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Plans for an upgraded CMS pixel detector

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Plans for an upgraded CMS pixel detector

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Abstract

The CMS inner pixel detector system is planned to be upgraded during the first phase of LHC upgrades. The plans call for an ultra low mass system with four barrel layers and with three disks on either end. With the expected increase in particle rates, the electronic readout chain will be changed for fast digital signals. There are constraints due to the services available. However, expectations are there will be improved tracking performance.

Key words:

CMS, pixel detector, upgrade

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1. The CMS pixel detector

The CMS detector is one of the large general purpose detectors in the Large Hadron Collider located near Geneva, Switzerland [1]. In the center of CMS is the pixel tracking system. There is a three layer barrel detector with a length of 56 cm and the innermost layer at a radius of 4.3 cm from the expected interaction. There are two disks at $z = \pm 34.5$ and $z = \pm 46.5$ cm on each side of the interaction region. The pixels have a size of $100 \mu\text{m} \times 150 \mu\text{m}$. There are approximately 66 million pixels in the system[2]. The pixel detector was installed into CMS in 2008, was commissioned with cosmic rays, and has been used to take collision data. The detector is performing well and meets design expectations[3].

The LHC run plan currently includes running at a center of mass energy of 7 TeV through 2011. After a shut down to prepare the machine for running at a center of mass energy of 14 TeV in 2012, there will be an extended run from 2013-2015 with the expected maximum instantaneous luminosity to be below $10^{34} \text{cm}^{-2} \text{s}^{-1}$. Then another shutdown is planned for 2016 before the so called "Phase I" run which starts around 2017 and continues past 2020. The expected center of mass energy will be 14 TeV and the peak luminosity will be $1 - 2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. Before the 2016 shutdown, it is anticipated that the integrated luminosity that CMS will receive is 30fb^{-1} .

The CMS pixel detector is a first generation hybrid pixel detector that was designed over 10 years ago. The detector will perform excellently for the first few years of LHC running. However, it has always been foreseen that there would be a replacement needed to upgrade the performance and replace radiation damaged components. The detector was designed so that it can be extracted independent of the beam pipe and strip tracker and replaced in a "few months" time frame. Improved

physics performance of the tracking system with the ultimate gain of improving the b quark jet finding is the main goal for a replacement pixel detector. To accomplish this, there are four intermediate goals: reduce the material, reduce the dead time from the readout chip as the luminosity increases, increase the geometric acceptance for 3 pixel hits, and replace the sensors to decrease radiation damage.

A plan is now in place to replace the entire pixel detector during the 2016 shutdown with a four layer barrel, 3 end disk detector which focusses on the intermediate goals mentioned. The new layout of the CMS pixel detector is shown in Figure 1. The innermost layer will reside at 3.9 cm in radius. The addition of the fourth layer at a radius of 16 cm and a third disk significantly improves pattern recognition in the higher occupancy environment of the upgraded LHC and it provides a safety factor if the first silicon strip layer of the Tracker Inner Barrel (TIB) degrades more rapidly than expected. As the time scale for producing the detector as well as commissioning the detector after it is installed is not long, a complete redesign is not called for. Reusing as much of the readout chain as possible is desirable. The upgraded detector must also re-use the existing cooling, power, and readout services. For simplicity, the barrel and forward pixel detectors will use a common module with 16 readout chips in a 2×8 arrangement.

The services (including cables, cooling lines, printed circuit boards) and mechanical support structure for the current pixel detector introduce a non-negligible amount of material in the tracking volume which in turn reduces the track reconstruction efficiency and degrades the impact parameter resolution. The new design calls for ultra light mechanics to reduce the material which will include CO_2 cooling instead of the present C_6F_{14} system. Bi-phase CO_2 cooling will use very small diameter stainless steel pipes with long cooling loops (2-3 m) instead of the large diameter parallel cooling pipes and manifold with the present system which reside in front of the pixel disks in the tracking region. Further material reduction will be achieved by

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Figure 1: Schematic view of the four layer, three end disk upgrade layout.

using longer micro-twisted pair cables to carry the signals to the optical hybrid boards which will be moved out of the tracking region. A carbon fiber prototype barrel support structure has been manufactured for the first layer of the barrel. For the forward disks, there will be outer and inner rings that can be assembled so that the inner rings can be replaced if necessary. The separation of each half disk into an inner and outer assembly enables the tilting of the sensors to obtain the best resolution in both the r and ϕ directions.

The current readout chip is the PSI46 chip made in the $0.25\mu\text{m}$ process which reads out 52 by 80 pixels and was designed for a maximum luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. This chip is well understood and tested, however with a first level trigger rate of 100 kHz and a luminosity of $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, there is a 16% data loss expected due to column drain and readout dead-times. There is enough room to make a new readout chip using the $0.25\mu\text{m}$ process with larger buffers. An increased bandwidth transmitted per fiber is needed as there are approximately 60% more modules. The plan is to switch from analog to a more robust signal by providing digital readout (with an on-chip ADC) from the readout chip to the Token Bit Manager (TBM) chip at 160 MHz. The multiplexing TBM chip will combine two token rings from a module into a 320 Mbps digital link. Because of the increase in the number of chips readout with the additional detectors, and the limits on the number of cables, the 320 Mbps digital readout is necessary.

The tracking performance and efficiency of the high level tracking trigger can be improved if the geometric acceptance for having at least three pixel layers with hits (three-hit coverage) is better. Presently, there are 10-15% inefficiencies in the region with $|\eta| < 1.5$ which slows the full tracking algorithm. The upgrade plans call for a 4 barrel layer, 3 disk geometry allowing one to have three pixel layers hit over the full detector coverage area. Adding a fourth layer at a radius of 16 cm also allows a smaller extrapolation uncertainty between the pixel track segments and the strip tracker segments which have the innermost layer at 25.5 cm.

