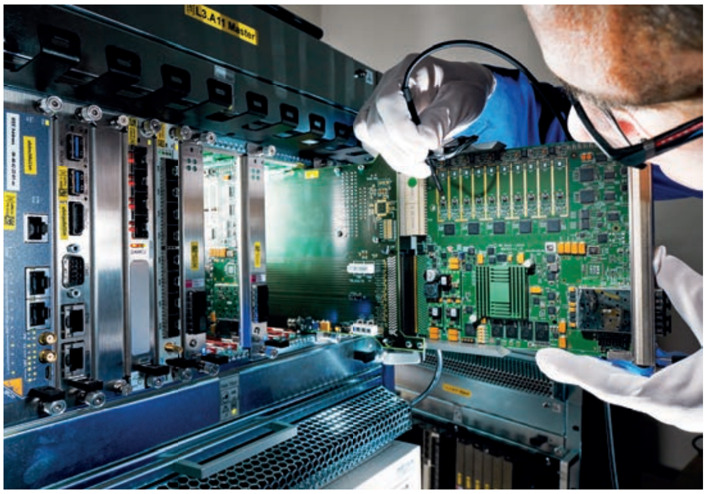
DESY Director Helmut Dosch (left) and Martin Kamprath from the Helmholtz Association at the opening of the MicroTCA Technology Lab

Top demands call for top precision, and this is made available by the electronics standard MicroTCA.4, which DESY has been instrumental in developing. MicroTCA.4 is based on the well-established telecommunications standard Micro Telecommunications Computing Architecture. It was adapted for the control of the European XFEL X-ray laser, among others. The high requirements related to the operation of such a large-scale research facility made an extension of the standard necessary with regard to safety, remote control and redundant operation. Today, the open electronics standard MicroTCA.4 not only ensures the safe operation of the superconducting particle accelerator of the European XFEL, it is also used by other research institutes and numerous industrial companies in Germany and abroad.

The MicroTCA Technology Lab was set up at DESY in order to give the business world access to the development of further applications of the technology. The MicroTCA team had already been working successfully for several years with a number of renowned companies in the electronics industry, among them CAENels, N.A.T., Schroff (PENTAIR), Power-bridge, Rohde & Schwarz, BEVATECH and elspec.

“The ongoing development of the deliberately open standard is now being driven forward both by industrial partners and by other research institutions, with everyone standing to benefit equally,” said Willner. “We are particularly pleased that so many industrial companies are now coming to our Technology Lab, which is one of seven Helmholtz Innovation Labs in Germany. Contract developments, carrying out measurements, offering advice on the design of new systems, training courses, test runs and quality checks as well as an open exchange of ideas at an annual workshop – all these services and elements of the Technology Lab can benefit industrial companies.”

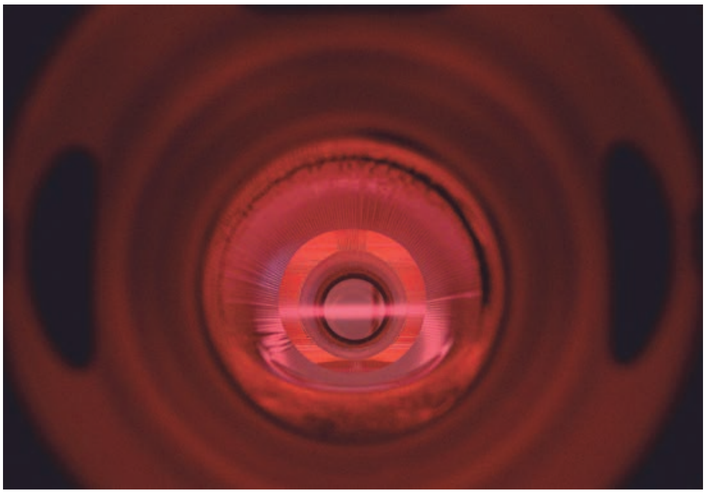
Helmholtz Innovation Labs are places where scientific expertise is brought together with the needs of industry and its customers. In the long term, these labs give rise to “enabling spaces” in which ideas are tried out. Their aim is to involve corporate partners in joint development projects on a long-term basis. This commercialisation concept as “think and do tanks” distinguishes Helmholtz Innovation Labs from pure research laboratories.



The electronics standard MicroTCA.4, which DESY has been instrumental in developing, allows for versatile, precise and extremely reliable applications not only in accelerator technology.

First experimental proof of self-modulation of particle bunches

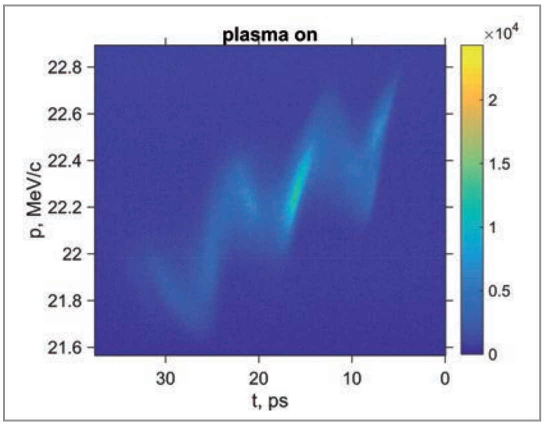
In a multinational effort, a team of researchers from DESY, the Lawrence Berkeley National Laboratory in the USA and other institutes demonstrated a remarkable form of self-organisation in a particle beam that can be of great use for developing a new generation of compact accelerators. Using the high-quality electron beam of DESY's PITZ photoinjector test facility in Zeuthen, the team was able to show that long electron bunches can chop themselves into a row of shorter bunches when flying through a plasma. In addition, the experiments revealed that the electron energy was modulated along each electron bunch. These results provide the experimental proof of a novel plasma acceleration concept pursued by the Advanced Wakefield Experiment (AWAKE) collaboration at the European particle physics centre CERN near Geneva, Switzerland.



View through the plasma cell along the flight path of the electron beam. The pink glow of the plasma is visible in the middle.

Particle accelerators at the energy frontier, such as the Large Hadron Collider (LHC) at CERN, are extremely costly to build and operate. Nevertheless, there is strong interest in increasing the available beam energies even further to refine the Standard Model of particle physics and discover new physics beyond it. Plasma wakefield accelerators could be the answer to this problem. Today's bulky structures could be replaced with millimetre-sized plasmas enabling several orders of magnitude stronger acceleration.

To accelerate an electron bunch in this way, the plasma electrons are separated from the plasma molecules, forming a plasma wakefield that creates an immense accelerating field. The separation of electrons and molecules in the plasma can be achieved through a high-energy bunch of charged particles. Using proton bunches is very attractive as sufficient energy can be stored in a proton beam to drive a plasma accelerator and generate electron bunches with energies in the LHC regime of teraelectronvolts in a single stage. The AWAKE experiment is hosted by CERN to investigate this promising scheme. However, proton bunches as they are generated in today's accelerators are much too long to be useful in plasma accelerators. Therefore, producing suitable proton bunches from a conventional accelerator is a key issue for the AWAKE setup.



Self-modulated electron bunch

This task can be accomplished by using the so-called self-modulation instability. In this case, a plasma wave is initiated at or near the front of the bunch, and the resulting electric fields lead to the desired re-organisation of the particle bunches in the beam. This self-modulation effect was described in theory and simulation, but so far only indirect indications were observed in experiments. This is where the unique capabilities of the PITZ facility came into play, said DESY group leader Frank Stephan: "The combination of a flexible photocathode laser, high electron beam quality and excellent diagnostics made it possible to demonstrate this effect unambiguously for the first time." The measurements showed that an incident long electron bunch split itself into three smaller bunches.

"The breakthrough results described in our publication can be scaled directly to the proton regime and thus open the path to validating the self-modulation scheme towards the next generation of high-energy physics accelerators at CERN," emphasised Matthias Groß from DESY, who led the international research team. "Our positive results show that the self-modulation can be practically used in experiments and that unwanted effects like beam hosing, which tend to destroy particle bunches, can be kept under control. This experimental data has been eagerly anticipated in the plasma wakefield accelerator community, especially by the AWAKE collaboration, for several years. The presented achievement is a further example where a plasma wakefield theory-based prediction is directly validated in experiment. And looking ahead, our special cross-shaped plasma cell that was used to obtain these results may also be of great interest to other groups working on beam-driven plasma wakefield acceleration."

May

Third X-ray light source at European XFEL operational

European XFEL started operation of its third X-ray light source in May, exactly a year to the day since the first X-ray light was generated in the European XFEL tunnels. The three light sources, which were successfully run in parallel for the first time on the anniversary of European XFEL's first light, will eventually provide X-ray flashes for at least six instruments. At any one time, three of these six instruments can simultaneously receive X-ray beam for experiments.

The monitor in the accelerator control room shows the three X-ray laser beams of the European XFEL in operation.

"The operation of the third light source, and the generation of light from all sources in parallel, is an important step towards our goal of achieving user operation on all six instruments," said European XFEL Managing Director Robert Feidenhans'l on the occasion. "I congratulate and thank all those involved in this significant accomplishment. It was a tremendous achievement to get all three light sources to generate light within one year."

To generate the X-ray flashes, electrons are first accelerated to near the speed of light in the superconducting particle accelerator of the facility before being steered through long undulators. The alternating magnetic fields of the magnets in the undulators force the electrons on a slalom course, causing them to emit light at each turn. Over the length of the undulator, the generated light interacts back on the electron bunch, thereby producing particularly intense light that accumulates into intensive X-ray laser flashes in a process known as self-amplified spontaneous emission (SASE).

European XFEL has three SASE X-ray light sources. The first one, SASE1, taken into operation at the beginning of May 2017, provides X-ray light to the Single Particles, Clusters, and Biomolecules / Serial Femtosecond Crystallography (SPB/SFX) and Femtosecond X-Ray Experiments (FXE) instruments, the first experimental stations available to users and operational since September 2017. The second light source, SASE3, was taken into operation in February 2018 and will deliver light to the Small Quantum Systems (SQS) and Spectroscopy and Coherent Scattering (SCS) instruments. SASE1 and SASE3 can be run simultaneously – high-speed electrons first generate X-ray light in SASE1, before being used a second time to produce X-ray flashes of longer wavelengths in SASE3.

The third light source, SASE2, will provide X-ray beams for the Materials Imaging and Dynamics (MID) and High Energy Density Science (HED) instruments, scheduled to start user operation in 2019. The MID instrument will be used to, for example, understand how glass forms on an atomic level and investigate cells and viruses with a range of imaging techniques. The HED instrument will enable the investigation of matter under extreme conditions, such as that inside exoplanets, and studies of how solids react in strong magnetic fields.

DESY and European XFEL staff worked hard over the last year to ensure the timely start of operation of all three X-ray light sources and at the same time to continually improve the parameters of the X-ray beams and instruments. From the start of user operation in September 2017 until May 2018, the number of X-ray pulses available for experiments was increased from 300 to 3000 per second. At full capacity, the European XFEL will produce 27 000 pulses per second. Construction and commissioning of the remaining four instruments continued as well.

June

Helmholtz Association supports ATHENA

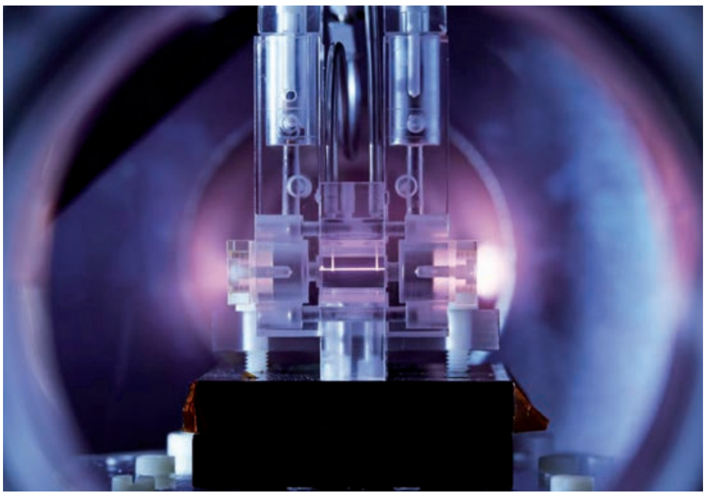
ATHENA (Accelerator Technology HElmholtz iNfrAstructure) is a new research and development platform focusing on accelerator technologies that draws on the resources of all the six research centres of the Helmholtz Association involved in accelerator physics (DESY, Forschungszentrum Jülich, HZB, HZDR, KIT and GSI with the Helmholtz Institute in Jena). In June, the Helmholtz Association decided to fund ATHENA as a strategic development project with almost 30 million euros. “This decision demonstrates the Helmholtz Association’s strong commitment to developing and supplying ground-breaking new accelerator technologies for solving the future challenges faced by society,” said Helmut Dosch, chairman of DESY’s Board of Directors and spokesperson for the Helmholtz Association’s research division “Matter”.

Together, the six Helmhotz centres aim to set up two German flagship projects in accelerator research based on innovative plasma-based particle accelerators and ultramodern laser technology: an electron accelerator at DESY in Hamburg and a hadron accelerator at HZDR in Dresden. At both facilities, different fields of application are to be developed, ranging from a compact free-electron laser through novel medical uses to new applications in nuclear and particle physics. As soon as they have reached the necessary level of maturity to be put to practical use in a particular area, new compact devices could be built for use in other Helmholtz centres as well as in universities and hospitals.

“The funding of the ATHENA project, which is coordinated by DESY, is an important milestone in the Accelerator Research and Development (ARD) programme, which was set up by the Helmholtz Association in 2011,” said Reinhard Brinkmann, one of the initiators of ARD and director of DESY’s Accelerator Division. “Channelling the competencies of the various Helmholtz accelerator centres promises to lead to ground-breaking developments and new applications for ultracompact particle accelerators.”

Ralph Aßmann, project coordinator of ATHENA and leading scientist at DESY, and Ulrich Schramm, head of laser particle acceleration at HZDR, agree that “the study of new types of plasma accelerators takes place in the context of strong international competition from the USA and Asia. ATHENA is consolidating the traditional leading role of Germany’s accelerator research and supporting Germany’s international competitiveness as a place for doing science.”

The work on ATHENA is closely embedded in the wider context of European research through the EU-funded design study EuPRAXIA with its 40 partner institutes, which is also coordinated by DESY. The top German research project ATHENA has thus had a clear European perspective and orientation right from the start.

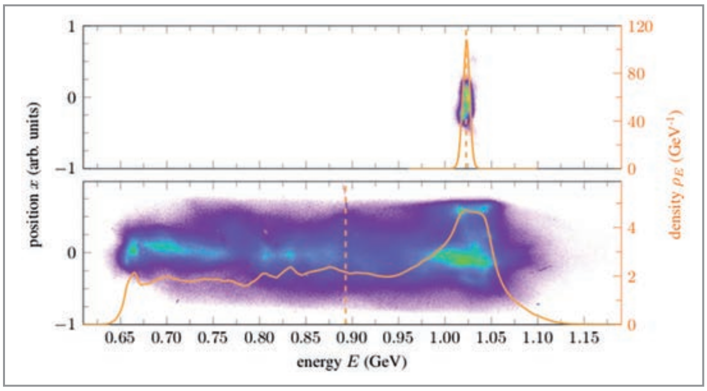


Plasma cells only a few centimetres long can accelerate particles to high energies.

June

FLASHForward generates strong wakefield in plasma

The plasma wakefield accelerator project FLASHForward at DESY reached an important milestone in June, when the team generated a wakefield with a field strength of more than 12 GV/m in a plasma using an electron beam from DESY's FLASH accelerator. The experimental demonstration confirmed that it is possible to use the FLASH beams to produce very strong accelerating fields in a plasma with field strengths exceeding those in conventional metallic accelerator cavities by more than two orders of magnitude. The next goal of the team is to accelerate particles in the wakefield generated by the beam.



The upper panel shows the energy spectrum of the FLASH electron beam without plasma interaction, the lower panel after interaction in the plasma cell.

"We were all really happy that it worked out on the very first day," said project leader Jens Osterhoff from DESY. "We managed to adjust the electron beam faster than expected and saw a clear signature of a wakefield in the three-centimetre plasma cell." The plasma – an ionised gas generated by a high-voltage discharge – had a lifetime of 10 µs.

In FLASHForward, an electron beam from the FLASH superconducting linear accelerator is steered into a cell filled with a plasma, in which it produces a charge density wave that will later be used to accelerate a second particle beam. A plasma can sustain electric field strengths a thousand times higher than those in conventional particle accelerators, making the acceleration very efficient and the accelerators very compact. In various projects around the world, scientists are testing whether the concept works as predicted.

This was the first time in Europe, and the second time ever, that an electron beam with an energy of more than 1 GeV generated a wakefield. The other success was achieved by the FACET experiment at the SLAC National Accelerator Laboratory in the USA.

July

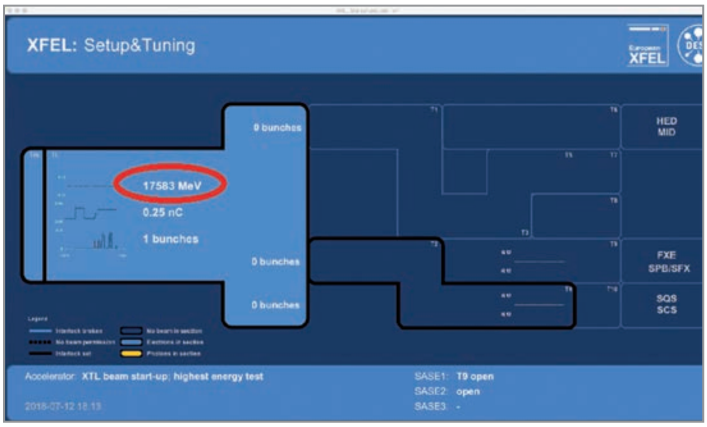
European XFEL accelerator reaches design energy of 17.5 GeV

In July, the accelerator driving the European XFEL brought electrons to the design energy of 17.5 GeV for the first time – an energy higher than that at any other X-ray free-electron laser in the world so far. Since the initial commissioning of the world's longest superconducting linear accelerator to 14.9 GeV in 2017, the energy had been gradually ramped up. The operators from the DESY Accelerator Division then powered up the last part of the 96-module accelerator and managed to accelerate electrons beyond the previous benchmark.

"This is a tremendous success for the superconducting TESLA accelerator technology, which has been pioneered by DESY and its international partners over the last three decades," said Winfried Decking, head of XFEL accelerator operation at DESY. DESY has led the international consortium of 16 accelerator institutes and universities that constructed the European XFEL accelerator and is responsible for its operation.

The accelerator of an X-ray free-electron laser such as the European XFEL provides the high-energy electrons that generate the intense, ultrashort laser pulses in the undulators. Initial user experiments at the European XFEL were performed with light generated from electrons of up to 14 GeV. In the future, the accelerator will be operated at energies ranging between 8 and 17.5 GeV, depending on experiment requirements. The increased energy range of the accelerator will enable the European XFEL to also generate a wider spectrum of X-ray laser flashes, giving users more flexibility in their methods and the possibility to attempt techniques not before possible at free-electron lasers.

