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Study of a Silicon External Tracker: SET

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Abstract

We propose to include an *"active interface"* between the TPC and the calorimeters made of a few layers of silicon strip detectors in the tracking system of the detector proposed in the TESLA TDR . These layers will form a complete silicon tracking system covering the full tracking volume when combined with the already proposed silicon detectors, i.e. the microvertex detector, the SIT and the FTD. The properties and advantages of such a device are discussed in this note. In particular, an accurate tracking point measured external to the TPC has already been under discussion as a possibly better device for the tracking calibration than the TPC laser system.

1 Introduction

With the active R&D period for LHC detectors during the last decade, the semi-conductor tracking technique has made impressive progresses, both on sensors and on the associated front-end electronics. This is the case not only for microvertex detectors, but also for large tracking devices. Based on the experience gained on silicon trackers at the LEP experiments, on those built for the present Tevatron experiments and especially on the R&D on large silicon tracking devices for the forthcoming LHC experiments, we study the possibility of inserting a few layers of silicon strip detectors between the TPC and the Si-W calorimeter of the TESLA detector as proposed in the TDR [1]. These layers would form the *Silicon External Tracker (SET)*. The space needed for SET could come from the outside of the TPC or inside of the ECAL or a combination of the two. The study here has been performed assuming the outer few cm of the TPC are used for SET, but the final decision as to where to position it will depend on details of the design of the TPC and ECAL.

The main motivations for having such a tracking device added are discussed in the Section 2. Section 3 briefly describes several possible set-ups for the SET. The following section (Section 4) presents the preliminary expected performances in terms of the momentum resolution of the proposed designs. A last section addresses the directions along which these studies are being pursued.

2 Motivations

First, the SET is aiming to be an *active interface* between the tracking in the TPC and the calorimeters. *Active* means that this device will fulfil several functions at the interface between the tracking system and the calorimeters. In a sense, the proposed SET device is a natural continuation of the Si-W calorimeter, as it uses the same detection-technology but without inter-leaved absorbers. Secondly, the system formed by the microvertex detector, the SIT, the FTD, and the SET, will form a silicon-tracking system covering the full tracking volume and thus could act as an autonomous system. The track-reconstruction would therefore be done in two ways (as has already been shown in the TDR without the SET): an all-silicon tracking (now including SET) that gives a fast track reconstruction and the TPC track-reconstruction which provides a detailed (of the order of 200 hits per track) 3-D track. Both would then be linked, and precision could be gained by the silicon tracking both by increasing the momentum resolution (see the next section) and by linking the TPC track to the interaction region.

2.1 *Interface with the tracking system*

The main utility of the SET device in the tracking system would be:

- *Improvement of the resolution*: the SET will improve the momentum resolution, as detailed in the next section.
- *Alignment*: the SET will help improve the absolute alignment of the overall tracking system, not only for the TPC by replacing the TPC laser, but also for the alignment of the silicon system itself.

- *Monitoring of tracking systematics*: The TPC is sensitive to ambient temperature, to atmospheric pressure, to inhomogeneities in E and B fields, etc. The SET gives the possibility to monitor such effects on real data. While the TPC systematics must be corrected to the 10 μm level, for the SET they are likewise stringent and must be understood to the 2 μm level. Thus the SET will also be sensitive to temperature fluctuations which can be monitored with an appropriate cross-calibration between the TPC and the SET.

- *Partial and temporary recovery*: In case of a problem with the TPC or the silicon tracking , the redundancy of the two systems would help to partly or temporarily recover the data until the problem is cured. Having redundancy in the tracking system is quite valuable.

- *Possible triggering*: Although a detector at TESLA would not need to be triggered, the ensemble microvertex+SIT+FTD+SET could serve, if needed, as at least a second-level trigger, (confer for instance with the XFT (eXtremely Fast Tracking Trigger) and the SVT (Secondary Vertex Trigger) that constitutes a complete tracking trigger system currently operational in the CDF experiment).

In summary, the contributions of SET to the already proposed tracking system are: alignment, monitoring, improvement of the resolution, partial and temporary recovery purposes and a fast tracking system together with the (microvertex+SIT+FTD) system both for online (including triggering) and off-line purposes.

2.2 *Interface with the Calorimetry*

The SET will be the tracking entry-point of the Si-W calorimeter, based on the same silicon detector technology, but without absorber. It will therefore be very useful to initiate the *"shower tracking"*, before the shower occurs, as well as to identify the entering object and precisely determining the impact point on the calorimeter. Thus it will essentially allow to quickly *"visualise"* the entering object in the calorimeter, without requiring the entire detailed track-reconstruction.

