Beam Test Characterization of CMS Silicon Pixel Detectors for the Phase-1 Upgrade

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Abstract

The Silicon Pixel Detector forms the innermost part of the CMS tracking system and is critical to track and vertex reconstruction. Being in close proximity to the beam interaction point, it is exposed to the highest radiation levels in the silicon tracker. In order to preserve the tracking performance with the LHC luminosity increase which is foreseen for the next years, the CMS collaboration has decided to build a new pixel detector with four barrel layers mounted around a reduced diameter beam pipe, as compared to the present three layer pixel detector in the central region. A new digital version of the front-end readout chip has been designed and tested; it has increased data buffering and readout link speed to maintain high efficiency at increasing occupancy. In addition, it offers lower charge thresholds that will improve the tracking efficiency and position resolution.
Single chip modules have been evaluated in the DESY electron test beam in terms of charge collection, noise, tracking efficiency and position resolution before and after irradiation with 24 GeV protons from the CERN Proton Synchroton equivalent to the fluence expected after 500 inverse femtobarn of integrated luminosity in the fourth layer of the pixel tracker. High efficiency and an excellent position resolution have been observed which are well maintained even after the proton irradiation. The results are well described by the CMS pixel detector simulation.

Keywords: CMS, Upgrade, Phase-1, silicon pixel detector, irradiation

1. Motivation

The Large Hadron Collider (LHC) is the worlds largest and most powerful proton-proton accelerator. The physics program at the LHC began in 2010 with pp collisions at a center of mass (CM) energy of 7 TeV. The CM energy was increased to 8 TeV in 2012, with instantaneous peak luminosities approaching 7 $\cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The Compact Muon Solenoid (CMS) [1] is a general-purpose detector at the LHC. It is designed to investigate a wide range of physics, including the search for the Higgs boson, extra dimensions, and particles that could make up dark matter.
Based on the upgrade plans for the accelerators, it is anticipated that the peak luminosity will be close to 2 $\cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ before 2018. It is also planned to raise the CM energy towards 14 TeV. The total integrated luminosity is planned to reach 500 fb^{-1} until 2022. As a result, CMS must be prepared to operate for the rest of this decade with average event pile-up of 50, which means increased fake rate in the tracking system, and higher track densities.
The central part of the CMS detector, mounted around the beam pipe, is the silicon pixel detector. It receives a high radiation dose and has to operate in a dense particle environment. Tests of the performance of pixel module prototypes after irradiation are essential for the upgrade preparations [2].
The upgraded CMS silicon pixel detector will use well-established technology. The pixels of size $100 \times 150\mu\mathrm{m}^2$ collect electrons from oxygenated high resistivity n-type silicon of 285μm thickness with n+ implants. The readout chip is fabricated in 250 nm CMOS technology and employs radiation hard design rules. For the upgrade, the data buffer depth is increased to cope with higher occupancy, the measured charges are digitized on chip, and transmitted at 160 MHz. Internal cross talk has been reduced by design optimization and use of a 6^{th} metal layer, allowing to operate at lower thresholds.

2. Experimental conditions

2.1. Irradiation

Prototypes pixel modules were irradiated with 24 GeV protons to fluences up to $3.8 \cdot 10^{14}$ p/cm^2, corresponding to the expected lifetime dose of the fourth pixel layer at 16 cm radius from the beam.
After irradiation, the modules were stored at -20^oC to minimize annealing. The readout chips received a dose of up to 130 kGy and were fully functional in laboratory tests. An absolute gain calibration is provided by measuring several X-ray lines from Cu to Te depositing between 2.2 and 7.8 ke in silicon.

