Radiation length (X/X_0) imaging with high resolution telescopes

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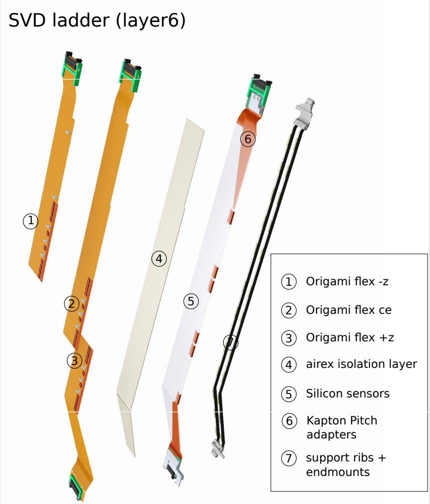
Motivation for spatially resolved X/X_0 measurements

Survey of complex material distributions

- Low material budget is an essential part of modern vertex detector development
- High level of integration (readout,cooling,electronics) leads to a complex module design
- Precise vertex reconstruction $\rightarrow X/X_0$ distribution of vertex detector must be known well

$\rightarrow$ Spatial resolved measurements based on multiple scattering to cross-check the detector model

Example: Belle II Si strip layer



Motivation for spatially resolved X/X_0 measurements

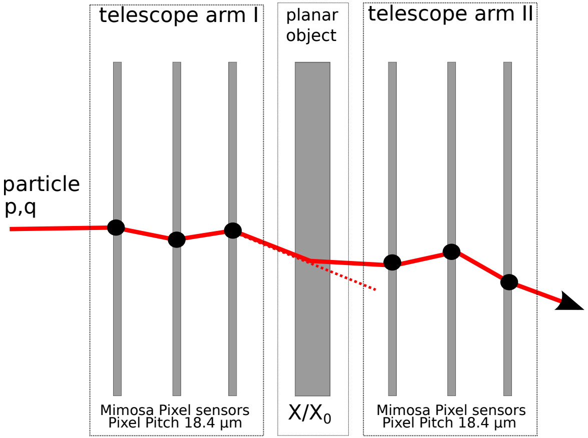
Measurement of Radiation length constant X_0

- Components with unknown radiation length often used in detector systems
- Glues, thermally conductive materials, metal compounds, capacitors etc.
- X/X_0 Measurement of a sample with a known thickness X allows estimation of radiation length constant X_0

$\rightarrow$ Possibility to create a database with X_0 values for relevant materials

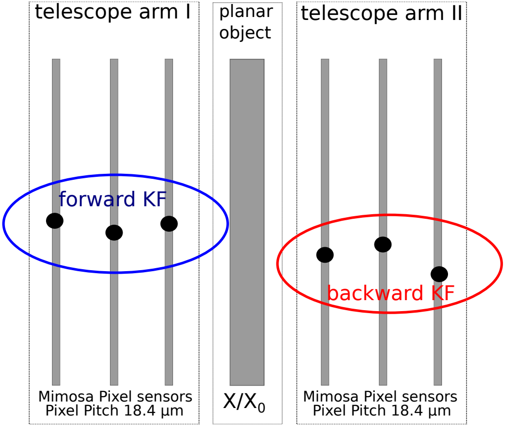
Reconstruction of multiple scattering angles

- Planar object centered in high resolution telescope
- Multi GeV particle beam → telescope sensor hits



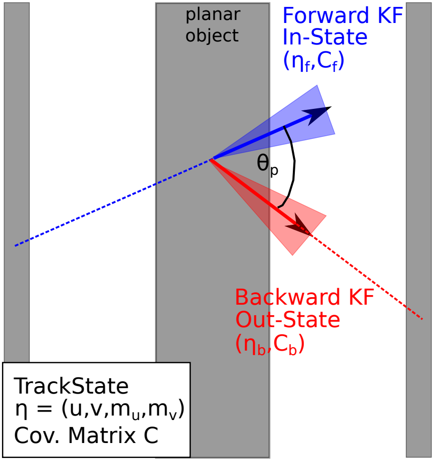
Reconstruction of multiple scattering angles

- Planar object centered in high resolution telescope
- Multi GeV particle beam → telescope sensor hits
- Forward- backward Kalman Filter (KF) pair on hits



Reconstruction of multiple scattering angles

- Planar object centered in high resolution telescope
- Multi GeV particle beam → telescope sensor hits
- Forward- backward Kalman Filter (KF) pair on hits
- θ_p calculated from track slopes (m_u,m_v)
- Intersection pos. (u,v) of particle from track states
- angle error σ_{err} from error propagation



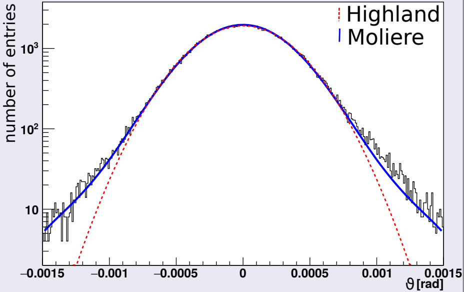
X/X_0 Measurements

Basic idea

- Reconstruct kink angle distributions in pixels on central plane
- Define u-v bins at the scattering plane and fill histograms with scatter kinks

