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Operational Experience with the CMS Pixel Detector

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The CMS pixel detector consists of 15840 readout chips, containing a total of almost 66 million pixels. In this paper, I describe the preparation for the first data-taking with LHC beams, in which the performance of the readout chips was optimized using a suite of calibrations. The detector thresholds have been adjusted to be less than 3000 electrons, and the effect of timing on the thresholds has been studied. After the arrival of LHC beam in December of 2009, the timing of the detector was optimized to achieve maximum efficiency, using both online and offline analysis. I will also discuss the challenges presented by beam backgrounds.

1. Introduction

The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN is a general-purpose detector for particle physics [1]. The pixel detector is the innermost subdetector, and is thus critical for tracking and vertexing in the high-multiplicity environment of the LHC. It is also subjected to the highest levels of backgrounds from stray particles due to the beams.

The pixel detector consists of a three layer barrel (BPix) and an endcap of two disks at each end (FPix). This arrangement provides three hits for $|\eta| < 2.4$ [2].

The silicon sensors are bump-bonded to readout chips (ROCs), each divided into 26 double columns of 80 rows for a total of 4160 pixels. 26 DAC settings are available to tune performance on a ROC-by-ROC basis. Zero suppression is performed on the ROC, with a threshold that is controllable at the pixel level. Data is buffered on the ROC until the arrival of a trigger [3].

The detector control and readout is performed via several VME components located in the counting room [4]. Of particular interest are the Front End Drivers (FEDs), which take the data from the detector, decode it, and send it to the CMS central data acquisition (DAQ) system [5].

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2. Preparation for beams

Because the performance of the ROC is highly customizable via both DAC settings and individual pixel thresholds, in 2009 a substantial effort was undertaken to optimize the settings. The key measure of ROC performance is the absolute threshold. We aimed to reduce the threshold to the minimum possible for each ROC independently. As shown in Fig. 1, the average ROC threshold is about 2460 electrons.

The absolute threshold is the minimum amount of charge that must be deposited in the sensor to create a hit in the ROC. However, the ROC has a readout window of only one LHC bunch crossing (25 ns). Low signals, just above the threshold, have a slower risetime and thus do not go over threshold until a subsequent bunch crossing, a phenomenon known as "time walk." Because of this effect, the effective threshold to leave a hit in the correct bunch crossing is somewhat higher than the absolute threshold. This "in-time" threshold is the quantity relevant for determining the detector's physics performance.

The difference between the absolute and in-time thresholds can be adjusted by changing the `Vana` DAC setting, which controls a voltage regulator on the analog portion of the ROC. Higher DAC settings result in a smaller difference between the two thresholds, at the expense of drawing more current from the power supply. This setting was adjusted so that the in-time thresh-

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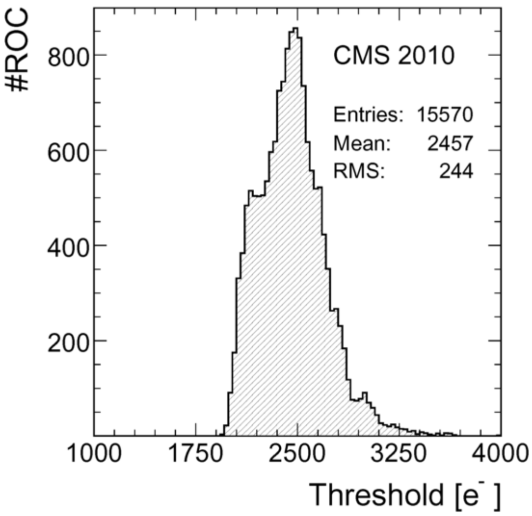

Figure 1. The mean ROC threshold, measured in late 2009.

old is about 800 electrons higher than the absolute threshold, which corresponds to an analog current of about 25 mA per ROC.

3. Operations with beams

3.1. Fine delay scans

Because of the one bunch crossing readout window, the timing of the pixel detector readout must be carefully adjusted with respect to the clock signal from the LHC. This adjustment can only be made with collision data. A typical particle traversing the detector leaves a cluster of pixel hits, consisting of central pixels with large charge deposits, and neighboring pixels with small charge deposits. For maximum efficiency, the pixels with large charge deposits must be read out in the correct bunch crossing. The resolution is improved if neighboring pixels can also be readout in the correct bunch crossing.

A preliminary scan of fine delay settings, in 6 ns increments, was made in December 2009 during the first significant fill with collisions. A preliminary evaluation of the scan points was made using the online data quality monitoring (DQM) tools.