2.2. DESY test beam and pixel telescope

The DESY synchrotron provides narrow band electron or positron test beams with energies between 1 and 6 GeV with intensities up to a few kHz/cm^2 and a divergence of about 1mrad. The bunch repetition rate is 1 MHz. The energy is cycled from injection at 0.45 GeV to the maximum at 6.3 GeV every 80 ms. Two beam lines are equipped with pixel telescopes of the EUDET/AIDA-family [3] as shown in Fig.1. They contain six

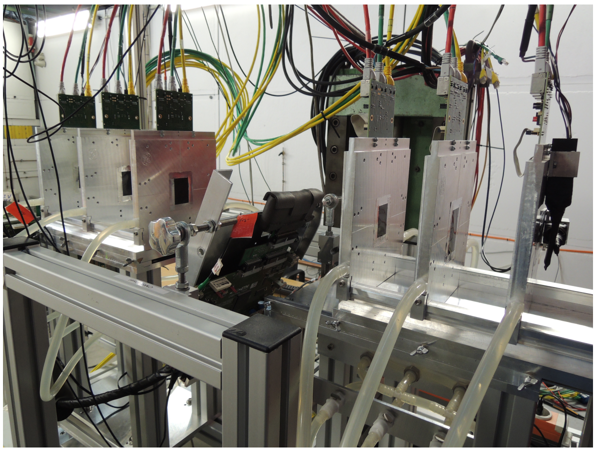

Figure 1: DESY test beam telescope made up from six planes of Mimosa26 pixel detectors and a tilted CMS single-chip pixel module in the center. The beam particles enter from the right and first traverse the upstream trigger scintillators.

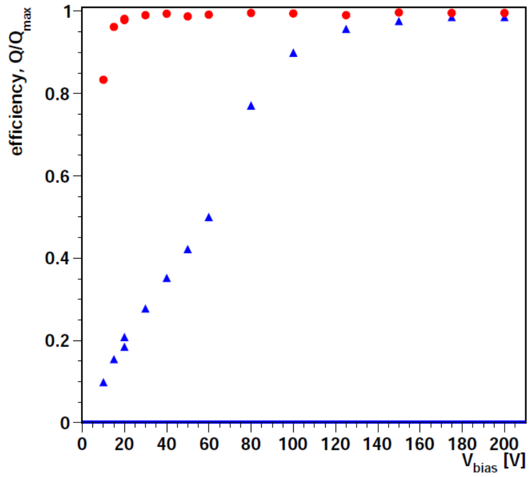

Figure 2: Charge collection efficiency, normalized to the maximum cluster charge (triangles) and tracking efficiency (circles) of the prototype silicon sensor for the CMS pixel tracker irradiated to $0.9 \cdot 10^{14}$ p/cm^2 as function of applied bias voltage. The charge threshold was set to 1.8 ke.

planes of Mimosa26 MAPS devices [4] covering an area of 21×11 mm^2 with squared pixels of size 18.4μm^2. They are thinned to 50μm to reduce the effect of multiple scattering. The device under test (DUT) can be placed in the center of the telescope on a frame that allows tilting around two axes relative to the beam. This enables studies of the detector behavior with inclined particle tracks producing multi-pixel clusters. There is no magnetic field in the area.

A second CMS prototype module was placed downstream at the end of the beam telescope to serve as a timing reference. This is necessary for efficiency measurements due to the rolling shutter readout of the Mimosa26 devices with an integration time of 0.1 ms, which results in a mean track multiplicity between 1.5 and 6 in the telescope.

The DUT and the telescope were triggered by the coincidence of four fast scintillators placed up- and downstream of the telescope. Typical runs were lasting between 10 and 30 minutes with several 100k triggers each.

Data analysis starts with clustering in the pixel planes, coarse track finding, and alignment using the Millepede [5] algorithm. A general broken lines track model [6] is used, which takes the multiple scattering in the known detector planes into account. The track is reconstructed using the information from the first and third telescope planes. The telescope hit resolution is monitored from the difference between the reconstructed track position and the hit on the second telescope plane (the unbiased residual) in each run and is stable at 3.5μm.

3. Measurement

3.1. Bias voltage variation and charge collection

The external bias voltage induces an electric field in the sensor which also depends on the space charge density in the bulk region. Radiation damage introduces acceptor- and donor-like defects which may trap electrons or holes and eventually dominate the space charge density.

