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Cosmic Ray Study of the CMS Pixel Tracker

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Abstract

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On behalf of the CMS collaboration

Abstract—The pixel detector of the Compact Muon Solenoid (CMS) experiment consists of three barrel layers and two endcap disks at each side of the barrel section. The detector was installed in summer 2008, commissioned with the readout chip internal pulse generator, and used in cosmic ray trigger data taking in a 3.8 T magnetic field. Despite the excellent detector performance some problems arose after installation. In about a year we went through a complete and important sequence of steps that go from the insertion of the detector in CMS, calibration, running, extraction, maintenance, to the re-insertion, re-calibration and final running. In this paper a summary of the knowledge acquired during the first year of running will be presented. Currently 98.6% of the whole pixel detector is fully functional and results on detector performance are found to be in line with the design specifications.

I. INTRODUCTION

THE CMS experiment [1] is designed to explore physics at the TeV energy scale exploiting the proton-proton collisions delivered by the Large Hadron Collider (LHC) [2]. The new energy frontier that is going to be attained by LHC requires the experiments to gather as much information as possible from each collision. To achieve such a challenging goal in the innermost, radiation hostile region, the high-precision and low-background tracking of CMS is based on the pixel detector. Installed in July 2008, it is a key component for reconstructing interaction vertices and detached heavy quark decays. The 66 M channels pixel detector is operated in a 3.8 T magnetic field and is composed by (see Fig. 1) three barrel layers (BPix) at r of 4.3, 7.2 and 11 cm with a total of ~ 48 million channels, read out by 11520 ReadOut Chips (ROCs), and four endcap disks (FPix) at z of ± 34.5 and ± 46.5 cm with a total of ~ 18 million channels, read out by 4320 ROCs. The pixel cell size of $150 \times 100 \mu\text{m}^2$ implies a maximum occupancy of $\sim 0.033\%$ at full LHC luminosity. The design allows for three pixel hits per track up to $|\eta|$ of ~ 2.1 ; providing:

- seeds for pattern recognition;
- precision vertexing near the Interaction Point (IP);
- fast tracking and vertexing in the High Level Trigger (HLT) using only the pixel information [3].

The ROCs are made in $0.25 \mu\text{m}$ CMOS radiation tolerant technology [4]. They are clocked with a 40 MHz clock and the average power consumption per chip is ~ 140 mW. The 80×52 pixel cells of a ROC are organized in double columns with buffers for data and timestamps, 32 and 12 word depth respectively. The readout is analog with zero suppression

Fig. 1. The CMS pixel detector is composed by three barrel layers and four endcap disks.

Fig. 2. Analog output of the pixel frontend electronics. On the left: ROC analog signal as seen at the oscilloscope. On the right: histogram of the level separation, in units of sigma, after digitization using the 10 bit ADC.

performed by a pixel-cell by pixel-cell adjustable threshold. In the 40 MHz analogue data packet (see Fig. 2), six clock cycles encode each hit pixel: the address is encoded with a discrete six-level scheme over five clock cycles, and the sixth clock cycle gives the pixel charge. The backend electronics digitize and record the data packets, and an FPGA firmware decodes the address for each pixel hit.

The sensors are n -on- n type with a p -spray isolation for BPix and with a partial open p -stop isolation for FPix [5]. The sensors are connected to the ROCs using In and $PbSn$ bump-bonds for BPix and FPix respectively. BPix and FPix have good resolution thanks to an average hit cluster size greater than one. BPix has an average hit cluster size of 2 in $r - \phi$ thanks to the large Lorentz angle and a cluster size between 1 and 7 in z , depending on the transverse incidence angle. FPix, with a turbine geometry with a tilt angle of 20° , presents an average hit cluster size of 2 both along r and $r - \phi$, thanks to the Lorentz drift in the former case and to the non-zero incident angle in the latter. The sensor bulk width is $\sim 285 \mu\text{m}$ and $\sim 270 \mu\text{m}$ for BPix and FPix respectively, which implies, for a non irradiated sensor, a Landau most probable value of $\sim 22,000$ electrons for a minimum ionizing particle.

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Fig. 3. Ratio of the charge integrated with an unirradiated and irradiated sensors as function of the square root of the bias voltage. The unirradiated sensor is operated at a bias voltage of 150 V (see [6]).

