High-Resolution Tracking Tools for the CMS Pixel Detector Upgrade.

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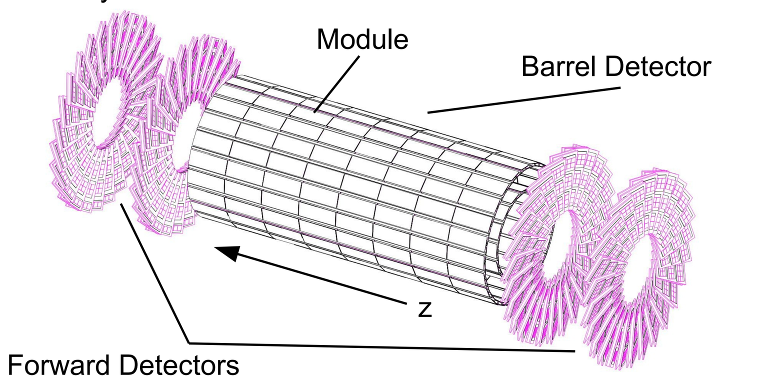
The CMS Pixel Detector and the Phase I Upgrade

With the impressive 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 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 the following changes in geometry and material budget:
> Additional 4th pixel layer
> 1st layer closer to the interaction point
> New cooling with thinner piping
Furthermore a new Readout Chip (ROC) is designed with:
> 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 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:
> Lower overall material budget
> Additional buffer cells for pixel hits and time stamps
> Fully-digital 160 MHz readout.
The ROC is being tested at various institutes in the laboratory and in test beams at DESY, CERN and FNAL.

The CMS Pixel Readout Chip and Sensor

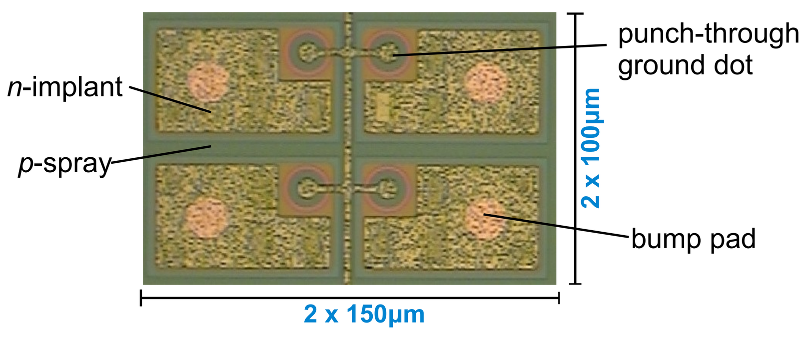
The modules of the CMS Pixel detector hold one sensor and 16 ROCs. Special single-ROC modules are produced for test purposes such as laboratory measurements or test beams.

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".

