Beam Test Studies on 2S Module Prototypes for the CMS Phase 2 Tracker Upgrade

KSETA Plenary Workshop 2020 – 19 February 2020

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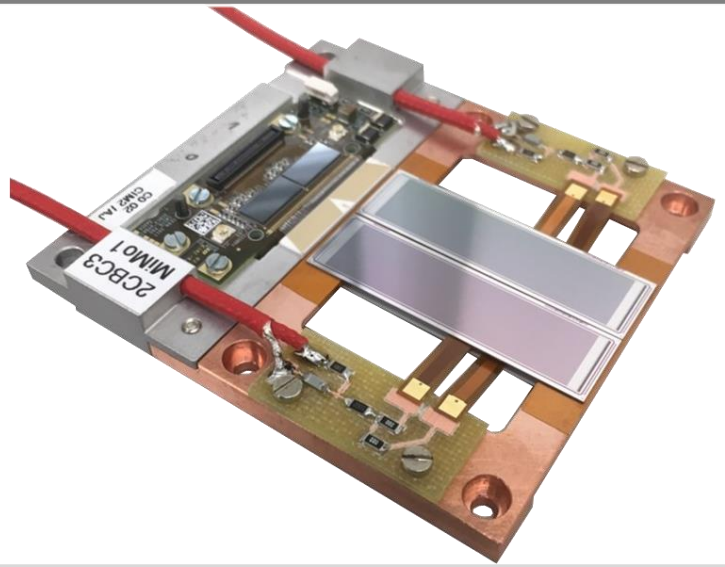
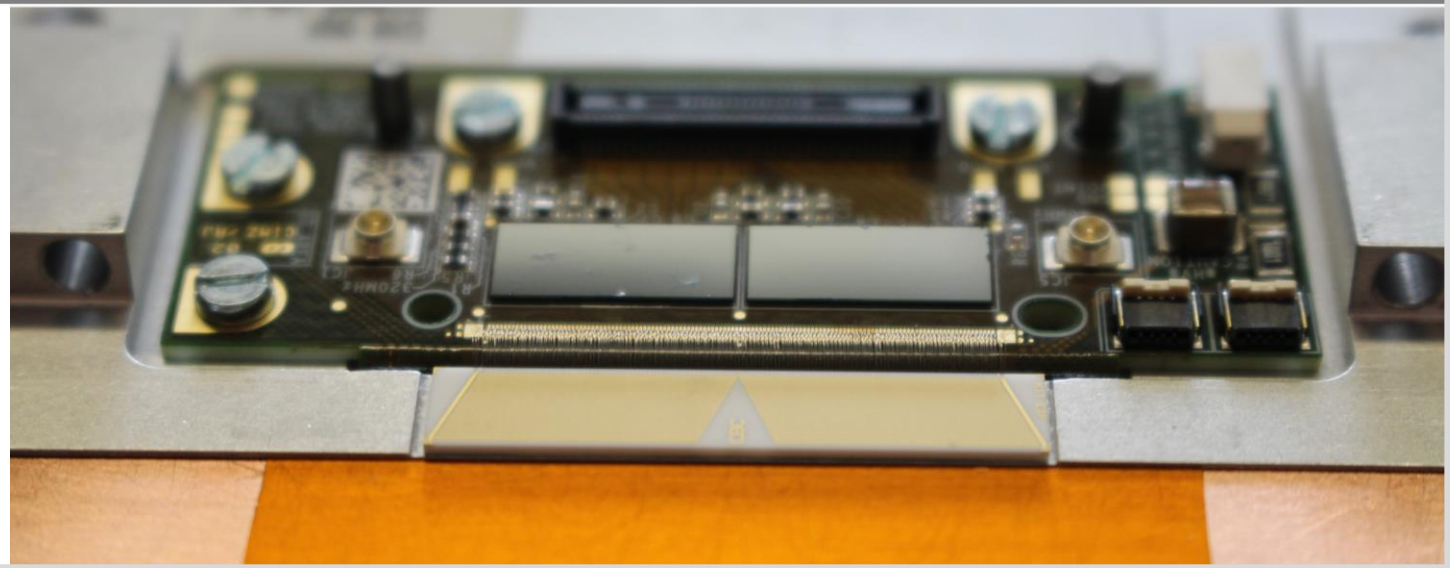
INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK, KARLSRUHER INSTITUT FÜR TECHNOLOGIE





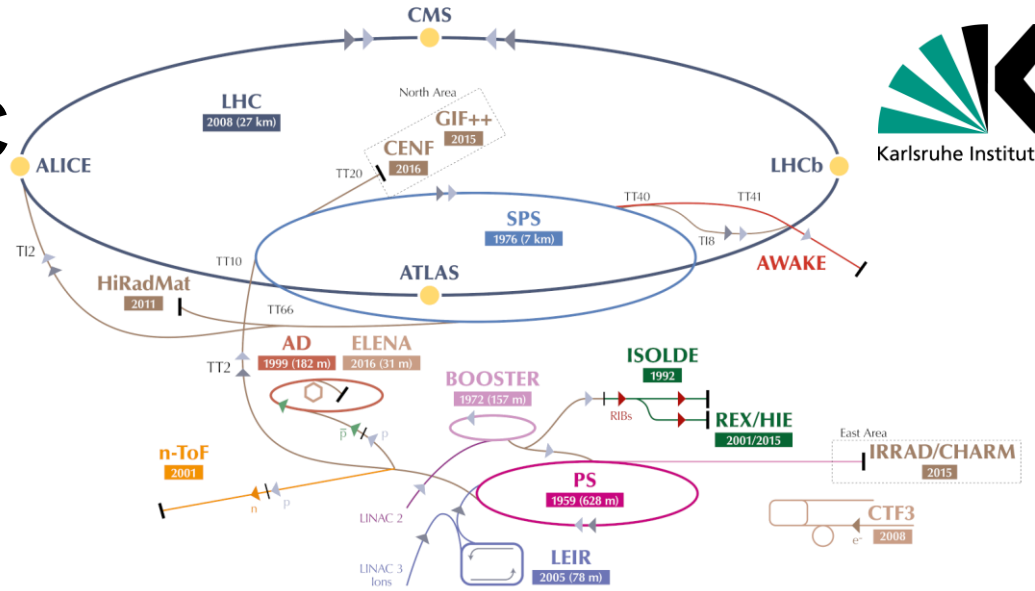
Content

- The High Luminosity LHC
- Particle detection with silicon detectors
- Prototyping and Beam Test at DESY
- Summary and Outlook

THE HIGH LUMINOSITY LHC

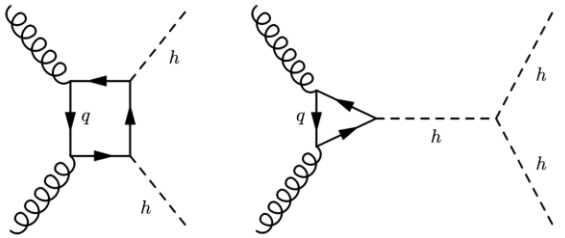
and the CMS Phase 2 Tracker Upgrade

The (High Luminosity) LHC

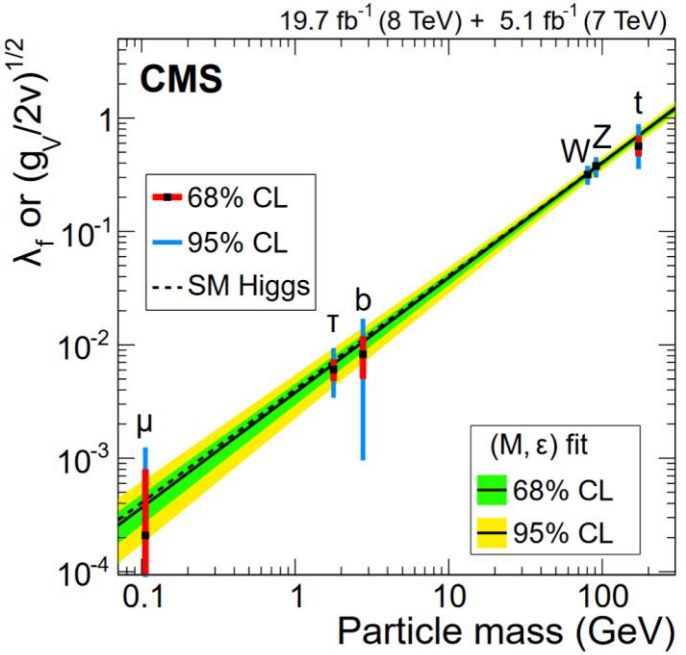


- Proton-proton collisions at
  - $\sqrt{s}$ = 13 TeV
  - 40 MHz bunch crossing rate

- High Luminosity LHC (HL-LHC)
  - Begin of operation in 2027
  - 5 to 7 times higher luminosity → increased interaction rate
  - 3000fb^{-1} after 10 years



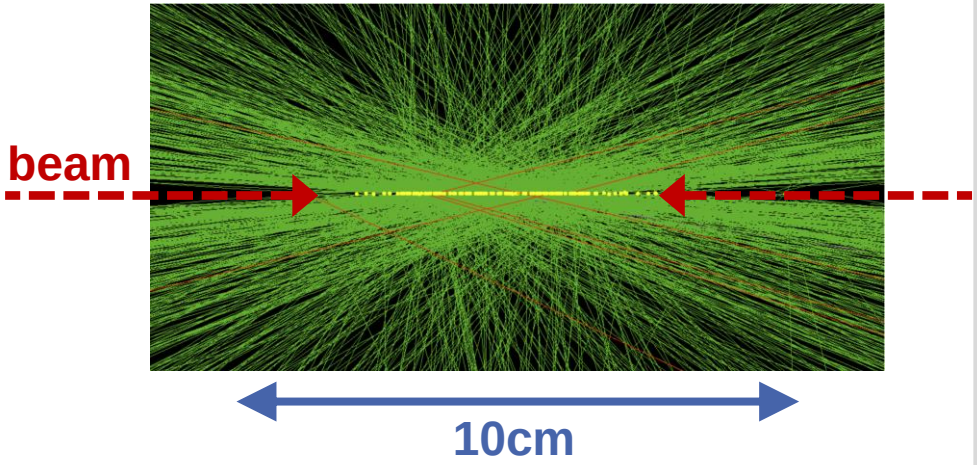
- But why high luminosity??
  - Precision measurements of key physics processes (e.g. Higgs coupling) improves with integrated luminosity (= statistics)!

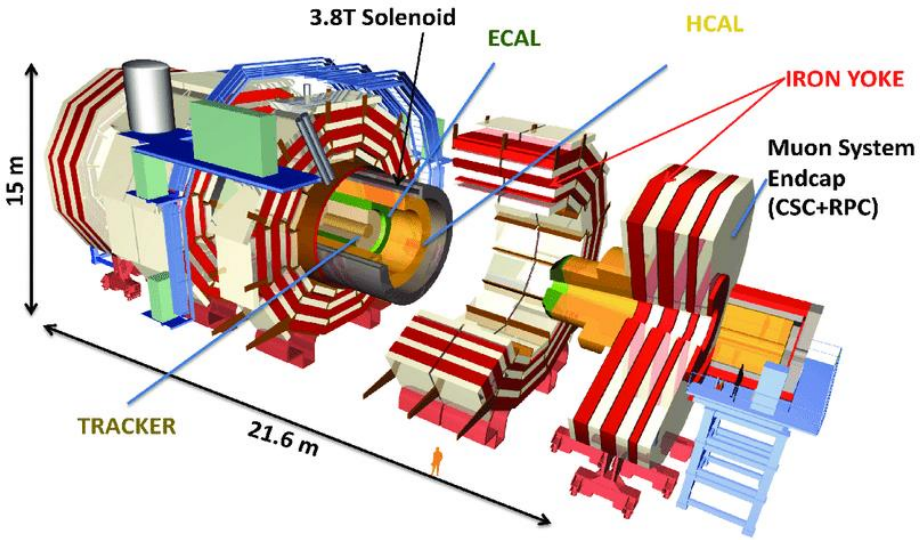


The CMS Phase 2 Upgrade

HL-LHC

- increased **pileup**: up to 200 interactions per BX
- Higher trigger rates and data output
- Higher radiation levels
- Efficient operation for at least 10 years





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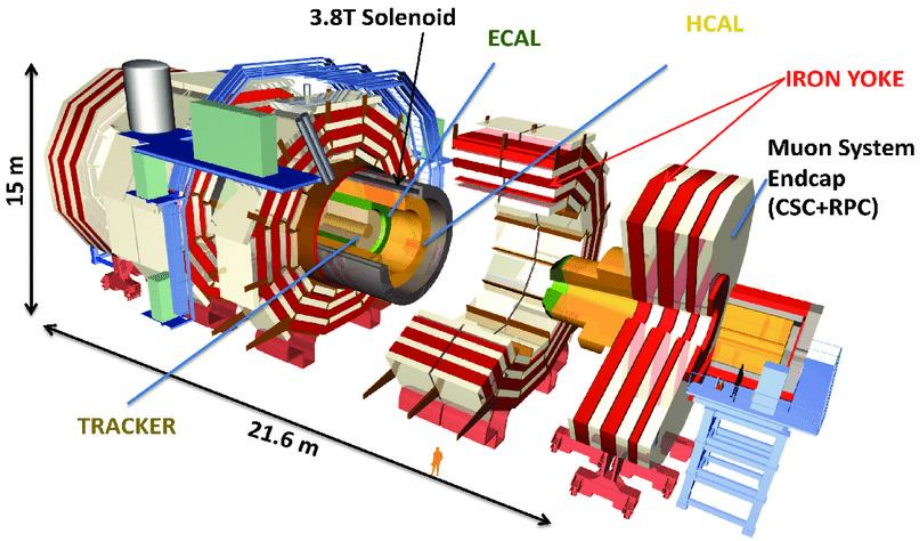
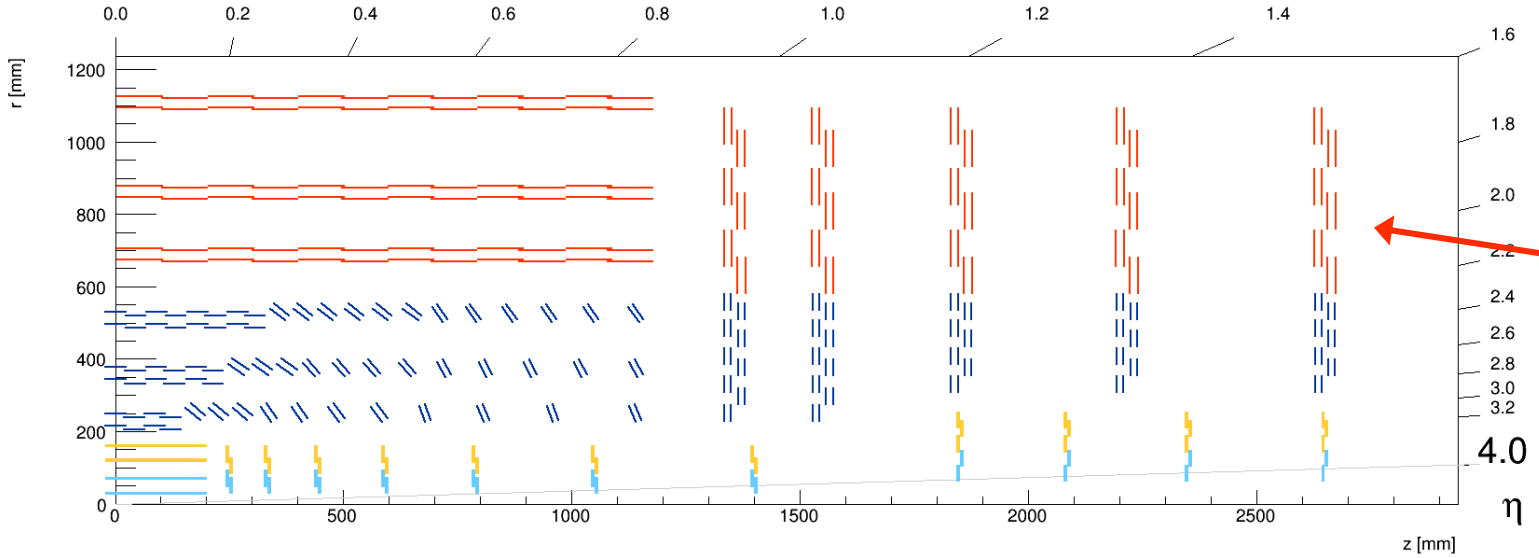
Upgrade of all subdetector systems

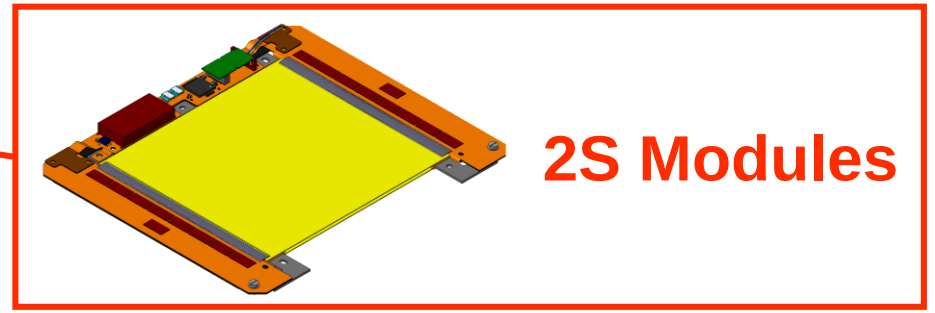


The Phase 2 Upgrade: Outer Tracker

Replacement of the current tracker

- Contribution to CMS trigger
- Higher granularity
- Data reduction by binary readout
- Improved radiation tolerance
- Increased trigger rate
- Less material

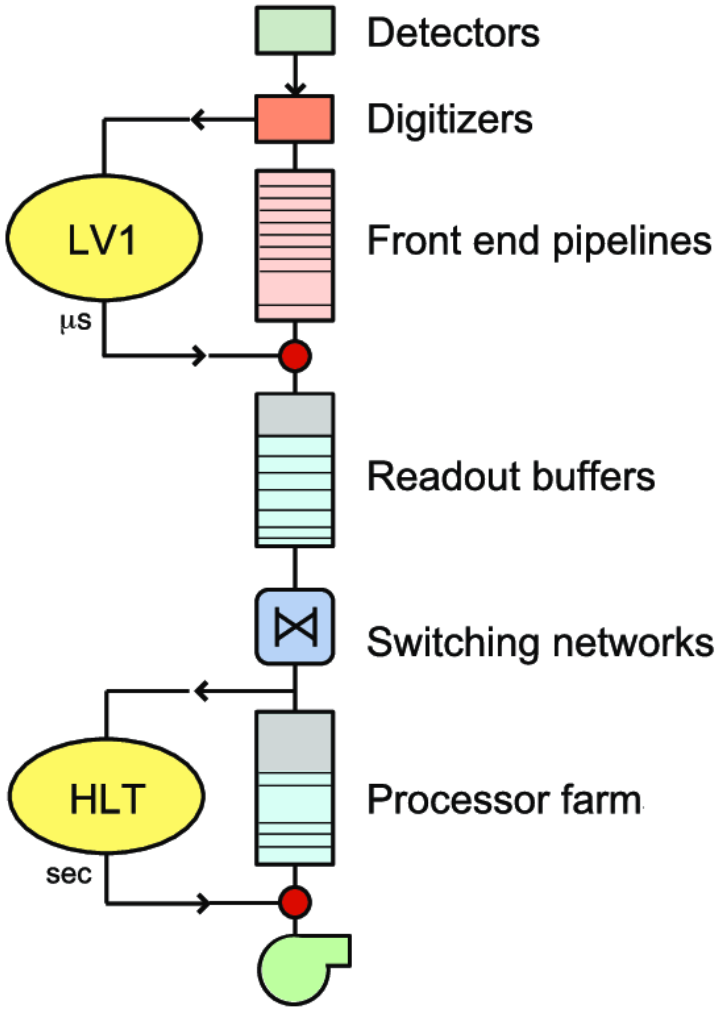




What is the CMS trigger?

