Nuclear Instruments and Methods in Physics Research A 658 (2011) 41–45

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A new CMS pixel detector for the LHC luminosity upgrade

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ARTICLE INFO

Available online 27 May 2011

Keywords:
LHC
CMS
Pixel
Silicon
SLHC
Vertex

ABSTRACT

The CMS inner pixel detector system is planned to be replaced during the first phase of the LHC luminosity upgrade. The plans foresee an ultra low mass system with four barrel layers and three disks on either end. With the expected increase in particle rates, the electronic readout chain will be changed for fast digital signals. An overview of the envisaged design options for the upgraded CMS pixel detector is given, as well as estimates of the tracking and vertexing performance.

1. Motivations for the Phase 1 upgrade of the pixel detector

The silicon pixel detector [1] is the innermost part of CMS. It has the key role to provide the precise spatial measurements used as seeds for the reconstruction of charged particle trajectories in proximity of the primary interaction point. Its performance is thus crucial for the identification of primary and secondary vertices, and for the measurement of long-lived particles such as b quarks and τ leptons. The present detector was designed for a maximum peak luminosity of $10^{34}\,cm^{-2}\,s^{-1}$, the design value of the Large Hadron Collider, which will be exceeded in the so called Phase 1. Higher luminosities are not sustainable, mostly due to readout inefficiencies.

To fully profit from the large datasets that will be collected by the CMS experiment, a new optimized silicon pixel detector will be installed during the long LHC shutdown in 2016.

The new detector will be required to retain a good hit detection efficiency and prevent data losses in the large occupancy environment, to assure good track seeding and pattern recognition performance, and to provide high resolution on track parameters.

All modifications will be constrained by the existing cables and off-detector services, since space limitations prevent the installation of additional components. Moreover, the number of detector module types will have to be reduced, in order to limit the time and costs for production and testing.

In addition, despite the use of radiation resistant technologies, the detector is not sufficiently radiation hard to survive until the end of the Phase 1, when a total integrated luminosity of $350\,fb^{-1}$ will be collected. The innermost barrel layer will have sustained a particle fluence of about $10^{16}\,n_{eq}\,cm^{-2}$, producing an irreversible degradation of its performance. An intermediate replacement of this layer will therefore be needed.

2. Detector design and material budget

The present pixel detector does not provide a hermetic three-hit coverage. The resulting seeding inefficiencies limit the performance of the High Level Trigger, and slow the offline reconstruction, based on a sophisticated iterative algorithm [2].

A new geometrical layout, shown in Fig. 1, will thus be implemented. The proposed barrel design includes four cylindrical layers, placed at radii of 3.9, 6.8, 10.9 and 16.0 cm. The innermost layer is moved closer to the interaction point, while the forth layer is added in the gap between the present third pixel and the first strip layers. This will result in a factor two increase of the radial acceptance and a reduction of the extrapolation distance between pixel and strip detectors, with a benefit to the pattern recognition.

Three endcap disks will be installed at each side of the barrel, at 29.1, 39.6 and 51.6 cm from the interaction point. The new layout will provide an almost hermetic four-hit coverage up to a pseudorapidity of 2.5.

One module type will be used in both barrel and endcap regions. Each module includes a silicon pixel sensor [3] bump-bonded to 16 readout chips. In the barrel, the modules will be mounted on carbon fiber ladders glued onto stainless steel cooling tubes. In the endcaps the support structure will be made of blades arranged radially into half-disks, with a similar turbine-like

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doi:10.1016/j.nima.2011.04.062

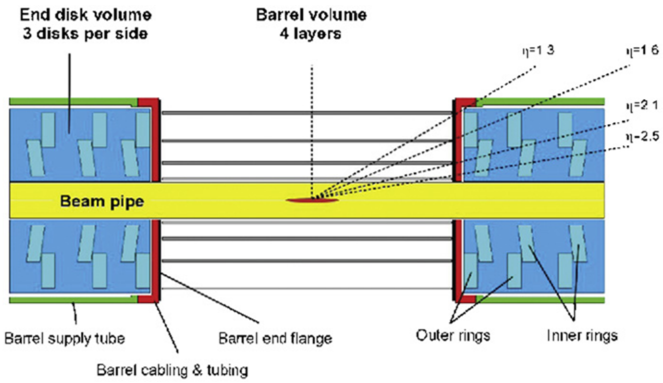

Fig. 1. Longitudinal cross-section of the upgraded pixel detector, showing the location of barrel layers and endcap disks.

