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Performance of the upgraded CMS pixel detector for the LHC Phase 1

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Abstract

After the Phase 1 upgrade the Large Hadron Collider is expected to reach an instantaneous luminosity of $2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ or higher, resulting in an extreme operating environment for the experiments, particularly their tracking devices. In order to maintain its current performance level, the CMS pixel detector will be replaced by a more lightweight system with additional instrumentation, better acceptance and refined front-end electronics. The upgraded pixel detector will provide improved track and vertex reconstruction, standalone tracking capabilities, as well as identification of long-lived particles, which will be key elements of many physics analyses with CMS.

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Performance of the upgraded CMS pixel detector for the LHC Phase 1

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ABSTRACT: After the Phase 1 upgrade the Large Hadron Collider is expected to reach an instantaneous luminosity of $2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ or higher, resulting in an extreme operating environment for the experiments, particularly their tracking devices. In order to maintain its current performance level, the CMS pixel detector will be replaced by a more lightweight system with additional instrumentation, better acceptance and refined front-end electronics. The upgraded pixel detector will provide improved track and vertex reconstruction, standalone tracking capabilities, as well as identification of long-lived particles, which will be key elements of many physics analyses with CMS.

KEYWORDS: Particle tracking detectors (Solid-state detectors), Performance of High Energy Physics Detectors.

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1. The Phase 1 upgrade of the CMS Pixel Detector

During a longer shutdown foreseen to take place around 2017/18, the LHC and its experiments will be upgraded for operation with peak luminosities of $2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ at 14 TeV center-of-mass energy. The pixel detector currently deployed in the CMS experiment [1] has not been designed for such conditions; its performance would seriously be affected by the high occupancy, large readout-induced dead time and radiation damage after several years of operation. Furthermore, an enhancement of the acceptance and a reduction of the amount of material within the sensitive volume is desirable.

As the innermost tracking system of the CMS experiment, the pixel detector plays an important role in providing spatial measurements of particle trajectories close to the collision point and thus its performance is crucial for the identification of interaction and decay vertices as well as for lifetime measurements of long-lived particles. In order to maintain high efficiency and excellent tracking performance, the pixel detector will be replaced by a completely new and enhanced system [2]. Figure 1 shows an overview of the new detector design. Key features are an additional fourth barrel layer at 160 mm radius and one additional end cap disk on either side ($z = \pm 514$ mm), providing four-hit coverage over the full acceptance. Furthermore, the radius of the innermost layer will be reduced from 44 mm to 39 mm or possibly even lower. In total, the upgraded detector will comprise 1856 modules with just under 125 million channels, which is almost a factor of two more with respect to the current system. Due to space limitations, a large fraction of the services cannot be accessed, such that current cables and optical fibers will have to be reused.

Despite the additional instrumentation, the overall material budget within the pixel detector is expected to decrease significantly with the Phase 1 upgrade due to a number of measures:

- the development of an ultra-light support structure made of carbon fiber glued onto Airex foam, in which the cooling pipes play an important role in terms of mechanical stability;
- with the introduction of low mass micro-twisted pair cables, electronic components of the services will partially be moved out of the active tracking volume;

Figure 1. *Left:* conceptual layout for the Phase 1 upgrade pixel detector. *Right:* transverse cross section through the barrel part of the pixel detector for the Phase 1 upgrade detector (top left) and for the present detector (bottom right).

- a 2-phase (evaporative) CO₂ cooling system will be installed instead of the current C₆F₁₄ system, allowing for thinner pipes and reduced coolant flow in the detector.

Figure 2 illustrates the material reduction in the pixel detector volume. Particularly in the forward section and the barrel to forward transition region (around $\eta = 1.5$), the amount of passive material will be significantly lower. Such a reduction will have a large impact on the charged particle tracking efficiency as well as electron and photon identification and resolution through the lesser amount of secondary interactions of particles with matter.

Figure 2. The amount of material in the pixel detector shown in units of radiation length for the barrel (*left*) and forward (*right*) sections as a function of pseudorapidity; this is given for the current pixel detector (black points), and the upgraded detector (green histogram). The shaded region at high $|\eta|$ is outside the region for track reconstruction.

The pixel size of $100 \times 150 \mu\text{m}^2$ will remain unchanged in the new design. In order to reduce dead time in the front-end electronics with high luminosity, an improved readout chip (ROC) design is under development [3]. It features larger data buffers to prevent overflow with high occupancy, digital readout with on-chip ADCs for faster data transfer, as well as a buffered readout stage which allows for simultaneous read/write operation. As a result, for 25 ns operation of the LHC at highest

Phase 1 luminosity, data loss due to dead time can be kept below 4.7 % on the innermost barrel layer (39 mm radius), while for the current detector it would amount to about 16 % (44 mm radius).

