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The Silicon Tracking System: Mechanical Integration and Alignement

SiLC Collaboration*

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Abstract

A brief review of the impact of some of the SiTRA-JRA2 related activities within the EUDET project on the studies for the Letter of Intents for the ILC are briefly summarized here. The impact especially of the beam tests performed on the Front End electronics, sensors and alignment developments are briefly reviewed and summarized here.

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1 Introduction

The tracking System of the ILD has been optimized to deliver an excellent resolution with high efficiency and adapted redundancy. It is made of the following sub-detectors:

- a VerteX Detector (VXD): it is the nearest detector to the Interaction Point (IP) and allows the reconstruction of the primary vertex. Pixel technology is useful to obtain a very high spatial resolution ($\sim 4\mu m$) and momentum resolution of charged particles;
- a Tracking Projection Chamber: record the evolution of charged particles with a spatial resolution of $80\mu m$;
- an assembly of calorimeter system: an Electromagnetic CALorimeter (ECAL) for charged particles identification and a Hadronic CALorimeter (HCAL) for hadron identification.

The whole set is coupled to a sophisticated system of Silicon Tracking System (STS) to cover the solid angle down to the forward region. The latter characteristics is really important to tackle some of the large backgrounds to processes involving Physics beyond the Standard Model. The main purpose of the STS is to provide many reference reconstructed points to fit the efficiency of the reconstruction process and obtain a consistent tracking system out of the calorimetry. In addition, it could help in the monitoring of the TPC field distortions, of the time stamping of the events or the alignment between the different components of the ILD detector.
The characteristics of the STS are presented in table 1, and an overall view in figure 1. It consists into four sub-detectors:

- the Silicon Inner Tracking (SIT);
- the Silicon External Tracking (SET);
- the End cap Tracking Detectors (ETD);
- the Forward Tracking Detectors (FTD);

For the STS of ILD concept, a first baseline was established to start our integration studies: each sub-detectors consists of an assembly of modules equipped with active edge silicon strip sensors of $9.15 \times 0.15 \times 0.02 * 10^{-3} cm^3$. The modules are designed to obtain a false double-sided silicon strip detector to provide three space time points. The main idea is to realize the most compact and flat detectors to cover a surface $\sim 180m^2$ as detailed in table 2. This note summarizes the challenges of the R&D integration for the sub-detectors and the status progress of the SiLC collaboration in this domain.

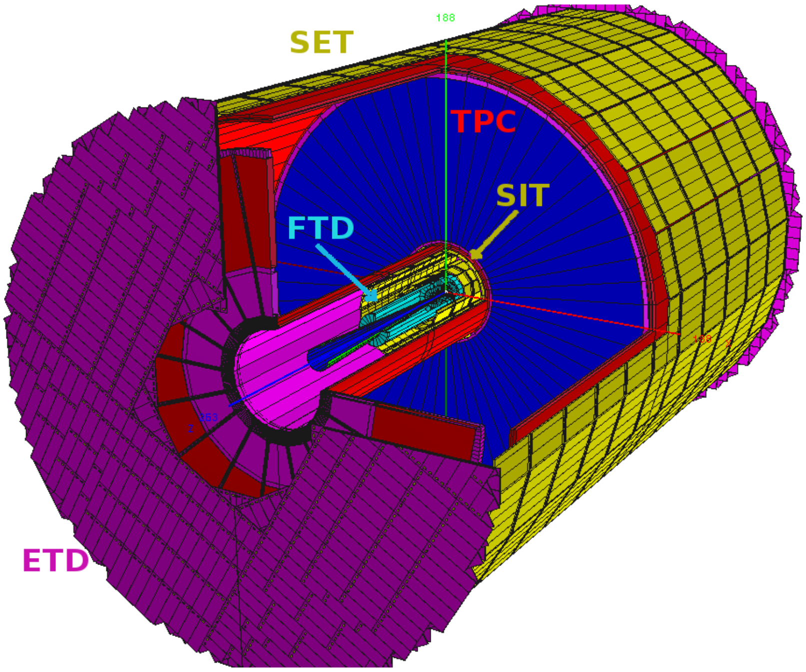

Figure 1: Overview of the ILD tracking system.

SIT characteristics (current baseline = false double-sided Si microstrips)					
Geometry			Characteristics		Material
R[mm]	Z[mm]	cosθ	Resolution R-ϕ[μm]	Time [ns]	RL[%]
165	371	0.910	R: σ=7.0,	307.7 (153.8)	0.65
309	645	0.902	z: σ=50.0	σ=80.0	0.65
SET characteristics (current baseline = false double-sided Si microstrips)					
Geometry			Characteristics		Material
R[mm]	Z[mm]	cosθ	Resolution R-ϕ[μm]	Time [ns]	RL[%]
1833	2350	0.789	R: σ=7.0,	307.7 (153.8)	0.65
1835	2350	0.789	z: σ=50.0	σ=80.0	0.65
ETD characteristics (current baseline = single-sided Si micro-strips, same as SET ones)					
Geometry			Characteristics		Material
R[mm]	Z[mm]	cosθ	Resolution R-ϕ[μm]		RL[%]
419.3-1822.7	2426	0.985-0.799	x:σ=7.0		0.65
419.3-1822.7	2428	0.985-0.799	y:σ=7.0		0.65
419.3-1822.7	2430	0.985-0.799	z:σ=7.0		0.65

Table 1: The projected values of basic SIT, SET, and ETD characteristics.