The sensors for the current pixel detector are made of n sub-

strates with n+ implants. As the pixel layers are very close to the interaction point, they will have to endure high particle fluences. The expected fluence per year for the innermost layer at the design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ is $3 \times 10^{14}n_{eq}/\text{cm}^2$ [4]. Expectations are that the track resolution and the efficiency of the detector will degrade slowly with irradiation. However, as the sensors collect electrons, after radiation-induced space charge sign inversion, the detector can be still be read out and there is a higher charge collection efficiency. Studies of both the barrel and forward sensors after irradiation have shown there is still sufficient charge after fluences above $10^{15}n_{eq}/\text{cm}^2$ [5, 6]. Because of the short timescale for producing a replacement, and as there are not other good options, the plan is to continue to use similar sensors to the present. As the inner layer may deteriorate before the end of the planned running time, the mechanical design allows the inner layer to be replaced separately.

Care has been taken to change as few components as possible. The readout chip, module controller chip, and the receivers for the front end electronics boards will change. There will be new digital optical receivers needed to read out the signals from the fibers on the VME Front End Driver board. A new daughtercard is being prototyped. The control and monitoring electronics will not change. This part of the system includes the fast control links at 40 MHz, the trigger, and the fast I^2C communications.

As the number of optical readout fibers remains the same but reading out more modules, the services that come in to the detector via the supply tube are complex. The optical hybrids will be moved out of the tracking volume as much as possible on the supply tube. Power considerations are an issue so low power operating links have been prototyped that operate using a differential voltage level of only 20mV. These have been found to consume only 1.2 mW per link[7]. To limit resistive power loss on the approximately 50 m long cables from the support cavern to the supply tube, a new powering scheme is being developed. In the support cavern, the supply is at a higher voltage with low current until the supply tube, where DC to DC buck converters will be used to convert the input voltages to those needed for operation. A new high efficiency ASIC converter which is tolerant of high radiation and high magnetic fields is being developed. A schematic showing the new barrel supply tube is shown in Figure 2.

The upgraded detector can be compared with the present detector on the intermediate goals set. The new barrel pixel detector, despite having 4 layers instead of 3 is estimated to weigh 2.4 times less, while the material in the forward disks has been reduced by 40%. Figure 3 shows the radiation length for each of the barrel and forward disk new and present detectors. This mass reduction reduces the photon conversion and electron bremsstrahlung probability which in turn enhances electron tracking. For example, the probability for a photon at $|\eta| = 1.5$ to convert to an electron-positron pair inside the pixel volume is 11% with the upgraded detector compared to 22% with the present detector. The resolution of the longitudinal and transverse impact parameters are significantly improved.

With the increased readout buffer sizes and improved chip architecture for the readout chip, simulations show that for the

Figure 2: Schematic drawing showing the new barrel supply tube with the location of the optical hybrids and DC to DC power converters.

Figure 3: Radiation length as a function of η of the barrel (top) and forward (bottom) pixel detectors. The dots represent the present detector while the histogram shows the proposed upgrade.

Figure 4: Comparison of the tracking efficiency (top) and fake track rate (bottom) as functions of pseudorapidity after requiring a minimum of three hits for the current (blue squares) and upgraded (red triangles) detectors. The instantaneous luminosity is assumed to be $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with 25 ns bunch spacing.

innermost layer at 3.9 cm, the peak inefficiency at a luminosity of $2^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is about 4.7% as compared to 16% for the present chip. The 320 Mbps readout over the optical fibers will provide three times the throughput of the existing analog links on the same fiber with a reduced power consumption.

The extra layers added have dramatically improved the efficiency and resolution of pixel only tracks which are a crucial part of the high level trigger and which seed the full tracking. The seeding efficiency has improved by 8% for $|\eta| < 1$. Fake tracks are also dramatically reduced (by about a factor of 20 in the central region). The efficiency and resolution enhancements lead to improved primary and secondary vertexing which is essential for associating the final state particles with correct primary vertex. Figure 4 shows the tracking efficiency and fake track rate.

The improvements in tracking efficiency, fake rate, param-

Figure 5: The b quark efficiency of the Combined Secondary Vertex Tag is plotted versus the light quark (and gluon) efficiency for a sample of dijet and multijet events of transverse momenta in the range 80-120 GeV/c. The upper curve (black points) represents the performance of the current tracker and the lower curve (red points) represents the performance of the Phase 1 upgrade. The instantaneous luminosity is assumed to be $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with 25 ns bunch spacing.

eter resolution, and vertexing all contribute to significant improvements in the b -tagging performance of the tracker. Full simulation results of the expected improvement in b jet tagging are shown in Figure 5. The plot shows that the higher the b jet efficiency is, the higher the light jet efficiency is. For the upgraded detector, for an expected b jet efficiency of 60%, the fake b jets will be reduced by a factor of 6 compared to the present detector.

In summary, the first phase upgrade of the LHC starting with a long shutdown in 2016 presents CMS with the opportunity to upgrade the pixel detector. The expected conditions after 2016 are a factor of 2-4 more intense than what was assumed for the design of the present detector. The design is proposed for an upgraded pixel detector with four barrel layers and 3 disks on each end. This new detector will have substantially reduced material and will enhance the robustness and efficiency of tracking. A revision of the readout chip and the change from 40 MHz analog to 320 Mbps digital readout will provide the necessary bandwidth for the larger system using the same number of readout fibers. The tracking and b -tagging performance has been shown to enhance the physics capability of CMS.

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