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Development of the CMS Phase-1 Pixel Online Monitoring System and the Evolution of Pixel Leakage Current

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Abstract

A new pixel online monitoring system has been developed to give a fast and intuitive view of the detector performance both offline and online. The source script was written modularly in Python programming language in association with the SQLite and Java languages. It establishes a connection with the CMS detector monitoring database, and extracts and stores detector information into a local database. Among all of the monitored detector parameters, the pixel leakage current is one of the most interesting, as it reflects the accumulated radiation damage of the silicon sensors. The leakage currents obtained from different module positions in the pixel detector are highly correlated with the distance from the beam pipe. Based on the new monitoring system, we have analyzed the pixel detector leakage current evolution since the recent Phase-1 upgrade of the pixel detector and its dependence on the environmental temperature influenced by the cooling loop arrangement inside the pixel detector. The results provide a crucial reference on the detector performance for the re-design of the detector in the Phase-2 upgrade.

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ABSTRACT: A new pixel online monitoring system has been developed to give a fast and intuitive view of the detector performance both offline and online. The source script was written modularly in Python programming language in association with the SQLite and Java languages. It establishes a connection with the CMS detector monitoring database, and extracts and stores detector information into a local database. Among all of the monitored detector parameters, the pixel leakage current is one of the most interesting, as it reflects the accumulated radiation damage of the silicon sensors. The leakage currents obtained from different module positions in the pixel detector are highly correlated with the distance from the beam pipe. Based on the new monitoring system, we have analyzed the pixel detector leakage current evolution since the recent Phase-1 upgrade of the pixel detector and its dependence on the environmental temperature influenced by the cooling loop arrangement inside the pixel detector. The results provide a crucial reference on the detector performance for the re-design of the detector in the Phase-2 upgrade.

KEYWORDS: Performance of High Energy Physics Detectors; Detector cooling and thermo-stabilization; Simulation methods and programs; Software architectures (event data models, frameworks and databases)

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1 Introduction

The Compact Muon Solenoid (CMS) detector has collected proton-proton collisions at the Large Hadron Collider at 13 TeV corresponding to an integrated luminosity of nearly 120 fb^{-1} . The Phase-1 pixel detector, which is the inner part of the CMS silicon tracking system and which starts at a distance of radius only 2.9 cm from the beam pipe, has been operated successfully for two years since 2017. It has a high granularity and gives a fast response to the particles coming from the beam collisions. It provides high resolution for particle track reconstruction. Figure 1 shows the schematics of the Phase-1 pixel detector, which is partitioned into a pixel barrel (BPix) and two pixel endcaps (FPix). The pixel barrel consists of four concentric layers of pixel modules. Each pixel endcap has three disks, each of which is made of two concentric rings of pixel modules. In total, there are 124 million pixels.

Figure 2 describes the sub-division of the pixel detector into coordinates which relate to the layout of the LHC ring and which are useful for the following sections.

2 Pixel online monitoring system

In order to keep the detector under good control, a comprehensive monitoring system is indispensable. Before 2018, the old version of the monitoring system for the pixel detector was difficult to use for systematic analyses on the detector parameter correlations, since it required many steps of manual selections on the operational menu. In order to solve this problem, a new monitoring system was developed to have a much easier access and quicker overview of the detector parameters, including correlations among them. The core script of the new monitoring tool was written in the Python [2] language with other parts written in Java [3] and using an SQLite [4] database as backend. It establishes a connection with the CMS detector monitoring database, and extracts the detector information to store into a local database. One of its merits is automatically producing

Figure 1. LEFT: schematics of CMS Phase-1 pixel detector. It is partitioned into a pixel barrel (BPix) and two pixel endcaps (FPix). The pixel barrel consists of four concentric layers made of arrays of ladders, in which the pixel modules are installed. One pixel endcap has three disks, and each disk is made of two concentric rings. Each ring has several arrays of blades with modules on so-called panels. RIGHT: BPix cross section showing the facet arrangement in the four detector layers. Figure taken from [1].

Figure 2. Schematics of the sub-division of a layer in BPix (a disk ring in FPix) in the LHC ring coordinates. Each layer of BPix (Each disk ring of FPix) is made of four half cylinders, which are located at the inner side $+z$ end (BpI), inner side $-z$ end (BmI), outer side $+z$ end (BpO), and outer side $-z$ end (BmO), respectively.

overview plots of pixel detector parameters during a default period with few manual clicks on the interface. Users can also customize the plot settings and have them immediately shown on the interface by accessing the data pre-collected in the local database.