Detectors characteristics						
Component	Barrel	Layer	Nb of Modules	*Sensors/module*	Nb Strips	Surface
SIT	1	1	33	3	$60,000$	$0.9m^2$
	1	1	99	1	$180,000$	$0.9m^2$
	2	1	90	3	$180,000$	$2.7m^2$
	2	2	270	1	$540,000$	$2.7m^2$
SET	3	1	1260	5	$2,260,000$	$55.2m^2$
	3	2	1260	5	$2,260,000$	$55.2m^2$
ETD	3	1	1260	5	$2,260,000$	$55.2m^2$
	3	2	1260	5	$2,260,000$	$55.2m^2$

Table 2: Detectors characteristics

2 Main Integration Challenges

Contrary to the full silicon integrated systems like those of CMS, SiD or sATLAS, hybrid tracking systems, the ILD concept is very challenging concerning the mechanical integration and the manufacturing of the detectors. Indeed in a full silicon tracking system as CMS, SiD or sATLAS detectors, all the tracking space is available, while the space to integrate in the ILD concept is really restricted to:

- a cylinder with a radius of 30 *cm* for the SIT;
- an icosikaitera (24-gon) with 2 *cm* of thickness for the SET;
- a cylinder with a thickness of 4 *cm*.

The support structure of the active area and its fixation depends on the available space and the surroundings; it is more complicated to get an independent support system. Another complication concerns the cooling interdependence of the different components.

3 The Silicon tracking system in the ILD detector Concept

The coordinate system is described as follows (see figure 1):

- the origin O is defined by the beam Interaction Point (IP);
- z axis is along the the beam direction (blue arrow);
- x axis is perpendicular to Oz and the plane Oxz is parallel to the floor;
- y axis is perpendicular to the Oxz;
- ϕ and θ angle are defined respectively by the rotation around Oz and Ox.

3.1 The silicon sensors

The silicon sensor design for the ETD is under investigation. Indeed, we are working with the mechanical team of the other parts of the Silicon Tracking System to find a common modules design.
We take into account the following technologies:

- the silicon sensors technology will be fixed with the next development and beam test results (active edge, SOI, 3D); but we consider silicon sensors size of $100 * 100 * 0.25\ mm^3$ with 50 μm pitch, a strip width of 12.5 μm;
- silicon sensors are considered edgeless;
- the Front End Electronic (FEE) technology is a SiTr90 chip its thickness depends of the available products;
- integrated "rootage" between the strip and the chip input during the silicon sensors manufacturing (Hamamatsu) according to bump-bond the FEE;
- the readout and the control/comand of the modules are serialized to minimize the cables;
- the transparent sensors for alignment calibration.

The investigated support design for the module respects the following points:

- minimization of the material budget;
- wired-bonding between silicon sensors;
- allowing a laser alignment system between the different layers of the ETD;
- sensors and FEE requirement like polarization of the sensors, power supply, control/command.

The silicon modules length is function of the multiplicity of particles versus θ angle: smaller sensors are located at forward rapidity.
To optimize the rigidity and the radiation length, the support consists in a composite foam included into two carbon fiber layers (0.8/2/0.8 mm of thickness) with the shape illustrated in figure 2. At the ends, the edges of the media are withdrawals 0.5 mm from the edge sensors. For one module, the distance between the sensors is 0.05 mm. The sensors are fixed on the support with a conductive glue and alignment is realized with a tolerance of 0.02 mm.
The polarization of the silicon sensor is done through the first layer of the carbon fiber, the second layer is connected to the ground. As shown in figure 2, first layer of the modules is inter-connected via dominos and conducting gluing to obtain a lattice. To validate this concept, resistivity of chain the carbon/gluing/domino must be very low to

