LC-DET-2003-013
June 3, 2003

A Silicon Envelope for the TPC [1]

J.E. Augustin, M. Baubillier, M. Berggren, B. Canton, C. Carimalo, W. Da Silva, D. Imbault, F. Kapusta, H. Lebbolo, F. Rossel, A. Savoy-Navarro, D. Vincent

Laboratoire de Physique Nucléaire et des Hautes Énergies
Universités Paris 6 et 7/CNRS-IN2P3.

Abstract

Physics at the future linear collider demands a highly performing tracking system. The addition to the detector defined in the TESLA TDR of an external tracking device made of three layers of Si microstrips (SET) is proposed, as well as the replacement of the straw tubes for the forward external tracker (FCH) with Si-tracking technique. The TPC would be thus surrounded by an autonomous Si-tracking system, made of the microvertex, the internal central (SIT) and forward (FTD) trackers plus the SET and the FCH in the outer corresponding parts. This ensemble - the *Si-Envelope* - would cover the full level-arm and would extend down to 7 degrees with respect to the beam axis. Its main assets are to combine two performing and - in various aspects - complementary tracking technologies, and to provide useful redundancy. It improves the expected detector performance on momentum measurements, as shown by simulation studies. The low machine frequency and the low radiation levels permit to envisage the use of long ladders of Si microstrips coupled to long shaping time. Furthermore, the machine cycle could allow to switch off the electronics in between train of bunches. All these facts converge toward the possibility of making highly transparent Si-trackers. This is the main goal of the starting R&D both on the related electronics and mechanical issues described in this note. It intends to improve the technological developments already achieved in the promising field of large area Si-trackers further.

[1]See also http://lpnhe-lc.in2p3.fr/lcnotes/

1 Introduction

Physics at the future linear collider demands a highly performing tracking system. The TESLA TDR [1] is thus revisited in this spirit. In a previous LC-Note [2], it was proposed to add a new Si-tracker called SET (Silicon External Tracker) to the tracking system, in order to further improve the tracking performance as well as the energy or particle flow measurement in the central calorimetry. In this note, we extend the proposal by proposing the replacement of straw tubes in the forward chambers (FCH) by Si-microstrips. This was suggested by several colleagues after the presentation of the SET device at the Cracow workshop in September 2001 [3]. By doing so, the tracking devices surrounding the TPC would all be based on the same technique. Hence, the ensemble formed by the SIT, the FTD, the SET and the FCH [2] is like an "*Si-envelope*" for the TPC [4].

The purpose of this note is to describe the Si-tracking system in detail. The motivations and main functions of the Si-envelope are discussed in Section 2. Section 3 describes the conceptual design of the Si-envelope including the overall design, the basic element, i.e. the long ladders and the so-called "*corner issues*", i.e. the questions related to the appropriate design of the region extending from 30 to 35 degrees with respect to the beam axis. This is the delicate place where the cabling and other infrastructure of the central part of the detector are brought out. In section 4, the R&D objectives as well as the present status of the R&D activities concerning electronics, mechanics and simulation are presented in detail. Section 5 gives the future perspectives of the overall activity.

2 Motivations and Main Functions of the Si Envelope

At the future linear collider, both standard physics and physics beyond the standard model will require:

- *Excellent pattern recognition.* The only affordable technique to have a large number of true 3-D measurements in a large volume is the TPC.

- *Very precise momentum measurement for all momenta.* Due to the very low amount of material in the detecting medium, and hence the low multiple-scattering, gaseous detectors are the detectors of choice to measure low momenta. At large momenta, the multiple-scattering becomes negligible, and silicon detectors, with their superior point-precision instead becomes the prime choice.

- *Very accurate momentum measurement at all angles* with respect to the beam axis. At the future linear collider, important physics events will be produced at all angles. Silicon detectors are easier to construct and operate in constrained spaces, such as those needed to instrument the low-angle region just outside the beam-pipe. Indeed, the addition of the FTD Si-disc-layers has been shown to be necessary.

- *The dE/dx measurement* will be needed both in the relativistic rise region - where only gaseous detectors have enough sensitivity, and in the $1/\beta^2$ region - where the Si-trackers and the TPC would complement each-other. (The interest of the $1/\beta^2$ region is physics beyond the SM, where high-mass stable or quasi-stable particles might occur.)

[2] *Labelled from now on: Si-FCH*

- *Energy flow.* About 60% of the total energy flow is carried by charged tracks. Charged tracks are in almost all situations measured with higher precision by the tracking system than by the calorimeters (the possible exception being electrons at the highest possible momentum).

  What regards the constraints on the tracking system, the design considerations to obtain the best possible measurement of the neutral component of the energy-flow (ie. of the calorimetric system), are two-fold: Firstly, the tracking system should be as thin as possible to reduce the amount of interactions that occurs before the calorimeters. This is best accomplished by gaseous detectors. Secondly, the extrapolation of charged tracks to the calorimeters should be as precise as possible, both in position and angle. This is best accomplished by silicon detectors (since - contrary to the TPC - the last measurement can be done at a position with virtually no material between it and the calorimeter).

Contrary to the LHC, at the future linear collider, the running conditions will allow the use of a TPC. As mentioned above, the assets of the TPC and the Si-tracking are complementary in various aspects. Combining both tracking techniques, as is proposed here, will provide an opportunity to make the best possible tracking system. The main difference with respect to the TDR detector is the addition of the SET [2], and the use of the same technology for all envelope detectors.

Specifically, in a detector for TESLA, the main functions of the Si-envelope are to act as:

- *A connexion of the TPC with the surrounding devices.* As shown in Fig.2 the SIT and the central parts of the FTD are occupying the space extending from just outside the VTX cryostat to just inside the inner support structure of the TPC. Hence they will act as a link of the TPC to the microvertex. Similarly, the SET and the FCH occupies the space extending from just outside the outer support structure of the TPC and the EM calorimeters. Hence, they act as links between the TPC to the calorimetry (the SET between 35 and 90 degrees, the FCH between 7 and 32 degrees). Note, however, that the SET is a new device compared to the TDR. In the TDR, the TPC itself would extend out to a radius just inside the barrel calorimeter. See the next point.

- *An active interface with the calorimetry.* The SET and the FCH can provide an improved *entry segment* to the calorimetry, as they would be placed outside the outer support-structures of the TPC. They thus might help the reconstruction of the calorimeter information and consequently to improve the energy flow measurement.

- *An autonomous Si-tracking system.* The ensemble made by the microvertex (VTX), the SIT and the FTD devices located in the inner region and the SET and FCH which are the correspondents of SIT and FTD in the outer region, covers the full level arm of the tracking system and the angular region down to about 7 degrees, with respect to the beam axis. The Si-envelope will therefore help in monitoring the TPC, in particular to measure possible distortions.

Simulation studies are needed to better estimate and evaluate the motivations and main functions discussed above. These studies address the physics issues, the precise detector-geometry definition, and the expected detector performance. This work is underway, as discussed in section 4.3 and references [2], [5] and [6].

3 Conceptual Design of the Si Envelope

The main characteristics of the design of the overall Si-envelope tracking system are given in the next subsection.

3.1 *General Design*

As shown in Fig.1, the Si-envelope includes the SIT and FTD respectively in the central and the forward inner tracking region and the SET and FCH, respectively in the central and forward outer tracking region.

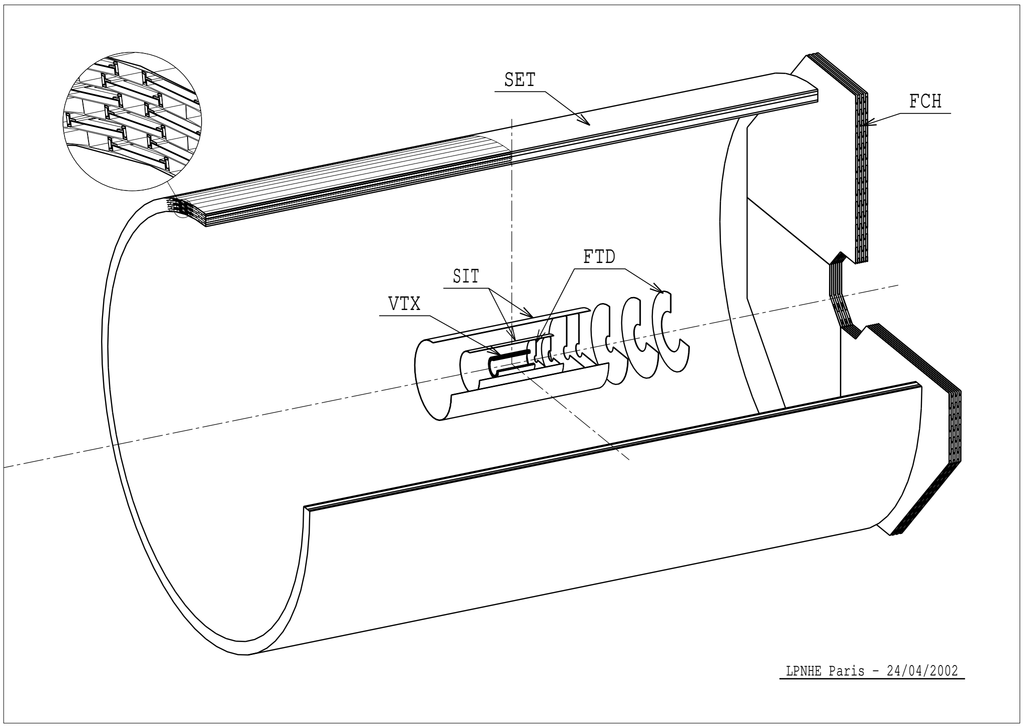

Figure 1: *3D-view of the Si-Envelope for the TPC. Except for the SET, all of the sub-detectors shown are part of the Tesla-TDR detector; the position shown for the SET is for study purposes only and occupies a space that was not foreseen for this purpose in the TDR.*

Fig.2 shows the coverage of the Si-envelope down to about 7 degrees with respect to the beam axis. Special attention has to be paid to the *corner region*, the region extending between 30 and 35 degrees with respect to the beam axis. It corresponds to the space reserved to bringing out the cabling and other infrastructure from all the inner detectors including the e.m. calorimetry.