Starting from n-type bulk material the introduction of acceptors leads to space charge sign inversion after which the depletion region starts from the pixel n+ implants. At full depletion, the electric field extends throughout the sensor bulk. However, limits on the power dissipation (ohmic heating) and the bias voltage supplies may prevent reaching this condition. The effects of partial depletion can be studied by varying the external bias voltage on irradiated devices.

Fig. 2 shows both the cluster charge normalized to the maximum charge collected and the tracking efficiency of a device irradiated to $0.9 \cdot 10^{14}$ p/cm^2 as a function of the bias voltage. The collected cluster charge drops quickly for bias voltages below 110 V. Near 30 V only a third of the charge is collected while the efficiency remains above 98% down to this point. This behavior may significantly extend the lifetime of the detector in terms of tracking efficiency. The upgraded detector will profit from the reduced charge threshold (1.8 ke) reachable with the improved readout chip.

An absolute measurement of the cluster charge distribution for a sensor irradiated to $3.8 \cdot 10^{14}$ p/cm^2 taken at 250 V bias is shown in Fig. 3. It has the expected Landau shape with the maximum occuring at 18 ke. Before irradiation the maximum was at 22 ke, indicating a charge loss due to trapping in the silicon bulk for longer than the 25 ns shaping time of the pixel amplifier.

3.2. Position resolution

The position resolution is primarily determined by the pixel dimensions. It can be improved by exploiting charge sharing, either due to inclined tracks or Lorentz drift in a magnetic field. The electronics threshold limits the smallest measurable charge and influences the position resolution.

Partial depletion or trapping may introduce systematic biases by influencing the charges generated at different depths and shifting the measured distributions of charge collection.

In the test beam the resolution in pixel row direction is derived from the width of the unbiased residual between the telescope

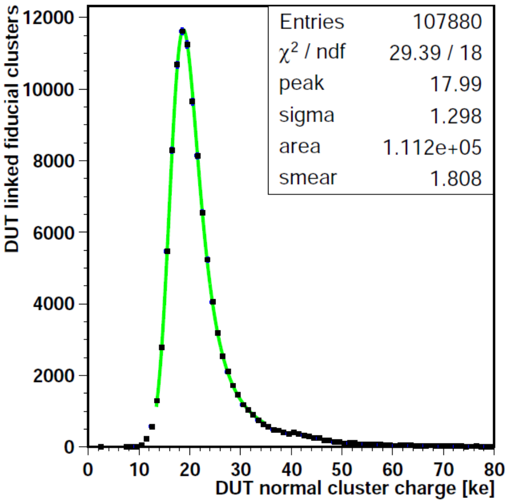

Figure 3: Cluster charge distribution measured in the electron beam for a 285μm thick pixel sensor irradiated to $3.8 \cdot 10^{14}$ p/cm^2 at a bias voltage of 250 V (plateau region).

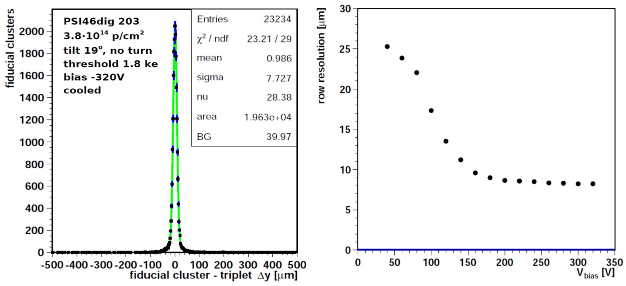

Figure 4: Residual between DUT cluster position and telescope track in the direction of the 100μm pixel size at a bias voltage of 320V (left) and resolution (mean of absolute residuals) as a function of the applied bias voltage without subtracting the telescope contribution (right).The sensor was tilted by an angle of 19^o to the beam direction. The charge threshold was set to 1.8 ke. The fluence is $3.8 \cdot 10^{14}$ p/cm^2.

track and the cluster position (defined as a weighted avarage of all the cluster positions) after subtracting the telescope contribution (about 4.3μm at 5 GeV and 150 mm spacing between the telescope planes). The DUT sensor is tilted by 19° in the direction of pixel rows in which the pixel has 100μm size, which should give the best geometric charge sharing at full depletion. Only clusters with charges in the peak region of the Landau distribution are selected, eliminating the deteriorating effect of delta rays. The residual distribution is well described by a Student's t function, see Fig. 4 left, and a hit resolution of 6.4μm is derived at 320 V bias for a sensor irradiated to $3.8 \cdot 10^{14}$ p/cm^2. For unirradiated modules a resolution of 5.1μm has been observed.