First part: Multiple scattering distribution $f_{\mathrm{scatt.}}$

- Fit angle distribution with a function f_{reco}, which is based on the Moliere or the Highland model of multiple scattering
- Highland: Gaussian dist., no description of tails
- Moliere: Describes whole distribution



X/X_0 Measurements

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Calibration with dedicated calibration target

- Fit function f_{reco} given by

$$\begin{aligned} f_{\mathrm{reco}} &= f_{\mathrm{scatt.}}\left(\theta, X/X_0, p, \kappa\right) \otimes f_{\mathrm{err}}\left(\theta, \lambda, \sigma_{\mathrm{err}}\right) \\ &= f_{\mathrm{scatt.}}\left(\theta, X/X_0, p, \kappa\right) \otimes \frac{1}{\lambda\sigma_{\mathrm{err}}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\theta}{\lambda\,\sigma_{\mathrm{err}}}\right)^2\right) \end{aligned}$$

- calibration factor λ corrects a systematic shift of the Kalman filter predicted angular resolution
- κ corrects a global scale error of the kink angle distribution width, caused by a small mistake in the telescope length and/or the beam energy

X/X_0 Measurements

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\end{aligned}
$$

- Target with well known material profile allows λ and κ calibration
- Find parameters by simultaneous fit of reconstructed angle distributions

X/X_0 Measurements

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$$

- Target with well known material profile allows λ and κ calibration
- Find parameters by simultaneous fit of reconstructed angle distributions

Second step: Measurement on materials

- Use optimal calibration parameters in f_{reco} to fit X/X_0

How to conduct radiation length measurements?

1. Preparation and experimental setup
2. Telescope alignment and Cluster calibration
3. Angle resolution calibration
4. Measurements

- More information on the X/X_0 measurements can be found at `https://doi.org/10.1016/j.nima.2016.06.086`
- The software that was used to analyse the beam test data and produce the results in this presentation can be found at `https://bitbucket.org/BenjaminSchwenker/tbsw`

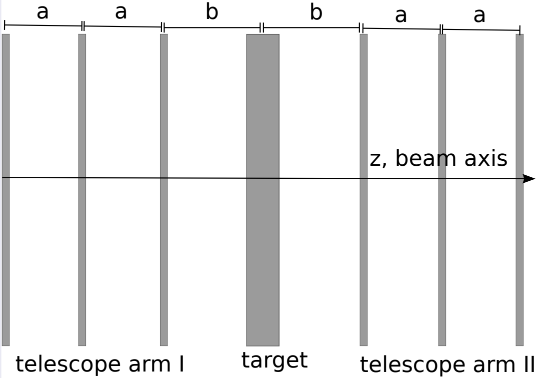
How to conduct radiation length measurements?

1. Preparation and experimental setup
2. Telescope alignment and Cluster calibration
3. Angle resolution calibration
4. Measurements

Preparation and experimental setup

- M26 distance of 40 to 50 mm is a compromise between good spatial resolution and scattering angle resolution σ_{err}
- space between telescope arms should be large enough to exchange measurement targets without moving the telescope arms
- z positions of M26 and target should be measured accurately ($\sigma_{\mathrm{z}} < 1.0\,\mathrm{mm}$)
- Good idea to also measure distance between first and last M26

Good Telescope setup for X/X_0 measurements



a should be 40-50mm
b should be large enough to exchange target, without moving telescope arms

How to conduct radiation length measurements?

1. Preparation and experimental setup
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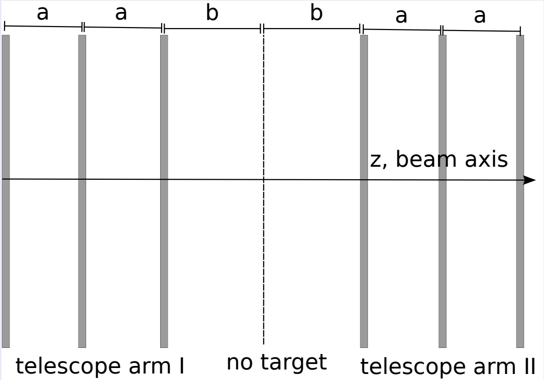
Telescope alignment and Cluster calibration

- Remove target during telescope alignment → air run
- Size of the M26 clusters during the telescope calibration important
- Tune M26 threshold in such a way that the ratio of 1 to 2 pixel size clusters is 1:1 → good resolution of reconstructed M26 hits
- Additionally: M26 occupancy shouldn't be too large ($<$ 10 hits/event per sensor)

Telescope setup during alignment



a should be 40-50mm
b should be large enough to exchange target, without moving telescope arms

How to conduct radiation length measurements?

