Test Beam Campaigns & Simulation for the CMS Pixel Detector Upgrade.

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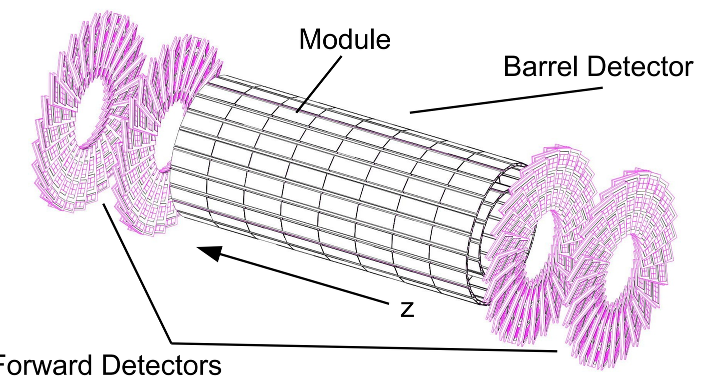
The CMS Pixel Detector and the Phase I Upgrade

The Pixel Detector is the innermost part of the CMS Tracker. It consists of three barrel and two forward layers as shown below, comprising a total of ~66 million readout channels.



With the good performance of the LHC delivering two times the design luminosity an upgrade of the CMS Pixel Detector is required to maintain and extend the tracking efficiency.

The upgrade plans comprise changes in geometry and material budget as well as additional 4th barrel and 3rd forward layers. A new Readout Chip (ROC) is designed to cope with the increasing occupancy and data rate. The design features:

> Additional buffer cells for pixel hits and time stamps
> Reduced dead time during readout by additional buffer
> Fully-digital 160 MHz readout.

The efficiency and performance of the new ROC has to be ensured before production in laboratories and test beams.

The CMS Pixel Readout Chip and Sensor

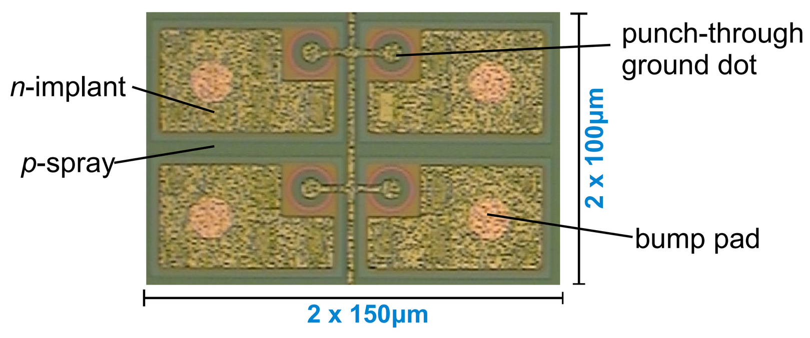
The modules of the CMS Pixel detector hold one sensor and 16 ROCs. Special single-ROC modules are produced for test purposes such as laboratory measurements or test beams.

The CMS Pixel ROC
> 4160 pixel cells in 26 double columns, with 80 rows each.
> Zero-suppressed readout via double column structure, each holding dedicated buffers for hits and timestamps.

The CMS Pixel Silicon Sensor
> *n*-in-*n* implant concept
> Thickness of 285µm, pixels pitch of 100µm x 150µm
> Optimal charge sharing with Lorentz drift in CMS magnet

The barrel pixel sensor feature a ground grid connecting all pixels via a *punch-through* dot. This ensures that pixel cells with poor bump bonding quality do not float to bias voltage and potentially spark to the ROC.

The edge pixels around ROCs are larger to allow for positioning and bump bonding. The inner pixels of one ROC are called „fiducial volume".

