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# SiLC: Silicon Tracking for the Linear Collider[1]

**Abstract**

SiLC is an International collaborative R&D effort on Si-based technology for tracking at the Future Linear Collider. It addresses as main goals: further progresses on Si-sensor technologies, the electronics for the readout and the data processing, the mechanical issues to build these tracking devices, together with the development of the needed test benches and simulation tools. The collaboration starts from the present-state-of-the-art and is gathering a large worldwide expertise including close contacts with Industry and high tech firms.

[1] *Also posted on: http://lpnhe-lc.in2p3.fr/ and then click on SiLC*

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# 1 Introduction

In the past 15 years, a new detecting technology based on the use of semi-conductor sensors, was developed in High Energy Physics (HEP). The R&D on these devices was driven by the need of highly performing microvertex detectors to tag heavy flavours and especially b-quark in the MARK II experiment at the SLC, in the LEP experiments and in the CDF experiment at Run I at the Tevatron. These devices were instrumental not only to both explore and perform accurate measurements in B-physics, but also to search for the Higgs decaying into $b\bar{b}$ at LEP, and to discover the top quark at the Tevatron. Such microvertex detectors are equipping the currently running B-factory experiments, i.e.: Babar, Belle and HeraB.

Furthermore, the appealing performances of these detectors, combined with the progresses on semi-conductors allowed to build larger size Si-trackers, and thus to use them, not only for tracking very nearby the interaction region, but also for more general tracking applications.

The first large area Si-trackers were achieved by AMS, an experiment embarked on the international spatial station, and by CDF at the Tevatron for Run II. Both detectors cover a surface of 5 to 6 $m^2$.

A challenging R&D was pursued in parallel, since the early 90's in order to develop both highly performing and very large size Si-trackers for the LHC experiments, ATLAS and CMS. At the same time the use of Si-drift detectors for heavy ion experiments led to progresses in this tracking technique (STAR at RHIC and ALICE at the LHC). Besides on the astroparticle side, GLAST is pushing ahead the R&D along the lines of AMS.

Therefore tremendous advances were achieved, making the Si-based tracking a well proven and widely used detector technology.

However Physics needs are always more and more demanding and thus motivate to further pursue this R&D. This is for instance the case, when studying the applications of this technique to the tracking at the future Linear Collider (LC), which is the scope of this proposal. [2]

Many of the groups that have been or still are collaborating to all these various experiments and related Si-tracking R&D's at LEP, B-factories, Tevatron, LHC, RHIC, or astroparticles, are very excited about the physics potential of the LC project. They are forming an international collaboration, SiLC, **Si**licon tracking for the **L**inear **C**ollider, with the aim to perform an active Si-tracking R&D for the LC . The collaboration was initiated at the LC Chicago Workshop in January 2002 and expanded over the last year. Its main R&D goals or "Manifesto" were presented at the various ECFA-DESY extended studies as well as the American LC Workshops and this strong and emerging international effort is converging now in this PRC proposal.

The proposal will discuss in Section 2, the main motivations for having Si-trackers in the LC experiment. Section 3 will be a review of the present-state-of-the-art, and thus

[2] *Besides it might be important to emphasize that the R&D proposed here will serve for future upgrades in the LHC detectors and for astroparticle experiments.*

the legacy from which we are benefitting at the start of this project. The proposed R&D program will be described, in details, in Section 4. It will address the R&D on sensor technologies, on electronics, on mechanical issues, and the related simulation studies and developments. It will also present the various test set-ups that exist in the collaboration or will be developed. It will include a discussion on the work to be done concerning the calibrations, monitoring and slow control needed by such detectors and by the LC environment. Section 5 will present the SiLC collaboration, the membership, the foreseen milestones and timescale, the sharing of the work, the present funding and the futur prospects and needs.

# 2 Motivations and Possible Applications of Si-tracking at the future Linear Collider

Highly performing tracking systems demonstrated to be crucial in all the most outstanding experiments in HEP. Indeed, due to the requirements both of very demanding experimental environment such as, high energy and high luminosity accelerators or sky experiments, and to the Physics to be explored, the detectors must be fully reliable. Besides, they have to be able to measure and reconstruct, in the greatest details, the physics processes occuring in such environments. This means indeed to be able to accurately *track* each produced object from the interaction point to the external parts of the detecting area. Tracking is, in this respect, quite instrumental.

The gaseous and semi-conductor trackers are the most commonly used and well proven techniques. The LHC environment makes it very hard if not impossible to make use of gasseous tracking in the nominal tracking volume. For the future LC, however, the more tractable environment coupled with the high granularity of the TPC will likely make gaseous tracking a workable option for a Linear Collider detector. A program of R&D for building a TPC central tracker for the LC is underway [1].

The option of a large-area silicon tracker, however, either in lieu of a gaseous central tracker, or as an enhancement to gaseous tracking, might well offer a number of advantages to a detector which relies on gaseous central tracking alone. Silicon layers surrounding a TPC could provide for improved momentum resolution, improved interfacing to the calorimeter and vertex detector, and act as a robust fiducial for the calibration of the gaseous TPC tracker. On the other hand, current all-silicon tracking designs are expected to exhibit a precision fully competitive with that of gaseous tracking options, while offering the potential for a substantial savings in material (particularly in the forward direction), a more straightforward calibration procedure, and greater resilence to backgrounds and aging. In addition, because of the compact nature of all-silicon designs, they may well entail a substantial savings in overall detector cost relative to that of detector designs incorporating gaseous tracking.

Our proposal aims to study all the possible applications of Si-tracking in the LC experiment apart from the microvertex. Different possible detector set-ups are considered. They include an all-Si-tracking system à-la-CMS as in the SD-detector proposal [2], or a tracking system that combines the use of Si-tracking with a gaseous central device which can be either a TPC (TESLA TDR [3], or L-project [4]), or a Jet chamber (JLC detector [5]). In this case, the Si-trackers could be positioned at the interface between the microvertex and the TPC chamber, and, similarly, at the interface of the TPC and the calorimetry, both in the central and the forward regions. This is the set-up proposed as the *Si-Envelope* [6]

Physics at the LC will consists in pushing much further the high precision measurements of the standard processes and in exploring all the possible scenarios, i.e. signatures that would indicate new phenomena. This implies the following requirements for the tracking:

- *Excellent pattern recognition.*
- *Very precise momentum measurement in the overall accessible momentum range.*
- *Very accurate momentum measurement at all angles* with respect to the beam axis.
- *Tolerance to backgrounds* and aging.
- *The dE/dx measurement* will be useful both in the relativistic rise region where gaseous detectors are unique, and in the $1/\beta^2$ region, where gaseous and Si-trackers would complement each other.
- *Energy flow.* About 60% of the total energy flow is carried out by charged tracks.
- *Jet recognition and measurement*; The accurate determination of the charged content of jets, dramatically improves the resolution in the jet energy; it also permits to tag the jet origin, i.e. whether it is a $\tau$-, or gluon- or light quark- or b-quark-jet. It also helps in disentangling between neighbouring jets.

An important part of the simulation studies, in the proposed R&D program, will concentrate on studying how well various Si-tracking set-ups address all the above listed issues and also how it compares with or how it could be complementary to other type of trackers and in particular the gaseous devices (see section 4.5).

# 3 Present state-of-the-art in Si-tracking technology

This section is not intended to be a complete review of this tracking technology. Its purpose is just to emphasize what are the main technological aspects that are the most relevant for our application, from the past experiments (LEP and SLC legacy), the presently running detectors (AMS, CDF II, and STAR), and the outcomes of the R&D for LHC (ATLAS and CMS).

## 3.1 *The legacy from past experiments: LEP*

While the first cylindrical geometry silicon tracker was built for the MARK II at the SLC, the technique was refined into its current state-of-the-art by CDF and the LEP experiments. The LEP experiments built microvertex detectors made of double sided Si-microstrip sensors. They developed expertise in minimizing the amount of material for the detector support, including the cooling pipes and the F.E. electronics plus the cabling on detector. They developed the technique for mounting several sensors within one ladder, i.e. building the first *long ladders*; For instance, the DELPHI microvertex was made of ladders comprising six sensors. Very low noise preamplifier and shaping chips, called VA-1 [7], were designed. They were a starting point for the VFE electronics used in other experiments such as for instance AMS, and they serve as starting point in our case too (see subsection 4.2).

## 3.2 *The Si-trackers in running experiments*

Here we are considering three main cases: AMS, CDF II and STAR. Each of them, provide useful outcomes that this R&D program intends to pursue.

### 3.2.1 *The AMS Si-tracker*

AMS tracker is presently serving as a starting point in the part of our activity devoted to develop long microstrips made by *long ladders*, as basic element of these type of Si-trackers. Also AMS is, with CDF II, the Si-tracking system that covers the largest area, namely: about 6 $m^2$. This is indeed in the AMS-02 version; It was 2.1 $m^2$ in the AMS-01 configuration [8], [9] and [10].

Indeed AMS experiment took over the advances achieved in building the microvertex for LEP II, and developed in particular: longer ladders and associated long shaping time and low noise VFE electronics.
A technique to build in a semi-automatised way, long ladders with up to 15 sensors and a resolution in the positioning of the sensors on the ladder of a few microns was set-up in this experiment with furthermore, a technological transfer to Industry [11]. To read out long ladders, a very front end chip derived from VA-1, included a long shaping time that permitted to keep low noise performances [12] and [13]. Both features are very interesting for one of the R& D alternatives considered in our project (see 4.1 and 4.2).

### 3.2.2 *The CDF II Si-tracking system*

For the Run II at the Tevatron, CDF built a new microvertex detector based on 5 layers of double-sided Si-microstrips [14]. Each ladder in this case includes 3 sensors bonded to each other. In addition there is the ISL detector [15] that plays the interface between the microvertex and the COT (pretty much as the SIT in the TESLA TDR detector design). All together this Si-system covers 5.5 $m^2$.

Due to the high luminosity and high energy $p\bar{p}$ environment, a very sophisticated and in realtime processing of the microvertex information was developed. The corresponding SVT processor [16], combines at the Level2 trigger, the information from the microvertex with the processed information from the COT as delivered by a dedicated trigger system that operates at Level 1 [17]. This realtime processing of the data could be interesting to adapt in the LC case. This is one aspect that we will further discuss in the section 4.2

of this proposal. Eventually also we are looking closely to the FE chips characteristics developed for this experiment. Some features might be interesting for the LC case.

### 3.2.3 *The STAR microvertex*

The STAR experiment at RHIC pioneered the concept of a large area Silicon vertex and tracking device based on Si-drift wafers [18] to [27]. Since this technology was successfully employed for single wafer multiplicity counters in CERN-SPS heavy-ion experiments, STAR decided to build a three barrel detector covering a total of 0.7 $m^2$ with about 13 Million pixels and 103,680 readout channels. This device, the STAR Silicon Vertex Tracker (SVT), is in operation since 2001 and demonstrates the capabilities of true 3d tracking detector based on Silicon.

The extensive R&D, production and construction work regarding sensor technology, associated frontend electronics, readout electronics, as well cooling and mechanical support was very detailed and is being continued for the inner tracking system in the LHC ALICE experiment. These accomplishments will serve as a solid starting point for further developments of silicon drift detectors towards a possible use at the LC, which is another R&D project pursued in our collaboration. Silicon drift is the only solid state alternative to gas detectors that provides actual 3d tracking. Furthermore it has very attractive features in terms of very precise time measurements.

These different aspects will be presented in detail in section 4.

## 3.3 *The Si-trackers for the future LHC experiments*

The particularly harsh LHC environment with very high radiation levels, high speed cycling, high luminosity and high energy led to very challenging R&D's particularly for the tracking systems. The Si-trackers are a key feature of the ATLAS and CMS trackers and cover very large surfaces of the order of 200 $m^2$. Although the environmental conditions are quite different at the futur LC, the advances made for the LHC are quite useful in several aspects. Among them certainly it is the first time that such impressive Si-detector area are built and there is a lot for us to learn. The pros and the cons about the construction of the CMS and ATLAS detector, in terms of support structure, cooling systems, cabling, transmission of data etc... are interesting to study. The sensor technology developed for the CMS external tracker is taken as start for our development on very large area Si-trackers [28]. The pros and cons of completely automatized production of the basic ladder element as opposed to the way it is handled in AMS are also part of our R&D developments and studies. All these various issues will be discussed in some details in the next section.

# 4 The R&D Program and Main Objectives

As introduced in Section 2, this proposal considers two Si-tracking concepts for the Linear collider. One of them is a all Si-tracking system as in the SD detector. The other one, the Si-Envelope, includes a TPC as main central tracker and an ensemble of Si-trackers that surrounds the gaseous device. These Si-trackers are positioned at the interface between the microvertex (SVX) and the TPC (SIT: Silicon Internal Tracker), at the interface between the TPC and the calorimetry (SET: Silicon External Tracker), and similarly in the forward direction, the FTD (Forward Tracking Detector), is located between the microvertex and the TPC and the FCH chambers are sitting between the TPC and the calorimetry and are all made in Silicon technology. Figure 1 shows a sketch of these two alternatives.

Independently of the detector concept, a common generic R&D will be pursued by this collaboration in the three coming years (mid 2003 till end 2006).
Its main R&D objectives as well as the first outcomes of the R&D activities that are already undertaken, are described in some details in this section.

The main goal of the collaboration is to start from the present-state-of-the-art briefly summarized in the previous section, and to push ahead these R&D's that led to the presently running Si-trackers, and to those now under construction for LHC.

## 4.1 *R&D on Sensor Technologies*

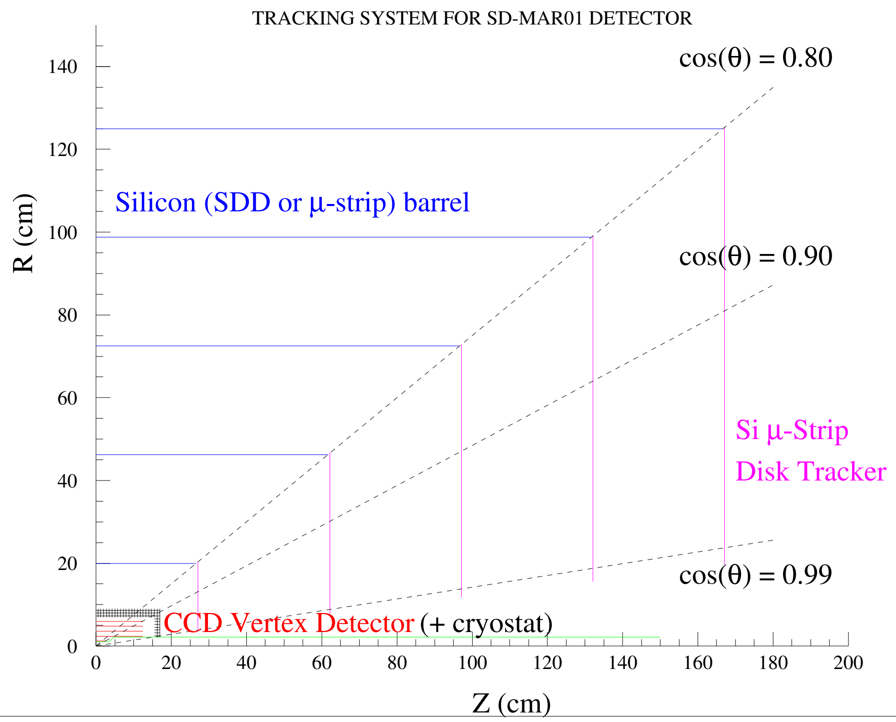
This collaboration intends to have an opened view on all the various possible sensor technologies that could be applied to our case. Thus a generic R&D on this topic will be pursued. This means that our studies will be done in collaboration both with some of the relevant high tech firms that produce such semi-conductors and with the solid state Institutes or Research Laboratories that are investigating the properties of semi-conducting materials. The goals are on one hand to make further progresses on the currently used sensor technologies such as the Si-microstrips or the Si-drift, and on the other hand, to keep an opened eye on the new developments.