The monitoring interface is a website for different categories of parameters, which are summarized partially in table 1. The function of this tool is centralizing and correlating these parameters.

Table 1. List of example parameters monitored by the pixel online monitoring system.

Environment variables	Detector parameters	Detector run property
Dew point	Power supply voltage	Luminosity
Air pressure	Power group current	Run status
Air temperature	Module temperature	Data acquisition status
Humidity	Cooling flow status	Data quality monitor
...	...	...

Figure 3 is an example plot produced by the monitoring interface, showing the overall leakage current of a group of modules and the instantaneous luminosity of proton-proton collisions at the same time. The leakage current is decreasing when the instantaneous luminosity is dropping due to the module temperature decreasing.

Figure 3. The instantaneous luminosity of proton-proton collisions during an LHC fill (blue), and the leakage currents of modules which are connected to one power sector (sector 1) in layer 3 of BPix (orange).

Figure 4 is another example plot produced by the monitoring tool. This plot shows the pixel module occupancy in layer 4 of BPix during ten minutes of proton-proton collisions in 2018. There are several modules with zero hits (marked red) due to power or electronics related issues, which are also recorded in a dedicated database. The problem recording is helpful for subsequent monitoring and analyses on these problematic units among other normal ones.

Figure 4. Pixel module digital occupancy in BPix layer 4. The four quadrant blocks represent the four half cylinders (see figure 2). Each half cylinder consists of 32 ladders, and each ladder has four modules installed. Each module contains 16 readout chips, which correspond to the colored bins. The red rectangles indicate known problems recorded in a database associated to the module occupancy.

3 Cooling loop & temperature distributions

Since 2017, CO_2 is used for the pixel detector as coolant. Its advantages are low density, excellent thermodynamical properties, and smaller impact on environment compared to C_6F_{14} cooling. Liquified CO_2 is supplied from the cooling plant to the pixel detector. When CO_2 enters the detector, it reaches a 2-phase state and starts to evaporate. The cooling loop schematics of the pixel detector are illustrated in figure 5. Each cooling loop is equipped with three temperature readout probes, which are located at the inlet, center, and outlet of the cooling loop, respectively. CO_2 becomes a mixture of vapor and liquid when it is going through a cooling loop. As the ratio of vapor to liquid is increasing, the heat exchange between the CO_2 and its surrounding becomes more efficient, which makes the temperature drop from upstream to downstream of the cooling loop. An example of this is shown in figure 6 (left). The temperature is higher during data taking with proton-proton collisions than during data taking with triggers on cosmic muons, as in the former more heat is dissipated by the readout chips because of higher hit rates in the silicon sensors. If the CO_2 flow rate decreases (must be above certain level), the heat exchange becomes more efficient, leading to a lower temperature (figure 6 (right)).

Figure 5. Cooling loop schematics of the pixel barrel. As represented by the colored curves, there are 4 cooling loops respectively in layer 1 and 2, and 8 cooling loops respectively in layer 3 and 4. The arrows of each curve stand for the direction of the coolant flow. The red curves are the cooling pipes entering and exiting from the same z end as viewed, while the blue curves are the cooling pipes entering and exiting from the other z end. Each cooling loop cools down the full barrel length over a given azimuthal range. Figure is taken from [1].

4 Leakage current distribution & temperature correction

The leakage current is an important parameter to characterize the silicon sensors, since it reflects radiation damage level of silicon sensors. For the pixel detector, the leakage current of a silicon sensor also highly depends on the cooling loop layout that affects the temperature distribution along the silicon sensors. As shown in figure 7, a temperature gradient along a cooling loop also gives rise to a leakage current gradient. Modules close to the outlet pipes have lower leakage current than those close to the inlet pipes, because the temperature in the outlet region is lower than that of the inlet part (cf. section 3).

Figure 6. LEFT: during a proton-proton collision period, 20 minutes after stable proton beams were established, temperature measured by the probes of four cooling loops in BPix layer 2. Inlet is at the beginning of a cooling loop, outlet is at the end of a cooling loop. RIGHT: during a data-taking with only cosmic rays, temperature distribution along each cooling loop (black arrows) for a given azimuthal range (ϕ) in BPix layer 2, for the comparing of three different coolant flow rates (g/s). The ϕ coordinate yields the structure shown in figure 5.