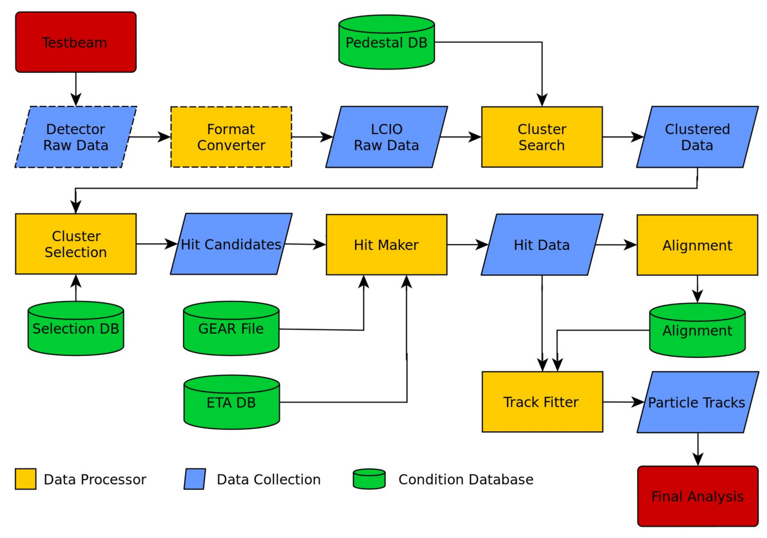


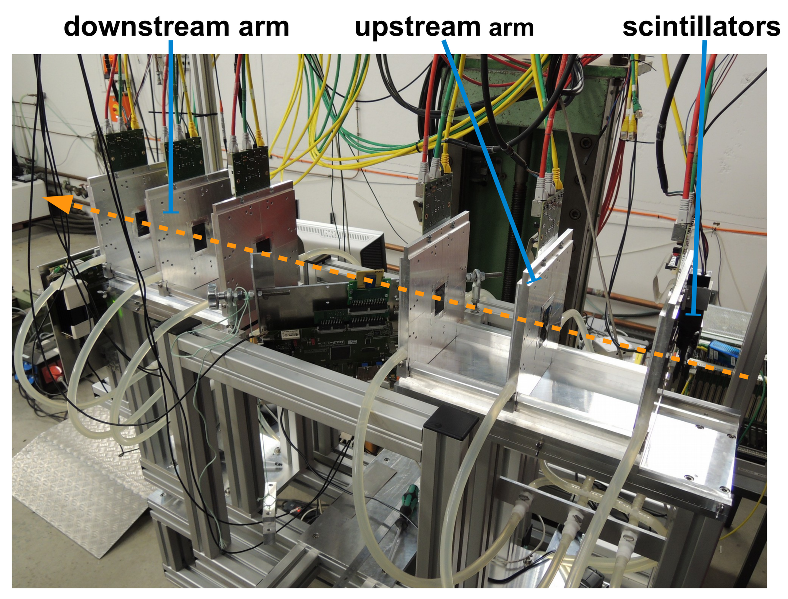
The DATURA Beam Telescope at the DESY Test Beam as High-Resolution Tracking Tool

Beam telescopes consist of consecutive planes tracking beam particles. This track information is used to investigate the performance of a Device Under Test (DUT).

The DATURA Beam Telescope
DATURA is developed at DESY and is equipped with:
> Six MIMOSA26 MAPS, 18.4µm pitch, 120µs integration
> Cooling, Trigger Logic Unit, four-fold coincidence trigger
> Full-featured Data Acquisition (DAQ) and analysis system

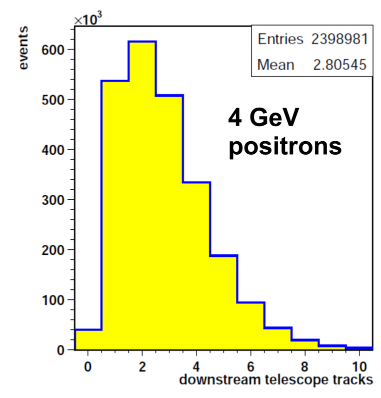
The EUTelescope Data Analysis Framework
Reconstruction & analysis of pixel telescope beam test data:
> Allows close integration of the DUT into analysis
> Pixel clustering & CoG, coordinate transformations
> Includes advanced algorithms for tracking & alignment





The DESY Test Beam
> From bremsstrahlung
> Energies from 1 to 6 GeV
> Energy spread of 5%
> Divergence of ~1mrad

The plot to the right shows the track multiplicity in the DATURA Telescope for a beam energy of 4.4 Gev in the downstream arm of the telescope after the DUT.