The superconducting TESLA accelerator technology also enables another unique feature of the European XFEL: It allows for acceleration of up to 27 000 electron bunches per second, producing 27 000 X-ray laser flashes per second compared to the up to 120 flashes per second at X-ray lasers based on conventional accelerator technology.

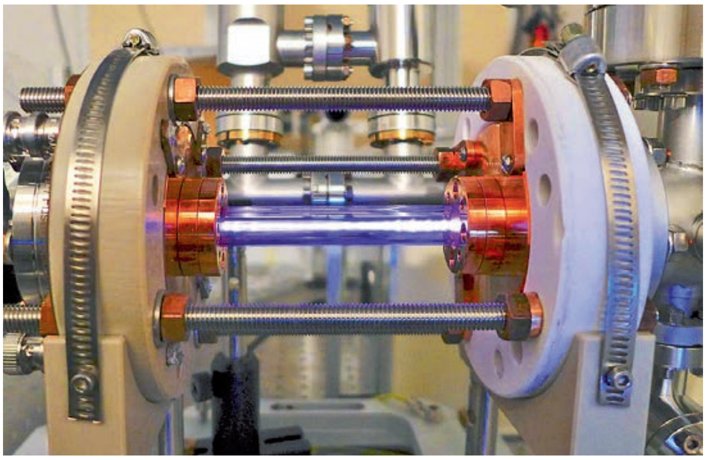


Screenshot of the European XFEL accelerator control display showing the electron energy at 17.5 GeV, or 17 583 MeV (DESY)

August

Low-draft electron bunches drive high plasma wakes

Scientists at DESY achieved a milestone towards the use of novel, plasma-based particle accelerators. As part of the LAOLA collaboration between DESY and Universität Hamburg, DESY physicist Frank Stephan and his group used the electron beam of DESY's PITZ photoinjector test facility in Zeuthen to accelerate electrons in a plasma wake with a world-record ratio between acceleration of the witness beam and deceleration of the driver beam. This "transformer ratio" defines the energy gain that can be achieved in such a plasma accelerator.



The plasma cell used for the experiments at PITZ. The glass tube is ten centimetres long, with about seven centimetres visible here.

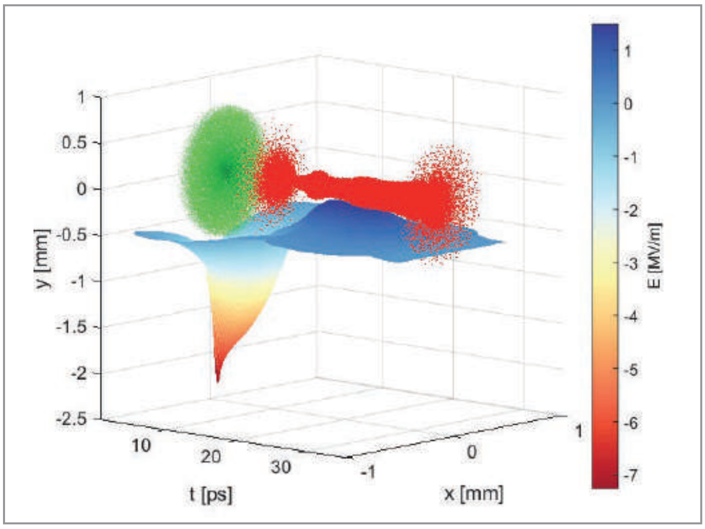
Plasma-based particle acceleration exploits the possibility to achieve accelerating field strengths in a plasma exceeding those of conventional accelerators by three orders of magnitude. In plasma wakefield acceleration, a pair of two electron bunches are shot into a plasma, where the first, high-energy driver bunch generates a plasma wake. The second, witness bunch, which trails the first one with a delay of about 5 ps, is accelerated in the plasma wake like a surfer riding the wake of a boat.

The electrons that drive the plasma wake are decelerated in the process and act as the energy source for the acceleration. Figuratively, a high transformer ration – the ratio between acceleration and deceleration – corresponds to a boat that slides lightly through the water but creates a high wake at its stern. For the electron beams used in plasma wakefield experiments so far, the transformer ratio was limited to 2. The experiments at PITZ aimed at breaking this limit, which was made possible by the specially formed electron bunches delivered by PITZ. Using the flexible photocathode laser of the facility, the researchers were able to investigate for the first time plasma acceleration driven by asymmetric, triangularly shaped driver bunches. Thanks to this crucial improvement, they achieved a transformer ratio of 4.6 – thus significantly exceeding the ratios in previous experiments.

"Application of our technique could reduce the length of a future plasma accelerator by more than half," said Gregor Loisch, the lead author of the study. "Now that we know that such high transformer ratios are generally possible, we will refine our methods to achieve this at higher accelerating fields."

Especially the high achievable accelerating field strength makes plasma acceleration one of the most promising candidates for novel particle accelerators. Increasing the field strength allows for shrinking the acceleration length at constant acceleration energy, which would significantly reduce the costs for building and operating such a facility. The studies performed at PITZ could also help to decrease the energy of the required conventional pre-accelerator that generates the driver beam, thereby contributing to a further reduction of the construction and operation costs.

Today, only a few facilities in the world are capable of producing the flexible electron beams needed for this scheme. Besides its bunch-shaping capabilities, DESY's research accelerator PITZ offers various diagnostics for accurately measuring the electron beams and the possibility to provide sufficient beam time for such experiments in accelerator reseach. In further studies, in addition to increasing the so far relatively moderate accelerating field strength of 3.6 MV/m, the team will focus on improving the bunch-shaping possibilities.



The simulation of the beam plasma interaction shows the driver beam electrons (red), the witness beam electrons (green) and the accelerating plasma wakefield (coloured surface).

September

DESY hosts meeting of collaboration for accelerator on a chip

The collaboration of the Accelerator on a Chip International Program (ACHIP) met at DESY in September. The ACHIP team is working on the design and construction of highly innovative electron accelerators manufactured using nanotechnology methods – the same methods used for the production of microchips. The goal is to realise ultracompact accelerators driven by compact lasers that reach accelerating fields of gigavolts per metre, about 10 to 100 times more than conventional accelerators today. The ACHIP accelerator will ultimately fit into a shoebox and achieve a beam energy of 1 MeV. This could open up various scientific applications. In the long term, the technology could enable nanoaccelerators that are compact enough, for example, to be carried on space ships as useful tools or used inside the human body to destroy tumour cells.

Participants of the ACHIP collaboration meeting at DESY

At their meeting, 52 experts from all over the world discussed their progress and the next development steps. Besides DESY and Universität Hamburg, the collaboration consists of the Technical University of Darmstadt and the University of Erlangen-Nuremberg in Germany, Stanford University, SLAC National Accelerator Laboratory, the University of California Los Angeles (UCLA) and Purdue University in the USA, the Paul Scherrer Institute (PSI) and the Swiss Federal Institute of Technology in Lausanne (EPFL) in Switzerland and the Tech-X Corporation.

The project is supported by the Gordon and Betty Moore Foundation (USA). Gordon Moore is known for Moore's Law, which describes the exponential growth of the number of transistors in computer chips over time. He is also one of the founders of the computer chip company Intel.

October

CHILFEL – Cooperation with China on FEL science and technology

Scientists from Germany and China joined forces in free-electron laser (FEL) research: DESY and the Shanghai Institute of Applied Physics (SINAP) decided to pool their resources in the CAS–Helmholtz International Laboratory for FEL Science and Technology (CHILFEL), which also includes European XFEL and ShanghaiTech University. The Helmholtz Association funds this research collaboration as a Helmholtz International Lab with 300 000 euros per year for a period of six years. Together with the funds provided by DESY and European XFEL and the Chinese contribution of 600 000 euros per year, CHILFEL will be able to draw on total annual funds of 1.2 million euros.

China is well on the way to becoming a scientific superpower and has chalked up some significant achievements in FEL research in recent years. The leading Chinese players are institutions run by the Chinese Academy of Sciences (CAS), such as SINAP, as well as the newly founded ShanghaiTech University. In addition to a modern synchrotron radiation source, an FEL for soft X-rays also went into operation in Shanghai some years ago. Approval was also given for the ambitious SHINE project, an FEL for short-wavelength X-ray beams on the Shanghai research campus, based on superconducting accelerator technology.

CHILFEL will be launched on 1 January 2019 and serve as the basis for common research projects and jointly used infrastructure. It will also offer a wide range of mobility and exchange programmes for promoting young scientists. The partnership is receiving substantial support from China's research policy-makers as a further building block on the way to institutionalised collaboration with European XFEL.

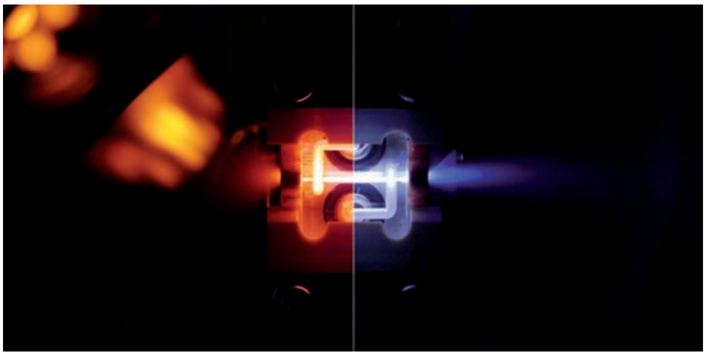
The scientific programme of CHILFEL will initially be based on five pillars: scientific applications at FELs using soft and hard X-rays; development of FEL methods and instruments; FEL seeding and synchronisation; detector development; and development of superconducting cavities.

Participants of the German–Chinese workshop that took place at DESY in June

November

Strong focus on plasma lenses

A team of researchers from Oslo, Oxford, DESY and CERN overcame a major obstacle that so far prevented the technical deployment of plasma lenses. Their simple solution paves the way for using such lenses both in plasma accelerators and in conventional accelerators for photon science or particle physics.



Montage of two photographs taken during operation of the plasma lens: with helium (red) and with argon (blue)

The high field strengths that arise in plasmas can be used not only to accelerate electrically charged particles, but also to focus particle beams. In an active plasma lens, a strong discharge current is passed through the plasma along the path of the particles, creating a magnetic field vortex. In contrast to classical quadrupole magnets, this field can simultaneously focus both the height and the width of the particle beam. Along with their high focusing power due to the strong magnetic fields, this feature makes such lenses extremely attractive for use in particle accelerators.

However, a key problem prevented such a deployment of plasma lenses so far: An optical flaw in the lens destroyed the focus of the particle beam as it passed through the plasma cell. This aberration occurs because zones of different temperatures form within the plasma when it is heated by the discharge current and at the same time cooled by the outer walls of the plasma cell. As a result, the strength of the focusing field varies in different regions of the plasma, leading to the aberration. This occurred so quickly after igniting the plasma that it was not possible to use the plasma lens to focus a particle bunch before the lens developed the flaw.

The solution that the group of scientists found overcomes this problem, which blocked the concept of plasma lenses for decades: They switched the type of gas used to create the plasma from the usual helium, a light gas, to the heavier argon. This slows down the conduction of heat within the gas for long enough to allow a bunch of particles to be focused immediately after the plasma has formed and the discharge current has been switched on, without the quality of the beam suffering as a result. The plasma lens only begins to distort the beam after the bunch has passed through it.

“An argon plasma is much more complex than a helium plasma,” said DESY physicist Jens Osterhoff, whose group came up with the idea of exploiting the lower heat conductivity and built the plasma lens to test the idea, “but this is not as crucial to its function as a magnetic lens as it is in particle acceleration. Here, the property of being a poor conductor of heat is the key factor.” The results of the experiments mark an important step towards making active plasma lenses a standard component of future accelerators.

December

Wim Leemans new director of DESY’s Accelerator Division

As of 1 February 2019, Wim Leemans will become the new director of DESY’s Accelerator Division. Leemans, who was born in Belgium, was previously in charge of the Accelerator Technology and Applied Physics Division at the Lawrence Berkeley National Laboratory (USA) and the head of the Berkeley Lab Laser Accelerator (BELLA) Center.

Wim Leemans

Wim Leemans moved to California early on in his career. He wrote his doctoral thesis in electrical engineering at the University of California Los Angeles, after which he worked at Berkeley Lab for 27 years. During this time, he established the laser accelerator programme and led it to international acclaim. His team at the BELLA Center was the first to accelerate electrons to energies on the order of 1 GeV in a laser plasma accelerator and later set the record of 4.2 GeV for the energy gained during a single stage of acceleration. The team also first demonstrated that multistage acceleration is possible using plasma accelerators. Leemans has received numerous prizes for his research.

Leemans succeeds Reinhard Brinkmann, who has been director of DESY’s Accelerator Division since July 2007 and is returning at his own request to DESY accelerator research as a leading scientist. He will focus in particular on the future project PETRA IV and on novel accelerator concepts.

Accelerator operation and construction

PETRA III

User operation and commissioning of an in-vacuum undulator

In March 2018, DESY's PETRA III synchrotron radiation source took up operation again after a shutdown period that had started on 23 December 2017 and that was mainly used to install an in-vacuum undulator for the beamline P21b and a short undulator for the side beamline P21a in the Ada Yonath hall. Regular user operation resumed on 26 March 2018 after a short commissioning period of only five weeks. A six-week-long summer shutdown was used to install a new absorber for the damping wigglers in the northern straight section and front-end components for the beamline P61 in the Peter P. Ewald hall. Furthermore, the in-vacuum undulator for the beamline P21b was replaced with an improved version. In 2018, a total of 4882 h of synchrotron radiation beam time was delivered to the users. During the next winter shutdown, an additional in-vacuum undulator will be installed for the beamline P07 in the Max von Laue hall.

User operation

During the two-month-long winter shutdown 2017/18, which ended in February 2018, an in-vacuum undulator and a short undulator for the side beamline including front-end components were installed for the beamline P21 in the Ada Yonath experimental hall (Fig. 1). Preparative work was done for the installation of components for the beamline P61 in the Peter P. Ewald hall, which will make use of the radiation from the damping wigglers in the northern straight section. Thanks to essential efforts of all the technical groups, all activities could be finished on schedule. Regular user operation resumed on 26 March 2018 after a short commissioning period of only five weeks.

A six-week-long summer shutdown was used to install a new absorber for the synchrotron radiation from the wigglers in the northern straight section as well as front-end components for the beamline P61. A photon extraction vacuum chamber is integrated in the new absorber, which opens up the possibility to use the wiggler radiation for the beamline P61. Furthermore, the in-vacuum undulator for the beamline P21b was replaced with an improved version. After a start-up period, regular user operation resumed on 3 September and continued until 21 December. The necessary maintenance was done in four dedicated service periods distributed over the year and additionally during the summer shutdown period. On Wednesdays, user operation was interrupted by weekly regular maintenance, machine development activities and test runs for about 24 h.

The distribution of the different machine states in 2017 is shown in Fig. 2. In total, about 4200 h were scheduled for the user run. In addition, 855 h of test run time were made available to users.

Figure 1

In 2018, an in-vacuum undulator was installed for the beamline P21 in the Ada Yonath experimental hall.

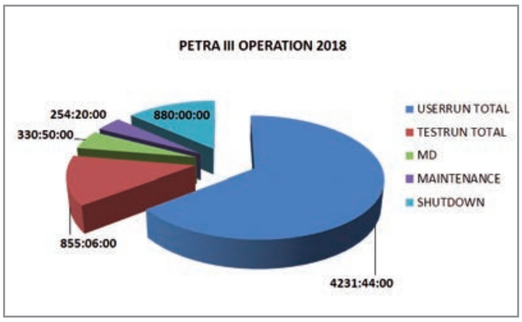


Figure 2

Distribution of the different machine states during the run period from 26 March to 21 December 2018

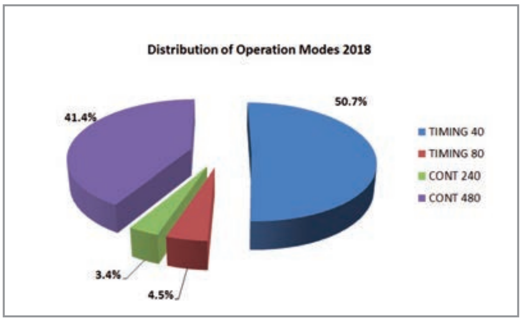


Figure 3

Distribution of the different operation modes in 2018

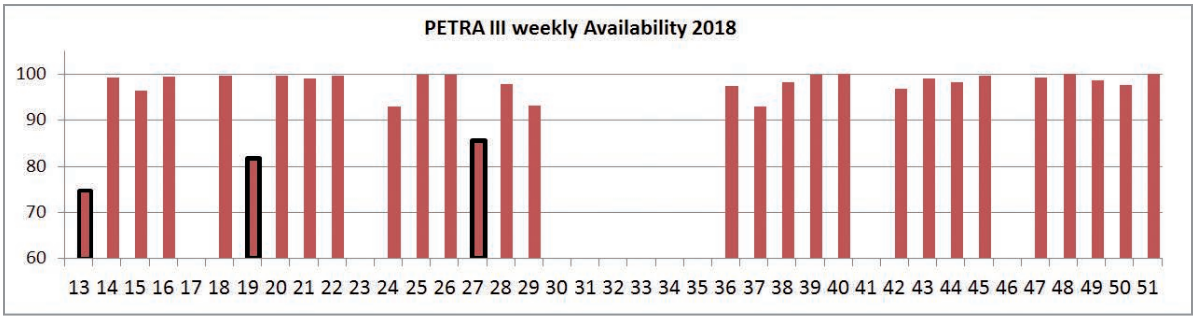


Figure 4
Weekly availability in 2018. The three major faults occurred in the weeks 13, 19 and 27 (marked with a black outline around the bars).

During user runs, the storage ring was operated in four distinct modes characterised by their bunch spacing. In the "continuous mode", 100 mA were filled in 480 or 240 evenly distributed bunches, corresponding to 16 ns or 32 ns bunch spacing. The "timing mode" allows users to perform time-resolved experiments and is thus characterised by a considerably larger bunch spacing of 192 ns, corresponding to 40 evenly distributed bunches. The detailed distribution of the operation modes in 2018 is shown in Fig. 3. For beam operation in the timing mode, very good bunch purity is required. Unwanted satellite bunches were routinely cleared using the multibunch feedback system. Furthermore, PETRA III was operated for a short period in 2018 in a timing mode with 80 evenly distributed bunches in order to provide timing-mode-like conditions to users during a period for which continuous-mode beam operation had originally been scheduled.

High reliability is one of the key requirements for a synchrotron radiation facility. The key performance indicators are availability and mean time between failures (MTBF). In 2018, the weekly availability reached 100% for several weeks of the year. At the end of the user run, the average availability turned out to be 96.37%, which is 1.73% lower than the availability of the previous year. This is due to three major faults during operation in 2018: a vacuum leak at a diagnostics device (current monitor) in week 13, a failure of a 10 kV switch in a power station on the DESY site in week 19 and a faulty synthesiser in the timing system in week 27.