Thus three main R&D streams will be pursued:

- *The Si-microstrips.* The present search is driven by the possibility to apply the long ladder technique to the construction of an overall Si-tracking system for the LC detector.
  Appealing benefits of this technique are: a substantial reduction of read-out channels, thus less material and less power consumption as well as a simplification of the mechanical design, leading to excellent momentum resolution at all momenta, and optimal interfacing with the calorimetry. (see next subsection 4.2)

  The present R&D starts from the expertise of both the AMS and the GLAST groups. The R&D on these detectors is associated to the development of long shaping time and low noise F.E. electronics and also on looking for larger size wafer. The commonly used wafer technology is based on 6" wafers. The 8" wafers are presently underway and we are also looking for 12" wafers. The goals are also to diminish as much as possible the wafer thickness at the same time they increase in size, to improve the yield and push further the double-sided technology.

  To test in detail the main features of long microstrip detectors obtained by bonding a large number of smaller size sensors, two prototype ladders are under construction. One, now built at LPNHE in Paris, is based on the AMS technique to make long ladders, and has output kapton designed in such way as to permit the testing of



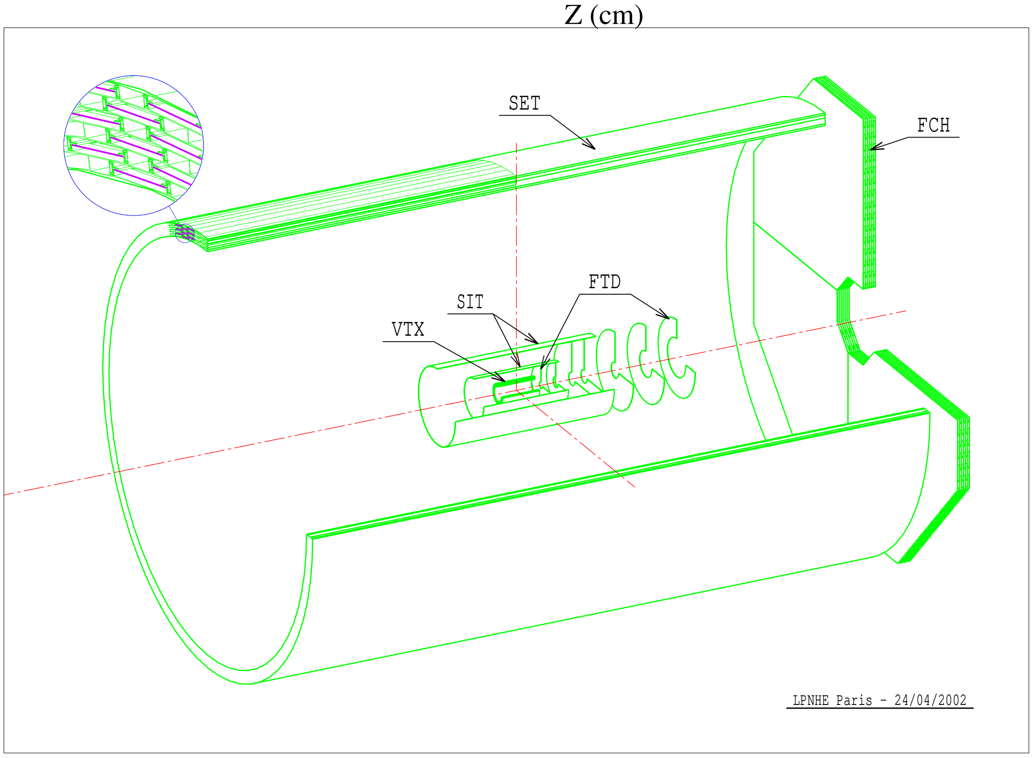




Figure 1: Schematic views of the two detector concepts: the all-Si-tracker as the SD detector (on the top) and the Si-Envelope (at the bottom), that comprises the following ensemble of Si trackers: SIT + SET + FTD + FCH, surrounding the gaseous central tracking device. The Si-envelope proposed for the TESLA detector also fits with a L-detector or the JLC detector as presently designed.

various microstrip lengthes. This is shown in Figure 2
The other, under development at SCIPP at the University of California at Santa Cruz, will be instrumented with an optimized custom ASIC that is currently under development at SCIPP (see Section 4.2.1)

- *The Si-drift sensors* A silicon drift detector may be envisioned as a solid state time projection chamber. In the STAR-SVT highly homogeneous Neutron Transmutation Doped (NTD) n-type silicon wafers, produced by Wacker with a thickness of 280 micron and a resistivity of 3 kOhm-cm, were used as starting material and several structures were implanted on each detector. p+ strips (cathodes) are implanted symmetrically on both the top and bottom of the wafer and symmetrically biased with a potential having a gradient in the drift direction ($\Delta V$ in STAR = -1500 V, which amounts to a drift velocity of 6.75 $\mu$m/ns, ).

  Segmented n+ anodes are located at the edge of the detector and run in a direction parallel to the p+ strips. A potential valley (as seen by an electron) is formed by the p+/n junctions on both sides of the wafer such that ionized electrons generated by the passage of an energetic charged particle drift to the middle of the detector and towards the segmented anodes. The valley thus serves to constrain the electrons away from the surface of the detector to ensure full charge collection. The hit anodes determine one coordinate, and the drift time from the initial particle hit to readout of the signal determines the second coordinate.

  The ongoing Si-drift R&D is based on the very successful completion and operation of the STAR Silicon Vertex Tracker and the ALICE Inner Tracking System which is presently under construction. Specific sensor R&D issues towards a large area barrel tracking detector for the LC include re-design of the sensor for longer drift distances, i.e. larger wafers (6 or 8 inch), higher on-detector voltage gradients (exceeding 2000 V), and possibly on-detector frontend electronics implantation to reduce the cooling and radiation length requirements. The position resolution achieved with the STAR vertex tracker is around 10 and 15 $\mu$m for the anode and drift direction, respectively. We believe the detector layout can be optimized to further improve these numbers.

  In addition, thinning of the sensors and electronics to reduce the material budget is actively pursued in collaboration with the LHC Si-pixel groups in CMS and ATLAS. Prototype ladders, based on the original STAR drift sensors and a novel mechanical support design employed in the STAR Silicon strip layer, have been designed, and will be tested with varying detector operation parameters, such as different drift voltage gradients and cooling conditions. A complete re-design of the original STAR detector mask layout is envisioned using various design options in terms of anode and cathode spacing, variation of implanted resistor strength, variation of high voltage gradient and thus of guard area size, and implantation of preamplification stage in the sensor itself.

  The BNL semi-conductor laboratory in the BNL Instrumentation division is collaborating with the WSU physicists on these mask designs and on subsequently

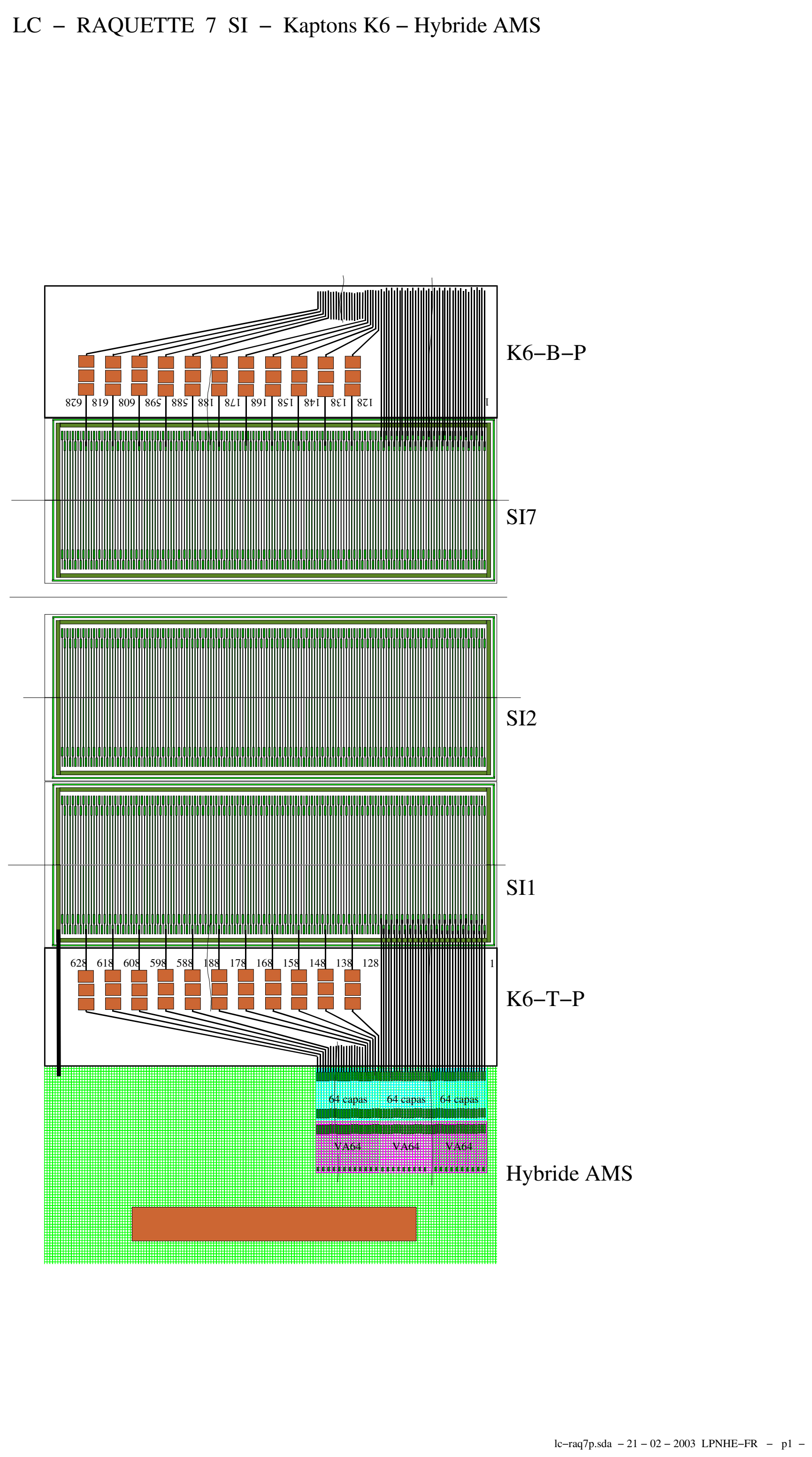



Figure 2: The long ladder prototype made from 7 AMS sensors, using the AMS technique to build long ladders and read out by VA-64-hdr chip.

producing a 25-wafer prototype batch in house. In addition, a mechanical support structure, originally designed for a layer of Silicon strip detectors at larger radii in STAR, will be modified to host a ladder of STAR drift detectors for the first 'long ladder' Si-drift prototype. WSU and BNL have collaborated on detector development, prototyping and testing of Silicon Drift detectors for the past ten years, and the clean room and testing facilities at BNL, specifically designed for Si-drift ladder production and testing, will be utilized to continue this work towards a LC tracking detector. Funding for this effort was requested from the National Science Foundation (NSF) and the proposal has received positive reviews. We expect funding to start by the middle of 2003.

- *New sensors*. The goal of this R&D will be to consider or even to trigger the development of new ideas as for instance investigating possible new materials, or solutions where the very front end readout is sitting on the sensor, like in the CMOS technique, or the SOI-type etc... These are possibilities that will be tested. Depending the location, the size and even the functions of the Si-tracker to be built it could be needed to consider different types of sensors.

The R&D work on sensor technologies will be performed in close contact with SINTEF, CSEM, EUROSYS, CANBERRA for the Si-drift, with HAMAMATSU, MICRON and ST Microelectronics for the the Si-microstrips. Note that it already exists, within our framework, a long term collaboration with some of these high tech firms. Besides, several solid state Laboratories or Microelectronics Research Lab [such as for instance: CNM (Centro Nacional de Microelectronica) in Barcelona (Spain), and ITC (Istituto Trentino per la Cultura–Istituto per la Ricerca Scientifica e Tecnologica) in Trento (Italy)], are or will be collaborating to this project.

## 4.2 *R&D on Electronics*

At the present time most of the ongoing activity is centered on the VFE electronics issues for each type of sensor. However the proposed R&D program will address all the issues related to the complete readout electronic chain for these devices. This includes the following list of questions:

- *Development of the VFE electronics related to each sensor-type.*
- *Digitization in the on-detector electronics.*
- *Sparsification, pedestal substraction in the on-detector electronics.*
- *Techniques for the time measurement.*
- *Charge thus pulseheight measurement, related to the next point on clusterization.*
- *Pre-processing of data at the earliest possible level (clusterization).*
- *"Triggering" or realtime processing of the Si-data, using in particular, the capabilities of a standalone Si-tracking system.*

- *Issues related to the transmission of the data from the detector to the outside DAQ system.*
- *Going to submicroelectronics.*
- *Packaging and Cabling*
- *Possibility of switching on-off the electronics with the machine cycle, for saving power consumption.*
- *Integration in the overall detector DAQ system.*

The currently on-going R&D activities on these topics are briefly summarized here below.

### 4.2.1 *VFE electronics for the long microstrips*

Two groups are investigating the VFE readout for the long microstrips, they start from the present experience.

- *The Santa Cruz team*
  SCIPP has embarked upon a program to develop an optimized front-end ASIC to read out long silicon detector ladders. This work is being funded by the Advanced Detector Research and Development (ADR) program of the United States Department of Energy [29]. The motivation for this work is as follows.

  Since signal-to-noise improves as the square root of shaping time, it may be possible to construct a large-volume central tracker, such as that of the North American SD design, with very long individual detector ladders, enabling the detector to be read out at its ends only. In addition, by exploiting the limited duty cycle of either the TESLA or JLC/NLC design ($10^{-2}$ or less), it should be possible to eliminate the need for active cooling of the electronics.