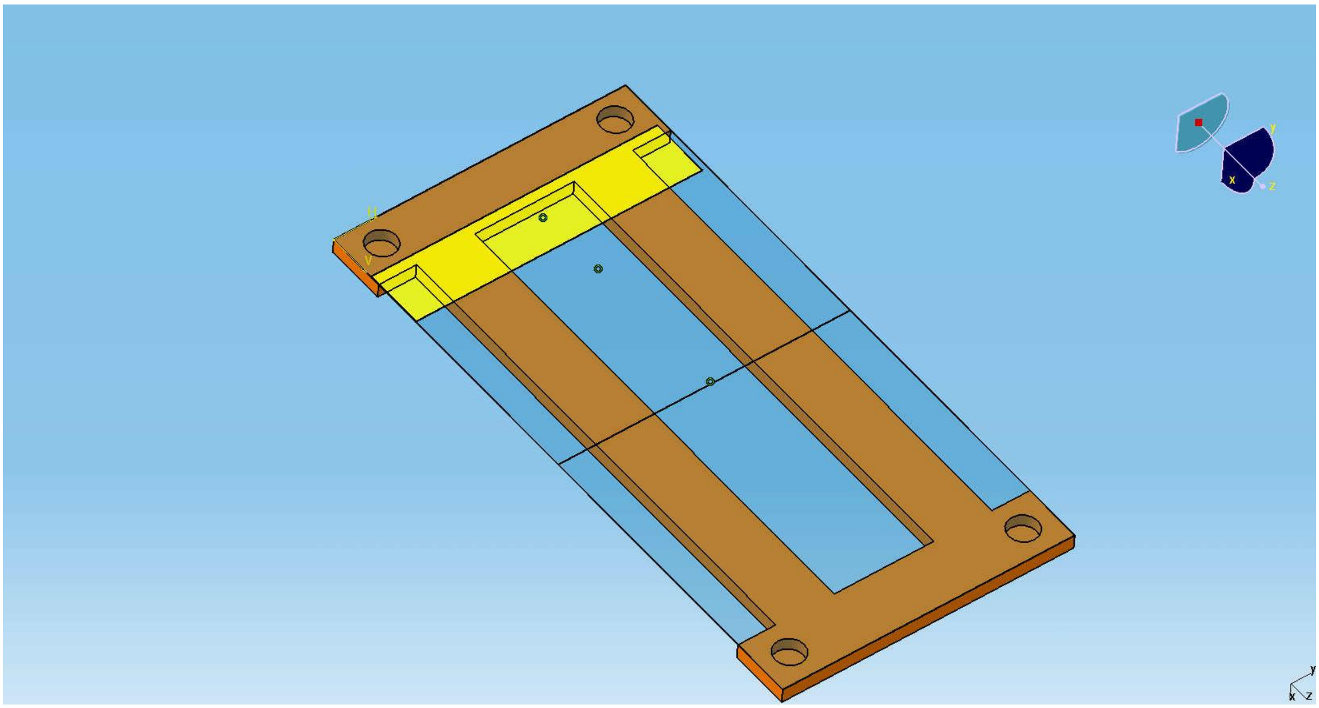

Figure 2: Modules equipped with two silicon sensors.

satisfy the current leakage of silicon sensors. For preliminary tests, resistivity was measured through an industrial carbon-faom-carbon sample of the module support structure and using the Van der Pauw method. Calculated resistivity is $3.5 * 10^{-5}\Omega.m^{-1}$ compared to a pure carbon fiber resistivity up to $10^{-9}\Omega.m^{-1}$.The protocol to produce the number of modules is under investigation.

3.2 The Endcap Tracking Detector

The ETD is positioned between the TPC end caps and the ECAL end caps. The purposes of ETD are:

- get an entry point for the calorimetry system. A high reconstructed point allows to reduce the material effect of the TPC end caps - estimated at 0.15 X_0 during the Kalman filter process. Result is an improvement of the momentum resolution of charged particles;
- complete the coverage of the calorimetry system and obtain the most consistent tracking system. The matching between the TPC tracks and the cluster shower of the ECAL; granularity is dictated by the multiplicity angle dependance to reach a spatial resolution with high tracking efficiency > 99%;

3.2.1 Integration environment

The basic reference values for geometry consideration are summarized in table 3. The engineering requirements of the ETD detectors are:

- ensure the full ECAL coverage between $10\circ < \theta < 37°$ and a full hermicity with the SET. The active area is included in the octagon;
- mechanical design should allow to support $\sim 30\ m^2$ of silicon sensors with a high stability and precise alignment;
- the maximum size allowed along the z direction should be 45 mm including the fixation and positionning system
- ECAL and caps support should be closely designed to support the ETD;
- the alignment system of the different components of the ETD parts, in particular between the different silicon layers should be ensured;
- the radiation length of used material should be minimized;
- keep a stable temperature $(35° \pm 5)$ inside the ETD system for the silicon sensor operating and have a calibration system

ETD characteristics					
Geometry					Material
Inner radius	Outer radius	$cos\theta$	Active surface	z position	Radiation length[1]
420 mm	1822 mm	0.985 to 0.799	$\sim 30m^2$	$\sim 2426\ mm$	0.8%

Table 3: ETD characterisitcs used in MOKKA

The reference outer shape is the octagonal shape of the ECAL end caps detectors with a maximum/minimum radius of 1960/X mm. Along the z axis the ETD is positioned between, $\sim 2426\ mm$. Near this region, the beam-pipe is equipped with the LUMICal and LHCal; this assembly is inserted into the ECAL detector (see figure 3). The Inner part of ETD have to be adapted to the LUMICal shape with a 800 mm square.
The baseline of the ETD sud-detectors is an the XUV and XY concept and two detector concepts will be describe. The inner part of the ETD should allow the LUMICal integration during the assembly of the whole detectors. The outer part of the barrel system and ECAL end caps system is an octagonal shape.
The description of the different concepts with their assembly is divided into three parts:

- the silicon strip modules
- the mechanical global structure
- assembly modules/global structure

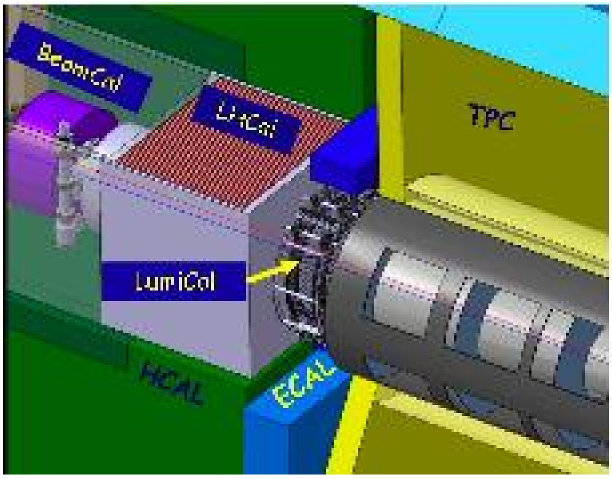

Figure 3: LUMICal, LHCal and beam pipe assembly.

Choice and modification will be done with the results of full simulation in the ILD concept:

- ”optimization” for Kalman filter method
- different way depends on the physic performance: compromising between coverage, resolution etc ...

