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Upgrades of the CMS pixel detector for the HL-LHC

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In 2023, the LHC will be upgraded to the HL-LHC, increasing the luminosity to 5 x 10^{34} cm^{-2} s^{-1}. The increased luminosity will present new challenges, such as higher data rates and increased radiation. The CMS Phase 2 Pixel upgrade will require a high bandwidth readout system and high radiation tolerance for sensors and on-detector ASICs. Several technologies for the upgrade sensors are being considered, including thin planar and 3D options. DC-DC conversion or serial powering schemes are under consideration to accommodate significant constraints on the system. These prospective designs, as well as new layout geometries that include very forward pixel discs, will be presented.

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1. Introduction

After Run 3 of the Large Hadron Collider, in approximately 2023, the LHC will be upgraded to the High-Luminosity LHC (HL-LHC). The HL-LHC will increase the instantaneous luminosity by at least a factor of two. This will present additional challenges for the CMS Pixel detector due to the increased radiation and additional secondary collisions (pileup). In order to maintain the efficiency of the Pixel Detector a series of upgrades are planned [1].

The CMS detector is one of four major experiments at the LHC and one of two multipurpose detectors. The CMS detector features a large 3.8 T solenoidal magnetic field. At the center of CMS is a large silicon tracking system, consisting of an outer silicon strip tracker and an inner pixel detector. The current CMS Pixel detector has three barrel layers and two endcap disks on each side. The current analog Read Out Chip (ROC) used in each pixel module, has a 40 MHz readout and is nearly reaching its design limits, resulting in a loss of efficiency at peak luminosity.

The Phase 1 upgrade, which is currently under construction, will feature an additional (4th) barrel layer and a 3rd disk in each endcap. This will double the number of channels to over 100 million. It will also feature a new digital ROC which has larger buffers to handle larger pileup, but the Phase 1 ROC was designed using the same 0.25 micron technology as the current Pixel ROC and has the same radiation tolerance. The Phase 1 pixel detector will be installed and begin operation in early 2017. By the conclusion of Run 3 it is estimated that the detector will have collected approximately 500 fb^{-1} of data with an equivalent dose on the order of 100 Mrad. Significant performance degradation due to radiation exposure is expected.

The Phase 2 Pixel upgrade will be required to remain efficient in the harsh HL-LHC environment. Over the lifetime of the detector, during which the HL-LHC is expect to deliver up to 3000 fb^{-1} of collisions, equivalent to over one Grad. The technologies used in the sensors and ROCs will need to be of sufficient radiation hardness to maintain efficiency over the full lifetime. The Phase 2 Pixel geometry is still under discussion. For expedience, the current technical proposal is based on the Phase 1 geometry with an extended Very Forward Pixel (VFPix) detector consisting of 10 disks (Fig. 1).

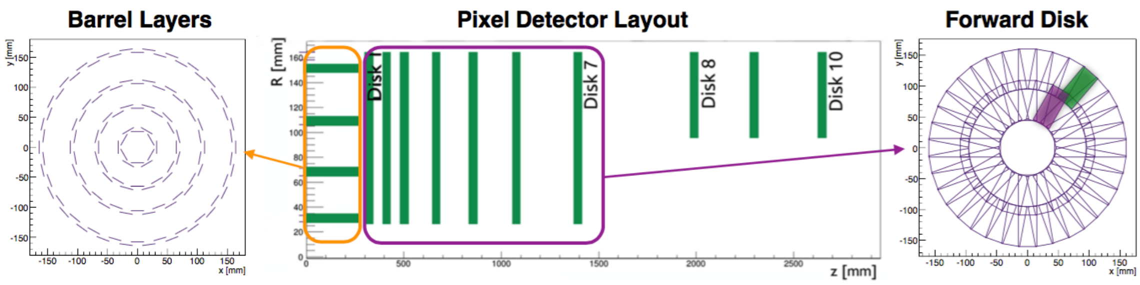

Figure 1: The CMS Phase 2 Pixel Upgrade.