  Taken together, these two attributes would allow for a detector that presents a minimum of material to passing tracks, both in the central and forward ('endcap') regions. Figure 3 shows the momentum resolution of such a detector, as a function of momentum, for central ($\cos\theta = 0$) tracks assuming a space-point resolution of 7 $\mu$m. Such a tracker would be fully competitive with proposed gaseous tracking solutions over the full range of track momenta, and would achieve the $\delta p_\perp/p_\perp^2$ resolution of $2-5\times10^{-5}$ GeV$^{-1}$ demanded by the Higgs recoil-mass analysis. In addition, it would provide a minimal degradation of track parameter information in the transition into the calorimeter. This is particularly true in the forward direction – a region that typically receives less attention in $e^+e^-$ physics, but which has an increased relevance at a TeV-scale machine.

  The initial phase of this study was to develop a pulse-development simulation that allows for the optimization of a prototype front-end Application Specific Integrated Circuit (ASIC) chip. This simulation package takes into account detector geometry and biasing, Landau statistics in the passage of minimum-ionizing particles through the detector bulk, Lorentz angle (magnetic field) effects, diffusion and instanteneous space-charge repulsion, shot and electronic readout noise, and digitzation effects.

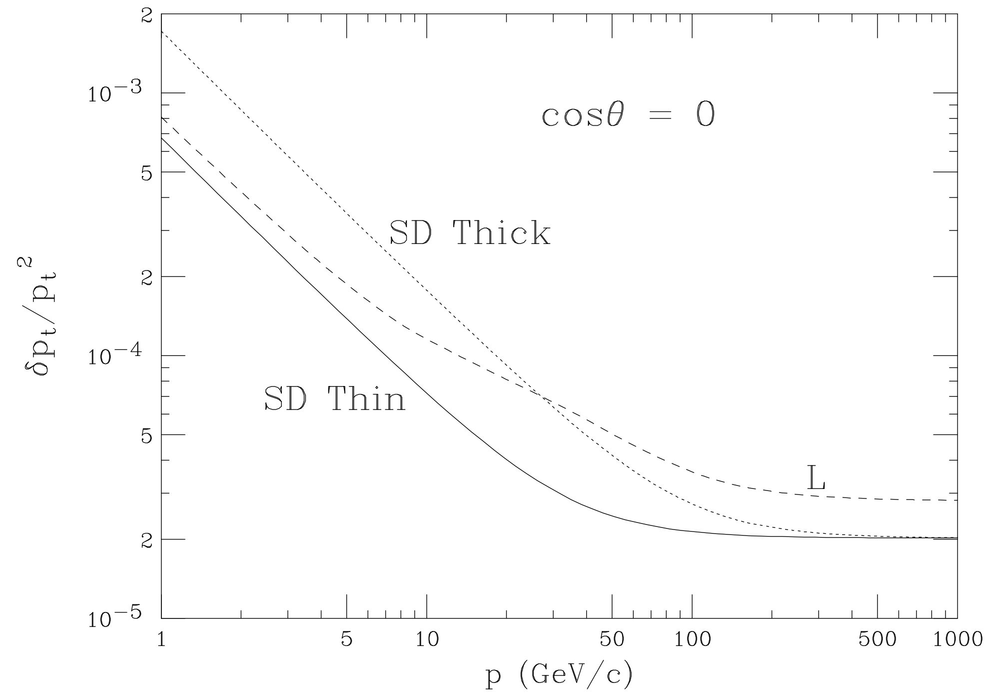



Figure 3: Momentum resolution for $\cos\theta = 0$ tracks for an ideal long shaping-time silicon tracker.

This simulation is currently being used to optimize the electronic shaping time, explore the tradeoffs between direct analog versus time-over-threshold pulse integration, establish digitization specifications, optimize detector geometry, and establish sensor specifications. Of particular importance for long ladders is the issue of signal-to-noise for minimum-ionizing particles. With long shaping time, there is no ballistic deficit (charge collection lost in the electronic filtering process); however, the high magnetic field leads to substantial sharing of charge between neighboring channels, due to the substantial Lorentz angle. Figure 4 shows the efficiency and occupancy expected for a 167 cm ladder of 300 $\mu$m-thick silicon sensors (the outermost layer of the proposed SD tracker) for straight-through minimum ionizing tracks, assuming a 3 $\mu$s shaping time and the nominal SD detector magnetic field of 5T. The process simulated is the Agilent 0.5 $\mu$m process, qualified by experience with the GLAST tracking-calorimeter [30] front-end readout chip. At an occupancy of 0.1%, the simulation shows an expected efficiency of 99.9%, indicating that it is realistic to consider operating a ladder of this length.

The process of laying designing the optimized ASIC has begun at SCIPP, and a submission in summer 2003 is envisioned.

- *The LPNHE - Paris 6 team*, after reviewing the F.E. electronics for Si-trackers currently available on the market, is now starting to work with the AMS VFE electronics device, i.e. the VA-64-hdr chip (see Figure 5). It is derived from the VA-1 series that was developed to read out some of the LEP microvertex detectors. In the case of AMS it is associated with a long shaping time of about 5 to 6 $\mu$sec. The

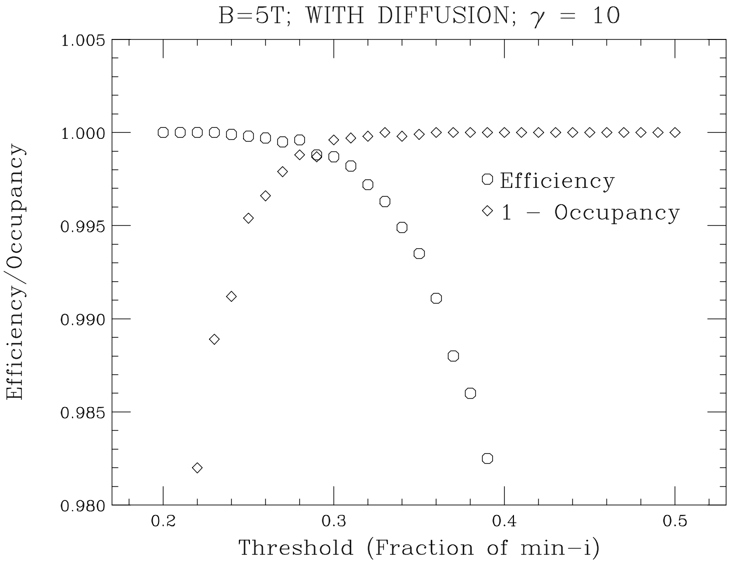



Figure 4: Plot of efficiency and (1 - occupancy) for a 167 ladder read out with a 3 $\mu$s shaping time, for a 300 $\mu$m thick detector operated in a 5T magentic field.

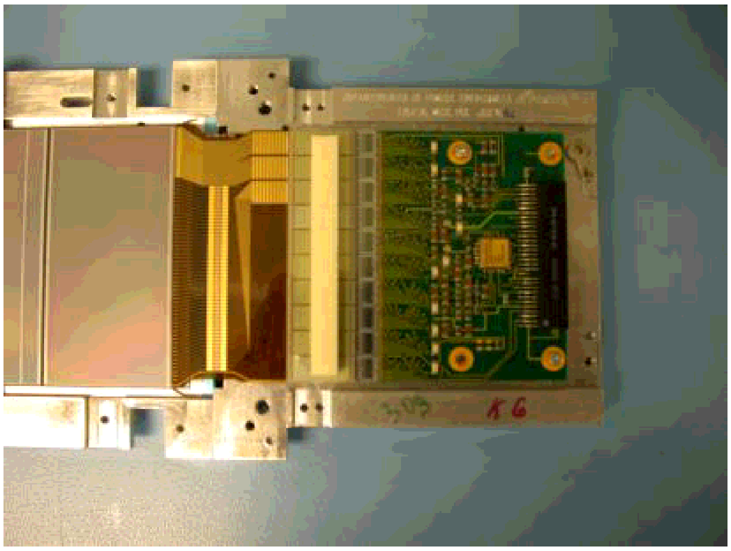


Figure 5: Photograph of the F.E. electronics readout installed on the output kapton of the long ladder prototype now under test.

total noise N in electron equivalent was measured to be: $N = 350 + 4 \times C$ [12]. The goal is to design a V.F.E. circuit with low noise performances, similar to the VA-circuitry but tunned to the LC specific needs, such as in particular a shaping time of order 1 $\mu$sec, and possibly with the option to be switched on-off with the machine cycle and a low power dissipation, about at most 0.3 mWatt. Apart from the VA-chip, other low noise preamplifier circuits that are currently available will be tested.
The noise and signal evolution in function of the microstrip length, of the shaping time duration, of the increase in temperature, and of the sensor characteristics, will be evaluated. These data will serve as useful inputs to define the characteristics of the VFE electronics that has to be built. This test work is now starting at the LPNHE-Paris 6 Laboratory. As a result of these studies, the design of a VFE chip is foreseen to start in fall 2003 and to be submitted to foundry towards the first trimester of 2004, in 0.35 $\mu$m AMS technology.

#### 4.2.2 *VFE electronics for the Si-drifts*

The existing frontend electronics design for Silicon drift detectors is based on the operating STAR design [19]. Due to the small driving capability of Silicon drift detectors a preamplification stage near or on the detector is required. STAR opted for a wirebonded frontend, but R&D towards tape automated bonding (TAB) and even frontend implantation is actively pursued by WSU and BNL in collaboration with the French STAR groups in Nantes and Strasbourg. TAB was successfully applied for the STAR Silicon strip layer.

Figure 6 shows the layout of the presently employed STAR-SVT frontend multi-chip module (MCM).

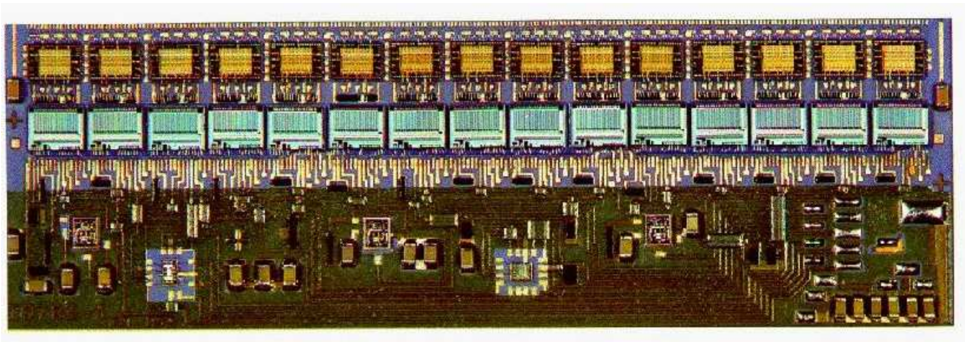


Figure 6: layout of a STAR-SVT beryllia based multi-chip module (MCM) hosting the frontend electronics (PASA,SCA,multiplexer).

A row of 240 input pads that are spaced at the detector anode pitch of 250 $\mu$m are intended to be wire bonded to the detector anodes. Each of these pads has a second wire bond to an input pad of the PreAmplifer ShAper (PASA) die. The low input capacitance permits a fast preamplifier-shaper response due to the lower series (capacitance dependent) noise. A fast impulse response is desirable for good separation of charge from two hits arriving on the same anode(two-track resolution). 'Fast' is therefore defined relative to the expected separations and widths of adjacent hits and in the case of the SVT refers to a risetime of 50 ns. It is necessary to have waveform sampling to preserve both timing and dE/dx information. In order to avoid corruption of the output waveform the sampling frequency should be greater than twice the PASA bandwidth of about 10 MHz. We chose 25MHz, which together with the drift time of about 4.5 $\mu$s suggests that the number of samples be greater than 112. The front-end is thus designed for 128 samples which, as a power of two, is naturally implemented. In order to reduce the number of output channels per MCM (nominally 240), it is desirable to have a level of multiplexing at the MCM. Due to the waveform sampling, however, there are $128 \times 240 = 30,720$ pixels per MCM.

A solution involving front-end digitization before multiplexing is prohibitive due to the large number of pixels. An analog multiplexing scheme is required and is implemented with Switched Capacitor Array (SCA) integrated circuits. Each SCA is operated as a circular memory buffer. The output PASA waveform is sequentially sampled on each of the 128 capacitors on a given SCA channel. After 128 capacitors have been written, an internal counter resets and sampling continues, overwriting previous values. The SCA and thus the detector is continuously active until a trigger is received and readout of the SCAs begins. The signals on all $128 \times 16 = 2048$ capacitors per SCA are multiplexed onto one common analog output. An arbitrary number of SCA's may be multiplexed together. In the implementation chosen for the SVT, groups of five SCA's (80 channels or 10,240 pixels) are multiplexed. Therefore there are three analog outputs per MCM. Analog Devices' Buf04 analog drivers were used to drive the output.

A commercial CMOS chip for the SCA control circuitry and an ECL chip for the differential clock to the SCA are also shown in Figure 6. Recently this design of separated PASA, SCA and off-detector ADC chips, has been modified by the ALICE collaboration, which successfully developed a three-stage (PASA,SCA,ADC) single low-noise, low power consumption CMOS chip. This new ALICE chip, as well as earlier prototypes of Darlington-pair type implanted pre-amplification stages are currently being considered by our collaboration for the development of a LC tracker.

#### 4.2.3 *Very preliminary sketch of the Si-readout system*

In the case of the Si-envelope, based on long microstrip technology, a preliminary sketch of the readout electronic chain is studied [6].
As outlined in Figure 7, and discussed in subsection 4.2.1, the very front-end will be defined by a low noise preamplifier, followed by the shaper, with a typical shaping time of 1$\mu$sec for a 60 cm long microstrip, and then stored on an analog pipeline. The long-shaped signal will be strobed. The strobe could be defined by the start of the train of bunches as given by the machine, and the bunch number in the train at which the signal occured.

The F.E. chain for 128 channels will be grouped into one single-chip (as it is done for instance in the APV25 front-end chip in CMS). An additional 2 to 1 multiplexing will be applied at the entrance of the ADC, that will thus treat 256 channels. The digitisation, sparsificitation and buffering will be done on the detector and possibly this F.E. readout chain will be implemented into one single chip.

