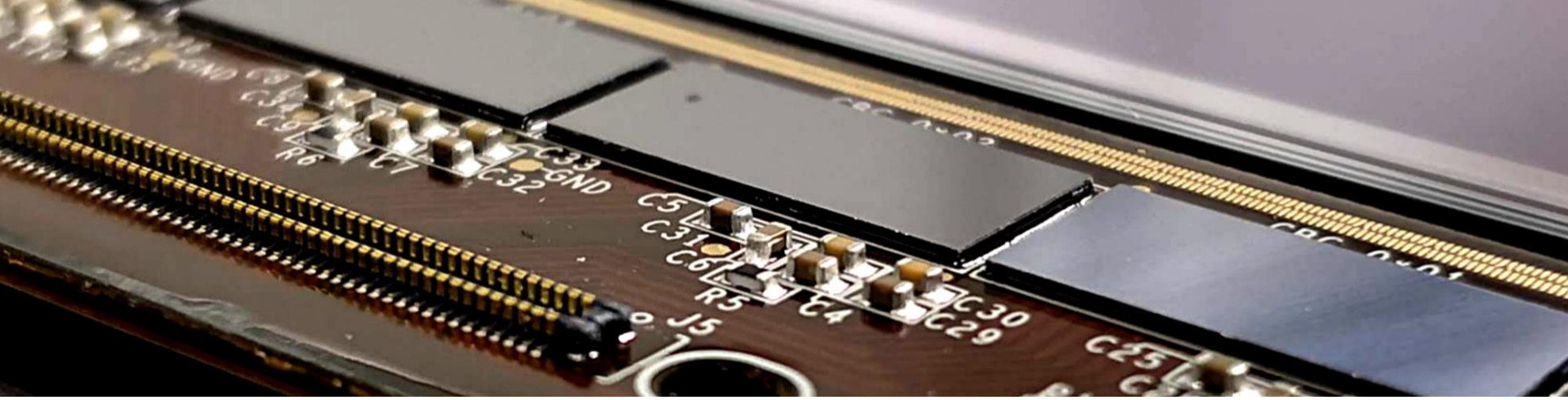

Beam test of 2S module prototypes for the Phase-2 CMS Outer Tracker

9th Beam Telescopes and Test Beams Workshop
10.02.2021

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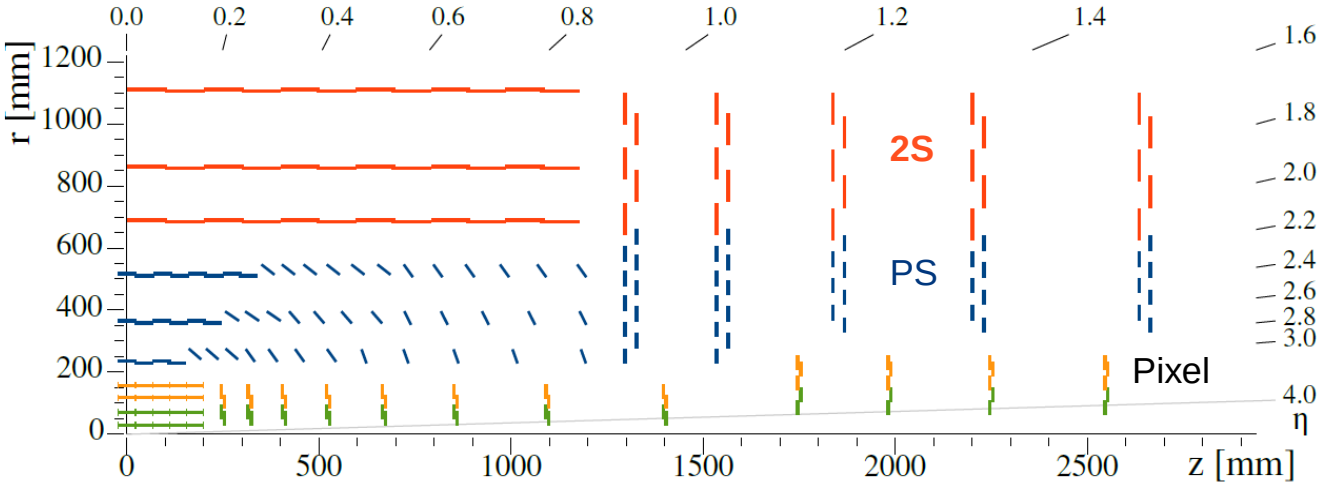
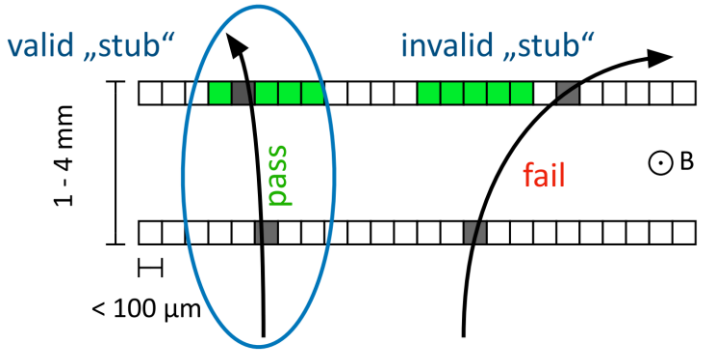
Introduction

Phase-2 tracker upgrade



From *The Phase-2 Upgrade of the CMS Tracker: Technical Design Report*

- HL-LHC upgrade: peak luminosities of $5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Replacement of entire tracker (radiation damage, more pileup)
- Tracker information for L1 trigger
- Design of PS and 2S modules driven by track trigger concept
  → two stacked sensor layers for p_T information