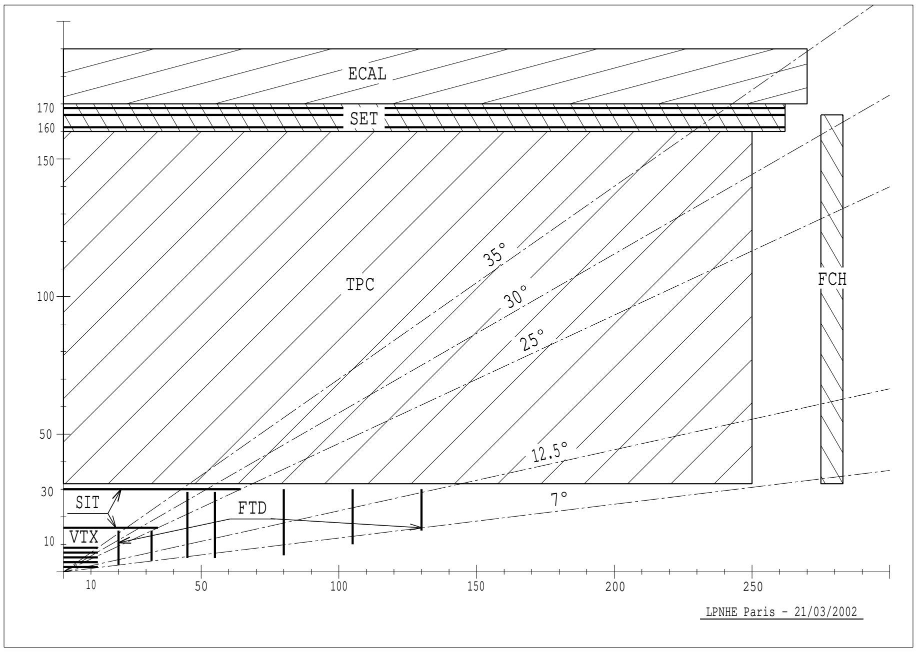

Figure 2: *Quadrant view of the Si-Envelope for the TPC. Except for the SET, all of the sub-detectors shown are part of the Tesla-TDR detector; the position shown for the SET is for study purposes only and occupies a space that was not foreseen for this purpose in the TDR.*

The figure also shows that on average there will be at least 8 to 10 hits per track in the Si-tracking system, including the microvertex (VTX) at all angles from 10 degrees with respect to the beam axis. Specifically:

At 10 degrees, the number of hits are: 1 (VTX) + 7 (FTD) + N (FCH)
At 20 degrees, the number of hits are: 2 (VTX) + 5 (FTD) + N (FCH)
At 25 degrees, the number of hits are: 3 (VTX) + 4 (FTD) + N (FCH)
At 30 degrees, the number of hits are: 4 (VTX) + 2 (SIT) + N (FCH)
At $\geq$ 35 degrees, the number of hits are: 5 (VTX) + 2 (SIT) + 3 (SET)

N depends on the number of FCH layers: at least 2 and most probably 4 but not yet defined, see below.

Presently, it is foreseen to have two double-sided layers in the SIT and seven wheels in the FTD, - three pixel wheels, followed by four wheels equipped with strip detectors [1]. The SET [2] is proposed to be located from 1.6 m to 1.7 m in radius and to comprise 3 layers of which the middle one is double-sided while the other two are single-sided. In the present TESLA TDR design the FCH is made of 4 sets of XUV straw tubes layers. The main issues in making a Si-FCH device are discussed at the end of this section.

3.2 *Basic component: the long ladder*

The basic elements of the Si-tracking in the central region are *long ladders* [7], made of elementary modules (sensors) that are bonded to each-other or through a kapton cable in the double-sided case. Long ladders are coupled to long shaping time. Because of the relatively low machine frequency and radiation levels, the Linear Collider makes it possible to use of long ladders and long shaping times. Study of the use and properties of this type of sensors and the associated front-end electronics will be an important part of our R&D program [3] (see next section).

Initially, the ladders will be based on today's standard technology. For the inner Si-tracking (the SIT), microstrips of 56 μm pitch, 300 μm thickness and 7.4 cm length will be used. The basic sensor consists of 1024 strips and covers 5.7×7.4 cm^2 surface. The long ladder will gather six such sensors and this leads to a total microstrip length of 34.2 cm. In the second layer of the SIT, the same sensors are used, but it is foreseen to bond together 12 sensors in order to make 68.4 cm long strips. If feasible[4] this long ladder arrangement will allow to have the readout chips at the two edges of the detector, thus greatly reducing the material in the detector as well as the number of readout channels and therefore the power dissipation. Thinning of the SIT is an important R&D issue.

For the outer central Si-tracking (the SET), the long ladders are made of six sensors. The sensors presently considered are those developed by Hamamatsu for the external Si-tracker in the CMS experiment, the Tracking Outer Barrel (TOB) [9]. It consists of Si-microstrips of 183 μm pitch, 500 μm thickness, and covering 9.45×9.45 cm^2 surface. Six such sensors bonded together will have a total 56.7 cm length.

3.3 *The endcaps*

Using Si-microstrips instead of straw tubes to build the FCH gives the benefit of unifying the technology used in the tracking system. Various alternatives are under consideration for the forward outer Si-tracker (the Si-FCH). The main questions are: what strips to use, short or long ones? Double-sided or XUV layers? How many 3D-points are needed?

Various conceptual designs are under study. Fig. 3 shows an arrangement for the Si-FCH similar to the one used in the first disks of the FTD (which are made of Si-pixels).

In the case of the Si-FCH, the pixels are replaced by short microstrips. Microstrips of 112 μm pitch, 300 μm thickness and 7.4 cm length, thus equivalent to the ones used in the SIT, could be used but with short strips. The innermost part of the Si-FCH wheels would be made of single-sensor modules, i.e. with strips of 7.4 cm length, while the rest of the wheel would consist of modules made of two such sensors bonded together. Thus the corresponding microstrip length would be 14.8 cm. In this design, the Si-FCH is made of short strips and its structure is compatible with double-sided layers.

Another possibility under consideration, is an octagonal shape rather than a wheel. It would thus fit with the shape of the Si-W e.m. calorimeter. As shown in Fig.4, this shape is compatible with long ladders of variable length. This design can fit both with a XY or a XUV orientation of the Si-microstrips.

[3] *Other groups are investigating the use of this technique for the future Linear Collider [8]. A joint collaborative effort is starting with them, see Section 5.*

[4] *Note that in the AMS experiment [7] the Si-tracker is made of double-sided long ladders with up to 15 sensors bonded to each-other.*

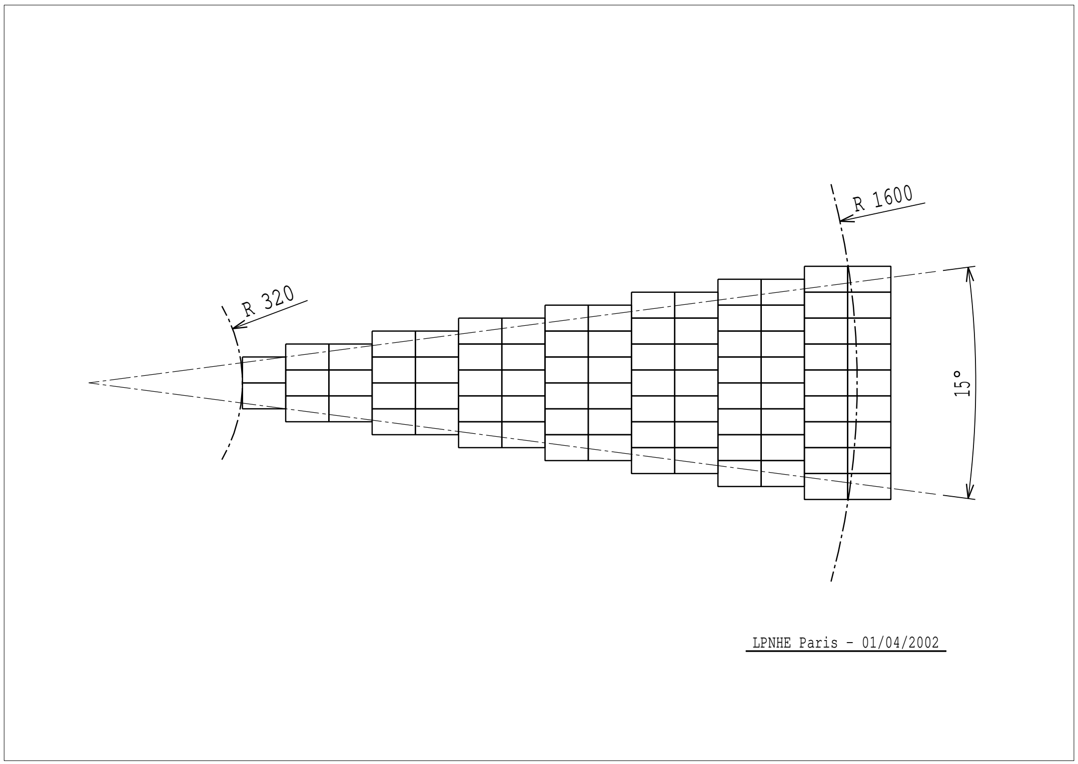

Figure 3: *Conceptual design for the Si-FCH similar to the one of the 3 first wheels of the FTD but replacing Si-pixels by Si-microstrips.*