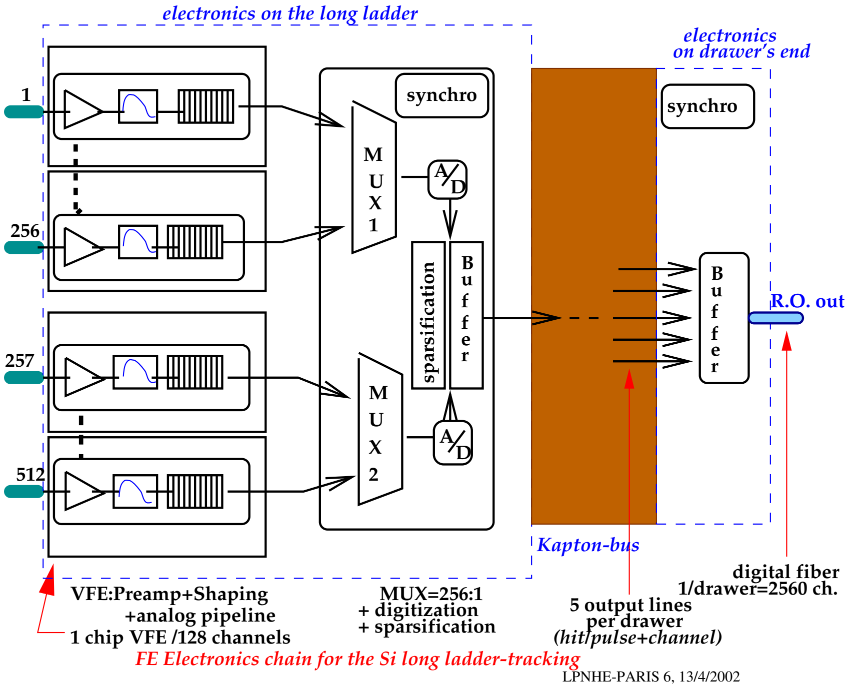



Figure 7: *Schema of the Front-End Electronic chain of the Si-trackers part of the Si-Envelope for the TPC (SET case)*

In this foreseen schema, a rather small number of digital optical fibers, will be sending the digitised signals to the outside world. At an upper stage in the DAQ system, a realtime processing of these data will perform clusterisation, centroid determination and eventually a full track reconstruction for the Si-standalone system.

Revisiting a few ideas presently implemented in AMS, LEP, CDF and CMS or ATLAS experiments, adding some new inputs and profiting from progresses in submicroelectronics and processors, a performant new readout system is going to be developed in this R&D program.

The Silicon drift detector readout for the LC will depend on which frontend will be chosen. Either the ADC is an on-detector component or it will require an off-detector RDO board including an analog line driver. This latter design is presently employed by STAR.

On the STAR TPC support wheel 24 SVT readout electronics (RDO) boxes are mounted, twelve on each side of STAR. Each RDO box has 54 analog inputs. Data acquisition is performed at 8/3 of the RHIC strobe frequency (25 MHz). Digitization occurs at 60/36 of the fiber link frequency of 60 MHz (1.67 MHz). The total duration of digitization and fiber optic transfer is about 7.3 ms. The RDO system is split into three functional blocks: a monitoring, power, trigger and slow control interface block (PTB), an analog to digital converter and data storage block (AMB), and a fiber optic transfer block (FOB). These blocks are implemented on VME 6U-size boards, connected via VME-like back planes. In STAR sparsification (zero-suppression) occurs in the DAQ part of the SVT electronics after data transfer through the fiberlinks. This function could also be transfered to the PGA's on the AMB boards, if necessary.

If the implementation of the ADC stage onto the detector via the ALICE prototype chip is successful and the power consumption sufficiently low to not require extensive external cooling one could envision on-detector sparsification. This is one of the major R&D areas of the SiLC silicon drift collaboration.

## 4.3 *R&D on Mechanics*

Mechanics are a major issue to build the appropriate Si-trackers for the LC. The main challenges are: the need for an "extreme" transparency or, in other words, as less material as (im)possible, very high precision in position, large detector surface, as well as cheap and easy to build devices. This implies a true and multi-facet R&D on those mechanics issues. A real step forward must be achieved in mechanics as compared to the presently running or under construction detectors. All these issues will be addressed in this project, following the list of items here below:

- *Detailed CAD design of a Si-tracker.* It includes the design of the basic element, namely: the ladder, all the various components of the mechanical structure of the detector up to the overall mechanical support structure.
- *Transparency related issues and studies.*
- *Cooling issues: Tests on mechanical prototypes and CAD computations.*
- *Tests and studies on the materials to use for the overall mechanical structure and also for the surrounding systems such as for instance the cooling system.*
- *Mechanical precision studies.*
- *Alignment issues.*
- *Mechanical constraints studies.*
- *Technique to build the basic element of the detector (as for instance the long ladder) and related study of technological transfer to Industry.*
- *Study on mechanical prototypes of the feasibility of proposed mechanical design for the various pieces of the Si-tracking detector and related study of technological transfer to Industry.*

It should be first noted that there is a special feature to the Si-detectors: for various aspects, mechanical studies are closely related to the electronics.

The R&D activities started on some of these issues are briefly described in the next subsections.

#### 4.3.1 *CAD design of the Si-envelope, and outcomes*

The LPNHE - Paris 6 group is studying a Si-tracking system based on the TESLA TDR detector design [3]. It is made of an ensemble of Si-trackers, namely: the SIT (Silicon Internal Tracker) plus the FTD (Forward Tracking Detector) located at the interface of the microvertex and the TPC, the SET (Silicon External Tracker) which is a proposed new device [31], at the interface of the TPC and the e.m. calorimetry in the central barrel; furthermore, it is proposed to build the FCH, Forward CHambers, using the Si-technique. This serie of Si-trackers that surrounds the TPC is called the *"Si-envelope"* [6].

A CAD mechanical design of the Si-envelope is undergoing. It is based on the use of long ladders as basic element to construct this ensemble. The different pieces of the corresponding mechanical architecture are thus:

- *The long ladders*, made of several sensors and, in average, 60 cm long in the present design. It includes the VFE electronics (as defined in subsection 4.2.3) sitting at one end of the ladder as shown in Figure 8

- *The drawers* that gather several ladders belonging to a same Si-layer in the detector. It includes the cabling, the cooling and the service electronics, as shown in Figure 8.

- *The overall mechanical support structure* which is a light C-fiber alveolar structure as shown in Figure 8.

A rather detailed mechanical design is already achieved using EUCLID and now CATIA CAD software packages, following the lines described just above, for the large area external tracker, SET, and for the internal tracker, SIT.

The CAD design of the Si-FCH device based on long ladders is underway. Two alternatives are worked out: a projective design and an XUV-design. The projective design similar to the FTD detector or to the forward Si-trackers of ATLAS and CMS experiments, was explored (see Figure 9).

It does not allow to use long microstrips and thus it leads to a dramatic increase in the number of channels, the power consumption and it makes the overall mechanical design more complicated and difficult to build. Besides, one should note that compared to the LHC experiment the radius to be covered by this detector is significantly larger.

On the contrary, a rather simple and modular Si-FCH design is underway, based on XUV geometry. In this case, the detector shape is octogonal as the one of the e.m. calorimeter behind it. The Si-FCH can be made either of one single piece or else divided into 2 pieces. It depends on the option that is chosen to open the overall detector to access the central barrel. Independently of this fact, the XUV alternative provides a simple and modular way to build the Si-FCH using only 3 different ladder lengthes, namely made of 4, 5 or 6 sensors. The sensors will be the same than the ones used for the SET device.

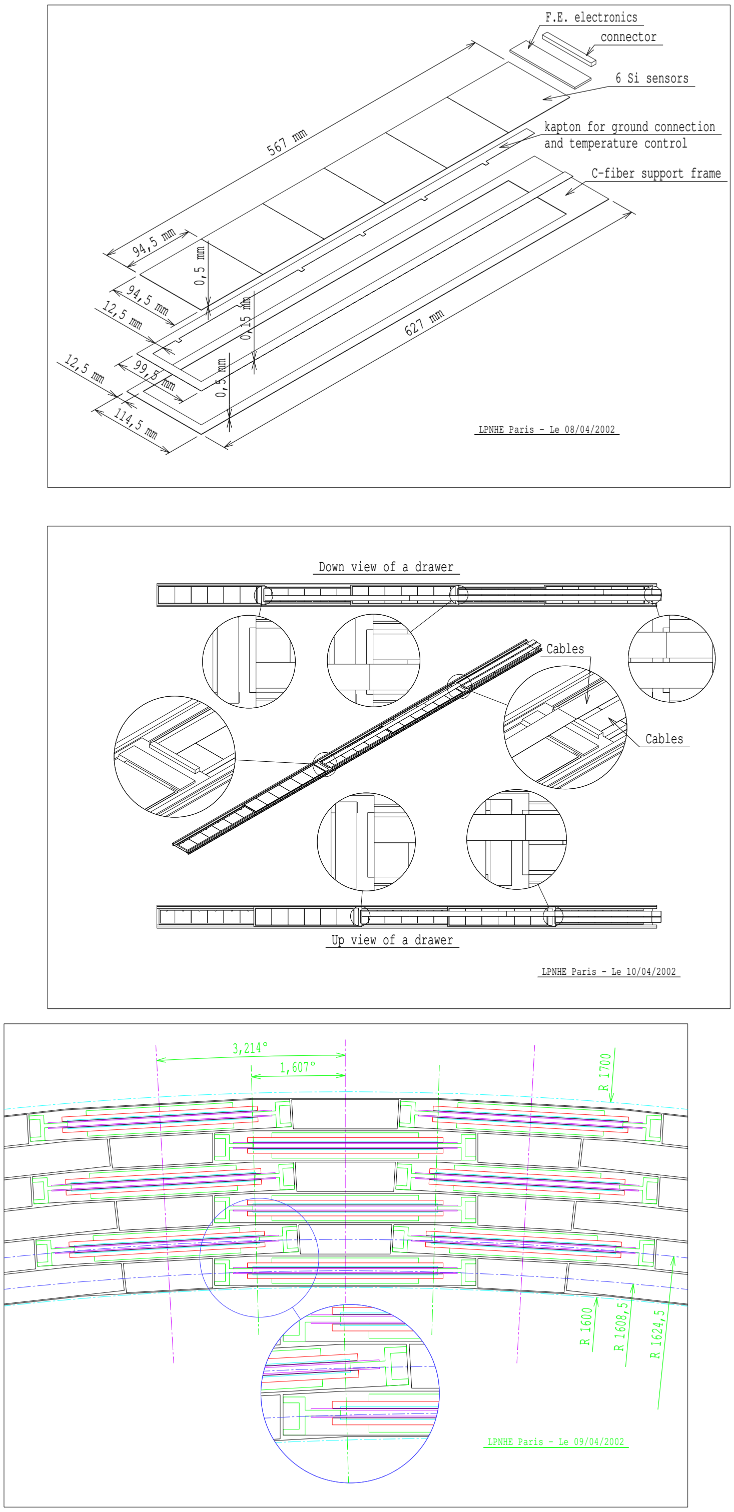



Figure 8: The various elements of the detailed EUCLID CAD design of the trackers in the Si-envelope are: the long ladder (top figure) that are included in the drawer (figure in the middle) and the overall alveolar structure (figure at the bottom).

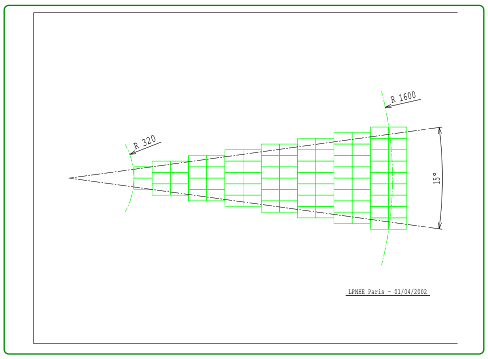



Figure 9: Si-FCH detector design assuming a projective layout, thus short microstrip sensors.

Two possible XUV designs are considered. One is based on single-sided sensors. It consists in building 3 honeycomb structures similar to the one of the SET detector and tilted by 45 degrees with respect to each other. The first structure will include 4 X-plans, the following one 4 U-plans and the last one, 4 V-plans (see Figure 10).

The other possibility is to build an honeycomb structure for each XUV-triplet, as shown in the Figure 11 and to have a total of 4 XUV honeycomb structures, one per triplet.

The second XUV design is based on the use of double-sided UV sensors. It consists of two single-sided X-plans that are located at the two extreme sides of the Si-FCH system, and in between, the 4 UV double-sided plans that will be included into one single honeycomb struture.

A detailed detector simulation is just starting in order to study the pros and the cons of each one of these alternatives in terms of the Si-FCH performances and especially of the track pattern and reconstructions issues.

It is important to make here the following remarks:

- *The design of the Si-envelope gives the opportunity to address all the different possible applications of a Si-tracker in the LC detector*, namely: large area central layers (SET) – also applicable to the SD-detector design –, internal tracking region (SIT and FTD), large angle external region (Si-FCH).
- *The progresses on the CAD detailed design* of such an ensemble, allows to address and even sometimes reveal the problems that have to be overcome to ensure the feasibility of the proposed systems. As by-products, this study leads to build the mechanical prototypes that are necessary to study some specific important issues (see subsection 4.3.4).
- *The detailed mechanical design of the detector* is a necessary input *to define each detector in the geometry database of the GEANT-4 based simulation* (see subsection

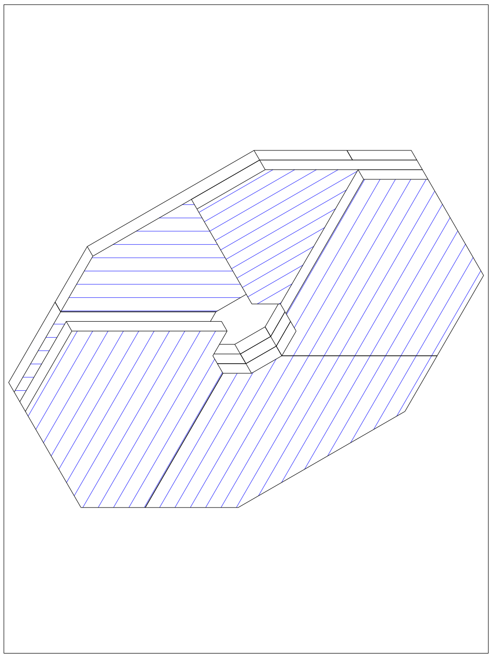


Figure 10: Si-FCH detector design assuming single-sided plans only, and grouping them into 3 honeycomb structures one for the 4 X-plans, followed by one for the 4 U-plans, followed by one for the 4 V-plans.

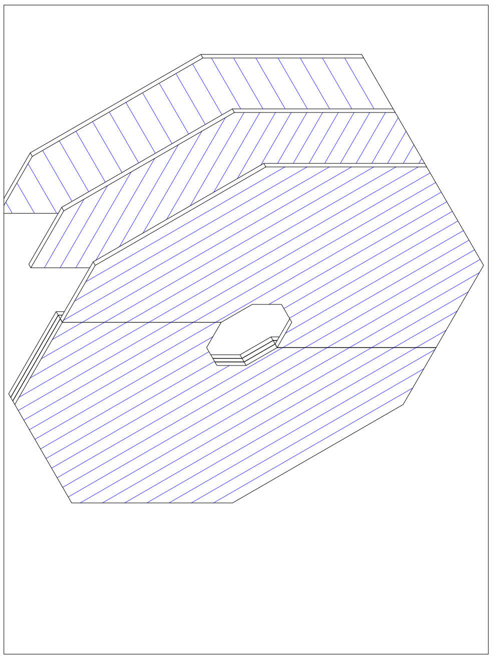


Figure 11: Si-FCH detector design assuming single-sided plans only, and one honeycomb struture per XUV-triplet, thus a total of 4 such structures. Shown here one such XUV-triplet.