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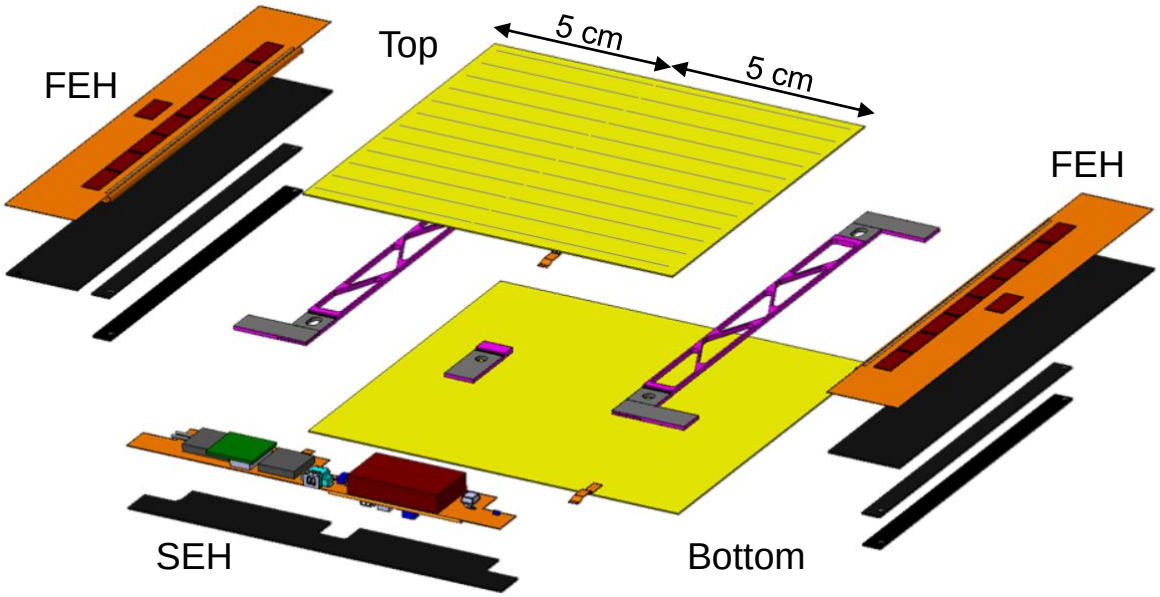
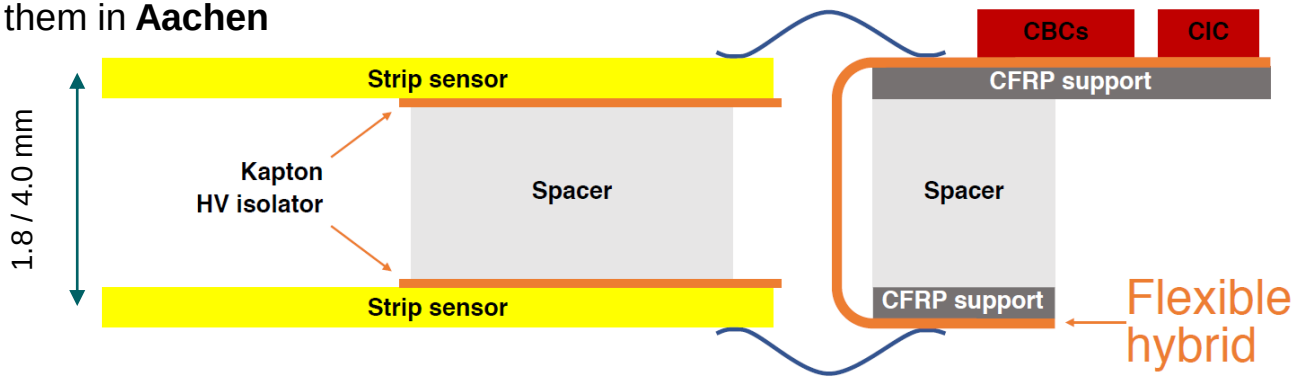
Introduction

2S module

- 2 coplanar strip sensors
- 2x1016 strips each
  - 90 µm pitch, 2x5 cm long
- Sensors electrically connected to front end hybrids via wire bonds
- CMS Binary Chips (CBCs) to form stubs
- Communication with backend and powering via service hybrid (SEH)

- 7,680 modules in Phase-2 tracker
- **Production** and **test** of at least **1,000** of them in **Aachen**