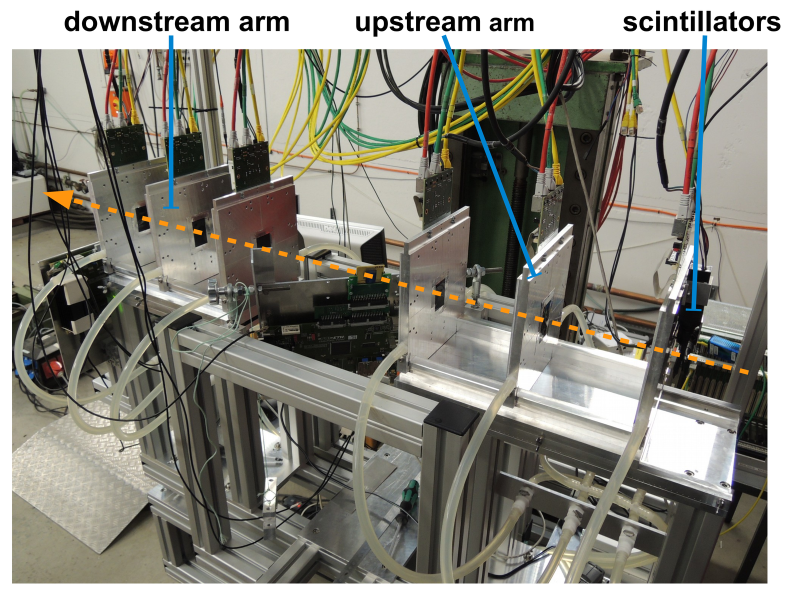


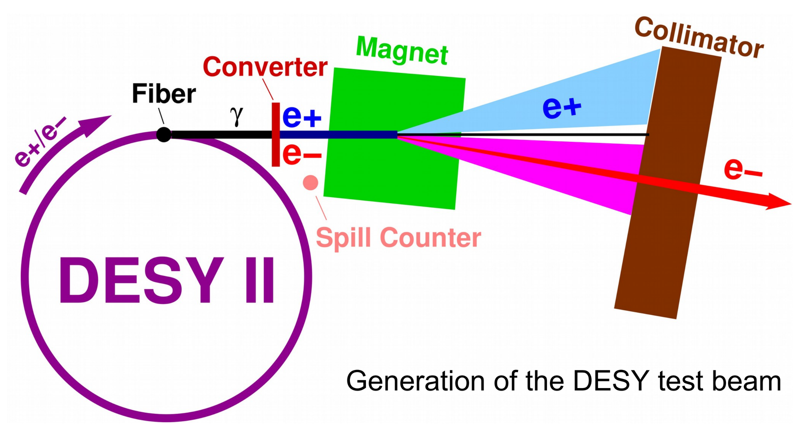
The DATURA Beam Telescope at the DESY Test Beam as High-Resolution Tracking Tool

Beam telescopes consist of several consecutive detector planes. By this, beam particles traversing the planes can be tracked and the 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 planes
> Cooling, mechanical support, Trigger Logic Unit (TLU)
> Crossed scintillators as four-fold coincidence trigger
> Full-featured Data Acquisition (DAQ) system
> Two movable arms with adjustable plane distances

The MIMOSA26 MAPS Sensors provide
> High-resolution position measurements
> Pixel pitch of 18.4µm
> Rolling-shutter readout, integration time of about 120µs

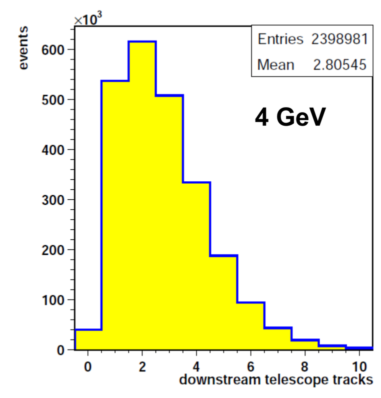




Generation of the DESY test beam

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

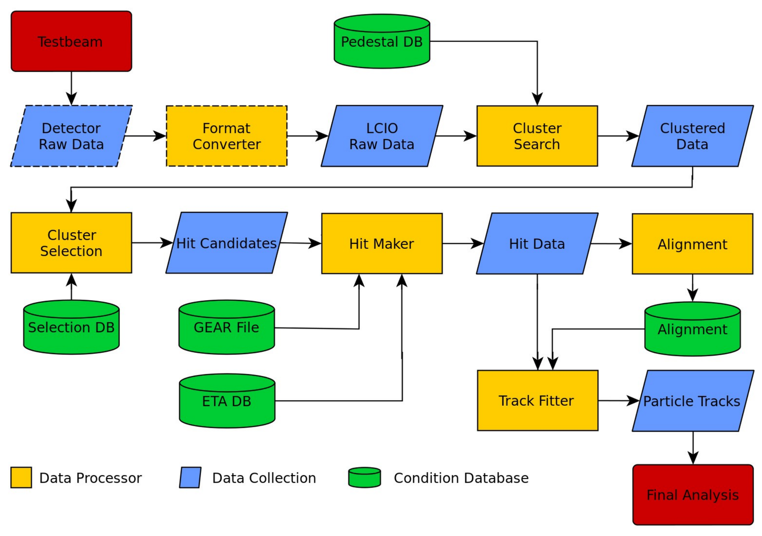
The plot to the right shows the track multiplicity in the DATURA Telescope for a beam energy of 4.4 Gev in the downstream arm of the telescope after the DUT.