1. Preparation and experimental setup
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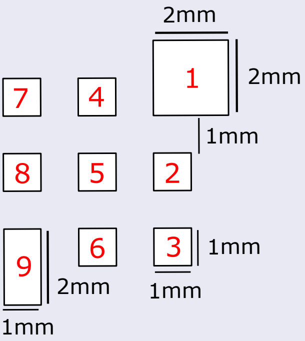
3. Angle resolution calibration
4. Measurements

Angle resolution calibration

- Use calibration target with well known material profiles for the calibration
- Calibration factors λ and κ should be close to 1.0 $\rightarrow$ systematic errors visible in calibration measurement

Example of a calibration target

1 air
2 0.2mm Al
3 0.4mm Al
4 0.6mm Al
5 0.8mm Al
6 1.0mm Al
7 1.2mm Al
8 1.4mm Al
9 1.6mm Al



total thickness 1.8mm Al

Angle resolution calibration

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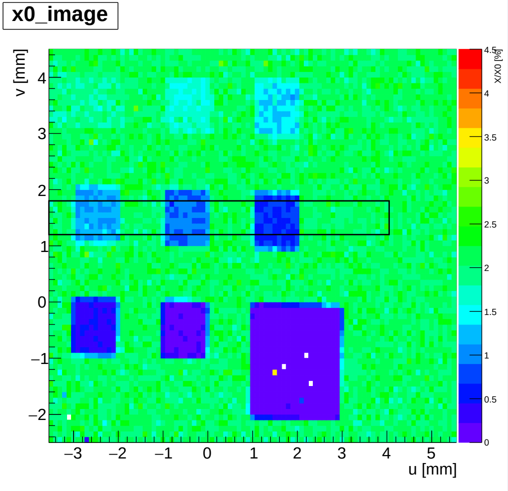
X/X_0 image of a calibration target



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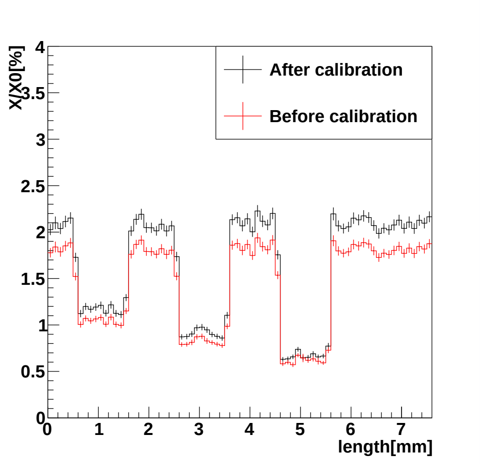
Comparison of radiation length profiles



Here: $\lambda = 1.085 \pm 0.003$, $\kappa = 0.915 \pm 0.02$

How to conduct radiation length measurements?

1. Preparation and experimental setup
2. Telescope alignment and Cluster calibration
3. Angle resolution calibration
4. Measurements

Measurements

- The minimal pixel size of the radiation length images depends on the total number of tracks in the beam spot region
- At least 1000 - 2000 tracks per pixel to ensure a stable fit
- This means for an image with 100x100 µm pixels and a beamspot size of 10x20mm (M26 acceptance) at least 20 mio tracks are needed
- Assuming an event rate of 1 kHz and 1 track per event (higher values are possible) the measurement would take approximately 6 hours
- $\sigma_{\mathrm{MSC}} \propto 1/p$ therefore a low beam energy should be used during measurements

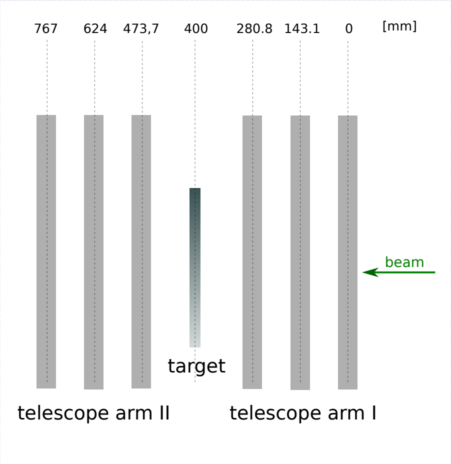
- You will have to repeat the alignment and calibration steps everytime you change the telescope geometry or the beam energy
- air run $\rightarrow$ calibration run$\rightarrow$ measurement

X/X_0 measurements on different glue samples

Overview

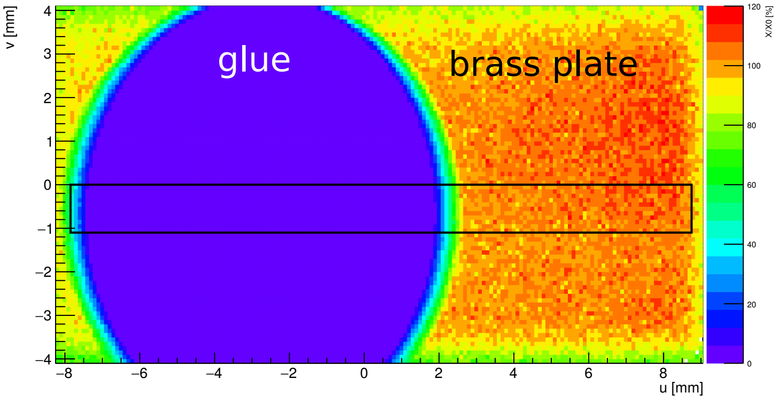
- Data from a DESY TB in 2016
- 4 glue samples (A-D)
- glue A-C: $X \approx 10mm$ embedded in brass plate
- glue D: Conductive silver glue with $X = 1.83\,\text{mm}$
- approximately 8 mio tracks per glue sample