3.2.2 ETD concepts

The ETD subdetectors design is based on the silicon strip device presented in section **??**. The active area is mapped with different size of modules according to the expected mutliplititicity of particles in the forward region along θ angle. The number of sensors per module will be fixed along the performance of the tracking efficiency, For this mechanical study, three zones with two, three and four sensors per module have been chosen, The selected design is an XUV or XY design and the final one depends on the results of the full simulation results.

XUV concept This concept is composed of three independent layers equipped with single strip sensors. Direction of the strip is the same for each plane, and each one is rotated with a 60° angle. In addition to the cable services of other sub-detectors, an outer disc shape with a radius of 1890 mm for the sensitive surface is selected . The later is included in the octagonal shape of ECAL end cap. The inner part constraints, a hole with a square shape and the integration environment leads to build each layer and an enlarges hole is to considered dur the rotation to a square with a side of 619 mm. The choice of a silicon pixel sensors to complete the dead zone is under development. Each layer consists into four eccentric quadrants shown in figure 4. To obtain a single strip direction, there are two modules implementation on the quadrants to consider: two are aligned along the smallest border and two along the tallest. The overlapping between the three layers is a guarantee to have a full sensitive coverage in this region and skip dead zone in the active area.

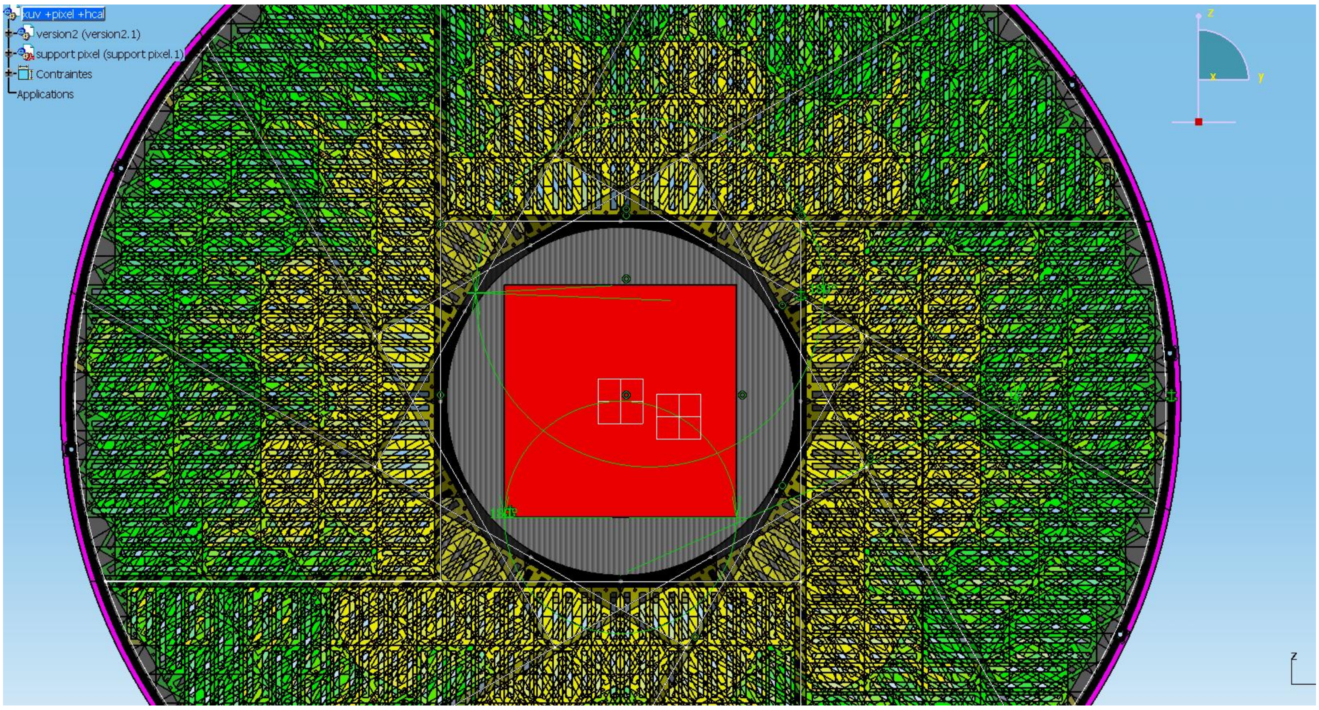

Figure 4: Front view of the ETD detector. The transparency show the different layers with a 60° angles and the pixel area to cover the beam-pipe region.

According the mechanical constraints and the radiation length requirements, selected material for the support is a carbon-foam-carbon sandwich with a thickness of 5 mm with and a mosaic of holes to reduce the global radiation length. These lasts are positioned to get the best uniformity of material budget with the module support completion (picture RL). At the borders, in extension of the first carbon layer, a L shape with a height of 20 mm and a total thickness at 15 mm is designed. Roles of this one are:

- to increase the rigidity of the whole quadrant structure;
- a robust fixation system composed of 3 holes included the L in outer parts and two holes in the inner parts (figure 4);
- ensure the pixel elements assemblies
- improve the EM compatibility.

The manufacturing will be the responsibility of the specialized industries in composite material which guarantee a flatness of 0.4 mm. Taking into account the supports, sensors, the DAQ and cables, the total weight is estimated to be of the order of 150 kg.