- Not possible to read out and store all events!
- CMS Trigger decides which events are on disk
  - Search for trigger primitives
- Hardware based readout decision by LV1 trigger stage within µs
- Software based reconstruction by HLT
  - Storage decision within seconds

- **HL-LHC: new Trigger!**
  - LV1 uses tracking information for better trigger performance

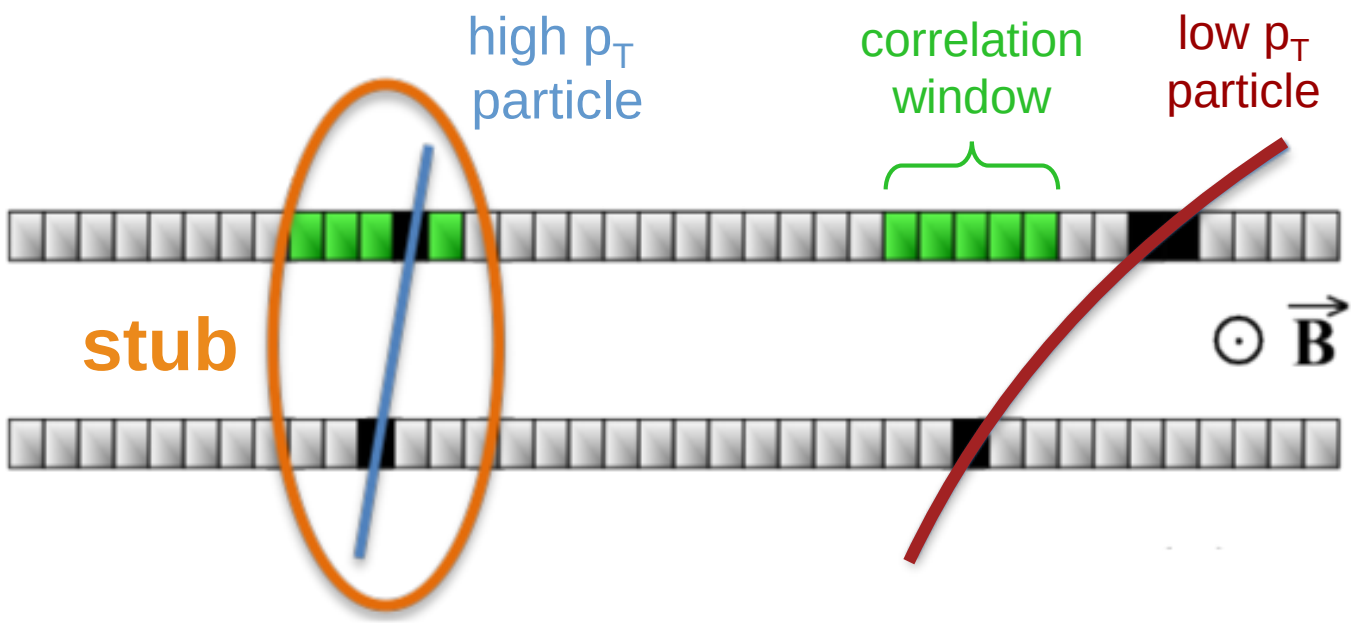


p_T Module Concept

- High pileup at HL-LHC
- tracker data exceeds available bandwith

Identify particles with $p_T > 2\ \mathrm{GeV/c}$ on module level

- Spatial correlation of hits in two sensor layers in strong B-field
  - Low p_T → strong bend
  - High p_T → low bend
    → generate stub
- Send stubs to LV1 trigger
  - LV1 track finding with stubs



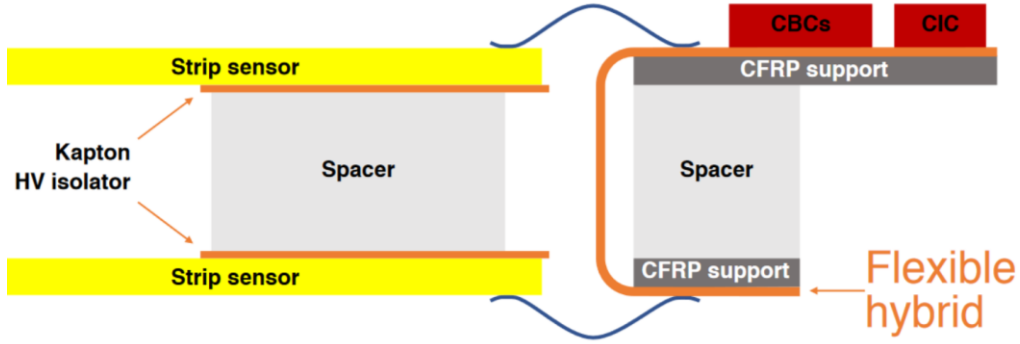
The 2S Module Design

Service hybrid
- Powering
- Optical data transmission

2 front-end flex hybrids
- 8 CMS Binary Chips (CBC)
- 1 concentrator chip (CIC)
- Read out of both sensors

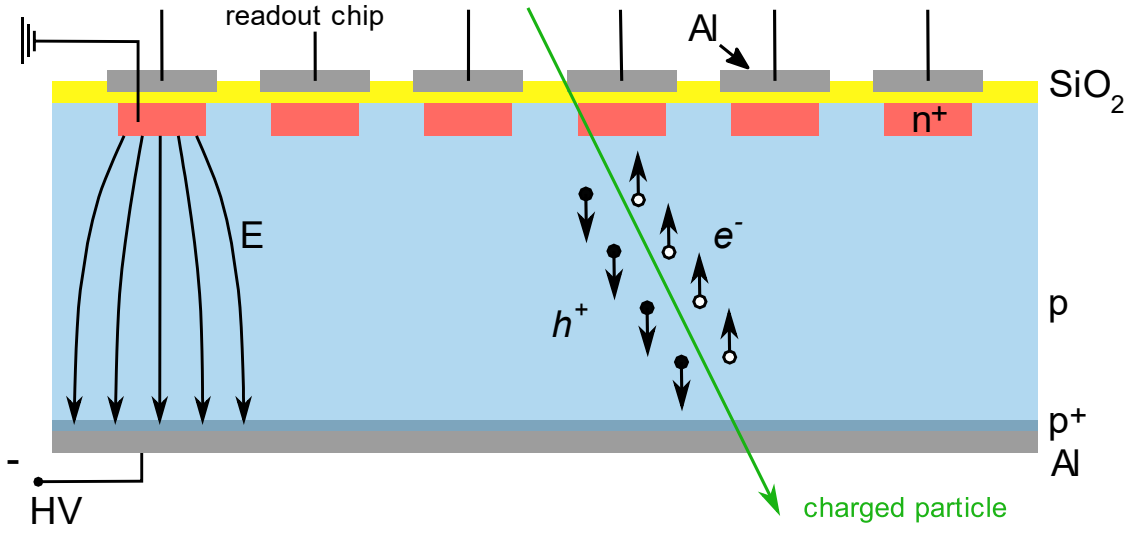
2 silicon strip sensors
- 2 x 1016 strips each

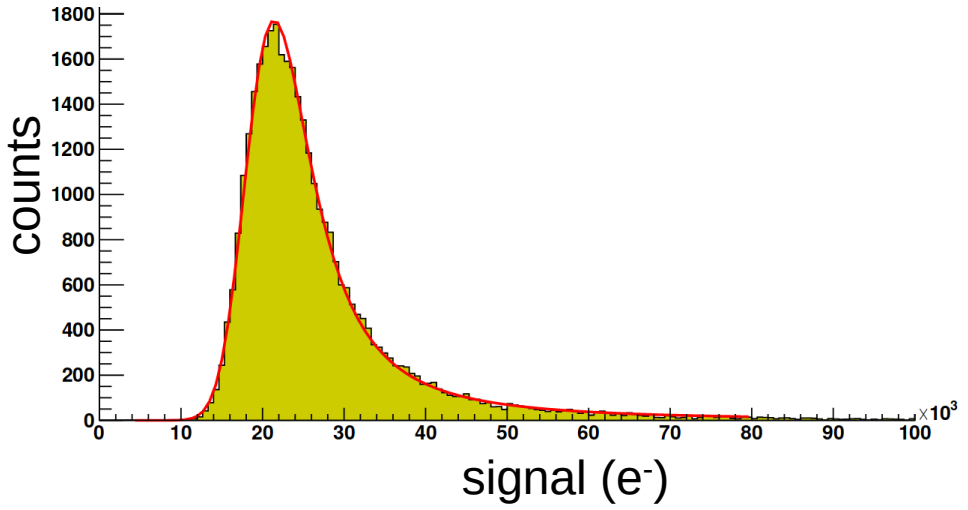
AlCF spacer



Silicon Sensors for Particle Detection

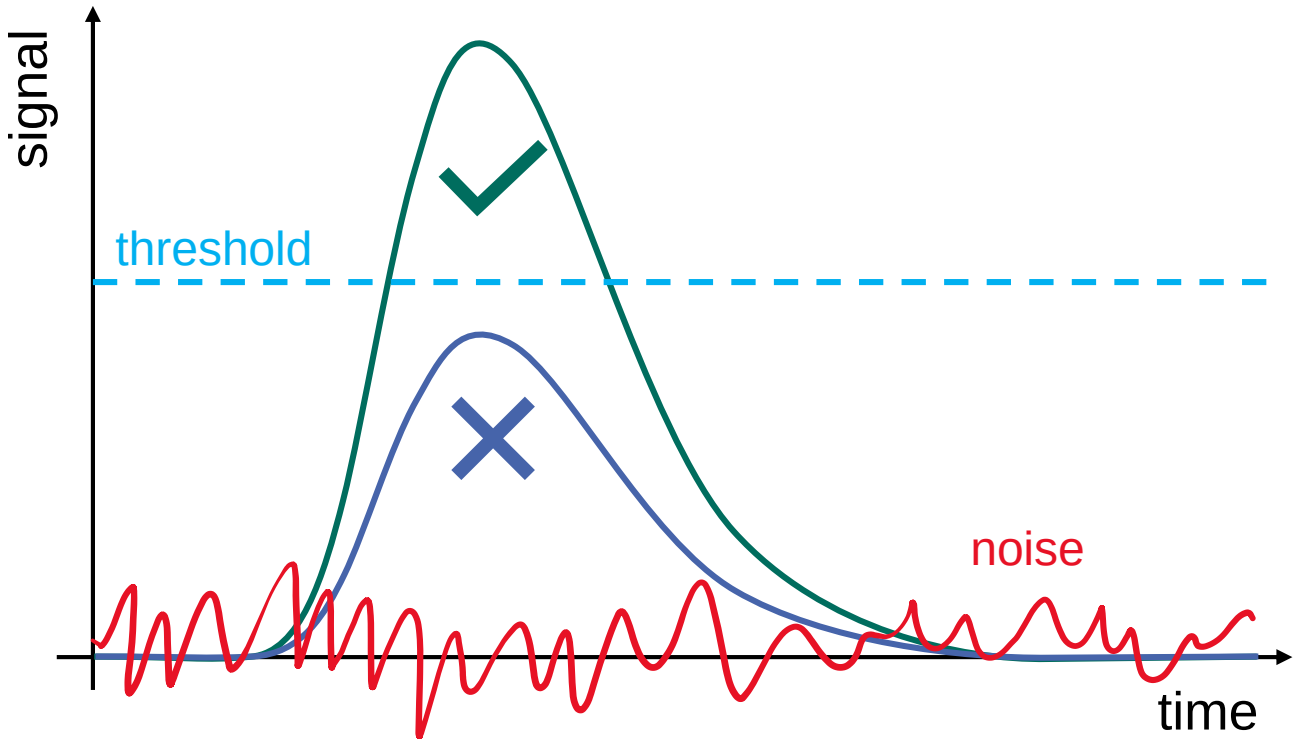
- **Silicon sensors:**
  - n^+ implants in p-doped bulk form strips
  - Reverse biasing for sensor depletion
    → Remove free charge carriers
    → Typical operation voltage ~300V
  - Segmentation results in position resolution
- **Particle detection:**
  - Traversing charged particles generate eh-pairs by ionization
  - Carrier drift in electric field
    → induction of signal in readout strips
  - Ionization is statistical process
    → Landau fluctuations
  - Charge collection effiency drops with irradiation





Binary Signal Detection

- Data reduction by binary readout
- Compare signal to threshold level
- No information about signal amplitude
- Choose your threshold wisely!
  - Too high:
    → loss of particle detection efficiency
  - Too low:
    → increase of occupancy by noise



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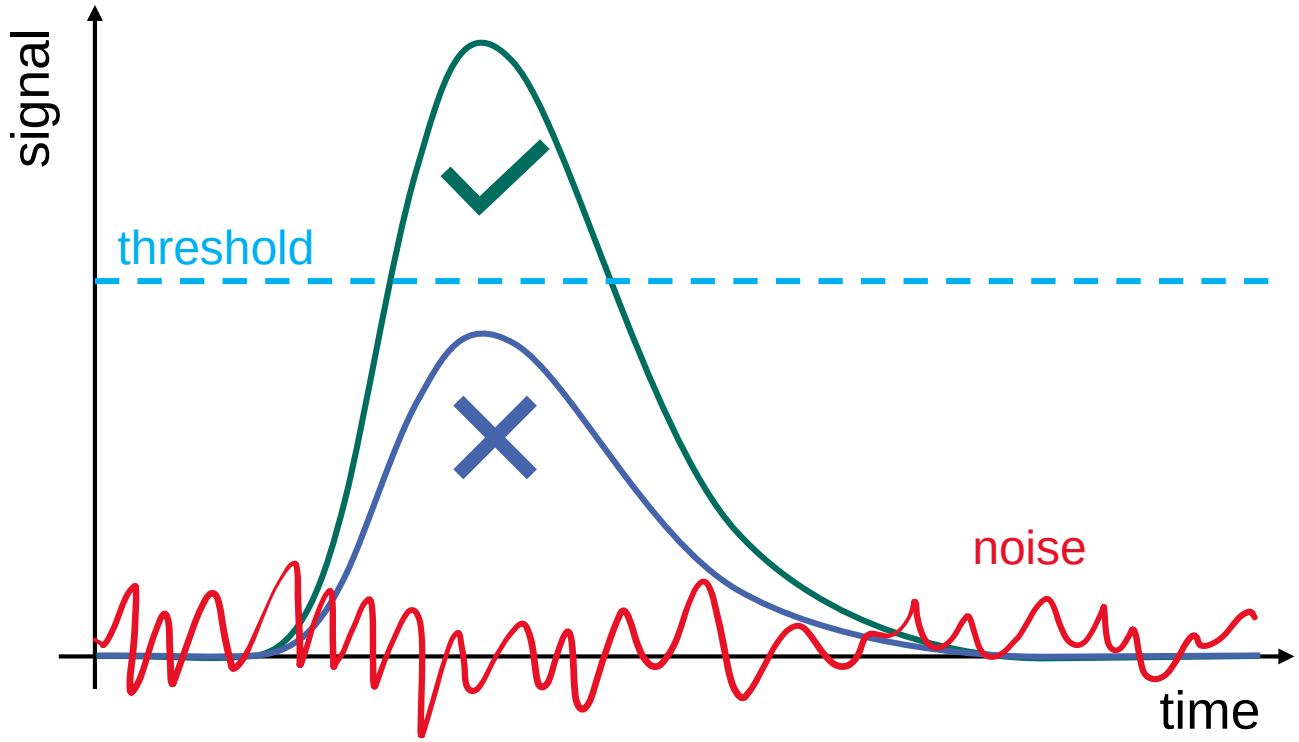
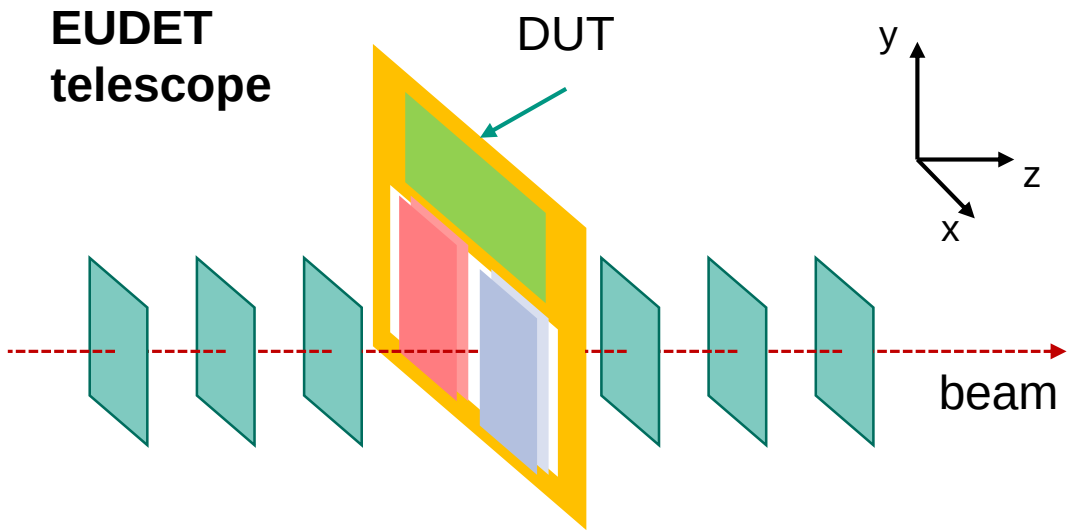


BEAM TEST

… a small but almost full experiment

What is a Beam Test (good for)?