Telescope setup



X_0 measurement of different glues

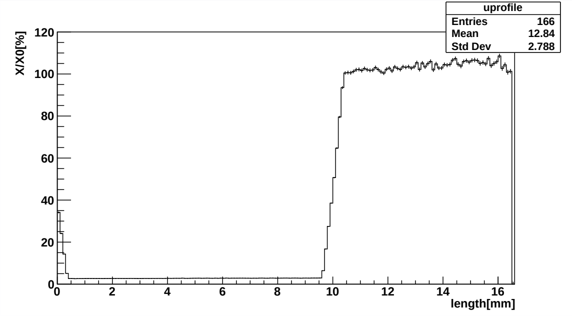
X0 image (4.6 GeV, 100 μm^2 pixels)



Radiation length image of glue B and the brass plate

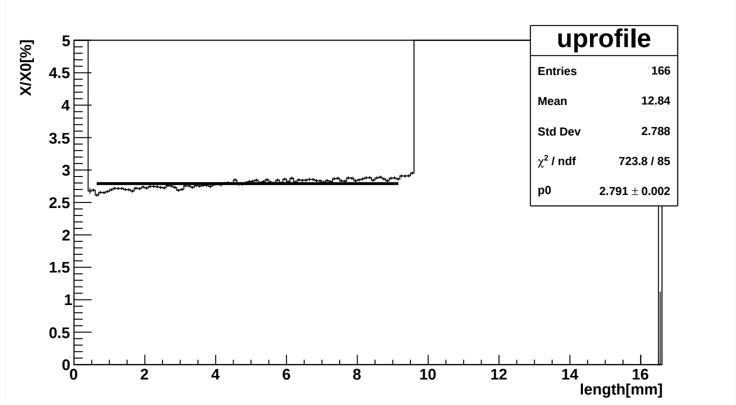
X_0 measurement of different glues

Radiation length profile



X_0 measurement of different glues

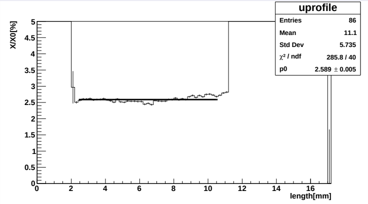
Radiation length profile: Zoom in and fit of X/X_0 in glue area

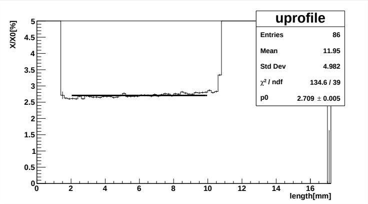


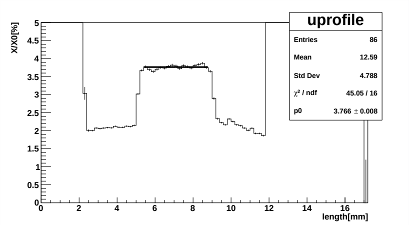
Fit yields X/X_0(10.17mm of glueB)=(2.8 ± 0.1)%, Visible gradient in profile: Use 0.1% error $\rightarrow$ X_0(glue B)=(360 ± 20) mm

X_0 measurement of different glues

Measurement of other glues







X_0 measurement of different glues

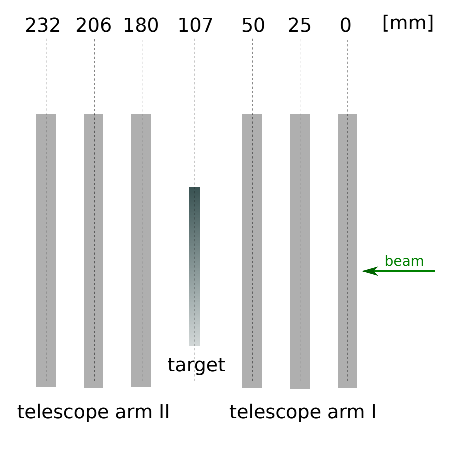
Summary of glue measurements

- X_0(glue A)=(400±20) mm
- X_0(glue A)=(360±20) mm
- X_0(glue C)=(370±20) mm
- X_0(glue D)=(48±2) mm
- The glues A-C are expected to have a radiation length constant larger than 320 mm

X/X_0 measurements on ITk dummy module

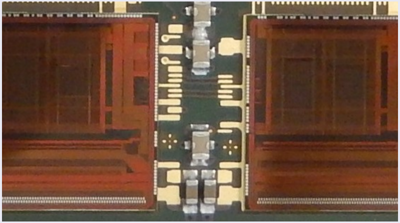
- Data from DESY TB in August 16
- ITk dummy module on a support structure with carbon fiber honeycomb structure
- beam energy 3GeV
- 140 mio tracks, image with 50 µm pixels

Telescope setup

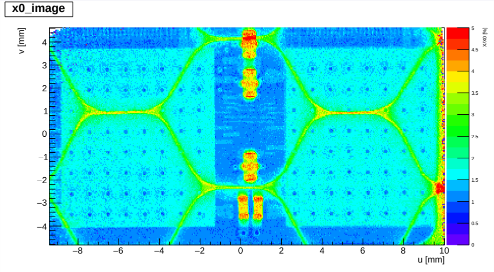


X/X_0 image of ITk dummy module with support structure

photograph



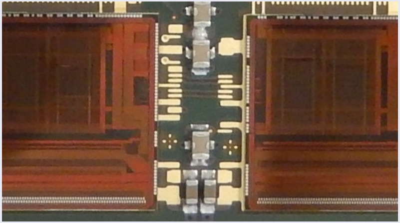
X0 image (3GeV, 50 μm^2 pixels)