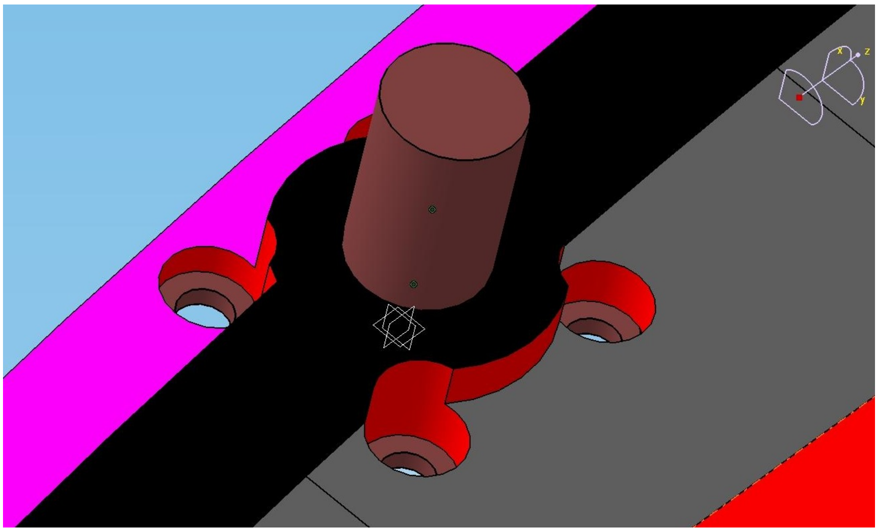

Figure 5: Fixation system: a pawn (brown) is inserted into a crown included int the "L" shape. The acqusisiton system system is integrated in the grey area.

The figure 4 shows a dead zone at the forward region, between the ETD quadrant and the LUMIcal system. This region is really important for the physics studies. To obtain the best performance, a silicon pixel layer solution is under study. This layer is fixed on the inner parts of the ETD system. Close as possible to the ECAL end cap sub-detectors. On this area, a dead zone of 10 mm will be considered to fix it.

An altternative XUV concept To reduce cost and get an homogeneous system for the DAQ system and simplify the quadrant manufacturing, a derived XUV concept is under study. As shown in picture 6, the main idea is to build the quadrant with the same modules implementation. Resulting design is an XUV-like: for one layer, strips are orthogonal between two successive quadrants. An orthogonal incident particle at fixed (X, Y) coordinate through a couple of 0, 30 and 60 degree; there is always a $60°$ angle between layers. The choice about the module positioning depends of the simulation results, but it is clear that the assembly of this design is simpler than the previous one.

XY concept Depending on the results of simulation, the LPNHE team works on the XY concept which is composed of two layers of silicon strip sensors in orthogonal direction. There are several advantages for this concept:

- adaption to the ECAL end shape is easier for a better coverage with no pixel sensors as XUV (see figure 6);
- a common support can be used for the silicon layers and obtain a lower material budget per layer. In this case, modules are glued on both sides of the support and the transverse view of figure 6 shows a T structure. Completion between module and quadrant support allows to reach 0.8 X_0;

- quadrants are strictly the same;
- total weight is ligther and is less than 50 Kg.