The EUTelescope Data Analysis Framework

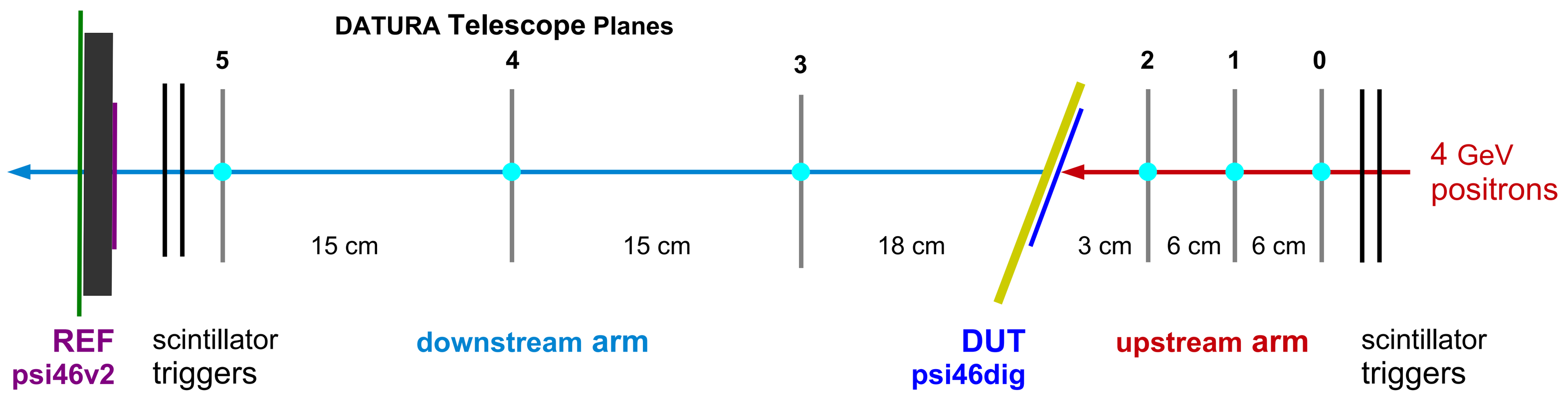
EUTelescope is a software framework for data reconstruction & analysis of beam test data recorded with pixel telescopes. It uses the common LCIO data format and provides a set of processors for *Marlin*, an event based data processor.

EUTelescope allows a close integration of the Device under test (DUT) into the reconstruction and analysis. A typical EUTelescope workflow looks as follows:



> Conversion of all data from raw formats into LCIO,
> Pixel grouping (clustering), position determination (CoG),
> Coordinate transformation into space points (global frame of reference),
> Alignment and tracking using various algorithms such as General Broken Lines (GBL), which has been used for this test beam analysis.

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:

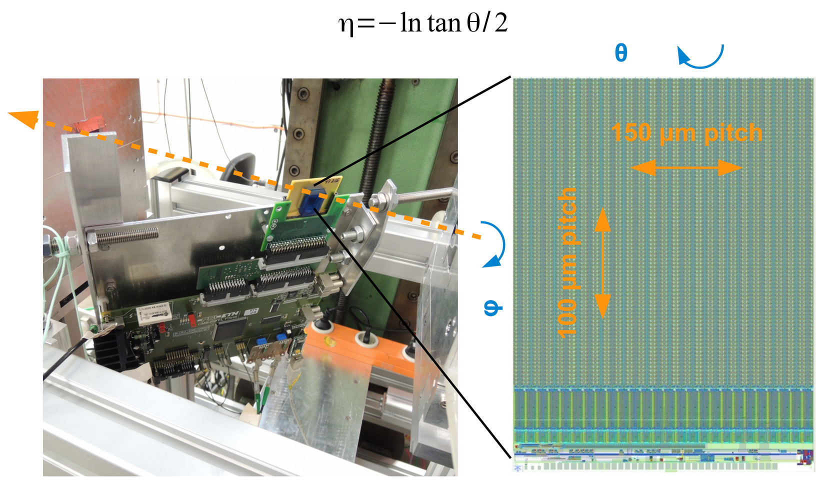
> **REF:** Analog **psi46v2** ROC (production series of the current CMS Pixel detector) as timing reference plane
> Needed for distinction of telescope tracks within and outside the CMS Pixel trigger window (nominal LHC bunch crossing, 25 ns).