Furthermore, it will act as a pre-shower detector, particularly useful to discriminate photons, electrons and π^0's. It should be note that even though the TPC would extend out to the calorimeter in the TDR design, a track must traverse the outer field-cage of the TPC after last measured point. In the TDR design, this represents 1.7 % X_0. In addition, due to construction constraints, the TPC is cylindrical, while the calorimeter is octogonal. Hence, at certain positions, there would be a sizeable distance between the two. The SET, on the other hand, would have virtually no material, and a very small distance, between the last measured point and the calorimeter.

In summary, the main role of the SET at the tracking-calorimetry interface would be to constitute a fast silicon tracking, when combined with the microvertex detector and the SIT. This will be helpful as input for the tracking in the Si-W calorimeter itself. Furthermore, the SET will act as a pre-shower detector. The points to be clarified are how much material it will add in front of the Si-W calorimeter, and to evaluate the real benefits for tracking in the Si-W calorimeter of having such a fast silicon tracking facility. This should be addressed in collaboration with the track-reconstruction team of the Si-W detector.

2.3 *An autonomous silicon tracking system*

As already underlined in the previous two subsections what we want to address in this study are the benefits and uses of having *complete silicon tracker*. This system would be obtained by combining the SET with the already proposed VTX, SIT and FTD silicon detectors. We will also of course study the eventual drawbacks.

A main feature already mentioned is that a silicon tracking ensemble could give a fast tracking system that could be useful for both the online and off-line track reconstruction. It would thus help both the TPC and the Si-W track reconstructions which are both based on a much larger number of points and thus are more time-consuming. This has to be quantified with detailed reconstruction studies.

3 SET design

The SET design is based on the present state of the art in silicon tracking devices: The Tevatron and the LHC experiments have silicon tracking devices that has served as starting point for the current design of the SET. To a large extent, the CMS all-silicon tracking system was used as a guide-line.

Following the CMS design, our working hypothesis is to use silicon strips of 9.45×2, i.e. 18.9 cm length, 183 μm pitch, and 500 μm thickness. The strips would be assembled in elementary modules of 512 strips each. The front-end electronic chip consisting of the pre-amplifier and the discriminator circuits will be in a submicron technology (the 0.25 μ technology is already currently available). Each chip could treat for instance 128 channels (i.e. the "canonical" number) and the analog output signal would be sent from the detector by analog fibres using optoelectronics already developed for the LHC experiments. The fibres would be running from the centre of the device, i.e. from 90 degrees with respect to the beam axis, up to the two edges of the detector 2.5 meters away. The signals would then be brought through the already foreseen cable-path at 45 degrees. The surface covered by each layer is roughly of 50 m^2, assuming a total length of 5 m and an average radius of 1.6 m. Mechanically, the SET would be incorporated in the structure of the Si-W calorimeter.

This preliminary concept is the input for the first rough mechanical design of the detector, which is used in the simulation package. It also allows to get a preliminary idea about the total number of electronics channels (i.e. number of strips), the total number of modules and thus the total number of fibres, the total number of radiation lengths, and the total weight of the device. For a three layer SET, of which one is a double-sided layer, a total 12,240 detectors (corresponding to a total of 3,080 detectors per layer), covering about 240 m^2, and of 6 millions of readout channels corresponding to 50,000 F.E. chips (each one corresponding to 128 channels) would be required. The total surface corresponds closely to the surface of the all-Si-tracking system of CMS. This SET would add of the order of 2% of X_0 as material budget.

Several scenarii concerning the number of layers, as well as their type and radial location are studied, ranging from one layer (only adding an external point to the overall tracking, before entering the e.m. calorimeter), over 2 or 3 layers (in order to add an external tracking segment in Rϕ), up to 5 layers. The impact of having single-sided (R, ϕ) or stereo-angle tilted detectors in some or all of the layers was also studied. As in the CMS design, we assume that a double-sided layer is in fact made of two single-sided layers, with different strip-orientations.

From the mechanical point of view the key issues are:

- *Transparency*: The SET should add a minimum of extra radiation lengths. Of course, this includes not only the detector itself but also the electronics, cabling and cooling that will be mounted onto the detector.
- *Integration issues*: These are related to the integration of SET in the overall detector design. Tentatively we consider to mount the SET on the Si-W calorimeter.
- *Cooling*: It is a less crucial issue than at the LHC where cooling is mandatory also for radiation hardness purposes, nevertheless still important since the mechanics must be stable to the micron level to keep the systematic effects small.
- *Alignment*: Precise alignment is one of the main purposes and issues of this detector. Currently used alignment-procedures for similar detectors are the Rasnik or ALMY methods based on laser beam and Si-detectors. These schemes could be investigated for the SET as well.
- *Cabling and electronics mechanical related issues.*

4 Expected Performances of SET

The expected performances are presently based on the use of a fast simulation package, the Simulation à Grande Vitesse (SGV) [2].