The sensors have been irradiated up to $12 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ (corresponding to ~ 4.5 years of CMS at full LHC luminosity for the innermost barrel layer). At this fluence the breakdown voltage is still above 600 V, the particle detection efficiency is still greater than 90%, but the collected charge drops to $\sim 50\%$, see Fig. 3. At this value of collected charge the detector might become no longer effective for impact parameter measurement, but it is still effective for seeding.

Despite the excellent detector performance during the production and assembly phases ($\sim 99.5\%$ and $\sim 100\%$ of good channels in BPix and FPix respectively) some problems arose after the installation and caused the loss of about 0.5% of the BPix detector and 6% of the FPix detector channels. Thanks to the modularity of CMS we decided to take advantage from the long shutdown and repair the broken parts and make some specific interventions to improve the robustness and stability of the FPix detector against the coolant pressure and temperature fluctuations.

II. DETECTOR CALIBRATIONS AND STATUS

The pixel data acquisition system is described in more detail in Ref. [7]. In this section it will be presented the results of linearization and characterization of the ADC to charge response, the threshold distributions, the average noise and the overall detector status.

A. ADC to charge response

Conversion of pixel charge measurements in ADC counts to charge units requires calibration of the net response function of the pixel readout chain. This calibration is essential to achieve a precise hit position, as the cluster position is interpolated using the charge information from all pixels in the cluster. The most probable charge deposition for normally incident minimum ionizing tracks is approximately 22,000 electrons. This charge is frequently deposited over more than one pixel due to the Lorentz drift and variation of impact angles. For each pixel the pulse height response in the ADC to a given amount of collected charge is measured using the charge injection feature of the ROC. For each chip, a DAC (VCAL) controls the amount of charge injection on each ROC in two overlapping ranges, covering the expected dynamic range for

Fig. 4. First plot: example of the ADC response as a function of injected charge in VCAL units (~ 65.5 electrons) for one pixel. Second plot: distribution of gains for all pixels. Third plot: distribution of pedestals for all pixels.

TABLE I
MEAN NOISE AND MEAN THRESHOLD OF THE WHOLE PIXEL DETECTOR

	Mean noise	RMS
Pixel barrel	141 e^-	35 e^-
Pixel endcap	85 e^-	26 e^-
	Mean threshold	RMS
Pixel barrel	3829 e^-	416 e^-
Pixel endcap	2941 e^-	237 e^-

pixel hits, from 2,000-30,000 electrons. The calibration of the internally injected charge was obtained using a spare BPix module and X-ray sources of known energies. From these data we determine an average of 65.5 electrons per VCAL unit. There is a pixel-to-pixel variation of order 15% for the injected charge as a function of the VCAL DAC, consistent with typical systematic variation of the charge-injection capacitors in each pixel cell. The average charge injection calibration is used for all pixels in the detector, recognizing at present a 15% systematic uncertainty on the calibration of the charge injection circuit. This can be reduced in principle using isolated tracks in collision data. The response is linearized by tuning some ROC parameters up to about 45,000 electrons, and the data are fit with a linear function in the low-charge region (see Fig. 4). The gain and pedestal parameters correspond to the inverse of the slope and intercept, respectively, and their distribution is given in Fig. 4 for the 2008 data taking. The tail in the pedestal distribution is due to unoptimized frontend parameters in some ROCs.

B. Threshold and noise distributions

The thresholds are controlled at pixel level using two 8-bit DACs per ROC plus one 4-bit trim value per pixel. As thresholds decrease, hit rates increase and increase very sharply when reaching the level where internal ROC readout induces cross talk. The minimum threshold is set by the most sensitive pixel on each chip. The readout thresholds and noise are measured by means of threshold scans. The threshold is the value of injected charge where the efficiency is 50%. The noise is measured as the RMS of the curve.

Figure 5 shows the distribution of the mean threshold per ROC in the barrel and endcap detectors. The overall average thresholds are found to be 3829 and 2941 electrons, for BPix and FPix, respectively (see Tab. I).

The mean noise is 141 and 85 electrons, for BPix and FPix, respectively. The noise levels are well below operating

Fig. 5. Distribution of ROC-mean threshold in the endcap and barrel detectors.

thresholds, which must be set above cross-talk levels. It should be noted that this noise represents the contribution from the frontend ROC only. The remainder of the readout chain (amplifiers, laser, and optical receiver) contributes an additional 300 electrons noise.