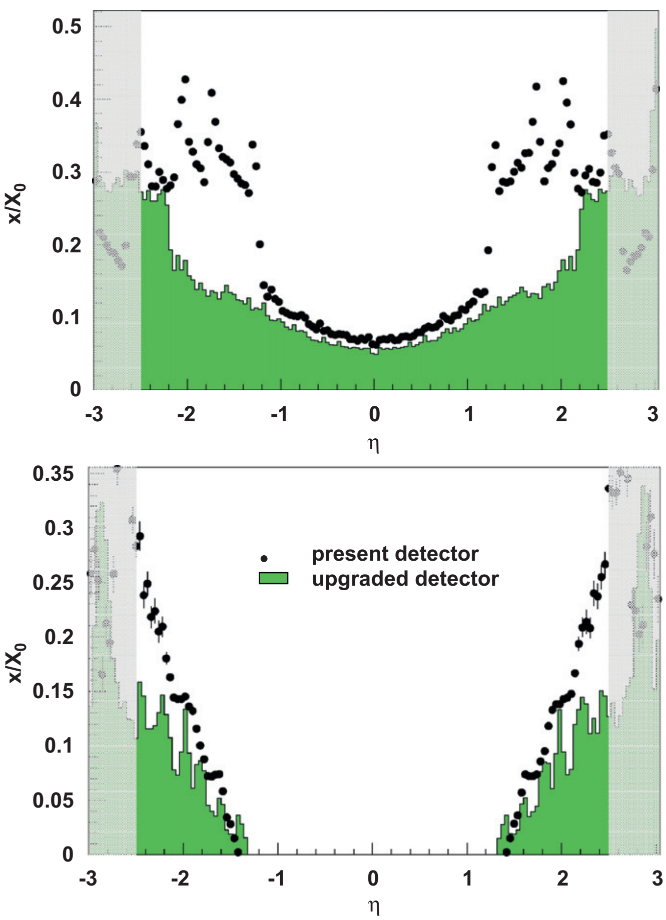

Fig. 2. Material budget of the barrel (top) and the endcap (bottom) detector in term of radiation lengths for the present (black dots) and the upgraded (green histogram) systems, as a function of track pseudorapidity. The grey bands show the pseudorapidity region outside the tracking acceptance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

geometry of the present detector. Each half-disk will be composed of two concentrical rings, to remove and replace independently the innermost part after radiation damage.

A limitation of the present pixel detector is the significant amount of material within the tracking acceptance, which degrades the performance of track reconstruction. The biggest contributions are the silicon sensors, the mechanical support, the cooling system, and electronics. In addition, the barrel endflange hosting cooling manifolds and electronic boards is a considerable amount of material located in front of the first forward disk. One of the objectives of the Phase 1 upgrade is a drastic reduction of the material budget. The present C_6F_{14} will be replaced by a two-phase CO_2 system, which has suitable thermodynamic properties for flowing in micro-channels, low mass and sufficient radiation hardness. In both barrel and endcap the modules will be installed on ultra-lightweight support structures. Most part of the barrel services currently on the endflange will be moved to the barrel supply tube, outside the tracking acceptance.

These modifications will result in at least a factor of two reduction of the material budget, as shown in Fig. 2.

Finally, a new powering system will be needed to power the increased number of components with the present cables and services. DC–DC converters will be used for this purpose.

3. Readout

The present pixel readout chip (PSI46v2) [4] was designed to provide high hit detection efficiency at the design LHC peak luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Assuming a Level 1 Trigger accepted rate of 100 kHz, at the instantaneous luminosity of $2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ the dynamic inefficiency of the innermost barrel layer is estimated to grow from 4% to 16%, with unacceptable deterioration of hit reconstruction and track seeding efficiencies.

The main sources of readout inefficiency must be addressed to prevent data losses. In order to keep a high single-hit efficiency, the size of the data buffers at the double column periphery will be extended from the present 32 to 80 units, compatibly with space limitations. An additional buffer stage will be introduced, to store the Level 1 Trigger accepted hit information while waiting for the readout token.

Moreover, the implementation of a faster readout will be needed to read the increased number of channels through the existing optical fibers. The plan is to switch from the current analogue signal to digital, with an on-chip ADC. In addition high speed (320 Mbps) links will be used to increase the bandwidth.

With these modifications the dynamic inefficiency is estimated to be about 5.7% for a trigger rate of 100 kHz and a peak luminosity of $2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

4. Performance improvement

The enhanced features of the new pixel detector will produce a significant improvement of the performance, in terms of track parameters resolution, tracking efficiency and fake rate, vertex reconstruction and b-tagging.

The material reduction, the increase of the radial acceptance, and the four-hit hermetic coverage will provide a better resolution of the track parameters. The improvement will affect both fully reconstructed and pixel-only tracks, used by the High Level Trigger.

Fig. 3 shows the transverse and longitudinal impact parameter resolution of fully reconstructed tracks, for the present and upgraded detectors. Only the result for the barrel is presented. The improvement will be about 25%, and will reach 40% in the forward region in correspondence of the location of the endflange. The effect is more pronounced in the low momentum region, where the multiple scattering is dominant and the sensitivity to the material reduction is thus bigger. A factor of four enhancement is also expected for pixel-only tracks, thanks to the extended radial coverage.

The better track parameter resolution will enhance the vertex reconstruction [2,5] performance. In Fig. 4 the primary vertex