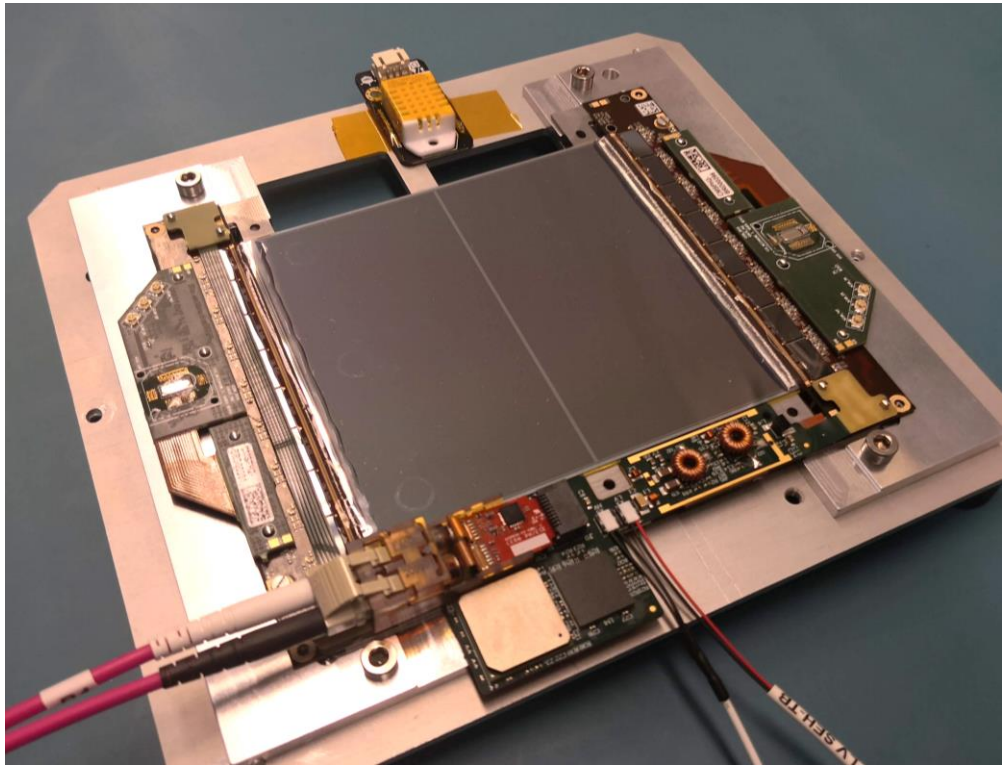




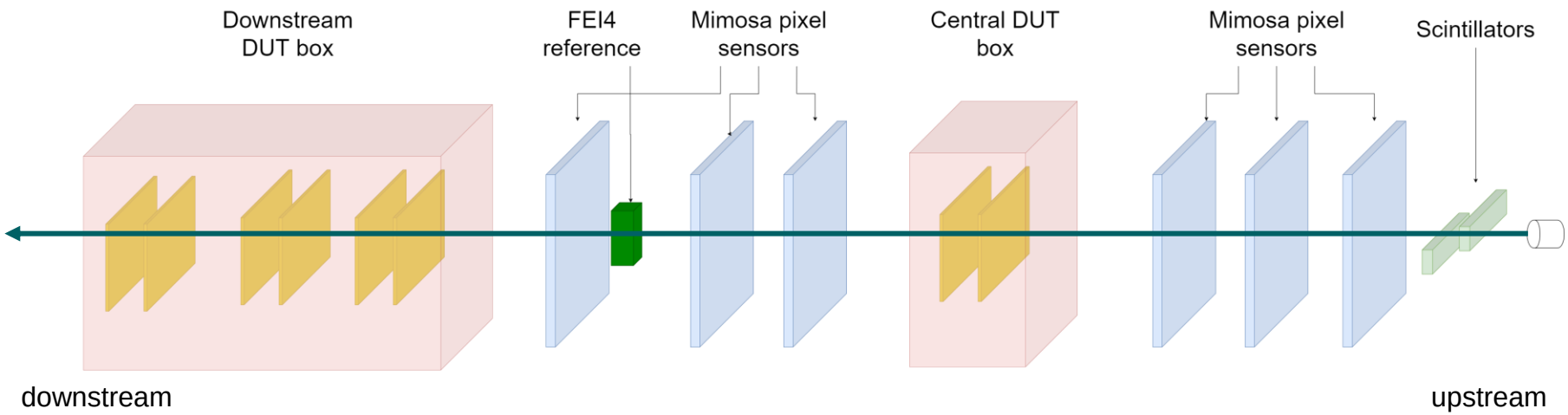
From *The Phase-2 Upgrade of the CMS Tracker: Technical Design Report*

Beam test

- Beam test in November / December 2019
- Goal:
  - Test newest generation of 2S module
  - Test functionality of CIC chips
  - Test functionality of SEH in module readout: optical readout and powering
  - Test readout of more than one module synchronously:
    - 1 module from KIT
    - 1 module from Brown University
    - 2 modules from RWTH Aachen
- Test at beam test facility DESY II with DATURA telescope (test beam line 21)
- Contribution from:
  CERN, Antwerp, Brussels, Karlsruhe, Aachen, DESY, Demokritos, Lyon, Brown