C. Overall status

In the BPix detector the number of dead pixels on otherwise functional ROCs is very low, 0.01%, and consistent with the fraction of faulty bump bond connections between the ROC and sensor observed during module testing. The net inefficiency due to defective connections or hardware is less than 1%. In the FPix detector the number of dead pixels and faulty bump bonds, measured during construction, contribute less than 0.1%. The overall percentage of dead channels during 2008 data taking was 6%, thanks to the maintenance that took place in the winter 2009 we fixed the broken 5.5%, we also replaced the internal silicone tubes with more robust ones that can withstand higher pressure, we improved the stability of the analog electro-opto transducer temperature during operation and we improved the humidity monitor. The current detector status is: pixel barrel has $\sim 99\%$ of working channels; pixel endcap has $\sim 97\%$ of working channels (it's not at 99.5% because after re-insertion we experienced a bandwidth reduction on the analog output for some modules).

The overall number of noisy pixels is negligible, less than 0.5×10^5 (a pixel is marked as noisy when the ratio between the number of events in which a given pixel registers a charge above the programmed readout threshold and the total number of events taken is > 0.001).

It's worthwhile mentioning the improvement obtained in the the stability of the analog electro-opto transducer temperature during operation. During the 2008 data taking we observed high fluctuations of the analog baseline in the FPix channels, inducing wrong decoding of the analog signal by the backend ADC. The fluctuations are caused by the extreme temperature sensitivity of the analog electro-opto transducer. The solution to the problem was to link and lock, as much as possible,

Fig. 6. Picture of the “cold finger” made of Pyrolytic Graphite Sheets (PGS) applied to an electro-opto transducer. The PGS has the following properties: density $\sim 1 \text{ g/cm}^3$, thermal conductivity: 600-800 W/(m K) along the plane and 15 W/(m K) perpendicular to the plane.

Fig. 7. Analog baseline as a function of time before and after applying the “cold finger” made of Pyrolytic Graphite Sheets to the electro-opto transducers of the endcap pixel detector. Different colored lines correspond to different readout channels.

the analog electro-opto transducer temperature to the pipes temperature instead of the environmental temperature. We implemented a “cold finger” made of Pyrolytic Graphite Sheets (PGS), G10 and Kapton, see Fig.6 for an example of “cold finger”. The improvement of the performance are shown in Fig. 7 comparing the baseline fluctuations as a function of time before and after the maintenance.

III. COSMIC RAY DATA ANALYSIS

Approximately 85,000 tracks traversing the pixel detector volume were reconstructed with the Combinatorial Track Finder (CTF) algorithm in the 3.8 T field. For this set of tracks the average number of pixel hits is 3.01, for a total of about 257,000 clusters reconstructed in the pixel system. The precision of the detector position with respect to particle trajectories after track-based alignment has been derived from the distribution of the median of the cosmic muon track residuals measured in each sensor. The barrel precision is 3-4 μm RMS while the endcap precision is 14 μm RMS along both coordinates.

A. Charge distribution

Pixel clusters are formed from adjacent pixels with a charge above the readout threshold. Both side and corner adjacent pixels are included in the cluster and a cut of 5,000 electrons is applied to the total charge. The cluster is projected along the sensitive directions by summing the charge collected in the

Fig. 8. Charge distribution in kiloelectrons (ke) for clusters larger than one pixel measured with the barrel and endcap pixel detector in the first and second plot respectively. The data points show the measurement with cosmic rays and the solid line the simulation. The simulated distributions are corrected as described in the text.

pixels with the same coordinate. Residual charge miscalibration due to the pixel-to-pixel variation of the charge injection capacitor is modeled in the Montecarlo simulation.

Figure 8 shows the simulated and measured cluster charge corrected for the track incident angle. To emulate the acceptance expected from collisions, tracks with angles in the transverse plane larger than 12° from normal are excluded from the study. Clusters are required to include at least two pixels and those with edge pixels are excluded from the sample. Finally, events with more than one cluster in the same sensor are excluded. The angular distribution of reconstructed tracks was compared with the CMSGEN [8] predictions and found to be in good agreement. To derive the most probable cluster charge and the width of the cluster charge distribution, fits to a Landau function convoluted with a Gaussian function are performed. The distribution widths agree well with the simulation. The simulated charge peak is shifted by 900 and 1,200 electrons in the barrel and endcap region, respectively. The discrepancy can be attributed to the uncertainty on the scale factors applied during the charge calibration. The simulation predicts the charge from the deposited energy in the active region of the simulated sensor and the ionization energy of Silicon; there is no other scale factor or calibration.