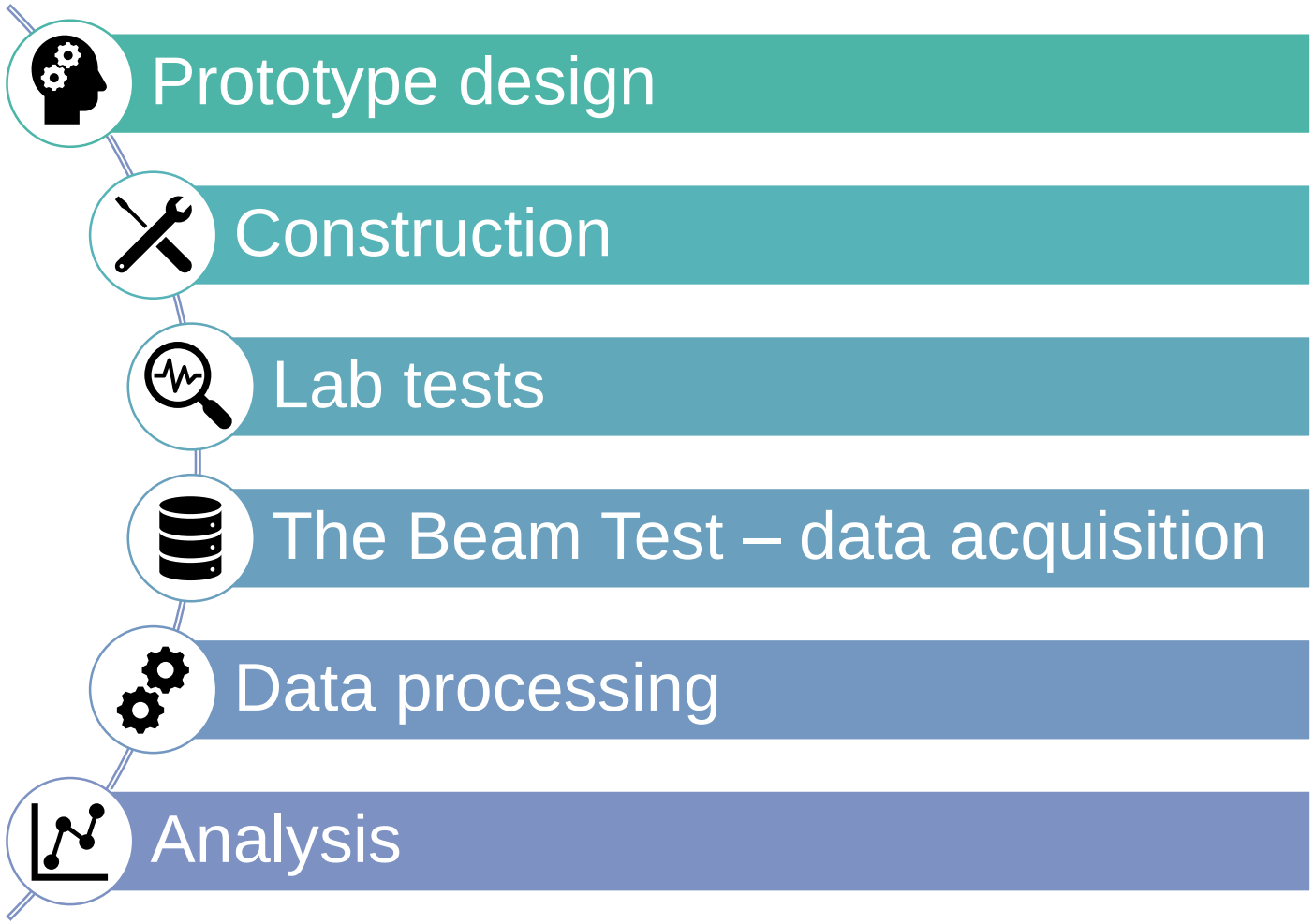
- High energetic particle beam
  - DESY: 1-6 GeV electrons (adjustable)
- Telescope for particle tracking
  - Knowledge about expected hits
  - µm precise track prediction on the device under test (DUT)



Efficiency and Resolution studies!

→ Probe the DUT on µm scale

The long way to the final results…

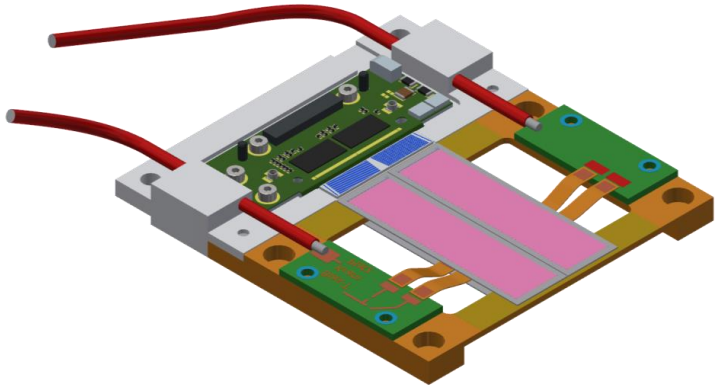


Designing the Prototype

Goal of the beam test

- **System tests: readout chip + sensor**
  - Stub finding functionality?
  - Stub efficiency/resolution?
  - Hit efficiency/resolution?
  - Noise and signal?
- **Test two remaining sensor thicknesses**
  - Behavior after irradiation?
  - Behavior after annealing?
  - Inefficient sensor areas?
  - Best operation conditions?

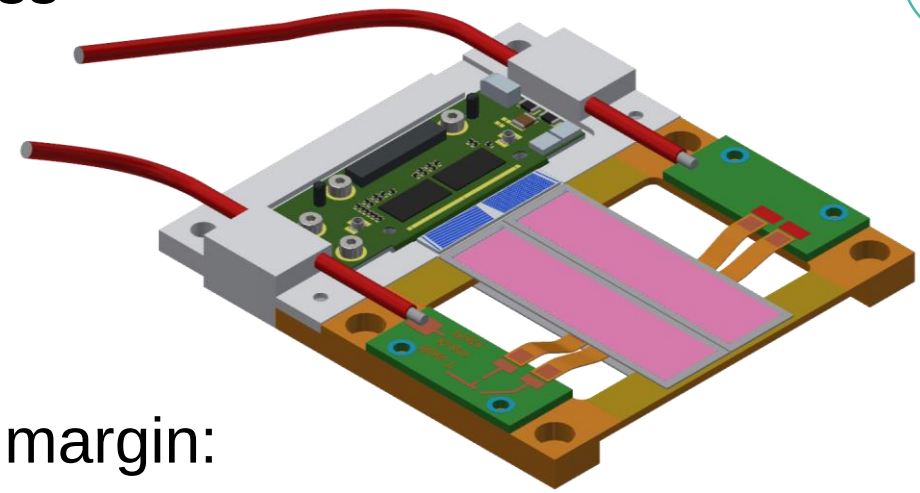
2S Mini Modules



Design
Construction
Lab tests
Beam Test
Processing
Analysis

The 2S Mini Module Design

- Four sensors in **two aligned layers**
  - 2x **290µm**, 2x **240µm** thickness
- Three modules:
  - Unirradiated:
    $\phi = 0\ \mathrm{n_{eq}/cm^2}$
  - Nominal fluence 3000 fb^{-1}:
    $\phi = 2.5 \cdot 10^{14}\ \mathrm{n_{eq}/cm^2}$
  - Ultimate scenario 4000 fb^{-1} + margin:
    $\phi = 5 \cdot 10^{14}\ \mathrm{n_{eq}/cm^2}$
- Two equivalent annealing times per module
  - two weeks at 21°C (beneficial)
  - 28 weeks at 21°C (expected)



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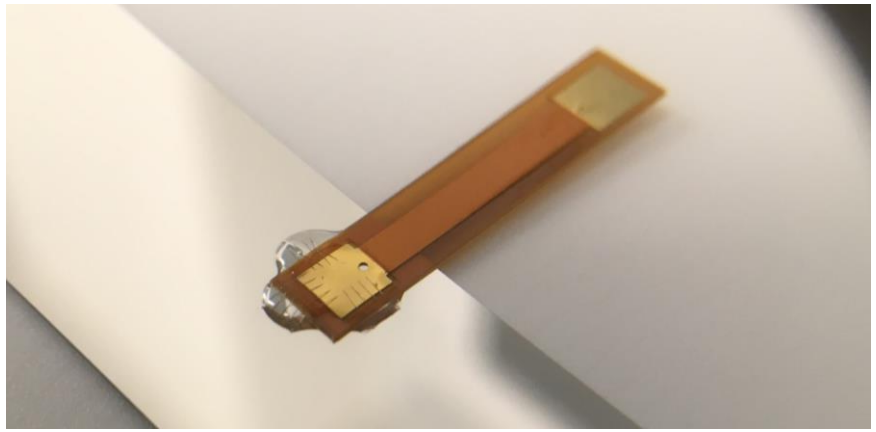
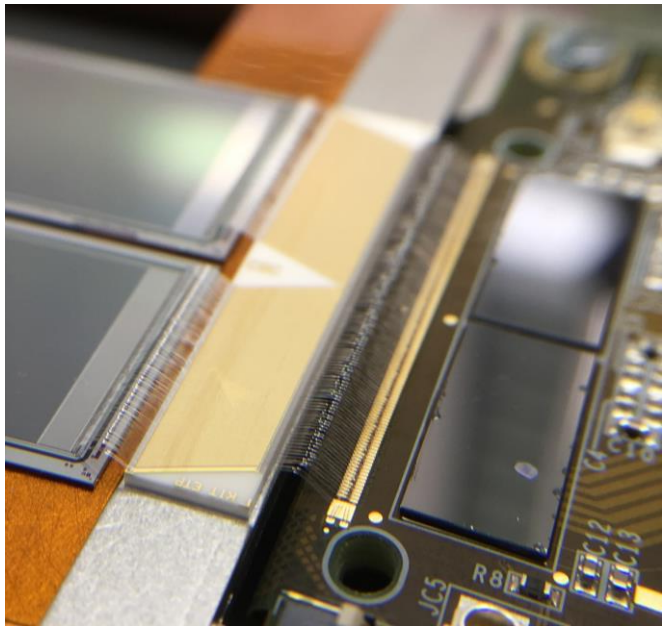
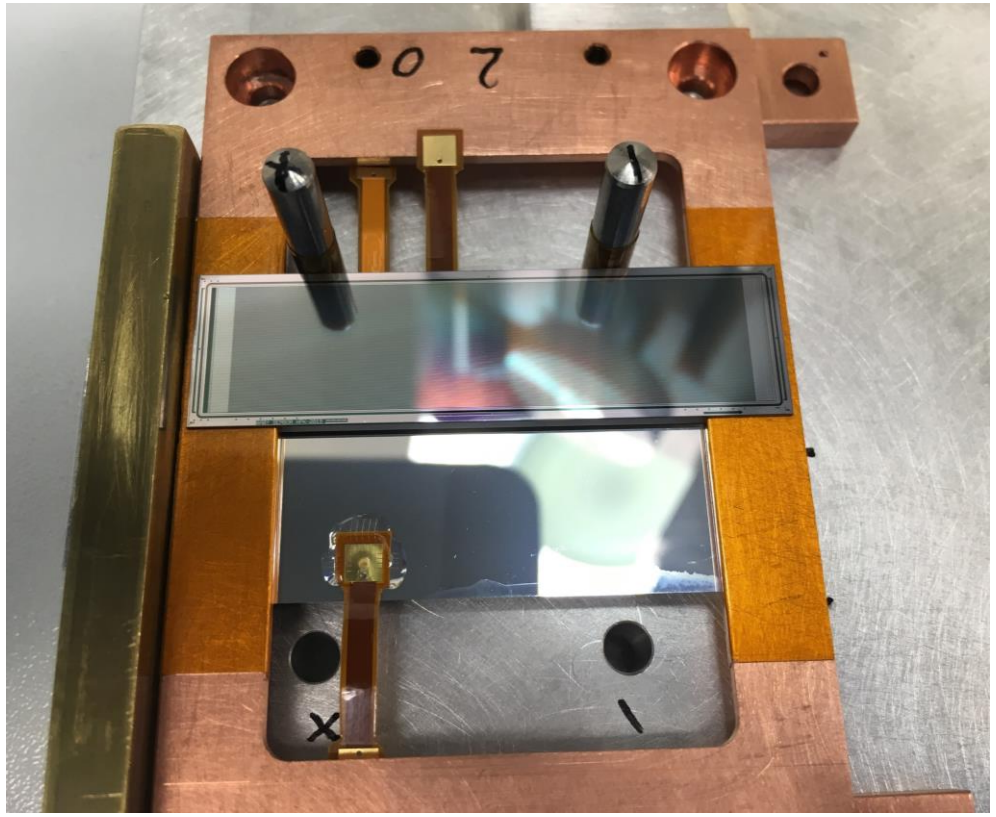
Prototype Construction







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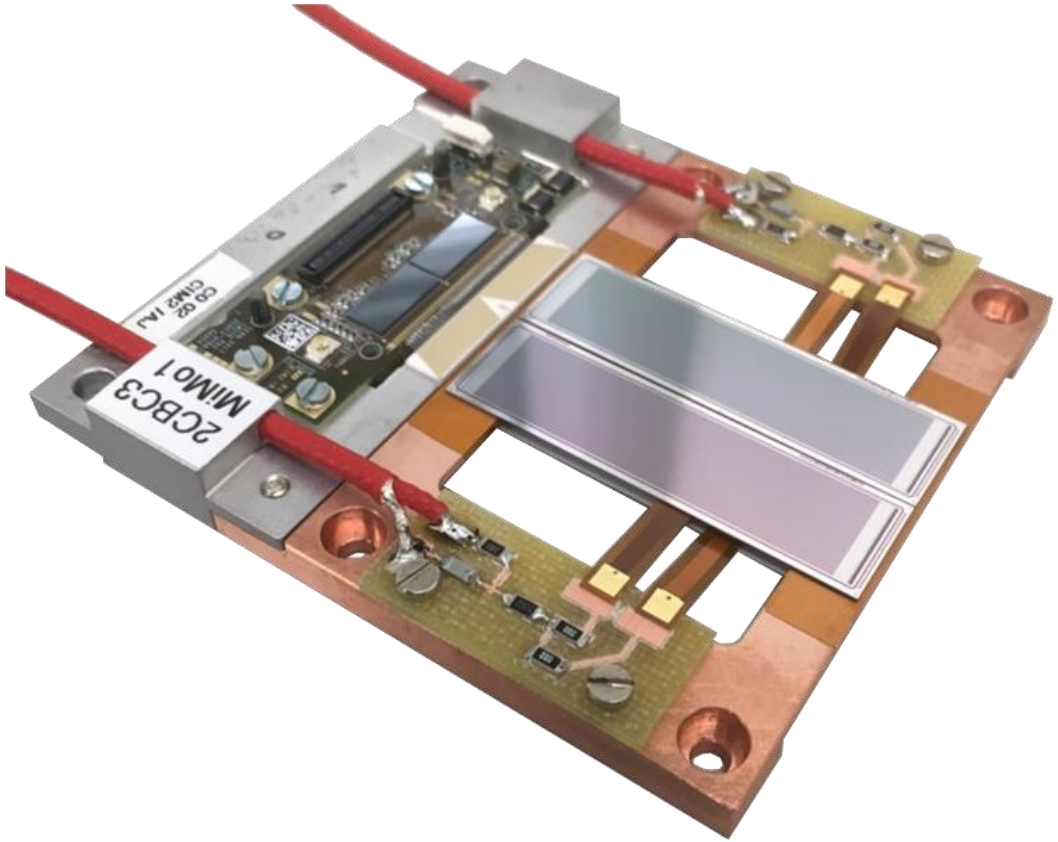
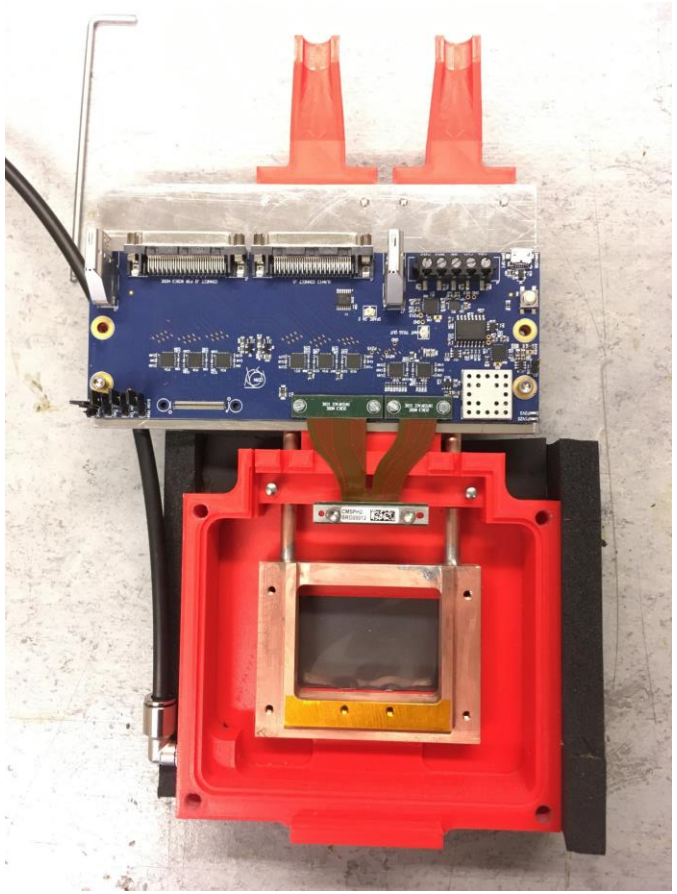
Prototype Construction





