Test-beam qualification of the modules for the CMS Phase-2 Outer Tracker

Daniil Rastorguev daniil.rastorguev@desy.de
Andreas Nürnberg, Paul Schütze, Lea Stockmeier
SiDet R&D
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HELMHOLTZ

Karlsruher Institut für Technologie

Overview of the Phase-2 CMS Outer Tracker Modules

Phase-2 CMS Outer Tracker

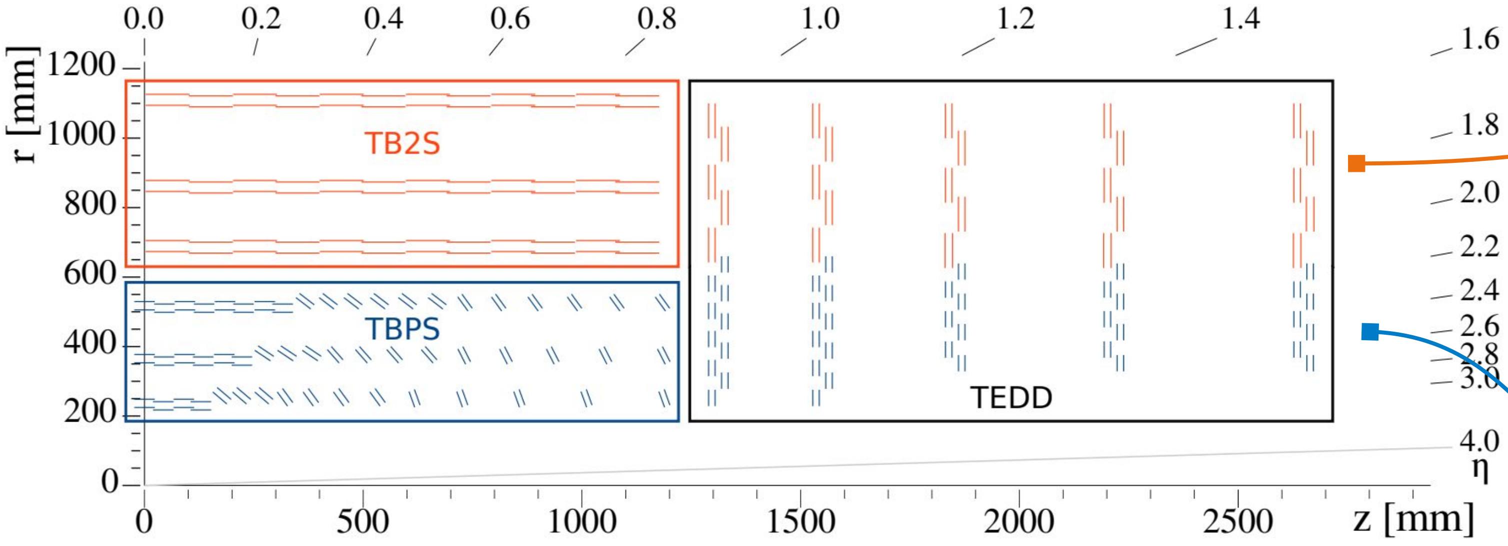
Harder, better, faster, stronger

HL-LHC upgrade:

- Instantaneous luminosity up to $\mathbf{7.5 \cdot 10^{34}\ cm^{-2}s^{-1}}$
- pile-up up to **200**

The all-new Outer Tracker, improved in every aspect:

- Higher granularity
- Higher radiation hardness
- Higher data rate
- Contribution to the fast hardware (L1) trigger by track p_T discrimination



Cross-section of one quarter of the Phase-2 Outer Tracker

Built of **two types** of **double sensor** layer modules:

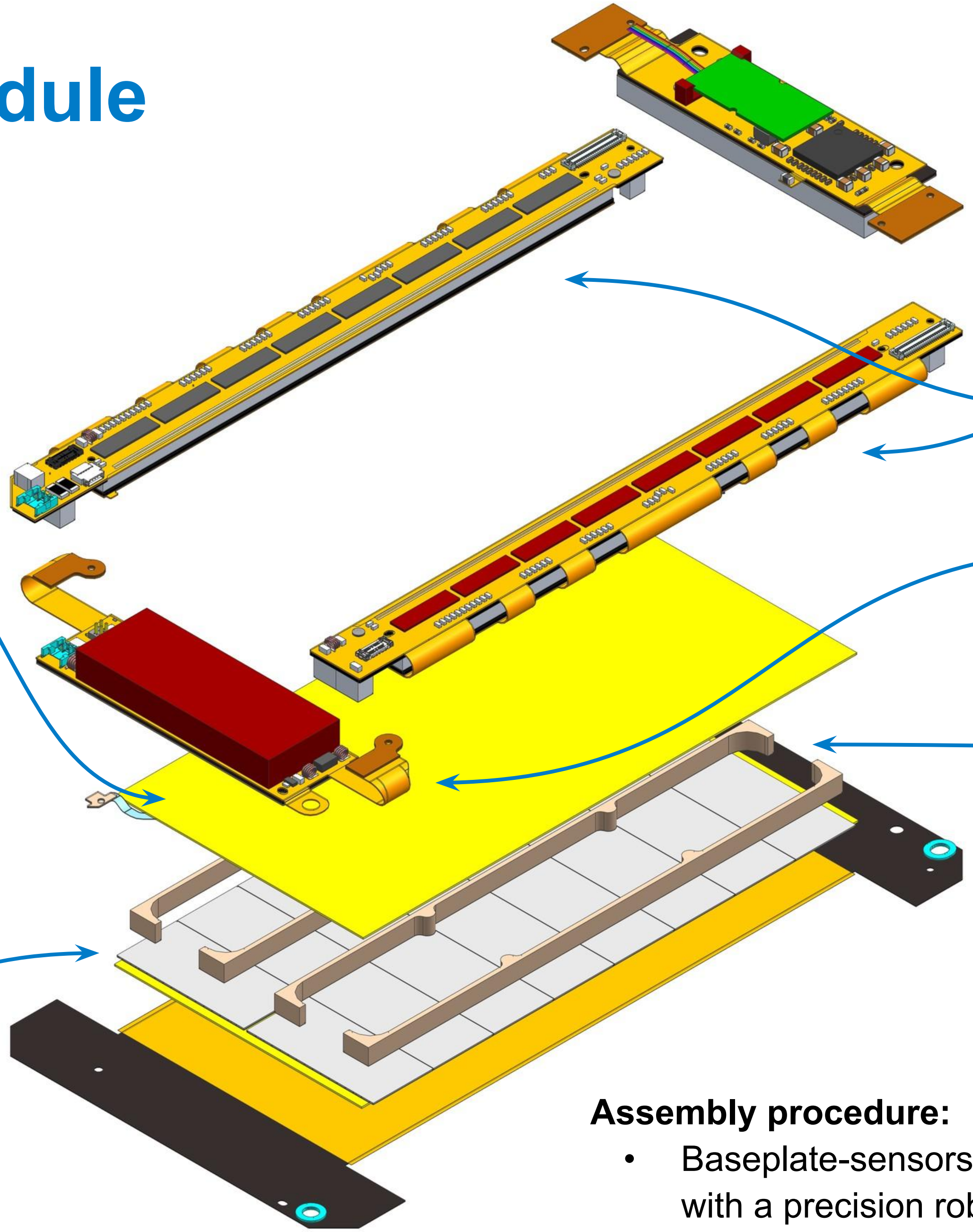
Strip-strip (2S)
7680 pcs.