B. Lorentz angle measurements

In the presence of combined electric and magnetic fields, the drift of the charge carriers is affected by the Lorentz force. In the case of n -on- n sensors electrons are collected at the n^+ pixel implant. The charges drift at an angle (Lorentz angle) relative to the direction of the electric field, which leads to charge sharing among neighboring pixels. The pixel hit reconstruction exploits this effect to improve the spatial resolution by interpolating the charge collected in a cluster. Once the interpolation is done the resulting position is adjusted to account for the Lorentz drift. Because the pixel barrel sensor planes are parallel to the magnetic field, the Lorentz drift is both maximal and in the azimuthal direction. The forward pixel sensors are deliberately rotated by 20 degrees with respect to the detector radial axes to produce a radial Lorentz drift and to increase azimuthal charge sharing.

The Lorentz angle extraction from the cosmic ray data is based on the cluster size method. The spread of the charge over neighboring pixels depends on the particle's incidence angle and has a minimum for tracks parallel to the drift

Fig. 9. Sketch of the track impact angles with respect to a pixel sensor (pixel cell dimensions not to scale). The axes represent the local coordinate system. The magnetic field vector is anti-parallel to the y axis for the barrel sensors and at 20° with respect to the z axis for the endcap sensors.

direction of the charge carriers. The Lorentz angle is extracted by finding the minimum of the mean cluster size along the local x coordinate measured as a function of the cotangent of the incidence angle α , as shown in Fig. 9. The fit function is given by:

$$f(\xi) = p_0 + \sqrt{p_1^2 + p_2^2(\xi - \xi_{min})^2}, \quad (1)$$

where $\xi = \cot(\alpha)$, ξ_{min} is the location of the function minimum and p_2 is independently fitted for ξ values larger and smaller than the function minimum.

Figure 10 shows the transverse cluster size as a function of $\cot(\alpha)$ in the barrel pixel detector with 3.8 T and no field, at sensor bias set to 100 V. The minimum, ξ_{min} , obtained for the data at 3.8 T is -0.462 ± 0.003 . The measured value corresponds to a Lorentz angle of $(24.8 \pm 0.2)^\circ$ and a shift of the transverse hit position of $65.9 \pm 0.5 \mu\text{m}$ for a $285 \mu\text{m}$ thick barrel sensor. Similarly, Fig. 10 shows the transverse cluster size as function of $\cot(\alpha)$ for the endcap section at bias set to 300 V. The minimum obtained with the 3.8 T field is -0.074 ± 0.005 . The measured value corresponds to a Lorentz angle of $(4.2 \pm 0.3)^\circ$ and a hit position shift of $9.9 \pm 0.7 \mu\text{m}$ for the $270 \mu\text{m}$ thick endcap sensors. The quoted uncertainty on the measurement is purely statistical. The systematic uncertainties on ξ_{min} related to the selection cuts and fit range are estimated to be approximately 3%. All results agree very well with detailed simulations performed with the PIXELAV program [9].

C. Hit detection efficiency

The hit reconstruction efficiency is measured by extrapolating tracks to the pixel sensors and checking the presence of a compatible hit. When the trajectory is projected to a given sensor, the tracking algorithm searches in a pre-defined window for a compatible hit. If one is found, it is added to the track and the trajectory is updated with the new information. In this case the hit is called valid. If no hit is found in the search window, a missing hit is added to the trajectory. The hit reconstruction efficiency is defined as:

$$\epsilon = \frac{\sum \text{valid}}{\sum (\text{valid} + \text{missing})} \quad (2)$$

Fig. 10. Cluster size along the local $r-\phi$ direction as a function of the impact angle measured in the barrel and endcap regions of the pixel detector in the first and second plot respectively. The circles correspond to the measurement with the 3.8 T field while the triangles correspond to the measurement without magnetic field. The dashed line shows the fit to the data points.