DUT Tracking Efficiency Measurement

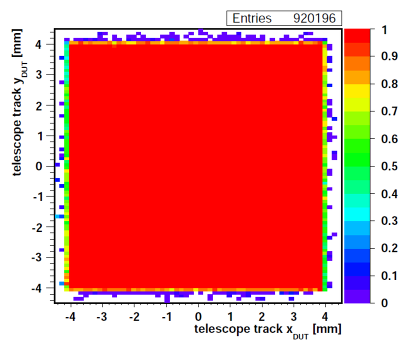
The tracking efficiency of the DUT is determined by first selecting tracks within the correct timing window. This is done by matching downstream triplets to the upstream ones. This is needed due to the MIMOSA26 integration time.

Then these tracks are matched to the DUT and the efficiency is calculated as:

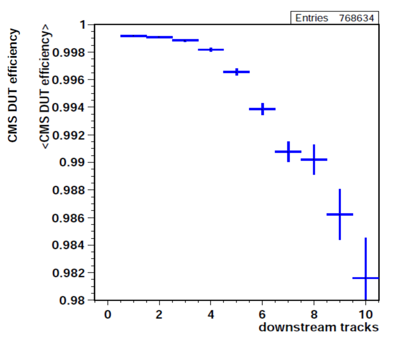
$$\text{eff} = \frac{\text{tracks linked to DUT cluster}}{\text{tracks with REF cluster}}$$

The tracking efficiency of the CMS psi46dig ROC at φ = 19° is 99.6% within the fiducial volume (see efficiency map). It depends on the number of telescope tracks recorded and can be increased by applying cuts to the multiplicity and thus eliminating ambiguities in cluster matching.

Only taking into account single telescope track events an efficiency of 99.9% can be achieved:

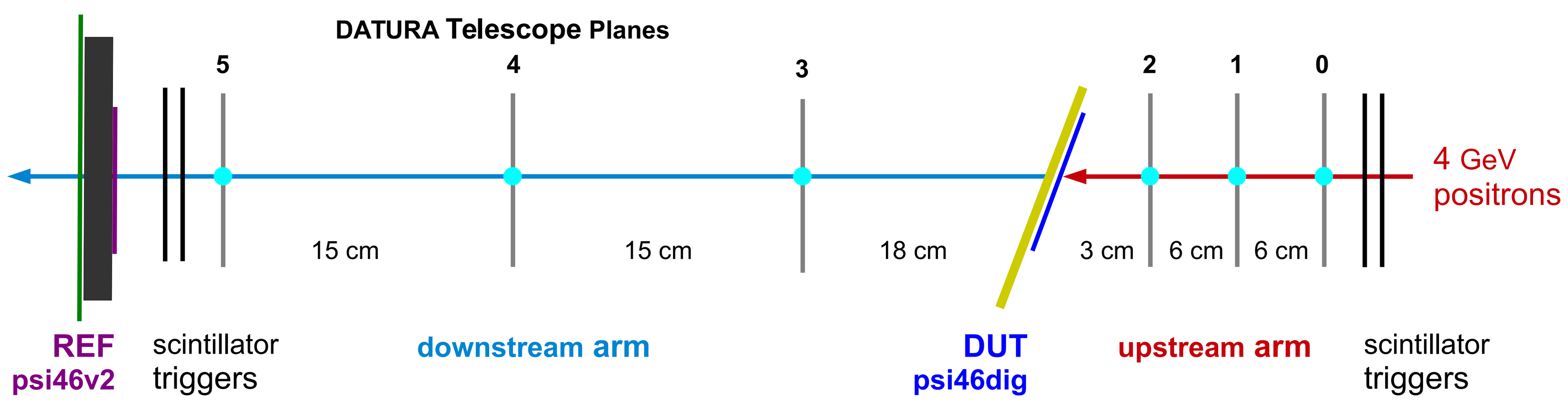


efficiency map of the DUT



efficiency vs. telescope track multiplicity

The CMS Pixel Readout Chip and Sensor as DUT and REF in the DATURA Beam Telescope