2. Sensors

As silicon sensors are exposed to radiation, defects develop in the structure. The defects can trap charge carriers causing a reduction in efficiency. In order to minimize the probability of charges being trapped, one should reduce the distance the charges must travel. Several different sensor technologies are under study that minimizes this distance.

Thin planar sensors reduce the drift length by keeping the thickness of the sensor below 150 μm. This reduces the probability of charge trapping and reduces the overall material used in the detector leading to less multiple scattering. Thinner sensors also produce higher fields at the same voltage, reducing power consumption. There are some disadvantages of thin planar sensors as well. Due to the reduced amount of material that the particle passes through, less charge is initially deposited. Also the manufacturing process is more complicated due to the thinning that must be performed and thin sensors are prone to bowing.

3D sensors reduce the drift length by using deep implants for charge collection. This allows for thicker sensors and more charge deposition. However, the 3D sensors are potentially more costly to produce and may limit the minimum pitch of the pixels. A goal for the sensors used in the Phase 2 upgrade is to reduce the pixel area to 2500 μm^2, from 15000 μm^2 as used in the Phase 1 pixel, allowing for finer resolution. Different geometries are being considered including square 50 μm x 50 μm pixels to long thin pixels 25 μm x 100 μm. These pixel geometries present some design challenges because the total pixel area is very small compared to the current pixel unit cell.

Several test structures, including both thin planar and 3D sensors, have been submitted for fabrication in 2015. The thin planar sensors will have an active thickness of 150 μm and will be tested for resolution and radiation tolerance. The 3D submissions, joint ATLAS and CMS projects, will test a new etching process (DRIE), thick and thin 3D wafers, and radiation tolerance.

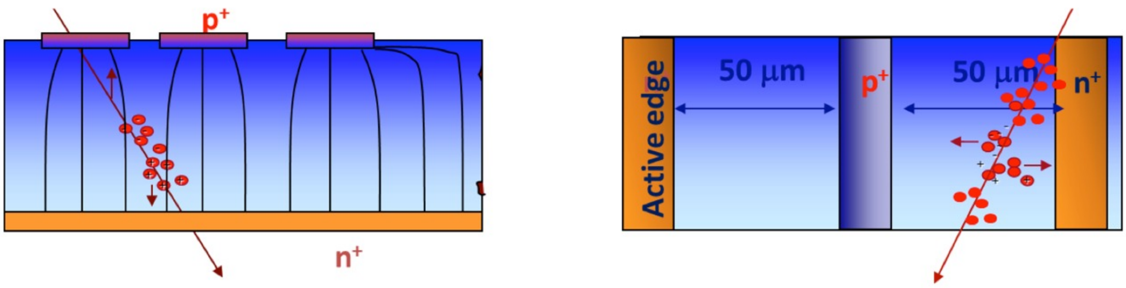

Figure 2: Diagram of thin planar and 3D sensors showing the structure, particle paths, and drift direction.

3. Read Out Chip

The Phase 2 Pixel Read Out Chip is currently being designed by the RD53 collaboration and plans exist for a demonstrator chip to be produced by approximately 2016. The RD53 collaboration consists of 20 institutes in both CMS and ATLAS. The Phase 2 Pixel ROC is being designed to be compatible with the potential sensor technology, supporting thin planar and 3D sensors with small pixels, 25x100 μm or 50x50 μm [1]. The ROC will have a low threshold (~1000e^-) and be able to handle high rates up to 3GHz. It must support a trigger rate of 1 MHz and have low power consumption. To survive the require lifetime of the detector in the HL-LHC environment the ROC must be tolerant up to a 1 GRad dose. A feature size of 65 nm will be used to allow for sufficient radiation hardness.

4. Pixel Electronics

In the high radiation environment of the HL-LHC, it will not be possible to have the optical links inside the detector. Additional cabling from the modules to the optical components, which will be placed on the service cylinder, will be necessary. In order to keep the amount within the allotted material budget, high speed links will be required. The Phase 1 Pixel detector uses twisted pair copper wire in the barrel and aluminum flex cables in the forward regions. Digital data is transmitted from the modules at a rate of 400 Mb/s [2]. It is estimated that higher speeds will be required for the Phase 2 Pixel due to the increased number of channels.