Statistics in the endcap region are not sufficient to perform this study. The module efficiency averaged over the modules in the barrel region is $96.6 \pm 3.9\%$, $93.6 \pm 17.3\%$ and $87.0 \pm 26.6\%$ in the first, second and third layer, respectively, where the statistical error is the RMS spread. The measured hit detection efficiencies after the cuts are about 3% lower than what is expected from test beam measurements [6]. The loss can be explained by random arrival times of cosmic rays with respect to the beam crossing clock and the time-walk effect giving different time stamps to high and low charge hits from the same track [4]. These effects are peculiar to data taking with cosmic ray particles and do not affect proton collisions where incoming particles are synchronized with the machine clock.

D. Hit residual and position resolution

The Silicon strip tracker and pixel detectors are spatially aligned using a sample of about 7 million cosmic tracks as described in Ref. [10]. After alignment the hit residuals are measured by refitting each track and comparing for each hit the track prediction and the reconstructed hit position. The measured hit is excluded from the track fit and only tracks with momentum larger than 10 GeV/c are taken. To exclude low charge pixels due to the time-walk effect, clusters of a single pixel are excluded if the cluster charge is below 10,000 electrons. In addition clusters are excluded if they are close to the sensor edges. The residual distributions are measured as a function of the impact angles and cluster charge and a Gaussian fit is performed in each bin. The contributions to the width of the residual distribution are the track extrapolation error, the detector intrinsic resolution and multiple scattering contribution. The track extrapolation error is the largest contribution and includes the uncertainties due to residual misalignment of the sensors used in the trajectory extrapolation with respect to the measured sensor. Figure 11 shows the width from the Gaussian fit of the residual distribution as a function of the α and β angles and total cluster charge (see Fig. 9). For tracks normal to the sensor plane the Gaussian sigma is about $30 \mu\text{m}$ and $65 \mu\text{m}$ along the local x and y coordinates, respectively. The width strongly depends on the cluster charge and impact angles.

Fig. 11. Pixel hit residuals as function of the transverse and longitudinal impact angles and cluster charge in kiloelectrons. The full circles correspond to the transverse coordinate and the full triangles to the longitudinal coordinate. Tracks have a momentum larger than 10 GeV/c. Impact angles of 90° correspond to normally incident tracks.

The intrinsic detector position resolution is measured using tracks traversing overlapping sensors in the barrel layers. Tracks passing through two overlapping modules in the same layer are used to compare the hit position with the expected position from the track trajectory. The difference in local hit position (ΔX_{hit}) of the track predictions is much more precisely known than the individual predicted positions. The double difference is formed by taking the difference between the hit position difference and the predicted position difference (ΔX_{pred}). The width of this double difference distribution is insensitive to translational misalignment of the overlapping modules. The double difference widths are fit with a Gaussian and the uncertainty from the tracking prediction are subtracted to recover the hit resolution on the position difference. With the assumption of equal resolution for each of the modules in the overlap, the final fit values for the resolution for a single module is $18.6 \pm 1.9 \mu\text{m}$ along x and $30.8 \pm 3.2 \mu\text{m}$ along y . Events with the same range of impact angles as in the measured sample are simulated using the PIXELAV program. The residual distributions are obtained comparing the true and reconstructed hit positions. A Gaussian fit to the simulated residual distribution gives a RMS of $22.1 \pm 0.2 \mu\text{m}$ and $28.5 \pm 0.1 \mu\text{m}$ along the x and y coordinates, respectively. The simulated values agree well with the measurements. A better position resolution is expected from the detector operation with a lower readout threshold [11].

E. Track parameter residuals at vertex

After detector alignment the track parameter resolution can be extracted from data [10]. The method consists of splitting the cosmic tracks at the point of closest approach to the beamline creating two track candidates. The top and bottom legs are taken as two independent tracks and re-fit accordingly with the track parameters propagated to their respective points of closest approach to the beamline. The transverse residual distribution is defined as: $\Delta d_{xy} = (d_{xy,1} - d_{xy,2})/\sqrt{2}$ where a factor of $\sqrt{2}$ is included due to statistically independent legs and $d_{xy,1/2}$ is the track transverse impact parameter of each track leg. The residual of the longitudinal impact parameter d_z is defined similarly. The distributions of the transverse (d_{xy}) and longitudinal (d_z) track impact parameter residuals are shown in Fig. 12. The histogram shows the measurement and the solid line is a Gaussian fit to the data. The value of the Gaussian width from the fit is $23.3 \pm 0.3 \mu\text{m}$ and

Fig. 12. Residuals of the transverse and longitudinal track impact parameters measured with the track splitting method. The solid line represents a Gaussian fit to the data. Tracks have momentum larger than 4 GeV/c.