- Design
- **Construction**
- Lab tests
- Beam Test
- Processing
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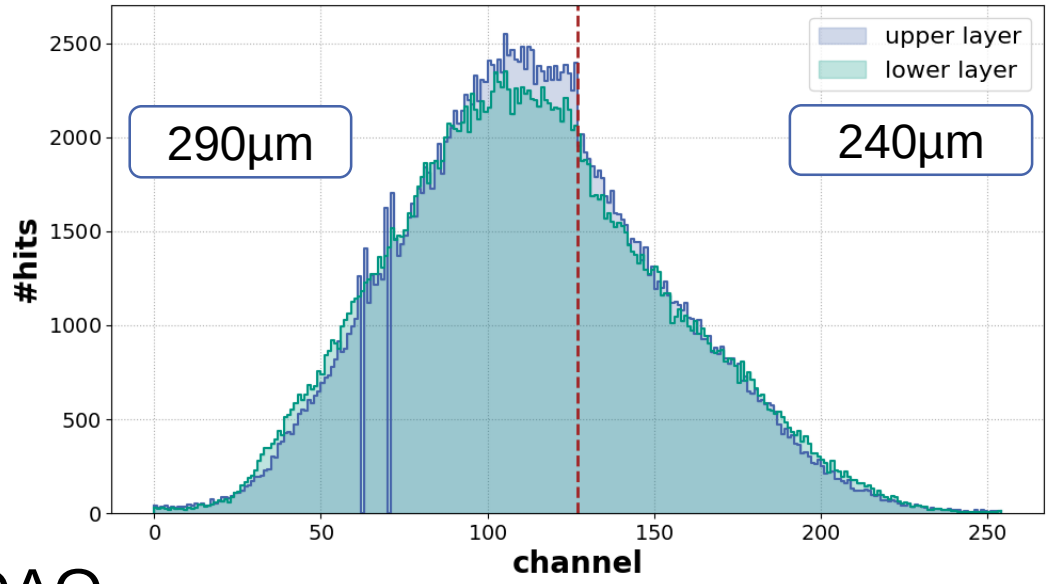
Lab Tests

- Functional tests of the modules:
  - Thermal cycling
  - HV stability
  - Sr90 source measurements to identify dead channels
  - Commissioning of the DAQ
  - Commissioning of the monitoring tools



Design
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Beam Test
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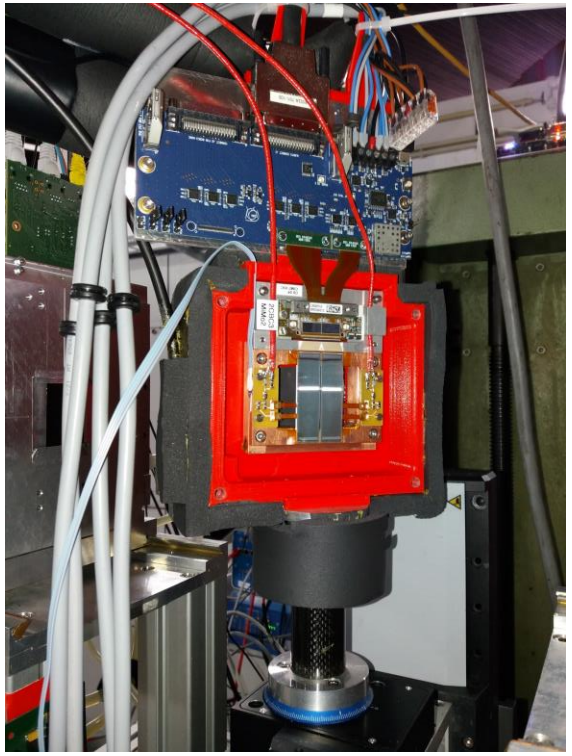
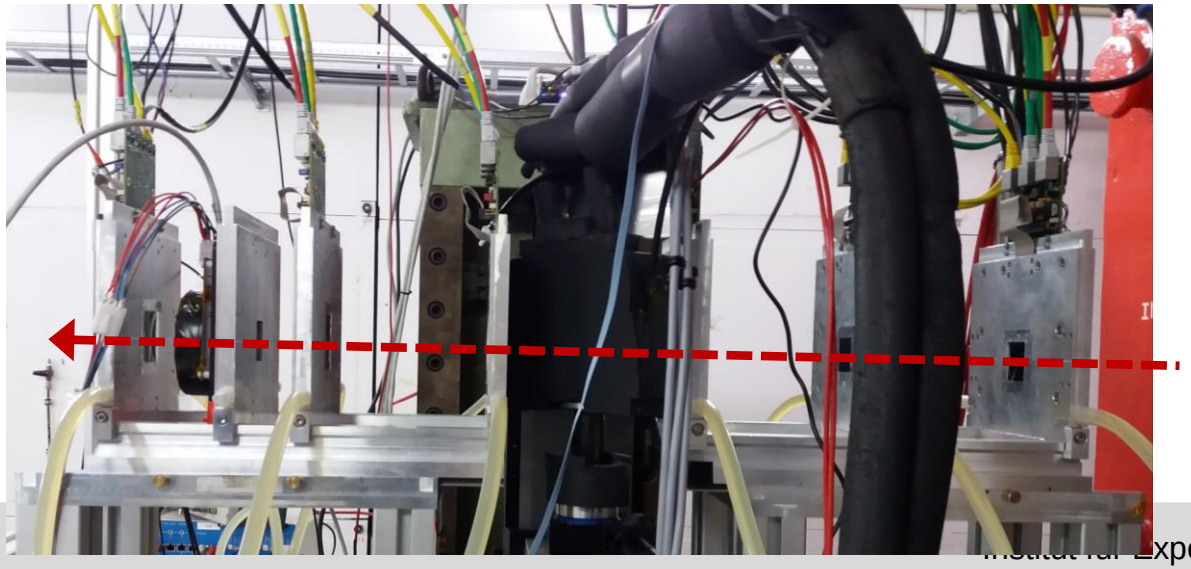
The Beam Test

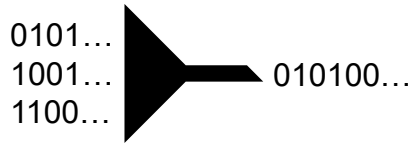
- One week for data taking in May
- Measurements:
  - Threshold scans
    → Signal and noise
  - Sensor HV scans
    → performance and irradiation
  - Angular scans
    → mimic bends
    → stub finding



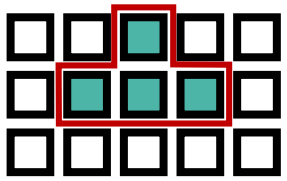


Data Processing

Converter
- RAW detector data into common data fomat



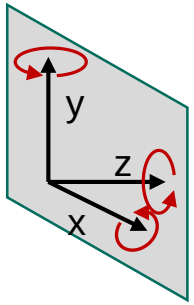
Clustering
- Combine single hits to cluster
- Masking (noisy, dead channels)



Hitmaker
- Convert cluster hits in space points

(x, y, z)

Alignment
- Shifts + rotations of telescope planes and DUT
  → Millipede2 algorithm

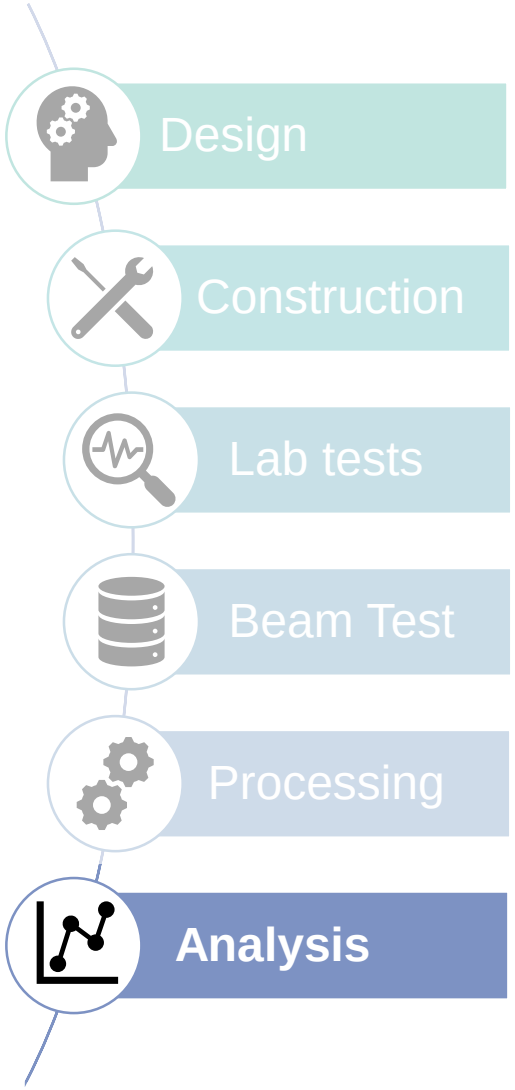


Tracking
- Fit particle tracks
- Find particle track position on the DUT

Design
Construction
Lab tests
Beam Test
Processing
Analysis

BEAM TEST RESULTS

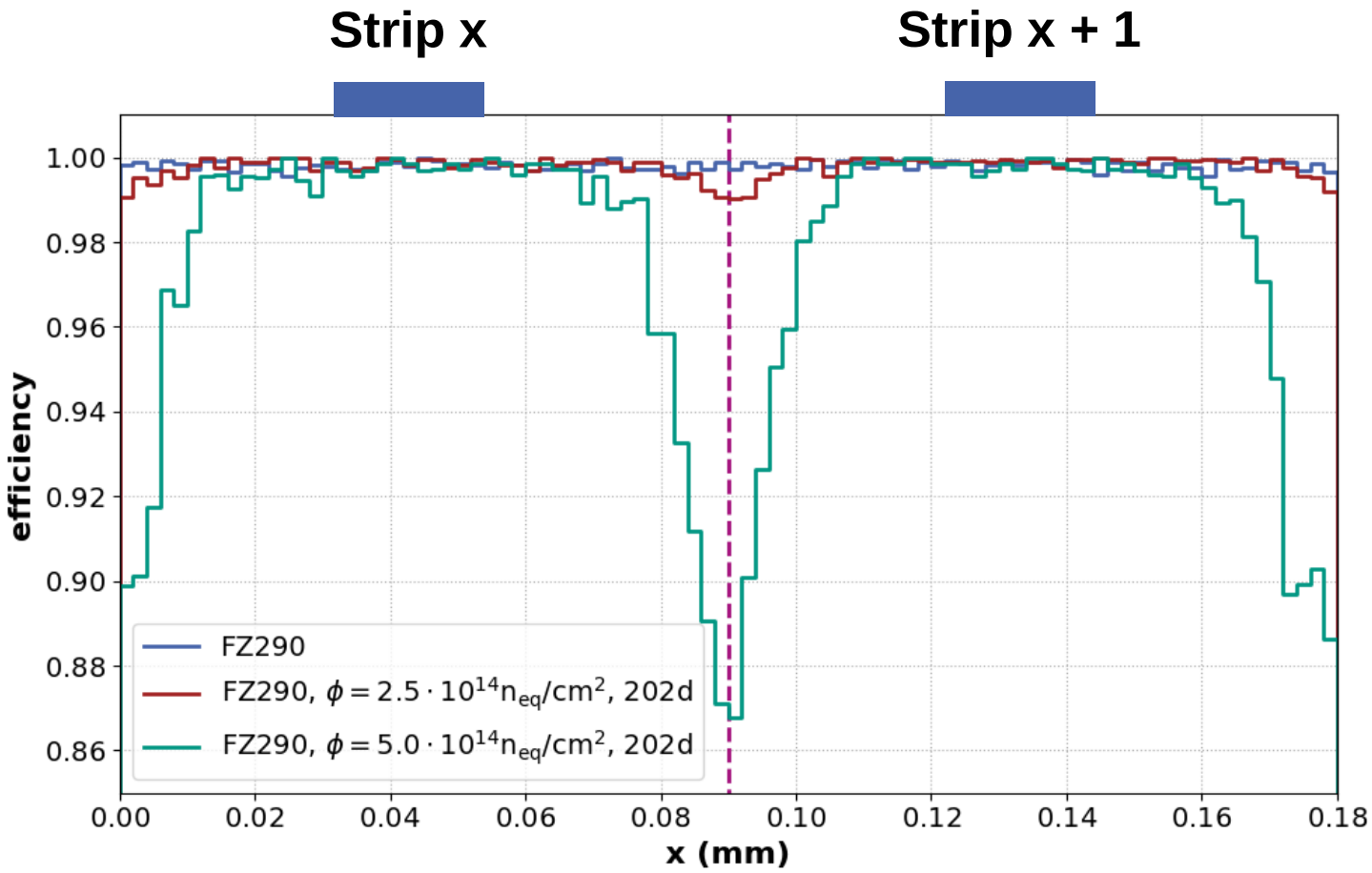
A small selection



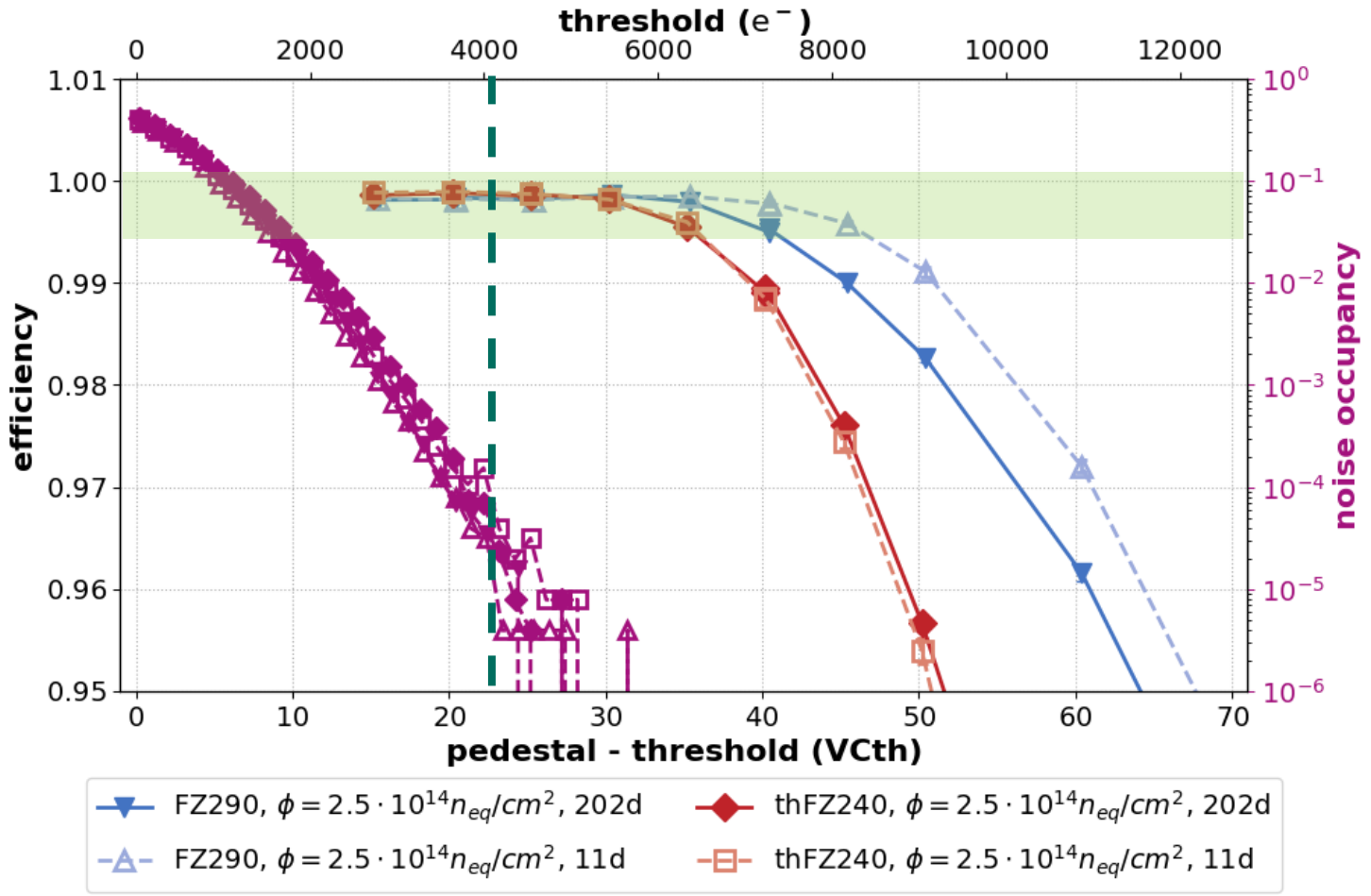
Strip Efficiency

- Inefficient areas in between strips after irradiation
  - Charge sharing
  - Sensor signal reduced by radiation damage

- 290µm thick sensors
- Nominal operation threshold (5500e^-)



Threshold Scan – 3000fb^{-1}



Expected scenario:

- $\phi = 2.5 \cdot 10^{14}\ \mathrm{n_{eq}/cm^2}$
- $U = 600\mathrm{V}$
- $1VCth = 180e^{-}$

Specifications:

Efficiency $> 99.5\%$ ✓

Noise occupancy $< 10^{-4}$ ✓

Summary

- Upgrade of LHC and CMS for High Luminosity operation
- ETP contributes to the development of the new CMS Outer Tracker
  - Development, construction and testing of 2S Module prototypes
- Beam test studies on 2S Mini Modules
  - Evaluation of 240µm and 290µm thick sensor materials
  - Different irradiation doses and annealing scenarios
  - $3000fb^{-1}$ scenario:
    → **290µm** shows slightly better performance