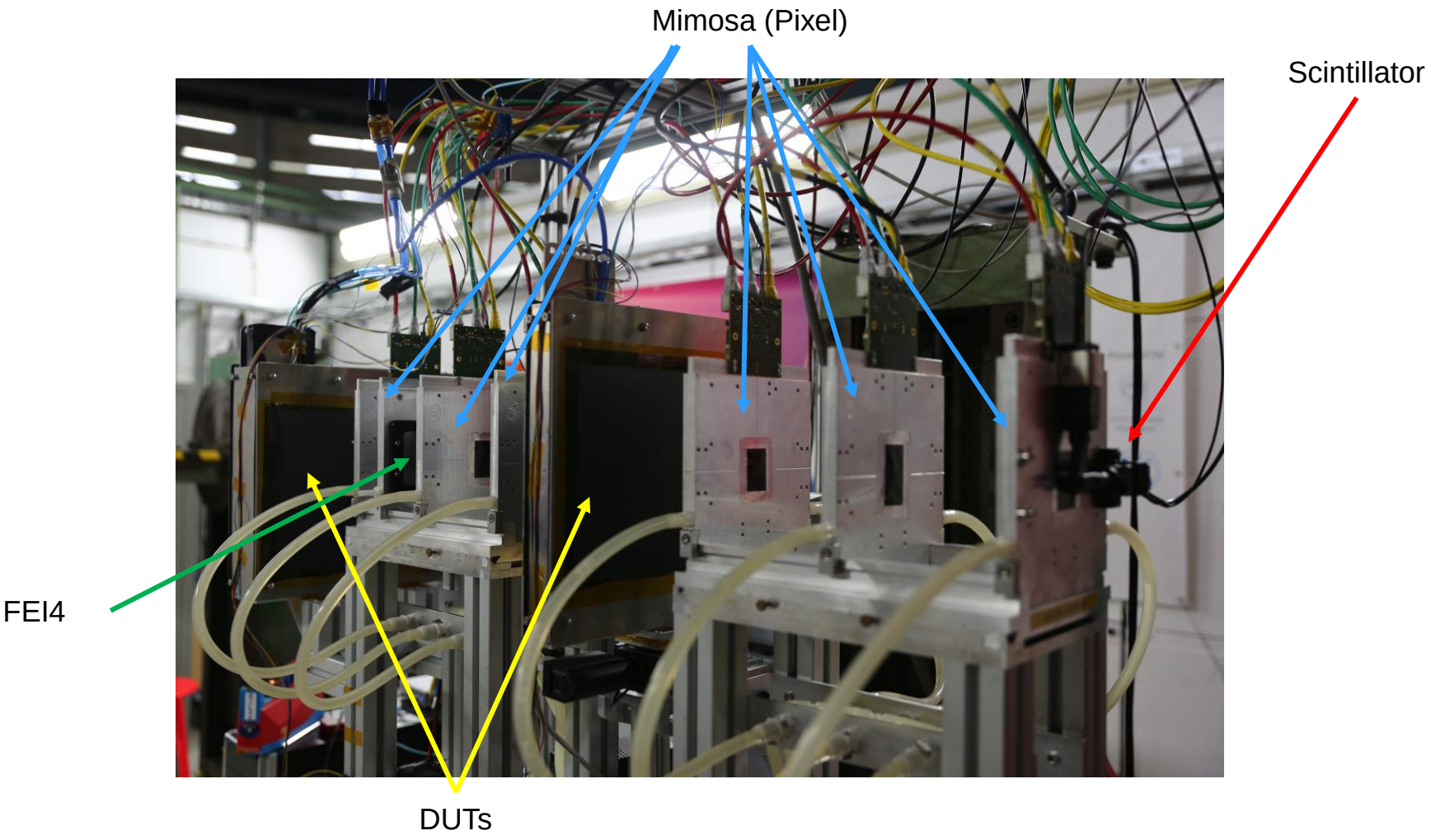


Beam test telescope



- Running with 4 GeV electron beam
- Used crossed scintillator pair on upstream end of telescope as trigger
- Mimosa pixel modules used for track reconstruction (576 x 1152 pixels, 18.5 µm pitch)
- Used FEI4 pixel module as time reference detector (80 x 336 pixel matrix, 50 x 250 µm pixel size)
- Central DUT box mounted on xy stage with rotation
- Downstream DUT box houses three DUT modules, fixed position

Beam test telescope



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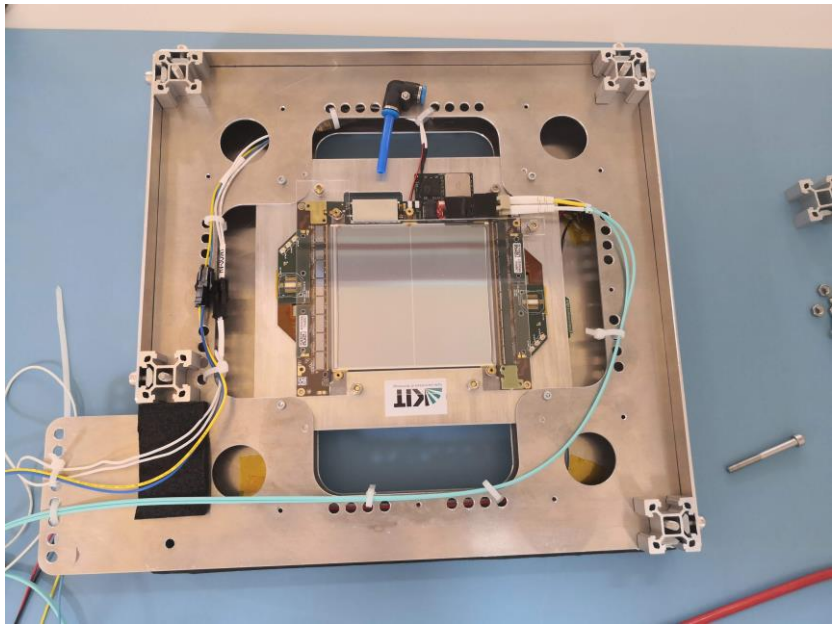
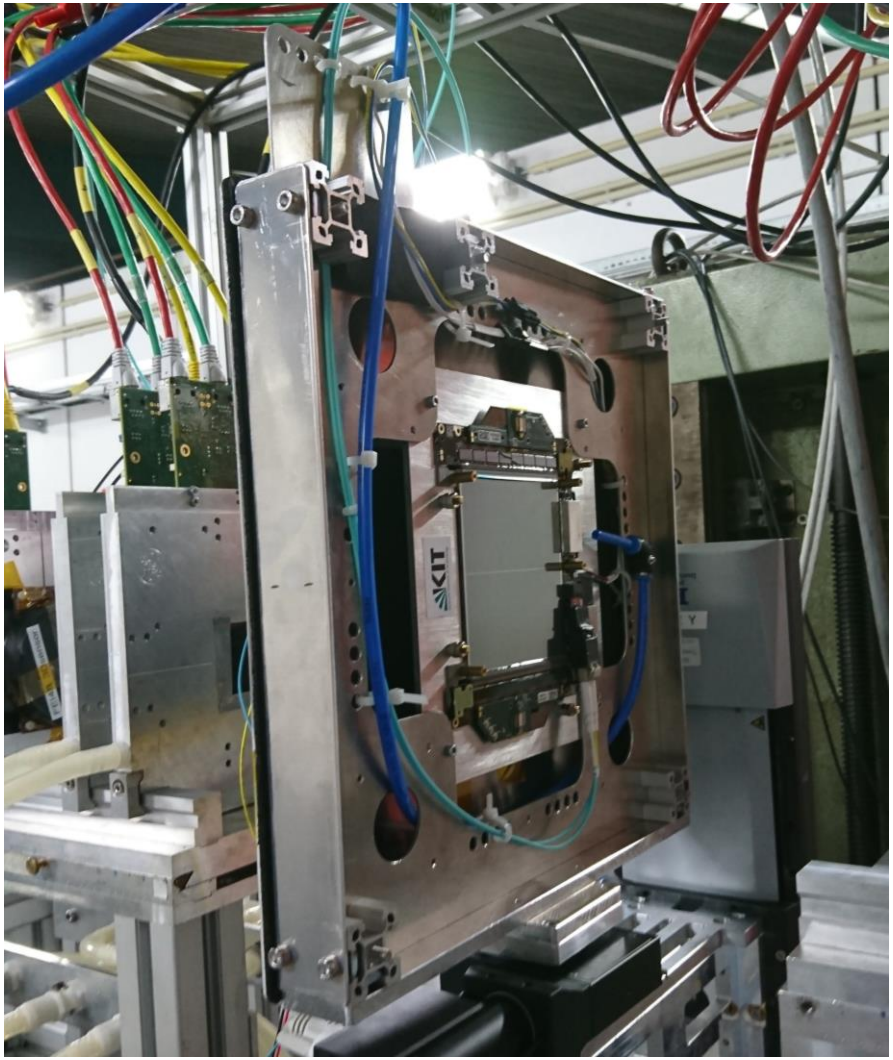
Beam test telescope