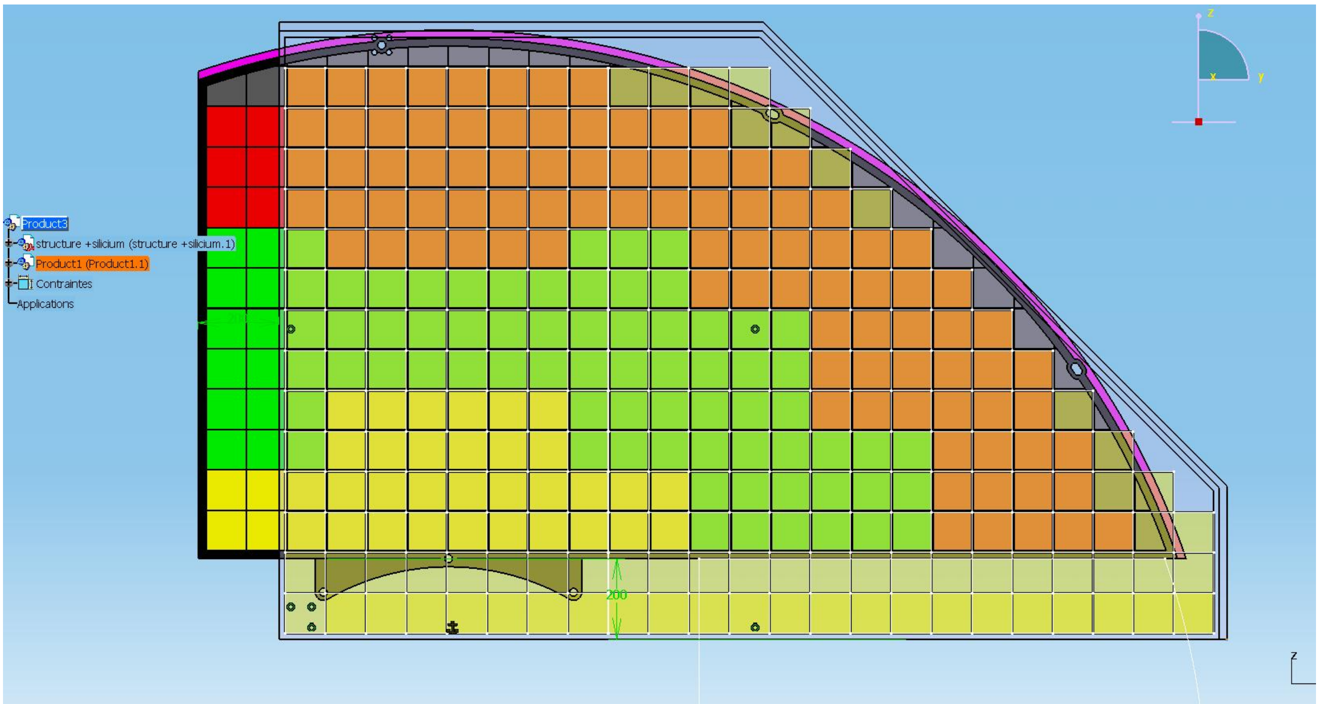

Figure 6: Comparison of the quadrant between XY and the XUV concept.

3.3 The Silicon Inner/External Tracking Detector

The SIT is positioned in the radial gap between the VXD and the inner part of the TPC. The SET is located in the barrel part between the TPC and the ECAL barrel. There are dedicated to:

- improve the linking efficiency between the vertex detector and the TPC, and then to improve the momentum resolution and the reconstruction of low p_T charged particles and improves the reconstruction of long lived stable particles;
- give a real consistency between the whole tracking, after the TPC end wall, and the ECAL calorimeter;
- extend the coverage and carried out a redundancy of the VXD and TPC;
- calibrate the alignment and deformation of the TPC with the VXD with a high position resolution;
- make a reference time-stamping to allow the bunch tagging of each event.

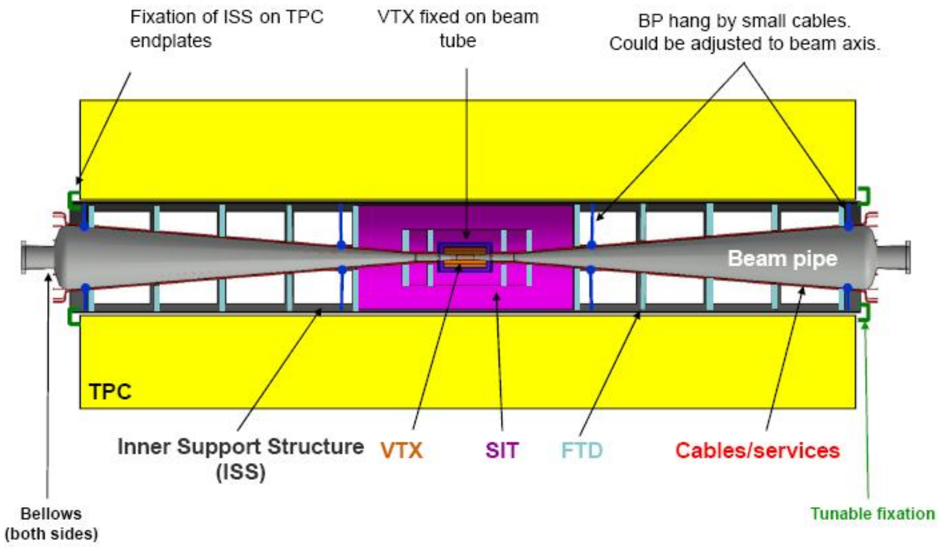

Figure 7: SIT and SET integration in the tracking system.

3.3.1 The Integration Environment

The mechanical structure of the SIT and the SET have their own constraints. SiLC collaboration have the responsibilities to realize some preliminary designs and studies. For the SIT and SET sub-detectors, the baseline is inspired from the sATLAS R&D and will be adapted to the ILD concept, along two existing strategies:

- the first option is to integrate and fix the different part of the sub-detectors the Silicon Tracking System on the others detectors. For example, the SET on the external TPC support. The convenient is the simplicity of the concept but the realization and could be really complicated. Indeed, the role to calibrate the TPC deformation and the alignment with other detector in the IP reference, included calorimetry, is much more difficult because the silicon sensors position is directly affected by the TPC shape deformation.

- the second option is to create an independent support structure. The SIT and SET are fixed on a common support maintained by a support wheel both part of theTPC. In this case, it is possible to build a ”solid” and consistent tracking system.

In both cases, the SIT is fixed in the inner part of the VXD-FTD-Beam pipe container shown in picture 8.
The SIT and the SET consist of two cylinders of false double-sided silicon strip sensors. Each cylinder is composed of two layers of silicon strip sensors with an angle of 90°. Depending on the results of the simulation optimization studies, the number of sensors

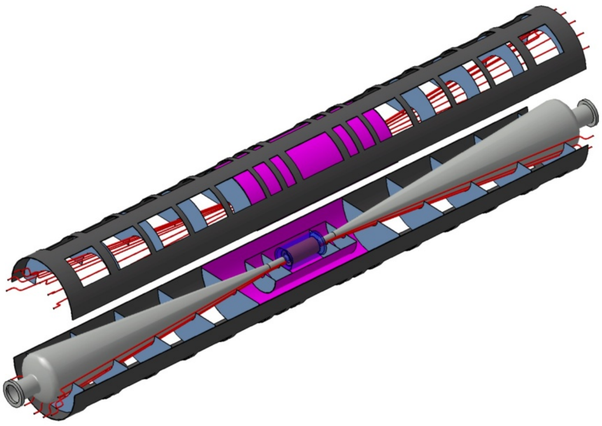

Figure 8: Mechanical integration of the VXD-FTD-Beam pipe container.

used per module will be defined. For example, the chosen baseline is a silicon module of three sensors for SIT and five sensors for SET.