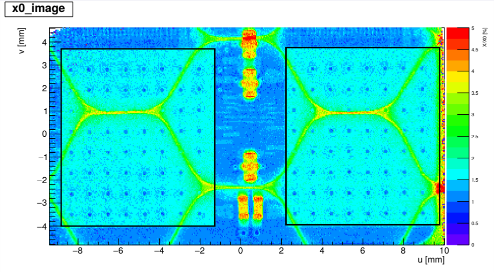
visible structures

X/X_0 image of ITk dummy module with support structure

photograph



X0 image (3GeV, 50 μm^2 pixels)

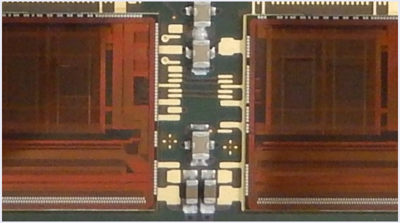


visible structures

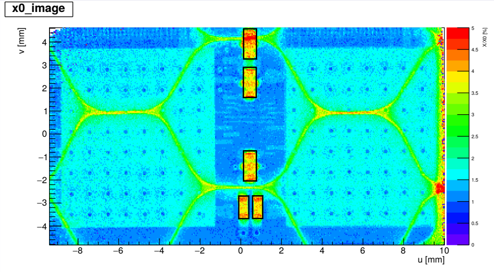
read-out chips,

X/X_0 image of ITk dummy module with support structure

photograph



X0 image (3GeV, 50 μm^2 pixels)

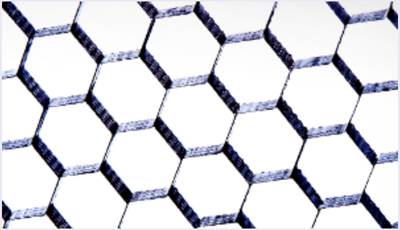


visible structures

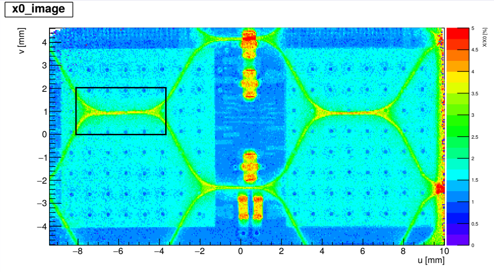
read-out chips, capacitor arrays with solder,

X/X_0 image of ITk dummy module with support structure

honeycomb structure



X0 image (3GeV, 50 μm^2 pixels)

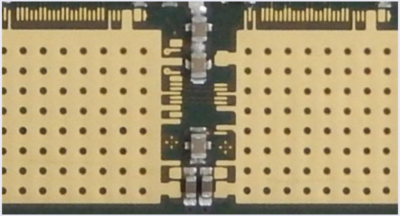


visible structures

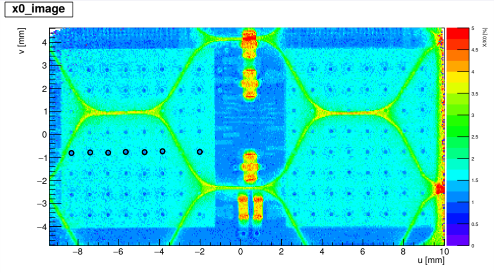
read-out chips, capacitor arrays with solder, honeycomb carbon fibers in support structure and glue halo,

X/X_0 image of ITk dummy module with support structure

photograph



X0 image (3GeV, 50 μm^2 pixels)

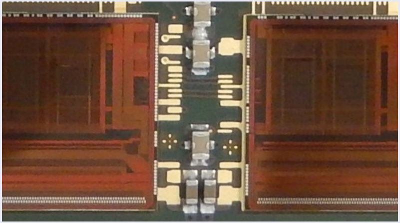


visible structures

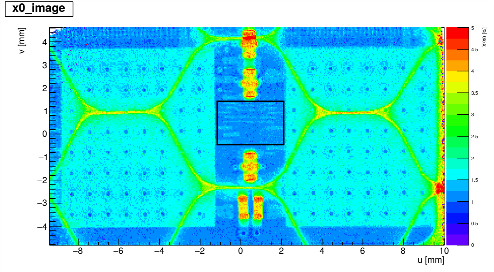
read-out chips, capacitor arrays with solder, honeycomb carbon fibers in support structure and glue halo, vias,

X/X_0 image of ITk dummy module with support structure

photograph



X0 image (3GeV, 50 μm^2 pixels)



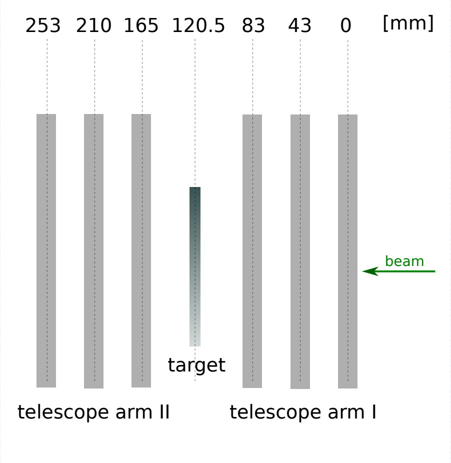
visible structures

read-out chips, capacitor arrays with solder, honeycomb carbon fibers in support structure and glue halo, vias, bond pads and metal traces