Test Beam Setup
Two different CMS Pixel single-ROC modules with readout chip and sensor have been used:

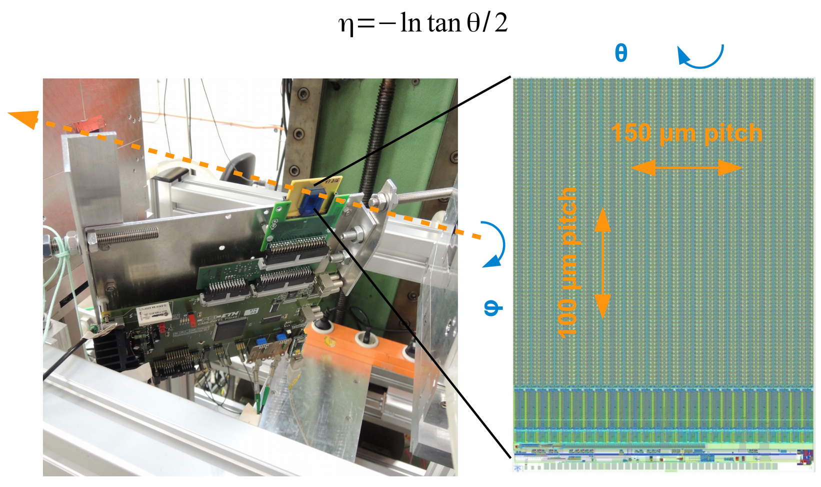
> **REF:** Analog **psi46v2** ROC (production series of the current CMS Pixel detector) as timing reference plane
> Needed for distinction of telescope tracks within and outside the CMS Pixel trigger window (nominal LHC bunch crossing, 25 ns).

> **DUT:** digital ROCs **psi46dig, psi46digV2, psi46digV2.1** between the up- and downstream telescope arms.
> Mounted on a hinged support with readout electronics
> Allowing rotations around two angles (see sketch)

The distance of the DUT and the telescope planes has been carefully chosen in order to reach the maximum resolution:
> DUT 3 cm from last upstream plane: **4.8µm** resolution
> DUT rotated, slightly larger distance: **7.5µm** resolution

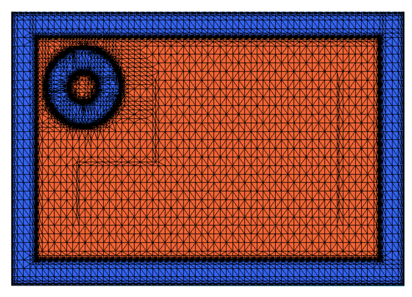
DUT Rotation around Two Angles
> Rotation around **φ** simulates the Lorentz angle
> Rotation around **θ** accounts for different pseudo rapidities:

$$\eta = -\ln \tan \theta / 2$$

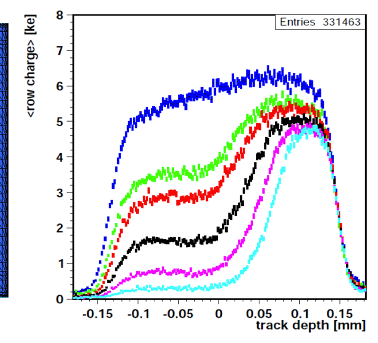


Particle-Level Detector Simulation

The DUT has been simulated using the *pixelav* package includes effects of scattering in Silicon, Delta rays as well as charge carrier drift & diffusion. The sensor is described using different electric fields for the different DUTs. Timing and threshold effects are simulated to model the ROC response.

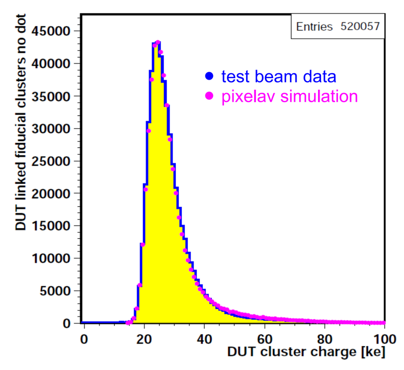


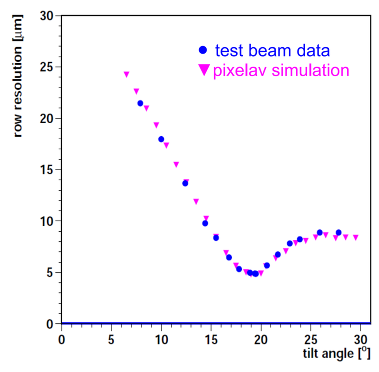
TCAD grid for one pixel cell with punch-through dot