Figure 7. Averaged module leakage current in unfolded BPix layer 2. Four half cylinders are respectively in the four quadrants. The bigger arrows correspond to the directions of the coolant flow in four cooling loops. The ones pointing into the blocks are inlet cooling pipes, while the other pointing out of the blocks are outlet cooling pipes. Each smaller arrow with a dotted line shows the path of a cooling loop.

Because the temperature probes in BPix layer 2 are not attached to the modules, the temperatures measured by these probes may not reflect accurately the temperature of the silicon sensors. In order to better understand the temperature spread within a layer of the pixel barrel and to have a better handle on the temperature of the individual silicon modules, a thermal mockup [5] was built, as shown in figure 8, which can emulate the thermal property of BPix layer 2. Its shape is the same as a half shell of BPix layer 2. Its silicon sensors and cooling loops are also placed as in the detector.

The sensors are dummy sensors mainly to have the correct thermal properties, and each module has a heater to emulate readout chip heating, and is equipped with a temperature probe, which can measure precisely the silicon sensor temperature. In order to compare the leakage currents of different silicon sensors that have suffered the same irradiation but have a different temperature, one needs to correct the measured leakage current of each silicon module to a common reference temperature. This can be done using formula 4.1, where I_0 is the measured sensor leakage current at a certain temperature, while I is the re-scaled leakage current at the reference temperature. T_0 and T are the measured temperature of a silicon sensor and the reference temperature, respectively. k_B is Boltzmann constant. ΔE is the activation energy for dissociation or migration in silicon sensors. Based on the temperature measured in the mockup, the correction factors derived using the formula are shown in figure 9, in which the reference temperature is the coolant temperature (-22°C).

$$\frac{I}{I_0} = \frac{T^2}{T_0^2} \exp \left[-\frac{\Delta E}{2k_B} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right] \quad (4.1)$$

Figure 8. Side view of the pixel thermal mockup.

Figure 9. Leakage current correction factor dependence on silicon sensor temperature measured in the thermal mockup.

5 Leakage current evolution & simulation

Due to the accumulated radiation damage, the pixel module leakage current gradually increases. Depending on the distance from the beam pipe, different pixel layers or rings receive different radiation doses. Figure 10 shows the module leakage current evolution in both BPix and FPix during the full operation time of the Phase-1 pixel detector. The layers/rings closer to the beam pipe have higher module leakage currents. There are some drops of leakage currents due to annealing effects.

Figure 10. Evolution of the measured module leakage current as a function of the integrated luminosity for BPix (left) and FPix (right) during proton-proton collisions. Each value was taken 20 minutes after stable proton beams were established. The leakage current of each high voltage group is divided by the number of modules in the group, and then averaged among all the groups for each layer/ring. MD: Machine Development; TS: Technical Stop; YETS: Year-End Technical Stop.

In order to have a better understanding of the leakage current evolution, the so-called “Hamburg Model” [6] can be used to predict the leakage current of a silicon sensor taking into account the irradiation history, temperature and silicon parameters. The expected irradiation field is provided by the FLUKA tool [6]. Figure 11 shows the comparison between the simulated and measured leakage currents during the years of 2017 and 2018 when the Phase-1 pixel detector was in operation. Good agreement is seen within the systematic uncertainties.

6 Conclusion

A sophisticated monitoring system has been developed for the Phase-1 pixel detector, which allows to correlate different categories of detector parameters. By studying the temperature distribution in the detector, together with a thermal mockup, a detailed understanding of the cooling of the pixel detector has been achieved. A comprehensive study has been conducted on the correlation between sensor leakage current and temperature, and good agreement has been achieved between the simulated and measured sensor leakage current.

Figure 11. Comparison of the sensor leakage current evolution in BPix layer 1 and 2, between measurement and simulation during the whole Phase-1 pixel operation period. Each measured leakage current value is the average of all sensors and averaged over a day. The coolant temperature is -22°C . The simulation was performed using the “Hamburg Model”. Radiation-induced increase of leakage current depends on fluence, time, temperature, the sensor volume.

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