> **DUT:** new digital ROC **psi46dig,** 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 pseudorapidities:

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



DUT Tracking Efficiency Measurement

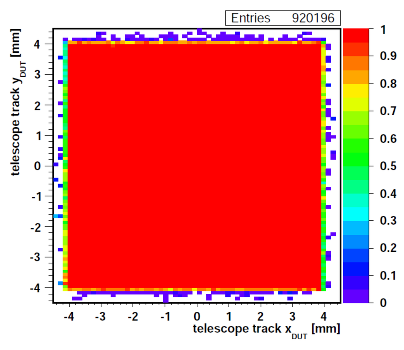
The tracking efficiency of the DUT is determined by first selecting tracks within the correct timing window. This is done by matching downstream triplets to the timing reference detector (REF). This is needed due to the MIMOSA26 integration time.

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

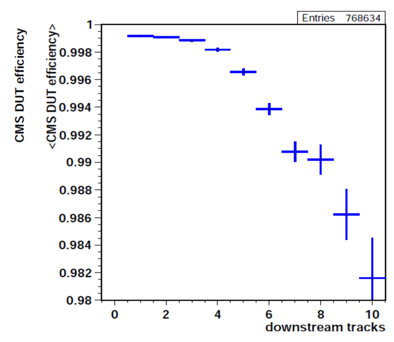
$$\text{eff} = \frac{\text{tracks linked to DUT cluster}}{\text{tracks with REF cluster}}$$

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:

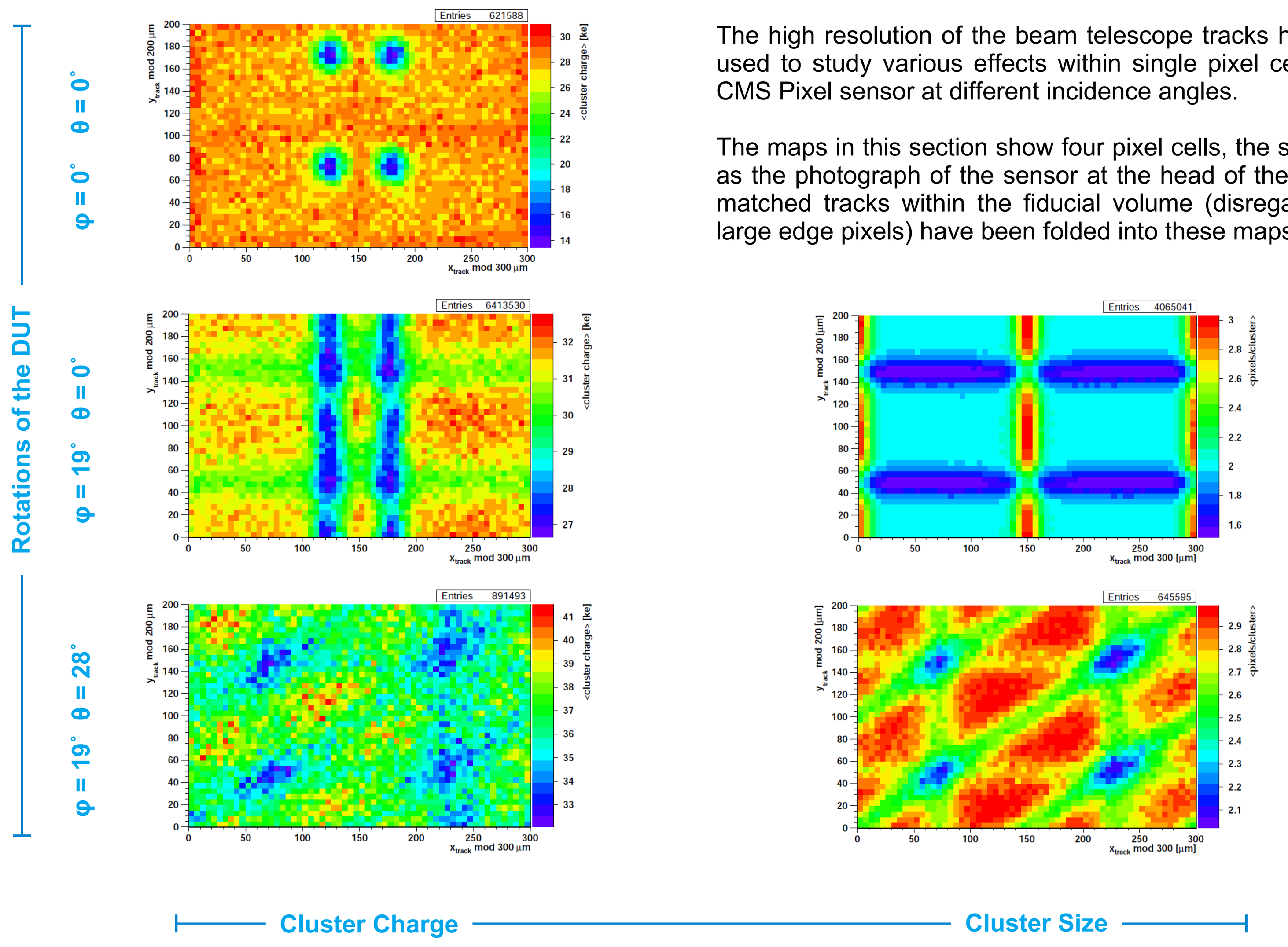


efficiency map of the DUT



efficiency vs. telescope track multiplicity

Intra-Pixel Charge Collection and Charge Sharing 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.

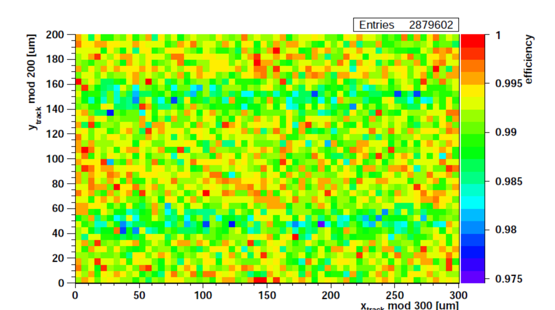
The maps in this section show four pixel cells, the same area as the photograph of the sensor at the head of the page. All matched tracks within the fiducial volume (disregarding the large edge pixels) have been folded into these maps.

Charge Collection Efficiency
At perpendicular incidence the effect of the punch-through dot on the charge collection efficiency 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.

At the used threshold settings of about 1,500 electrons even 50% signal loss does not affect the cluster as shown in the cluster size maps. The banding structure results from threshold effects in case of small charge sharing.

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.



Conclusions

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.

Outlook

Plans for CMS Pixel ROC Test Beams
Several more test beams with CMS DUTs are scheduled for the next months:

> Measurements with highly irradiated ROCs to simulate the LHC environment after 500fb^{-1}, the lifetime dose of the CMS Pixel Detector.
> Studies of the latest ROC design submissions
> Studies on the influence of threshold effects and different clustering algorithms on the tracking efficiency.
> High-rate beam test (up to 400MHz / ROC) at FNAL to validate the design. For this purpose a beam telescope consisting of eight CMS Pixel ROCs has been built.

The results from the test beams will be compared to detailed simulations of the sensor and the ROC.

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