Material decision in September 2019:
290µm for the OT

Outlook

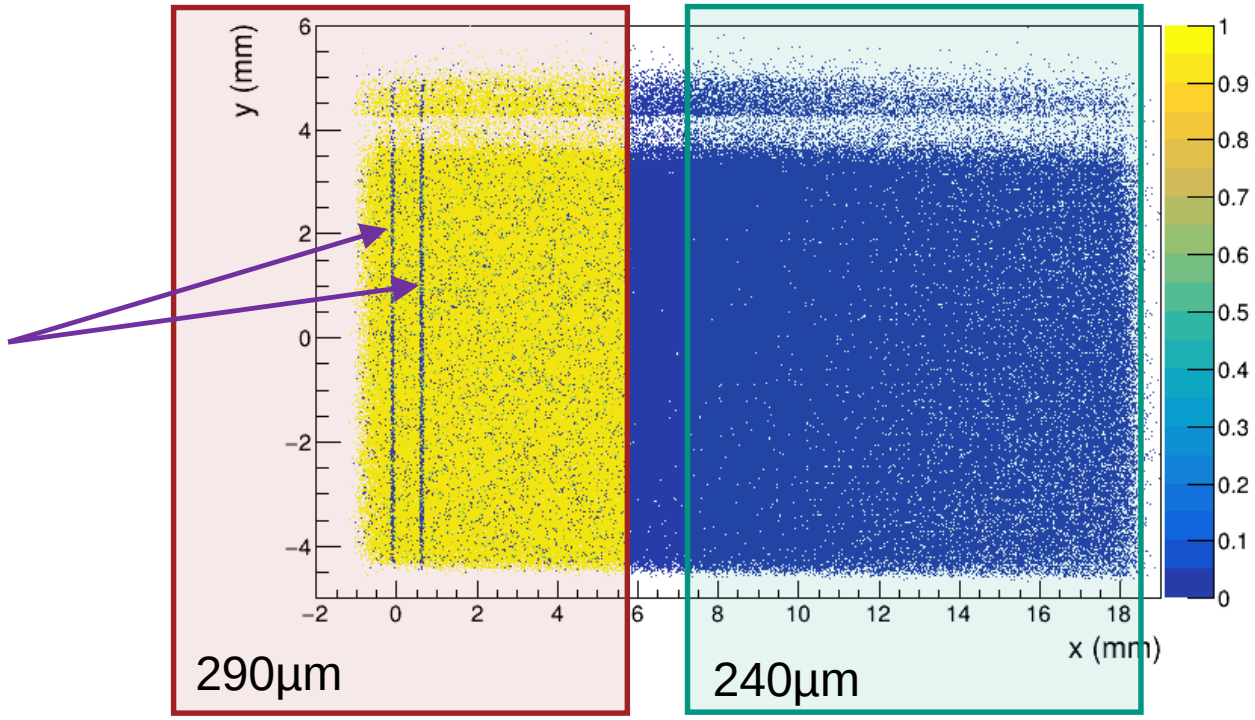
- More Beam tests!!!
  - High rate tests in cyclotron in Strasbourg
  - Test high trigger rates (up to >750kHz) and realistic hit occupancy (~1%)
  - Full 2S Modules (optical readout + service hybrid)

BACKUP

From Tracks and Spacepoints to Efficiencies

Applying cuts:

- Track chi2
- Masking (noisy, edge strips, unbonded/dead channels)
- Acceptance
- Residual
- Timing (TDC)



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Lab tests
Test Beam
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From tracks and spacepoints to efficiencies

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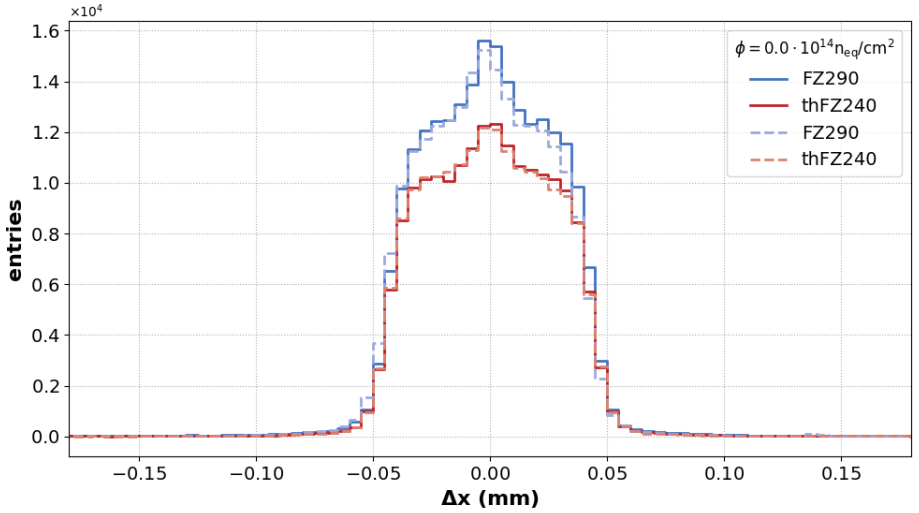
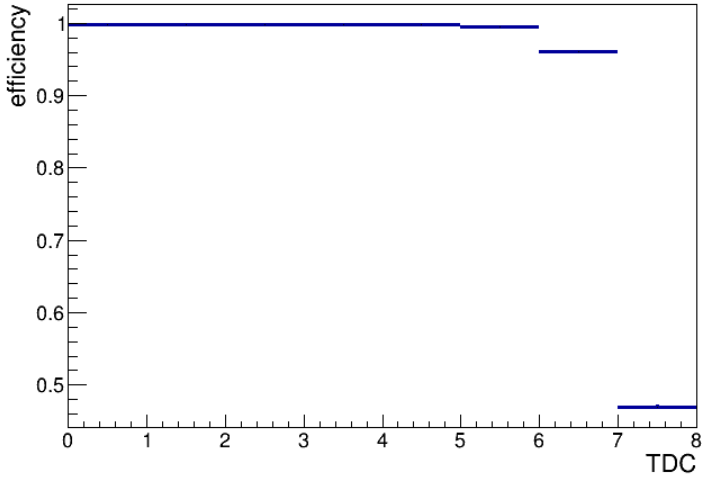




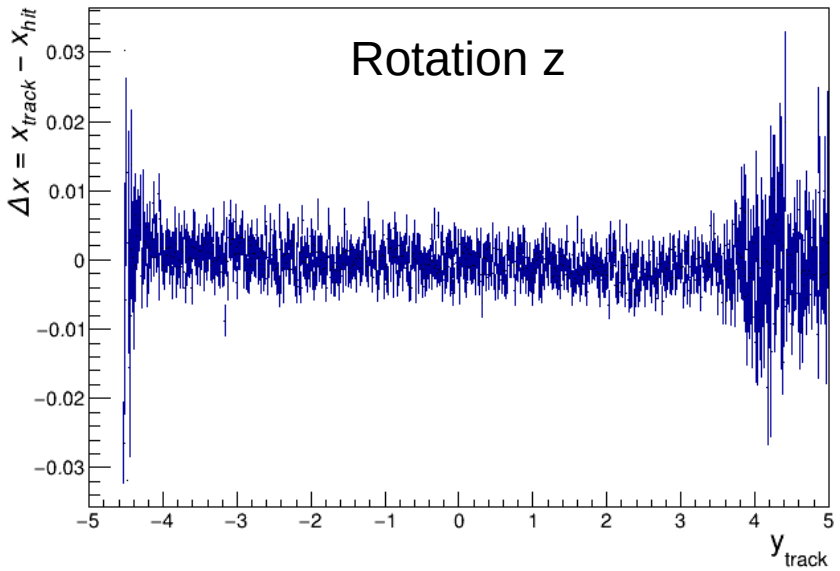
Design
Construction
Lab tests
DAQ
Processing
Analysis

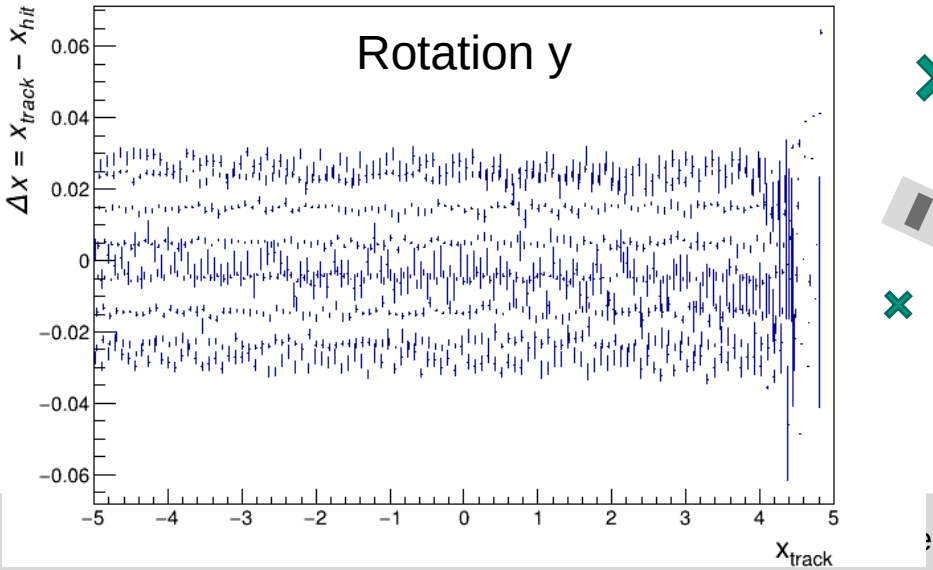
Alignment

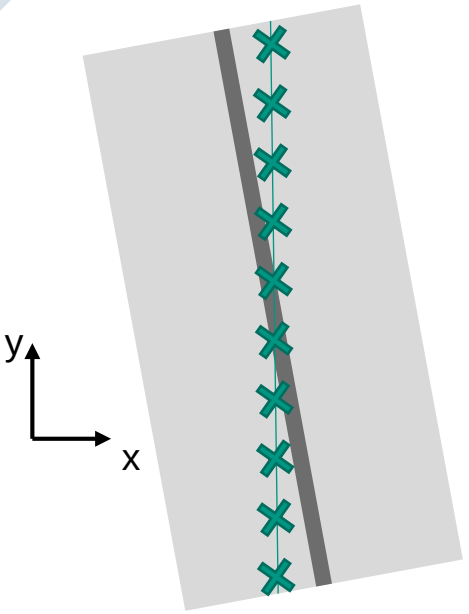
Alignment

- Shifts + rotations of telescope planes and DUT
  → Millipede2 algorithm

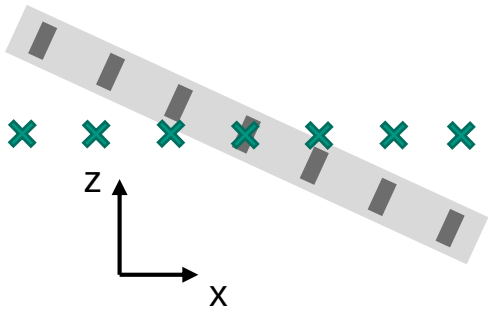
- Control plots:
  - Residuals $\Delta(x, y, z)$
    → shift along x, y, z
  - Residual $\Delta x(y)$
    → rotation around z
  - Residual $\Delta x(x)$
    → rotation around y
  - Strip sensors are not that sensitive for rotation around x