The weekly availably of PETRA III during the user run period is shown in Fig. 4. A black outline around the bars marks the weeks in which the major faults occurred. This availability statics is based on a metrics that is in agreement with internationally used metrics and does not include "warm-up" time after each fault.

Although the availably of PETRA III in 2018 was lower than in 2017, the total number of faults could be further reduced. The average MTBF at the end of the year was 50 h, which is also better than in the previous year. The number of faults normalised to 1000 h of user operation has decreased during the last four years (Fig. 5), indicating that the process to improve the technical reliability of PETRA III has made some progress in the wake of the availability review held in 2016.

Although an internal review process was implemented in 2018 to monitor the availability of PETRA III and guarantee a good root cause analysis of all faults during the user run, it was not possible to maintain the availability level of 2017 (Fig. 6).

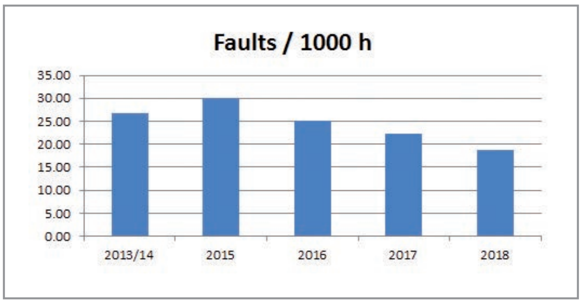


Figure 5
Long-time development of the number of faults per 1000 h of user operation

Figure 6
Long-time development of the availability of PETRA III

Plans for the next operation period

During the winter shutdown 2018/19, it is foreseen to replace a two-metre-long insertion device with a four-metre long in-vacuum undulator for the beamline P07 in the Max von Laue hall. Additional front-end components will be installed in the Peter P. Ewald hall to prepare the possibilities for installing additional insertion devices. In the west to northwest arc region, ten vacuum chambers in the dipole magnets will be replaced with NEG-coated vacuum chambers to investigate the activation process of the NEG material related to synchrotron radiation. A better understanding of this process will be beneficial for the technical design of the upgrade of PETRA III to the ultralow-emittance synchrotron light source PETRA IV. This will only be possible with a major effort from all the technical groups involved.

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FLASH

Consolidating operation for users in both beamlines

DESY's FLASH free-electron laser (FEL) facility features two undulator beamlines, FLASH1 and FLASH2, operated in parallel as a tandem. In 2018, FLASH1 ran for a total of 7103 h, FLASH2 for 6831 h. A new pump–probe laser for FLASH2 was put into operation in September with a successful pilot experiment. FLASH2 shutdowns were extended – whenever possible – to allow installation work for the FLASHForward experiment. A new S-band radio frequency (RF) cavity named BACCA and new pick-ups for arrival time measurements were installed in the FLASH linear accelerator. Together, they will push the intra-train arrival time stability below 5 fs. The optical synchronisation system was completely renewed. New polarisation-preserving fibres of the upgraded fibre links will significantly improve the synchronisation stability of external lasers.

Operation

For three years now, FLASH has been operated with two undulator beamlines in parallel as a tandem delivering self-amplified spontaneous emission (SASE) radiation to the Albert Einstein and Kai Siegbahn experimental halls. A third electron beamline, FLASH3, is being set up for the beam-driven plasma acceleration experiment FLASHForward.

In 2018, FLASH1 was operated for a total of 7103 h, FLASH2 for 6831 h. As usual, the year was divided into two user periods, numbered 11 and 12. FLASH1 delivered 4189 h to users, FLASH2 2269 h (Fig. 1). FLASH provided beam time for 38 experiments; many wavelengths in the extreme-ultra-violet (XUV) and soft X-ray range from 52 nm down to 4.4 nm were realised. The demand for pump–probe experiments using optical lasers increased from 58% in period 11 to 71% in period 12. As a highlight, the new FLASH2 pump–probe laser was commissioned in September 2018 with a successful pilot experiment. Thanks to the continued extension of the beamlines, more and more beam time could be scheduled for user experiments at FLASH2, a plus of 50% compared to 2017.

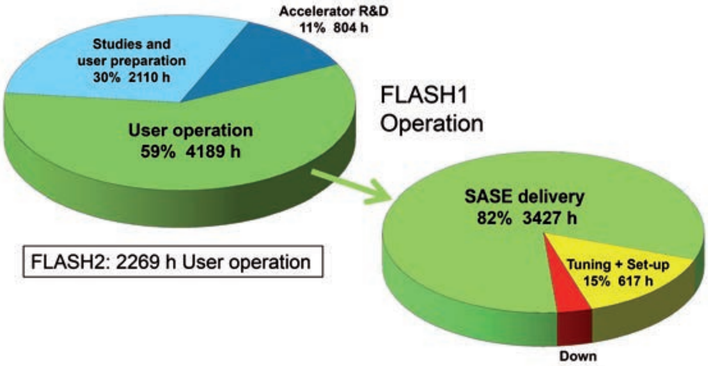

Figure 1

FLASH1 operation statistics in 2018. FLASH1 was operated for a total of 7103 h, FLASH2 for 6831 h.

The winter shutdown in January 2018 was extended to install the new S-band RF cavity BACCA (Fig. 2). In the three-week summer shutdown, new pick-ups for the beam arrival time monitors were installed in the linear accelerator section. The new pick-ups will provide an improved resolution also for small bunch charges. Together with BACCA, in a fast intra-train feedback, they will enable the arrival time stability of the electron beam to be further improved, from the present 20 fs level to below 5 fs. The ultimate goal is to reach 1 fs. First tests of BACCA showed a low latency of 0.7 µs and an actuator bandwidth of 500 kHz as expected from the design and laboratory tests. We expect full commissioning of the system in early 2019.

As part of the effort to improve the arrival time stability, the whole optical synchronisation system was renewed. This is important not only to improve the beam-related measurements but also to achieve a better synchronisation with external lasers. The synchronisation signals are now distributed through new polarisation-maintaining optical fibres, pushing the jitter of signal transmission from 3 fs to 0.5 fs. At first, a few links mandatory for FLASH operation were installed and commissioned. The number of possible links will increase from 8 to 24. Further optical links will be installed step by step. The full new system is expected to be available in 2020.

Together with the optical synchronisation system, the master RF oscillator system providing reference RF signals was reworked and brought into operation with improved performance in stability and reliability. The timing system was

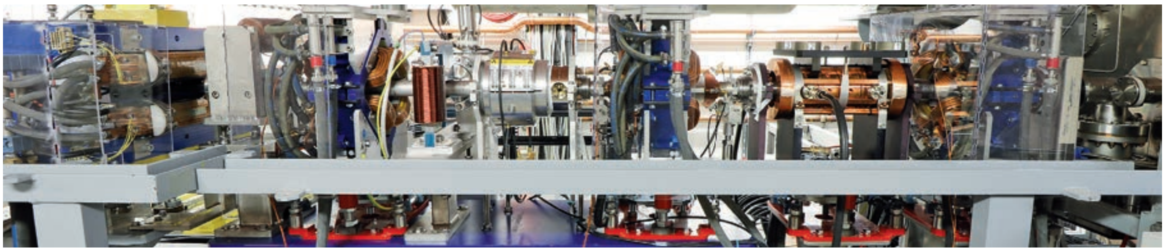

Figure 2

BACCA, the new S-band RF cavity for fast arrival time feedback (copper structure on the right) installed upstream of the first bunch compressor at FLASH

moved from the old VME-based system to the new MTCA-based system. Together with the new machine protection system, it provides more flexibility in the tricky operation of FLASH with three beamlines.

RF gun and cathode

After four years of continuous operation in the FLASH RF gun, cathode 73.3 was finally exchanged for the fresh cathode 105.2. This is by far the longest time such a cathode has been operated continuously anywhere in the world. Both cathodes were produced at LASA in Milano, Italy, in 2013 and stored under permanent ultrahigh vacuum since then. The cathode is a thin film of caesium telluride (Cs_2Te) on a molybdenum plug with a diameter of 5 mm and a thickness of 60 nm. Cs_2Te is very sensitive to oxygen-containing gases in the vacuum. The cathode is situated at the backplane of the RF gun and is responsible for the emission of electron bunches triggered by UV laser pulses. An important figure of merit is the efficiency to extract electrons. This quantum efficiency was remarkably stable over the years (Fig. 3). Degradation was observed a few times when vacuum leaks occurred in the close-by beamline or at the RF window of the RF gun.

Indeed, the RF window developed a vacuum leak in summer 2018 and had to be exchanged. The exchange is usually done within a day, but RF conditioning includes a ramp-up time of at least two months to the full RF pulse length of > 600 µs. The RF gun itself has been in operation since August 2013. The current window is the fourth to be operated with this gun at FLASH. The lifetime of the last two windows was two years.

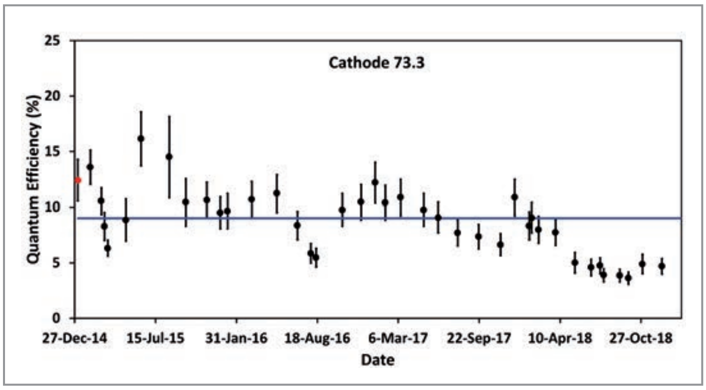

Figure 3

Quantum efficiency (QE) history of cathode 73.3 in operation at FLASH since February 2015. The red data point indicates the QE measured after production (26 June 2013). The blue line indicates the overall average QE of 9%.

Other highlights

An online single-shot measurement of the SASE wavelength spectrum along the bunch train is now available thanks to a novel line detector named KALYPSO, which was installed in the FLASH1 photon beamline. The detector allows us to tune the shape of the spectrum over the bunch train and to apply a slow feedback acting on the electron beam energy. This significantly improves the performance of experiments requiring stable long pulse trains, in particular those at the plane-grating monochromator beamline.

The experiments using the variable-gap feature of the FLASH2 undulators to test novel lasing schemes continued. A scheme to generate two colours in one shot was recently tested. Furthermore, the harmonic lasing self-seeding scheme (HLSS) was successfully employed in an in-house user experiment. Both SASE and HLSS were used keeping the same pulse energy, pulse duration and source position, but improving the coherence time with HLSS.

Single-spike lasing is now a standard technique used by many experiments. As an example, a train of 400 single-spike pulses at 4.5 nm was employed in an experiment tracing charge carrier dynamics in glycine.

Installation and commissioning of the FLASHForward beamline at FLASH3 are ongoing. Two major components, the beam scraper to generate witness and driver bunches and the central plasma chamber, were installed and brought into operation. In a first attempt, a field strength of 10 GV/m was observed in the plasma, and external bunches could be accelerated with 0.5 GV/m. A dechirping experiment was successfully conducted, fully compensating an incoming chirp of 60.5 MeV/mm by adjusting the arrival time of the electron bunch with respect to the plasma discharge time. The applied dechirping strength of 1.8 GeV/mm/m is two orders of magnitude greater than that of competing state-of-the-art techniques.

The seeding experiment sFLASH continued its experimental programme. High-gain harmonic generation (HGHG) seeding was established. The next step will be a proof-of-principle experiment showing that the echo-enabled harmonic generation (EEHG) seeding scheme is also a possible option. EEHG would allow us to reach shorter wavelengths. To fully explore EEHG later on, a new chicane with a larger longitudinal dispersion is being designed.

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PITZ

Accelerator R&D and applications

In 2018, besides publishing two highly ranked papers on beam-driven plasma acceleration, the PITZ group operating the photoinjector test facility at DESY in Zeuthen made continuous progress in accelerator R&D, both for further improving the photoinjectors of the free-electron laser (FEL) facilities in operation in Hamburg and working towards a future continuous-wave (CW) upgrade of the European XFEL X-ray free-electron laser. Moreover, in 2018, funding was awarded for a conceptual design study on a THz self-amplified spontaneous emission (SASE) FEL for pump–probe experiments at the European XFEL and for corresponding proof-of-principle experiments at PITZ.

Preparations for THz SASE FEL experiments

PITZ has been proposed as a suitable facility for developing an accelerator-based tuneable high-power THz source for pump–probe experiments at the European XFEL [1]. A THz SASE FEL based on a PITZ-like photoinjector is considered a main option for such a source. In order to perform corresponding proof-of-principle experiments, the existing PITZ linear accelerator has to be extended by an undulator. Start-to-end simulations with the PITZ photoinjector and 4 nC electron bunches promise mJ-level THz pulses for the full bunch repetition rate, i.e. pulse energies four orders of magnitude higher than what can be expected from state-of-the-art laser-based THz sources. This fact makes the proposed source an attractive tool for THz/infrared-driven dynamics studies, which is why European XFEL has decided to fund a corresponding conceptual design study.

For the proof-of-principle THz SASE FEL experiments, LCLS-I undulators available on loan from SLAC will be installed downstream of the PITZ beamline. To this end, the PITZ tunnel will be extended into an existing annex. In 2018, the conversion of this room into an accelerator tunnel started. Based on radiation shielding simulations, one of the tunnel concrete walls was enforced, and a 16 t movable entrance door was installed in early 2019 (Fig. 1).

The main challenges of the ongoing design study are the generation and transport of high-charge electron bunches. A part of the experimental programme at PITZ in 2018 was devoted to the characterisation of such bunches. Preliminary optimisation for 4.7 nC beams yielded a measured projected normalised RMS emittance of ~5.5 mm mrad. This beam was transported through the whole PITZ beamline and focused at the last screen station (18.3 m from the photocathode) to a spot size of only ~0.6 mm RMS.

Figure 1

PITZ accelerator tunnel annex with improved radiation shielding (left) and new movable concrete door (weight 16 t).

Results of plasma experiments

In previous years, the PITZ group successfully conducted experiments in the field of beam-driven plasma acceleration. The results were published in 2018 in the highly ranked journal *Physical Review Letters*, with the observation of self-modulation instability appearing in April [2]. Time-resolved measurements had shown this effect unambiguously for the first time (Fig. 2a). The demonstration of highly efficient plasma acceleration with a high transformer ratio was published in August [3]. This had been the first time that this important technique was demonstrated in a plasma medium (Fig. 2b). Both experiments took advantage of the very flexible pulse-shaping capabilities of the photocathode laser system installed at PITZ, which was provided by the Max Born Institute (MBI) in Berlin.

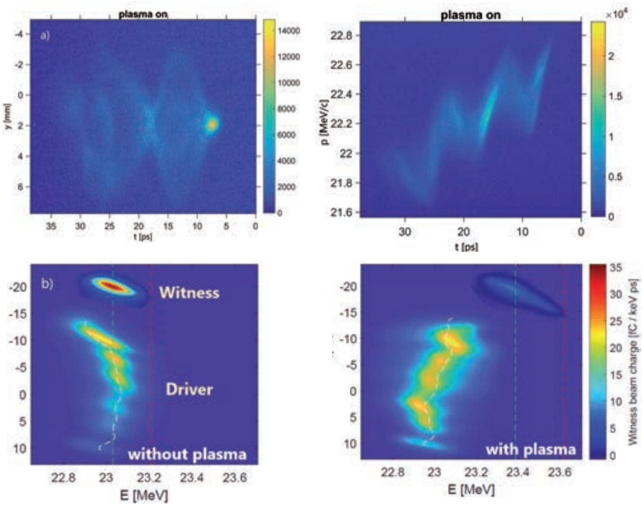

Figure 2

Main experimental results of the published plasma experiments: (a) Electron bunch modulated by self-modulation and resulting longitudinal phase space.
(b) Efficiently accelerated electron witness bunch.

Upgrade of laser pulse length characterisation

The optical sampling system (OSS), an important diagnostic tool within the MBI photocathode laser system, was upgraded and put back into operation by MBI. The OSS is an optical cross-correlator that uses the pulse trains produced by the laser to scan the ultraviolet laser pulses with a continuously shifted comb of short laser pulses. The upgraded system uses a new short-pulse oscillator. A test measurement of a temporally modulated laser pulse is shown as an oscilloscope trace in Fig. 3. A corresponding measurement of the temporal electron profile generated with such a laser distribution is overlaid in red.

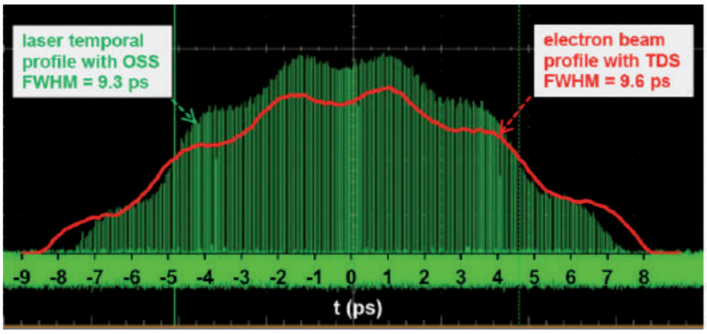

Figure 3

Test measurement of the MBI laser pulse shape conducted with the newly upgraded OSS (green shape), compared with the resulting electron bunch current profile at low charge (~5 pC) measured with a transverse deflecting structure (TDS, red line)

Online slice emittance measurements

Slice emittance measurements for space-charge-dominated beams can be conducted by combining the slit scan method with a transverse deflecting structure. Online slice emittance measurements were successfully performed in autumn 2018. One example with 50 µm step width is shown in Fig. 4.

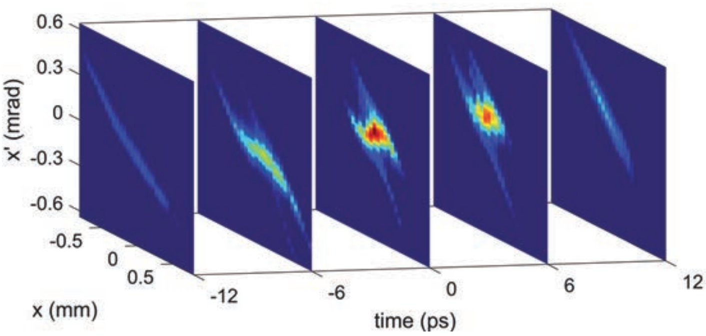

Figure 4

Time-resolved transverse phase space of the electron beam at PITZ. The gun was operated close to one of the European XFEL working points.