SGV simulates colliding beam detectors in a solenoidal magnetic field. The detector geometry is read from an external file, and is described as cylinders with a common axis, parallel to the magnetic field, and as planes perpendicular to the common axis. The cylinders are described by their radius and minimum and maximum extent along this common axis. The planes are described by their position along the axis and their minimum and maximum radius. In addition, the material, the thickness in radiation lengths, and the type and precision of measurements are also given. Each cylinder or plane can be divided in repeating sectors of measuring and non-measuring parts, so that eg. blind sector-boundaries between detector sectors or over-lapping detectors can be simulated. The overall detector set-up used in these studies is the one described in the present TESLA TDR [1].

For each charged particle generated by the event-generator, and which is either stable or decays weakly, SGV calculates which of the tracking-detector surfaces the track helix intersects. (In these studies, single charged pions were generated with a uniform momentum distribution between 0 and 250 GeV/c, and at random angles within the barrel region of the detector.) From the list of those surfaces, the program analytically calculates the precision with which the parameters of the track can be measured, and the correlations between them. This calculation includes the multiple-scattering in the traversed surfaces, and the measurement precision at each surface that measures the track position. It takes into account the effect of the angle-of-incidence upon the detector-plane, both on multiple-scattering and on point-precision. The track-parameters are then polled from a correlated multidimensional Gaussian distribution according to the calculated covariance-matrix.

The following set-ups have been used in these preliminary studies:

- One two-sided layer to add an external point to the Si-W calorimeter, with a decrease in the TPC level-arm of 20 cm. A 25 μm resolution per point is assumed.
- Two single-sided layers to add one elementary tracking segment in (R,ϕ) at the entrance of the Si-W calorimeter, and to cover 20 cm of the tracking space.
- Three layers, of which two are single sided and the middle is double-sided. In this case the following layer-dispositions are considered:
  - Two layers close to the calorimeter, and one layer close to the TPC.
  - The three layers are equidistant from each other.
  - Two layers close to TPC, and one layer close to calorimeter.
  - Also studied is the case where two of the three layers are close to the calorimeter but only a 10 cm gap is left between the TPC and the calorimeter to accommodate the SET, instead of the 20 cm in the other considered cases.
- Three layers, but with 250 μm resolution, for comparison: this represents a wire-chamber, rather than a silicon detector .
- Five layers of which two are double-sided and three are single-sided.

For comparison, the scenario with the TPC alone but with 20 cm less in radius, and the system with only the Si-trackers have been also considered. Furthermore, a more *"radical"* approach is also studied, namely one with no TPC but a all-Si-tracker , similar to the tracking system of CMS, including 10 layers.

In the TDR, the challenge is to achieve a over-all resolution of 5 $\times$ 10^{-5} (GeV/c)$^{-1}$ in Δ(1/p). The main parameters that describe the TPC in the simulation are taken from the specifications given in the TESLA TDR, and are: 180 pad-rows, each with a point-resolution of 180 μm in (R,ϕ), and 1 mm along the beam direction. The material budget assumed for the TPC is 1.7% X_0 in the outer wall, and 1.3% in the inner wall. The gas represents 0.03 per mill per pad row. The assumed resolution per point for the Si-strip detector is 25 μm, which is a rather conservative value, and a material budget of 0.5% X_0 per Si-layer. The scenario with 10 μm resolution per point for the Si-strip is also checked for comparison. It is interesting to note that the SET and the TPC have opposite angular dependence in the point-error: the lower the angle is, the shorter the drift is and the better the resolution is for the TPC. In the SET, the best resolution is at perpendicular incidence, and it gets worse at more slanting angles. The latter effect is taken into account in SGV. The results of this very preliminary study are summarised in Fig.1.

The main conclusions that can be drawn from these curves are:

- By adding an external layer to the Si-W calorimeter, i.e. an external tracking point, while decreasing the radius of the TPC by 20 cm at the same time, the same momentum resolution curve is obtained.