- Boxes designed and manufactured at DESY
- Light tight aluminum case
- Fixation plate with many drill holes for
  - Fixation of 2S module on carrier
  - Guidance of LV and HV power
  - Guidance of optical fibre
  - Guidance of dry air tube
- Mounting socket for fixation on rotation stage





Telescope alignment and detector resolution

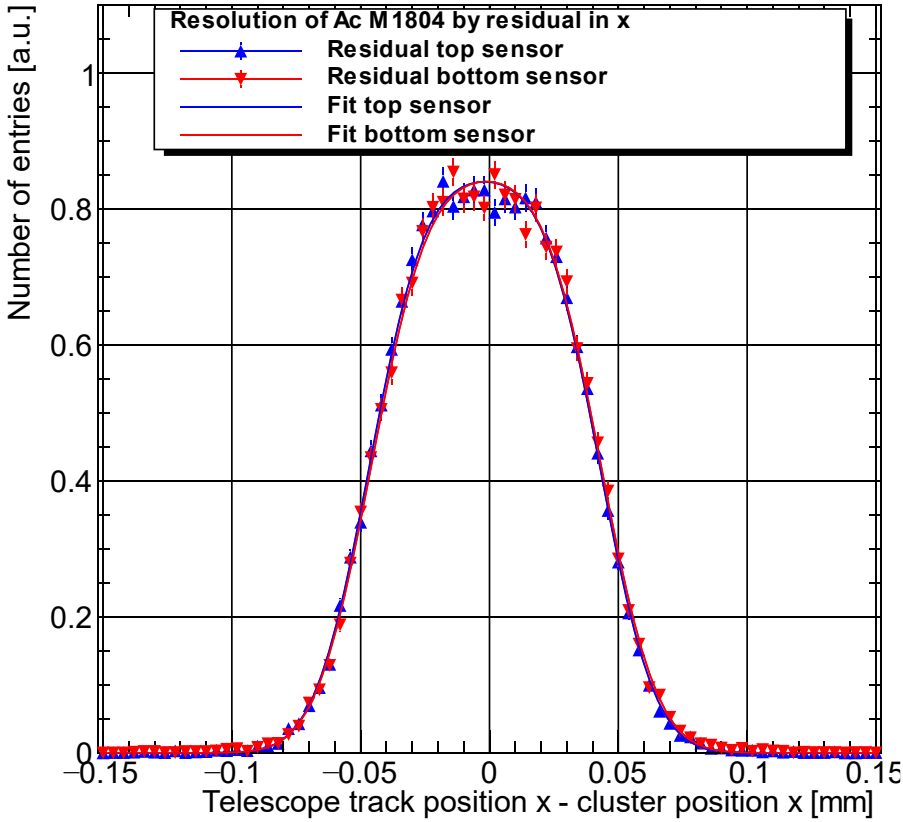
- Used EUTelescope for data conversion and telescope alignment
- Residual centered around 0
- Binary readout and strip pitch of 90 µm
- Expect residual distribution to have shape of rectangle function convolved with Gauss distribution for telescope track uncertainties

$$P_{res}(x) = \int_{-\infty}^{\infty} \left[\Theta\left(t+\frac{w}{2}\right) - \Theta\left(t-\frac{w}{2}\right)\right] \cdot \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(t-x)^2}{2\sigma^2}\right) dt$$
$$= \frac{1}{2}\left[\mathrm{erf}\left(\frac{x+\frac{w}{2}}{\sqrt{2\sigma^2}}\right) - \mathrm{erf}\left(\frac{x-\frac{w}{2}}{\sqrt{2\sigma^2}}\right)\right]$$

- Fit parameters:

Parameter	Top	Bottom
W	89.2 ± 0.6 µm	89.0 ± 0.6 µm
σ	16.9 ± 0.3 µm	17.3 ± 0.3 µm

- Total RMS of residual: 31.5 µm



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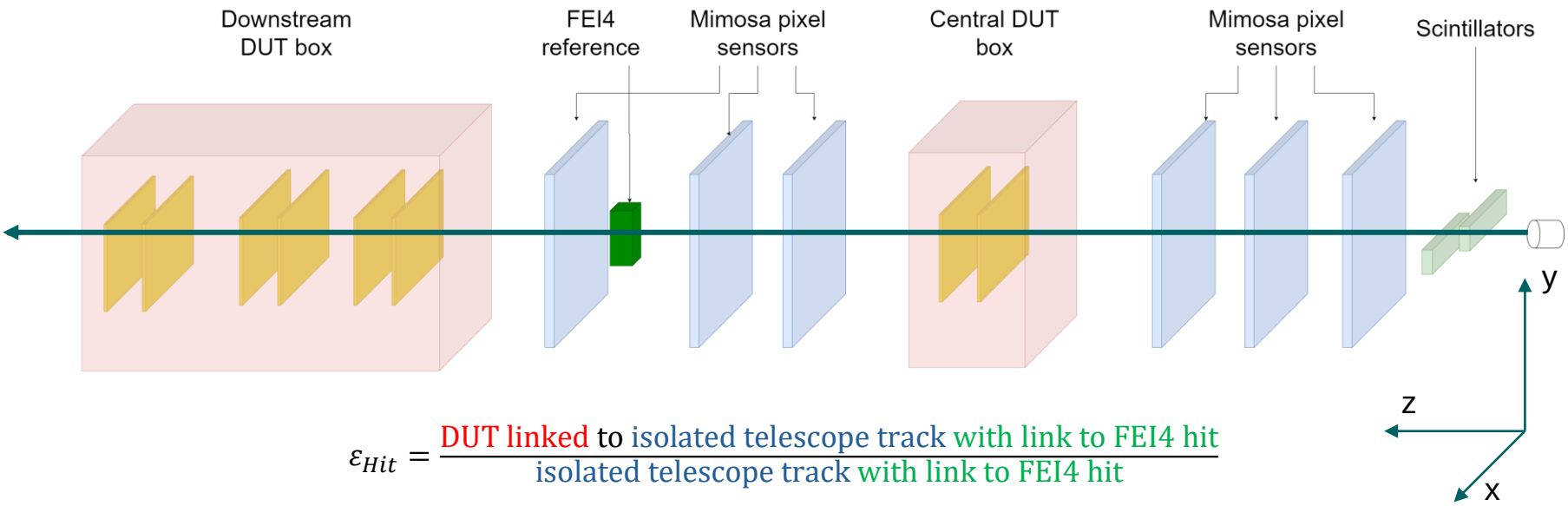
Efficiency definition



$$\varepsilon_{Hit} = \frac{\text{DUT linked to isolated telescope track with link to FEI4 hit}}{\text{isolated telescope track with link to FEI4 hit}}$$

- FEI4 link: cut 200 µm in x and 80 µm in y
- Isolation: no other telescope track within 600 µm at FEI4
- DUT link: 200 µm cut in x (perpendicular to strip direction)

- Stub efficiency:
  - Cut on events passing hit efficiency criteria
  - Comparing number of online stubs from CBC to number of offline stubs reconstructed from clusters

$$\varepsilon_{Stub} = \frac{N_{CBC\ stubs}}{N_{reco\ stubs}}$$

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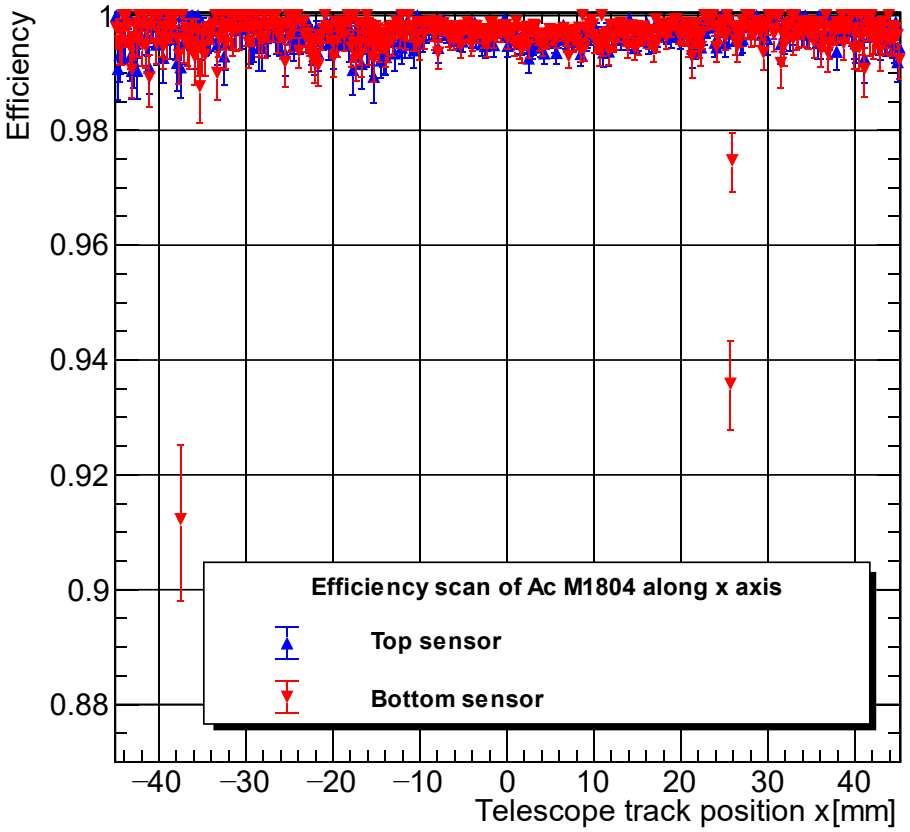
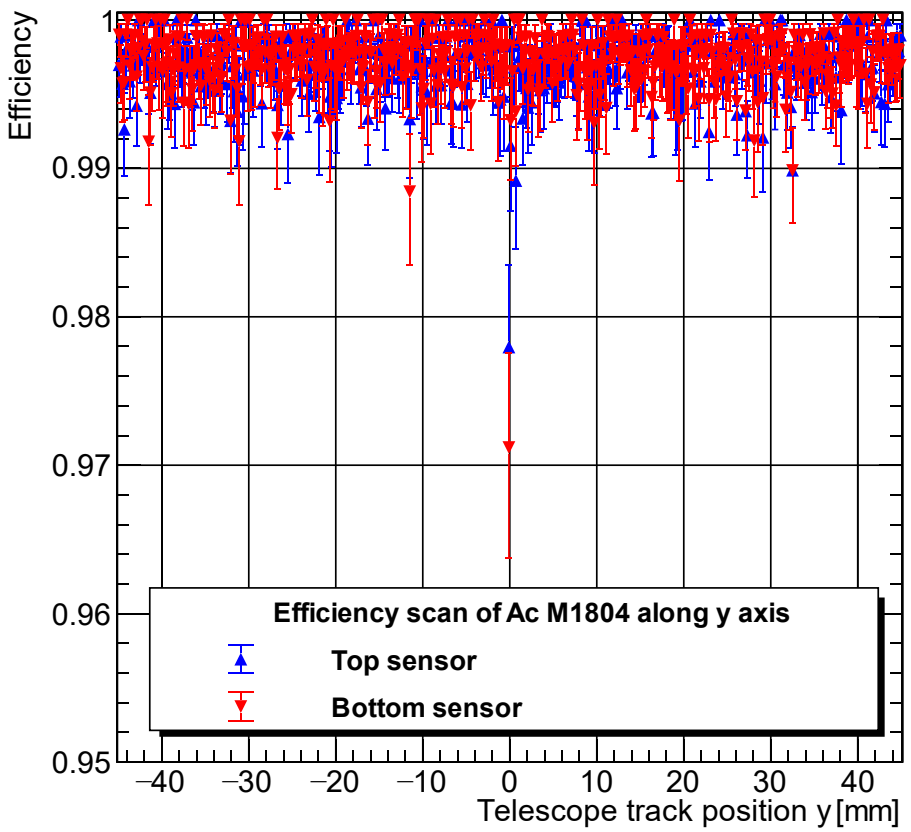
Uniformity of efficiency