A initial attempt to design the detailed ladder structure of a Si-FCH assuming the octagonal structure is shown in Fig.5. This design is based on 9.45 $\times$ 9.45 cm^2 sensors, identical to the ones used for the current SET design. It assumes that double-sided sensors will be available. Both XY or XUV frameworks are considered. In the case of XUV-frame, double sided XU-oriented strips are considered together with double-sided VV strips. This would allow to have XUV,VUX,XUV,VUX, thus in total 6 double-sided planes to make 4 planes with XUV-orientation. In addition, the same mechanical structure as the one used in SET is used for the support of each Si-FCH end-cap. In this design there are drawers of different dimensions, but it is possible to make them using only 3 different types of long ladders, with 4, 5 or 6 Si-sensors. A total of 128 ladders made of 4 Si-sensors, 320 ladders made of 5 Si-sensors and 192 ladders made of 6 Si-sensors will be needed to make a Si-FCH end-cap with 4 XY planes, yielding a total of 640 ladders per end-cap. To make a Si-FCH end-cap with 4 XUV planes, a total of 192 ladders made of 4 Si-sensors, 480 ladders made of 5 Si-sensors and 288 ladders made of 6 Si-sensors will be needed yielding a total of 960 ladders per end-cap in this case.

This Si-FCH design is very preliminary and should be considered as an educated guess. Nevertheless, it shows that in terms of number of ladders, and as we will see later, in number of readout channels, the Si-FCH is comparable to the SET. Work is in progress to better define the Si-FCH conceptual design and it is coupled to simulation studies.

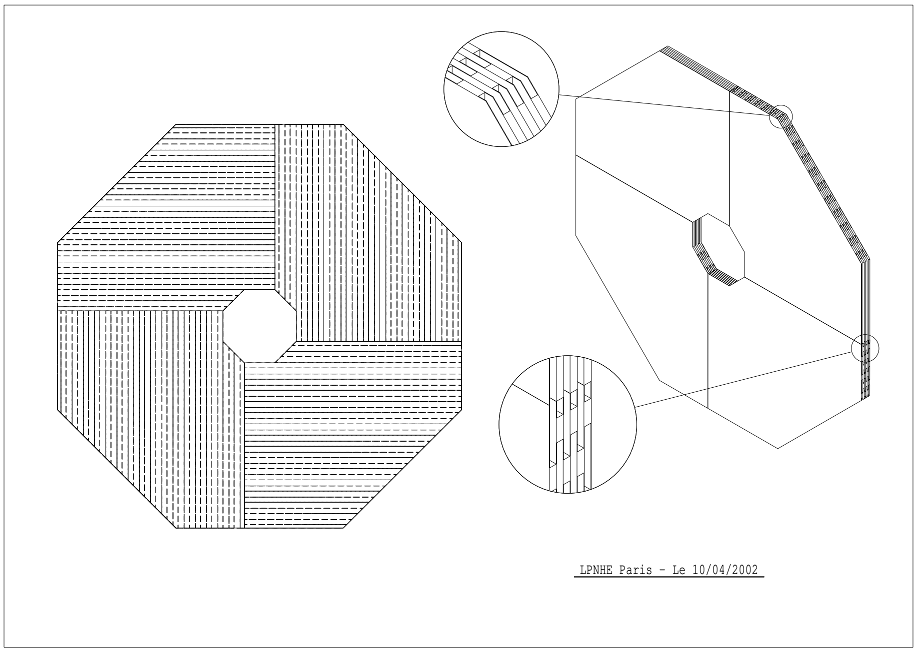

Figure 4: *Conceptual design for the Si-FCH, assuming an octagonal geometry and chest support-structure.*

4 The R&D Objectives and Present Status

The main goal is to push further the impressive R&D that led to the present generation of Si-trackers for LHC, now under construction [9]. *Transparency* is the keyword and also the most challenging aim of this R&D for the Si-trackers for the future LC. It should be noted that these new developments will also be useful for the second generation (upgrades) of the LHC experiments and for astroparticle experiments, eg. GLAST [10].

The R&D will be pursued in parallel along the three following lines: mechanics, electronics (including new developments on sensor technology) and simulation studies. The foreseen objectives and the present status of these various R&D aspects are discussed in the next subsections.

4.1 *R&D on Mechanics*

The main emphasis is in making a realistic design of the Si tracking system. This means taking into account the environmental conditions necessary for the functioning of the device, i.e.: the mechanical structure and support, the readout and service electronics, the packaging, connectics and cabling and the cooling system (if needed). These objectives has to be attained without compromising the central issues of transparency, of large dimensions (in particular for the detectors in the outer tracking region), of hermetic coverage, of the ease to produce (thus need for modularity), of robustness and reliability, and of very high precision.

Presently, most of the work has been concentrated on the SET design. This is the largest area component of the Si-envelope. In the present study, the SET is located between 1.6 and 1.7 m in radius, is about 5 meters long and is comprised of three layers

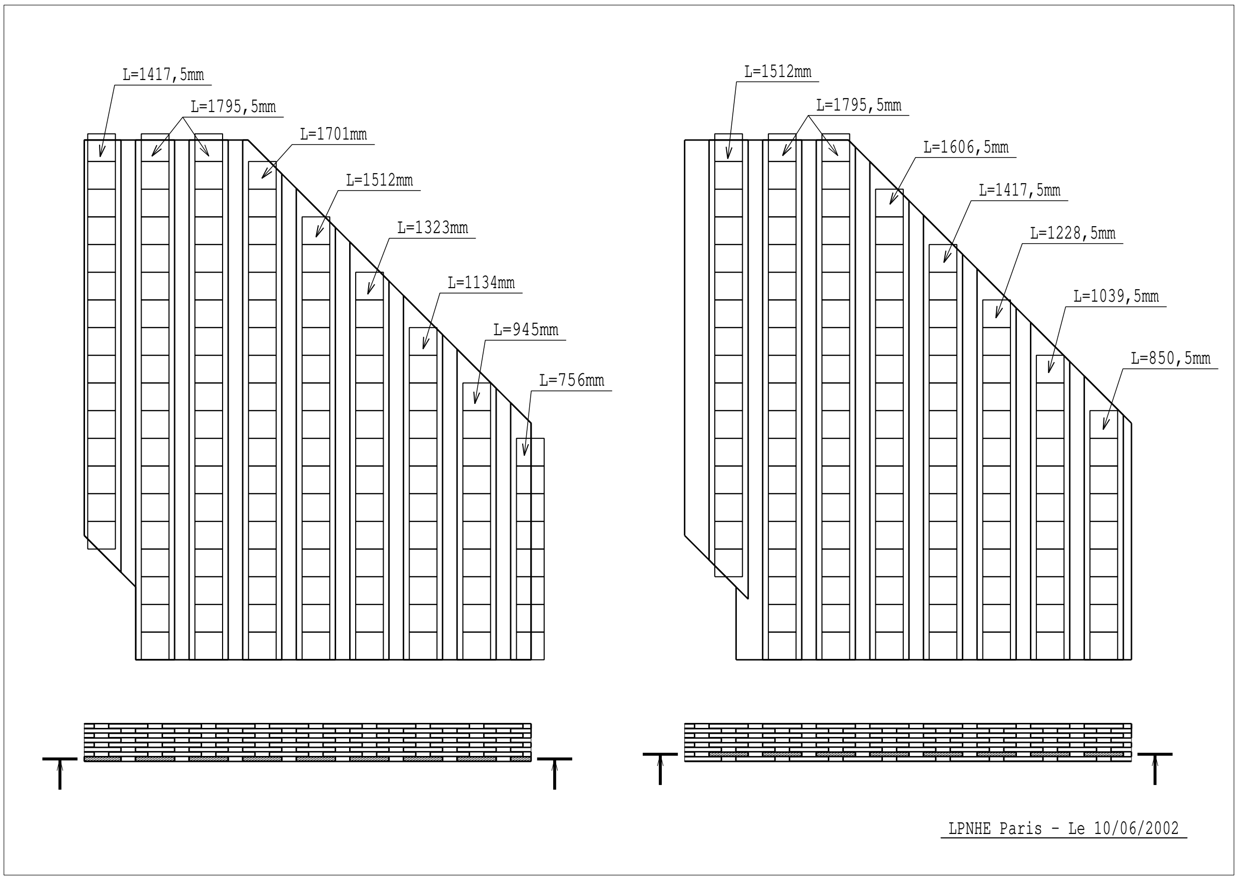

Figure 5: *Details of one sector of the Si-FCH, assuming an octagonal geometry and chest support-structure. It shows the various length of the drawers as well as the positioning of the Si-sensors on the down-side (left) and on the up-side (right) with respect to their drawer support.*

of microstrips, two single-sided and one double-sided. Thus it will represent a total area of about 200 m^2.