2. Detector performance

At highest envisaged Phase 1 luminosities of $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ with 25 ns bunch spacing, about 40-50 proton interactions per bunch crossing will occur in the CMS detector (“pile-up”), leading to the creation of several thousand particles altogether. This imposes an unprecedented challenge for the pattern recognition capabilities of the pixel detector. A key feature of the upgraded design will therefore be the additional instrumentation in the barrel and end cap sections by which the detector obtains a good four-hit coverage over its whole sensitive volume. The redundancy provided by the additional trajectory measurements results in better track finding efficiency and track quality as well as a significantly reduced fake track rate. The tracking performance also benefits much from the reduced distance of the innermost barrel layer from the interaction point, the lower material budget and the better capabilities of the new ROC design.

The performance of the upgraded detector has been studied using simulated collision events involving the production of top-quark pairs, assuming 14 TeV center-of-mass energy and highest Phase 1 luminosity (on average 50 pile-up interactions superimposed on the signal) with a bunch spacing of 25 ns. Expected data loss due to ROC dead time has been taken into account for the current and upgraded detector design. For the latter, an innermost barrel layer radius of 39 mm has been chosen for the simulation.

2.1 Track and vertex finding

Figure 3 shows a comparison of the track finding efficiency and fake rate for the current and Phase 1 upgraded detectors. The efficiency is significantly higher with the upgraded design, particularly in the central region where the efficiency gain is up to 50 %. The number of fake tracks – which are caused by incorrect association of hits – is slightly lower for the upgraded detector, especially in the forward and the barrel to forward transition region.

Figure 3. Track finding efficiency (left) and fake rate (right) as functions of pseudorapidity at high luminosity and 25 ns operation for the current (blue squares) and upgraded (red circles) detector.

Among the primary tasks of the pixel detector is the identification and localisation of primary and secondary vertices. The longitudinal and transverse primary vertex position resolutions as functions of the number of tracks associated to the vertices are shown in Figure 4 for high luminosity. With the detector upgrade, an overall improvement in the vertex resolution of about 20 % can be achieved.

Figure 4. Transverse (left) and longitudinal (right) vertex position resolution at high luminosity for the current (black circles) and upgraded (red triangles) detector. The lower parts of the panels show the ratios of the resolutions for the current and the upgraded detector.

2.2 B-tagging

The b-tagging capability of the CMS experiment is essential for its physics program, since a large number of interesting processes involve long-lived b-quarks in their final states, such as certain predicted production and decay mechanisms of the Higgs boson or supersymmetric particles. Almost all b-tagging algorithms rely on efficient track reconstruction and precise spatial reconstruction of particle trajectories close to the interaction point. The performance improvement provided by the upgraded detector is shown in Figure 5 for the high luminosity scenario with 25 ns bunch spacing. For a b-tagging efficiency of 60 %, the light quark background to the b-tagging would after the upgrade be reduced by roughly a factor of six with respect to the current detector. As a result, the new detector can almost fully recover the degradation in b-tagging performance of the current detector due to the large track multiplicity at high luminosity.

2.3 Pixel-only track reconstruction

Pixel-only tracks play an important part in the event reconstruction, particularly during the initial steps of vertex and track finding. Due to the additional barrel layer and end cap disks, the pixel-only track quality improves drastically with the upgraded detector. Figure 6 shows the pixel-only track impact parameter resolution, which is an important quantity for vertex and lifetime measurements, at low luminosity (without pile-up). Over a large track momentum range, the resolution of the upgraded detector is improved by approximately a factor of two compared to the current detector. Similar results are obtained for the resolutions of the track parameters, such as track momentum and direction. The studies of pixel-only tracking performance with high luminosity conditions are currently in progress.

Figure 5. B-jet efficiency versus light jet efficiency (current detector: open squares, upgraded detector: filled circles) and charm-jet efficiency (current detector: open triangles, upgraded detector: filled triangles) for top-quark pair events at high luminosity.

Figure 6. Transverse (a) and longitudinal (b) impact parameter resolution for pixel-only tracks in top-quark pair events at low luminosity (no pile-up) for the current (squares) and upgraded (circles) detector.

3. Summary

Around 2017/18 the pixel detector of the CMS experiment will be replaced by an enhanced system to accommodate for the high luminosity phase of the LHC. Among the new features of the upgraded detector design are extended instrumentation with broadly improved acceptance and precision, significantly less passive material and new front-end electronics with higher efficiency. Simulations of the new detector reveal significantly improved tracking efficiency and fake rate as well as better impact parameter and spatial vertex resolutions. Particularly, the upgraded detector can almost fully recover the degradation in b-tagging performance of the current detector at high luminosity.

References

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