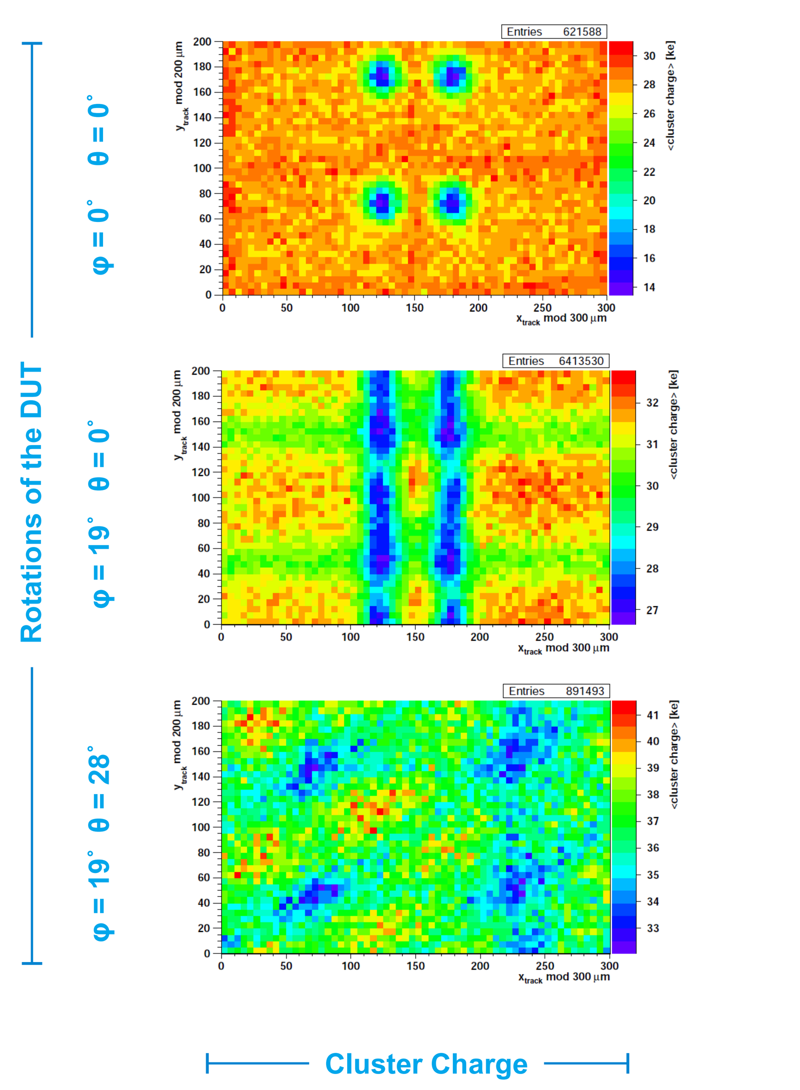
test beam data with φ = 72° for simulation tuning

The simulation is in good agreement with the test beam data recorded as shown below for the Landau distribution and the row resolution as function of φ:





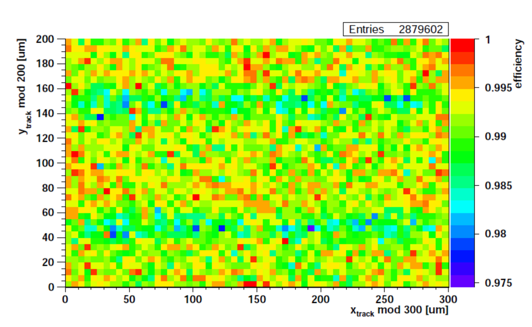
Intra-Pixel Charge Collection Efficiency Studies



The high resolution of the beam telescope tracks have been used to study various effects within single pixel cells of the CMS Pixel sensor at different incidence angles. The maps show the four pixel cells of the sensor photograph at the head of the page. All matched tracks within the fiducial volume have been folded into these maps.