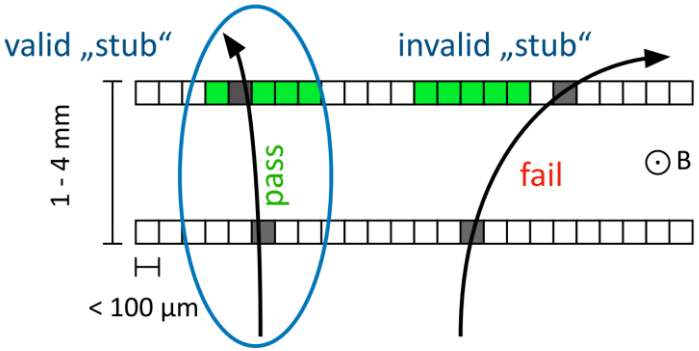


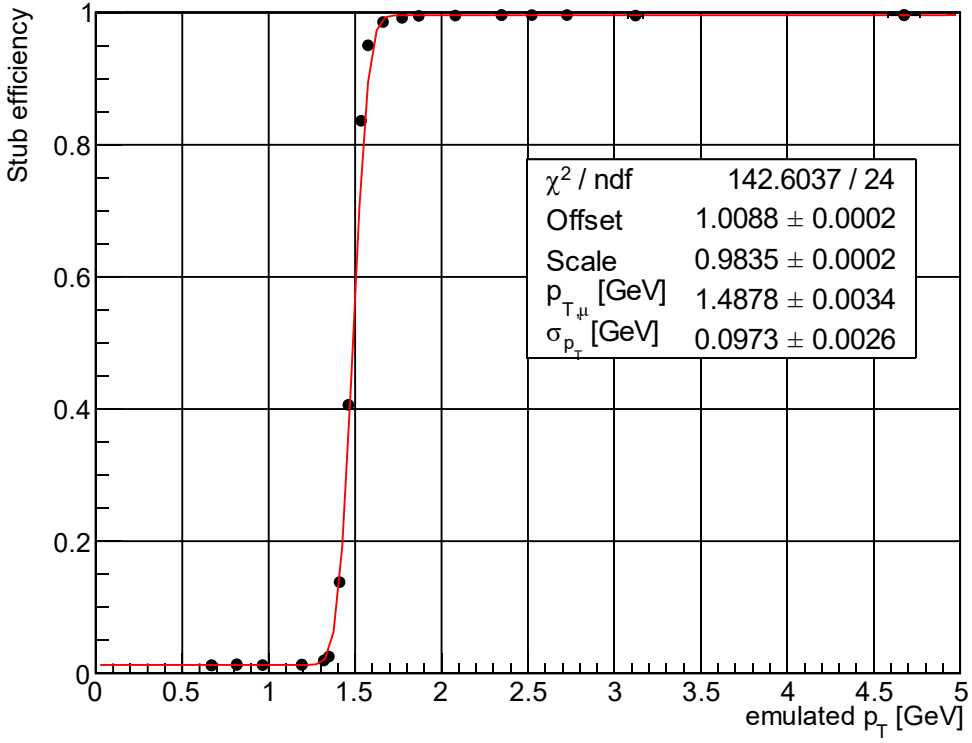


- Moved module along x axis (perpendicular to strips) and y axis (along strips) to check uniformity of efficiency
- Efficiency well above 99 %
- Two unconnected channels on bottom sensor, efficiency drop in center (y = 0 mm) by ~2%