- 10×10 cm^2
- 2 strip layers

Pixel-strip (PS)
5616 pcs.

- 10×5 cm^2
- 1 macro-pixel layer
- 1 strip layer

Design of a PS module



Transceiver

Strip front-end x2

Power supply

Spacers x4
different thicknesses for modules at different *rz* positions

CFRP baseplate

Strip layer (PS-s):

- 960 $\times$ 2 strips
- 100 μm pitch

Double sensor for angle discrimination

Macro-pixel layer (PS-p):

- 960 $\times$ 32 macro-pixels
- 100 $\times$ 1467 μm^2 pitch
- 16 ASICs on top

Assembly procedure:

- Baseplate-sensors-spacers subassembly built with a precision robot
- Hybrids are glued with jigs and wire-bonded to sensors and ASICs

On-module p_T discrimination

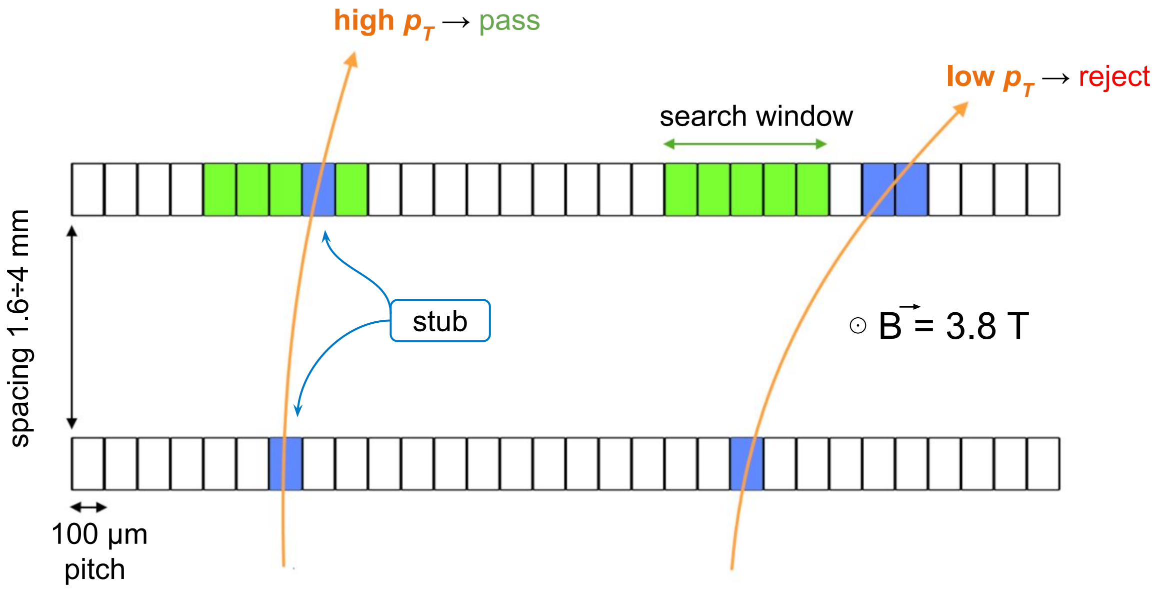
How the modules contribute to the L1 trigger

Modules are able to spot **high p_T tracks (> 2 GeV)**
= candidates for interesting events:

- high p_T → ~perpendicular traverse
- low p_T → traverse at an angle

A **stub** is a special data instance, produced by the module as a response to a high p_T track
→ contains position and bend angle

Modules are designed to produce and send out **stubs** at the BX rate (40 MHz) and with low latency
→ to be used in the fast hardware (Level-1) trigger



Stub pipeline, run on the module onboard ASICs:

Clustering → Correlation between two planes → Discrimination by a given window → if passed: a **stub** is generated → Stubs are sent out via dedicated low-latency data path