Next-generation normal-conducting CW gun design

For a possible future CW upgrade of the European XFEL, high-brightness CW electron sources are being developed at DESY. In collaboration with LBNL, a design study for a next-generation normal-conducting CW gun was started in 2018, aiming at a higher cathode gradient and gun voltage for further improving the beam quality. A first gun physics design was finished (Fig. 5), including iterations of radio frequency, beam dynamics and thermal load simulations. The gun features a 30 MV/m cathode gradient and 860 kV gun voltage. Beam dynamics simulations show a ~30% improvement in beam transverse emittance and a ~50% improvement in beam longitudinal emittance.

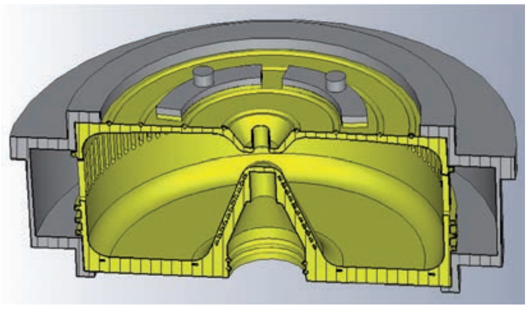

Figure 5

Preliminary model of an upgraded normal-conducting CW gun

Space-charge-dominated photoemission studies

Advanced modelling and precise simulation of transient space-charge-dominated photoemission are a prime requisite for understanding the slice emittance formation of high-brightness beams for various cathode laser pulse shapes. Detailed understanding of the photoemission mechanism is also of special interest for the development of photocathodes sensitive at green wavelengths, which can be essential for a future CW upgrade of the European XFEL. A three-dimensional improved modelling approach has been developed, allowing more accurate beam dynamics studies for further improving photoinjector performance (Fig. 6).

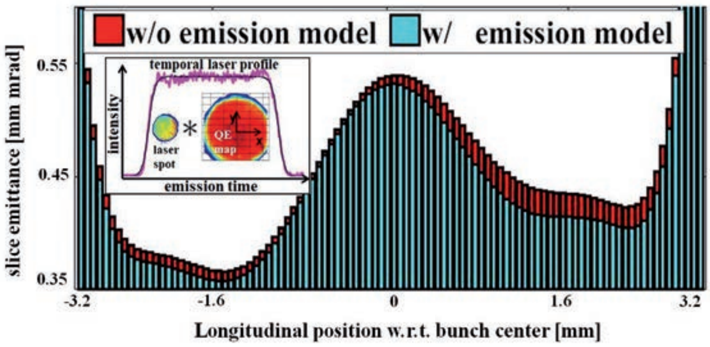

Figure 6

Simulated slice emittance at $z = 5.277$ m from the cathode with and without improved emission model for 500 pC. The inset shows the electron bunch generation process at the photocathode according to spatial and temporal distributions of the cathode drive laser and the quantum efficiency of the cathode.

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REGAE

Ready for plasma and more...

In preparation for new experiments, DESY's Relativistic Electron Gun for Atomic Exploration (REGAE) underwent a major beamline modification in 2018. In addition to the newly installed target chamber, a sophisticated laser transport beamline was set up. Moreover, additional diagnostics including a transverse deflecting cavity for bunch length measurements and a second modulator plus klystron for improved tuning performance of the bunching cavity were installed. Besides the already planned experiments on the linearisation of the longitudinal phase space and on plasma acceleration, further experiments to employ THz radiation for beam manipulation are in preparation.

In 2018, REGAE underwent a major beamline upgrade. The whole beamline between the photoinjector front end and the diffraction detector at the end of the facility was removed and replaced by new components. With this setup in place, the accelerator is equipped for machine studies towards the generation of sub-femtosecond electron pulses as well as for the exploration of new accelerating techniques, such as laser wakefield acceleration (LWFA) using plasmas or energy gain based on THz radiation. In addition, the new setup provides enhanced capabilities for diffraction experiments, the purpose the facility has been built for.

The facility is now equipped with a bigger and very versatile target chamber that allows for several new experiments (Fig. 1). Firstly, it is accompanied by a load-lock system, which enables a quick exchange of diffraction targets and other items, required for diagnostics or different experimental purposes. Secondly, an elaborated gas distribution system was installed at the target chamber, which can feed several plasma targets required for the LWFA studies. Together with the piezo-based high-precision alignment system for the plasma targets, these elements for the planned merging of conventional and plasma acceleration techniques are driven in and out of the beamline from below the REGAE target chamber.

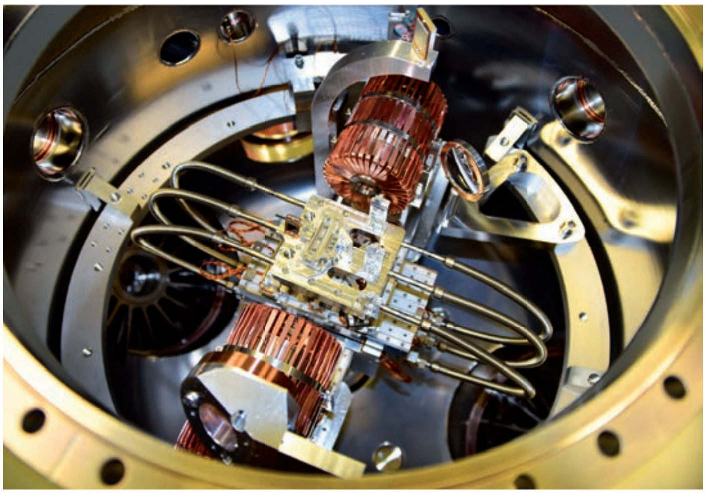

Figure 1

View into the new REGAE target chamber. Among other components, the image shows the plasma targets on the piezo-based positioning devices and the hoses for the gas supply.

As part of this upgrade, the REGAE beamline was also connected to the high-power laser system ANGUS, which is located in building 22, right next to the accelerator tunnel. First ANGUS laser pulses were successfully sent into the REGAE electron beamline through these vacuum pipes and the six turning mirror chambers. The plan is to precisely align the laser beam path with the electron trajectory and establish a timing stability between the electron and photon pulses on the femtosecond level. Given that the laser enters the gas-filled plasma targets with a certain head start of a few 100 fs, the successive electrons will be captured and rapidly accelerated by the plasma wakefield created by the ANGUS pulses. The resulting energy gain can then be determined using the electron spectrometer, which was shifted downstream of the target chamber during the upgrade. With these planned laser pump / electron probe measurements, the structure of the plasma wakefields can be determined and the effects on the electron bunch quality can be studied.

Another important upgrade was the inclusion of a transverse deflecting cavity (TDS), specifically tailored to the properties of REGAE. It is located right behind the target chamber. With

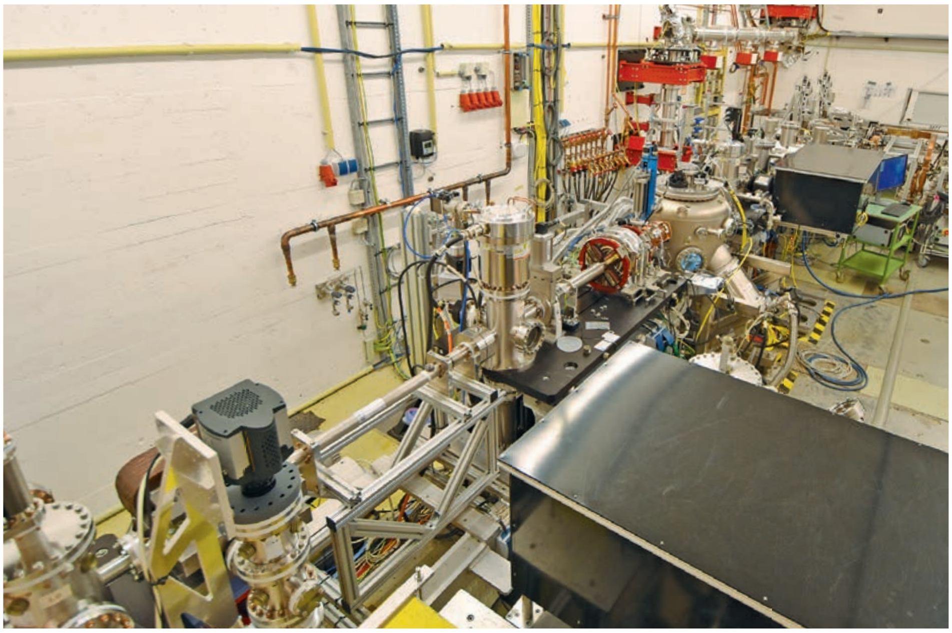

Figure 2

View along the upgraded REGAE beamline. The new target chamber is located to the right of the centre of the picture. The laser transport beamline of the ANGUS laser system can be seen in the background, along the wall.

this device, it is now possible to accurately determine the length of the REGAE electron bunches, which can be as short as 10 fs – according to simulations. In addition, thanks to the shift of the electron spectrometer downstream of the target chamber, it is now possible to disperse the bunches that have passed the TDS. Using this configuration even allows for mapping the longitudinal phase space and thus yields (much) more information about the electron bunch structure.

In general, the longitudinal phase space will show a certain curvature based on the curved nature of the accelerating fields and on kinematic effects of the drifting particles resulting from the correlated energy spread in the bunch. This effect limits the achievable bunch length at REGAE to about 10 fs. Reducing or even eliminating this curvature would hence yield the opportunity to further compress the electron pulses. Typically, higher-harmonic structures are used for such a linearisation. However, since this is not an option at REGAE, due to space constraints among other things, a novel method has been developed in the last years, which can now finally be put to the test: By carefully balancing the kinematic drift contribution against the impact of the radio frequency (RF) curvature, it is possible to obtain configurations so that the actions of these effects exactly cancel at the position of the longitudinal focus, thus removing the curvature. The result would be a linearisation of the longitudinal phase space without higher-harmonic fields – and, according to simulations, bunch lengths below the 1 fs barrier.

Since the facility was equipped with a second modulator and klystron in the context of the upgrade, the required cavity parameters can now be tuned very precisely. Hence, the new linearisation procedure can be tested experimentally in the near future – at least conceptually, because the resolution of the TDS will not suffice to determine such short bunch lengths and structures. Therefore, another diagnostics is under development, which can be immediately incorporated into the facility thanks to the newly gained versatility. Making use of THz fields instead of RF-based cavities, it is possible to achieve higher streaking gradients, which result in increased resolution of a THz transverse deflector compared to the conventional TDS mentioned above. In particular, a certain mode in simple dielectric capillaries yields a transverse force that is independent of the transverse position in the structure – a fact that marks an ideal streaking field. The capillary – typically a tube with a length of a few centimetres and a diameter of less than a millimetre – can be mounted on the piezo positioning system while the THz field is generated by rectification of a laser pulse. THz-based streaking techniques are more than suited to be applied to linearised REGAE bunches, since they not only allow the measurement of shorter bunches, but can also be benchmarked against the already installed TDS.

To close the circle, the other diagnostics added to the facility can also be used to benchmark the THz performance and concepts: In a similar way to plasma acceleration, THz fields too can be used to accelerate electrons. Hence, to analyse this method, it is also possible to simply switch to a THz target and make use of all the components now included in the REGAE beamline to characterise the performance and behaviour of THz-based energy gain.

We are looking forward to an exciting year 2019.

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European XFEL accelerator

Demonstrating the design performance of the superconducting accelerator

In 2018, the European XFEL X-ray free-electron laser was operated for about 6800 h and delivered electron beam and photons for user experiments as well as for photon systems and accelerator development. While at the beginning of the year only the SASE1 undulator and the corresponding electron beam transport were operational, at the end of the year all three undulators provided FEL light for experiment commissioning and user operation. In addition, the linear accelerator reached its design performance by delivering a final energy of 17.5 GeV and accelerating 27 000 electron bunches per second. This progress was only possible thanks to the continued efforts of all the groups of DESY's Accelerator Division joining forces with the operating teams from European XFEL.

Operation in 2018

In 2018, the European XFEL accelerator was in operation for about 6800 h. Of this time, about 3800 h were devoted to self-amplified spontaneous amplification (SASE) delivery for photon systems development (750 h) and for partly parallel experiment commissioning (2000 h) and user programme at the undulators SASE1 and SASE3 (1500 h). Further commissioning and development of the accelerator were scheduled for 1750 h. Within this time, major milestones could be achieved:

- First lasing at SASE3 in February
- Commissioning of the 1000 m long SASE2 electron beamline in March
- First lasing at SASE2 in May
- Commissioning of the beam distribution system in May
- Reaching the accelerator design energy in July
- Commissioning of the fresh-bunch technique to enable parallel operation of SASE1 and SASE3 in October
- Acceleration of the full 2700 bunches per RF pulse in November

About 1300 h were required for access, set-up and tuning. This included the time needed for transitions between different operation states, preparation for experiment operation and urgent repair access in between scheduled maintenance.

Overall availability is determined systematically only during user operation. It amounted to 85% delivery during scheduled user time.

Reaching linear accelerator design performance

The European XFEL linear accelerator comprises 24 radio frequency (RF) stations, each powering four superconducting accelerator modules. Installed in the years 2012 to 2016, most of the RF stations were commissioned in 2017. Installation work and technical commissioning of the last two stations were finished in April 2018 during two scheduled maintenance periods. Commissioning with beam of the eight accelerator modules powered by these stations followed in parallel to standard beam operation. In addition, all other RF stations were systematically investigated, and factors limiting the accelerating voltage were identified and improved. Finally, electrons could be accelerated to the design energy of 17.5 GeV in July.

Usually, the third section of the main linear accelerator (L3) is operated with at least one RF station in reserve. This allows fast swapping of RF stations during operation. At 17.5 GeV, no reserve station is available, and operation at this energy is only possible at the expense of a somewhat reduced availability. During most of 2018, the nominal operation energy was 14 GeV. This is also a good compromise in terms of reaching high photon energies in SASE1 and SASE2 while at the same time allowing operation of SASE3 at rather long wavelengths.

One of the biggest advantages of superconducting technology is the possibility to accelerate many bunches within one RF pulse. The European XFEL design value of 27 000 electron bunches per second was achieved when 2700 bunches with a 4.5 MHz spacing were accelerated by a 600 µs flat-top RF pulse with a 10 Hz repetition rate in November. Achieving these numbers poses various challenges:

- The RF pulse has to be sufficiently long, leading to increased average power, an issue mainly for the normal-conducting photoinjector cavity.
- The RF flat-top has to be regulated over the complete pulse length with high precision also in the presence of beam loading.
- The 80 kW beam power electron beam has to be safely guided to the beam dump without losses and potential damage to surrounding equipment.

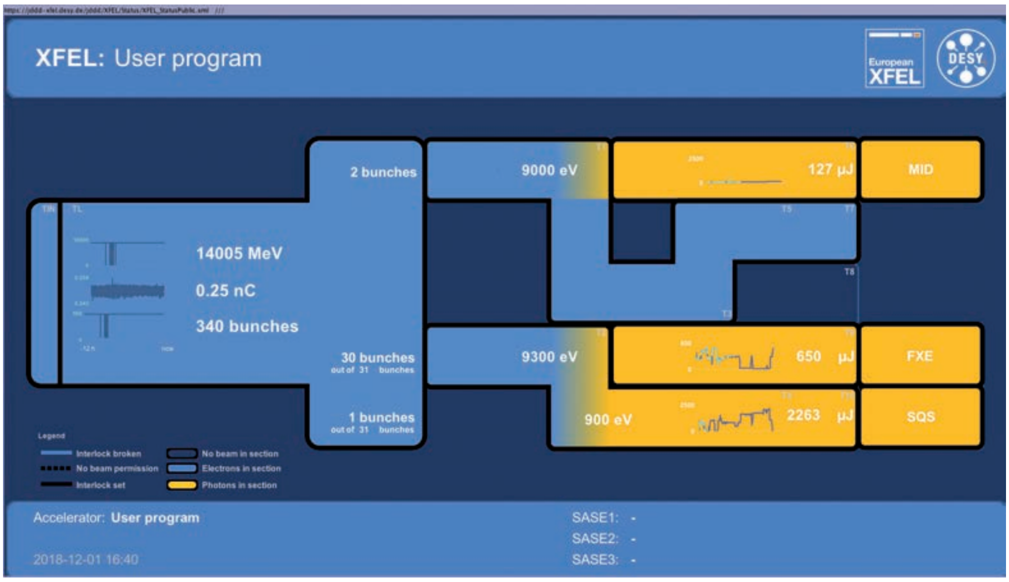

Figure 1

Screenshot of the public status panel at http://ttfinfo2.desy.de/doocs/status_PNGs/ from December 2018 showing the operation of all three SASE FELs of the European XFEL X-ray laser at the same time. The performance of the accelerator is summarised on the left (340 bunches per RF pulse with a charge of 250 pC accelerated to 14 GeV). The performance of the SASE undulators (photon energy and pulse energy) for SASE2, SASE1 and SASE3 (top to bottom) is shown on the right.

This was the first time that a bunch train of such length was accelerated in a long superconducting linear accelerator, and several of the predicted beam dynamics aspects could be observed. In the future, operation at high beam power will be further consolidated. While standard operation in 2018 has been with about 300 bunches per RF pulse, up to 600 bunches and photon pulses respectively are foreseen for user beam times in 2019.

Operating three SASE FELs in parallel

The SASE1 undulator and its photon beamline had been commissioned in 2017, and in 2018, pioneering experiments could be performed at the two SASE1 experimental stations. The operation of SASE1 was further consolidated, and photon pulse intensities of up to 2 mJ were achieved towards the end of the year. Typical photon energies ranged between 9 and 14 keV, and lasing could be demonstrated up to 19.3 keV. An average X-ray power of up to 8 W was reached during test runs with up to 5000 photon pulses per second. Nominal user operation is presently restricted to a beam power below 2.5 W.

First lasing in SASE3 was observed in February 2018 shortly after the winter shutdown. Due to the relaxed tolerances at long photon wavelength and high electron energies, tuning is comparably easy, and an X-ray power of up to 10 W was achieved. The high X-ray power can lead to damage to the beam shutters, and additional safety measures were implemented in the photon beamlines during the year. Both SASE3 experimental stations were able to host first users by the end of the year.

SASE3 is located behind SASE1 on the same electron beamline. The quality of an electron beam that lases in SASE1 suffers significantly, which affects the subsequent lasing in SASE3. Even if SASE3 still delivers sufficient intensity, the coupling of the SASE1 and SASE3 performance appears to not be acceptable for user operation. A way out is the "fresh-bunch" technique, in which betatron oscillations are excited for individual bunches. At betatron amplitudes of several 10 µm, lasing in SASE1 is hampered and thus a fresh bunch can lase in SASE3 with optimal performance. This technique was implemented on the fly by intentionally "misusing" one of the fast beam distribution kickers. A remaining challenge is the unavoidable spontaneous synchrotron radiation and eventual residual SASE background of kicked bunches that still have to be transported through all the undulators.

The last undulator, SASE2, was put into operation after a very swift commissioning of the 1000 m long electron beam transport from the switchyard to the beam dump. First lasing was observed at the beginning of May 2018, and only a day later, all three SASE FELs were operated in parallel by using the beam switchyard, which allows the bunches to be distributed into the different beamlines within the RF pulse.