4.4.4).

### 4.3.2 *Cooling studies*

Cooling is a main concern both for the electronics and the mechanics of the detector. On the electronics side, power cycling the F.E. electronics is a major issue that will be studied in this R&D program. If possible it could end up in only requesting a passive cooling. At the same time, a special attention is dedicated to design a F.E. readout which is the least power dissipating possible.
On the mechanics side there is also dedicated studies that are going on, on this topic Taking into account a certain amount of power dissipation mainly due to the electronics, the goal for the mechanics is to design the cooling system able to handle this power dissipation, but at the same time, the cheapest in material budget, the simplest from the mechanical design point of view, and the most reliable. In order to achieve these goals, cooling studies are undertaken, based on two types of tools:

- *Mechanical prototypes:*
  As an example, the LPNHE - Paris 6 team has undertaken a series of cooling studies based on a mechanical prototype that mimics the power dissipation due to the electronics sitting on the detector, within the overall C-fiber structure.
  A first set of measurements were achieved on a 2.5 meter long C-fiber prototype of the drawer as designed for the SET device (see Figure 12).

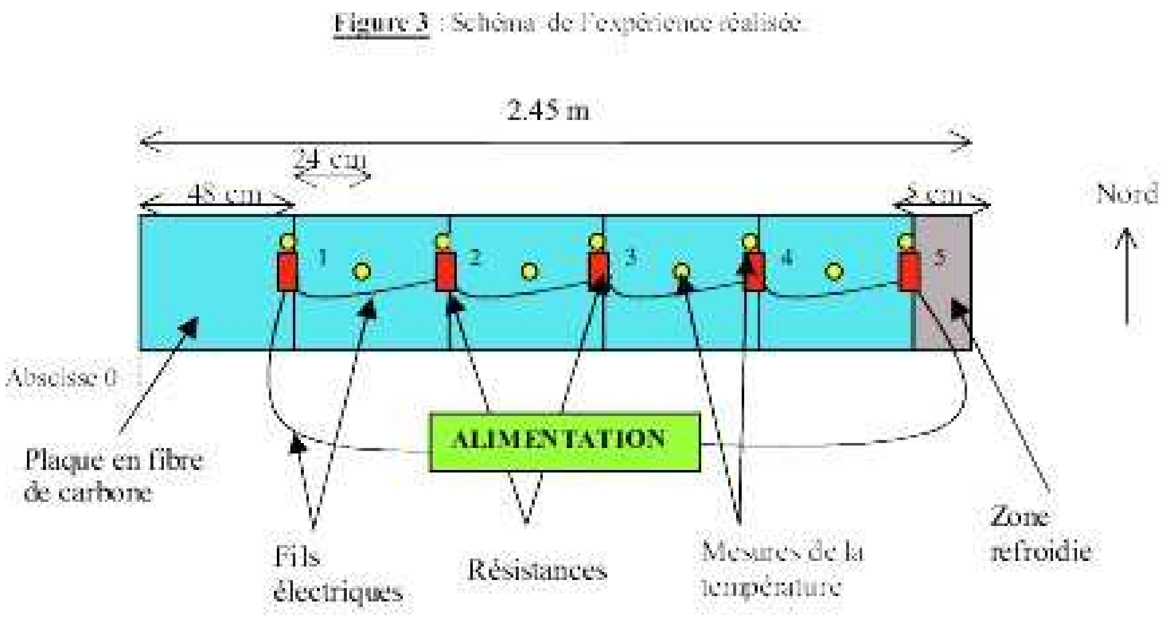



Figure 12: Mechanical Prototype of a long drawer for preliminary tests on power dissipation due to the FE electronics sitting on the detector, in case of ladders of 60 cm length.

The electronics on board is represented by resistors that are located each 60 cm along the drawer. They are powered such as to represent indeed 3 to 6 times more

power dissipation than anticipated. A water cooling is applied at one edge of the drawer with water temperature at 19 or 21 degrees C. The temperature gradient variation along the drawer is measured with or without air convection. The very preliminary results tend to indicate that water cooling applied at the very end of the detector would be sufficient to maintain the temperature gradient within allowed limits.
This is the very beginning of a whole series of studies that will be performed in this R&D with a few successive mechanical prototypes that will be more and more similar to the final detector mechanical design.

- *Dedicated software packages*, as ACORD or SAMCEF packages, are used in parallel to the mechanical prototype tools, to study the power dissipation. They produce the corresponding maps of variation of the temperature gradient within the detector and thus they help to determine the appropriate cooling system. The modelling of these packages will evolve with the results obtained with the prototype studies, in such a way as to give more and more realistic estimates.

The comparisons and the cross-checks between these two methods will end up in a reliable and detailed estimates of the cooling related issues, crucial for the overall material budget and the final detector design.

#### 4.3.3 *R&D on support structures*

An interesting R&D on the support structures has been performed by the group of the Wayne University.
The early layouts of a barrel Silicon Tracker for the LC already demonstrated that the mechanical structures of the STAR-SVT are not applicable for such a design. The SVT ladders, based on carbon-fiber and Beryllium, are rather short (maximum length is 53 cm) and can therefore be subtended from two Beryllium endrings without any middle support or reinforcement along the ladder, which is not realistic for the LC tracker. A more appropriate design was developed for the intermediate Silicon strip layer in STAR, which features triangular carbon-fiber structures of about 1 m length, see Figure 13.

For the LC Silicon ladder prototypes we have decided to extend these ladders to a length of about 2.5 m, still possibly 1m too short for the final, longest ladders of the LC tracker, but a good compromise between presently achievable prototype designs and the final construction layout. First simulations of a ladder that length show promising deflection gradients (less than 10 $\mu$m) without load from detector and electronics, though.

We will, in the near future, continue to develop a final prototype using existing STAR Silicon drift wafers and TAB bonded 'mock' frontend electronics to measure the mechanical properties of such a design. The basic assumption in all drift detector designs for the LC is that if any cooling is necessary it can be accomplished by simple moderate airflow over the detector. This is a substantial R&D effort inasmuch as the actual STAR and ALICE designs both required water or alternate liquid cooling, respectively. We believe that based on the latest electronics developments the frontend power consumption can be

Figure 13: Prototype of a Carbon-fiber support structure originally designed for the STAR-SSD (Silicon Strip Detector).

lowered to the level that liquid cooling will not be necessary. In addition, power cycling schemes could further reduce the power load, also in Silicon drift devices.

### 4.3.4 *Mechanical prototypes*

The development of various mechanical prototypes is a needed path towards achieving a fully realistic and reliable detector design.

They follow in parallel and indeed are complementary to the evolution of the detailed detector design. They allow to study various problems that may show up when studying such detectors. At the present stage of the CAD design studies on the Si-envelope, a few needed mechanical prototypes are identified. These are:

- *The mechanical prototypes for the long ladder*:
  A first prototype is built following the AMS proceadure. Then, the AMS, and CMS or ATLAS ways to build these elements will be compared in order to come up with the best solution. In fact,the LC case combines a very large surface à-la-LHC, with long ladders à-la-AMS, which require a challenging precision in position when aligning the sensors on the the ladder support. Possibility of industrial transfers will be further studied for this issue too.

- *The mechanical prototypes for drawers*
  Preliminary prototype studies are going on, to test the feasibility of the proposed C-fiber structure for the drawer. The mechanical studies, design and fabrication of the necessary tools and, the cast of the C-fiber structure drawer section were achieved at the Lab. Figure 14 shows a photograph of the very preliminary work

on the drawer structure. It is a C-fiber structure realized with 2 mm thickness and 20 cm length.

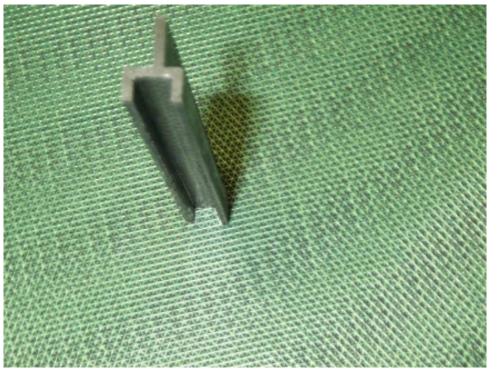


Figure 14: Photograph of the very first mechanical prototype of a C-fiber support structure for a drawer, realized with 2 mm thickness and 20 cm length.

For the SET drawer, the structure will have to be 1 mm thick and 2.5 meter long. It is estimated to be doable by the relevant Industrial firms; however they suggest that by cutting the structure into two pieces and then by gluing them, it would be much easier. This is an example of the mechanical studies that will have to be further pursued in this R&D program.

- *The mechanical structure for the overall detector support*
  Industry has been contacted for the building of a portion of the large C-fiber structure of the overall detector support. Composite Material firms are interested in fabricating the detector support and they think that the proposed alveolar structure with the quoted dimensions is indeed feasible.

These various prototypes are useful to check the mechanical constraints, the power dissipation inside the detector structure and thus gives feedbacks and cross-checks on both the CAD technical calculations and also the MC simulation studies on detector performances and geometry.
It must be noted that these various prototypes will need a non negligeable financial support to build them.

#### 4.3.5 *Collaboration with Industry*

The mechanics R&D will be done in collaboration with Industry on various aspects and it will even imply technological transfers to Industry, as already underlined in the previous sections. This R&D project is benefiting from already existing contacts with Industry; they will be further developed.

## 4.4 *Simulation Studies and developments*

Simulations are necessary tools to accompany the overall proposed R&D project. Developing them will thus be an important task to successfully achieve our project. We are using either full detailed simulation, GEANT-4 based, or so-called fast MC simulations. Various fast simulation packages are available within this present collaboration. Some were developed for previous experiments such as for instance DELPHI at LEP (SGV package [32]), or STAR experiment at RHIC. They have been adapted to the case of the Linear Collider. They are based on a solid expertise and were used in running experiments, thus these are well proven tools. Furthermore, a fast simulation tool was developed for NLC, LCDTRK, by B. Schumm. The GEANT-4 based package is still under development. Both types of simulations will be used for detector performances studies and for evaluating what is the best detector design.

Therefore the main topics to be addressed are:

- *Development of a full GEANT-4 simulation package for the tracking, thus also,*
- *Development of the pattern recognition and tracking fit algorithms within this GEANT-4 based framework.*
- *Studies of the best detector design with the full simulation.*
- *Studies of the integration issues with the full simulation.*
- *Studies of some detector performances needing full simulation.*
- *Studies of detector perfomances with Fast simulations.*
- *Comparing performances between various detector geometries and various detector technologies (including gaseous detector).*
- *Studies of background issues (in particular at large angle regions – beamstrahlung effects).*

Some studies and developments were already performed or are underway.

### 4.4.1 *Performance studies on a barrel tracker based on Si-Drift technology*

A barrel tracker based on Silicon drift technology will provide full 3d information similar to a TPC but with much higher position resolution. Over the years STAR, which consists of a detector system that employs an inner Silicon tracker in conjunction with a large TPC, has developed two tracking models for their analysis. The original package, which used independent tracking in SVT and TPC with subsequent track and/or hit matching, was recently replaced with a so-called integrated tracker which uses all space points from both tracking detectors in a more integrated, global, weighted fashion. The question of whether there is a necessity to port these codes to the LC software environment or whether optimization of the existing TPC 3d tracker for the Silicon tracker is sufficient was, to first order, answered with a set of simulations in 2002. The TPC code as implemented by

Mike Ronan, was modified for use in the so-called ' North American SD-design', which features a five-barrel central Silicon tracker.

As input high occupancy $t\bar{t}$ to six jet events at $\sqrt{(s)}$ =500 GeV from the LC database were used. Figure 15 shows the resulting tracking efficiency distribution for a 100% efficient Silicon tracker.

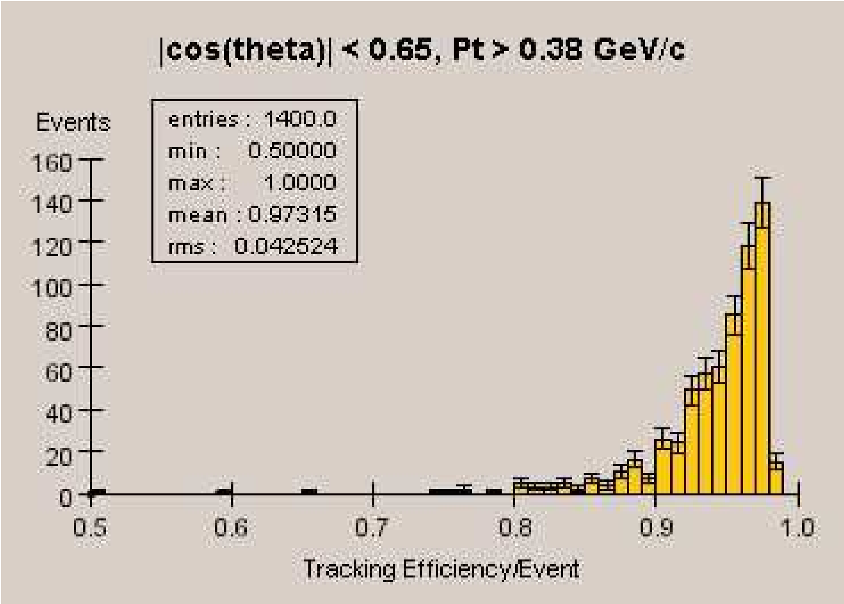



Figure 15: Tracking efficiency in typical $t\bar{t}$ event from the LC simulation database, based on optimized 3d LC tracker in GEANT-4 .

The efficiency curve averages 97.3%, very similar to results obtained with the TPC for the alternative "North-American L-design". A comparison of the momentum resolution as a function of momentum for the Silicon SD-design and the TPC L-design, obtained with an analytical method as shown in Figure 3 of chapter 4.2.1., was corroborated by the detailed simulations.
The concern associated with the limited redundancy offered by a five barrel solid-state tracker is vulnerability to problems in pattern recognition.

We therefore ran the simulations in a more realistic way by reducing the number of active channels to 90%. The efficiency dropped only to 92.7%. These results show that the detector, largely due to the overconstraint in terms of position resolution, is very robust with respect to the number of active channels.

Additional simulations of the performance under the assumption of large (realistic) background levels are shown in Figure 16 and confirm independent studies by the Tokyo group for a Silicon strip based tracker.