Reducing the bias voltage below 150 V, the position resolution degrades, approaching binary resolution at lowest voltages, where only 1-pixel clusters remain. The lifetime extension of operating at partial depletion comes at a price in terms of resolution.

The resolution was also measured at different angles of incidence for a sensor irradiated to $3.8 \cdot 10^{14}$ p/cm^2 and at 200 V bias. Geometrically, optimal charge sharing is expected at 19.3^o tilt for 100μm pixels and 285μm sensor thickness. The measured resolution has a minimum just above 20^o, see Fig. 5, which might be explained by trapping of deep charges, thus reducing the effective thickness.

For the outer layers of the CMS barrel pixel detector, prompt high transverse momentum tracks have a small angle of incidence but the charge cloud is drifting under the Lorentz angle in the solenoid field, which leads to near-optimal charge sharing for unirradiated devices. The corresponding resolution degradation can be read off from Fig. 5.

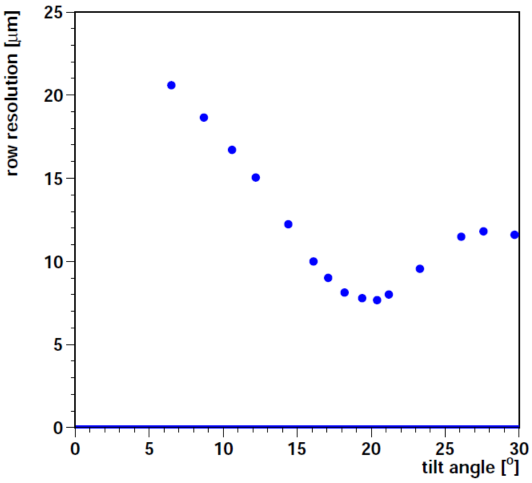

Figure 5: Resolution as a function of the tilt angle for a prototype silicon pixel module irradiated to $3.8 \cdot 10^{14}$ p/cm^2. The bias voltage was set to 200V and the threshold to 1.8 ke.

4. Summary

The CMS detector is being prepared for the operation with higher luminosities. The pixel detector will be upgraded as proposed in [2] to perform efficiently in the environment of high track density.
The prototype pixel modules with the upgraded readout chips were irradiated to $3.8 \cdot 10^{14}$ p/cm^2 and operated in a beam test at DESY. The test showed the properties of the irradiated prototypes. The depletion voltage was at about 150 V, full efficiency was reached at 70 V and the position resolution was measured to be 6.4μm.
The results of the studies show good performance characteristics for the pixel modules after irradiation.

5. References

[1] CMS Collaboration, The CMS Experiment at the CERN LHC, JINST 3 (S08004).

[2] CMS Collaboration, CMS Technical Design Report for the Pixel Detector Upgrade, CERN-LHCC-2012-016.

[3] The EUDET Consortium, Infrastructure for Detector Research and Development towards the International Linear Collider, arXiv:1201.4657 (2012).

[4] C. Hu-Guo et al., First reticule size MAPS with digital output and integrated zero suppression for the EUDET-JRA1 beam telescope, Nucl. Instr. and Meth. A (623) (2010) 480–482.

[5] G. Flucke, P. Schleper, G. Steinbruck et al., CMS silicon tracker alignment strategy with the Millepede II algorythm, JINST 3 (P09002).

[6] V. Blobel, A new fast track-fit algorithm based on broken lines, Nuclear Instruments and Methods in Physics Research A: Accelerators, Spectrometers, Detectors and Associated Equipment (566(1)) (2006) 14 – 17.