CMS Conference Report

September 13, 2002

The Atlas and CMS trackers

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Abstract

An overview of the tracking detectors of the ATLAS and CMS experiments at the LHC is presented. The ATLAS tracking system is composed of a pixel detector, a silicon micro-strip tracker and a straw tube transition radiation tracker. The CMS tracking system features an all-silicon layout consisting of a pixel detector and a silicon micro-strip tracker. These detectors are designed to operate with a 40 MHz bunch crossing frequency in a high particle flux density and extreme radiation environment.

Presented at *5th International Conference on Hyperons, Charm and Beauty Hadrons*,
Vancouver, Canada, June 28, 2002

The LHC is a proton-proton collider with a centre-of-mass energy of $\sqrt{s} = 14$ TeV and a bunch crossing time of 25 ns. Initially, a low-luminosity phase is foreseen, where, with an instantaneous luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, 10 fb^{-1} of data could be collected per year, with a later high-luminosity phase, with an instantaneous luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

ATLAS and CMS are the two general purpose experiments which will be operated at the LHC, and these have been designed to explore the full range of physics that can be accessed at LHC energies. To fulfill this task, a robust and versatile tracking system within a strong magnetic field is essential. Reconstruction efficiencies have to be high and track parameters have to be measured with a good resolution. The resolution on the transverse momentum is required to be between 1 and 2% at a track-momentum of 100 GeV/ c to be able to reconstruct narrow heavy objects and good impact parameter resolutions are needed to reconstruct secondary vertices.

The operating conditions put severe requirements on the detectors used in the trackers. At high-luminosity, an average of 20 minimum bias events are expected per bunch crossing, which will produce more than 1000 in the trackers. This will result in track densities which can be as high as 10 tracks per cm^2 per bunch crossing at a radius of 2 cm. A very fine granularity is thus needed to resolve nearby tracks and a fast response time is needed to resolve bunch crossings. Furthermore, the trackers will feature a harsh radiation environment, with very high particle fluxes. Therefore, to contain reverse annealing and limit leakage current, the silicon detectors will have to be operated between -7° C and -10° C .

1 The ATLAS Inner Detector

Located inside a solenoid magnet generating a 2 T magnetic field, the Inner Detector (ID) [1] is a 110 cm-radius, 7 m long tracker (Fig. 1) composed of three sub-detectors, each employing a different technology. The first two detectors, a Pixel detector followed by a silicon strip tracker (SCT), offer precision tracking, and the outer straw tube Transition Radiation Tracker (TRT) offers continuous tracking and electron identification.

Figure 1: Cross-section of the ATLAS ID.

1.1 The Pixel detector

The Pixel detector [2] has been extensively redesigned in the last years due to delays in radiation-hard integrated circuit electronics and to modifications of the beam pipe. The latter had to be redesigned to allow for its bake-out while the pixel detector is already installed. It now features two $800 \mu\text{m}$ -thick beryllium layers separated by a 4 mm vacuum insulating gap.

The pixel detector features now a fully insertable layout, and it can thus be inserted and removed with the remainder of the ID in place. While this design will facilitate maintenance, repair and upgrades, it features nevertheless a smaller outer radius and a higher material budget. In the barrel, three cylindrical layers are now located at radii of 5.05 cm (*B-layer*), 9.85 cm and 12.25 cm, and in the end-caps, three symmetric pairs of disks are located at $|z| = 49.5$ cm, 56.0 cm and 65.0 cm. This layout ensures that only 2% of tracks up to $|\eta| < 2.5$ have less than three measurement points.

The basic building bloc of the system is the module. Each module has an active sensor area of $16.4 \times 60.8 \text{ mm}^2$, read out by 16 front-end chips (FE), bump-bonded to the sensors, each serving a 18×160 pixel matrix. The FE chip features an adjustable offset for every channel and provides pulse-height information using time over threshold (TOT). This improves hit resolution as charge-sharing can be used. The 16 FE chips are controlled by a *Module Controller Chip* (MCC). A Flex-Hybrid circuit glued on the sensor backside provides the signal routing between the FE chips and the MCC, and the power routing for the FE's, MCC and sensor. The pixel size is of $50 \times 300 \mu\text{m}^2$

in the B-layer and $50 \times 400 \mu\text{m}^2$ in the other layers. With 1456 modules in the barrel and 288 in the end-caps, this results in $8 \cdot 10^7$ channels and a total sensitive area of approximately 2.0 m^2 .