Much experience was gained by studying both the CMS [9], and the AMS Si-trackers [7] and also by fruitful discussions with experts from both experiments.

4.1.1 *The long ladders*

In the present SET design, the basic element is a long ladder made of six sensors as described in Section 3. The six sensors are bonded together and mounted on a very light carbon fibre frame of about 1mm width. The frame has a ladder structure (Fig.6).

The sensors will be positioned by an appropriate system of positioning pins, similar to those used in the CMS tracker for the placement of the ladders on their carbon fibre support-structure. A kapton cable of about 50 μm is placed between the carbon fibre frame and the sensor and serves as a bias-cable. The very front-end electronics will be at the end of the ladder as can be seen in Fig.7, which shows all components of the long ladder.

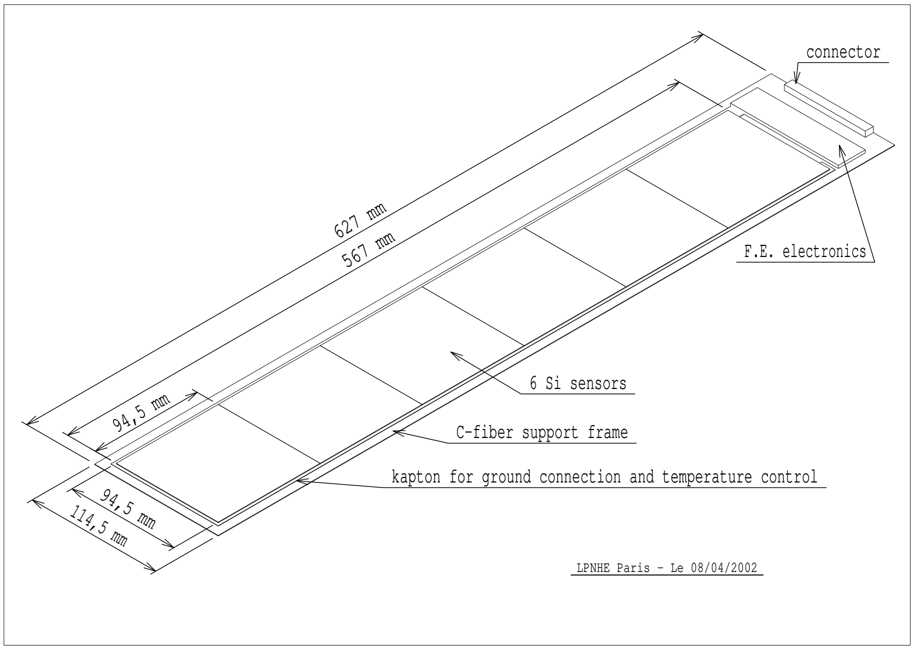

Figure 6: *Detailed design of a long ladder for the SET*

4.1.2 *The drawers*

The second-level component is the drawer. As shown in Fig.8, the drawer will host five long ladders of the type described above.

The drawer length is half the total detector length. The frame of the drawer is a very light carbon fibre ladder structure. To ensure the longitudinal hermeticity, the long ladders will be distributed alternatively upon and beneath the drawer-frame, and there will be an overlap of about 2% in surface between the sensitive parts of each neighbouring ladder in the drawer.

The signals from each ladder will be sent to the end of the drawer through a thin kapton cable (see next section for more details on the electronics front-end). This cable will also be used to transmit the needed service signals (voltages, clock etc...). The external edge of the drawer support has a C-shaped section. If it is found that cooling is necessary, this groove could be used to accommodate the cooling pipe, following the design of the CMS TOB.

4.1.3 *The support structure*

The drawers will be inserted in the support structure. For reasons both of rigidity and lightness, a “honeycomb” cylindrical structure is proposed, as shown in Fig.9.

It is made of thin carbon fibre partitions, about 1 mm to 1.4 mm thick. The azimuthal hermeticity is ensured by staggering the drawers and requiring a 2% overlap in surface between the adjacent drawers. Every two voids in the “honeycomb” structure are empty, a space which could be used for cooling purposes or electronics. However, to preserve lightness, our aim is to keep these spaces empty.

The overall structure will be made of two parts: Two supports with an internal radius

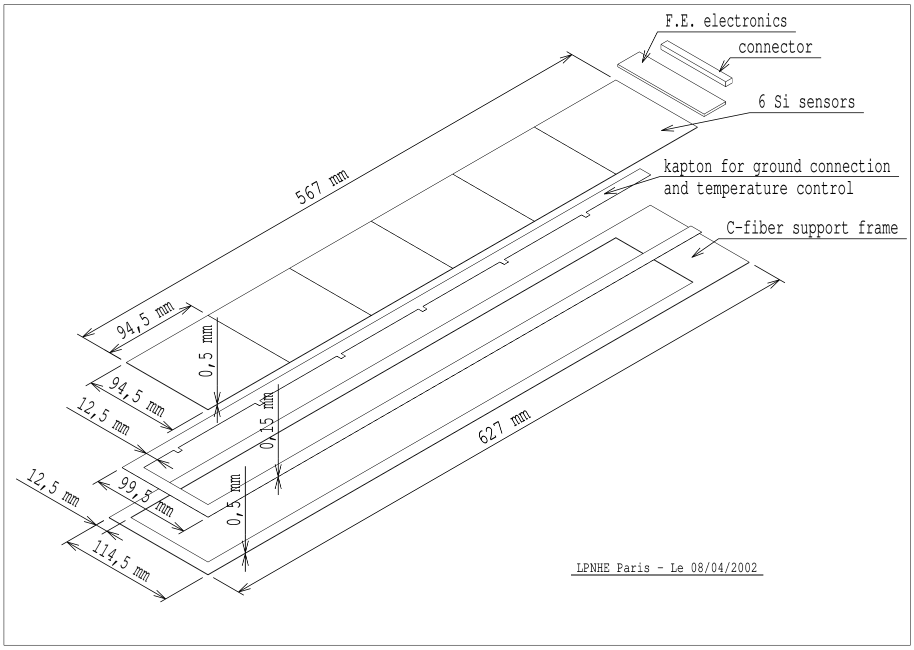

Figure 7: *Various components of a long ladder for the SET*

of 1.6 m, an external radius of 1.7 m and a total length equal to the half length of the SET device. Each support will carry a weight of about 300 kg. The weight is estimated assuming 50% due to the Si-sensors and 50% due to the electronics on the detector, the cabling and possibly the cooling system. In order to further decrease the support structure mass, the possibility of slicing it in shorter longitudinal parts - thus supporting the drawers by a series of rings rather than all along their length - will be studied.

Mechanical studies are ongoing on the material choice. Even for the carbon-fibre baseline choice, there are many different carbon fibre qualities to evaluate. There is also the possibility of making thin partitions of a foam sandwiched between two thin carbon fibre foils. Novel materials could also be investigated. Estimates of rigidity and magnitude of deformations as well as of power dissipation in the mechanical structure are under-way. The calculations will be cross-checked by measurements on a mechanical prototype.

This design is a first realistic approach that serves as basis both to advance the mechanical R&D further and to develop the detailed simulation studies. The two will be giving each-other constant feedback. The introduction of the present design in the geometry database of a GEANT4-based simulation package such as MOKKA [11] is described in Section 4.3. The development on the mechanical design will closely interact with the R&D on electronics.

Table 1 summarises the proposed mechanical design for the SET in a few numbers.

4.2 *R&D on Electronics*

The field of electronics is expected to see much advance in the next five to seven years. Such advances will have important implications to the mechanical design, and thus on the transparency issue.

The main fields of interest are:

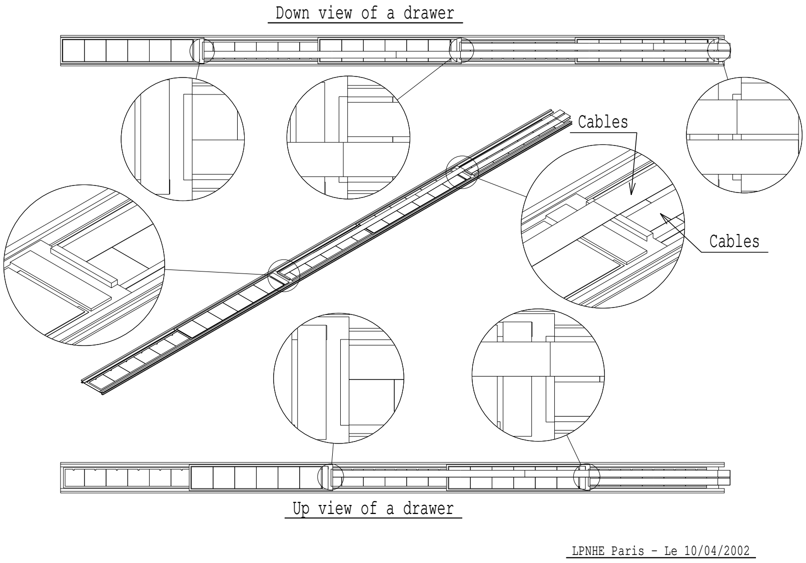

Figure 8: *Detailed design of the drawer hosting 5 long ladders in the SET*

- *Developing the very front-end electronics associated to the long microstrips*; this implies to have a *long shaping time*. Related low noise issues, strobing and analog pipelining of the signals will be studied.
- *Diminishing the power dissipation* to reduce the need for cooling as much as possible. Different manners to achieve this are:
  - *Diminution of the number of readout channels (long instead of short strips)*
  - *Smaller submicronic technology (i.e.* $< 0.25\mu m$*)*
  - *New packaging technology*
  - *Connectics and Cabling*
- *New developments on sensor technology* that include larger surface and thinner sensors and also including some very front-end electronics in active substrate.