- A TPC with 20 cm less in radius and a 3 layer SET with a resolution of 250 μm, – equivalent to adding a wire chamber detector – give similar momentum resolution. It is roughly 30% worse compared to the TDR design.
- A TPC with 20 cm smaller outer radius and a SET with 3 layers of which two are closer to the Si-W calorimeter, gives a resolution curve that is about 15% better than the original design in the TDR.
- A TPC with 20 cm smaller outer radius and a SET with 5 layers give a slightly better performance in momentum resolution than the previously quoted design for the large momentum values, but when the momenta become of the order of 30 GeV/c or less, the performance is comparable to the one of the original TDR design.
- A all-silicon tracker with 10 layers gives about 20% better momentum resolution for high momentum values. However when the momentum is of the order of 50 GeV/c or less, the performance of this device becomes worse than most of the other scenarios and just slightly better than the TPC with a radius reduced by 20 cm.
- A TPC with 10 cm smaller outer radius and a SET with 3 layers of which two are closer to the Si-W calorimeter, gives the best resolution – about 20% better – in the full momentum range.

The obtained results are quite in agreement with the expectations. In particular, a full silicon tracking is better for high momenta compared to a gas chamber solution, but when going to smaller momentum values it becomes worse due to the larger amount of multiple scattering. However, this deserves a more careful study in order to find the best compromise between the amount of material in the silicon tracker, the number of layers, and the point-errors in the different layers. Here a total of 10 identical layers has been used in the all-Si scenario.

In Table 1, the resolutions found for all the 14 different configurations are given at three values of the particle momentum. In particular, the various cases corresponding to the 3 layer-design and the one corresponding to the 2 layers SET are detailed. It shows that there is little difference between the different ways to distribute the layers, but nevertheless that the configuration with the 3-layer SET where two of the three layers are close to the Si-W calorimeter is the best choice, and a configuration with two layers close to the TPC is the "worst" one. This is the expected behaviour, when multiple scattering is taken into account.

As a conclusion, this very preliminary study shows that the addition of a silicon tracking segment external to the TPC, allows to improve the overall momentum resolution by 15% to 20% compared to the TDR design, and at the same time to decrease the radius of the TPC by 10 to 20 cm.
An important point is by how much the reduction in radius of the TPC would degrade the dE/dX measurement. The truncated mean on dE/dX depends on the number and the size of the samples as well as on the gas pressure according to the following law:

$$\sigma(dE/dX) \propto N^{-0.43} \times (P \times l)^{-0.32},$$

where N is the number of TPC samples, l is their length, and P is the gas pressure.

According to this law, diminishing the number of samples by about 10%, $\sigma(dE/dX)$ would worsen by roughly 4%.

Configuration	$\Delta(1/p) \times 10^{-5}$ (GeV/c)$^{-1}$ at different momenta		
	10 GeV/c	60 GeV/c	250 GeV/c
TDR	12.3	4.2	3.4
TDR with TPC radius reduced by 20 cm	17.2	5.7	4.7
Single layer	12.0	4.1	3.3
Two layers	11.2	3.7	2.9
Two layers close to TPC, one close to calorimeter	11.8	3.8	3.0
Three equidistant layers	11.4	3.7	3.0
Two layers close to calorimeter, one close to TPC	11.2	3.7	2.9
Same, each layer2% X_0 thick	11.8	3.7	3.0
Same, with resolution 250 μm	16.2	5.6	4.6
Same, with resolution 10 μm	11.0	3.3	2.6
Same, with TPC radius reduced by 10 cm	10.1	3.4	2.7
Same, TPC not used in fit	16.0	4.4	3.4
Five layers	11.4	3.6	2.8
TPC replaced by 10 layers	15.2	3.7	2.7

Table 1: Values of $\Delta(1/p)$ for the studied SET configurations at different values of the particle momentum.

5 Future prospects

This project is just at its beginning therefore a number of questions remain to be addressed and carefully studied, e.g.:

- Implementing the present proposed device in a full simulation (BRAHMS or GEANT4), in order to evaluate the performances of the device and to compare with what is obtained by the fast simulation.
- Impact on the energy-flow measurement since in this note only the momentum resolution has been addressed and the energy-flow is equally important.
- Pursuing the various aspects of the mechanical studies further.
- Addressing the electronics related issues; in particular the very front-end chip, the output of the signals from the detectors using the optoelectronic approach to start with, and of course, further on, the readout system itself.
- "Tracking links" both with the TPC and the tracking team of the Si-W calorimeter.
- Possible advantages of this detector for various physics channels.

In conclusion, the physics at a future Linear Collider – as well as the physics at presently running experiments or the forthcoming ones at the LHC – require highly performing detectors.