In the course of the year, this scheme has been further developed, and today, users can actually change the number of photon pulses they are getting for their experiment themselves. This unique feature is widely used and allows the bunch train capability of the European XFEL to be fully explored.

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Highlights · New technology · Developments

Seeding R&D at sFLASH

Controlled FEL start-up for fully coherent photons

The sFLASH experiment has been operated at DESY's FLASH free-electron laser (FEL) facility since 2010 in a collaboration of DESY, Universität Hamburg and TU Dortmund University. It is dedicated to the investigation of externally seeded FELs, with an external, coherent light pulse controlling the start-up of the FEL amplification process. Currently, the experiment is operated in the high-gain harmonic generation seeding scheme, producing fully coherent FEL pulses at harmonics of the 267 nm seed radiation. THz streaking reveals the duration and chirp of the emitted light pulses, a first step towards tailored seeded FEL pulses.

External seeding of FELs

FELs generate photon pulses of unparalleled brilliance. The exponential amplification process in these devices is typically initiated by spontaneous radiation emitted at the entrance of the undulator. The statistical nature of this self-amplified spontaneous emission (SASE) mode of operation results in poor longitudinal coherence. In the extreme ultraviolet (XUV) and soft X-ray range, the start-up of the amplification process can be controlled using coherent light pulses from an external source.

The seeding experiment sFLASH was installed at the FLASH facility in 2010. Figure 1 shows the current schematic layout. External UV seed laser pulses are injected into the beamline, where they are used to manipulate the phase space distribution of the electron bunches arriving from the linear accelerator. FEL emission takes place in the 10 m long variable-gap radiator. After extraction of the generated photon pulses, the electron bunches can be analysed by means of a transverse deflecting structure (TDS) and a dipole spectrometer.

Currently, the sFLASH experiment is operated in the high-gain harmonic generation (HGHG) [1] seeding scheme. The electron bunches first interact with 267 nm laser pulses in a few-period undulator called the modulator. In the subsequent chicane, the sinusoidal energy modulation is converted into a periodic density modulation. The rich harmonic content of this periodic current modulation enables the controlled start-up of the FEL on a selected harmonic of the seed laser wavelength.

Probing the quality of plasma lenses

The pulse energy and spectrum of the seeded FEL pulses can be measured already in the accelerator tunnel. For more sophisticated diagnostic capabilities, the seeded FEL pulses

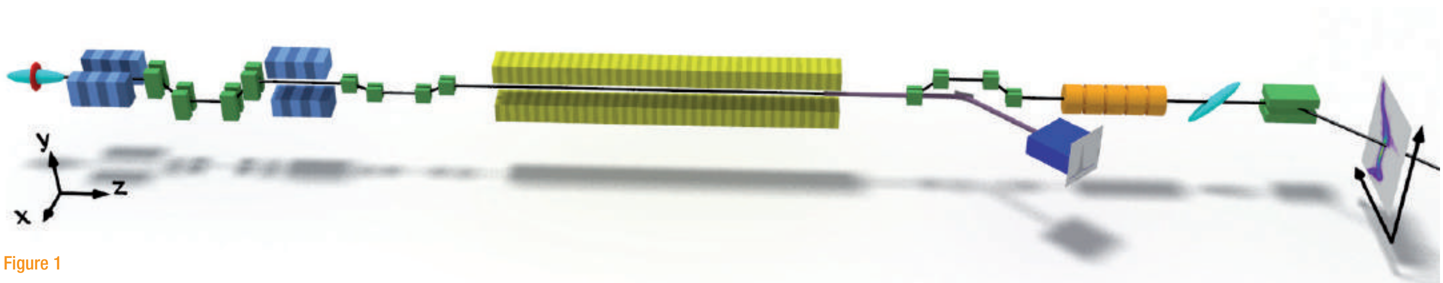

Figure 1

Illustration of the seeding experiment sFLASH. The electron bunches arriving from the accelerator and the seed laser pulses propagate from left to right through two five-period undulators (blue) and two magnetic chicanes (green dipole magnets). Here, the electron bunches are microstructured before they are injected into the 10 m long undulator (yellow) where the exponential FEL process takes place. The resulting photon pulses are transported to photon diagnostics in the tunnel or into an external laboratory, while the longitudinal phase space distribution of the electron bunches is mapped out in a combination of a transverse deflecting structure (orange) and a horizontally deflecting dipole spectrometer.

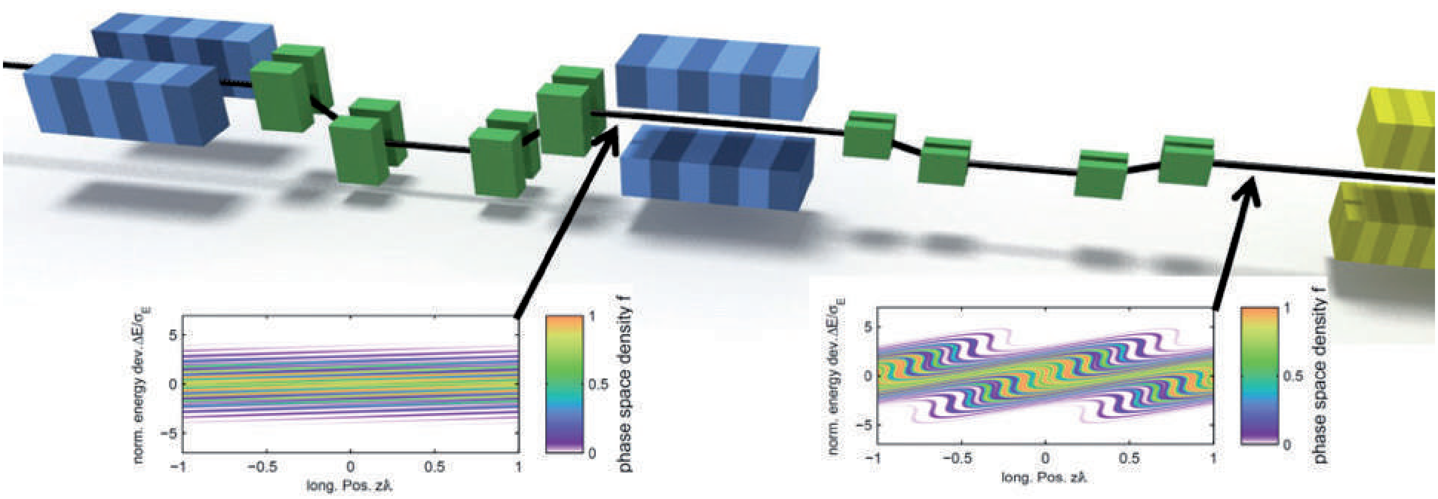

Figure 2

Operating principle of the echo-enabled harmonic generation (EEHG) seeding scheme. In the first modulator (blue), the uniform electron beam arriving from the accelerator interacts with the first seed laser pulse. The resulting sinusoidal energy modulation is then sheared over in the first chicane with a typical longitudinal dispersion of a few millimetres (the left inset shows the resulting longitudinal phase space distribution). After a second laser-based manipulation, the bunch microstructured at the desired harmonic (right inset) is injected into the radiator (yellow).

can be transported to a dedicated photon diagnostics laboratory, where a THz streaking setup is installed. Here, the FEL radiation impinges a noble-gas target, releasing photoelectrons. A co-propagating THz field interacts with these released electrons, mapping the longitudinal pulse properties onto the kinetic energy spectrum of the photoelectrons. Analysis of the measured energy spectrum reveals information about the temporal profile of the FEL pulse.

The THz streaking technique was recently applied at sFLASH for the characterisation of seeded FEL pulses [2]. The chirp of the seeded FEL pulses was found to be (-1940 ± 800) THz/ps, and the pulse durations were in agreement with an analysis of the electron bunches driving the FEL process [2, 3]: Mapping out the longitudinal phase space distribution with a TDS installed downstream of the sFLASH experiment, the power profile of the seeded FEL pulses was inferred on a single-shot basis.

After a recent upgrade, the THz streaking setup was recommissioned with seeded FEL radiation. In first experiments, the UV seed pulses were manipulated by introducing different amounts of dispersive material into the beam path. Simulations with the FEL code GENESIS were conducted to study the effect on the seeded FEL pulses [4]. Measurements with THz streaking will reveal the impact of these manipulations on the seeded FEL pulses, and data analysis is currently ongoing. In a later phase, both amplitude and phase of the UV seed pulses could be manipulated, enabling *a priori* phase shaping of the seeded FEL pulses.

Towards echo-enabled harmonic generation

Single-stage HGHG seeding is limited to harmonic numbers of about 15. The advanced echo-enabled harmonic generation (EEHG) seeding scheme [5] has a number of advantages, including efficient bunching generation at higher harmonics and a reduced impact of electron beam imperfections on the generated photon pulses. Figure 2 illustrates the underlying manipulations of the electron beam. Experimental studies towards the demonstration of EEHG seeding at sFLASH are presently ongoing. While the hardware installed at sFLASH is sufficient for HGHG seeding, the longitudinal dispersion of the chicanes is only sufficient for EEHG pilot experiments. To enable the exploration of EEHG seeding, especially at shorter FEL wavelengths, a chicane upgrade allowing larger longitudinal dispersions is currently being engineered.

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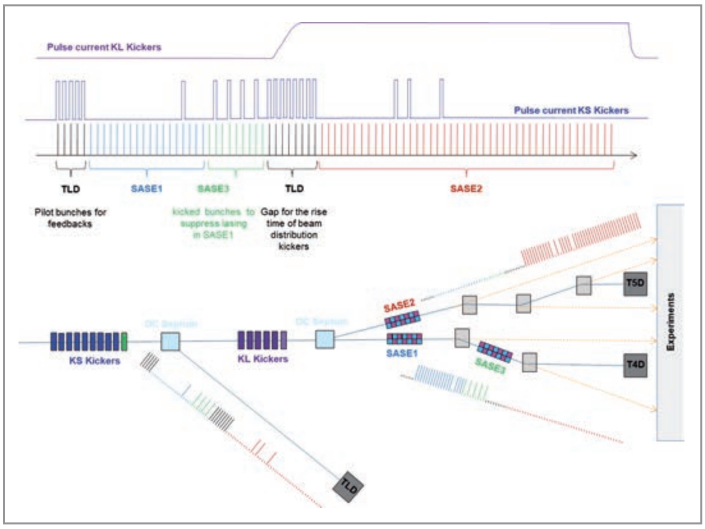
European XFEL beam distribution

Sophisticated kicker systems

A special feature of the European XFEL X-ray laser is the possibility to distribute the electron bunches of one beam pulse to different free-electron laser (FEL) beamlines. This is achieved through a combination of kickers and a Lambertson DC septum. The integration of a beam abort dump allows a flexible selection of the bunch pattern at the FEL experiment, while the superconducting linear accelerator operates with constant beam loading. The driver linac of the FEL can deliver up to 600 µs long bunch trains with a repetition rate of 10 Hz and a maximum energy of 17.5 GeV. The FEL process poses very strict requirements on the stability of the beam position and hence on all upstream magnets. It was therefore decided to split the beam distribution system into two kicker systems, flat-top kickers (KL) with very stable amplitude (10^{-4}) and relatively slow pulses (~300 µs) and fast stripline kickers (KS) with moderate stability but very fast pulses (~50 ns).

Overview

Figure 1 shows a schematic overview of the European XFEL fill pattern and beam distribution system. The six KL flat-top kickers are operated with a rectangular pulse with variable pulse length and switch the beam between the two main FEL beamlines. To create the flexible bunch pattern, a kicker–septum combination consisting of ten KS stripline kickers is installed, with which it is possible to extract individual bunches into the dump beamline (TLD) with a maximum frequency of 4.5 MHz. Pilot bunches for the intra-bunch feedback needed to stabilise the beam, bunches during the still-required gap for rise time of the KL beam distribution kickers and all bunches not needed for lasing are extracted to the dump. Bunches for the SASE3 undulator can be stimulated with a KS kicker so that they do not lase in the SASE1 undulator. All of this requires a sophisticated bunch pattern generator and timing system.



Concept of the stripline kicker magnet (KS)

The KS stripline kickers are located inside the vacuum and act as a transmission line with an impedance of 50 Ω. In order to obtain a small reflection factor, it is important to take into account the dimensions of the kickers on parallelism, separation and concentricity of the striplines (Item 5 in Fig. 2) to each other and the location of the striplines within the vessel. The striplines are mounted to half-shells with ceramic spacers. After assembling the striplines, the half-shells of the vacuum tank are welded together with a 2 m weld. Ceramic spacers allow for mechanical expansion of the striplines relative to the vessel and vice versa, e.g. during vacuum bake-out. The centre spacer is fixed, whilst the end spacers allow for longitudinal movement (sliding). Bellows (Item 13) are installed for decoupling so that the forces of the length change (thermal expansion) of the conductor (Item 5) do not damage the insulating ceramics of the high-voltage feed-throughs (Item 17).

Concept of the kicker magnet (KL)

The KL kicker magnets are realised as air coils outside the beam vacuum system (Fig. 3). They use striplines that form a single vertical conductor loop around a ceramic beam chamber, which is sputtered (metal-coated) on the inside. The conductor consists of high-frequency litz wires to reduce eddy current effect, skin effect and proximity effect. The

Figure 1

European XFEL fill pattern scheme: The flexible bunch pattern for the FEL lines is created by kicking all bunches that are not used for lasing into the main dump line (TLD) by means of the KS kickers. The bunch train parts for the FEL lines are distributed by the KL kickers. SASE2 bunches are kicked, SASE1/3 bunches are not.

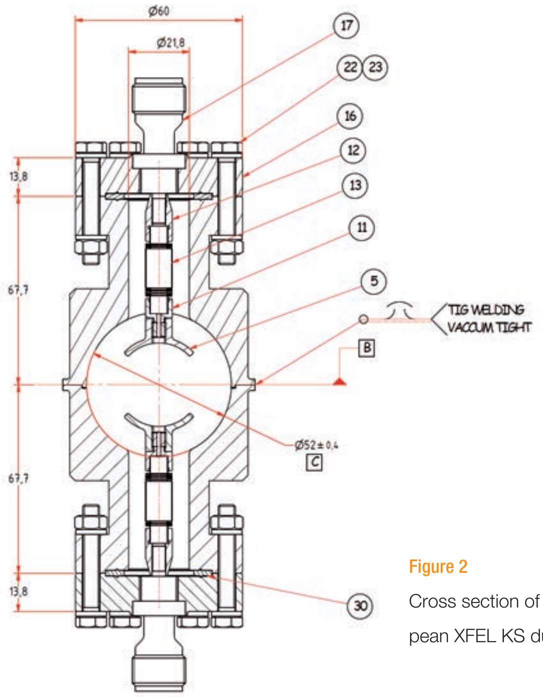


Figure 2

Cross section of the European XFEL KS dump kicker

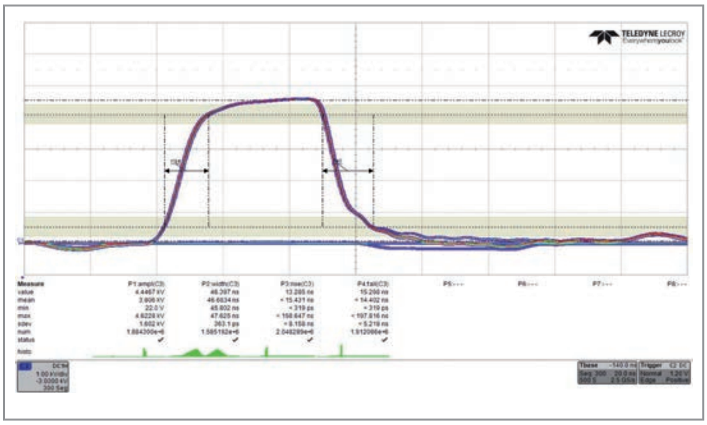


Figure 4

Scope screen showing overlaid pattern of pulses with stable flat top and non-ripple baseline

mounting structure of the kickers needs to be non-metallic, as eddy currents strongly distort the magnetic field of the current pulses. The thermoplastic PEI was chosen for radiation, heat resistance and mechanical properties.

The design of the kickers requires a metal-coated ceramic chamber. The following aspects of sputtered ceramic chambers are important: Sputtering is necessary in order to transport the mirror current of the beam and to contain the radio frequency (RF) fields from the beam inside the chamber while the magnetic field of the kickers (at lower frequency) penetrates the chamber wall. The coating material is stainless steel 4.4541 (titanium-stabilised). The thickness of the coating is determined by a compromise between reduction of the magnetic field and heat dissipation due to the mirror current.

Concept of the KS pulser

For the KS dump kickers, commercially available pulse generators from the company FID are used. Very important

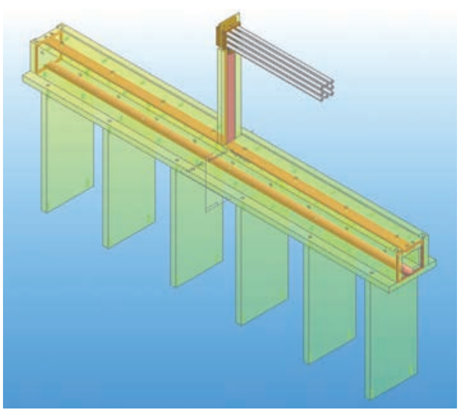


Figure 3

Sketch of the KL beam distribution kicker without ceramic chamber

aspects for the pulse specification were the residual baseline ripple after 222 ns (4.5 MHz maximum pulse frequency) for those bunches that are passing into the undulator lines and maintaining a reasonable stability of the pulse amplitude for those bunches that are kicked into the dump line (Fig. 4). The pulse rise and fall time is 14 ns. The duration of the pulse flat top was fixed to 30 ns so pulse jitter will not influence the bunch to be deflected.

During commissioning, there were still many failures of the system, but these were quickly eliminated by partial redesign, more radiation shielding and improved operating procedures. In 2018, there were no more outages.

Concept of the KL pulser

For the KL beam distribution kickers, a nearly rectangular current pulse is required, so rise and fall times of less than 15 µs and a very stable flat top of the pulse are important. Therefore, a pulse-regulated current source with MOSFET technology is used. The main MOSFET is switched by a push–pull driver providing a fast rise time. While turned on, the current through the kicker magnet is sensed and fed back to the main MOSFET through an operational amplifier circuit, providing a very stable flat top. Eight MOSFETs are operated in parallel, generating a pulse current of up to 600 A. Data communications, internal timings, power-up and power-down sequences and some service modes are realised with a field-programmable gate array (FPGA) board. The pulser is triggered with a 5 V TTL signal from the MTCA-based main timing system, with the pulse length and trigger start time being controlled by the bunch pattern.