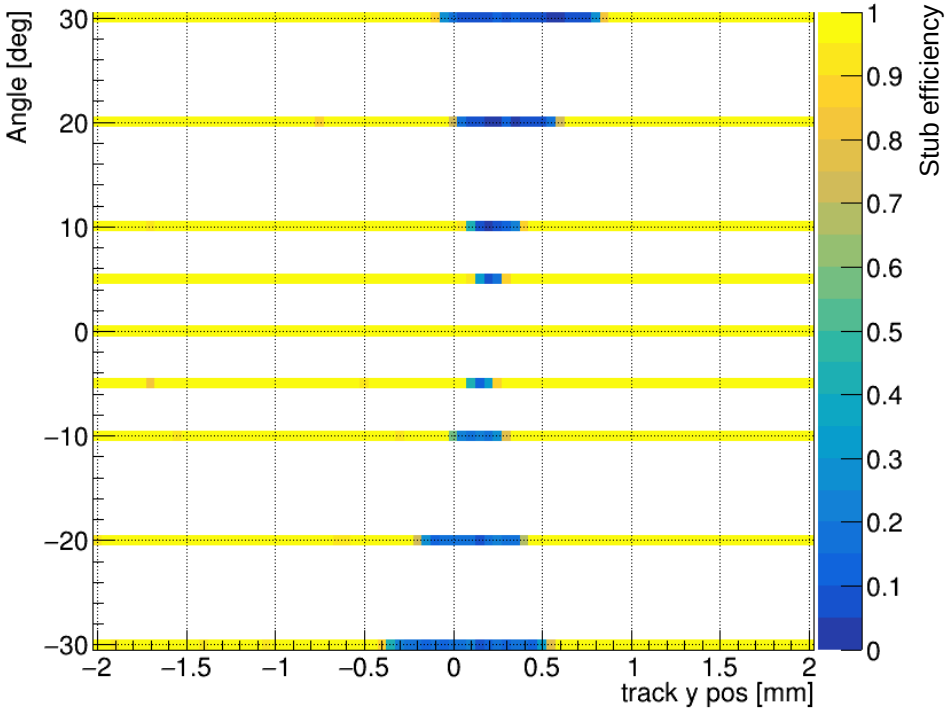
Angle scan

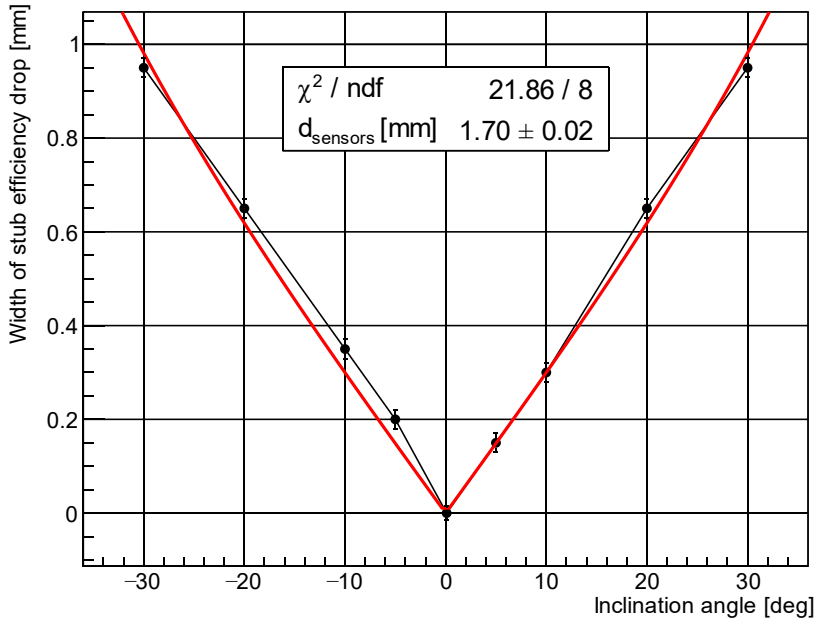
- Rotate 2S module around strip axis to mimic particles of different p_T in magnetic field
- Transformation to p_T:
  - $p_T[GeV] = 0.57 \cdot \frac{R_{module}\,[m]}{\sin(\theta)}$ for magnetic field of 3.8 T
  - Transformation with $R_{module} = 0.715\ m$ (approximately first barrel layer)
- Fitted error-function:
  - $\varepsilon_{stub} = \frac{1}{2} \cdot \left[\text{Offset} + \text{Scale} \cdot \text{erf}\left(\frac{x - p_{T_\mu}}{\sigma_{p_T}}\right)\right]$
  - Turn-on at about 1.5 GeV
  - In good agreement with expectation from stub window setup of ± 5 strips





Angle scan





- Angle scan with rotation around mid sensor axis (around x axis)
- Stubs formed in CBC on either side of the module → possible efficiency loss in center of module if cluster on right / left side on top sensor and left / right side on bottom sensor
- Expect inefficiency drop to become larger for higher inclination angles
- Model: $W = d_{sensors} \cdot |\tan(\theta)|$, $d_{sensors}$ is distance between both sensors
- Width of inefficiency region (cut at conservatively picked 85% stub efficiency) fits naïve geometric expectation

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Summary & outlook

- Built 2S prototype module and tested performance at DESY beam test facility with DATURA telescope
- Module efficiency well above 99%, gap in center slightly less efficient
- Stub mechanism proved to work fine
- Stub efficiency drops in center for increasing inclination angles

- Paper in preparation

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

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