An example real-time observable in DQM is the cluster charge distribution. If the data is read too late, then pixels with a large charge deposit will have already gone over threshold in the previous bunch crossing. The cluster charge distribution will be strongly biased towards low values. If the readout is too early, then the efficiency for low-charge pixels will be low, reducing the cluster charge slightly. Therefore, the optimal setting is the one that maximized the average cluster charge. At the luminosity of the initial LHC fill at 900 GeV, adequate statistics to determine a good delay setting were obtained after between 5 and 15 minutes at each delay setting.

Using this online DQM analysis, we determined that a delay setting of +6 ns would provide optimal efficiency. This result was then confirmed using an offline analysis.

A higher-statistics scan, with delay settings adjusted in 2 ns increments, was performed early in the 7 TeV running in 2010. Analysis to measure the hit efficiency was performed offline. This analysis also allowed for evaluation of the intradetector timing. Figure 2 shows the results averaged over layers of the BPix and disks of the FPix. To achieve the best possible resolution while maintaining a high efficiency, we adjusted the fine delay setting to +10 ns (+8 ns) for the BPix (FPix). We also corrected the timing of individual control groups of the detector that were found to differ from the global timing.

3.2. Beam backgrounds

Although beam backgrounds have not posed a threat to detector safety at this point, they have presented a challenge for the pixel DAQ system. Interactions with residual gas in the beam pipe creates showers of particles that pass through the pixel detector volume nearly parallel to the beam. As shown in Fig. 3, these particles can leave long tracks in contiguous sections of the BPix.

If more than 192 hits are received on one FED channel (one optical fiber from the detector to the FED) for a trigger, the FED raises an error flag and stops reading the hits on the channel. How-

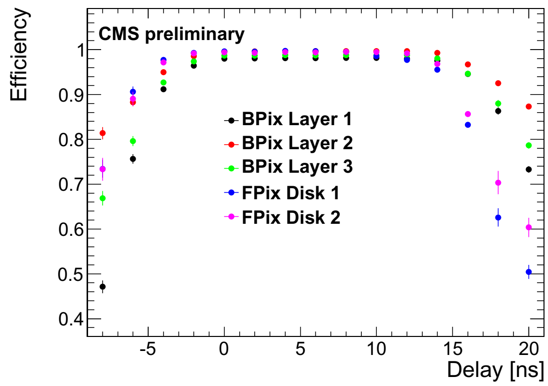

Figure 2. Hit efficiency as a function of fine delay setting.

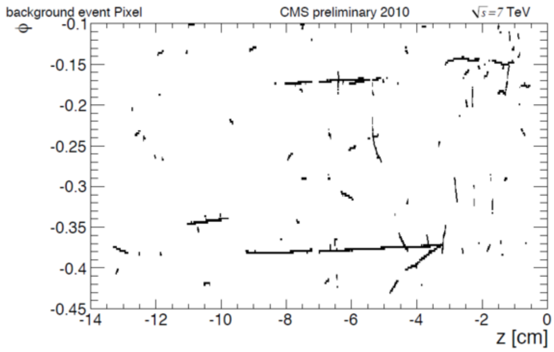

Figure 3. Hits in the barrel pixel detector from a beam background event.

ever, the ROCs continue to send data for that trigger until all hits have been sent. For background events with many hits concentrated in a small region of the detector, the data flow can continue for some time. If another trigger arrives while data from the previous trigger is still coming, the FED waits up to 80 bunch crossings for the new event to arrive. If this time passes without the event header arriving, that FED channel will go out of synchronization.

To cope with this problem, a counting mechanism was implemented in the FED firmware to track this loss of synchronization and automatically resynchronize after the data from the large event has finished arriving. To facilitate this, if a FED channel falls too far behind, the FED raises a "Busy" flag to the CMS trigger system. This stops triggers and allows the FED to recover. This mechanism has been found to be effective, and generates a deadtime of less than 1%.

4. Conclusions

Before the start of LHC operations, the CMS pixel detector performance was optimized by adjusting ROC settings and measuring the detector thresholds. The average readout threshold is 2460 electrons. During the initial beam running, delay scans were performed to ensure optimal detector efficiency and resolution. Finally, we have faced problems in the readout system caused by large beam background events. These have been addressed with firmware modification in the readout hardware. The CMS pixel detector is now collecting LHC data and playing a critical role in physics analyses.

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