X/X_0 measurements on a Belle II pixel dummy module

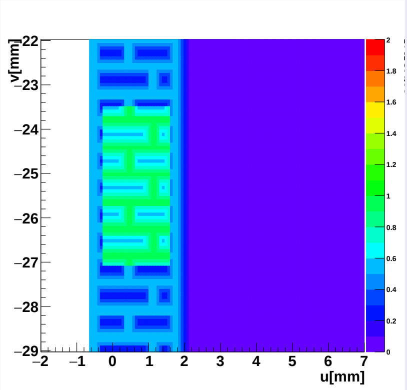
- Data from DESY TB in March 15
- Mechanical sample of a Belle II pixel module
- beam energy 4 and 2 GeV
- 50 and 45 mio tracks respectively, image with 75 µm pixels

Telescope setup

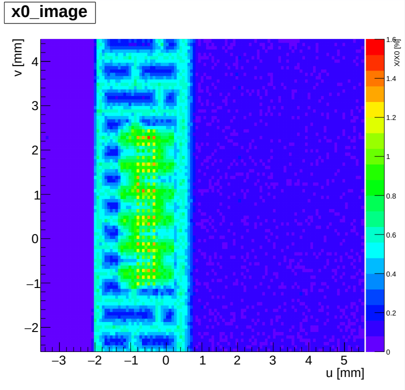


X/X_0 image of Belle II pixel dummy module

Geant 4 Detector model



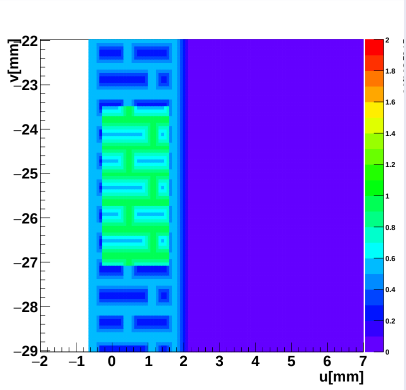
X0 image (2GeV, 75 μm^2 pixels)



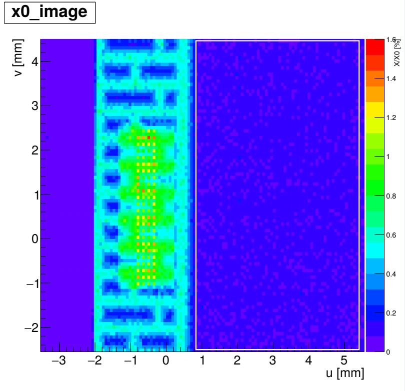
visible structures

X/X_0 image of Belle II pixel dummy module

Geant 4 Detector model



X0 image (2GeV, 75 μm^2 pixels)

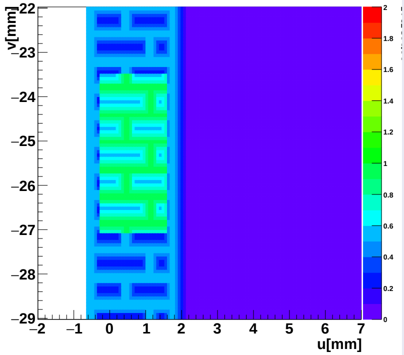


visible structures

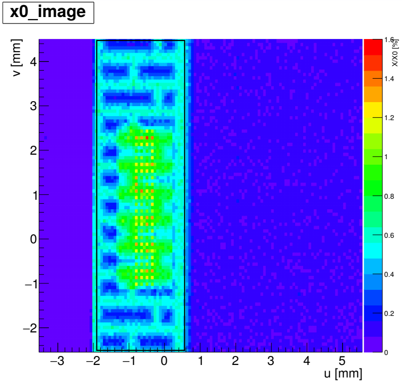
sensitive area,

X/X_0 image of Belle II pixel dummy module

Geant 4 Detector model



X0 image (2GeV, 75 μm^2 pixels)

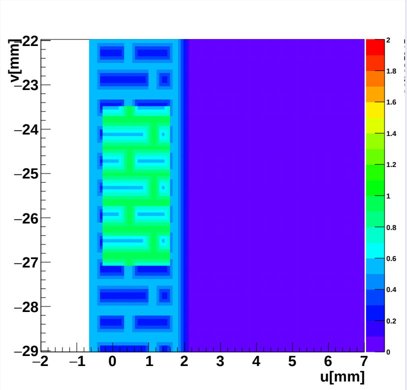


visible structures

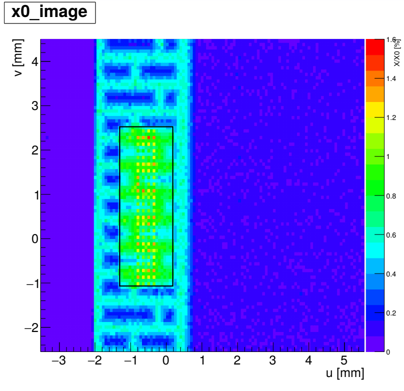
sensitive area, balcony with groove etchings,