The detectors are designed to withstand the 10^{15} 1 MeV neutron equivalent per cm^2 fluence, 50 Mrad dose, that are expected in 10 years of LHC operation at the radius of the middle layer. Nevertheless, the flux at the lower radius of the B-layer will be five times higher, and this layer should be replaced every few years.

1.2 The Silicon strip tracker

The SCT is composed of four cylindrical layers in the barrel and nine symmetric pairs of disks in the end-caps. The barrel layers are approximately 1.5 m long and are located at radii between 28.4 cm and 50 cm.

The modules composing the SCT are all double sided, with detectors glued back-to-back with a stereo angle of 40 mrad. Except for the innermost modules of the end-cap disks, two detectors are daisy-chained on each side. In the barrel, modules have an active area of $12.52 \times 6.16 \text{ cm}^2$, with 768 axially oriented strips of $80 \mu\text{m}$ pitch. The end-cap modules have a trapezoidal shape with 768 keystone-shaped radially oriented strips. Four types of end-cap modules exist, depending on their radial placement on the disks, and each type will have different dimension and pitches, ranging from 63 to $85 \mu\text{m}$ at the centre of the module. With 4088 modules in total, the SCT has an active area of 61 m^2 of silicon and $6.3 \cdot 10^6$ channels. The readout electronics is purely binary providing no pulse-height information, with channel-offsets individually correctable and a threshold common to all 128 channels of a chip.

1.3 The Transition Radiation Tracker

The TRT is a straw tube tracker. Its detecting elements are 4 mm diameter straws filled with a fast and robust gas mixture (70% Xe, 20% CF_4 and 10% CO_2), with a $15 \mu\text{m}$ gold-plated tungsten wire in the middle. The straws are interspersed with a radiator to stimulate transition radiation (TR) from electrons

In the barrel, 72 layers of axial straws are placed at radii between 56 and 107 cm. Below a radius of 63 cm, because of the high occupancy in that region, straws are shorter and only cover the region $40 < |z| < 74 \text{ cm}$. At radii above 63 cm, two independent 74 cm long straws cover the entire region $-74 < z < 74 \text{ cm}$. The end-caps consist of 18 pairs of multi-plane wheels of radial straws. The straws in the first 14 wheels extend from $r = 64 \text{ cm}$ to 102 cm, and the inner radius of the straws in the last four wheels is reduced to 48 cm in order to extend the coverage to higher rapidities.

The readout electronics will have two thresholds. The lower threshold will detect ionisation signals in the gas, for which the ToT will also be measured, while the higher threshold will detect the TR. Drift-time will also be measured to improve spatial resolution, which, depending on the local occupancy, is around $170 \mu\text{m}$.

These informations can be used to separate electrons from pions. For an electron efficiency of 90%, a pion rejection factor of a 100 is obtained. In addition, by using dE/dx information, a K/π separation of 0.5 to 1σ can be achieved.

1.4 Performance

The ID provides coverage up to $|\eta| = 2.5$, with an average of three measurement points per track in the pixel, eight in the SCT and more than 36 in the TRT. Reconstruction efficiencies are in the order of 98% for muons and 90-95% for pions, with a fake rate at high luminosity below 10^{-5} . The resolution [3] on the track parameters can be parameterized as:

$$\begin{aligned}\sigma(p_T)/p_T &= 0.00036 \cdot p_T \oplus 0.013/\sqrt{\sin \vartheta} , \\ \sigma(\varphi_0) &= 0.075 \oplus 1.8/(p_T \sqrt{\sin \vartheta}) \text{ mrad} , \\ \sigma(\cot \vartheta_0) &= (0.7 \oplus 2.0/(p_T \sqrt{\sin^3 \vartheta})) \cdot 10^{-3} , \\ \sigma(d_0) &= 11 \oplus 98/(p_T \sqrt{\sin \vartheta}) \mu\text{m} , \\ \sigma(z_0) &= 87 \oplus 115/(p_T \sqrt{\sin^3 \vartheta}) \mu\text{m} .\end{aligned}$$

2 The CMS Tracker

The CMS Tracker [4] is located, together with the electromagnetic and hadronic calorimeters, inside a solenoid magnet generating a 4 T field. CMS has chosen an all-silicon configuration, relying on a few measurement layers, each able to provide robust and precise coordinate determination. The tracker is thus composed of a Pixel detector, providing two to three hits, followed by a Silicon Strip Tracker (SST) providing 10 to 14 hits per track. Due to the fine granularity and hence the low occupancy obtained, pattern recognition problems are solved after the first few layers, and track parameter resolutions reach an asymptotic value after using only the first five to six hits.