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Energy beam position monitor for the European XFEL

Button electrode pick-up array and electronics in operation

Commissioning of the European XFEL X-ray laser started in early 2017. In July 2018, the electron beam was accelerated to its final energy of 17.5 GeV. The length of the electron bunches can be compressed in three bunch compression chicanes at 130 MeV, 700 MeV and 2400 MeV. An independent measurement of the energy in the bunch compressors is required to optimise and stabilise the bunch compression. A custom-type button array beam position monitor (BPM) and its analogue and digital readout electronics were designed for this purpose. The system has been in operation from the very first day and has been continuously improved. It is also used in slow orbit feedbacks to stabilise the electron beam energy and thereby improve the stability of the photon pulses in the experimental stations at the end of the facility.

Energy beam position monitor

Bunch compressors are installed in the European XFEL at the locations BC0, BC1 and BC2 at the three ascending energies 130 MeV, 700 MeV and 2400 MeV, allowing flexible compression scenarios of the electron bunches. The vacuum pipe diameter in these chicanes is tapered from 40 mm diameter to 400 mm vertically into a rectangular form. In order to determine the energy in the dispersive part of the chicane, a novel type of button electrode array was designed. Two 13-button pickups are arranged in such a way as to allow precise beam position measurements within the full height of 400 mm in the vertical plane (Fig. 1). In total, 26 radio frequency (RF) channels thus have to be processed.

RF/digital electronics and front-end server

The MTCA.4 standard was chosen as the main platform for the European XFEL electronics. The electronic crates are located underneath the accelerator modules inside the accelerator tunnel. The 26 pickup signals from the energy BPM are read out with custom-made RF electronics and commercial off-the-shelf (COTS) digitiser/firmware electronics (Fig. 2). Each RF front end is composed of four RF channels. The acquisition is based on peak detector electronics with a bandwidth of >600 MHz to measure the pickup signals, which have a rise time on the order of a few hundred picoseconds. After the peak detection, the signals are digitised with a sample rate of 108 MHz and a resolution of 16 bits. In total, six RF and digitiser cards are used to

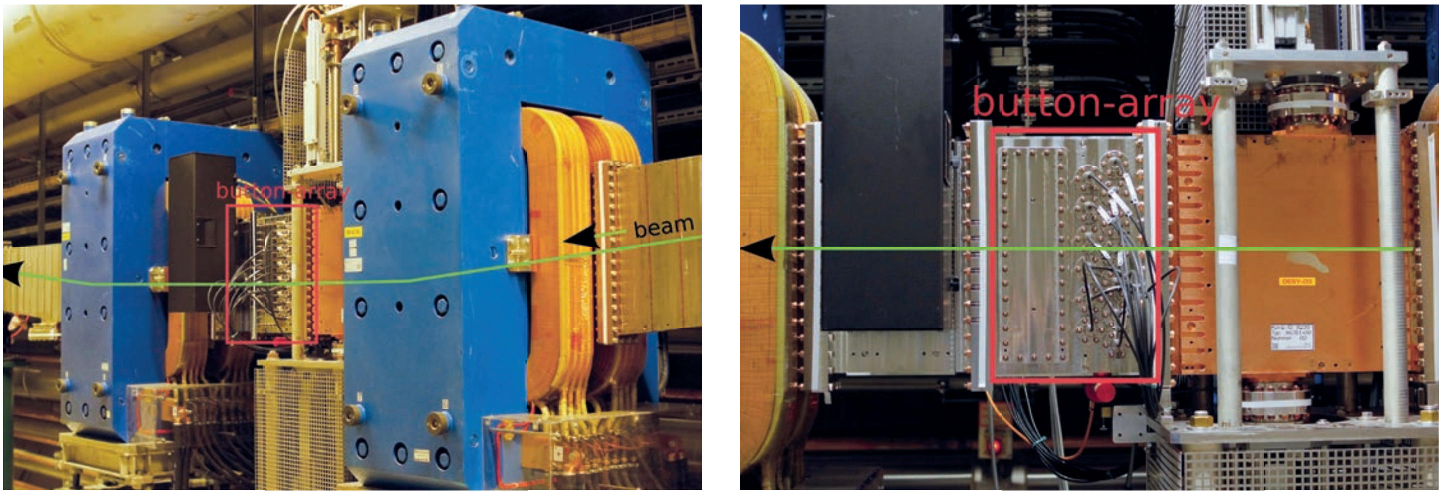

Figure 1

European XFEL beam position monitor array and compression chicane at 700 MeV

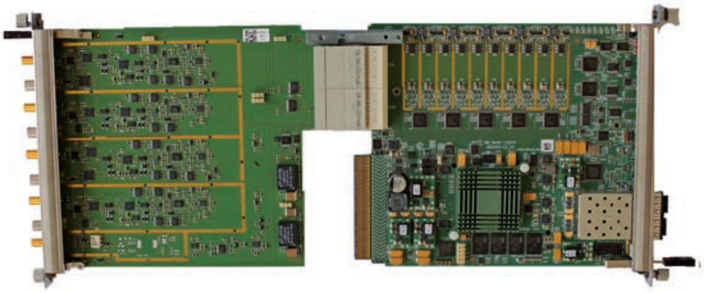

Figure 2

Single custom RF front-end card and COTS digitiser

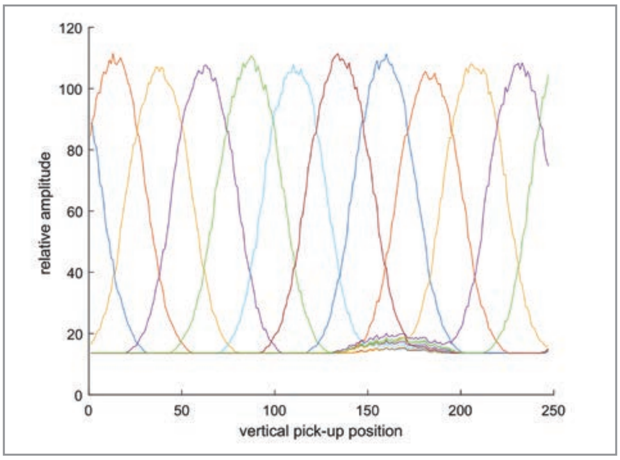

Figure 4

Amplitude variation of the pickup signals as a function of the vertical position

read out 24 (of 26) pickup signals. A software front-end server collects the raw data from the six digitiser/firmware cards and calculates the individual pickup signal strength (Fig. 3).

Calibration

In order to obtain the vertical calibration constant of the pickup array, the raw amplitude signals from the individual pickups are acquired when the beam is steered through the chamber in the vertical direction (Fig. 4). The calibration constant and offsets are defined in a piece-wise fashion to achieve a smooth transition when the beam position is moving across the electrodes (Fig. 5).

Operational experience

The position readings from the BPM system are used to calculate the energy in the chicane sections with the help of a special energy server. They feed a feedback system to stabilise the electron beam energy. These energy readings are also used for energy calibration of the estimated energy gain of the accelerated electron beam in the low-level RF system. The relative resolution fluctuations of the energy BPM are on the order of 10^{-4} down to 10^{-5}, while the estimated absolute energy measurement is better than 1%. This instrument offers the only independent measurement of the electron beam energy in the whole facility.

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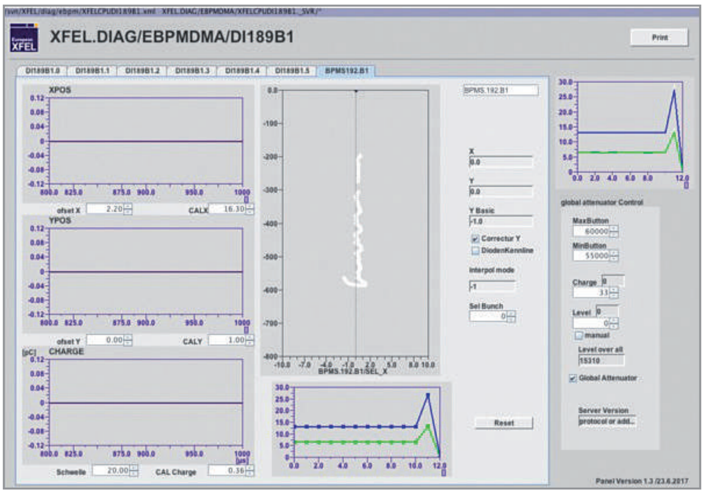

Figure 3

Server graphical interface with position scan in the vertical direction

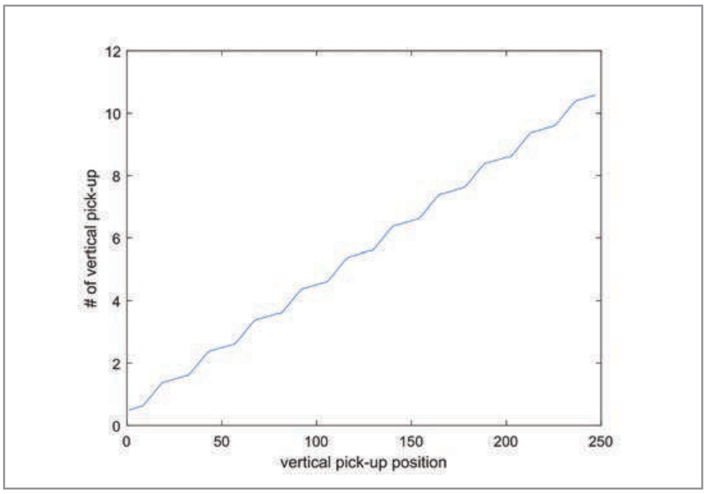

Figure 5

Piece-wise linear calibration curve of the vacuum chamber

KALYPSO line scan camera

A linear array detector with continuous MHz readout rates

A collaboration of KIT, PSI, Lodz University of Technology and DESY has developed a novel line detector, KALYPSO (for Karlsruhe Linear Array Detector for MHz Repetition Rate Spectroscopy), for measuring one-dimensional profiles at high-repetition-rate free-electron lasers (FELs) and synchrotron radiation facilities. The current version of KALYPSO has 256 pixels with a continuous data readout at a maximum frame rate of 2.7 MHz. At the European XFEL and FLASH FEL facilities, first results with KALYPSO were obtained in beam diagnostics applications for the measurement of bunch-resolved longitudinal beam profiles and photon-pulse-resolved FEL spectra.

The KALYPSO detector

The linear array detector KALYPSO [1] was developed for electron and photon beam diagnostics for measuring one-dimensional profiles with continuous data readout at MHz frame rates. The detector is designed in a modular architecture: The radiation-sensitive part, the analogue signal amplification and the analogue-to-digital signal conversion are placed on a mezzanine card that can be plugged onto application-specific carrier boards. For the applications at FLASH and the European XFEL, a novel field-programmable gate array (FPGA) readout board (Fig. 1) was developed for data acquisition and transmission to the accelerator front-end electronics in the MicroTCA.4 standard. Clock and trigger signals are received from a MicroTCA.4 board (NAMC-psTimer, N.A.T.) of the accelerator timing system for electron bunch or photon pulse synchronous data recording. Recorded data is streamed out to another MicroTCA.4 board (MFMC, AIES) integrated in the accelerator control system DOOCS.

Two types of radiation sensors can be mounted: a Si sensor for the detection of X-rays and visible radiation, or an InGaAs sensor sensitive in the wavelength range from 900 nm to 1.7 µm. In the current version, the sensors have 256 pixels with a width of 50 µm.

Photon-pulse-resolved FEL spectra

The FLASH1 and FLASH2 beamlines are driven by a superconducting linear accelerator that operates at a 10 Hz repetition rate with bursts of up to 800 bunches at a maximum repetition rate of 1.0 MHz. FLASH1 is a single-pass FEL, and the FEL radiation is of stochastic nature, i.e. individual FEL

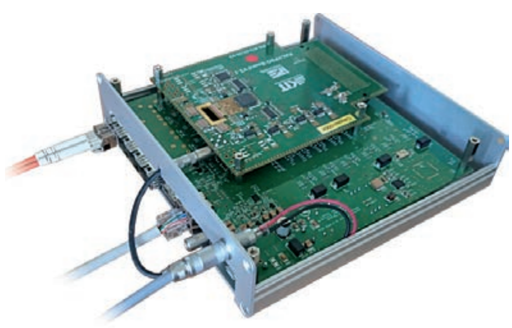

Figure 1

KALYPSO detector board mounted on the FPGA-based carrier for data acquisition and transmission to the MicroTCA.4 front-end electronics

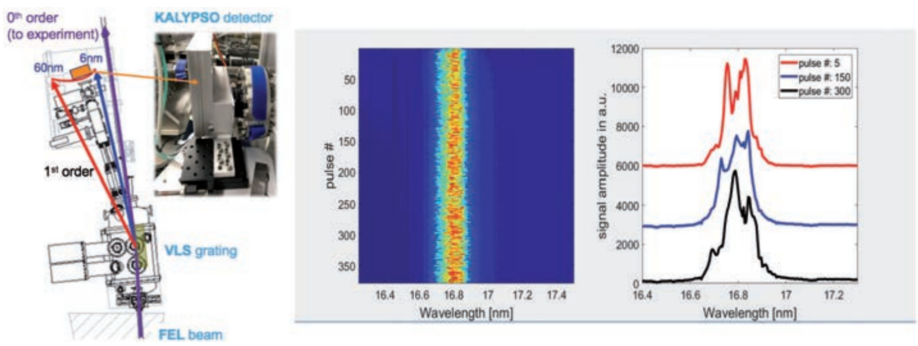

Figure 2

Left: Sketch of the VLS spectrometer equipped with the KALYPSO detector.

Right: Single-pulse-resolved FEL spectra for a pulse train of 380 pulses recorded at 1.0 MHz repetition rate. Three individual spectra have been offset vertically for better distinction.

pulses vary in intensity, temporal structure and spectral distribution. Many user experiments are sensitive to the wavelength of the FEL radiation and demand information on the spectral distributions of the individual FEL pulses.

For the monitoring of pulse-resolved FEL spectra, a KALYPSO detector equipped with a Si sensor was installed at the variable line spacing (VLS) grating spectrometer [2] in the FLASH1 beamline. The VLS spectrometer is equipped with two gratings optimised for zeroth-order diffraction such that the main part of the FEL radiation is transmitted to the user experiment, while a fraction of the FEL radiation intensity is dispersed into the first order for the online measurement of FEL spectra (Fig. 2 left). The first-order diffraction is focused onto a Ce:YAG crystal located in the focal plane of the VLS spectrometer, and the visible fluorescence light is imaged onto the Si sensor of the KALYPSO detector.

Figure 2 (right) shows the pulse-resolved FEL spectra of a pulse train with 380 pulses measured with the KALYPSO detector at a repetition rate of 1.0 MHz as well as three individual spectra for the pulse numbers 5, 150 and 300. Typical FEL spectra with many spikes can be seen. FLASH operators use this online measurement of the FEL spectra for accelerator tuning to keep the FEL pulses along the pulse train within a spectral bandwidth of about 1%, which is the typical spectral width of the FEL radiation. The spectra are stored in the data acquisition system at FLASH, and the information about the spectral shape of individual FEL pulses can be used for post-analysis of experimental results.

Bunch-resolved longitudinal beam profiles

The superconducting linear accelerator of the European XFEL X-ray laser also operates at 10 Hz repetition rate with bursts of up to 2700 electron bunches, which can be distributed into three FEL beamlines. To measure the longitudinal electron bunch profile, an electro-optical diagnostics (EOD) system was installed after the second bunch compressor. The Coulomb field of an electron bunch, passing by a gallium phosphide (GaP) crystal installed inside the electron beam-pipe, induces a birefringence leading to a modulation of the polarisation of a co-propagating laser pulse. This polarisation modulation is transferred after a polariser to an amplitude modulation in the laser spectrum. The laser spectrum is measured with a spectrometer using a KALYPSO detector equipped with an InGaAs sensor.

As the GaP crystal is non-invasive on the electron beam, the EOD system can monitor individual longitudinal profiles of the bunches in a bunch train with sub-picosecond resolution at a repetition rate of 1.1 MHz.

Figure 3 shows data recorded for a single bunch train with 120 electron bunches. The recording of the detector (at 1.1 MHz) starts 100 frames before the first electron bunch in order to acquire unmodulated laser spectra, followed by 120 laser spectra that have timing overlap with the electron bunches, and a number of frames without laser pulses present in order to measure the detector background. The averaged background (blue line) and averaged unmodulated laser spectrum (black line) are used to calculate, from the modulated laser spectra (red line as example), the normalised signals representing the longitudinal bunch profiles (Fig. 4). The longitudinal profile of the 50th electron bunch (blue line) is shown together with a Gaussian fit with a width of 330 fs (RMS).

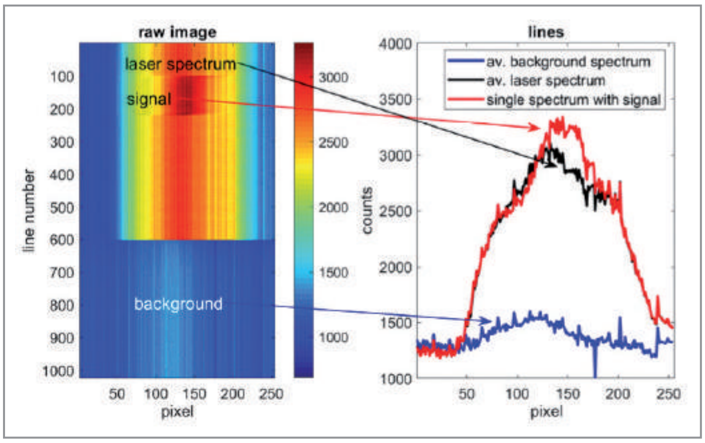

Figure 3

Left: The image represents 1000 consecutive frames recorded with KALYPSO around one electron bunch train at 1.1 MHz. Right: Unmodulated laser spectrum (black), laser spectrum modulated by an electron bunch (red) and background signal (blue).

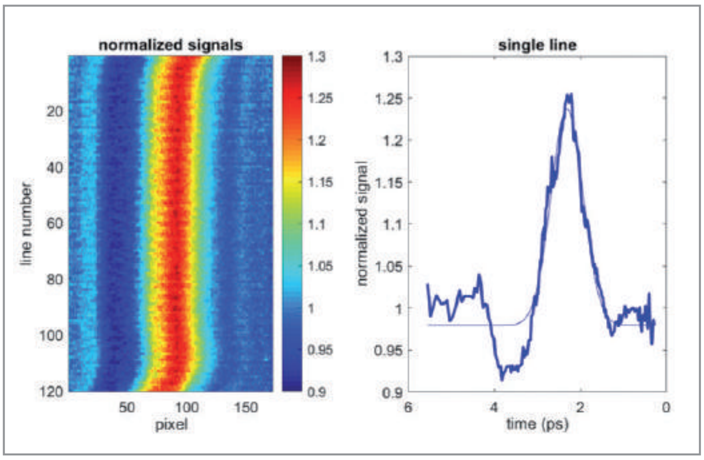

Figure 4

Left: Longitudinal profiles of the 120 electron bunches calculated from the data set in Figure 3. Right: Longitudinal profile of the 50th bunch together with a Gaussian fit.