X/X_0 image of Belle II pixel dummy module

Geant 4 Detector model



X0 image (2GeV, 75 μm^2 pixels)

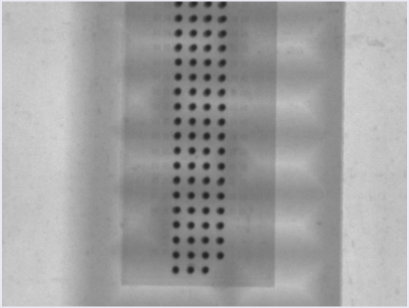


visible structures

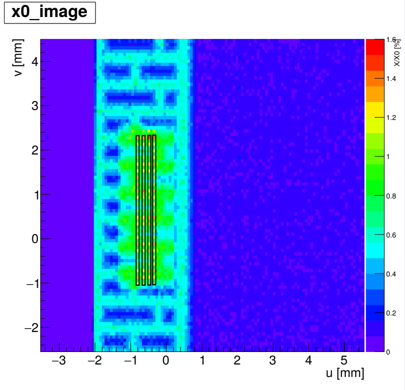
sensitive area, balcony with groove etchings, ASIC

X/X_0 image of Belle II pixel dummy module

X-ray of ASIC and bump bonds



X0 image (2GeV, 75 μm^2 pixels)

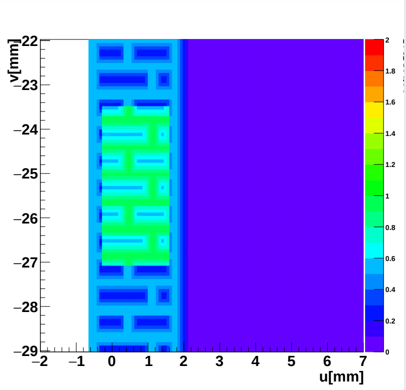


visible structures

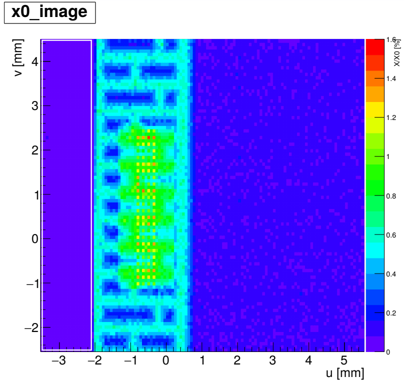
sensitive area, balcony with groove etchings, ASIC bump bonds,

X/X_0 image of Belle II pixel dummy module

Geant 4 Detector model



X0 image (2GeV, 75 μm^2 pixels)

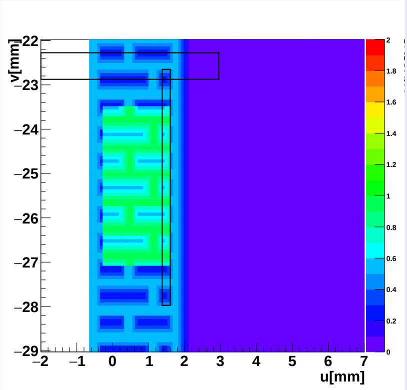


visible structures

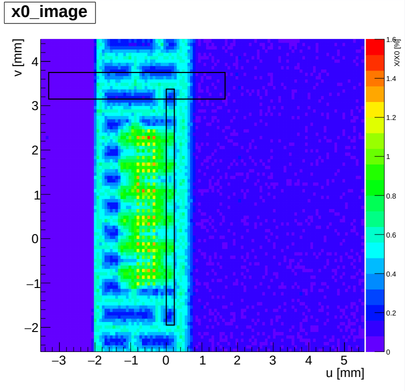
sensitive area, balcony with groove etchings, ASIC bump bonds, and air

X/X_0 image of Belle II pixel dummy module II

Geant 4 Detector model



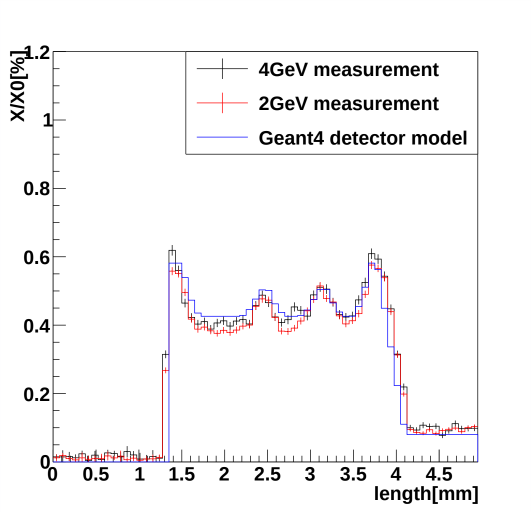
X0 image (2GeV, 75 μm^2 pixels)



Comparision of radiation length profiles between GEANT4 detector model and X/X_0 measurements