Test-beam campaign

3x 2S in the telescope

Test beam campaign

DESY-II, Feb 5th – Feb 18th 2024

DSY_101
PS kick-off, 2.6 mm, 5G, DESY

- full characterization
- validation of kick-off components

IPG_103
PS kick-off, 2.6 mm, 10G, Perugia

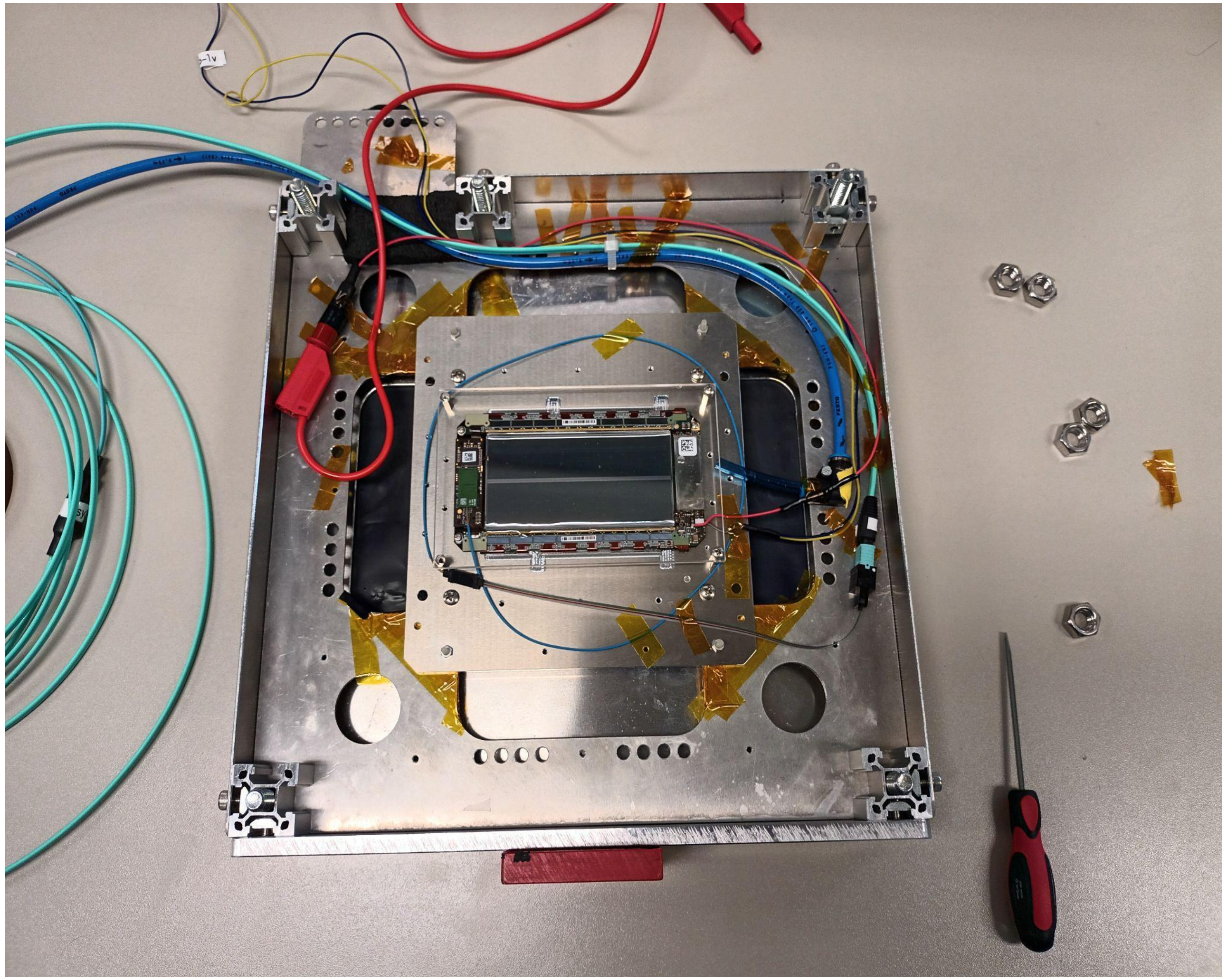
- tests of 10 Gbps readout

BRN_009
PS prototype, 1.6 mm, irrad. PS-s, 10G, US East

- tests of an irradiated PS-s sensor

KIT_101, KIT_102, KIT_104
3x. 2S kick-off, Karlsruhe

- full characterization
- validation of kick-off components
- simultaneous readout of 3 modules