Fig. 13. Distribution of ROC-mean threshold in the endcap and barrel detectors due to the re-tuning that took place after the maintenance and reinstallation.

TABLE II
MEAN NOISE AND MEAN THRESHOLD OF THE WHOLE PIXEL DETECTOR

	Threshold 2008	Threshold 2009
Pixel barrel	3829 e ⁻	2733 e ⁻
Pixel endcap	2941 e ⁻	2483 e ⁻

$39.4 \pm 0.5 \mu\text{m}$ in the transverse and longitudinal plane, respectively. The width of the residual distribution is $18.3 \pm 0.4 \mu\text{m}$ and $35.3 \pm 0.6 \mu\text{m}$ in the transverse and longitudinal plane, respectively, if the track momentum cut is increased to 20 GeV/c.

IV. MORE CALIBRATIONS AND COSMIC RAYS DURING 2009 DATA TAKING

After the maintenance of the pixel endcap detector and reinsertion in CMS more calibrations were re-performed in order to better tune the detector parameters. The thresholds of the whole pixel detector were lowered close to the minimum achievable as shown in Fig. 13. The three peaks in the BPix distribution arise from the threshold setting procedure. In a first iteration, all modules had their target threshold set to 2948 electrons. The modules, where this failed, were then targeted to 3275 electrons. Those failing here, were then targeted to 3603 electrons. The last 4 ROCs had to be set to 3930 electrons. In Tab. II is reported the difference between 2008 and 2009 tuning of the average threshold for BPix and FPIX sub-detectors.

In Fig. 14 is reported the Distribution of the Median of the Residuals (DMR) for the BPix modules. The RMS of the

Fig. 14. Distribution of the median of track residuals in barrel pixel modules for the 2008 geometry (black) and the 2009 geometry obtained after alignment (orange) along both local coordinates. Intervention on the pixel systems during the shutdown between 2008 and 2009 data taking explains the geometry variations ($\sim 100(250) \mu\text{m}$ for BPix(FPIX)), full precision on the geometry was recovered with the re-alignment during 2009 data taking.

DMR gives an indication on how well are aligned the different modules among themselves. Intervention on the FPIX detector during the shutdown between 2008 and 2009 influenced the geometry of the whole pixel system. With the 2009 cosmic ray data taking we were able to recover the full precision of the geometry achieved in the previous year.

V. CONCLUSIONS

After installation in July 2008, the CMS Silicon pixel detector was rapidly commissioned and then operated in a month-long cosmic ray trigger run in October 2008. About 94% of the forward disks and 99% of the central barrel were included in this commissioning cosmic ray run. Online charge calibration permitted comparison of charge measurements with expectations from simulation, showing good agreement for charge distributions. The Lorentz shift was extracted from data and used to correct the hit position. Good agreement of the measured values was obtained with simulation for both barrel and endcap regions. Although limited by the narrow time acceptance of the frontend electronics and the random arrival time of cosmic rays, a hit efficiency study shows efficiencies greater than 95% for most detector modules. Hit resolutions even at this early stage of tuning show the power of a pixel detector. Using tracks intersecting overlapping modules, hit resolutions of $20 \mu\text{m}$ ($r - \phi$) and $30 \mu\text{m}$ (z) are extracted from the small statistics available in the barrel detector. While dominated by multiple scattering contributions for low momentum cosmic rays, the transverse (longitudinal) impact parameter resolution is found to be $23 \mu\text{m}$ ($39 \mu\text{m}$) for high momentum tracks using a split track technique. These results are in line with the expectations presented in Ref. [12]. After the removal, maintenance and reinsertion of the pixel endcap in March 2009 there has been a new campaign of calibrations and cosmic ray data taking. Currently 98.6% of the whole pixel detector is fully functional. The thresholds are close to the minimum achievable. Before the beam comes a better tuning of Montecarlo with data is foreseen. With the first data taken with the beam it is planned to time-align the different portions of the pixel detector with respect to the beam collisions and improve the spatial alignment.

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