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Plasma gymnastics

Removing large correlated energy spreads with plasma

The wakefield structure in a plasma-based particle accelerator offers distinct advantages for future free-electron laser (FEL) and high-energy physics (HEP) applications, such as strong intrinsic focusing and high accelerating gradients. A challenge of plasma-based concepts, however, is the development of the longitudinal phase space of the beam, which is accelerated in an environment that may imprint a large linear energy–time dependency – or chirp – on the beam. Upon exit of the plasma cell, these chirps will halt FEL gain and result in a decreased luminosity in HEP experiments, and, as such, they should be removed. The DESY plasma acceleration group has therefore developed a proof-of-principle plasma-based dechirping technique, which takes advantage of the large gradients intrinsic to the plasma acceleration concept. This novel dechirping technique was recently demonstrated to generate dechirping gradients orders of magnitude greater than other state-of-the-art techniques, thus increasing the applicability of plasma-based accelerators to future facilities.

Longitudinal phase space manipulation

The technique of longitudinal phase space manipulation using radiofrequency (RF) cavities is well understood. For example, an electron bunch is routinely accelerated off-crest in order to imprint a linear head-to-tail energy correlation – or chirp – with typical magnitudes on the MeV/mm level. This off-crest acceleration is necessary to temporally compress the bunch in a dispersive magnetic chicane. Similar methodology is also used to remove any residual chirp present after the acceleration and compression process to prevent the chirp from limiting FEL performance through an increased energy bandwidth.

In plasma-based acceleration techniques, a bunch is also typically accelerated off-crest, such that it is simultaneously accelerated and focused by the plasma fields (the focusing fields are zero on-crest), resulting in a similarly chirped beam. However, due to the extreme accelerating gradients inherent to the method, these chirps may be on the GeV/mm level and are hence too large to be compensated for by conventional techniques over length scales comparable to the acceleration distance.

Removal of energy chirps using corrugated pipes and dielectric-based slab structures has been experimentally demonstrated [1]. To date, however, these structures have been shown to remove chirps on the sub-MeV/mm level. To compensate the extreme energy chirps generated in plasma-based accelerators within distances comparable or shorter than the accelerator size, a technique capable of removing chirps far exceeding those experimentally demonstrated is required. This can be achieved by taking advantage of the large electric fields inherent to the plasma acceleration process. One such mitigation strategy, based on the observation that a beam driving a plasma wakefield will be subjected to a decelerating longitudinal field with a particular longitudinal dependency, was developed by members of the FLASHForward experiment at DESY.

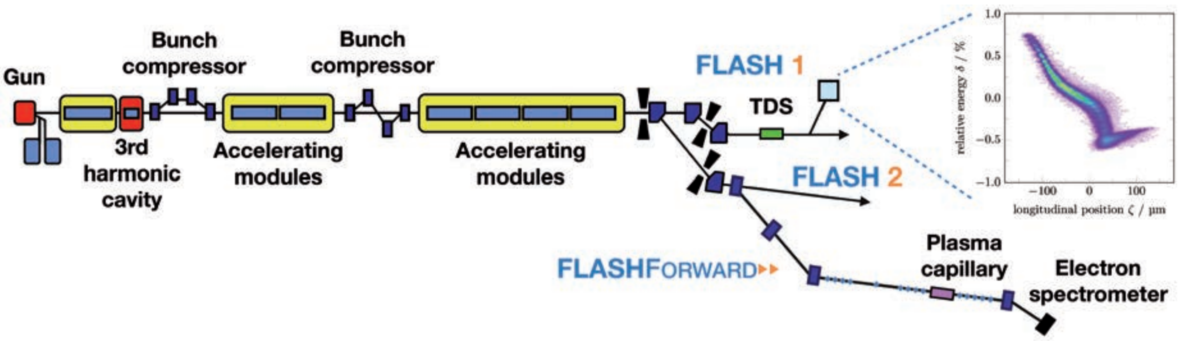

Figure 1

Beamline schematic of the FLASH facility illustrating the RF gun and linear accelerator components used to accelerate, compress and chirp the electron beams. Also shown are the magnetic dipoles deflecting the beam into FLASHForward as well as some components of the FLASHForward beamline itself. The linearly chirped longitudinal phase space of the beam used in this experiment, as measured by the LOLA transverse deflecting structure (TDS), is shown in the upper right inset.

Dechirping at FLASHForward

The FLASHForward experiment [2], which is attached to DESY's FLASH FEL facility (Fig. 1), is designed to generate the characteristically high accelerating fields in the wake of FLASH electron beams interacting with a plasma. In the proof-of-principle dechirping experiment, a chirped bunch was created with the FLASH front end and characterised using the LOLA transverse deflection structure. This bunch, with a length of 63 µm and a linear chirp of 60.5 MeV/mm, was transported from FLASH to the FLASHForward beamline.

Once in the FLASHForward beamline, the chirped bunch was injected into a 33 mm long plasma, generated by firing a high-voltage discharge through pumped argon gas. After the discharge pulse ends, the density of the plasma electrons decays exponentially due to plasma recombination and expansion into vacuum. The plasma density can therefore be controlled by delaying the arrival time of the electron beam relative to the discharge, with the electron beam experiencing lower densities – and therefore lower dechirping gradients – at ever longer times after the discharge.

An electron spectrometer located downstream of the plasma capillary was used to disperse the bunch in energy and record the dechirping effect. Figure 2 (top) shows the energy spectrum of the chirped bunch without interaction with the plasma as well as two cases after interaction with the plasma. The experimentally derived parameters were used to simulate the dechirping effect by means of a particle-in-cell code. The plasma density was varied, with the maximum dechirping effect observed at a plasma density of 2 x 10^{15} cm^{-3} (Fig. 2 bottom). The spectra and dechirping effect in these two cases show good agreement. In addition, the fluctuation of the spectra over 50 consecutive shots with and without plasma interaction is consistent, suggesting that the plasma dechirper does not decrease the stability of the incoming beam – which in turn increases the technique's applicability to future FEL and HEP facilities.

Simulations of the chirped bunch interacting with the plasma over the full discharge delay time can be seen in Fig. 3. A comparison of the profile and absolute values of dechirping for both the experimental and simulated data sets shows excellent agreement. The incoming 60.5 MeV/mm chirp is fully compensated 7.9 µs after discharge, implying a dechirping strength of 1.8 GeV/mm/m – two orders of magnitude greater than competing state-of-the-art techniques, with the potential to compensate even greater chirps in shorter distances in future experiments. As such, the principle may be used to mitigate the large energy chirps of electron bunches generated in plasma, thus drastically improving the applicability of plasma wakefield schemes to future experiments where a negligible correlated energy spread is required.

This proof-of-principle result [3] is not only the first observation of its type, but the first experimental result from FLASHForward, achieved during the very first beam time after commissioning. This shows that FLASHForward has the potential to play an integral role in the future development of advanced accelerator concepts.

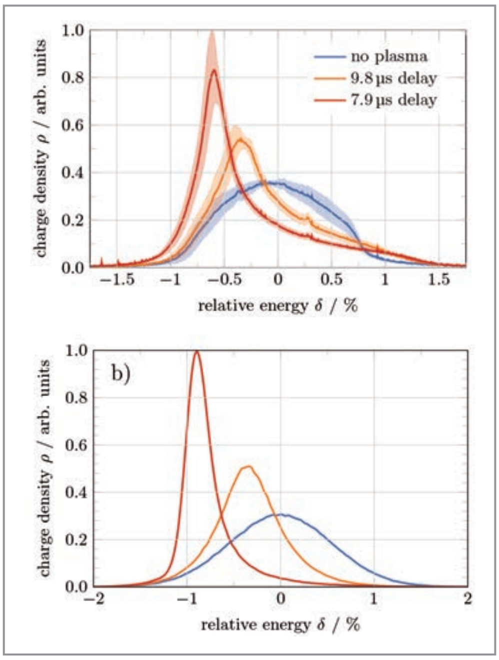

Figure 2

Top: Series of energy spectra as recorded by the optical system surrounding the dipole spectrometer, for no interaction with the plasma and for two dechirping plasma densities. The error ranges indicate the standard deviation for each energy slice – an average over 50 consecutive shots. Bottom: Simulated energy spectra for the corresponding plasma densities.

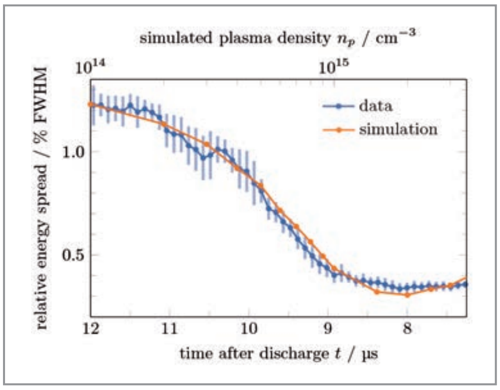

Figure 3

FWHM of the chirped bunch energy as a function of discharge time relative to the arrival time of the electron bunch. The plotted standard deviation represents the shot-to-shot fluctuations per delay step. Simulated FWHM of the chirped bunch energy spectra as a function of electron plasma density over the identical range are shown for comparison.

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SINBAD-ARES

First experiment at SINBAD ready for start-up

The Helmholtz Association has identified accelerator R&D as one of its core tasks. In line with this objective, DESY is currently setting up the dedicated, long-term accelerator R&D facility SINBAD (for Short Innovative Bunches and Accelerators at DESY) in the premises of the old DORIS accelerator complex. In the last years, the design, procurement and installation of the first experiment – the SINBAD-ARES linear accelerator (linac) – progressed well, and it was ready for commissioning at the beginning of 2019. The linac will allow studies of the generation of ultrashort electron bunches and serve as an injector for advanced acceleration schemes. With the approval of the Helmholtz strategic investment funds for the Accelerator Technology Helmholtz Infrastructure (ATHENA) project, the linac will be used as an external injector for a laser-driven plasma acceleration stage.

Starting in 2015, DESY's old DORIS accelerator along with its outdated infrastructure was removed and the building refurbished. The SINBAD-ARES experiment is the first of the multiple independent experiments at SINBAD to start operation.

R&D on ultrashort electron bunch production

In 2018, the installation of the required technical infrastructure was completed, and the first stage of the ARES linac – the 5 MeV radio frequency (RF) gun section – was installed (Fig. 1). While the installation of the future stages will continue over the next years, the RF gun stage was ready for hardware and beam commissioning at the beginning of 2019.

Once completed, the linac will accelerate electron bunches with charges ranging from 0.5 pC to 30 pC to 100 MeV and compress them to single/sub-femtosecond pulse duration. The first goal for the SINBAD-ARES linac will be the

Figure 1

The first stage of the SINBAD-ARES linac was installed and ready for beam commissioning at the beginning of 2019.

Figure 2

SINBAD hosted the yearly collaboration meeting of the ACHIP collaboration in September 2018.

production of high-brightness sub-femtosecond bunches. The linac will allow for the experimental comparison of different compression techniques. Studying the limitations for achieving high-brightness ultrashort bunches with excellent (< 10 fs RMS) arrival time stability will be the main focus of R&D on the linac itself. To this end, a novel diagnostics beamline will be procured within the ATHENA upgrade. The diagnostics beamline designed for SINBAD-ARES will allow a unique characterisation of the three-dimensional distribution of the electrons in the bunch with sub-femtosecond resolution. This beamline will host two novel polarizable X-band transverse deflection structures (PolariX TDS), which will be realised in collaboration with CERN and PSI. In a dogleg, a second experimental area will be added to ARES.

Studying advanced acceleration concepts

Advanced acceleration concepts will be studied with dielectric structures at ARES in the context of the Accelerator on a Chip International Program (ACHIP) collaboration, which held its yearly collaboration meeting at DESY/SINBAD (Fig. 2). Equipment for a dedicated experimental area is currently being procured and installed to focus the ARES beam into the micrometre-scale, laser-driven dielectric structures. The ultrashort bunches of ARES should – for the first time worldwide – allow the demonstration of net acceleration.

Finally, the Helmholtz strategic investment funds for the ATHENA collaboration were approved in 2018. This funding will allow the ARES linac (and SINBAD in general) to be extended significantly over the next few years to become the flagship project on laser-driven plasma acceleration of this collaboration of seven Helmholtz centres and institutes. In this context, a high-power laser lab will be constructed, and the ANGUS 200 TW laser system, which is managed by Andreas Maier from Universität Hamburg, will be installed there. While ARES will be used to study laser-driven plasma wakefield acceleration with external injection, the move of the LUX plasma accelerator to the second long straight section of SINBAD will allow for direct comparison of the results to internal injection.

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Model-based engineering

Managing design complexity in accelerator projects

Developing an accelerator facility is a complex technical endeavour. It requires the organisation of an efficient engineering collaboration, which is yet another challenge of its own. Adopting experience gained from the construction of the European XFEL X-ray free-electron laser, DESY is further optimising its collaborative engineering design processes, in which the growing applications of visualisation models become increasingly important tools.

Motivation

Building an accelerator facility involves the mostly parallel development of numerous interconnected subsystems of very different nature, including beam optics and transportation, diagnostics and controls, technical infrastructures and supplies as well as buildings and safety. All systems have to integrate seamlessly and fit together precisely, requiring top-level engineering design to achieve the best possible overall performance.

The construction of the European XFEL has shown that 3D visualisation models are an effective means of coordinating collaborative and distributed design activities. In preparation for next-generation accelerator projects, DESY is upgrading its computer-aided design (CAD) and data management systems and expanding methods and applications of visual modelling to further optimise its sophisticated engineering design processes.

Challenge: Managing complexity

Designing an accelerator facility involves complexity in many aspects, each of which needs to be thoroughly managed. Complexity arises from design teams, which are spread out over various partner institutes, from extremely large design models, which are integrating tens of thousands of parts and components, and from engineering design processes, which have to be able to handle the fast-paced technological developments of leading-edge research projects.

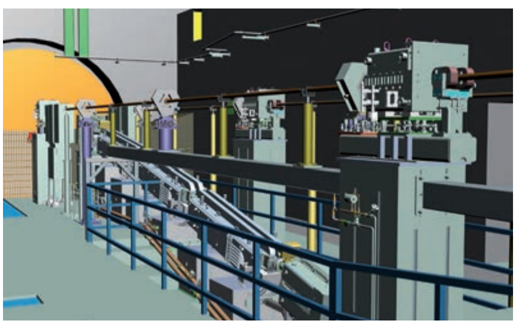

Figure 1

Accelerator facility design model, integrating 3D models of accelerator components, infrastructure subsystems and buildings

Visualisation: See what you're doing

Visualisation models depict the planned accelerator complex from the very start of the project, thus generating a common understanding of the facility among the entire project team. They enable the allocation of space for all contributions, and they help to match designs and negotiate interfaces. The models provide a basis for the technical specification of single components as well as for assessing the installation, operation and maintenance procedures of the full facility.

An accelerator facility's visualisation model integrates subsystem models from different, distributed engineering groups and makes sure that the designs fit, e.g. that system interfaces match, systems do not overlap and required transportation paths and lines of sight for alignment are not blocked (Fig. 1).

Parameterisation: Driven by physics simulation

Accelerator design is based on beam optics simulation, which computes the properties of a beam for a given sequence of accelerator components. The visualisation model is parameterised with the simulation results, which are used to automatically place components in the design model and generate the geometry of the beam envelope (Fig. 2 and 3). The parameterised model tightly connects the engineering

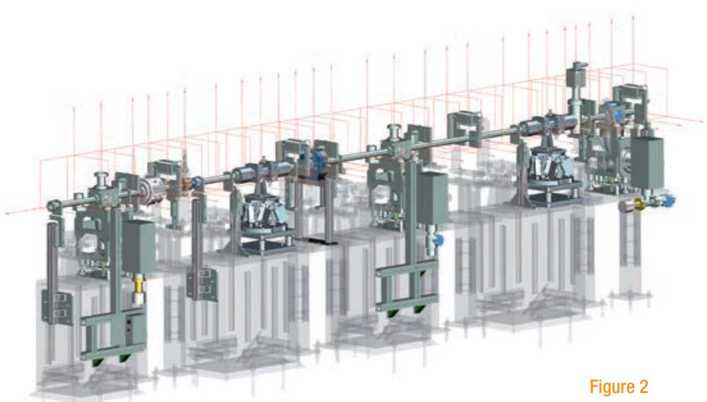

Figure 2

Design model of an accelerator beamline: The components are automatically placed at the red positions resulting from the beam optics simulation.

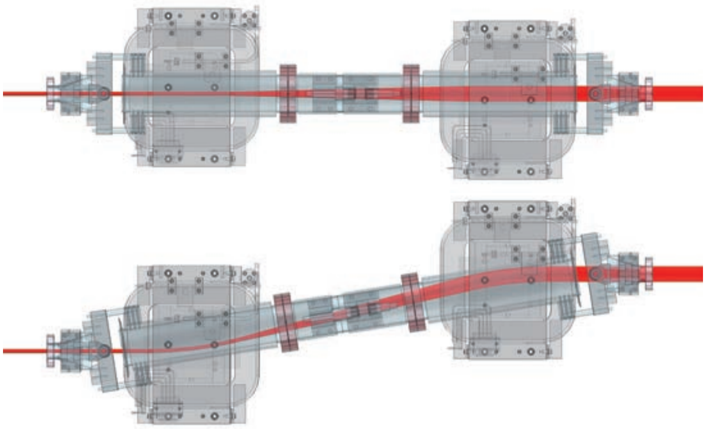

Figure 3

Mechanical design model of a movable beamline chicane, consisting of two bending magnets and a vacuum pipe, with an overlay of the simulated beam envelope showing the beam position in two configurations of the chicane

design and the physics parameters. It can instantly visualise new accelerator configurations and beam trajectories, resulting in faster design iteration cycles.

Evolutionary design: Setting the pace of progress

Design models can drive the progress of the project. They enable coarse-grained space allocation during facility planning, provide detailed specifications for fabrication and installation and keep track of the as-built facility during operation and maintenance.

To reflect the design evolution, the 3D models accumulate component geometry at increasing levels of detail in the course of the project (Fig. 4). The geometry can be switched according to purpose.

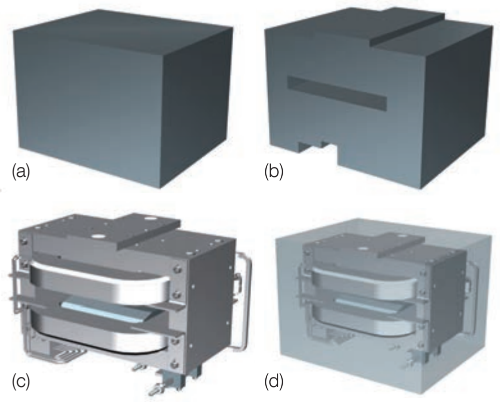

Figure 4

Design model of a bending magnet: (a) Placeholder for early space allocation. (b) Shape for interface definition. (c) Detailed model for technical specification. (d) Verification that the detailed model stays within the allocated space.