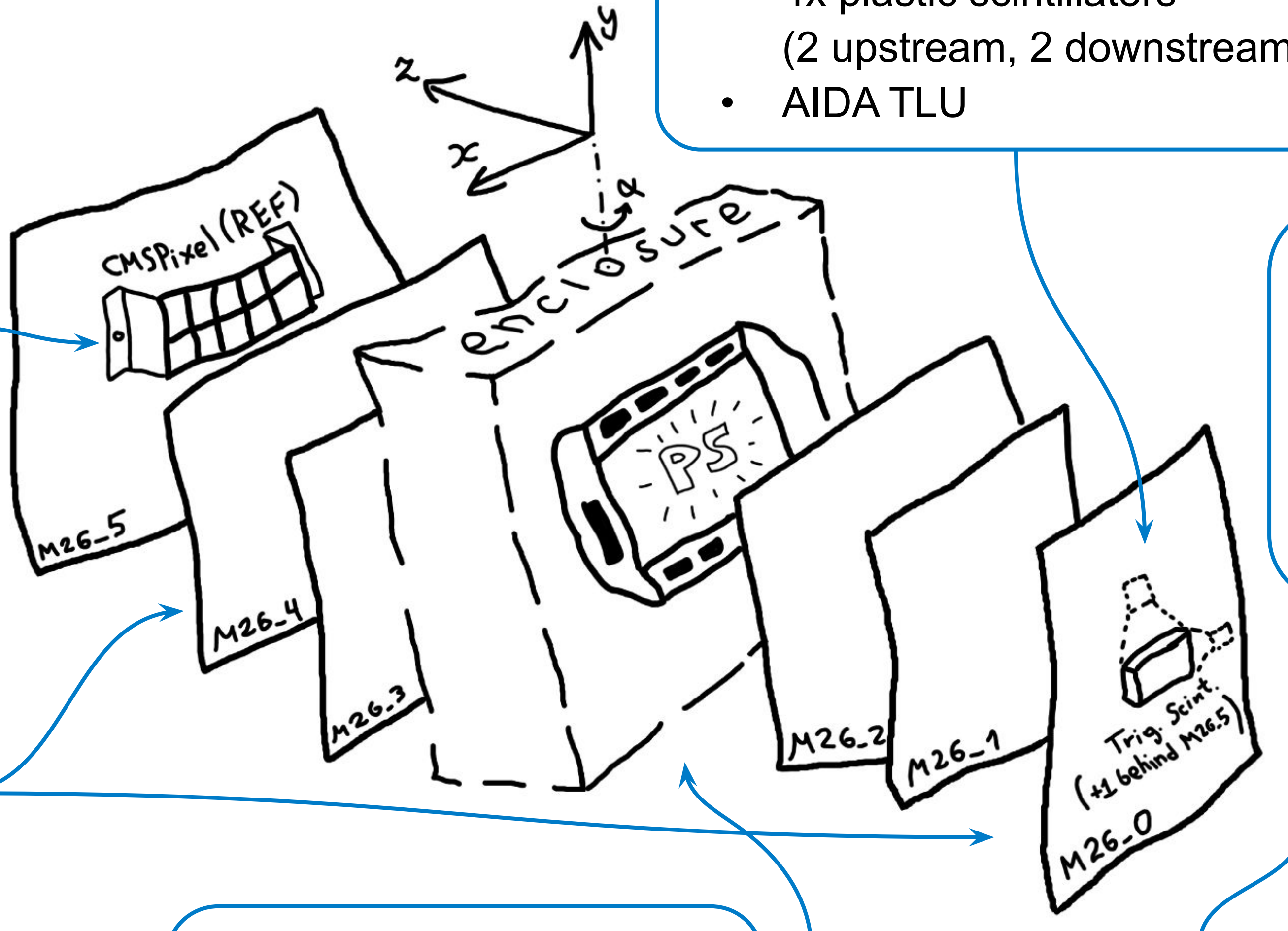


PS module on a carrier plate inside of a test box

Test beam setup trivia

Trigger logic
- 4x plastic scintillators (2 upstream, 2 downstream)
- AIDA TLU

Reference plane
- CMS Phase-1 pixel module
- 150✕100 μm^2 pitch
- to spatially select tracks within a given time window



Quick animal fact

Most bobcats are not named bob

DATURA beam telescope
- 6x MIMOSA26 planes
- 18.4 μm pitch
- 115 μs time frame
- Tracking resolution ~O(μm)

Our case (1x PS module):
- narrow conf.: ~4 μm
- wide conf.: ~9 μm

DUT enclosure
- on a rotation stage
- nitrogen/cooling
- holds module(s) inside

DESY-II beamline 21
- adjustable energy (5 GeV used)
- O(kHz) rate

Observable quantities

Definitions of detector performance FOMs

Reconstruction performed with Corryvreckan with GBL tracking

$$\text{Residuals}_x = \{x_{\text{track}} - x_{\text{cluster}}\}_{\text{tracks}}$$

$$\text{Resolution}_x = \text{RMS}(\text{Residuals}) \ominus \sigma_{\text{telescope}}$$

Fit the distribution and take fit RMS instead
→ more robust

$$\mathcal{E}(\text{DUT}) = \frac{\text{Tracks} \cap \text{Matched REF} \cap \text{Matched DUT}}{\text{Tracks} \cap \text{Matched REF}}$$

Efficiency = chance for the DUT to *properly respond* to a *good track*

Criteria for track matching:

PS-p: $|x_{\text{track}} - x_{\text{cluster}}| \leq 200\mu\text{m}$, $|y_{\text{track}} - y_{\text{cluster}}| \leq 2\text{mm}$

PS-s: $|x_{\text{track}} - x_{\text{cluster}}| \leq 200\mu\text{m}$, $|y_{\text{track}} - y_{\text{cluster}}| \leq 26\text{mm}$

REF: $|x_{\text{track}} - x_{\text{cluster}}| \leq 300\mu\text{m}$, $|y_{\text{track}} - y_{\text{cluster}}| \leq 200\mu\text{m}$

→ distance(hit↔track) ≲ 2x pitch

It's almost twelve at the Doomsday clock?

Great, at twelve I got my lunch break...

Angular calibration of the setup

by cluster size vs angle dependency

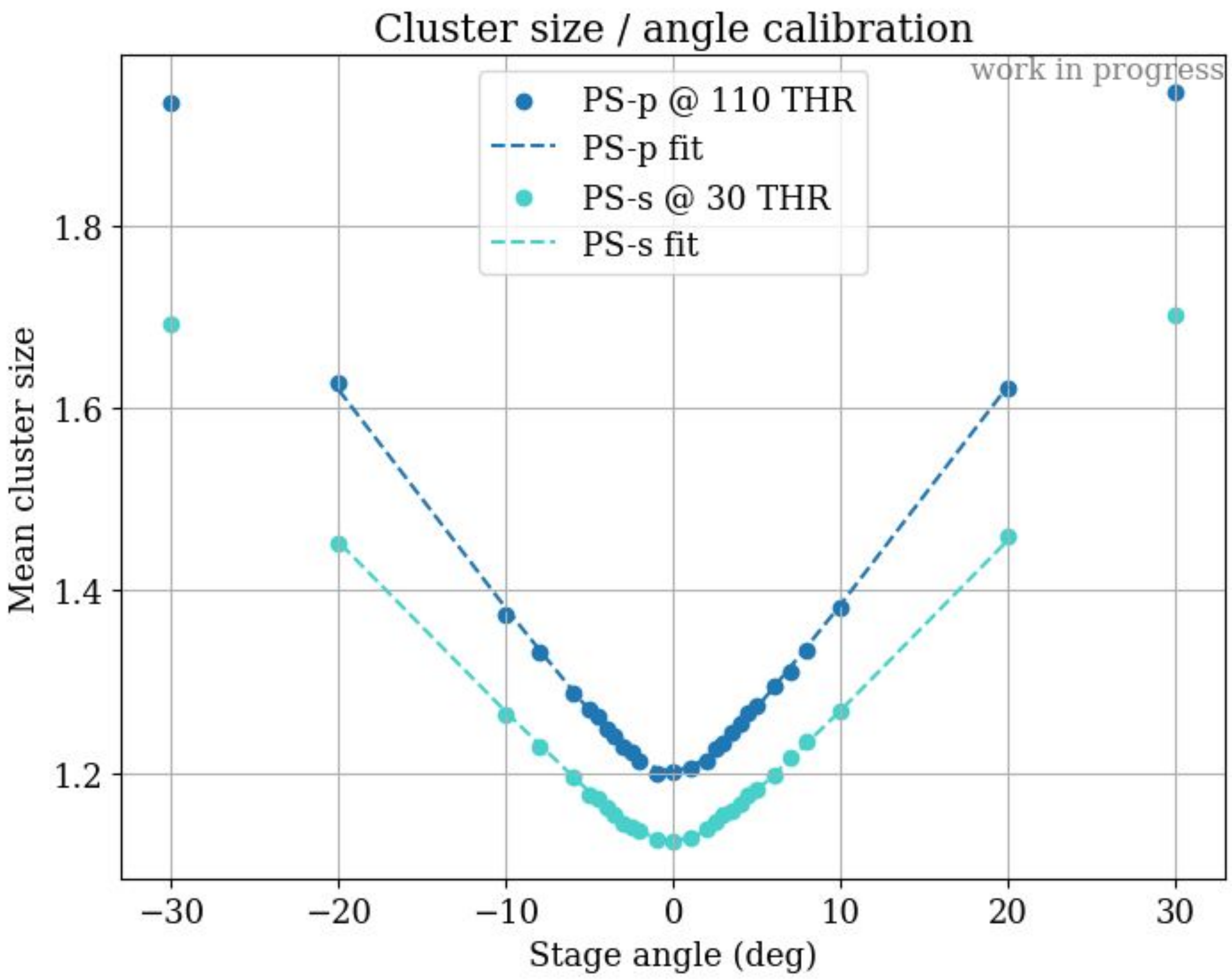
Cluster size vs. incidence angle
is a precise way of zeroing of the rotation stage:

- independent of tracking/reconstruction
- strongly dependent on the angle

convolution

$$\mathrm{size}(\alpha) = s_0 + k \cdot \langle \tan|x - \alpha_0| * \exp - \frac{y^2}{\sigma^2} \rangle(\alpha)$$

→ angular offset α_0 extracted from the fit and applied to all angle readings from the rotational stage



Results

DSY_101 kick-off (1/4)

sensor efficiency and working points

For non-irradiated sensors,
the working point was determined as follows:

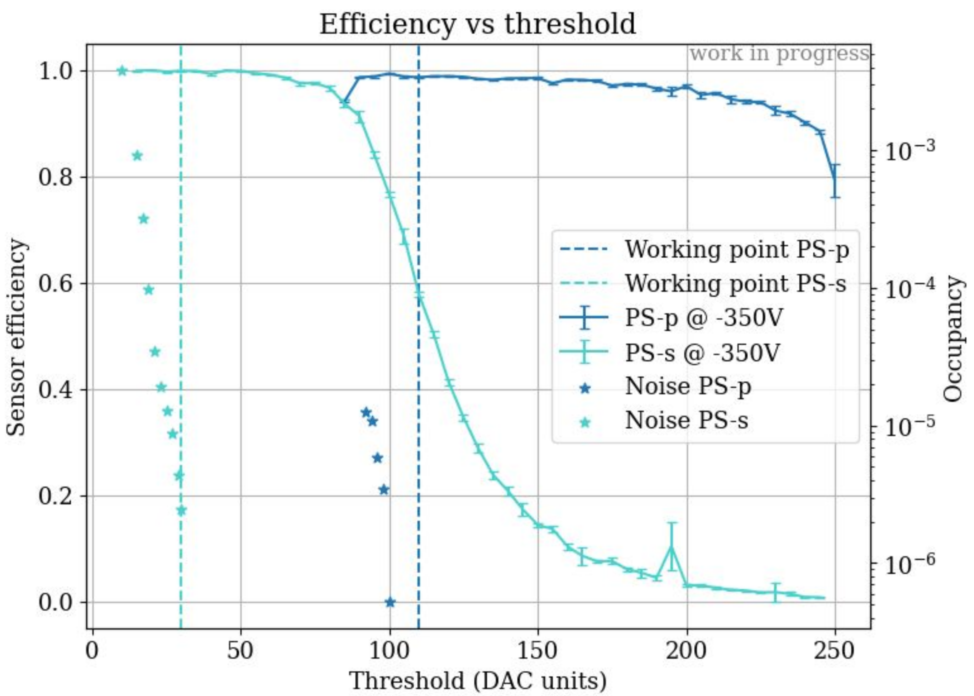
- Thr MPA = **110 DAC units ≈ 3 ke$^-$**
- Thr SSA = **30 DAC units ≈ 7.5 ke$^-$**
- Bias = **– 350 V**

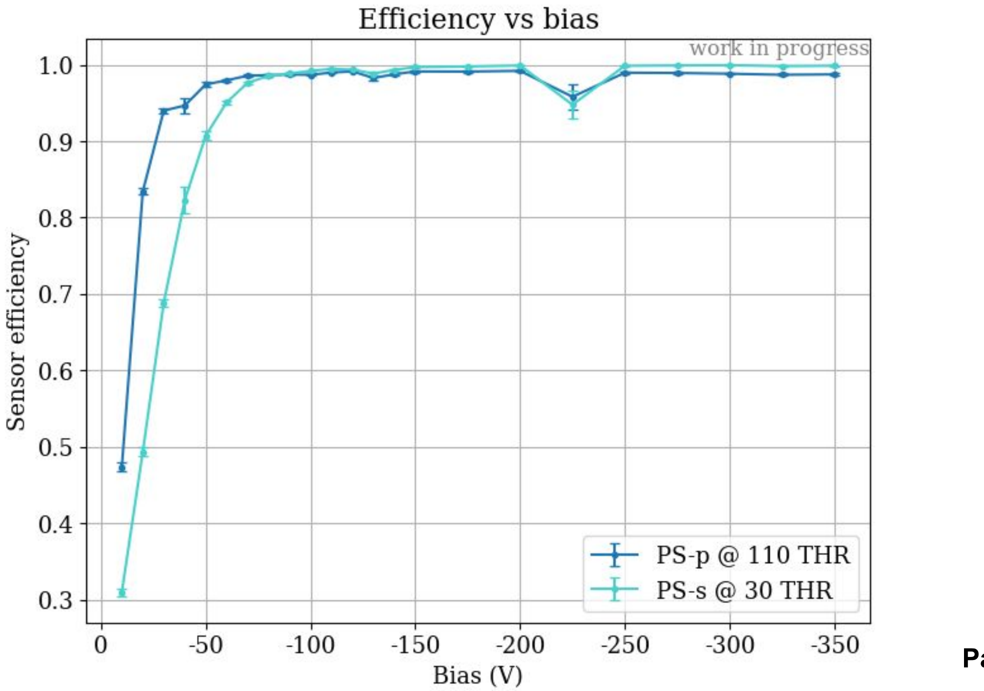
This yields efficiencies:

- ε(PS-p) = **98.7±0.1%**
- ε(PS-s) = **99.7±0.1%**

NB: results shown are work in progress

- outliers in plots
  → data points with unphysical monitoring values and too little statistics
- not reproducible with EUTelescope
  → most likely is a Corryvreckan analysis artifact, under investigation



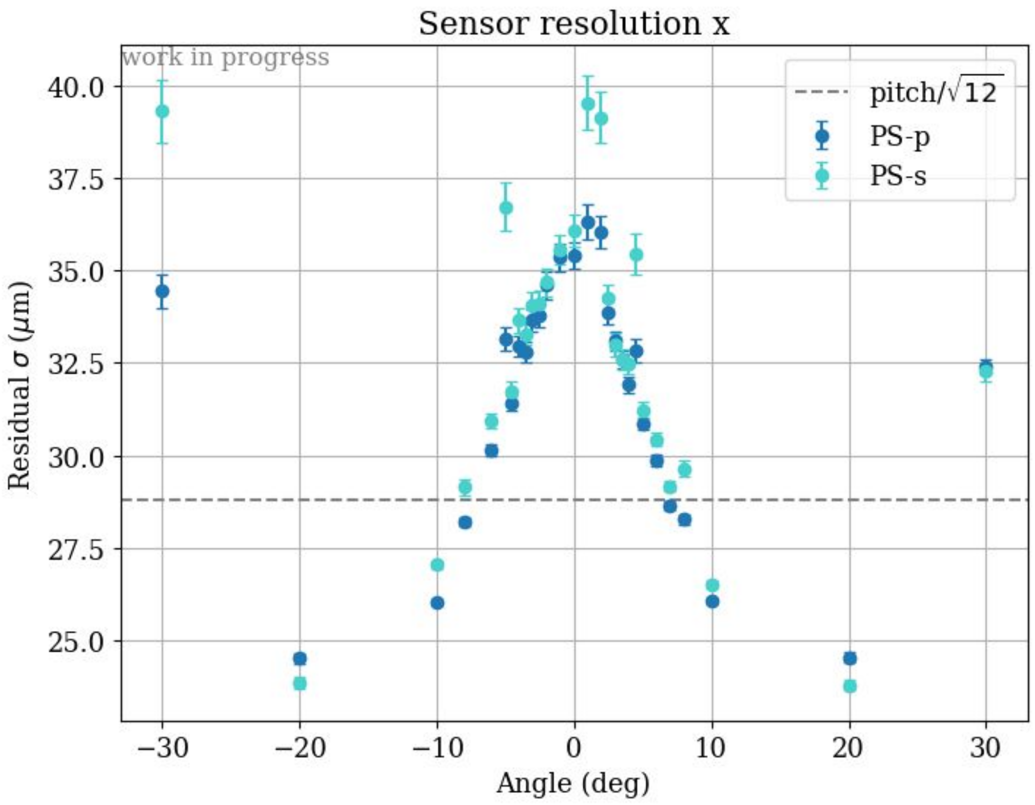


DSY_101 kick-off (2/4)

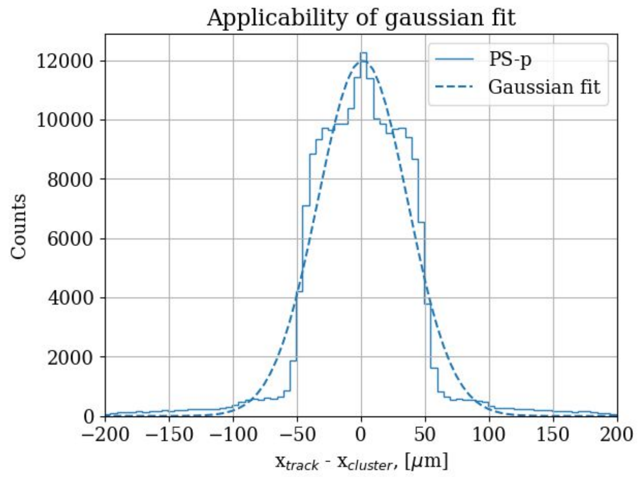
Spatial resolution vs incidence angle

Coordinate resolution quantified by fitting a **Gaussian** to the distribution of *local* residuals

- Telescope resolution of ~8.6 μm estimated by [1] is subtracted



Preliminary: fitting strategy to be improved



Worst case
(*least Gaussian distribution*)

For both sensors,

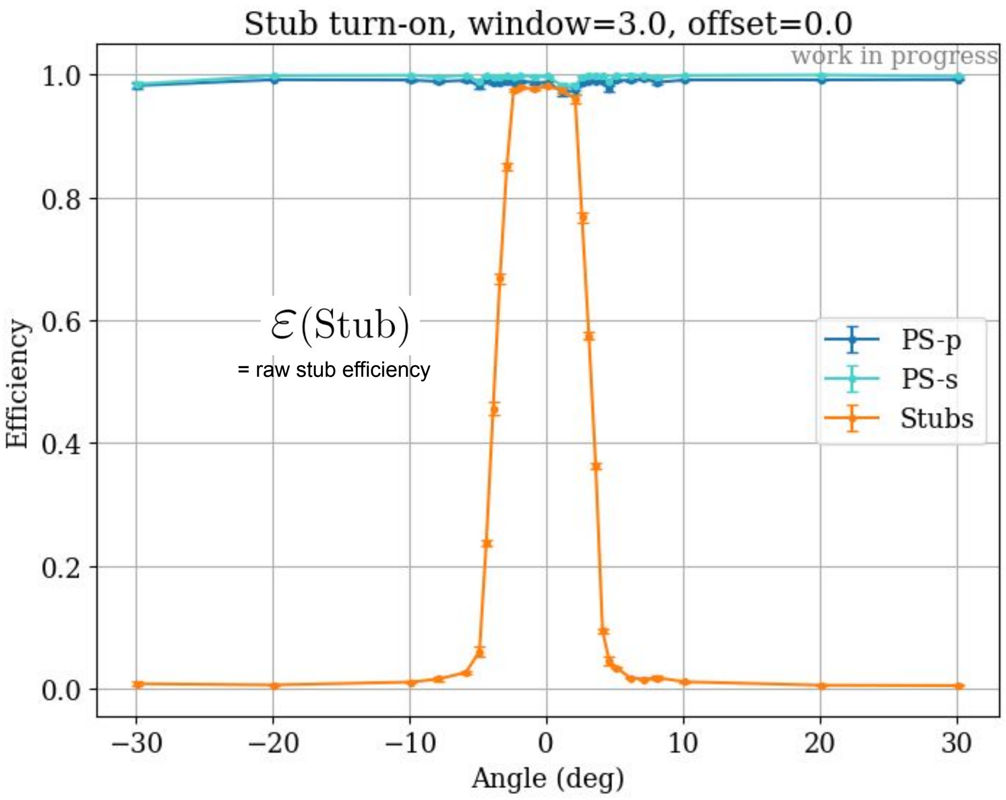
- Resolution of **~35 μm** for perpendicular incidence
- This improves with incidence angle, **overcoming binary limit** due to increasing cluster size