Charge Collection Efficiency
At perpendicular incidence the effect of the punch-through dot is clearly visible. Up to 50% charge is lost compared to hits in the implant region. Increasing the charge sharing by tilting the sensor clearly mitigates the effect, only around 10% of the charge carriers are lost. The effect gets even smaller when rotating the sensor around two axes.

Tracking Efficiency
The efficiency for a track to be detected in the DUT as function of the hit position within one pixel is shown in the map below. The charge loss around the punch-through dot does not affect the efficiency for track finding, but threshold effects can be seen in the banding.

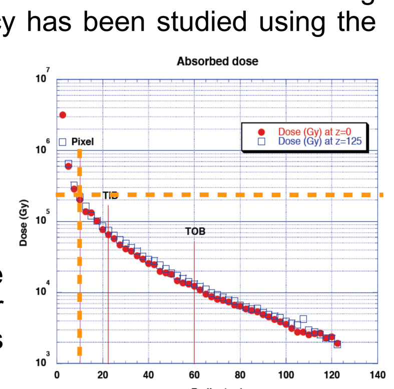


Studies on Irradiated Readout Chips

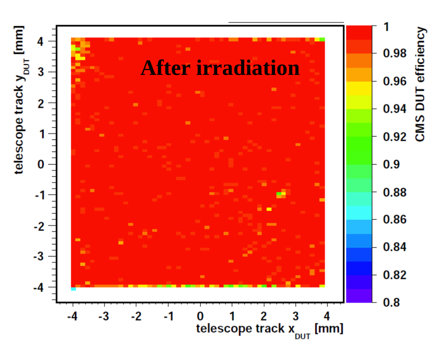
CMS Pixel single-ROC modules for Layer 3 and 4 of the new detector have been irradiated up to their expected lifetime dose in the harsh LHC environment. Their tracking and charge collection efficiency has been studied using the DESY test beam.

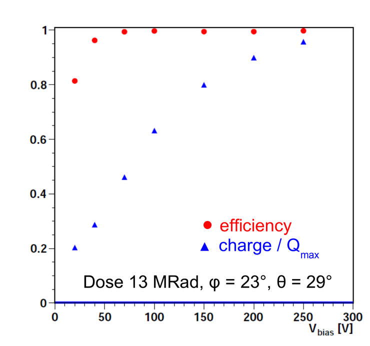
> Irradiation: 24 GeV protons
> Two devices, doses up to D = 13 Mrad, $\Phi \approx 2.3 \cdot 10^{14}\ n_{eq} / cm^2$

The plot to the right shows the expected lifetime doses after $500 fb^{-1}$ at different distances from the interaction region.



With limits on power dissipation the sensor volume is only partially depleted after irradiation. But due to the *n*-in-*n* implant concept the sensor undergoes type inversion. Thus charge is collected at the implant side and charge collection and tracking efficiency can be sustained as shown below.





Conclusions

The DESY Test Beam Infrastructure
The DATURA Beam Telescope is a high-resolution tracking tool which allows in-pixel studies of various effects in the device under test. EUTelescope provides tools for data reconstruction and analysis and allows a flexible workflow for both DUT and telescope data.

Test Beams for the CMS Pixel Detector Upgrade
Several test beam campaigns have been conducted over the last years to provide quality assurance for the Readout Chip upgrade and allow further insights into the detector's parameter space.

Both irradiated and non-irradiated devices have been measured and characterized in terms of tracking efficiency, charge collection and tracking resolution. All devices have been found to have an outstanding performance and provide good resolution and efficiency even under problematic conditions.

The test beam data has been compared with detailed simulations to better understand various effects seen in the data. All important quantities compare well with simulation.

Outlook

After start of the series production of CMS Pixel Detector modules in Fall 2014 the quality and performance of the modules will be checked using test beam measurements. Furthermore first prototypes of the special chip design for the innermost detector layer will be qualified.

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