Tracking studies and R&D for the future Linear Collider are mainly focusing, at the present time, on the microvertex technologies on one side, and on the TPC design with different readout technologies (GEM, Micromegas etc...) on the other side. This note would like to point out the possibility of improving the silicon tracking part and thereby further ameliorate the over-all performance of the tracking of the TESLA-TDR detector. We also point out that such an improvement would increase the freedom in the optimisation of the overall tracking system as well as of the whole detector design. The R&D pursued for the LHC detectors on silicon technology both for the sensor and the related readout achieved impressives advances that will be very valuable for our case. However some more R&D work is needed to, for instance, further reduce the material budget of silicon tracking . What has also to be undertaken is to put more thought on the design of the full tracking design, including the detailed mechanics, as well as on the reconstruction and the energy-flow measurement issues. This is what we are starting to reinvestigate, and of course this project is totally open to other contributors whose collaboration is more than welcome.

References

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

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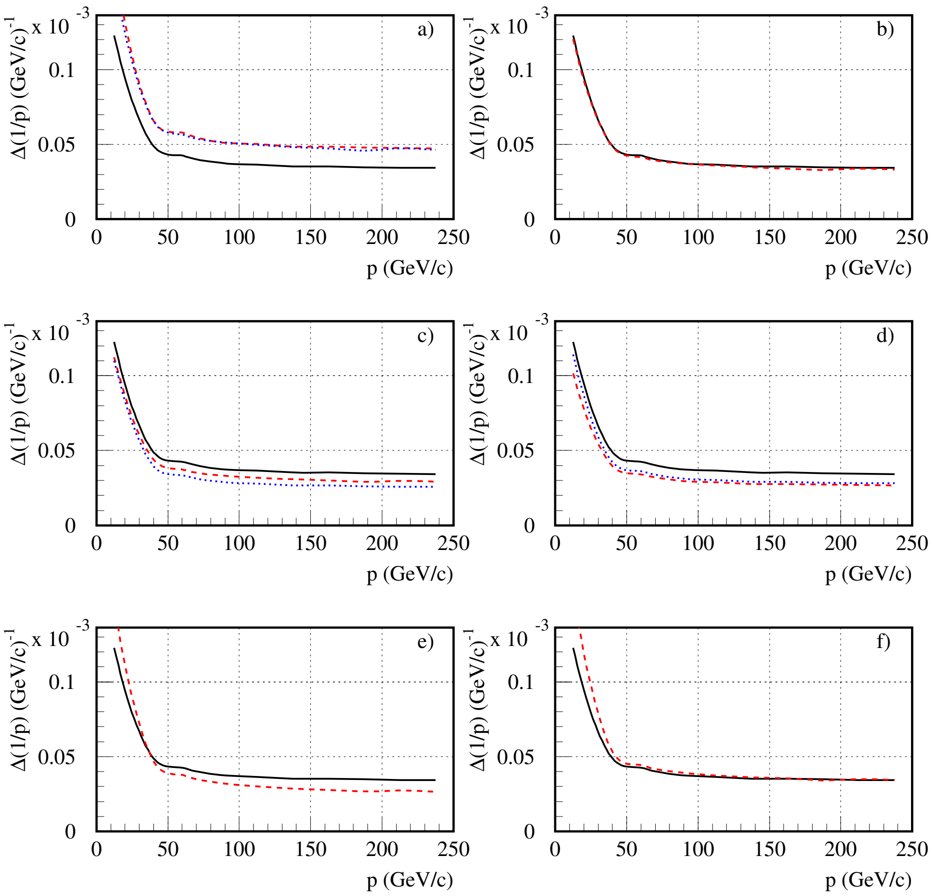

Figure 1: Curves of resolutions as a function of the momentum of the charged particle for various SET scenarios. In all figures the solid curve represents the TDR geometry. For the other curves: If nothing else is stated, the TPC radius was decreased by 20 cm wrt. the TDR, and the point-resolution in each SET layer was 25 μ. a) dashed: TPC radius decreased by 20 cm. dotted: A three-layer detector with a 250 μ resolution installed. b) dashed: One layer of a SET installed. c) dashed: Three layer SET installed. dotted: idem, but the resolution was 10 μ per point. d) dashed: Three layer SET installed while the TPC radius was decreased by only 10 cm wrt. the TDR. dotted: Five layer SET installed. e) dashed: TPC replaced by a 10 layer SET. f) dashed: Three layer SET installed, the TPC present, but its measurements were not used (ie. the result of “silicon-only” tracking)