CMS Conference Report

19 August 2003

Layout and performance of the CMS Silicon Strip Tracker

D. Abbaneo, on behalf of the CMS Collaboration

Abstract

The layout of the the CMS Silicon Strip Tracker is described and discussed. Some figures illustrating the expected performance are presented, discussing the effects of the material in the tracking volume.

1 REQUIREMENTS AND LAYOUT

Tracking charged particles produced in pp collisions at the LHC requires fine granularity and fast response time of detectors and readout electronics. At high-luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$), on average 20 minimum bias events are produced every 25 ns; the resulting charged track density is expected to be 1 track per cm^2 at 10 cm from the interaction point, 0.1 at 25 cm, 0.01 at 60 cm: the tracker is immersed in a 4 T solenoidal magnetic field for precise transverse momentum measurement that modifies the $1/r^2$ scaling law for the charged track density. The tracker has to be able to resolve and measure precisely all tracks, in order to identify those that may belong to an interesting interaction. A transverse momentum resolution of $1 - 2\%$ for 100 GeV/c tracks is required for precise reconstruction of heavy narrow particles; an impact parameter resolution of $10 - 20 \mu\text{m}$ is needed for b and τ tagging with displaced vertices.

A sketch representing 1/4 of the tracker is shown in Fig. 1. The innermost region (at radii below 15 cm) is occupied by the pixel vertex detector (not shown); the Silicon Strip Tracker covers the radial range between 20 and 110 cm. The barrel region ($|z| < 120 \text{ cm}$) is split into an Inner Barrel (TIB) made of four layers, and an Outer Barrel (TOB) made of six layers. The TIB is shorter than the TOB, and is complemented by three Inner Disks (TID) made of three rings. The region $120 < |z| < 280 \text{ cm}$ is covered by the nine End-Cap (TEC) disks, each made of seven rings. In the sketch presented, each line represent a detector module. Thin lines represent modules made by one single detector with the readout strips oriented along the z axis in TIB and TOB, oriented radially in TID and TEC, therefore measuring the $r\phi$ or ϕ coordinate. Thick lines represent modules composed by two detectors mounted back-to-back, one of which has the strips along z (r), while the other has the sensor tilted by 100 milliradians: the combination of the two measurements provides a space point.

Detectors of the TIB, TID, and of the four innermost rings of the TEC have strip lengths around 10 cm and pitch around $100 \mu\text{m}$, giving a surface of about 0.1 cm^2 per channel (all strips are read out). These detectors are made of one sensor of $320 \mu\text{m}$ thickness. All tracker sensors are produced from 6" wafers. In the outer part of the tracker (TOB and three outermost TEC rings), in order to limit the number of channels, strip length and pitch are increased by about a factor of two, giving a surface of about 0.4 cm^2 per channel. The increase in strip length is realized by bonding together two sensors. To compensate for the increase of noise due to the higher inter-strip capacitance, a silicon thickness of $500 \mu\text{m}$ is chosen for these larger detectors. The area covered by one electronic channel combined with the expected track densities given above, implies that the tracker has an average occupancy in the 1% range or below, if the readout electronics is efficient for one bunch crossing only.

Figure 1: Sketch view of 1/4 of the Silicon Strip Tracker, in the $r - z$ projection, also showing the pseudorapidity coverage. Each line represents a detector module. Thin lines represent modules made out of a single detector; thick lines represent modules made of two detectors mounted back-to-back that provide a space point.

Figure 2: Shapes and dimensions of all the silicon detector types of the tracker.

The shapes and dimensions of all tracker detectors are represented in Fig. 2, while the evolution of strip length and pitch with the radius is shown in Fig 3, for Barrel layers and End-Cap rings.

The entire tracker volume, a cylinder of approximately 2.4 m diameter and 5.4 m length, has to be kept below 0°C all the time, to avoid the “reverse annealing” of silicon sensors, implying that a dry atmosphere has to be maintained for several years. After the sensors have integrated substantial hadron fluence, the power dissipation due to the leakage current becomes significant, imposing even more stringent requirements on the cooling parameters. It is estimated that after 10 years of operation in the LHC the sensors have to be kept below -10°C to avoid thermal runaway; this sets the nominal running temperature for the tracker and defines the technical requirements for the cooling system.

Figure 3: Evolution of the strip length and strip pitch of the tracker detectors with the radius. Markers represent Barrel layers, lines represent End-Cap rings. At the same radius, length and pitch are consistent between Barrel and End-Cap.

2 A LARGE SCALE CHALLENGE

The CMS tracker is the first large scale tracker entirely equipped with silicon strip detectors. The realization of such a device has been made possible by a few key steps.

The tracker contains almost 10 million readout channels, *i.e.* over 75,000 readout chips. Such chips are realized in 0.25 μm technology [1], that provides radiation hard devices, with excellent noise performance, at low price from reliable high-yield industrial process.

The silicon sensor design has been optimized during several years of R&D [2]. P on N sensors maintain adequate performance after bulk type inversion, if operated at high bias voltage; metal over-hang is implemented to avoid high-field regions from the bulk to the oxide, so obtaining sensors with high breakdown voltage.

The $\langle 100 \rangle$ orientation of the crystals minimizes the surface damage.

Simple design rules are used for guard ring and strip geometries, obtaining sensors that can be produced in large 6" industrial lines, with high yield and affordable price.

The assembly of over 15,000 detector modules, composed by the silicon sensor(s), the front-end hybrid carrying the front-end ASICs, and the supporting carbon fibre frame, is carried out in a completely automatized way in dedicated "Gantry" stations [3]. The module components are localized by a camera that identifies specific markers with a pattern recognition algorithm; they are picked up and assembled together by dedicated tools, while the glue is dispensed by high precision syringes. Module components can be assembled with a precision of 3 μm in the positioning and of 1.5 milliradians in the alignment. Three modules can be assembled in parallel in about one hour.