4.2.1 *Front-End Architecture*

The noise N, in electron equivalent is given by $N = A + B \times C$, where C is the detector capacitance in pF, typically 1.4 pF/cm.

For short shaping times, such as those necessary at the LHC, the noise N is given by $N = 600 + 30 \times C$, and this limits the length of the sensors to about 20 cm.

The AMS experiment has developed front-end chips with long shaping times (of the order of 5 μs), and obtained $N = 350 + 4 \times C$. This type of front-end is also under development for the GLAST Si-tracker (see Ref [10]). We foresee to develop and test front-end electronics of this type for the central trackers of the proposed Si-envelope. In

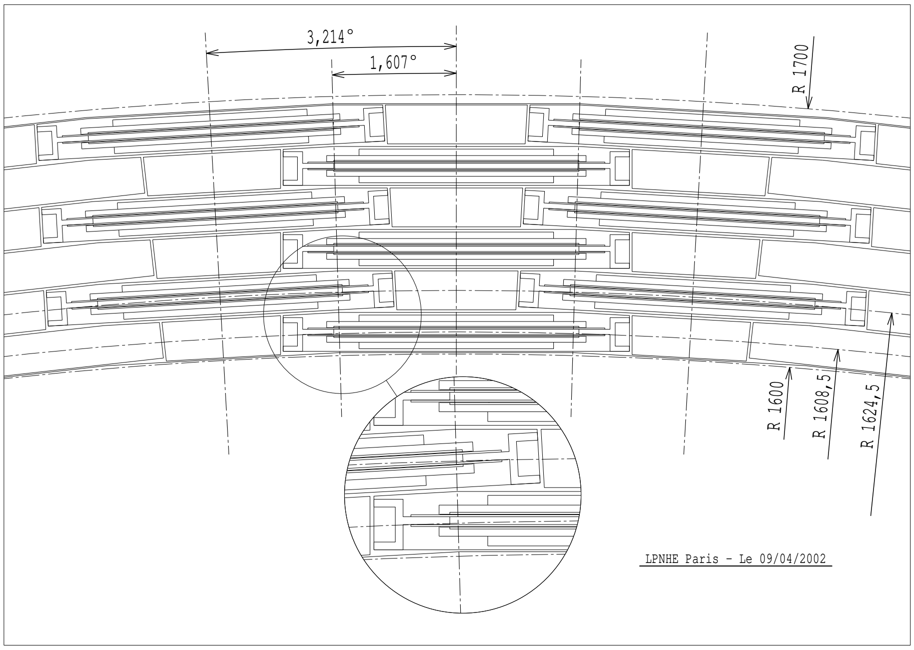

Figure 9: *Transverse view of the carbon fibre support structure of the SET*

our case, it would be a readout system for a 60 cm ladder, with a shaping time of order 1 μs. The principles of the AMS design would be followed. If the tests prove the feasibility of such a design under LC conditions, it would be pursued as the main alternative in the further development of the final design.

The draw-back of long shaping time is the increase in leakage current. The signal to noise ratio, S/N, is proportional to $1/\sqrt{\tau_S}$, where τ_S is the shaping time. However, at the future Linear Collider the radiation level is expected to be quite low, especially in the SET location ($\leq$ 100 Rad per year), thus very little leakage current is expected.

To cope with the machine cycle, an analog pipeline of a few tenth of cells will be part of the very front-end electronics. 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 occurred. As outlined in Fig.10, the very front-end will be defined by a low noise preamplifier, followed by the shaper with a typical 1 μs shaping time and then stored in the analog pipeline.

It is foreseen to have the front-end chain for 128 channels grouped into one single chip, as it is done in the APV25 front-end chip in CMS [9]. An additional 2 to 1 multiplexing factor will be applied at the entrance of the ADC. Therefore there will be 4 very front-end circuits per drawer and two ADCs per drawer in the SET case and twice these numbers for the SIT. As shown in Fig.10, the digitisation, the sparsification and the buffering will also be on the detector, on the circuit located at the end of each ladder. Most probably, all the front-end readout chain could be implemented in a single chip.

The output signal from each ladder consists of only one digital output, which must be sent to the readout system outside the detector. Transmitting the signal from the ladder to the end of the drawer can be done either via digital lines on a kapton cable that also

SET Component	Parameters	Dimensions	Total number
basic sensor	sensor area pitch/thickness nb of strips	94.5×94.5 mm ^{2} 183μm/500μm 512	6/ladder
Long ladder	sensor area pitch/thickness nb of strips nb dig. outputs external length external width nb R.O. channels	94.5×567.0 mm ^{2} 183μm/500μm 512 1/ladder 627 mm 114.7 mm 512 channels	5/drawer
Drawer	total length nb of long-ladder nb R.O. channels nb dig. output	1/2 SET length 5/drawer 2560 channels 1/drawer	224 /SET layer
Support structure	total length shape internal radius external radius weight $\%X_0$	1/2 SET length cylindrical 1.6 m 1.7 m 300 kg 4.5%	2/SET
SET device	total length nb of ladders nb of drawers nb of supports weight $\%X_0$	5.5 m 4480 896 2 600 kg 6.5%	

Table 1: *Main components and parameters of the SET mechanical design*

contains all the other needed service signals, or via digital optical fibres (at most 2 m long). In this framework and within the present SET design, there are 5 digital signal outputs per drawer (one per ladder). A buffer located at the end of the drawer will merge these five outputs into one single output signal per drawer. Further multiplexing should then be applied to further decrease the number of output cables. For instance through a patch panel, a first multiplexing factor of 4 to 1 will give a unique signal from the 4 layers (2 single sided plus one double-sided layer signals), for the elementary sector in azimuthal angle (ϕ) in the SET. It will cover an angle in ϕ of about 3.2 degrees. The signals provided by a few such basic sectors could then be merged into a single one, reducing even more the number of digital fibres at each SET edge.

However, one has to take into account the cabling to transport the voltages, clocks and other needed service signals.

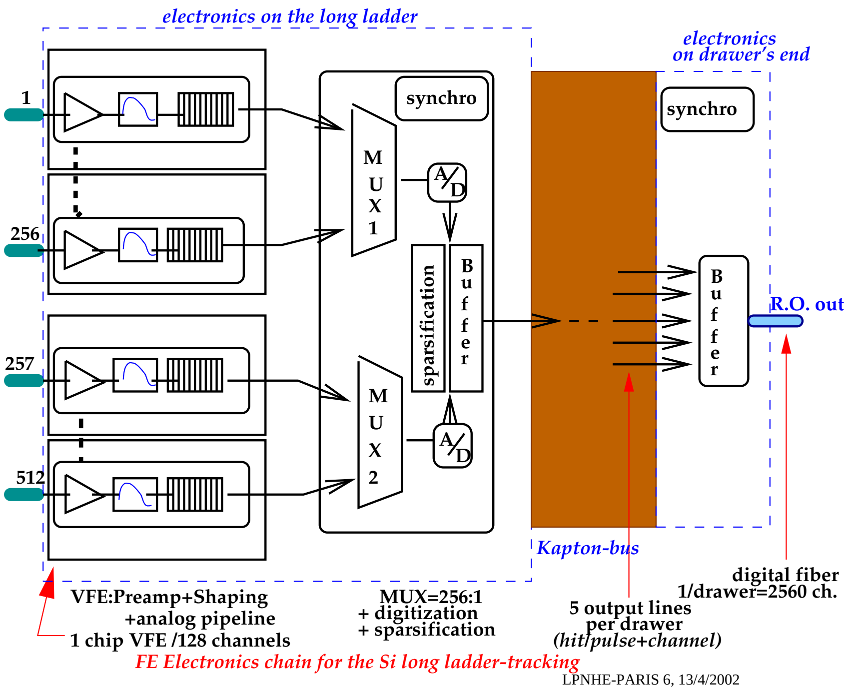

Figure 10: *Schema of the Front-End Electronic chain of the Si-trackers part of the Si-Envelope for the TPC (SET case)*

4.2.2 *Power Dissipation*

A low power-dissipation front-end is the goal. From the present experience on the AMS front-end, it seems feasible that the front-end circuit described above could attain a power dissipation of 0.4 mW per channel. It would be divided into 0.3 mW for the analog part and 0.1 mW for the digitisation part. The needed ADC is not very demanding. Presently, a 1MHz clock and 8 bit ADC is under consideration. ADCs in 0.35 μm AMS technology are available on the market and have a power dissipation of 1.2 mW, to be shared in our case by 256 channels. Thus the type of ADC needed for our application should not render any problems what regards power dissipation.

A preliminary estimate of the temperature gradient in the SET has been performed. Assuming 0.4 mW power dissipation per channel gives 0.460 kW per support structure, thus about 1 kW for the whole SET device. The heat is assumed to be conducted entirely through the carbon fibre mechanical support. The goal is to have the temperature difference between the first and the last ladders in a drawer less than 10 degrees C. The T_0 temperature [5] should stay very near to the temperature at the first front-end location. The overall transfer section is 0.092 m^2, for a radius of 1.7 m and a total circumference of 11 m. The total average width of the mechanical structure should be equal to 8.36 mm. As this total width is subdivided into seven internal partitions in the proposed support structure, this gives a thickness per partition of about 1.2 mm, compatible with the present design (see Section 4.1).