Both groups used high level photon backgrounds, simulated by T.Maruyama, for their study. Here the background contributes around 30,000 photons per event with an average photon energy of about 1 MeV. Although this leads to a signal to background level of close to 1:10 the overall occupancy on the innermost layer of the Silicon drift tracker only

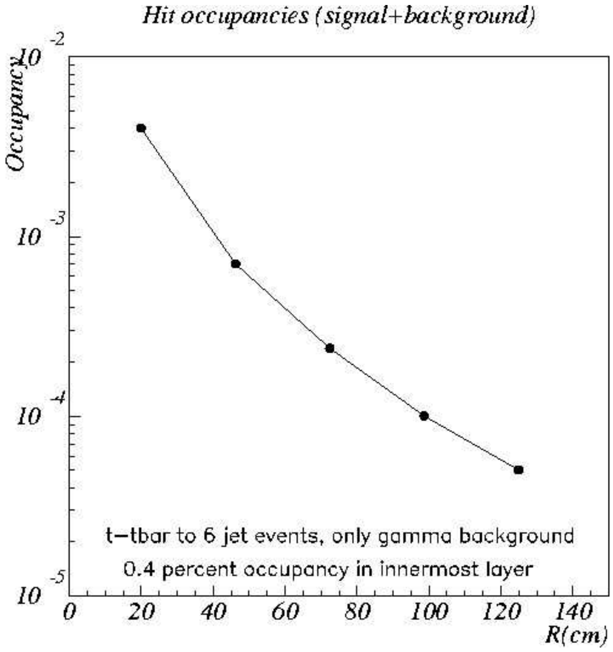



Figure 16: Occupancy in the five SD layers after including realistic background simulations.

increases to about 0.4%, see Figure 16. A comparison of the tracking efficiency to the one shown in Figure 15 indicates that the effect of background in the pattern recognition is negligible. The tracking efficiency drops from 97.3% to 97.1%, the purity as measured by the number of ghost tracks (3.3%) stays constant at 96.7%. Based on the present level of results we have concluded that the existing 3d tracking program can be applied to TPC and Si-drift as long as the optimization is specific to the technology.

Whether more sophisticated programs, such as the STAR code, will be necessary will depend on ongoing studies regarding two-track resolution and energy flow matching. In order to continue more realistic GEANT based simulations, the Si-drift collaboration has provided detailed geometry files for the five layer barrel design and decided to port the detector response code from STAR to the LC simulation archive. An additional study of the track-timing features of Silicon drift detectors can be found in the literature [33]. It concludes that drift detectors are perfect to discriminate pile-up or spurious events by simply using their timing capabilities, which allow to time and select a track on the nano-second or even sub nanosecond level.

### 4.4.2 *Performance studies of the Si-Envelope detector design*

Different SET designs were studied within the silicon envelope framework, using the fast simulation package SGV [34] The conclusion was that the detector should be made of three layers, packed as closely as possible, and with the best possible point-resolution. Making the detector as thin as possible is useful, but nevertheless a second priority.

$\Longrightarrow$ *Momentum resolution*

Following the above conclusions, a detector with three layers of 0.5 % $X_0$ detectors closely packed in 10 cm was studied more closely. The layers are placed at radii 160.5 cm, 165 cm and 169.5 cm, each with a point-resolution of 25 $\mu$m and a thickness representing 0.5 % of a radiation-length. The radius of the TPC was reduced to 155 cm.

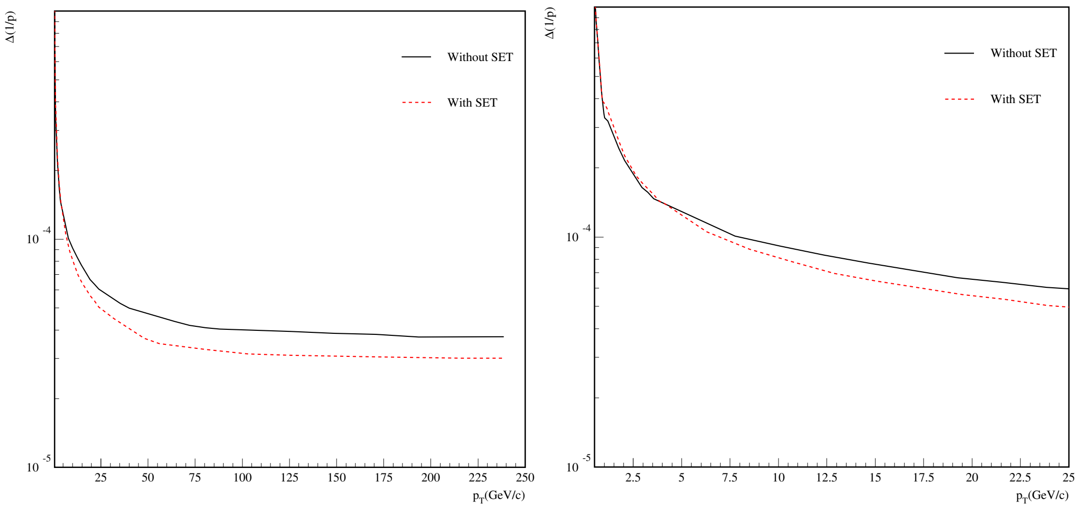



Figure 17: *Effect of the SET on the momentum resolution of the tracking system, for transverse momenta up to 250 GeV/c. The SET design used to obtain these results consisted of three layers of Si-detectors, at radii 160.5 cm, 165 cm and 169.5 cm. The point-resolution was 25 $\mu$m and each layer represented 0.5 % of a radiation-length. The simulated particles were pions at 90 degrees.*

The resolution study was done for pions at 90 degrees. The TPC point-resolution was nevertheless kept at 180 $\mu$m, rather than 230 $\mu$m which is what would be obtained from table 2.3.5 of [3] by extrapolation to the maximum drift-distance.

Under these assumptions, an improvement up to 20% is observed at high transverse momenta (fig 17, left). Under the same assumptions, the blow-up of the low $P_T$ region (fig. 17, right), shows that the two resolution-curves cross at 4.5 GeV/c in transverse momentum, and then join again to yield identical results for the two configurations below 1 GeV/c, since at this transverse momentum, tracks do not reach the SET. Hence, for charged tracks with transverse momentum between 1 and 4.5 GeV/c, the introduction of the SET deteriorates the momentum resolution. However, the deterioration is modest: it does not exceed 5 % between 2 and 4.5 GeV/c, and rises to 10 % at 1.5 GeV/c. Only in a 300 MeV/c wide range just above 1 GeV/c does it reach the maximal 15 %.

Figure 18 show a similar study performed at low angles and comparing the momentum resolution with either a straw-tube FCH, or with the Si-FCH added to the TPC for different angular values. As expected at low momenta and independently of the angle of the track with respect to the beam axis, the gain is small. On the other hand, for high momenta, i.e. above 25 GeV/c, the gain becomes larger especially when going from 10 to

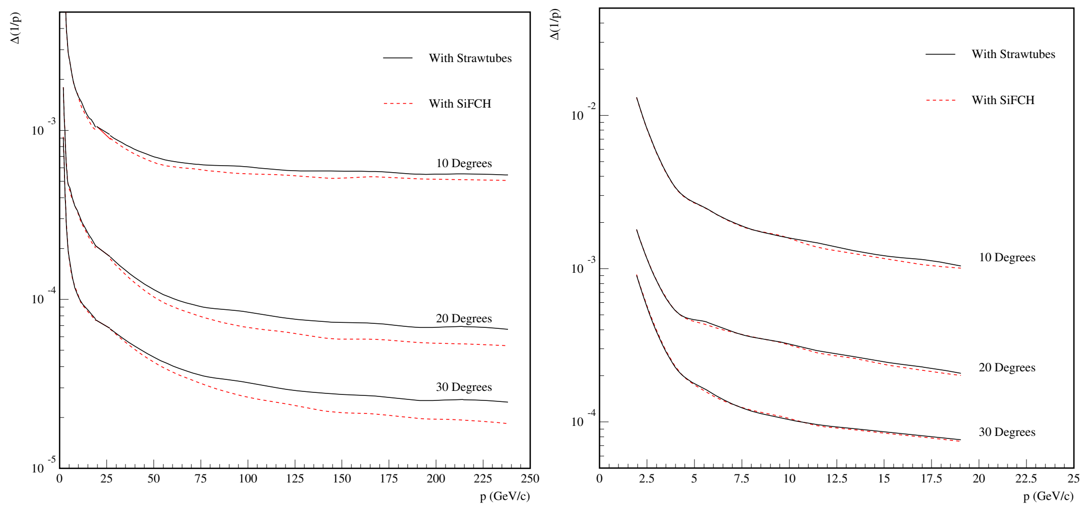



Figure 18: *Effect of the Si-FCH on the improvement of the momentum resolution of the tracking system, in the high momentum range, for various angular values. The Si-FCH design used to obtain these results consisted of six layers of Si-detectors. The point-resolution was 25 $\mu m$ and each layer represented 1 % of a radiation-length.*

30 degrees in angle.

$\Longrightarrow$ *Hit density in the SET*

To evaluate how many hits are expected in the SET ladders (ie. the smallest physical readout sub-division), the number of tracks traversing such a sector was simulated for $q\bar{q}$ and WW events. It was found that the probability that a hit ladder will have more than one track traversing it is about 10% (less for low thrust WW-events, more for high thrust $q\bar{q}$-events). Hence, the number of left-right ambiguities in the association of the R$\phi$ and z measurements in the double-sided middle layer will be small. It also indicates that internal pattern-recognition in the SET should not pose any major problems. Furthermore, since each ladder in the the present design would have 128 strips, the probability to have two tracks hitting the same strip, or two neighbouring strips is negligible.

These observations point to the tentative conclusion that for the SET, there is no need to be able to determine the z-coordinate (by reading both ends of the strip, and measuring the difference in time-of-arrival and/or pulse-height) of an R$\phi$ hit, or vice-versa.

$\Longrightarrow$ *The effect of SET on gammas*

While the SET gives a better momentum resolution at large momenta, it introduces a longer distance between the outer field cage of the TPC and the calorimeter, and introduces some more material. Therefore, the potential effects on the energy resolution for $\gamma$'s was also studied, and the resulting effect on the over-all energy measurement[3]. If

[3]It should be noted that the interaction length in the outer cage of the TPC and the SET is of the

the presence of the conversion is detected and the entry points of the two electrons can be given to the calorimetric reconstruction procedure, no loss in resolution will result, since the observable of the calorimeter is essentially the total number of tracks in the shower and this does not change if the first conversion is in a thin layer just before the calorimeter, or in the first absorber-layer.

A study of the resolution on energy that can be obtained by the momentum measurement in the SET of the two electrons from a conversion in the outer cage of the TPC was also done. It was found that for converted photons with energy below 4 GeV/c, the energy is better measured by the SET than the calorimeter. SGV was used to demonstrate that the fraction of the total $\gamma$ energy carried by such $\gamma$'s can be quite important - between 20 and 35 % [35].

Finally, it can be noted that the effect of multiple scattering in the outer cage introduces an additional uncertainty on the direction of a charged track with $\sigma \approx 1$ mRad. The SET measurement would reduce this to 0.5 mRad. At this moment, it is unclear if the calorimetric reconstruction algorithm can take advantage of this added precision

Hence, it can be tentatively concluded that the introduction of the SET would not deteriorate the over-all neutral energy measurement - quite on the contrary in some cases it would ameliorate it. However, a firm statement on this aspect has to await the development of the calorimeter reconstruction code, and the availability of test-beam data.

#### 4.4.3 *GEANT-4 based performance studies of a Si-microstrip central tracker*

Using the full detector simulation, we study the basic performance of the silicon microstrip central tracker. For the detector configuration, we use the parameters considered for the NLC SD silicon tracker[36], consisting of five concentric double-sided silicon microstrip layers located at radii between 20cm and 125cm, immersed in the magnetic field of 5 Tesla. The thickness of each layer is assumed to be 0.5% of one radiation length. GEANT4[37] is used to simulate detector hits and generated hit positions are smeared by a resolution of 7$\mu$m. In order to reconstruct the track, the hits belonging to a particle are grouped and the track fitting program using Kalman filter is applied to the hits. Throughout the study presented here, we assume the center-of-mass energy of 500GeV.

Figure 19(a) shows the occupancy of the silicon layer as a function of its radial position. We use the high multiplicity events of $e^+e^- \rightarrow t\bar{t} \rightarrow 6$ jets. The strip length is assumed to be 20 cm while the strip pitch varies from 50$\mu$m to 1mm. We find that the occupancy of the innermost layer is $10^{-3} - 10^{-2}$, depending on the pitch size, for signal-only events.

The simulation of the interaction region (IR) indicates that the tracking system is expected to have photon backgrounds from unconverted beamstrahlung radiations. To estimate the effects caused by the background we generate beamstrahlung photon backgrounds using the IR simulation, feed them to the GEANT4 detector simulation, and superimpose the resulting hits to the signal hits. For the NLC accelerator parameter of 190 bunches/train, we find $\sim$ 34000 photons with the average energy of 1 MeV are produced in an event. Of those produced photons about 2000 photons with the average energy of 0.7 GeV generate hits in the tracker. We find that one photon generate 1.04 hits on average. The resulting occupancy is shown as a dashed line in Fig.19(b). The occupancy is an order of magnitude higher than that of signal-only events, but still remains

order of 3.5% $X_0$, and the mean free path is 2/3 of that, so that at most 2.5% of the $\gamma$'s are expected to convert.

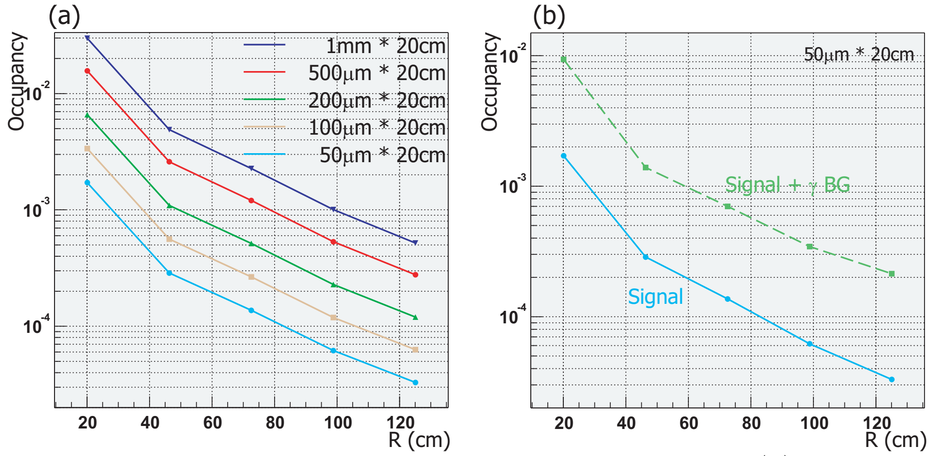



Figure 19: Occupancy distributions as a function of the radius, (a) for signal only with different strip-pitch sizes, and (b) for signal only (solid line) and signal plus photon background at the IR (dashed line).

low enough ($\sim 1\%$) even at the innermost layer.