3.3.2 The Silicon Internal Tracking

Due to the multiplicity of particles and the radius of curvature, the choice of SiLC collaboration for ILD concept is a coupling of three sensors module with three side by side single sensors modules.This concept is able to combine high spatial resolution performance and limits the number of ghost tracks during the track reconstruction. This sub-detectors being nearby the interaction point, the support of these layers have to be compact and light for the material budget point of view. The design studies are in synergy with the sATLAS development; figure 9 shows one of the possibilities to integrate the layers taking into account the fact we consider edgeless sensors. This part is in under studies and depends strongly about the others subdetectors.

3.3.3 The Silicon External Tracking

For the SET, the constraints are really specific due to its position between a cylinder shape and hexagonal shape of the electromagnetic calorimeter barrel. The mechanical structure of the SET is divided in 2 halves composed of 24 panels called "super-modules" of $2,4 \times 0,48$ m due to the 24-gon shape. Each panel is independently fixed on a support wheel positioned in the middle and both short side of the outer surface of the TPC structure. The solution allow to avoid in an additional outer frame and therefore keeping the material budget at its minimum. The static deflection with a payload of $1kg.m^{-2}$ is shown in figure 10. The silicon modules detector are fixed on the surface of each panel and the process under studies.

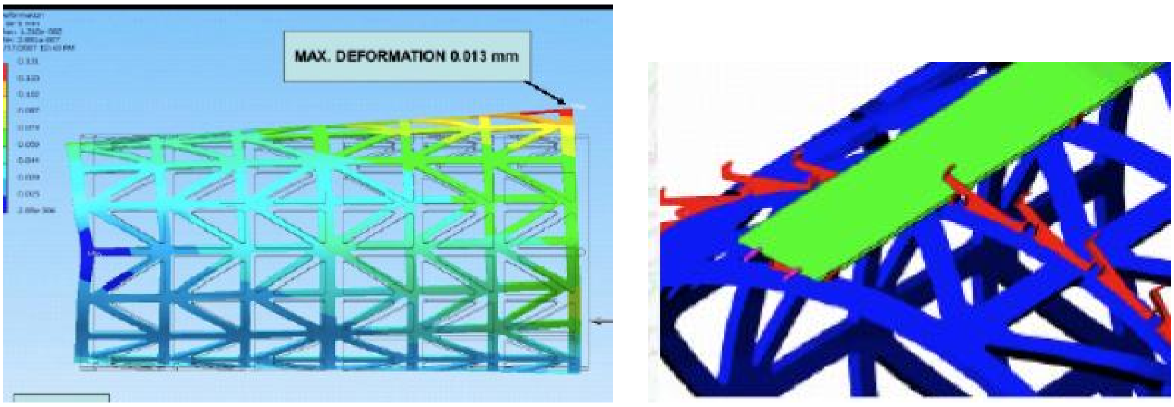

Figure 9: Integration and deformation studies of the barrel support structure of the ATLAS experiement.

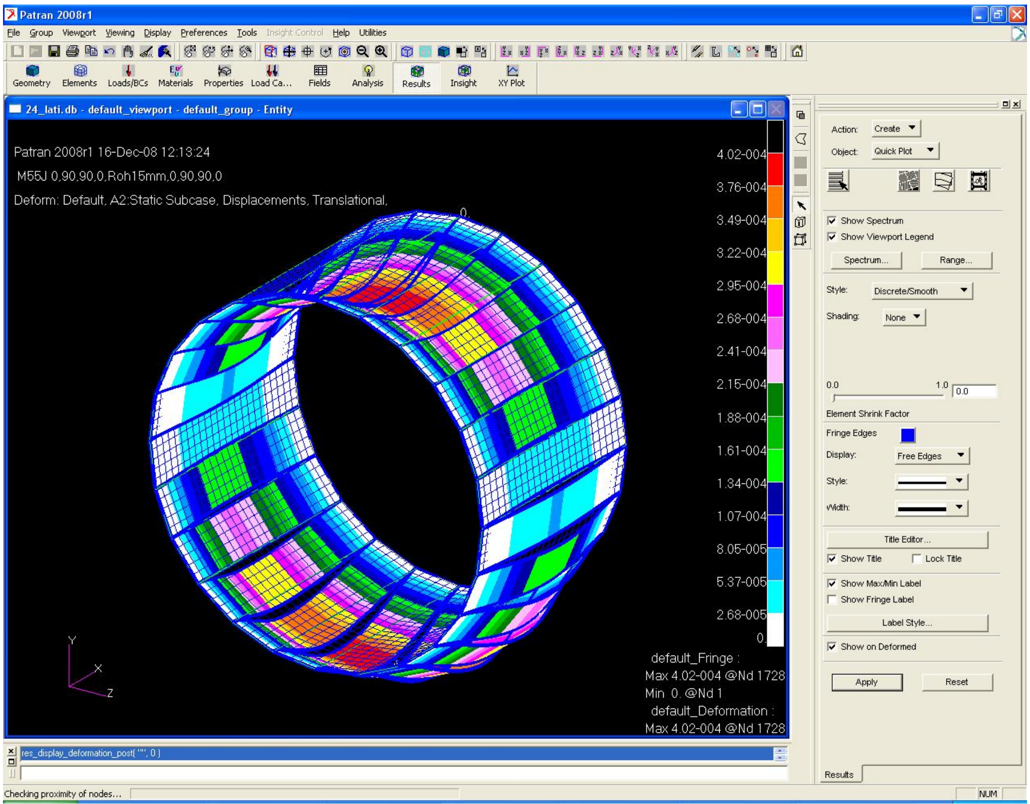

Figure 10: SET panel deformation studies.