2.1 Validation of the system

The data are converted into optical signals in opto-hybrids that are located at minimal distance from the FE hybrids, and then travel in optical fibres to the back-end, where they are converted back to electrical signals, digitized and processed.

The performance of the full system, including the optical link, has been verified with pion and muon beams, cosmic muons and beta sources. Fig. 4 shows the performance of an Outer Barrel detector integrated in the full system. The signal-to-noise ratio, measured with cosmic muons, is found to be above 25; a time scan performed using a beta source shows an efficiency plateau of about ± 15 ns around the optimal timing. The performance matches the expected figures.

After 10 years of operation in the LHC environment, the S/N figure is expected to be degraded to about 15 for thick/large detectors, 13 for thin/small detectors.

Figure 4: Performance of an Outer Barrel detector integrated in the system. The S/N ratio measured with cosmic muons (a) is larger than 25; the efficiency plateau obtained with a beta source (b) is about ± 15 ns around the optimal timing. Both figures are consistent with expectations.

2.2 Material inside the Tracking volume

The material is a crucial issue for the CMS tracker: bremsstrahlung is the limiting factor for the electron energy resolution; multiple scattering degrades substantially the momentum resolution for low-Pt muons, and affects high-Pt muons as well; nuclear interactions are the main source of pion reconstruction inefficiency. The material in the tracking volume affects the performance in all physics channels.

The relatively high mass of the tracker is the consequence of several facts inherent to its design:

- the active material has high density;
- given the size of the device, the FE electronics cannot be located outside the sensitive region (it is in fact spread all over the tracking volume);
- the high track density expected in LHC collisions requires high density of electronics channels;
- the low-noise rad-hard FE electronics has high current consumption (over 15 kA for the Silicon Strip Tracker), requiring large cross sections of conductors populating the tracking volume;
- the tracker has high modularity: over 15000 detectors have to be held in place with a few hundred micron precision and a stability in the 10 μm range, requiring stiff mechanical structures;
- the stringent limit on the silicon running temperature requires a high-capillarity cooling system, able to remove efficiently the heat from every single electronic element.

In the design of the mechanics, the electronics and the cooling, all efforts were made to minimize the material. The present estimate of the radiation length of the tracker (including the pixel system) as a function of pseudorapidity is given in Fig. 5. Such estimate is derived from a detailed simulation based on engineering drawings.

All components are contributing significantly to the total material in the tracking volume, that ranges from 0.3 radiation lengths in the central part to about 1.0 radiation length at $\eta = 1.5$. In the End-Cap region there is also a substantial amount of material outside the tracking volume but in front of the Electromagnetic Calorimeter (up to 0.4 radiation lengths at large η).

3 PERFORMANCE

The transverse momentum and transverse impact parameter resolutions for muons of different energies are shown as a function of pseudorapidity in Fig. 6. The Pt resolution is around 2% or better for $P_t < 100 \text{ GeV}/c$, in the range $\eta < 1.7$; at larger pseudorapidity the performance degrades because of the reduction of the lever arm; the Pt resolution does not scale with Pt because of the substantial effect of the multiple scattering. The transverse impact parameter resolution is better than 20 μm in the whole pseudorapidity range covered by the tracker, for muons of $P_t = 100 \text{ GeV}/c$; at lower energy the performance is again degraded by the multiple scattering.

Figure 5: Radiation length of the CMS tracker (including the pixel system) as a function of pseudorapidity. In the left plot the contributions of the subsystems are shown separately, in the right plot the different components are detailed.

Figure 6: Transverse momentum resolution (left plot) and transverse impact parameter resolution (right plot) as a function of pseudorapidity for muons of different energies.

The track reconstruction efficiency is close to 100% for muons in most of the pseudorapidity range, while it drops to 90%–95% for pions, mostly because of nuclear interactions.

Tracks can be reconstructed using the pixel hits and a reduced number of silicon strip hits. As shown in Fig. 7, sufficient precision is achieved already with four coordinates from the silicon strip system. Such figures on one hand demonstrate the redundancy and robustness of the tracker, on the other hand allow a “fast track reconstruction” to be developed, based on 4-6 hits only, that is to be used in the High Level Trigger [4].

Figure 7: Transverse momentum resolution (left plot) and transverse impact parameter resolution (right plot) for tracks reconstructed using the pixel hits and a reduced number of silicon strip hits. With a number of hits ≥ 4 the precision is close to the figure obtained with the full tracking, indicated by the points at zero reconstructed hits.

4 CONCLUSIONS

The silicon strip technology, developed for vertex detectors, is used in CMS for a large scale tracker. The feasibility of such a project relies on the use of silicon sensors produced in 6" industrial lines, on the availability of ASICs in 0.25 μm technology, and on high-precision fully automatic module assembly stations.

The performance of the system has been measured, with final components, to be consistent with the design figures.

The solution of a tracker with a small number of high precision coordinates is proven to be sufficiently redundant and robust, while providing high tracking performance.

The relatively large amount of material inside the tracking volume remains a limiting factor for the tracking efficiency and resolution.

References

- [1] M.J. French *et al*, Nucl. Instrum. Meth. A466, 359-365, 2001.
- [2] C. Civinini, Proceedings of HEP 2001.
- [3] A. Honma *et al*, CMS NOTE-2002/005.
- [4] The Trigger and Data Acquisition project, Volume II. CERN/LHCC 2002-26.