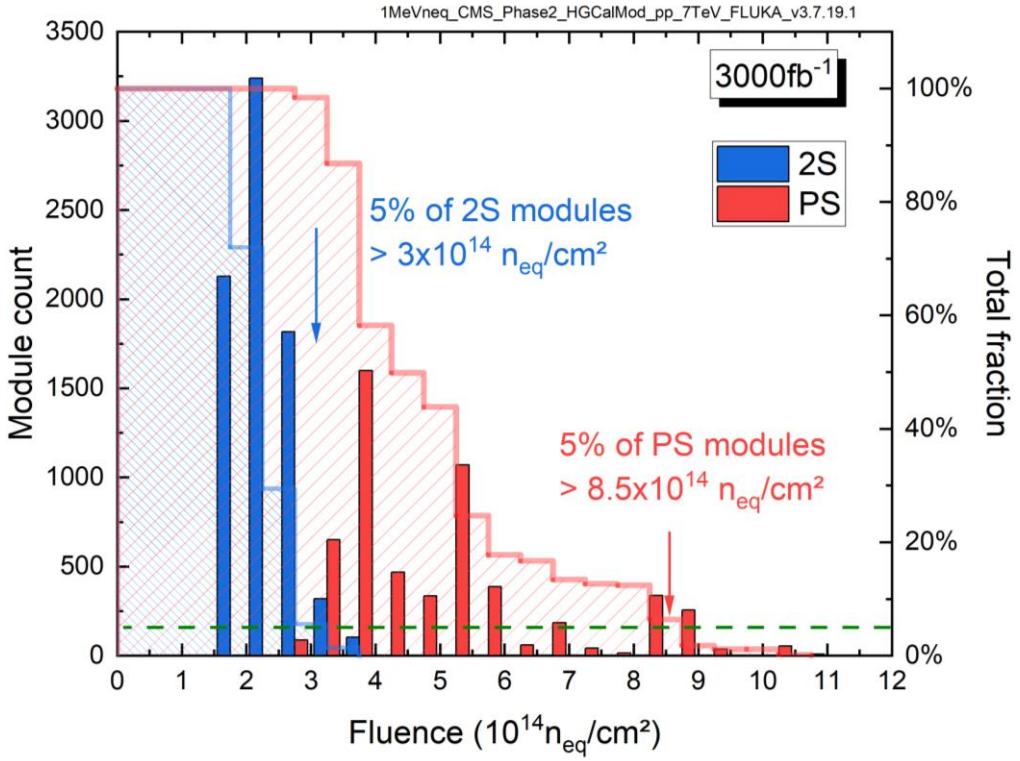


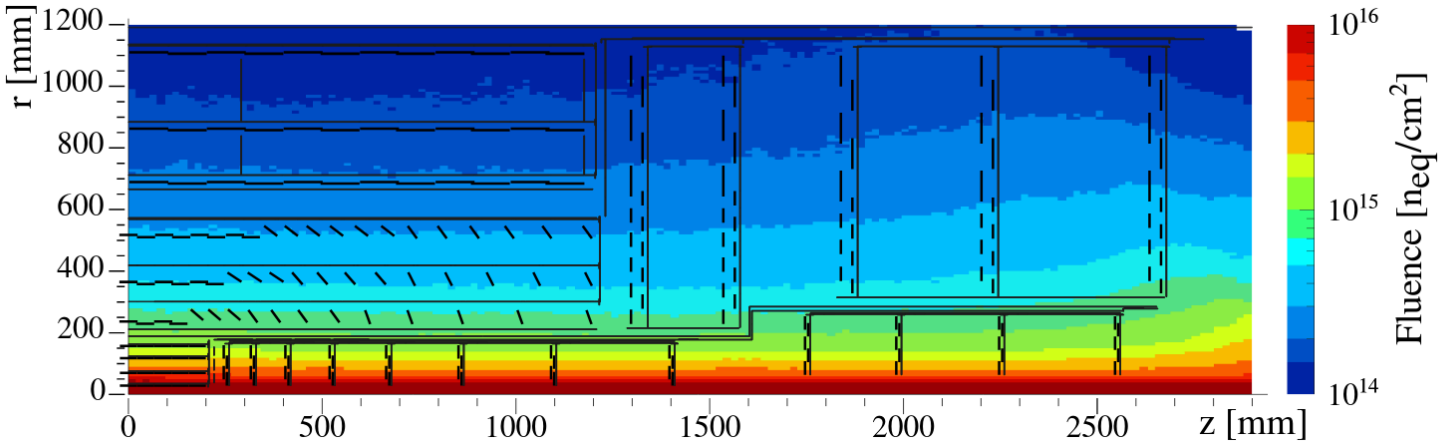


Track position



Expected fluence for 2S and PS Modules

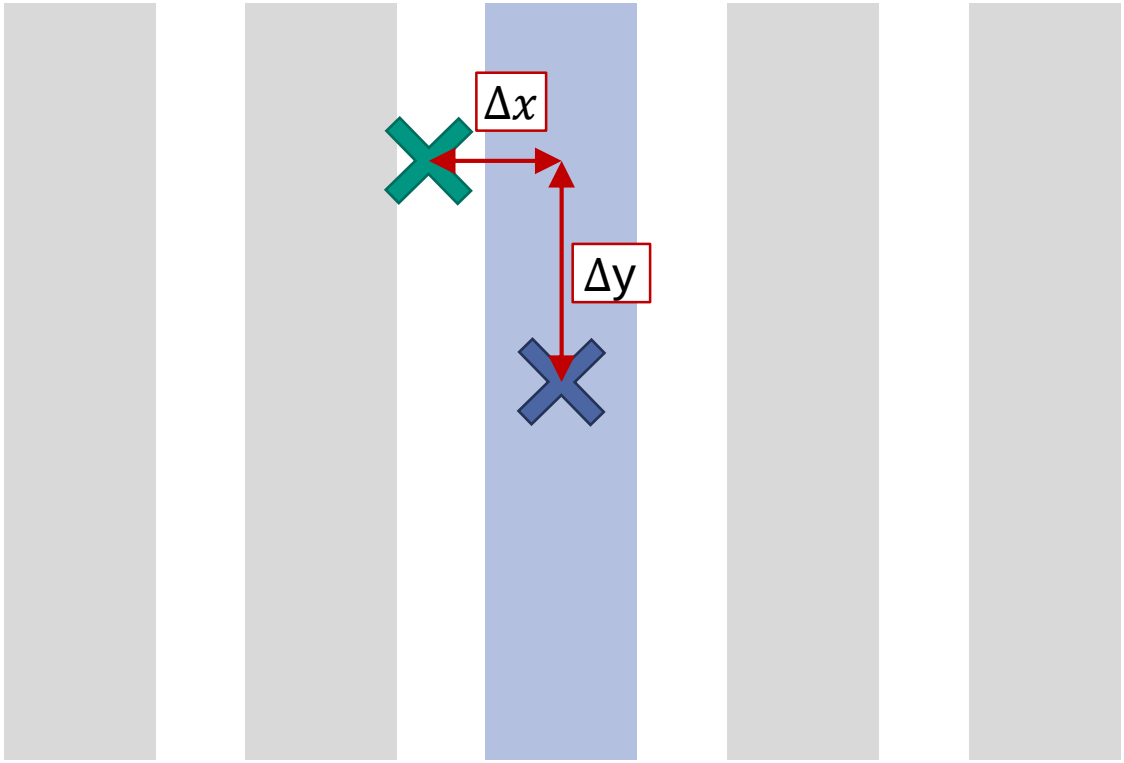




Residual x, y

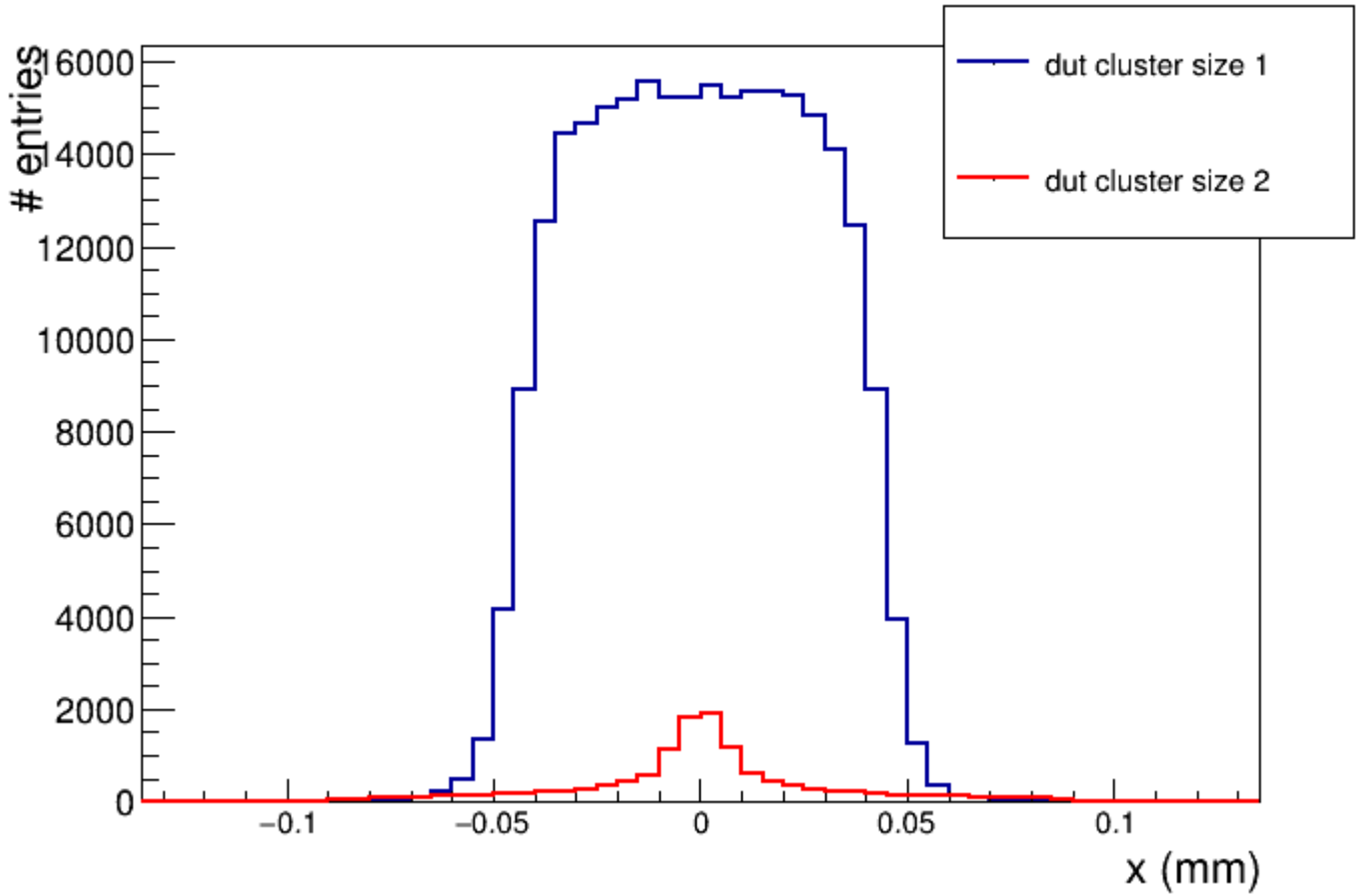
Cluster position

Track position



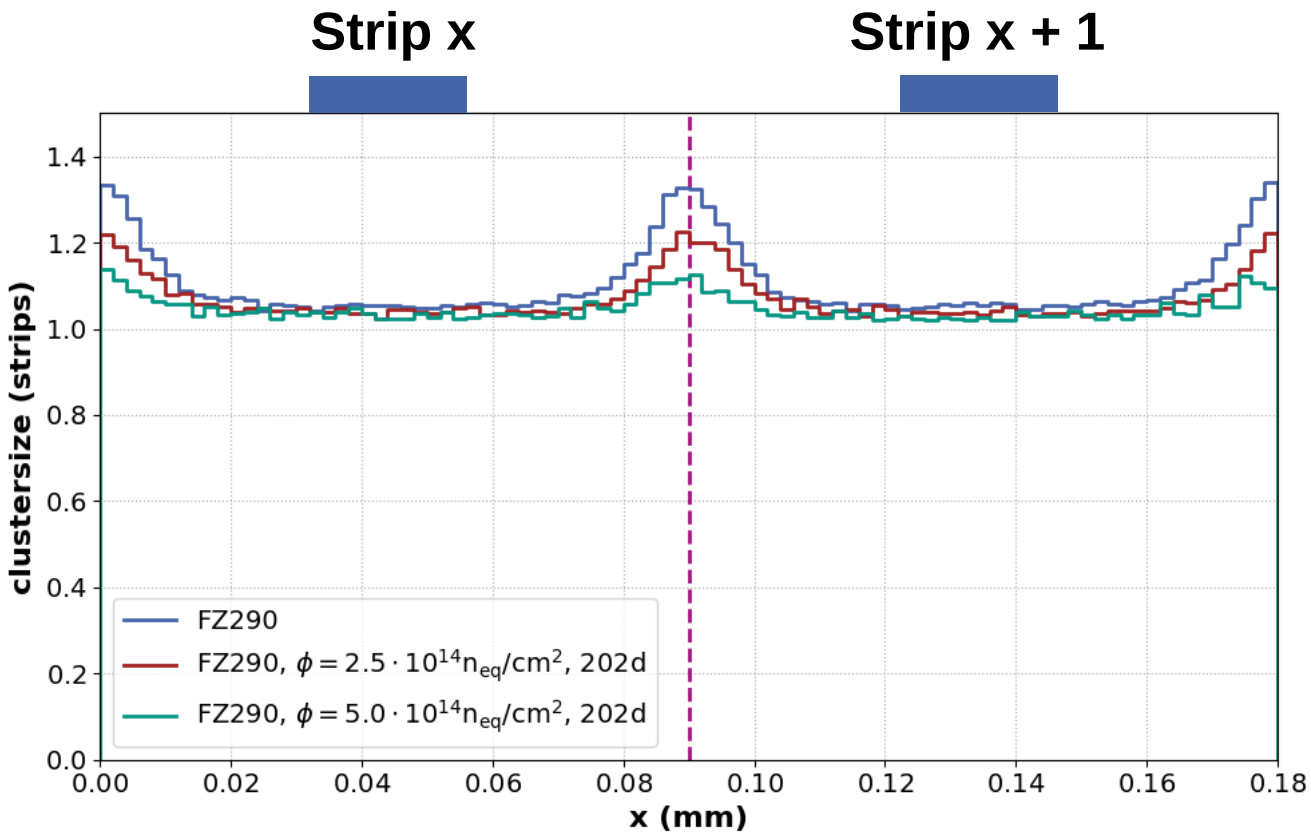
Resolution and Clustersize

- For one strip clusters
  - Resolution:
    $\sigma_x \approx 26\mu m \approx \text{pitch}/\sqrt{12}$
- Two strip clusters have large tails (e.g. δ electrons)

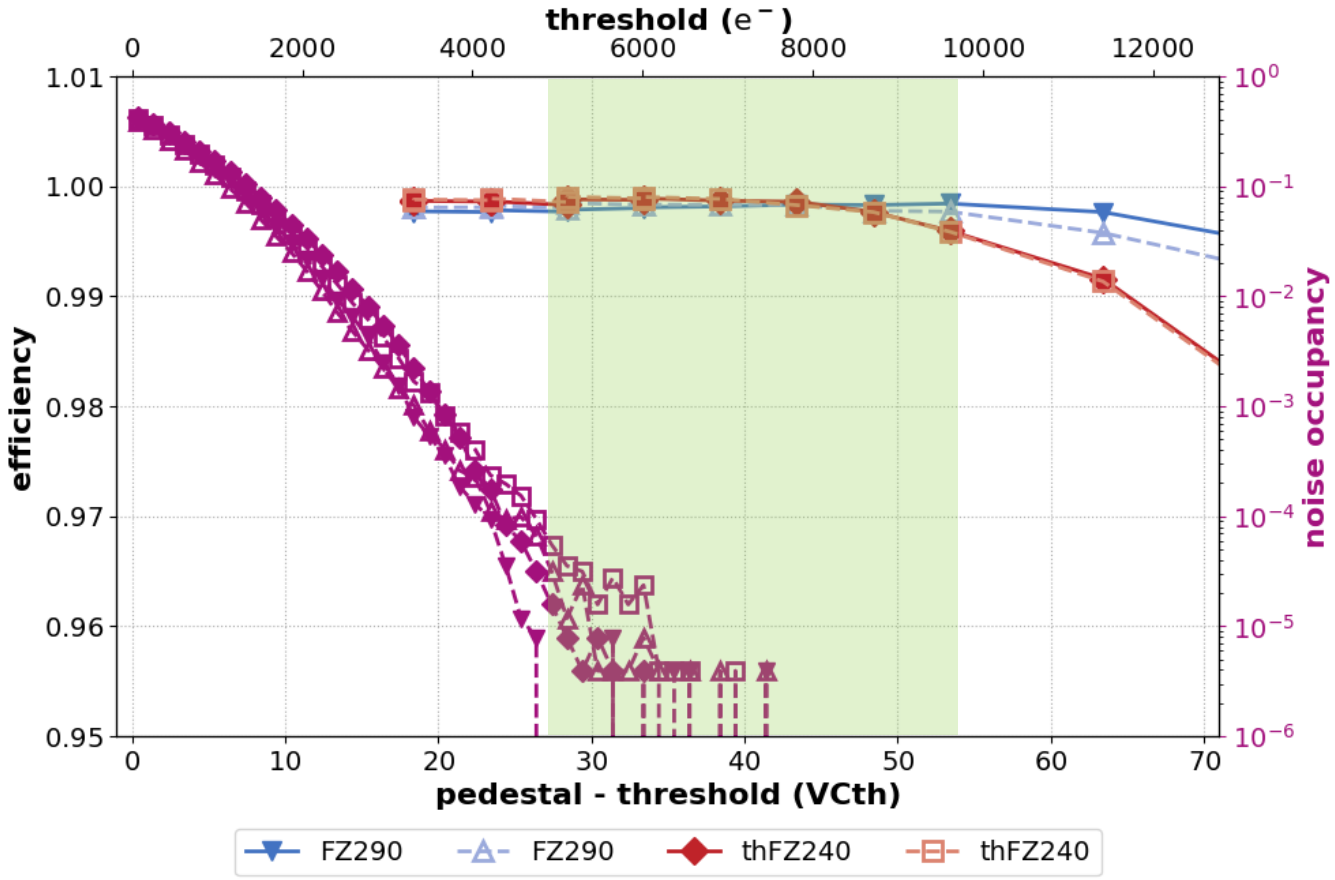


Strip Clustersize

- Clustersize scan over strip
- Threshold ~33VCth (5500e)
- Small clustersize for vertical tracks



Threshold scans



New sensors:

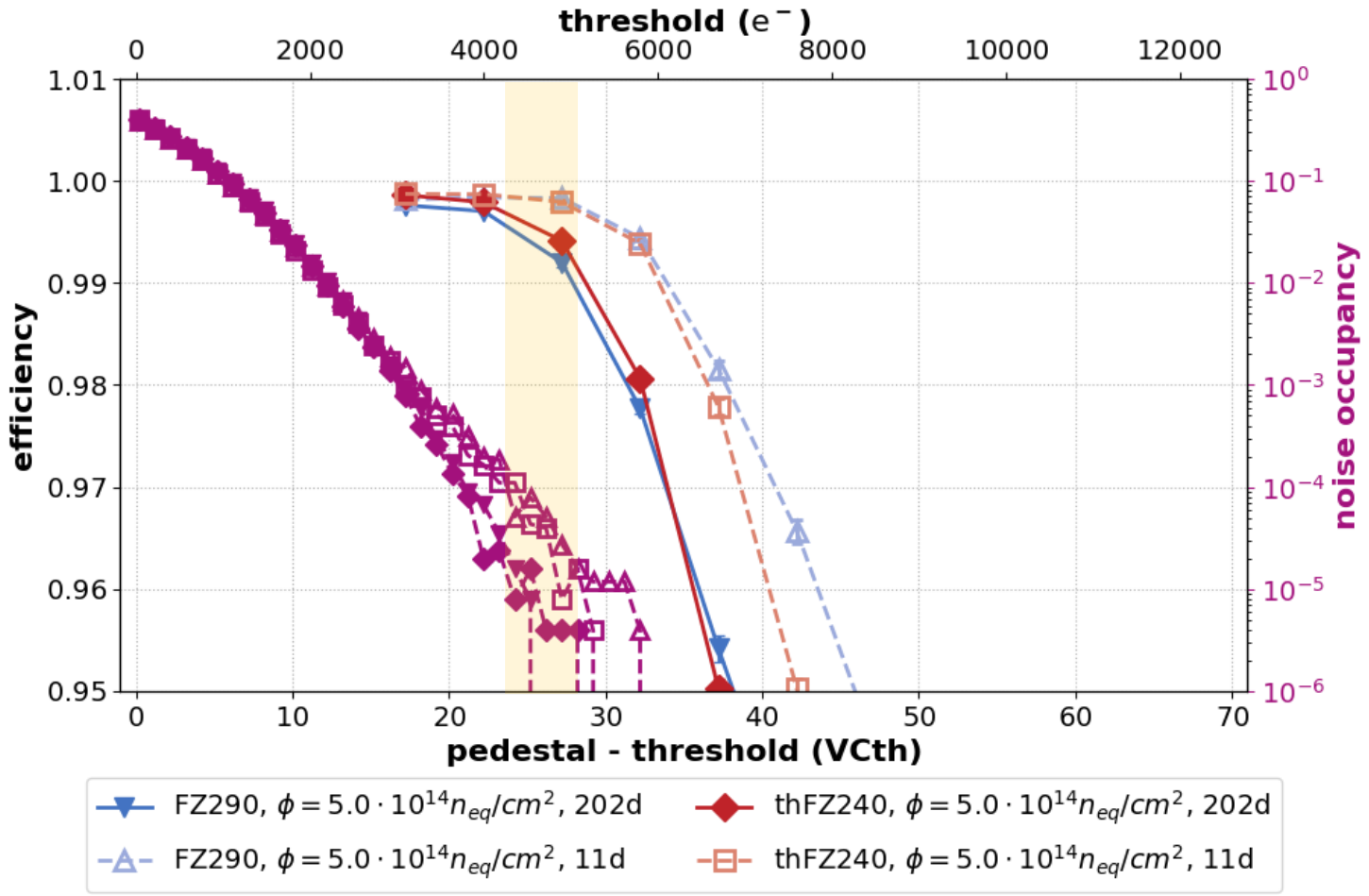
- $\phi = 0\ \mathrm{n_{eq}/cm^2}$
- $U = 400\mathrm{V}$
- $1VCth = 180e^{-}$

Specifications:

Efficiency $> 99.5\%$

Noise occupancy $< 10^{-4}$

Threshold scans



Ultimate scenario:

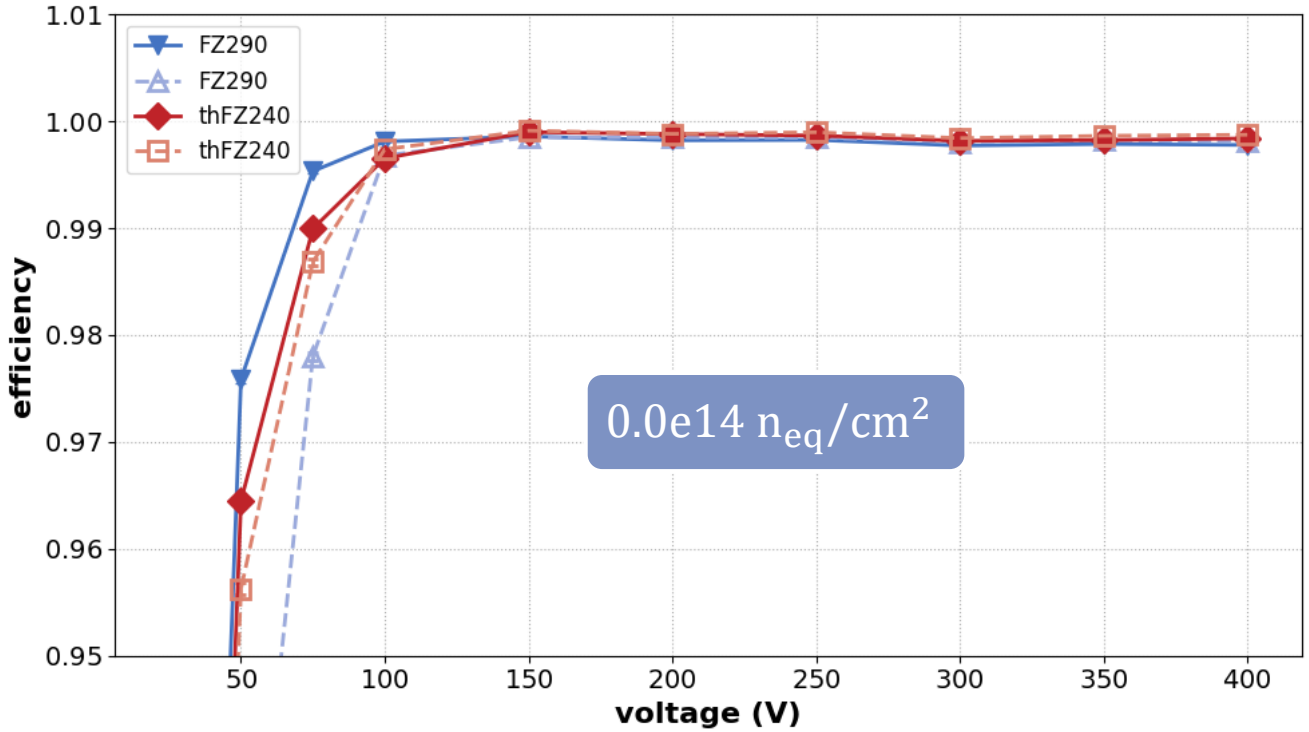
- $\phi = 5e14\ n_{eq}/cm^2$
- $U = 600V$
- $1VCth = 180e^-$

Specifications:

Efficiency $> 99.5\%$

Noise occupancy $< 10^{-4}$

Bias voltage scans

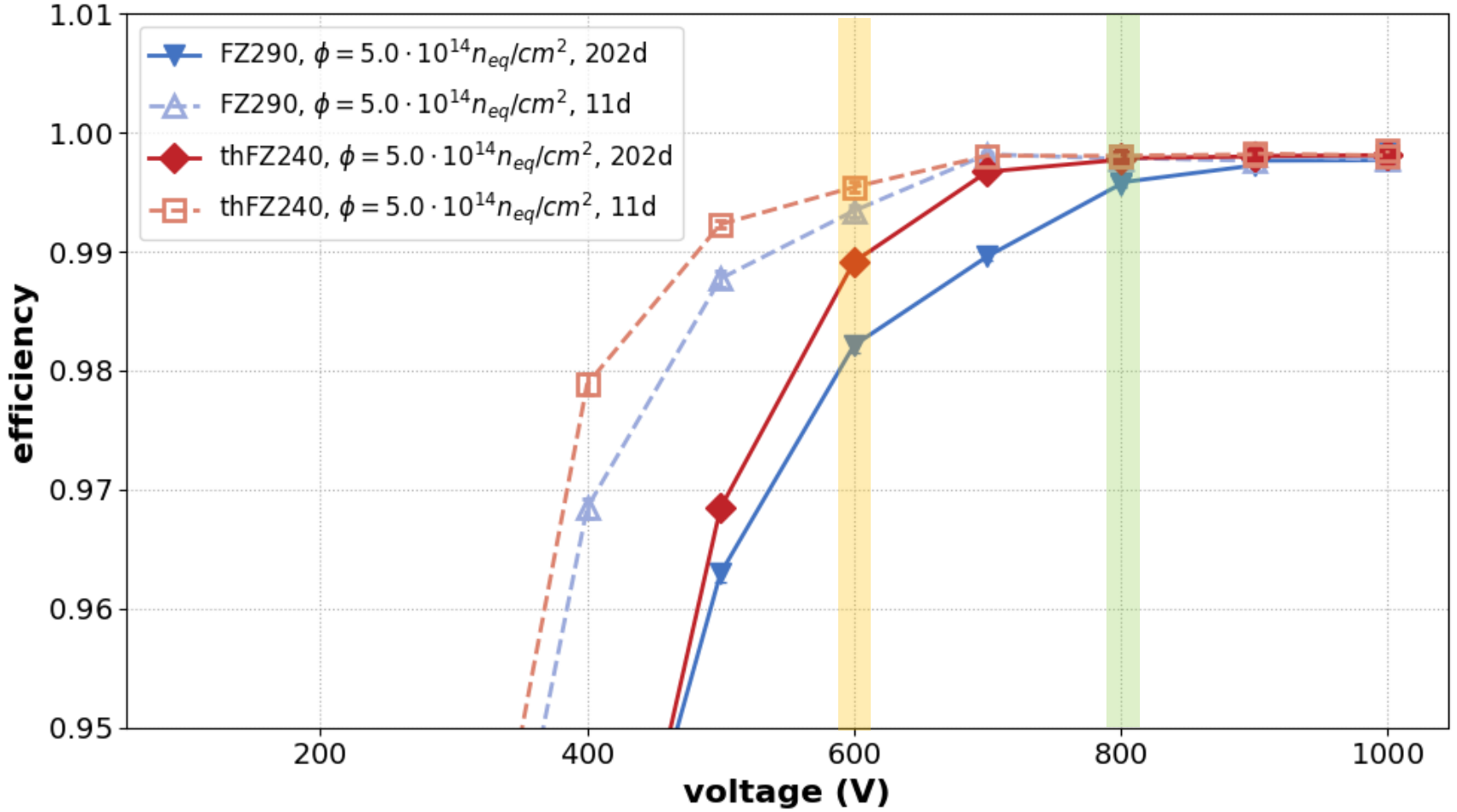


Nominal operation voltage

600V

Fully efficient at about 150V

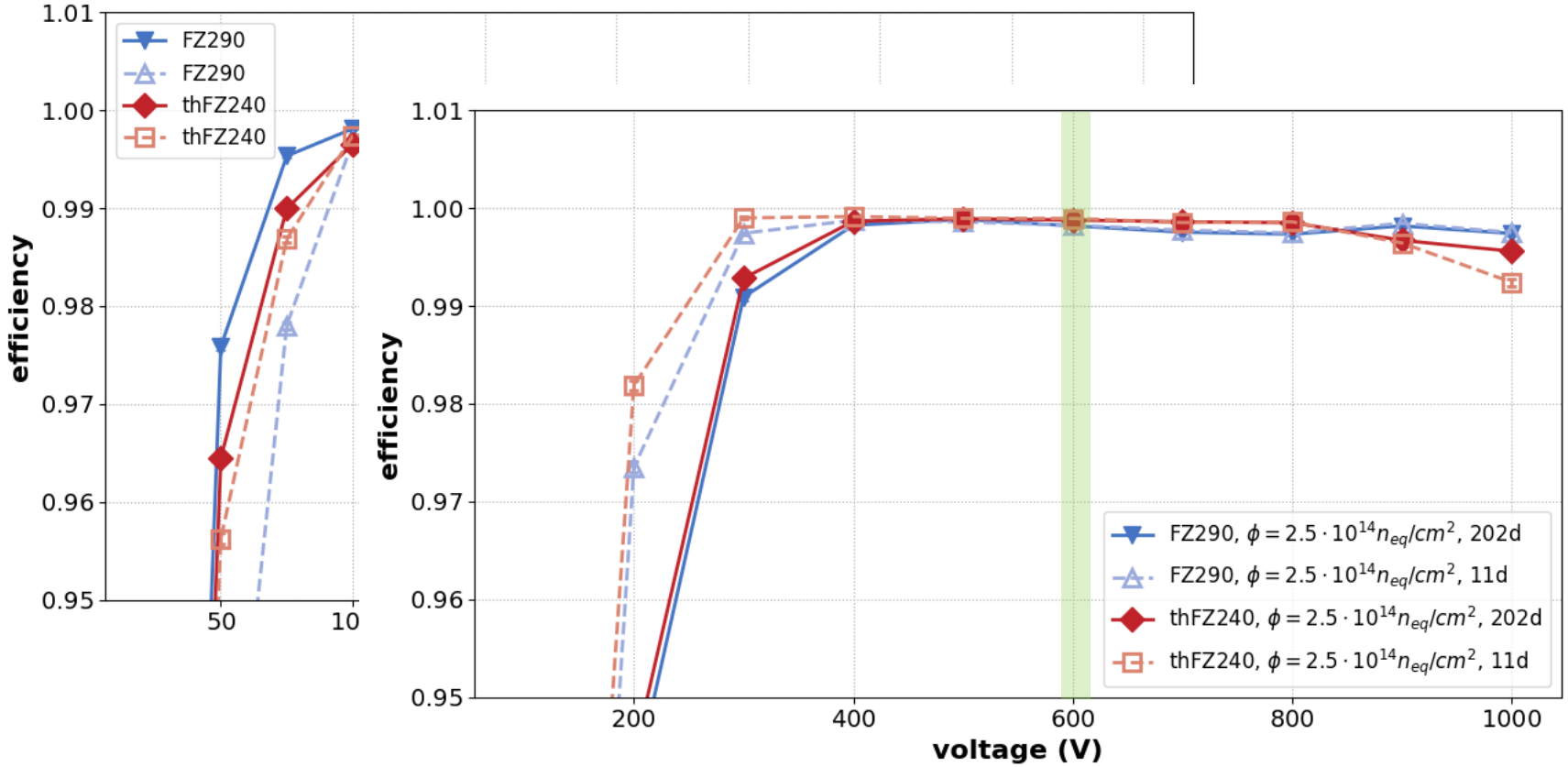
Bias Voltage Scan – 4000fb^{-1}



Nominal operation voltage

Optional bias voltage boost

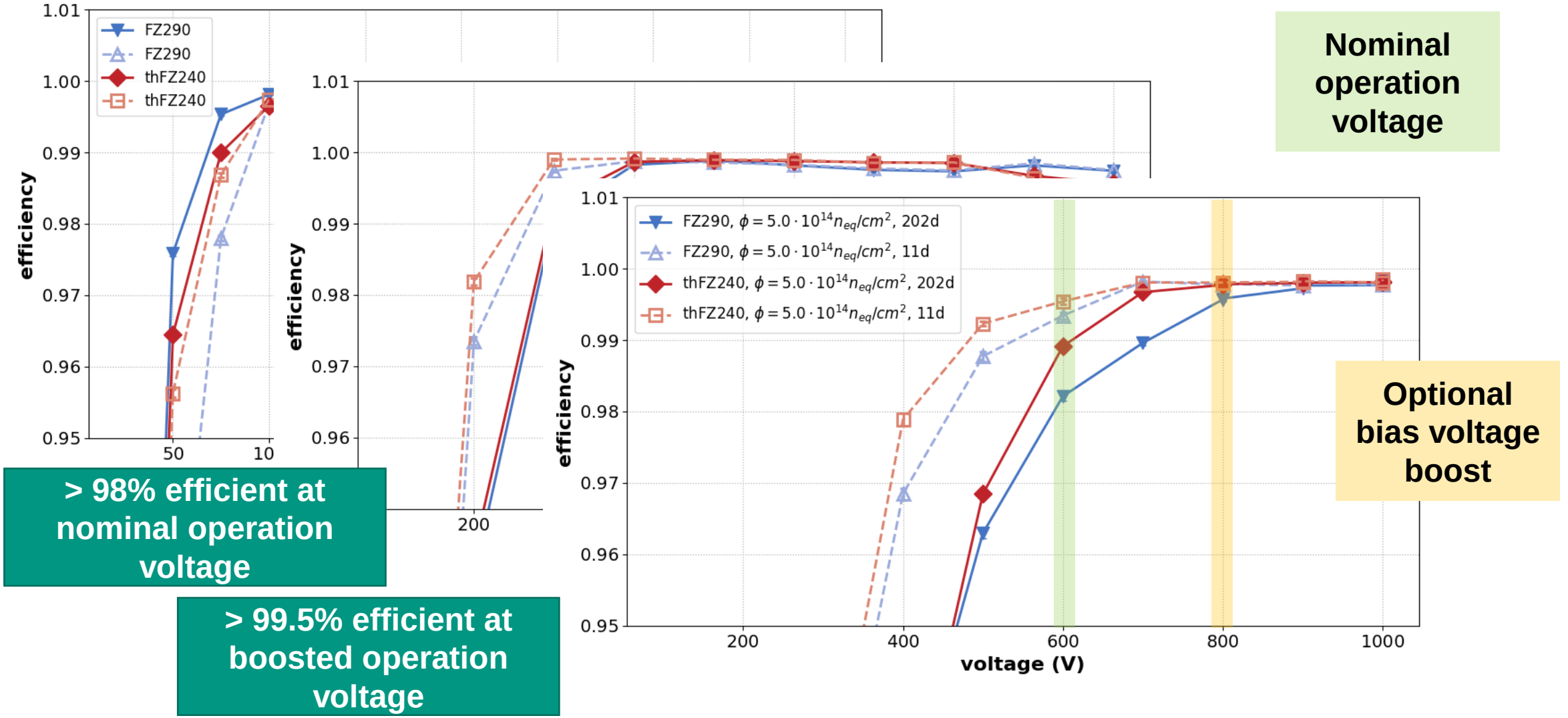
Bias voltage scans – nominal operation



Nominal operation voltage

all sensors still efficient

Bias voltage scans – ultimate scenario



Nominal operation voltage

Optional bias voltage boost

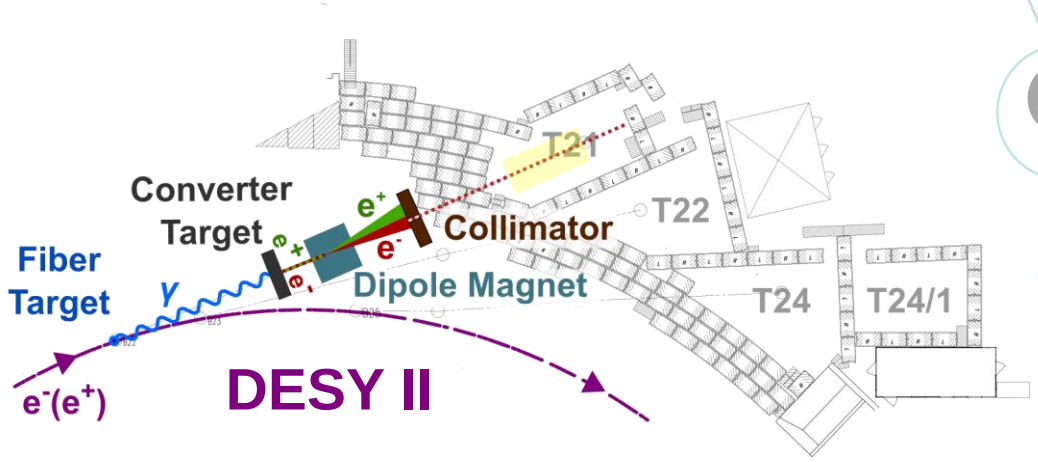
> 98% efficient at nominal operation voltage

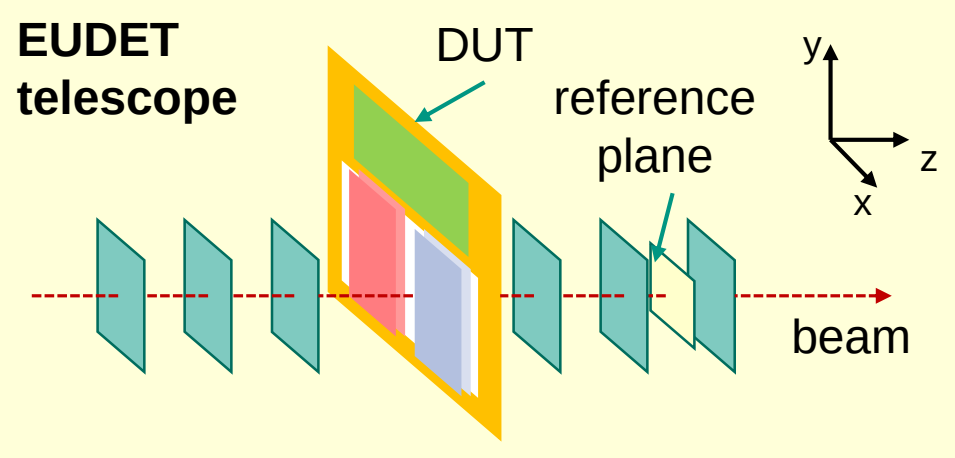
> 99.5% efficient at boosted operation voltage

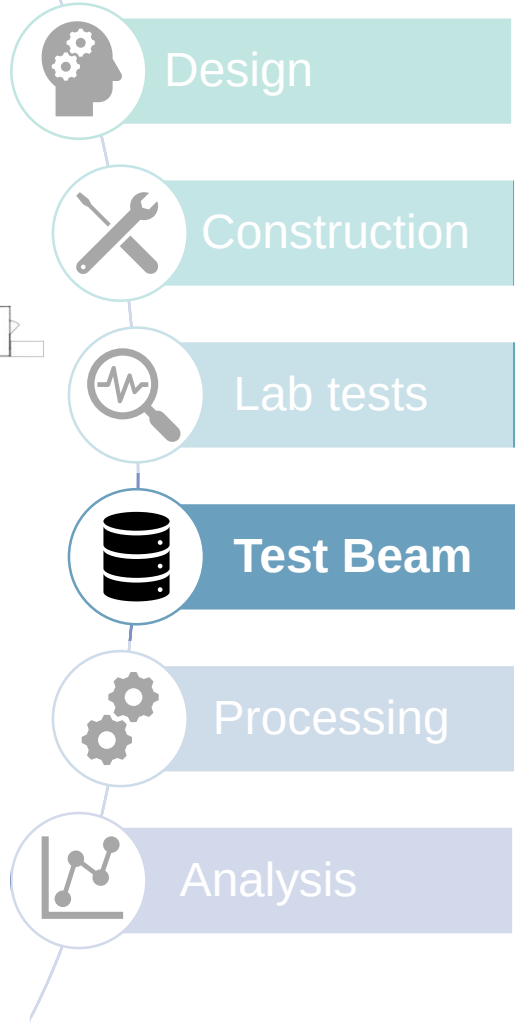
The DESY Test Beam Facility

- Adjustable 1 to 6 GeV electron beam
- EUDET telescopes for tracking
  - 6 telescope planes (MIMOSA pixel detectors)
  - Up to 2.88 µm track resolution
  - Reference plane
  - Linear and rotation stages for the device under test (DUT)