5. Powering

The powering of a detector with the large number of channels as in the Phase 2 Pixel implies a large mass of cabling. It is estimated that the required cabling would add 12kg of copper to the detector which would have an effect on traversing particles. In order to reduce the mass of cables in the detector, several novel powering schemes are being considered [3].

The most attractive powering scheme is a serial powering option. Serial powering is thought to be less complex in its implementation than other methods and reduces the cable mass proportionally to the number of units put in series. The serial wiring can be accomplished in two ways: either across each module or within each module (Fig. 3). If connected across each module the effective local cable reduction would be determined by the number of modules in series. Serial connection within modules would reduce the cable mass by a factor determined by the number of chips in series.

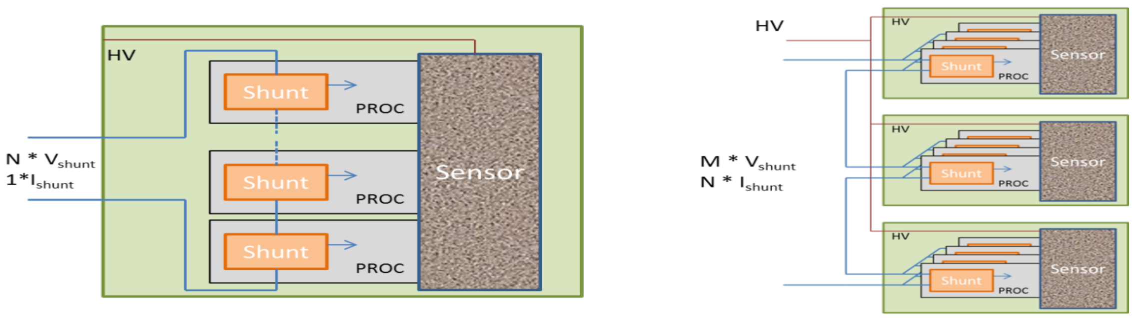

Figure 3: Left: Serial powering within modules. Right: Serial powering across modules.

A second powering option uses a two-stage DC-DC converter scheme. This DC-DC converter would evolve from the converters that will be used in the Phase 1 detector [4]. The DC-DC conversion may not reduce the cable mass enough to be a viable solution and it increases the complexity of the system, but it is still being considered as a backup plan. The DC-DC conversion uses two stages, one outside the detector (remote DC-DC) on the service cylinder and the other on the chips themselves.

Powering Scheme	Cable Mass	Reduction Factor
Serial (Within Modules)	2.08kg	5.8
Serial (Across Modules)	1.74kg	6.9

Table 1: Effective reduction in cable mass compared with 12 kg used by conventional powering.

6. Physics Simulations

In order to study the performance of the proposed design, studies have been performed using simulated $t\bar{t}$ events to examine the effect of the new detector on b quark jet identification (b-tagging). The b-tagging efficiency is shown in Fig. 4 vs. the mis-tag rate for charm quark jets and light quark jets. The $t\bar{t}$ events are examined in three scenarios for comparison: the Phase 1 detector with an average 50 pileup events, the Phase 1 detector assuming the radiation damage after Run 3 and an average 140 pileup events, and using the Phase 2 geometry with an average 140 pileup events (Fig. 4). It is shown that the performance of the Phase 2 detector with 140 PU performs similarly to the Phase 1 detector with 50 PU. At high purity (mis-tag rate of 1%), the Phase 2 performs 10 percent better than the aged Phase 1 detector with 140 PU.