Figure 20(a) shows the track reconstruction efficiency as a function of the track momentum, for using the central tracker only (solid lines) and using the central tracker and vertex detector (dashed lines). Because the solenoid field is high (5 Tesla), the presence of the vertex detector is important to reconstruct the low momentum tracks. Figure 20(b) shows the transverse momentum resolution as a function of the track momentum obtained using the central tracker and vertex detector. Here the single track is generated at a zero dip angle (perpendicular to the beam axis).

We note that it is important to use a realistic track-finding algorithm for further study. In order to estimate the accelerator background, the beam delivery system (BDS) simulation is also important. Using a newly developed BDS simulation package, LCBDS[38], based on GEANT4, we plan to study the effects due to IR backgrounds.

### 4.4.4 *Detailed Detector definition in GEANT-4 geometry database*

A general GEANT-4 based framework, called MOKKA was developed by P. de Moraes [39]. It is now becoming the worldwide agreed framework for developing a full LC detector GEANT4 based simulation program.
The LPNHE-Paris team has started to collaborate to this effort [40] by defining the geometry Database of the various elements of the Si-envelope. This is now possible thanks to a detailed CAD mechanical design of these devices. As an example, Figure 21, shows the MOKKA implementation of the SET (Silicon External Tracker), as defined in the Si-Envelope. Presently the Si-FCH, i.e. the forward chambers as described earlier in this proposal is being also implemented. It is intended to push further this work in particular by collaborating with the Tokyo team to implement the pattern recognition and track reconstruction within this GEANT4 framework. This is part of our R&D program.

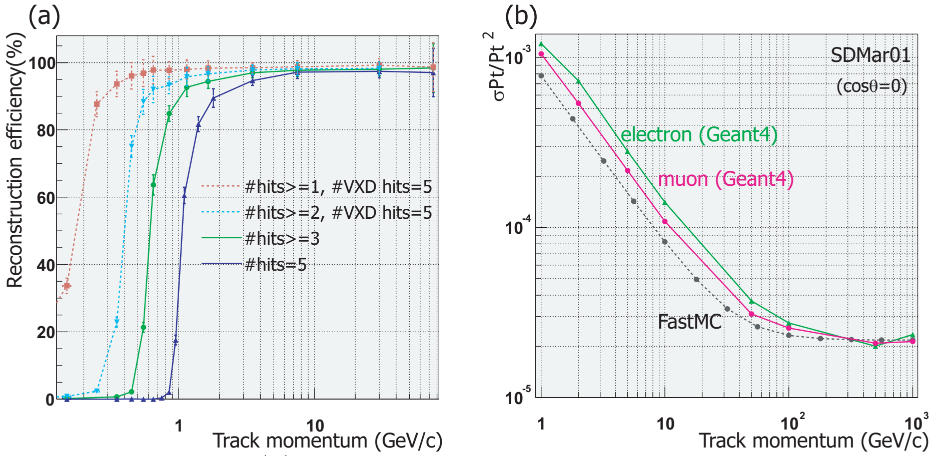



Figure 20: Distributions of (a) track reconstruction efficiency as a function of the momentum for the central tracker only (solid) and for the central tracker plus vertex detector(dashed), and (b) the transverse momentum resolution obtained for the central tracker plus vertex detector.

## 4.5 *Test set-ups*

They include the basic test-bench for studying the long ladders response and developing the related front-end readout, and a similar test bench for developing the Si-drift technology and associated FE electronics or any other sensor technology. Because of the conditions in which these detectors must be operated, this means to have this test set-up installed in a clean room. Many of the Institutes involved in this collaboration benefit from such a test framework from their past and/or current activity in this R&D field.
The other type of test bench needed are those for power dissipation studies and other mechanical studies performed on mechanical prototypes of the detector.
Furthermore, the Charles University team has developed for ATLAS Silicon forward tracker an automized test bench with a radioactive source that will be useful to evaluate the response characteristics of our various prototyped Si-trackers [41]. Last but not least, it will be necessary in a later stage of this R&D to perform tests on a test beam (see Section 5).

## 4.6 *Calibration, Monitoring and Slow Control issues*

The unprecedented excellent track momentum resolutions contemplated for a linear collider detector will demand minimizing systematic uncertainties in subdetector relative alignments. At the same time, the low material budget may lead to a structure that is far from rigid. The short time scales on which alignment can change (e.g., from beam-driven temperature fluctuations) probably preclude reliance on traditional alignment schemes based on detected tracks, where it is assumed the alignment drifts slowly, if at all, during the time required to accumulate sufficient statistics. A system that can monitor alignment drifts "in real time" would be highly desirable in any precise tracker and probably essential to an aggressive, low-material silicon tracker. The tradeoff one would make in the future between low material budget and rigidity will depend critically upon what a

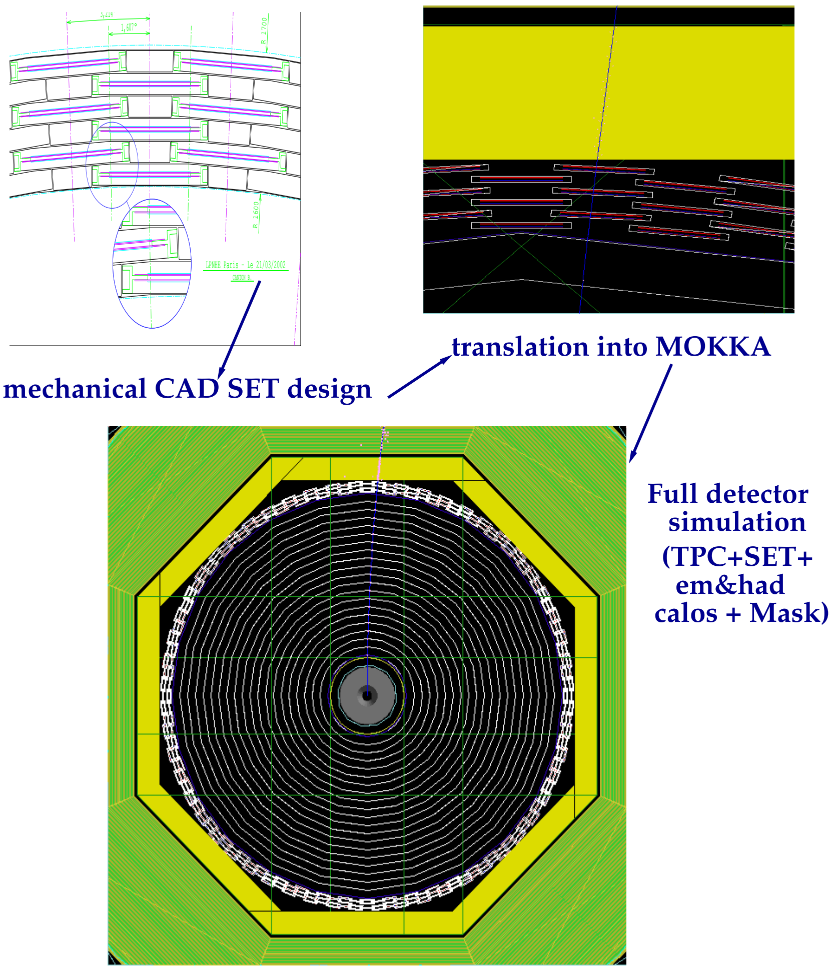



Figure 21: The SET device as visualized by MOKKA, a GEANT4-based simulation framework. The geometry database of this detector follows its detailed mechanical design, shown on the top left figure.

feasible alignment system permits. Indeed the two approaches will be studied in this R&D collaboration, namely the alignment scheme based on detected tracks (in the case of the Si-envelope) and the one relying on a performing alignment system that is discussed for the SD detector but would apply to both detector concepts.

Among the main issues there are:

- *The handling of the distorsions (Si-envelope case)*

  Experience with the operation of large TPC's as in DELPHI has shown the absolute necessity of reference track measuring devices to give a precise and continuous monitoring of the drift parameters, in particular the magnetic and electric fields in the whole drift volume. In order to be able to take advantage of a foreseen point resolution in the TPC of less than 100 micrometer, any distorsion has to be measured and continuously monitored to a precision of less than 20$\mu$m.

  This will be done by measuring the TPC tracking properties of reference tracks. UV laser rays inside the drift volume have been used with success, they allow to follow continuously the drift behaviour, and in particular to alert if some space charge develops in the drift volume. But the exploration of the whole drift volume requires the use of isolated non radiating tracks precisely measured in mechanically stable detectors outside the TPC volume. The vertex and SIT detectors will be available for this, by extrapolation inside the TPC volume. A much more precise interpolation will be possible with the SET, built as an autonomous mechanical reference surface on the outside of the TPC.

  A similar detector, the outer detector of DELPHI, has provided the required accuracy [42]. Moreover, this process is part of the overall tracking system alignment of which it is the last step. On top of the increase in momentum accuracy provided by the SET and the TPC envelope, they will specially bring reliability and fiability to the accuracy of the whole detector tracking system.

- *The alignment system (Si-envelope case).*

  To start the track based alignment just described, a mechanical alignment has to be provided by construction, with an accuracy of a tenth of a millimeter or less. This requirement must be included in the mechanical design of the Si detectors. It involves also stability in time and this must be continuously monitored by an active alignment monitoring system. This system should on top provide the relative alignment of the tracking system with the Calorimeters and with the muon system with a similar accuracy. Studies of this alignment system have to be undertaken. The recent laser based systems being built for ATLAS and for CMS are excellent starting points. They are described in the respective TDR's. The Si devices are naturally photosensitive and this can be put to use. Special photosensitive alignment targets are to be used on the TPC and on the other components of the detector to obtain the required relative accuracy of about 100 $\mu$m which will then allow to efficiently use the track themselves for precise alignment purposes.

The laser beam optical components and its path through the whole detector will have to be foreseen from the start of the overall design as well as in the detailed design of any large detector component.

- *Developing a dedicated alignment scheme based on Frequency Scanned Interferometer (FSI)*

  The University of Michigan group will investigate the capability of existing precise alignment schemes and to develop a system customized to the needs of a linear collider detector. Two natural candidate schemes to explore include the Rasnik alignment system implemented for the CDF detector and the Frequency Scanned Interferometer (FSI) system being developed for the ATLAS detector. Both are designed to achieve 1-D or 2-D point resolutions of order 1 micron, which should be adequate for a linear collider tracking system. The Rasnik system is based on many CCD cameras trained on 2-D images whose positions are sensitive to relative misalignments. The FSI system is based on multiple interferometers fed by optical fibers from the same laser source, where the laser frequency is scanned and fringes counted to obtain a set of absolute lengths. Given the desire for low material burden in a silicon tracker, it's not clear that either system in its present design will be appropriate for a linear collider detector, although the FSI method seems more promising in that respect and is the one Michigan will at least initially focus upon.

  It should be noted that the methods developed for central and forward tracker alignment may also prove useful for a vertex detector, where again, there is a strong desire for thin detector material that may be subject to short-term position fluctuations.

The Michigan group has initiated a program of alignment R&D. Specifically, the group is acquiring the components for and will build a demonstration-level frequency-scanned interferometer on an optical bench. In parallel, the group will come up with a conceptual design of an alignment scheme for the American baseline silicon barrel tracker and the silicon forward disk trackers and write a general simulation program that allows the performance evaluation of various schemes. It is envisioned that hundreds of absolute length measurements between pairs of reference points would be used in a global fit to determine the local and global alignment parameters of the tracking subsystems. A progress report on this effort will be delivered no later than the winter 2004 American linear collider physics group meeting.

Using the FSI infrastructure put together in the first year, the Michigan group will, in the second year, carry out measurements on the bench of performance and explore modifications to improve absolute precision, robustness, and measurement speed. A technical report will be written on the findings.

It is expected that by the start of the third year, the Michigan group will have a concrete design in hand for a full alignment system and will have evaluated singly the primary issues affecting that design. At that point the group proposes to build a partial prototype of the system to test system integration issues, including miniaturization of the components tested previously on the optical bench.

# 5 SiLC Collaboration: milestones, schedule, finances

The SiLC collaboration is a worldwide growing collaboration, that will gather teams from Asia (Japan, South Korea and Taiwan), Europe (Czech Republic, Finland, Italy, France, Switzerland, Spain), and from USA.

Most of these teams have already a strong expertise in this detector technology and some of them are even pioneers in the field (see Table 1). Close contacts are already existing with some of the proeminent high tech firms that are furnishing the sensors and interested in further R&D activity in this domain. Also contacts are established or even collaborations are undergoing with Labs or firms that are of interest for various aspects of our project.

| Institutions | Current relevant expertise in each Institution |
|---|---|
| BNL | Central role in STAR Si-drift tracker at RHIC<br>Participation to the ATLAS experiment<br>Pioneering expertise in very low noise front end electronics |
| Charles University | Central role in the ATLAS forward Silicon Tracker<br>Long expertise in the development of Silicon Tracker |
| Torino | Participation to the construction of the CMS Silicon Tracker<br>Central role in ALICE Si-drift inner tracking system<br>Expertise in large detector mechanical design and studies (Alice) |
| Michigan University | Interferometry experience in the LIGO Experiment |
| SCIPP/UCSC | Exploration of CMOS and bipolar readout for particle physics detection<br>Central role in GLAST tracking calorimeter<br>Central role in ATLAS Silicon Tracker |
| Wayne University | Central role in STAR Si-drift tracker at RHIC |
| LPNHE-Paris | Participation to the construction of DELPHI Microvertex<br>Expertise in Low noise preamplifier, DAQ electronics<br>Expertise in large detector mechanical design and studies (ATLAS) |
| Tokyo University | Central role in Belle Silicon vertex detector<br>Expertise in Geant4-based detailed Simulations |
| Korean Universities | Experience in design/simulation/fabrication<br>of Si sensor including flexible<br>PCB cables and mechanics |

Table 1: *List of the most relevant expertises for this project in each Institution*

The sharing of tasks among the collaboration is for the time being, summarized in the Table 2.

A tentative roadmap for the three next coming years of our project is described here below in terms of milestones, schedule and very preliminary estimate of the needed financial support to achieve our goals until end 2006.

| Institutions | Sensor techno | Electronics | Mechanics | Simus | Tests set-ups |
|---|---|---|---|---|---|
| BNL | Yes | Yes | Yes | Yes | Yes |
| Charles University | — | Yes | Yes | Yes | Yes |
| SCIPP/UCSC | Yes | Yes | — | Yes | Yes |
| Wayne University | Yes | Yes | Yes | Yes | Yes |
| LPNHE-Paris | Yes | Yes | Yes | Yes | Yes |
| Michigan University | — | — | Yes | Yes | Yes |
| Torino University | Yes | Yes | Yes | Yes | Yes |
| Tokyo University | — | — | — | Yes | Yes |
| Korean Universities | Yes | Yes | Yes | — | — |

Table 2: *Sharing of responsabilities*

## 5.1 *Milestones*

The roadmap for the three coming years, i.e. from mid 2003 to end 2006 comprises two main phases:

- *Phase 0*: from mid 2003 to mid 2004 is the *"warm-up"* period for the collaboration. It implies extending and organizing our collaborative work and accomplishing a first series of tests on prototyped Si-sensors and on the VFE electronics as well as a first step towards a final detailed CAD mechanical design of the various Si-trackers.