[5] *T_0 is the temperature at the end point of the first ladder opposite to the one where the front-end electronics of this ladder is located, thus about 60 cm away of it.*

Si-Envelope Component	Items	Total number
SET	nb of layers	2 single-sided + 1 double-sided
	nb of ladders	4480
	nb of R.O. channels	2.293.760
	nb of V.F.E. chips (4 per ladder)	17920
	nb of ADCs (2 per ladder)	8960
	Power dissipation	920 Watts
	nb of dig. outputs	112 × 2
SIT	nb of layers	2 double-sided
	nb of ladders (1024 × 2 ch/ladder)	38+94=132
	nb of R.O. channels	270.336
	nb of V.F.E. chips (16 per ladder)	2116
	nb of ADCs (8 per ladder)	1056
	Power dissipation (if no power cycling)	110 Watts
	nb of dig. outputs	134 × 2

Table 2: *Front-End Electronics of the Si-Envelope in a few numbers, in the central barrel*

With the beam time-structure foreseen at TESLA, *power cycling* of the front-end electronics would be possible, which could reduce the total power consumption by a factor of 100. The power dissipation of the SET would be reduced to about 10 W, to 4 W for each end-cap of the SiFCH, and to 2 W for the SIT. This would imply that only passive cooling is needed and thus a substantial gain in the detector transparency.

4.2.3 *What Data?*

To answer this question, several issues must be studied by simulation and/or measurements on a test bench; namely:

- *How many ADC bits?*: this relates to the pulse-height measurement. The resolution per point should be better than 25 μm (see simulation studies) and possibly of the order of 10 μm. Due to the pitch size, the pitch resolution is not good enough (pitch/$\sqrt{12}$), thus centroid finding is needed. This means that the pulse-height must be recorded, above a certain threshold.

- *Is the dE/dx measurement needed?* If yes, this also relates to the required number of ADC bits.

- *Timing information*: do we want timing information? If yes, what is the required resolution on the timing?

Si-Envelope Component	Items	Total number
Si-FCH (XY)	nb of layers	4 double-sided + 1 double-sided
	nb of ladders with 4 sensors/end-cap	128
	nb of ladders with 5 sensors/end-cap	320
	nb of ladders with 6 sensors/end-cap	192
	nb of R.O. channels/end-cap	655.360
	Power dissipation	262 Watts
Si-FCH (XUV)	nb of layers	4 XU-double-sided + 2 VV-double-sided
	nb of ladders with 4 sensors/end-cap	192
	nb of ladders with 5 sensors/end-cap	480
	nb of ladders with 6 sensors/end-cap	288
	nb of R.O. channels/end-cap	983.040
	Power dissipation	393 Watts
FTD	see TESLA TDR	see TESLA TDR

Table 3: *Front-End Electronics of the Si-Envelope in a few numbers, in the end-caps*

- *Triggering with Si-trackers*: it may be useful to use the Si-tracking information for a Level-2 trigger à-la-CDF [12].
- *Occupancy and Ambiguities*: Double- or multi-hit issues must be estimated in more detail and consequently the need for timing information should be revisited here.

4.2.4 *The Front-End Electronics in a few numbers*

Table 2 summarises the front-end electronic chain of the barrel Si-envelope (SIT and SET) in a few numbers.

Similarly, table 3 summarises the front-end electronic chain of the end-cap Si-envelope (SiFCH and FTD). For the FTD we refer to the design and numbers quoted in the TESLA TDR, and for the Si-FCH we consider the case with the octagonal structure as roughly sketched in Section 3.3.

The very preliminary numbers quoted in table 3, show that the two Si-FCH end-caps, made of 4 planes of XUV-strips, will represent a total number of readout channels comparable to the SET device. This is if the structure with long ladders of relatively modest length (40, 50 and 60 cm) proves to be adequate for the good functioning of these Si-FCH detectors.

4.3 *Simulation studies*

A forthcoming LC-Note describes the simulation studies already achieved [5] in detail. Here the main aspects and results of these studies are briefly summarised. Most of the present studies are based on the SGV package [13]. SGV correctly takes into account the distribution in space both of scattering material and point measurements, including the spiralling of low P_T charged tracks in the magnetic field. It also correctly calculates correlations between the five track parameters, and the dependence of the point-resolution on the angle of incidence of the tracks on silicon detectors. The production-vertex can be chosen to be at any position in the detector, and the decay-length can also be freely chosen. Finally, precise formulae for multiple scattering [14] are used, taking the rest-mass of the particles into account.

Some progress has also been made in implementing the Si-envelope and (in particular the SET) in the detailed simulation packages, BRAHMS (GEANT3) and MOKKA (GEANT4) (See References [15] and [11]).

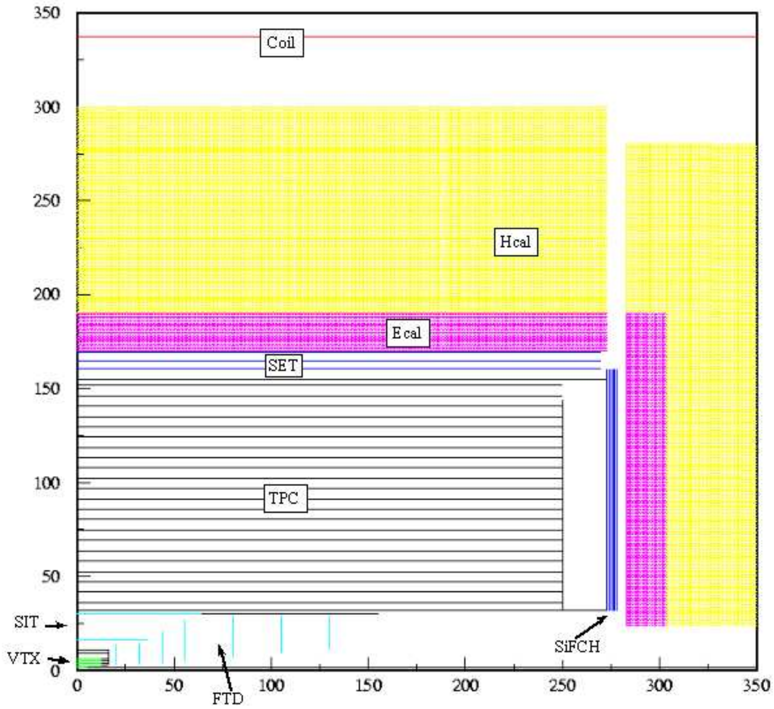

Figure 11: *A view of the central part of the detector, as it is described in the SGV geometry database.*

4.3.1 *Summary on fast simulation studies*

The SGV package [13] was used to perform various preliminary studies on the detector performance. It was used to define the geometry of the new SET device in terms of needed space, detector location and number of layers. These parameters are essentially estimated on the basis of the momentum resolution improvement obtained when adding the SET to the tracking system as proposed in the TESLA TDR. The key performance figures for the TDR detector were taken from Part IV, chapter 2 of [1], and were the following:

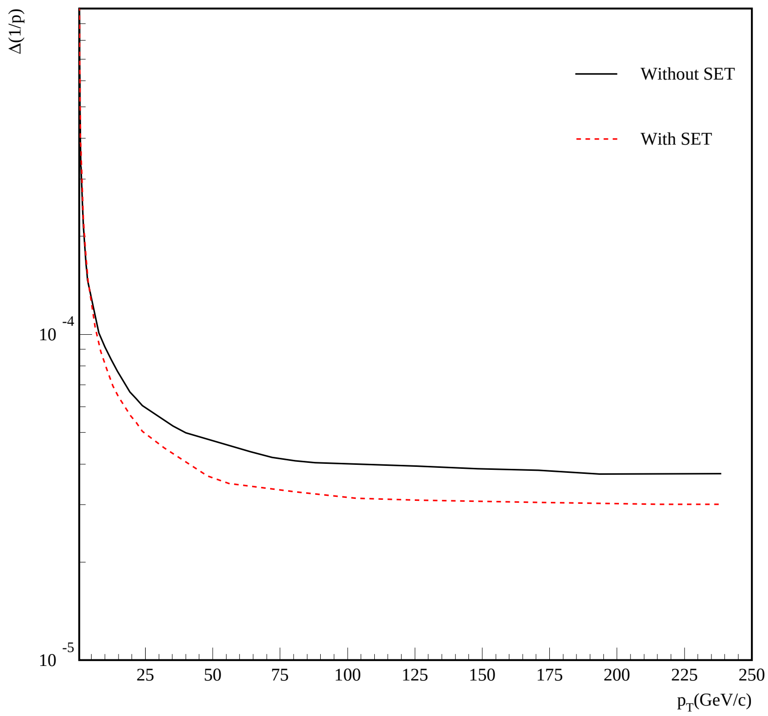

Figure 12: *Effect of the SET on the momentum resolution of the tracking system, for transverse momenta up to 250 GeV/c. The SET design used to obtain these results consisted of three layers of Si-detectors, at radii 160.5 cm, 165 cm and 169.5 cm. The point-resolution was 25 μm and each layer represented 0.5 % of a radiation-length. The simulated particles were pions at 90 degrees.*

- Magnetic field : 4.0 T.
- Beam-pipe : 0.425 % X_0.
- VD : 5 layers, point resolution 2 μm, thickness per layer 0.06 % X_0. The cryostat represents 0.25 % X_0 (section 2.1.4.6 of [1]).
- SIT : 2 Layers, point resolution 10 μm, thickness per layer 0.13 % X_0 (section 2.2.1, figure 2.0.2 of [1]).
- TPC : 225 layers, point resolution 180 μm for tracks at 90 degrees - slightly better than the value estimated for the preferred Ar-CO_2-CH_4 gas-mixture at maximum drift-distance, with "Chevron" pads. The thickness per layer is 0.002 % X_0, and the inner field-cage represents 1.3 % X_0, the outer 1.7 % X_0. The end-plate represents 40 % X_0. (section 2.3 of [1] - in particular tables 2.3.3, 2.3.5, and figure 2.3.4 b - and figure 2.0.2).
- FCH : 6 layers, point resolution 100 μm, thickness per layer 0.01 % X_0 (section 2.3.2 of [1]).