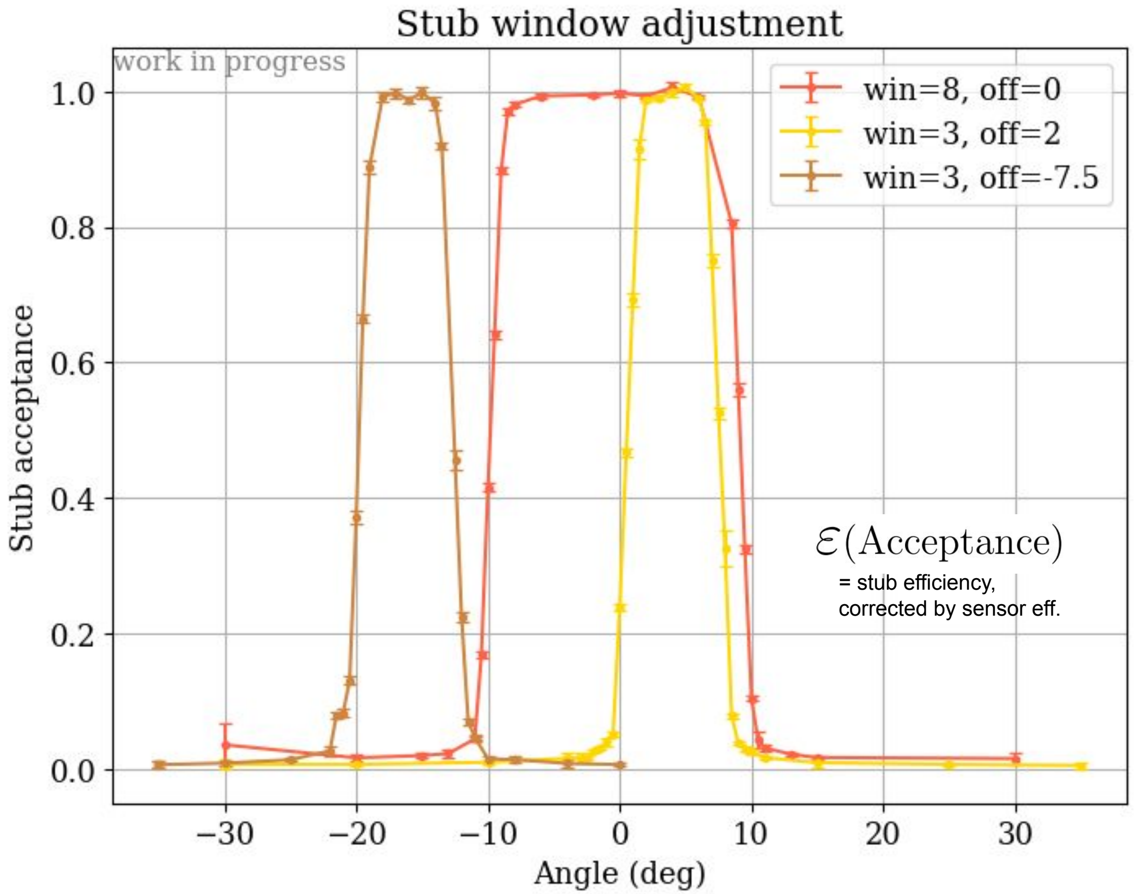
[1] GBL track resolution calculator: https://zenodo.org/records/48795

DSY_101 kick-off (3/4)

stub discrimination

Discrimination window width and offset are adjusted to ensure equal p_T cut for different module locations in the Tracker



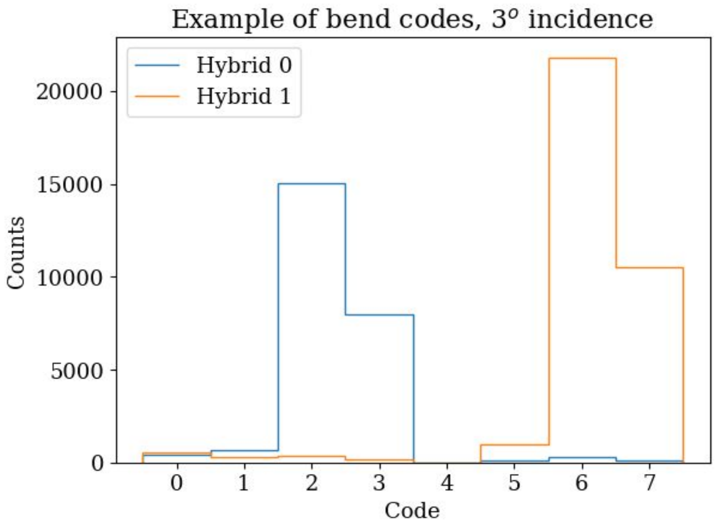


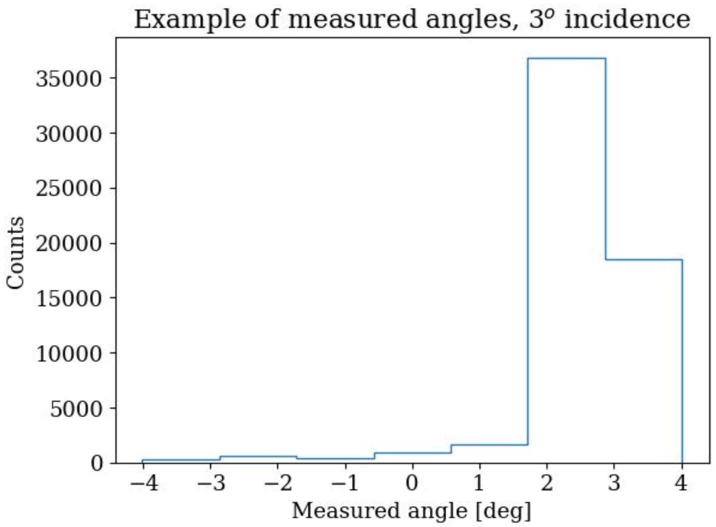
$$\mathcal{E}(\text{Stub}) = \mathcal{E}(\text{PS-p}) \cdot \mathcal{E}(\text{PS-s}) \cdot \mathcal{E}(\text{Acceptance})$$