Furthermore, accelerator facilities are often built in stages, with early completion of basic sections to enable timely beam commissioning, and more beamline components being added as the project evolves. The 3D models reflect the staged development by storing configurations that include components according to the stages in which the facility is being installed. Configurations enable the concurrent planning, design and fabrication of all the subsystems in the facility.

Collaboration: Let's work together, independently

Different subsystems are designed and built at different times. Civil construction and technical infrastructures of tunnels and buildings have to be completed before the first components can be installed, and accelerator R&D may still continue after civil construction has started. At that time, buildings and infrastructure systems are already designed in full detail and final, while component designs are still evolving and may yet be represented as placeholders only.

The visualisation model is structured in a similar way to the project teams. Separating the design model into subsystem models decouples the design activities of the different project teams. Technical changes that stay inside the reserved volumes and respect the agreed interfaces can be safely introduced and quickly accepted without fear of side effects and without the need for time-consuming project reviews. Access control and versioning protect against unauthorised changes and ensure that teams stay in control of their designs (Fig. 5).

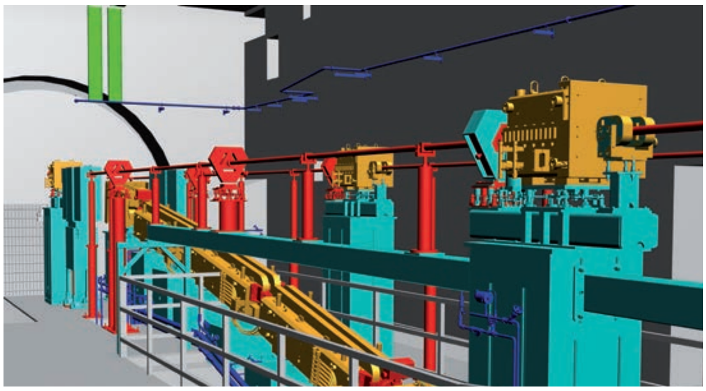

Figure 5

Accelerator facility design model with colour coding showing which project team is responsible for which subsystem

Experience

The advanced model-based engineering design approach is being validated in the SINBAD/ARES project at DESY (Fig. 6). The resulting design models serve as reference for upcoming next-generation accelerator projects. They confirm that visual modelling leads to better communication, better decision-making and better design quality. The reference model captures experience, increases design reuse and facilitates knowledge transfer between projects.

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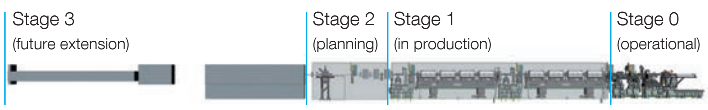

Figure 6

Design model of SINBAD/ARES showing the staged development of the facility. From right to left: First stage with gun section (operational); second stage adding linear acceleration sections (in production); third stage adding bunch compression (planning); and further stages with diagnostics and experimental area (future extensions).

EuPRAXIA

Conceptual design study lays out its pan-European vision for the future

The Horizon2020 project "European Plasma Research Accelerator with eXcellence In Applications" (EuPRAXIA) is preparing a conceptual design report for a highly compact and cost-effective European research infrastructure. The goal is to accelerate a 5 GeV electron beam based on laser- and beam-driven plasma accelerator technology in order to provide this beam for high-energy physics (HEP) detector tests, pilot free-electron laser (FEL) experiments and other compact X-ray sources. The study is funded by the European Union, and the design report will be submitted to the EU in the second half of 2019.

Six European centres of excellence

EuPRAXIA's concept foresees six different centres of excellence across the continent: two main construction sites (one at INFN in Frascati, Italy, and one at DESY in Hamburg, Germany) and one centre each in France, Portugal, the United Kingdom and the Czech Republic.

In the beam-driven case, a radio frequency (RF) injector based on S-band and X-band technology (with electron energy up to 1 GeV) will be constructed and used as a drive beam for beam-driven plasma wakefield acceleration (PWFA). The final electron beam energies will reach up to 5 GeV. In the case of laser-driven plasma wakefield acceleration (LWFA), an RF injector based on S-band technology (with electron energy up to 240 MeV) or alternatively a plasma injector (with electron energy up to 150 MeV) will be employed before the beam is injected into a plasma accelerator for external LWFA to final energies of up to 5 GeV. A single-stage approach based on LWFA with internal injection will also be used to reach the 5 GeV target energy. User areas at both sites will provide access to FEL pilot experiments, positron generation, compact radiation sources and test beams for HEP detector development. All cases studied by both sites are shown in Figure 1.

Each country involved in EuPRAXIA will have a particular specialisation within the project. A centre for FEL research will be based in France, which will also coordinate the development of laser technology for the EuPRAXIA laser together with the European laser industry. The laser design has been finalised and encompasses a titanium sapphire technology system with diode-pumped solid-state lasers. Laser pulse energies of 5 J, 15 J and 50 J will be available for different acceleration stages.

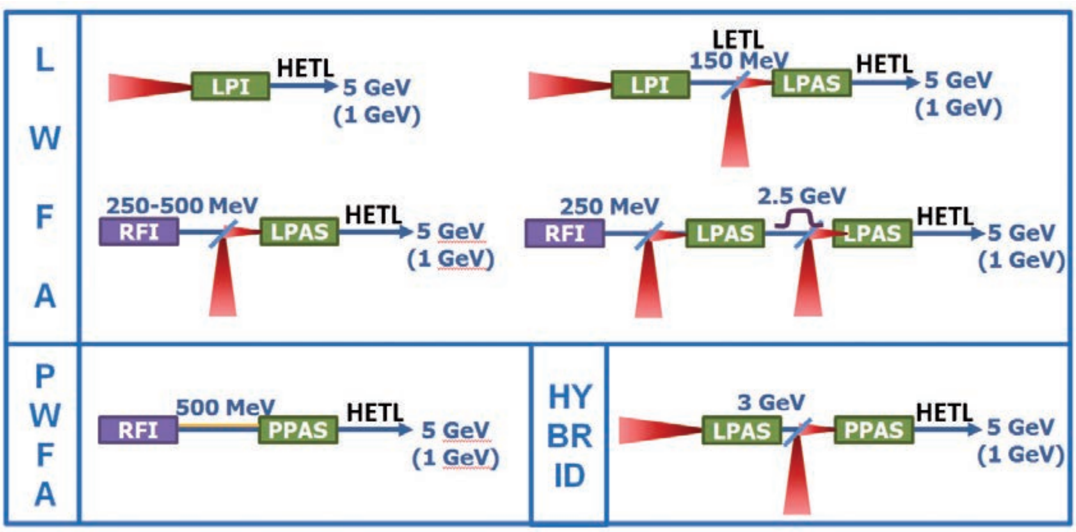

Figure 1
Studied injection and acceleration schemes. LPI, RFI, LPAS, PPAS, LETL, HETL stand for: laser plasma injector, RF injector, laser plasma acceleration stage, particle-driven plasma acceleration stage, low-energy transfer line, high-energy transfer line. Laser beams are presented in red, electron beams in blue. (Picture: Phi Nghiem)

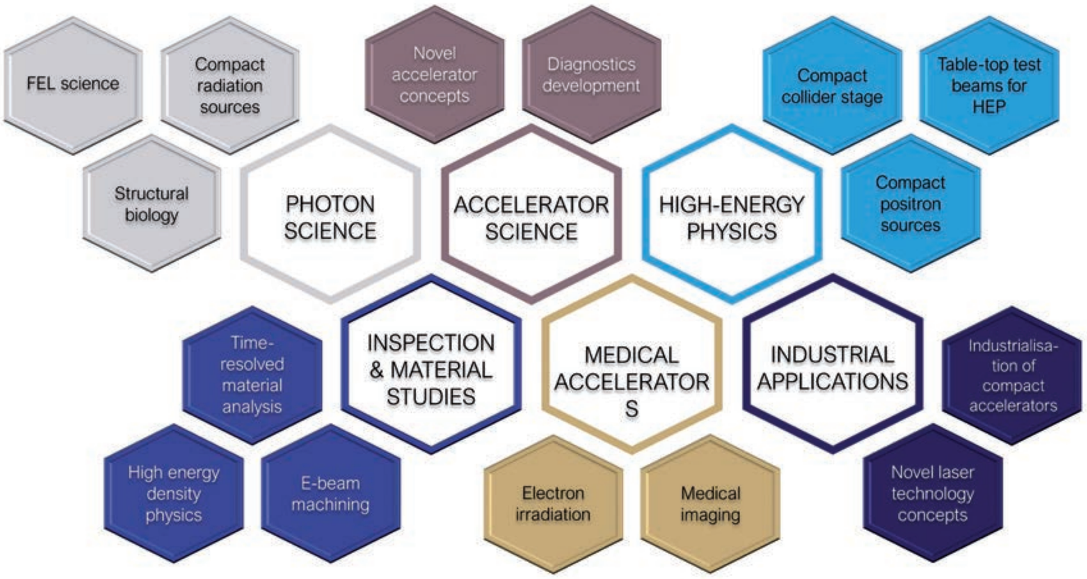

Figure 2

Overview of the applications EuPRAXIA will attempt to reach (Picture: M. Weikum)

The theory and plasma simulation centre will be located in Portugal, building on a long tradition of excellent simulation work at the Instituto Superior Técnico (IST) in Lisbon. So far, many of the simulations for the EuPRAXIA design study have used codes developed by IST, and Lisbon will lead on EuPRAXIA's future simulation efforts.

The application beamlines will be coordinated by a centre in the UK. In the beginning, each experimental site in Germany and Italy will focus on three main applications: Both sites at DESY and INFN plan to offer pilot experiments using FEL radiation as well as positron generation. While DESY focuses on creating ultracompact positron beam sources and table-top test beams, INFN will specialise in generating GeV-class positron beams and provide them for HEP detector test stands. The third specialisation is different: INFN will build a compact Compton source, while Universität Hamburg and DESY focus on medical imaging using X-rays generated as betatron radiation. All these initial application foci are rooted in experience on-site and therefore complement the laboratory environments at both INFN and DESY.

Outreach

While EuPRAXIA members met again in over 20 meetings all over Europe in 2018 to discuss the physics of EuPRAXIA, 2018 marked the year in which EuPRAXIA organised a major outreach event for the public. Participants of the collaboration met with members of the public in July for the "Quantum Leap Towards the Next Generation of Particle Accelerators" symposium in Liverpool, UK. The special outreach occasion offered the public insight into the EuPRAXIA design study as well as opportunities to explore accelerator physics in general both theoretically and experimentally, which especially several visiting school classes took ample advantage of.

The morning session of the symposium featured talks about the science and technology of plasma accelerators. Hands-on demonstrations, such as building marshmallow waves and salad bowl accelerators and playing with the "Surfatron" computer game, helped to explain how this new type of accelerator works and how high-energy particle beams can be controlled and optimised. A poster session additionally showcased the results from EuPRAXIA research to date. In the later part of the day, targeted to newspapers and journalists, the event focused more on the importance of industry–academia collaboration for large-scale research infrastructures such as EuPRAXIA. It included an industry exhibition highlighting the latest technologies and market-ready products as well as talks about the wide range of applications in which accelerators may find use in the future.

Outlook

In the spring of 2019, the whole EuPRAXIA collaboration will meet in Germany in the "EuPRAXIA Retreat in the Alps" to work on and discuss the first draft for the conceptual design report. The aim of the workshop is to exchange open points and remaining technical questions in order to develop a common and exact idea of the conceptual design of EuPRAXIA. The final report will then be prepared over the following months and submitted to the EU at the end of October 2019.

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LUX

A laser plasma accelerator

The Laser-Plasma Driven Undulator X-Ray Source (LUX) is a novel laser plasma accelerator that combines the state of the art in two fields: novel plasma acceleration and modern accelerator technology and diagnostics. After commissioning, LUX demonstrated the first generation of spontaneous, synchrotron-type X-ray pulses at few-nanometre wavelength using a miniature undulator in 2017. In 2018, the facility was tuned to provide more stable and reliable electron beams. It is currently being upgraded to demonstrate first free-electron laser (FEL) gain from a laser plasma accelerator.

The LUX beamline is developed and operated within a close collaboration of DESY and its strategic partner, Universität Hamburg (UHH). Building on the combined expertise of both partners in plasma acceleration and state-of-the-art accelerator technology, the mission of LUX is to advance the technology from single-shot experiments towards stable operation of a laser plasma accelerator and thus to demonstrate the possibility of first pilot applications.

To generate electrons, the ultrashort pulses of the ANGUS 200 TW high-intensity laser are focused into a hydrogen-filled capillary. Here, the laser creates a plasma wave, which traps electrons from the plasma background and then accelerates them to GeV-scale energies within only a few millimetres. LUX has demonstrated the generation of 1 GeV electron beams with 200 pC charge at 1 Hz repetition rate, but is typically operated around 300 MeV and with few 10 pC of bunch charge.

With its 15 m length, the LUX beamline is still very compact, but features state-of-the-art diagnostic instruments, such as beam profile and position monitors, to study the properties of the electron beams as a result of the complex dynamics inside the plasma. Stable operation of the plasma accelerator requires precise control over all the parameters of the facility, especially a well-controlled operation of the driver laser. At LUX, the laser and the plasma accelerator are integrated into the same machine control system that operates the large facilities on the DESY campus. This allows the LUX team to perform extensive parameter scans and to correlate different properties of the generated electron beams with laser and machine parameters. This approach provides valuable tools for studying the laser–plasma interaction and acceleration mechanism and is essential for setting up the facility with optimised electron beam parameters.

Extensive machine studies were used to tune the electron beam parameters with a special focus on improving the electron beam divergence and pointing stability out of the target. LUX will now be upgraded with new beam optics and a cryogenically cooled undulator, which was developed in a close collaboration by UHH and the group of Johannes Bahrdt at HZB in Berlin. The goal is to demonstrate the on-set of FEL lasing using plasma electron beams.

The demoFEL experiment uses a small chicane to longitudinally decompress the electron bunch, which reduces the local energy spread. Although the decompression also reduces the bunch current, simulations have shown that, by carefully balancing the operation parameters and using a tailored undulator design, it should be possible to demonstrate FEL gain.

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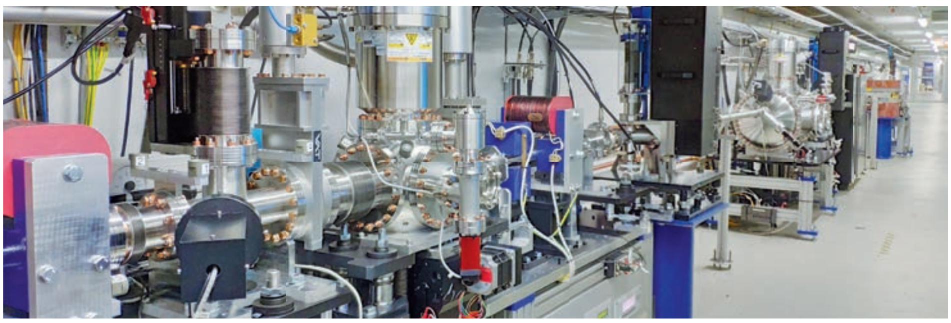
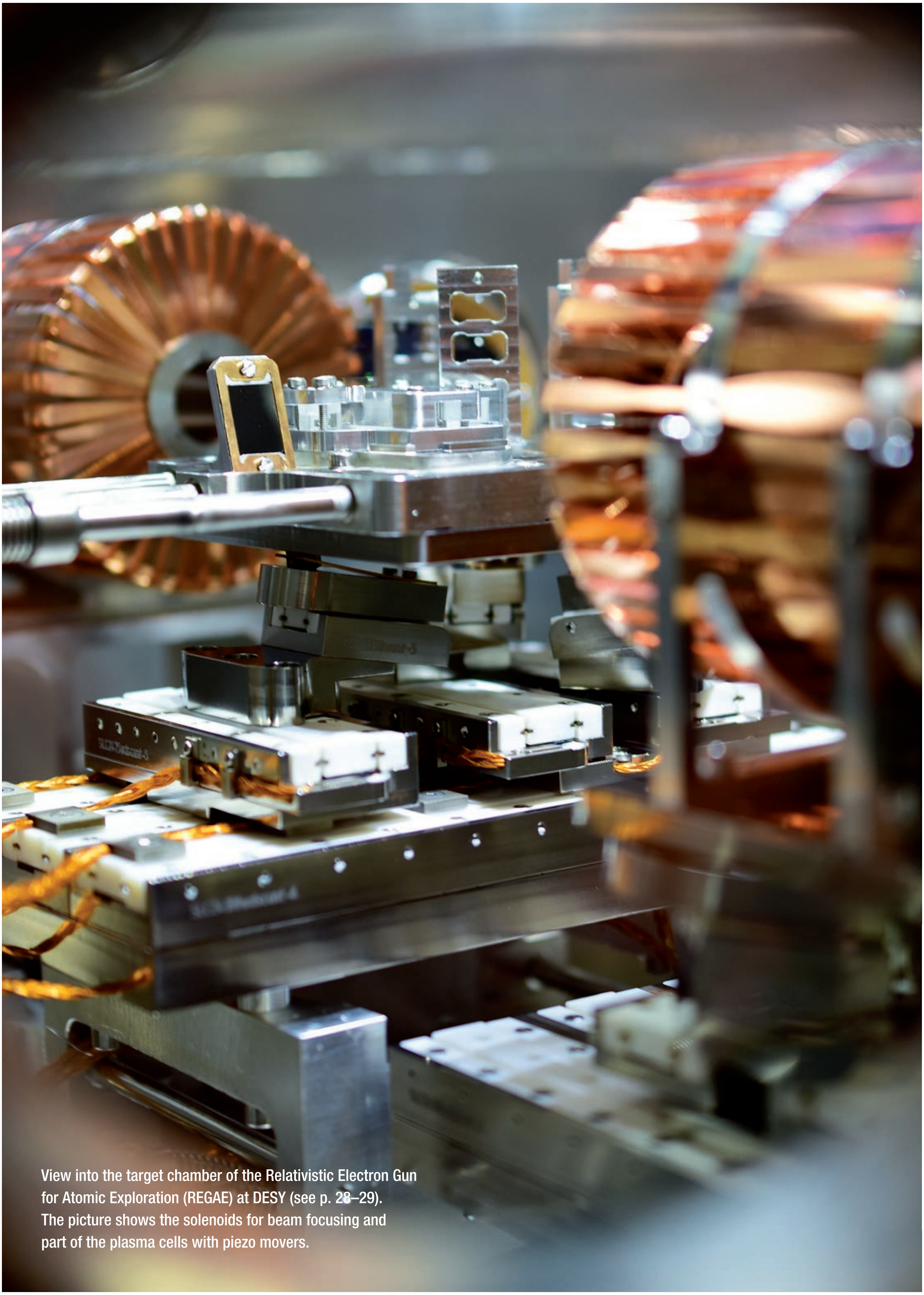


Figure 1

The LUX laser plasma accelerator



View into the target chamber of the Relativistic Electron Gun for Atomic Exploration (REGAE) at DESY (see p. 28–29). The picture shows the solenoids for beam focusing and part of the plasma cells with piezo movers.

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