3.4 Data Acquisition System

In this subsection, the following description is based on the XUV design but can be applied for the alternatives ones. For one quadrant, the Data AcQuisition (DAQ) system consists of:

- the readout is serialized per ladder as 4 to 5 modules are inter-connected with a thin Kapton (see figure 2). the width of this last will be defined according the requierments of the front-end electronic;
- the present design has 24 ladders of sensors but many ladders with less than three modules should be serialized;
- Each group of serialized modules are linked to a PCB - called Concentrator - where data are routed to one micro-FPGA; this latter gather, tag and form the raw data format;
- optical fiber towards the general acquisition system;
- take into account the readout chip sequences and dead time;

The concentrator should be positioned in the inner part of the quadrant, between the internal side of the L beam and the outest sensors. Cable services for power supply and optical fiber should be implemented this space.

3.5 Manufacturing

This subsection discusses the different manufacturing step to assembly an ETD detectors.

3.5.1 The silicon modules

The basic silicon sensors are the smallest elements of the ETD detectors. The positioning and the gluing of the silicon sensors are realized with a tolerance of 0.02 mm. A custom manufacturing system has been realized by the LPNHE and is shown in picture 11. Main parts of this tool are:

- a vaccum system for the positioning with the respect of the chip bump-bonding requirements;
- a vaccum system equiped with micrometric screw for a precise positioning;
- a precise reference point for the positioning;
- a camera system for the alignment in order to reach a precision of 0.02 mm;
- a gluing machine (internal LPNHE note).

For these operations, only a clean room and a storage chamber for the conductive glue is required. Each module is sent to the bonding labs to link the different sensors. The final step is to validate the modules. Each ones will be tested independently with a laser; a database containing the charachertistcs of the silicon module response will be created.

Figure 11: Picture of the manufacturing tool of the silicon module.

3.5.2 The quadrants and super-modules

The next step of the manufacturing is the positioning of the module on the quadrant. The main requirement is to reach a precision less than the intrinsic spatial resolution of the silicon sensors equal to $7 - 8$ μm. Given the size of quadrants, it is a real challenge to build a specific tools to align the modules on the quadrant structure and reach a precision of 0.03 mm. The quadrant support will be built and prepared by a third company.
The laboratories which are manufacturing the quadrant of ETD and super-module of SIT-SET. This operation will be complete on a calibrated marble and resurfacing. This marble will be used for the positioning of the quadrant on the ECAL end-cap detectors. The alignment system of the silicon modules will be realized with a camera system and the reference points on the quadrant. This tools will be design with a special attention to the edgeless properties of the sensors which are very sensitive to the shock.
The final process is to validate the quadrant and the super-modules with a laser alignment checking. A database containing the position of the modules on the these elements will be created and necessary for the alignment process.

3.5.3 The ETD quadrant fixation on the ECAL end-cap support

The final step is the positioning of the ETD quadrant on the layer of the ECAL. An external spatial reference point and many fixation points on the ECAL end-caps (shown in picture 12 and figure 6) are requested for this operation. The inset are designed to be used with a micro-metric system for the alignment. The first inset is positioned using the reference points given by a land surveyor. The others fixation will be positioned with a fine outline. The setting up of the quadrant is just done by slide the quadrants along the inset. Then with an internal alignment laser system of the ETD assembly, the relative positioning of the quadrants will be calibrated.
During these mechanical integration studies, many degree of freedom of misalignment

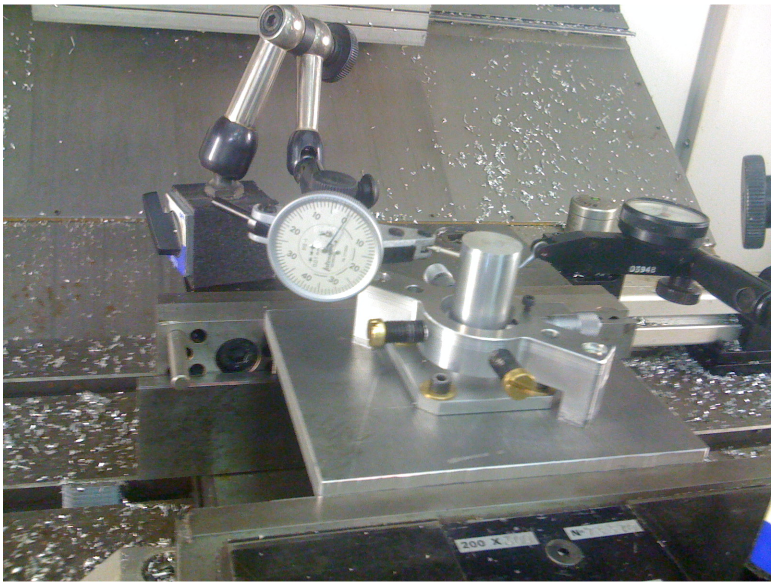

Figure 12: Prototype of the ETD quadrant fixation point fixed on the ETD end-caps.

were identified. They will be introduced in the simulation studies and examine the impact on the spatial and momentum resolution.