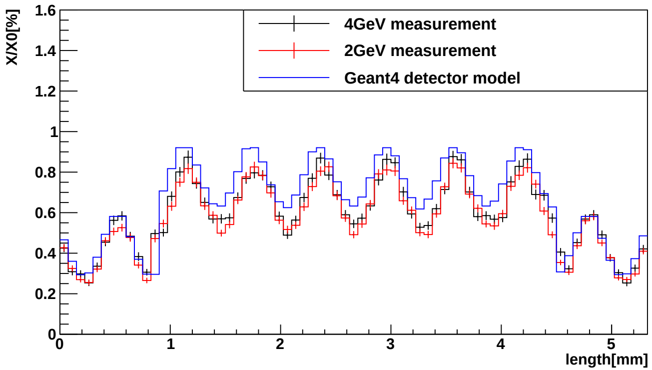
X/X_0 image of Belle II pixel dummy module II

u profile across the balcony



X/X_0 image of Belle II pixel dummy module II

v profile along the balcony



Conclusion and Outlook

Acknowledgment and disclaimer

- Measurements presented here were conducted at DESY with the DURANTA and DATURA beam telescopes
- The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025
- The information herein only reflects the views of its authors and not those of the European Commission and no warranty expressed or implied is made with regard to such information or its use

Conclusion and Outlook

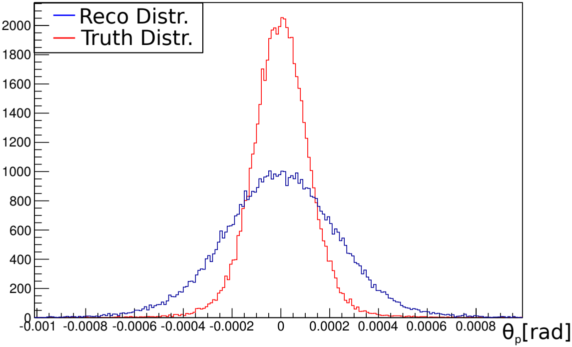
Conclusion and Outlook

- Spatially resolved radiation length measurements can be used to cross check GEANT4 and CAD detector models
- Small structures like 50 µm diameter bump bonds can be resolved
- X/X_0 resolution good enough to measure 75 µm of silicon ($X/X_0 \approx 0.08\%$)
- Additionally the material constant X_0 of previously unknown detector components like for example glue can be determined
- Measurements can easily be conducted, the only requirements are:
  - A high-resolution telescopes, which are for example present at the DESY test beam facilities
  - A calibration target, for example a single or multiple aluminium plates with different thicknesses
  - A few hours of beam time

Thank you!

Backup Slides

Example of a reconstructed angle distribution



Composition of the Reco Distribution

Reconstructed MSC angle distribution is a convolution between the pure MSC angle distribution and a Gaussian noise distribution caused by the reconstruction errors

MSC models

Highland (HL) model

$$\sigma = \frac{0.0136 \cdot q[e]}{\beta \cdot p\,[\mathrm{GeV}]} \cdot \sqrt{\frac{X}{X_0}} \left(1 + 0.0038 \ln\left(\frac{X}{X_0}\right)\right)$$

V. L. Highland, *Some practical remarks on multiple scattering*, Nuclear Instruments and Methods,1975

Moliere model

$$f(\theta)\,\mathrm{d}\theta = \frac{1}{\chi_c \sqrt{B}} \left(\frac{2}{\sqrt{\pi}} e^{-\frac{\theta}{\chi_c \sqrt{B}}} + \frac{f_1(\theta)}{B} + \frac{f_2(\theta)}{B^2} \right) \mathrm{d}\theta \text{ , where}$$

$$\chi_c = \frac{22.9\, z\, Z}{p\, c\, \beta} \cdot \sqrt{\frac{\rho X}{A}} .$$

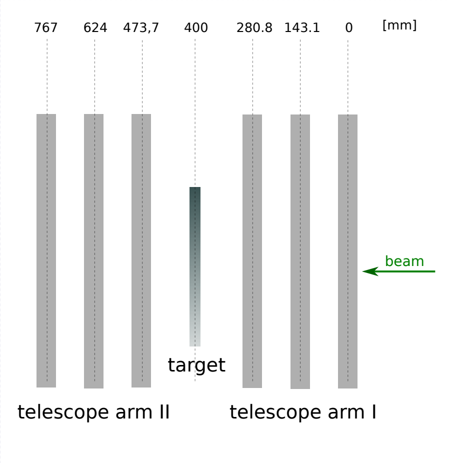
Correction terms f_1 and f_2. Values can be calculated or taken from a table (see paper by Moliere).

Moliere, Z. Naturfschg 1948

X/X_0 measurements on different glue samples

- Data from a DESY TB in 2016
- 4 glue samples (A-D)
- glue A-C: $X \approx 10mm$ embedded in brass plate
- glueD: Conductive silver glue with $X = 1.83$ mm
- beam energy 4.6 GeV, $\sigma_{\mathrm{err}} = 113$ µrad
- approximately 8 mio tracks per glue sample
- Calibration parameters: λ=1.104 ± 0.001, κ=1.040 ± 0.002

Telescope setup



X/X_0 measurements on ITk dummy module

- Data from DESY TB in August 16
- beam energy 3GeV
- 140 mio tracks, image with 50 µm pixels
- nominal angle resolution σ_{err}=246 µrad
- Calibration parameters: λ=1.040 ± 0.001, κ=0.915 ± 0.001

Telescope setup