2.1 The Pixel detector

The Pixel detector is composed of three cylindrical barrel layers and two pairs of disks in the end-caps, such that three points are measured per tracks for $|\eta| < 2.2$. In the barrel, the three layers are located at radii of 4.4 cm, 7.5 cm and 10.2 cm, and in the end-caps, the two pairs of disks are located at $|z| = 34.5$ cm and 46.5 cm. A later upgrade to a third pair of disks is envisaged. The pixel size is $150 \times 150 \mu\text{m}^2$, and the hit resolution is approximately of $10 \mu\text{m}$ in $r - \phi$, using charge sharing induced by the Lorentz angle of 28° , and $17 \mu\text{m}$ in $r - z$. With a radiation tolerance of $6 \cdot 10^{14}$ 1 MeV neutron equivalent per cm^2 , the lifetime at full luminosity is 2 years for the inner layer, 5 years for the middle layer and 10 years for the outer layer.

The barrel layers are composed of ladders, each composed of eight modules. These modules have an active area of $16 \times 66 \text{ mm}^2$, read out by 16 readout chips (ROC), bump-bonded to the sensors, each reading out an array of 52×53 pixels. The end-cap disks are turbine disks consisting of 24 blades, each rotated by 20° to ensure higher track inclinations and a higher Lorentz angle, thus improving charge sharing. Each blade is composed of seven modules of varying size, with between 2 and 10 ROCs per module. The ROC features a fully analog readout, providing pixel pulse height information and analog coded row/column addresses.

2.2 The Silicon Strip Tracker

Figure 2: Cross-section of the CMS SST.

The SST is divided in four parts (Fig. 2). The *Inner Barrel* (TIB) is constituted of four cylindrical layers, enclosed by three pairs of disks (*Inner Disks* – TID). It is then followed by the six cylindrical layers of the *Outer Barrel* (TOB), and the *End-Caps* (TEC) are made of nine pairs of disks. The disks of the TID are composed of 3 rings of modules and the TEC disks of 7 rings. The first two layers of both the TIB and the TOB, the first two rings of the TID and rings 1, 2 and 5 of the TEC are instrumented with double sided modules, where the detectors are glued back-to-back with a stereo angle of 100 mrad.

In the inner part of the SST (TIB, TID and first four rings of the TEC), modules are made of single, $320 \mu\text{m}$ -thick sensors. In the outer part (TOB and last three rings of the TEC), to reduce the number of channels, sensors are daisy-chained in pairs. To increase the thus-degraded signal-to-noise ratio, $500 \mu\text{m}$ -thick sensors are used. Strip lengths range from 9 cm in the inner part to 21 cm in the outer part, and pitches range from 80 to $205 \mu\text{m}$. With this variety of detectors, there are 14 different sensor geometries. The SST has 6'136 thin and 18'192 thick sensors in total, for an active area of 210 m^2 of silicon and $9.6 \cdot 10^6$ channels.

2.3 Performance

Track reconstruction efficiencies are better than 98% for muons up to $|\eta| = 2.2$ and around 90% for tracks in jets up to $|\eta| = 2.5$. The resolutions for the transverse momentum and the transverse impact parameter are shown in Fig. 3.

Figure 3: Resolution of the transverse momentum and transverse impact parameter at CMS.

3 Conclusion

Tracking at LHC is a very challenging task: it is a very harsh radiation environment with very high rates and a high accuracy is necessary. An extensive R&D program to devise detectors which meet these requirements has been conducted. Design of the different detectors is nearly completed, and production and construction of various components has already started. Both the ATLAS and the CMS Trackers are expected to have robust performances in a difficult environment.

References

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