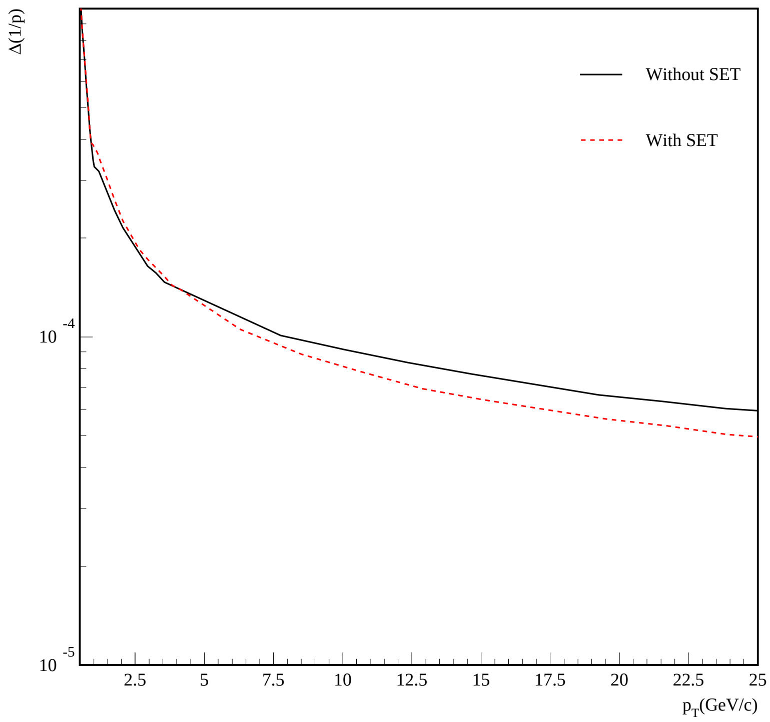

Figure 13: *As fig. 12, for transverse momenta up to 25 GeV/c.*

- FTD : 7 layers, point resolution 25 μm, thickness per layer 0.1 % X_0 (sections 2.2.1 and 2.2.2 of [1]).

In addition, the position and thickness of the infrastructure (electronics, mechanical support, cooling) of the VTX, SIT and FTD are included. A view of a quadrant of the central part of the detector, extracted directly from the SGV geometry database is shown in figure 11.

The results of the study are quoted in detail in Reference [2]. Figs.12 and 13 shows the effect on the momentum resolution when adding the SET to the TPC in different regions of P_T. 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 μm and each layer represented 0.5 % of a radiation-length.

Under these assumptions, an improvement up to 20% is expected at high transverse momenta (fig 12). Under the same assumptions, the blow-up of the low P_T region (fig. 13), 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 %.

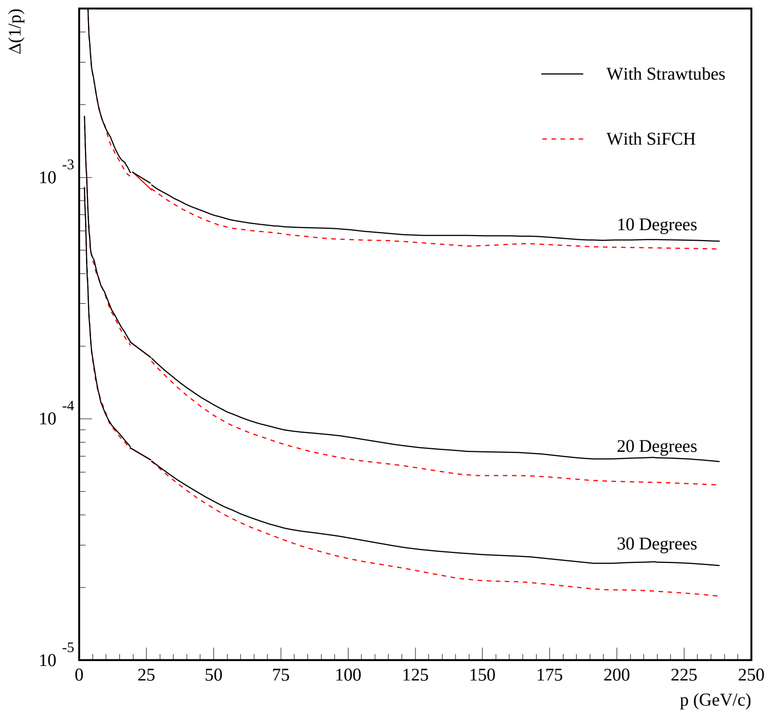

Figure 14: *Effect of the Si-FCH on the improvement of the momentum resolution of the tracking system, in the high momentum range, for various angular values. The Si-FCH design used to obtain these results consisted of six layers of Si-detectors. The point-resolution was 25 μm and each layer represented 1 % of a radiation-length.*

Figures 14 and 15 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 30 degrees in angle.

SGV-based studies were performed for various other issues, such as estimate of how the SET helps the calorimetry to measure the incoming photons, conversions etc..; to estimate the SET occupancy and thus the double-hit and multi-hit rates; to estimate the contribution of the SET and the Si-FCH in the energy flow measurement [6]. Several of these studies use events generated according physics processes such as: $e^+e^- \longrightarrow q\bar{q}$, WW or HZ. More details on these simulation studies are given in Ref. [5].

4.3.2 *Implementing the Si-Envelope in the detailed simulation*

Once the detailed and realistic design of the detector is achieved, it can be used to define the geometry database of the device for the GEANT simulation. The mechanical design of the SET, previously described in this note, has been entered into the database of the GEANT4-based package, MOKKA. The result of this work is shown in Fig.16 [16]. It

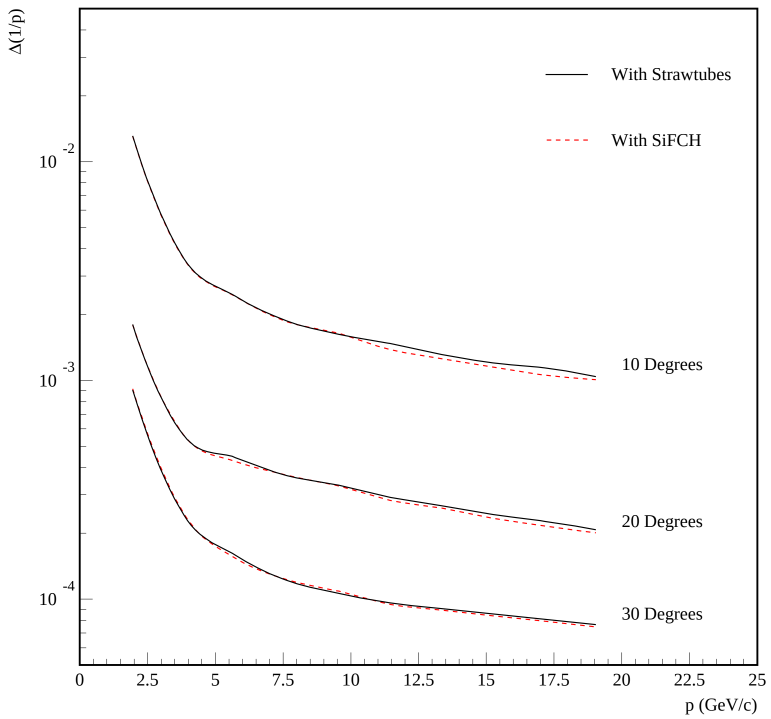

Figure 15: *As fig. 14, for transverse momenta up to 25 GeV/c.*

demonstrates how accurately the detailed mechanical design is implemented in GEANT4. This is now the starting point to perform detailed simulation studies. MOKKA contains a feature that allows to automatically generate the FORTRAN code that describes the geometry for GEANT3 from the database. Hence, the same geometry database has been included into the GEANT3-based BRAHMS [15].

The most crucial task is to have a track reconstruction programme running in these detailed simulation packages with the complete Si-envelope.

5 Perspectives

Much interest has been shown to develop an international collaboration on Si-tracking for the future Linear Collider. Our project is part of this emerging R&D program. It is based on the worldwide expertise on Si-tracking techniques that has been acquired with the construction of microvertex detectors at the LEP experiments, at BaBar, at BELLE, at CDF I and at STAR. New expertise is now emerging on devices of larger dimension such as the ISL (Intermediate Silicon Layers) in CDF or the AMS tracker. The largest ones are currently starting to be built for the LHC experiments, ATLAS and CMS.