Particle tracking
for efficiency studies





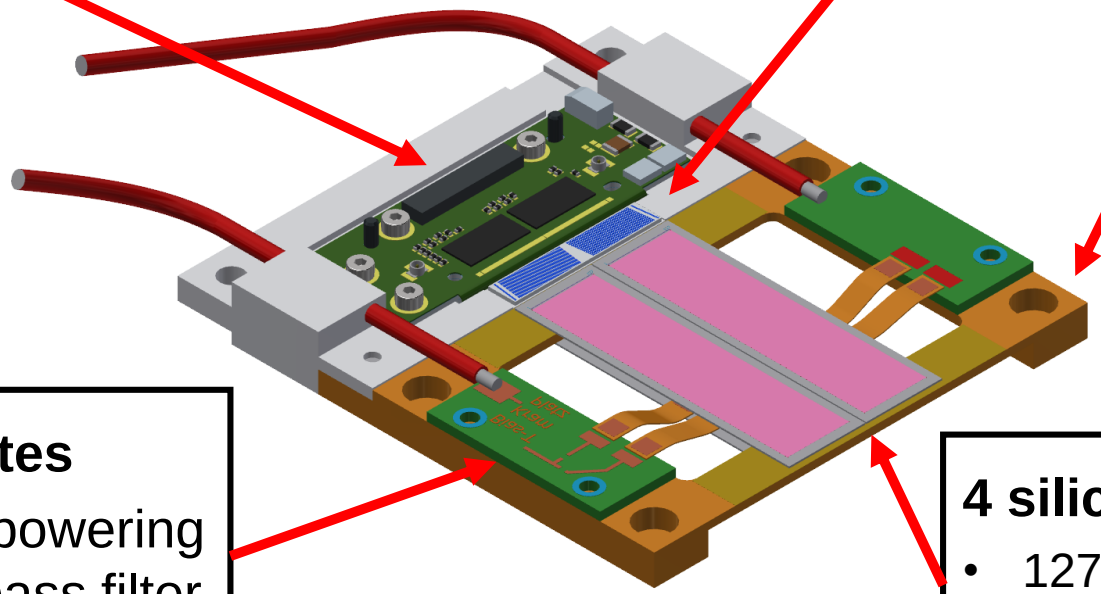


The 2S Mini Module Design

Front-end flex hybrid
- 2 x CBC3
- Electrical readout

Pitch adapter
- Signal transmission

Copper frame
- Cooling
- Spacing

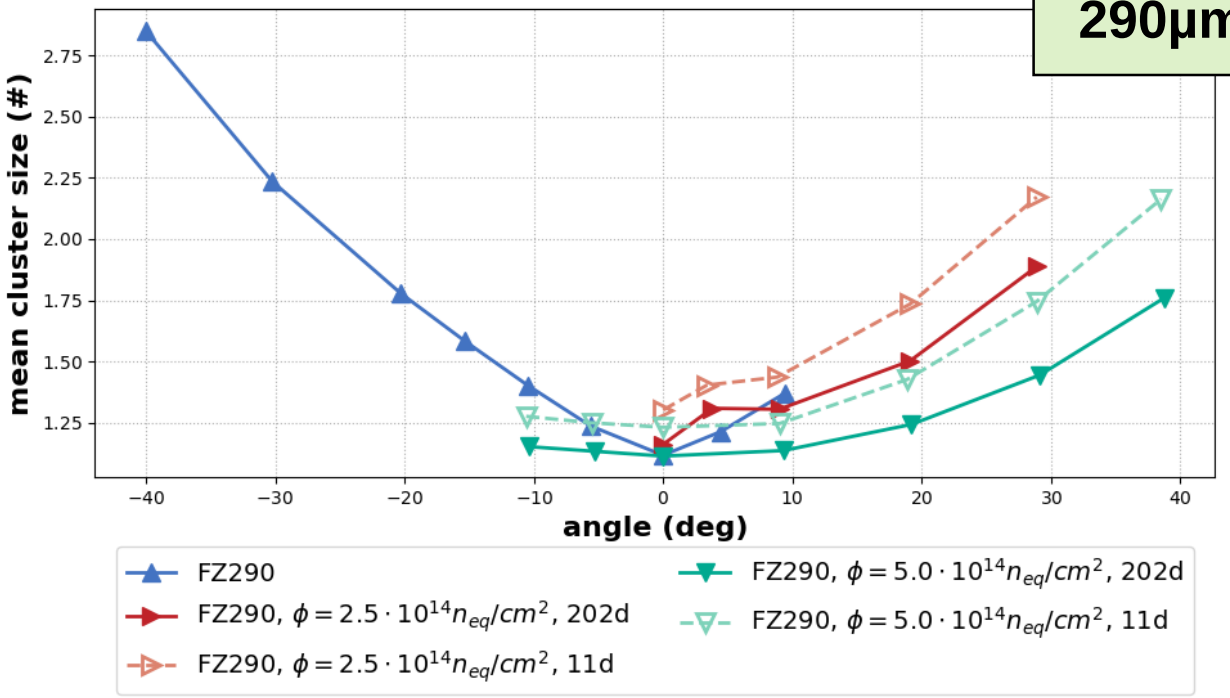


Power plates
- Sensor powering
- HV lowpass filter
- HV pigtails

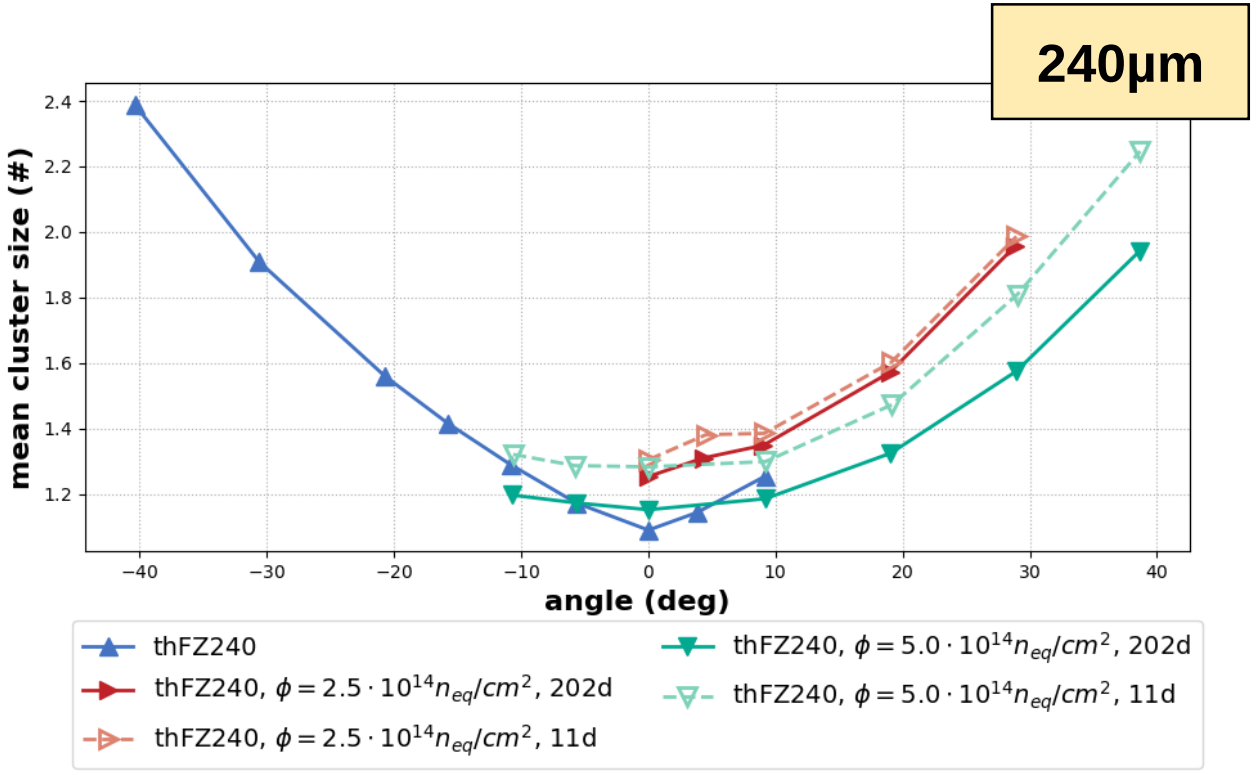
4 silicon strip sensors
- 127 strips each
- 240/290µm thickness
- Arranged in two layers

Angle cluster size

290µm

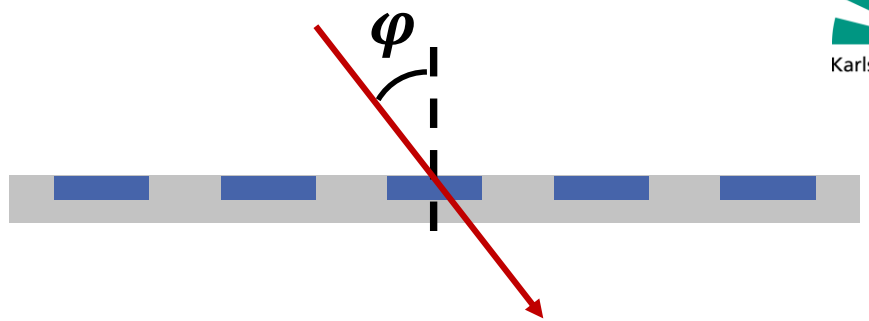


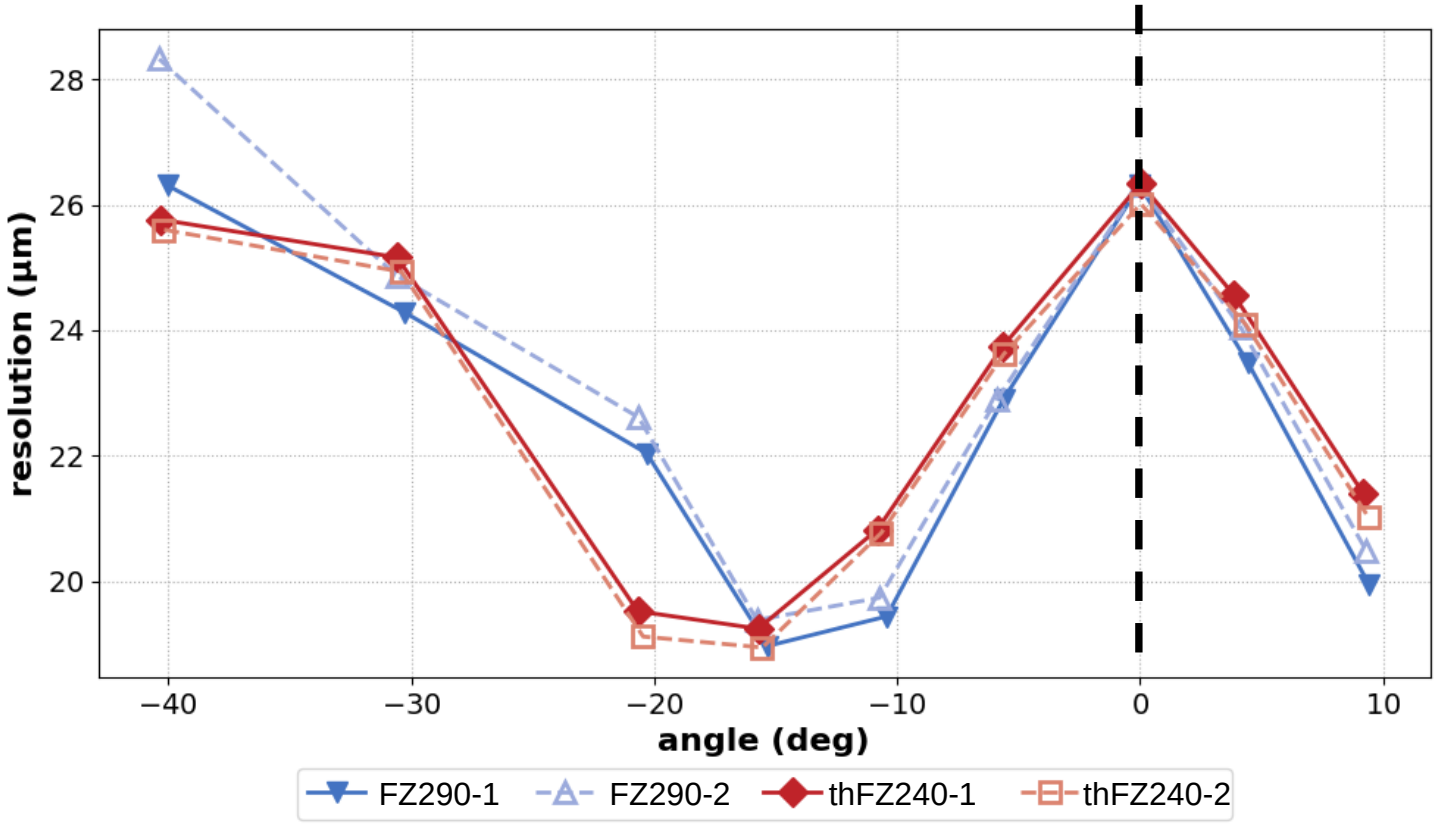
240µm



Angle Resolution Scan

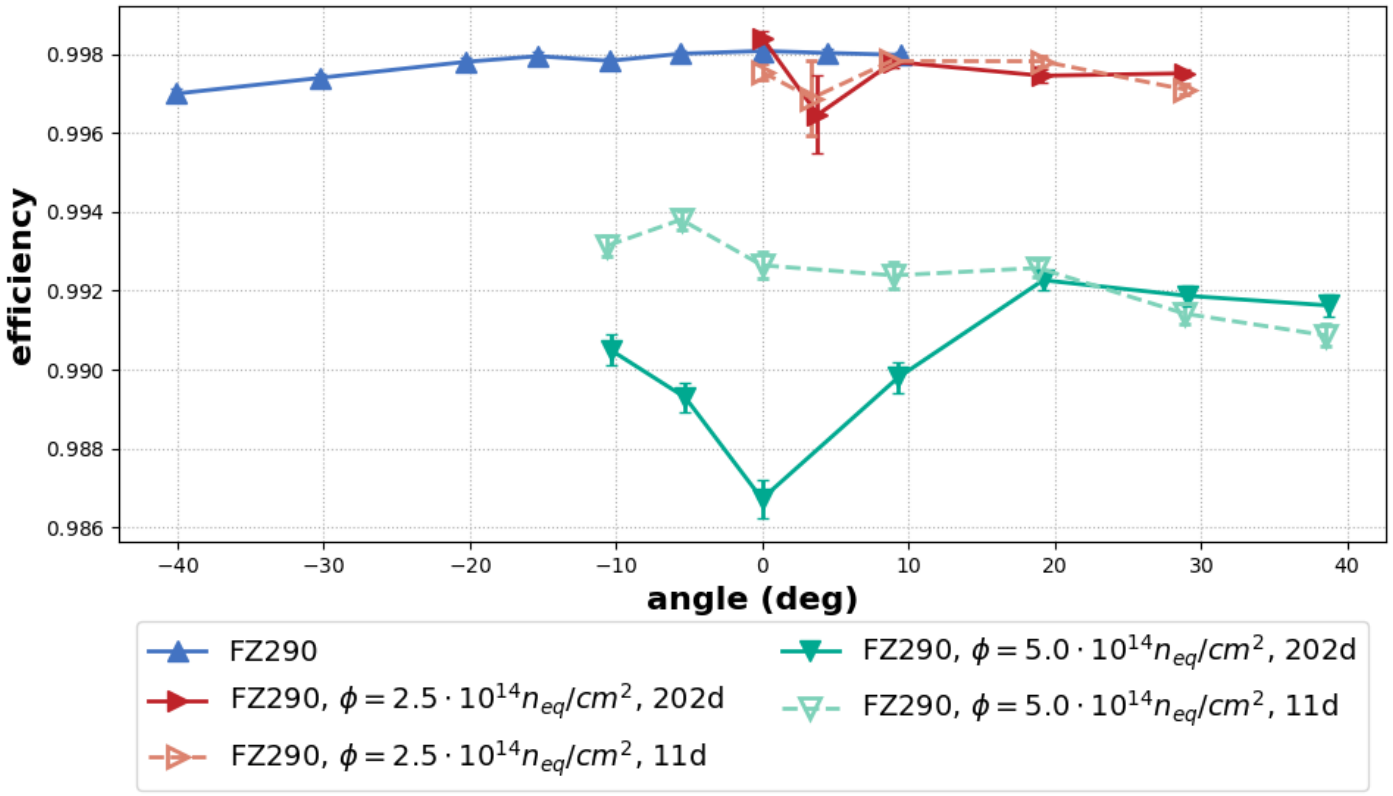
- Non zero incident angles improve resolution
  - Charge sharing
  - Clustering
- Best resolution for:
  240µm: $\varphi \approx 15° - 20°$
  290µm: $\varphi \approx 15°$





Angular Efficiency Scan – 290µm sensors

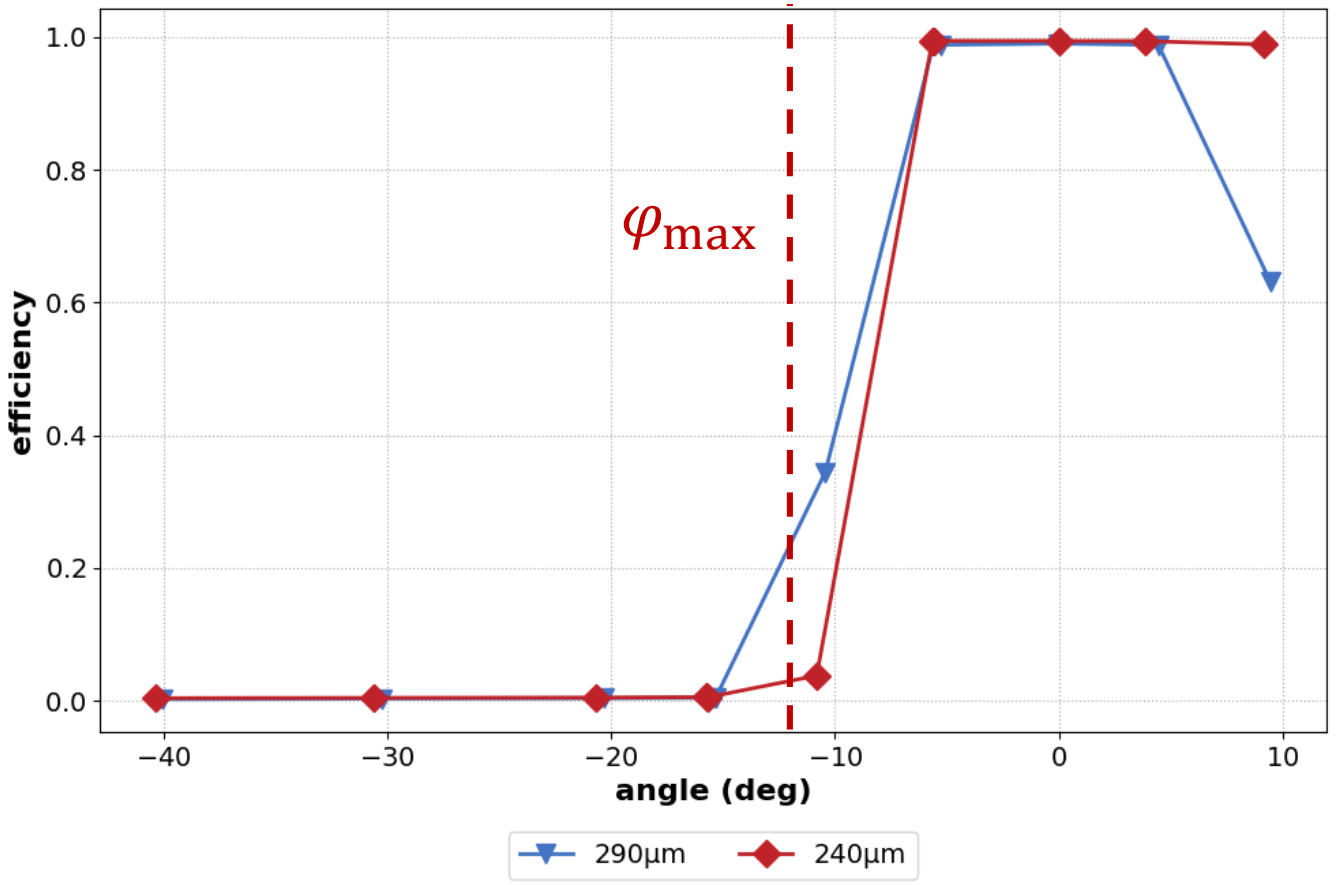
- Efficiency decreases with irradiation
- High irradiated 290µm more sensitive to annealing



Angle stub efficiency

Max. accepted stub bend:
3.5 strips ↔ $\varphi_{max} \approx 12.7°$

- Efficiency drop for $\varphi > \varphi_{\mathrm{max}}$



Angle stub bend

Max. accepted stub bend:
3.5 strips ↔ $\varphi_{max} \approx 12.7°$

- Stubs disappear for $|\varphi| > \varphi_{\max}$