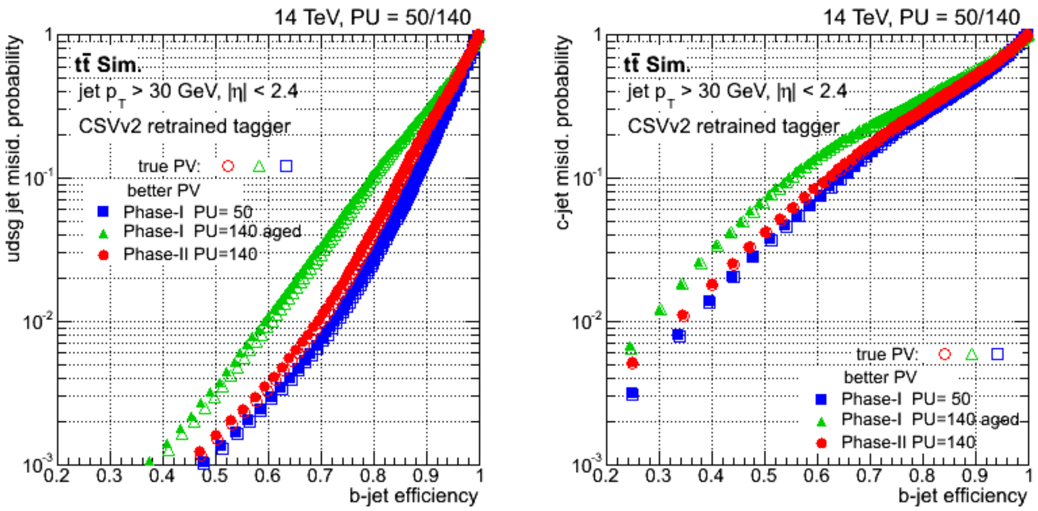

Figure 4: Simulated $t\bar{t}$ events with a jet $p_T > 30$ GeV using three different scenarios: Phase 1 Pixel with 50 PU, Phase 1 Pixel (aged) with 140 PU, and Phase 2 Pixel with 140 PU. Left: B-tagging efficiencies vs. mis-tag rates of light jets. Right: B-Tagging efficiencies vs. mis-tag rates of charm jets.

7. Further Studies

Several further studies are planned for the Phase 2 Pixel. The current simulations using the technical proposal do not contain accurate representations of the supplementary materials (power cables, cooling pipes, etc...). An updated simulation is being prepared and will soon be implemented into the CMS analysis software. Additional studies are being performed using different pixel sizes and different geometries. One such geometry that was presented utilizes a conical design in the forward regions in an attempt to provide better tracking of forward jets. At the LHC, Vector Boson Fusion and Vector Boson Scattering processes both produce forward jets and are important production channels.

8. Conclusion

The HL-LHC will at least double the instantaneous luminosity delivered to the experiments. This increased rate will present new challenges in terms of rates, radiation, and pileup. The CMS Phase 2 Pixel upgrade, to be installed during the HL-LHC upgrade in approximately 2023 will feature some improvements compared to the previous design. New sensors will have smaller pixel sizes, improving resolution, and utilize new technologies suitable for the high radiation environment. New Read Out Chips will improve speed and radiation hardness. New powering schemes are being developed to reduce the material budget and power losses. Early simulations show that the Phase 2 design will have improved performance in key areas, such as b-tagging, that will be very relevant for physics analyses at the HL-LHC. In summary, the development of the CMS Phase 2 Pixel Detector is progressing well and is on track for use in the HL-LHC.

References

[1] The CMS Collaboration, *Technical Proposal for the Phase-II Upgrade of the CMS Detector*, *Technical Report CERN-LHCC-2015-010*. LHCC-P-008, CERN, Geneva. (2015)

[2] R. Stringer. *A digital readout system for the CMS Phase I Pixel Upgrade*, *JINST* **10** (04):C04037 (2015)

[3] S. Mersi. *Phase 2 Upgrade of the CMS Tracker*, *CMS Conference Report CR-2014/336*, CERN, Geneva, (2014)

[4] L. Feld, W. Karpinski, K. Klein, M. Lipinski, M. Preuten, M. Rauch, St. Schmitz, and M. Wlochal, *The DC-DC conversion power system of the CMS Phase-1 pixel upgrade*, *JINST* **10** C01052 (2015)