The collaboration will focus on two detector concepts. One is the all-Si-tracking design, as suggested in the SD (Silicon Detector) proposal at the Snowmass Workshop in 2001 [17]. The other is based on the Si-envelope, which fits both with the TESLA detector design and the one of the Large Detector (LD) proposal at Snowmass'2001. Whatever the detector concept, the following generic R&D work will be pursued considering various alternative techniques for the sensors, ie. short or long strips or Si-drift or any novel Si-sensor technique that might reveal to be promising for our applications. The R&D will be performed along the following main lines:

- *Si-sensors*: as mentioned above.
- *Electronics*: Front-end adapted to each sensor case, digitisation, readout architecture, trigger logic, timing information, cabling and packaging.
- *Mechanical issues:* Transparency, hermiticity, architecture, support, modularity, rigidity and deformation studies, cabling and cooling issues...
- *Simulation studies:* Developing the necessary tools (in particular track reconstruction), study of physics issues and needs, detector performance, comparison between different detector techniques and concepts.

Combining the two most powerful and in many ways complementary tracking techniques - Si-detectors and the TPC - makes our project particularly appealing. We believe that this solution is a good candidate for the best tracking system for the future Linear Collider.

Acknowledgements

We are very grateful to some of the CMS experts in the Si-tracking in particular to Ariella Cattai, D.Abbaneo, A. Honma, L. Mirabito, P.Petagna, P. Siegrist, J.Torska, for their very friendly and competent collaboration. We would like to thank some colleagues from SCUC and SCIPP in Santa Cruz and especially B. Schumm for fruitful collaborative contacts and W. Lustermann, G.Viertel (ETH Zurich), M. Pohl and his group (Geneva University), participating to the AMS experiment, for their valuable help and many useful discussions. We are also very much indebted to these CMS and AMS teams for helping us in getting a few sensors to test the long-ladder issues. All our thanks to P. Mora de Freitas for translating the SET mechanical design into the geometry database of MOKKA. All our thanks to JP Brient, JL Faure and H.Videau for useful discussions and to C. Damerell, R. Heuer and R. Settles for their follow up of the project and useful advice.

References

[1] TESLA Technical Design Report, DESY 2001-011, ECFA 2001-209, March 2001.

[2] J.E. Augustin, M. Berggren and A. Savoy-Navarro, "*Study of a Silicon External Tracker:SET*", LC-Note 2001-075, 30th of August 2001 .

[3] A. Savoy-Navarro, Talk at the 1st Extended ECFA-DESY Studies Workshop in Cracow, Sept. 2001, in http://www.fatcat.ifj.edu.pl/ecfadesy-krakow/.

[4] The concept of the Si-envelope proposed by the LPNHE-Paris 6 team was first presented, at the tracking sessions of the First North American Workshop for the Future Linear Collider, in January 2002 at Chicago (USA), and of the ECFA-DESY Extended Studies Workshop in April 2002 at St Malo (France); See copies of ASN's transparencies in http://lpnhe-lc.in2p3.fr/ and in http://www-dapnia.cea.fr/ecfadesy-stmalo.

[5] J.E. Augustin et al., "*Preliminary Monte-Carlo Studies on the Si-envelope performances and related physics issues*", LC Note in preparation.

[6] M. Berggren, Talk at the 2nd Extended ECFA-DESY Studies Workshop in St Malo, April 2002, at the session on EFLOW measurement, in http://www-dapnia.cea.fr/ecfadesy-stmalo.

[7] G. Ambrosi, Nucl. Instr and Meth., A436, 215 (1999).
B. Alpat et al., Nucl. Instr and Meth., A439, 53 (2000).

[8] D. Dorfan, H. Sadrozinski, B.A. Schumm(PI), N. Spencer and A. Seiden,"*Use of Silicon Strip Detectors in Low Duty-Cycle Applications*", proposal to the DOE, unpublished and references therein.

[9] The CMS Collaboration, "*The Tracker Project*", Technical Design report CERN/LHCC 98-6, CMS-TDR 5, 15 April 1998, and "*The Tracker Project Technical Design Report*", Draft4, and references therein.

[10] R.P.Johnson et al, SLAC-PUB 8549, August 2000.

[11] P. Mora de Freitas, "*Calorimeter Studies with GEANT4*" in Proceedings of the LCWS'2000 at FERMILAB, Oct. 2000. And also the most recent information on the MOKKA package in the following Web pages:
http://polype.in2p3.fr/geant4/tesla/www/mokka/mokka.html,
http://polype.in2p3.fr/geant4/tesla/www/mokka/talks/talklist.html

[12] W.Ashmankas et al., "*Performance of the CDF Online Silicon Vertex Tracker*", Published in Proceedings 2001 IEEE Nuclear Science Symposium (NSS) and Medical Imaging Conference (MIC), San Diego CA, 4-10 Nov. 2001, P100-107 and FERMILAB-CONF-02/035-E.
W.Ashmankas et al., "*The CDF-II Online Vertex Tracker*", in Proceedings of the ICALEPS 2001 Conference (8th International Conference on Accelerator and Large Experimental Physics Control Systems), 12/22/2001.

[13] M. Berggren, *" SGV: Simulation à Grande Vitesse A Fast simulation Package"*, in http://home.cern.ch/ berggren/sgv.html.

[14] G. R. Lynch and O. I. Dahl, *"Approximations to multiple Coulomb scattering"*, LBL-28165-rev. (1991)

[15] T. Behnke, G. Blair, et al., *BRAHMS: A Monte-Carlo for a Detector at a 500/800 GeV Linear Collider*, LC-TOOL-2001-005, 11/1/2001.

[16] J.C. Brient and H. Videau presentations at the 2nd Extended ECFA-DESY Studies Workshop in St Malo, April 2002, at the session on Simulation, in http://www-dapnia.cea.fr/ecfadesy-stmalo.

[17] SD Detector proposal to appear in the Proceedings of the Snowmass'2001 Workshop on the Future of Particle Physics, Snowmass, Colorado, July 1-21, 2001. And also: B.A.Schumm, *" Research and Development towards a Detector for a High Energy Electron-Positron Linear Collider"* to appear in these Proceedings too.

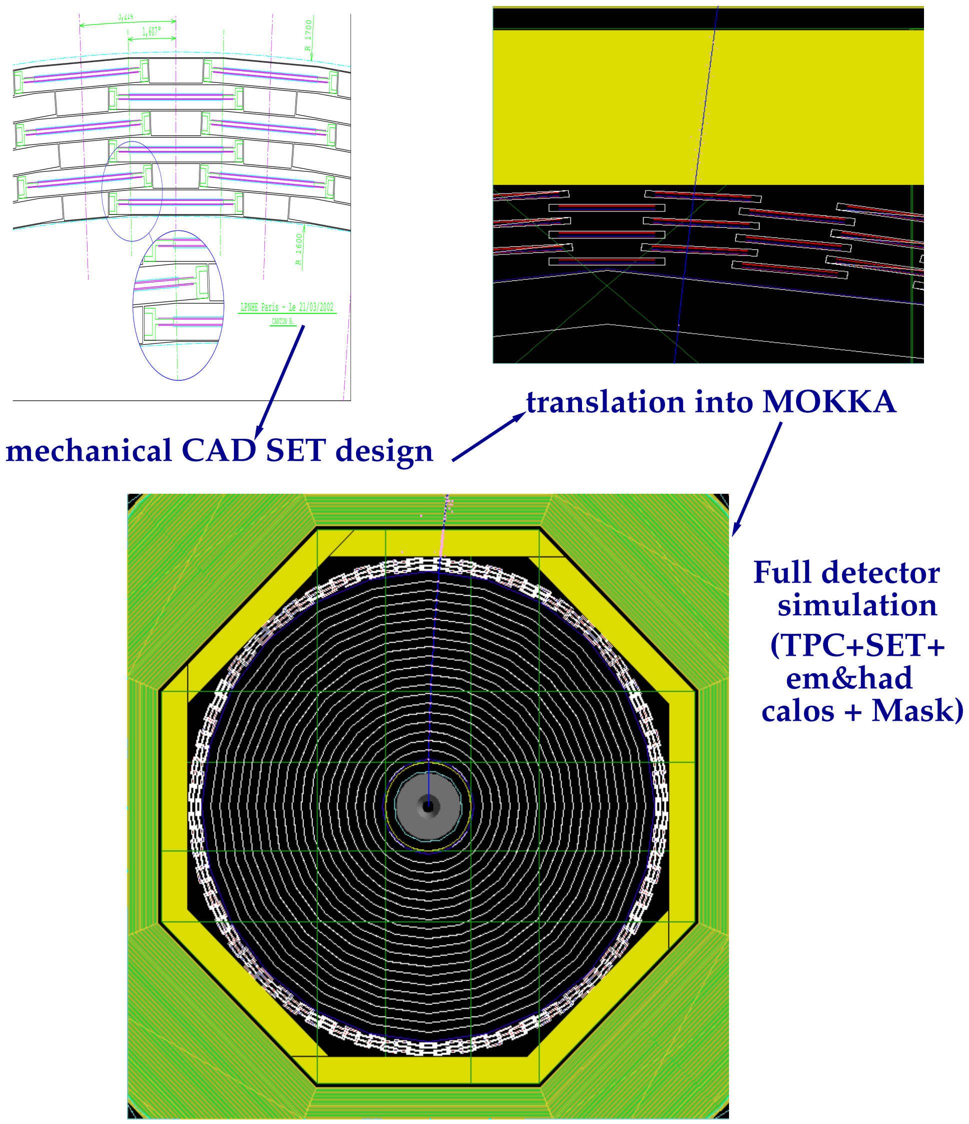

Figure 16: *SET device as visualised by MOKKA, a GEANT4-based simulation package. The geometry database of this detector follows its detailed mechanical design*