- *Phase A*: from mid 2004 to mid 2006, the collaboration will aim to achieve a series of measurements on Si-sensor prototypes and to design and produce prototypes of the associated FE readout. This generic R&D will result in the construction of a prototype ready for testbeam by fall 2006. On the mechanical side, the R&D will focuse on a full detailed design (including tools and related prototype studies] of:

  - *Detector architecture, together with the*
  - *Related Industrial transfer studies*
  - *Cooling system*
  - *Alignment, mechanical Calibration and Monitoring systems*

## 5.2 *The schedule*

The foreseen schedule is summarized in three detailed chart-maps: one for the sensor R&D (Figure 22) , one for the electronics R&D (Figure 23), and one for the mechanics R&D (Figure 24). They include the construction of a tracking set-up for a test beam in fall 2006.

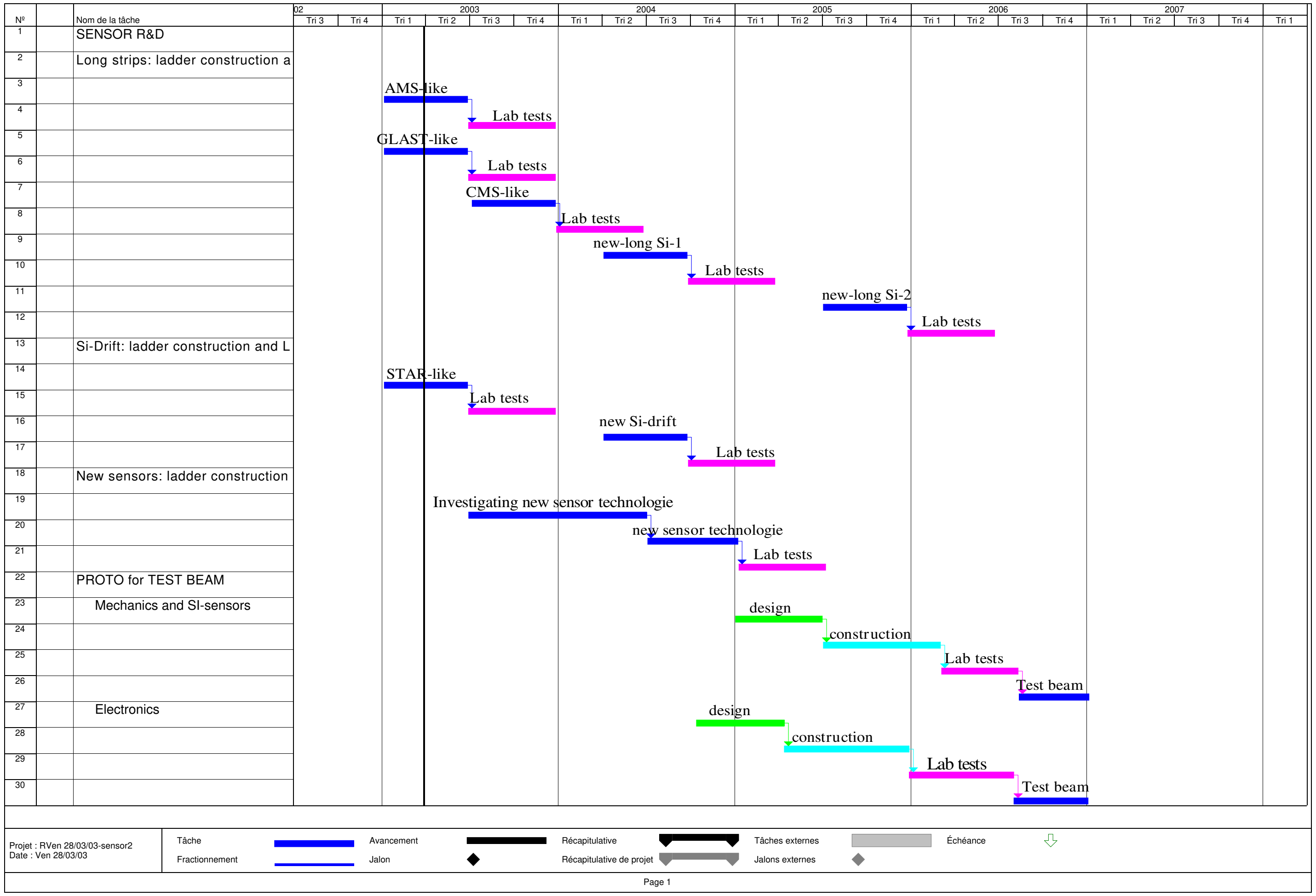



Figure 22: Schedule/Milestones for the R&D on sensors.

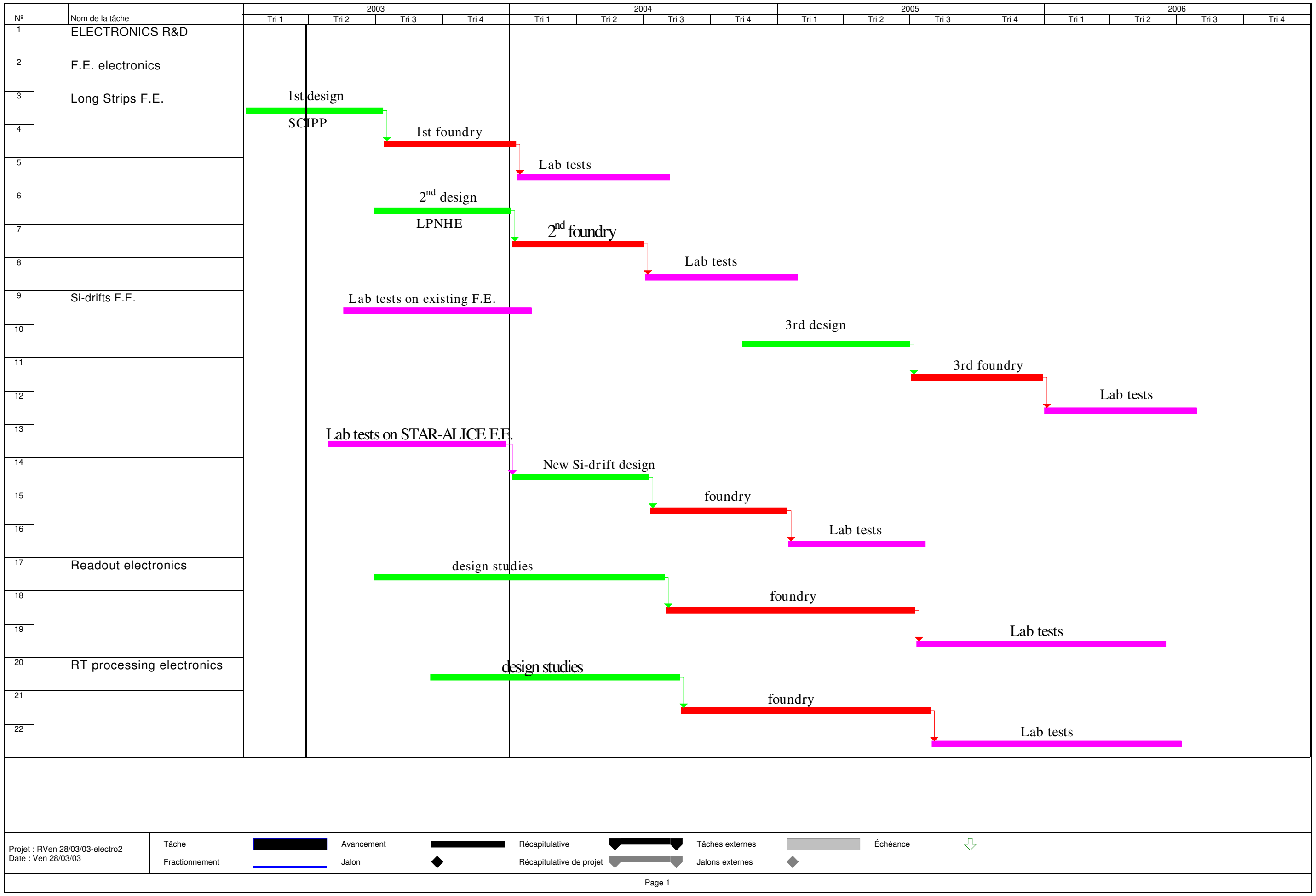



Figure 23: Schedule/Milestones for the R&D on Electronics.

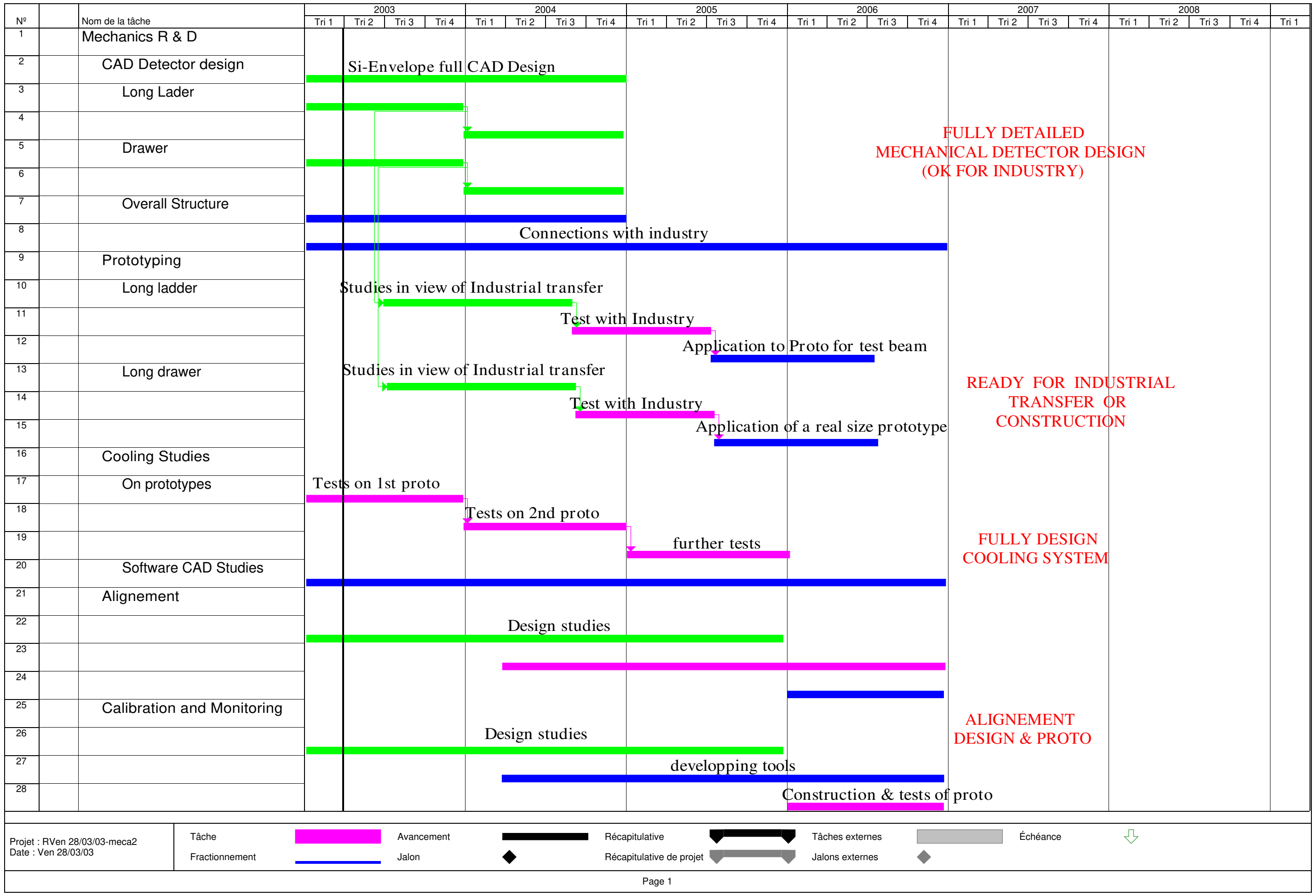



Figure 24: Schedule/Milestones for the R&D on Mechanics.

### 5.3 *The finance*

Most of the teams are benefitting from Labs that have been already equipped for R&D activity in this field. Thus it allows to most of them to get started for the first round of activities. Furthermore some R&D fundings have been already provided by a few national funding agencies (such as: DOE, NSF, IN2P3) to get started. This organized R&D project, should help in sharing among us the expertises and needed tools, thus decreasing the equipment cost up to a certain extend, and in getting the funds for the next coming years. A very preliminary cost estimate of this overall R&D program for the three coming years is given in Table 3.

| Items | Individual cost | Subtotal cost |
|---|---|---|
| Si-sensor R&D | | |
| Long Strips | $3 \times (3 \times 1.5$ KEuros) | 13.5 KEuros |
| Si-Drift | $4 \times 1.5$ KEuros | 6 KEuros |
| New Sensors | $3 \times 2$ KEuros | 6 KEuros |
| Mechanical ladders | $5 \times 1$ KEuros | 5 KEuros |
| Total Cost Sensors | | 30.5 KEuros |
| Electronics R&D | | |
| V.F.E. prototypes | | |
| Foundry | $4 \times 7.5$ KEuros | 30 KEuros |
| R.O. electronics | | about 5 KEuros |
| Total Cost Electronics | | 35 KEuros |
| Testbeam Proto | | |
| Mechanics | | about 10 KEuros |
| Sensors | N sensors | about 20 KEuros |
| R.O. electronics | 2048 R.O. channels (15 Euros/ch) | 30 KEuros |
| Total Cost testbeam | | 60 KEuros |
| Mechanics R&D | | |
| Prototypes | | about 60 KEuros |
| Tools development | | about 20 KEuros |
| Alignment | | about 30 KEuros |
| Total Mechanics | | about 110 KEuros |

Table 3: *Cost estimate for this R&D project for the period from mid 2003 to end 2006.*

# 6 Conclusions

Since more than a decade, the Si-trackers are demonstrating to be very appealing devices. Their use is extending in $e^+e^-$ (LEP, SLC, B-factories), pp (Tevatron, LHC) and sky experiments (AMS, GLAST), as well as their applications. Initially used as microvertex detectors, they are now acting as large tracking systems, and the realtime processing of their data is becoming more and more sophisticated still enhancing their interesting features.

There is a strong interest in the worldwide community to actively pursue the impressive advances achieved in this field, for presently running or under construction Si-tracking systems. High tech firms and research Labs are willing to collaborate to this international effort.
Our collaboration gathers a large international expertise in this R&D field, including pioneers. This collaboration initiated one year ago, is expected to still grow in the next months or year. It takes over the present-state-of-the-art and will thus profit from the past experience and means to make further progress this promising technology.

The applications of this tracking technique for the future LC experiment will be developed, carefully evaluated and tested within the framework of this proposed R&D program.

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