DSY_101 kick-off (4/4)

on-module angle measurement via stub bend codes

For each stub, a **bend code** is stored
- contains information on track angle
- to be used in Level-1 trigger



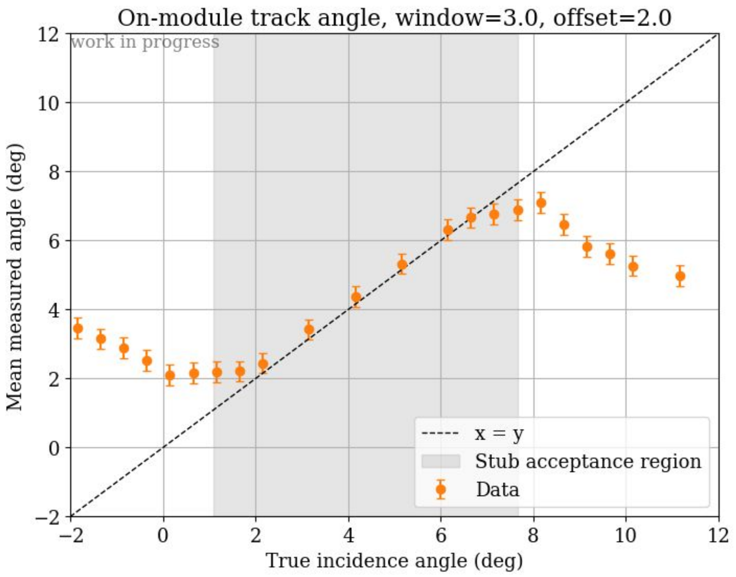


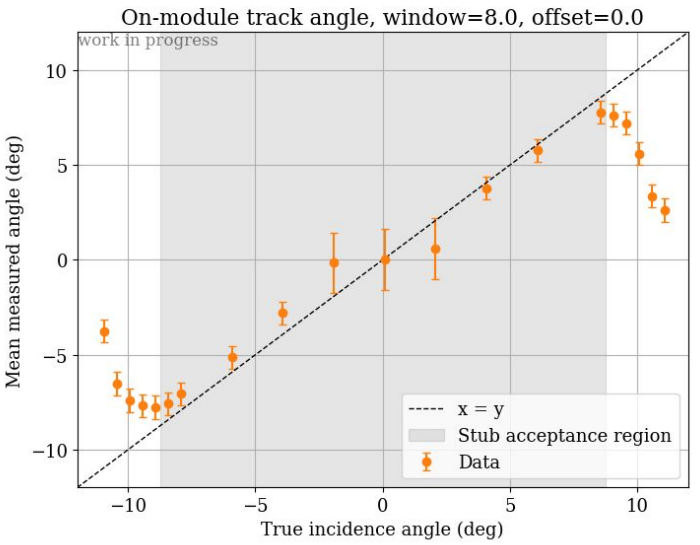
Each stub has a physical bend encoded

Which translates to the track angle:

α=atan((phys_bend+offset) · pitch/(2 · spacing))

~1.15° per half-strip for a 2.6 mm module





NB: error bars represent only encoding/binning errors

BRN_009 irradiated PS-s (1/2)

experimental environment

BRN_009 module

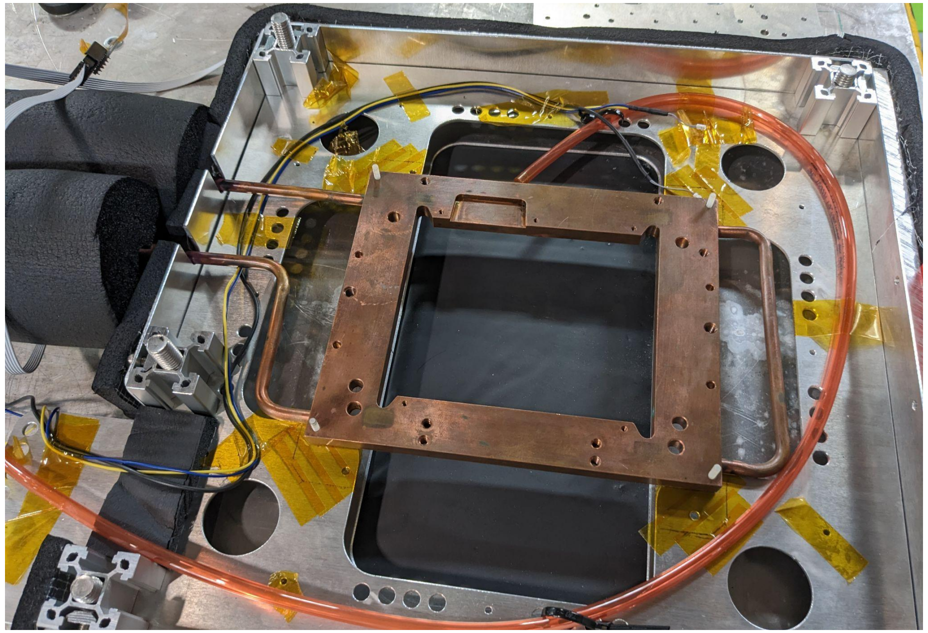
- PS-s irradiated, 1.1×10^{15} neutrons/cm^2
- no wire-bonds encapsulation

Cooling system:

- Copper thermoblock for 2S, SiOil ~ −40°C
- Dry (warm) N_2 supply
- Module on a solid Al carrier plate, no thermal interface material underneath

Temperature maintained on module: **−20°C** (est.)

→ don't exceed 600 V bias
→ reduced tracking precision due to scattering

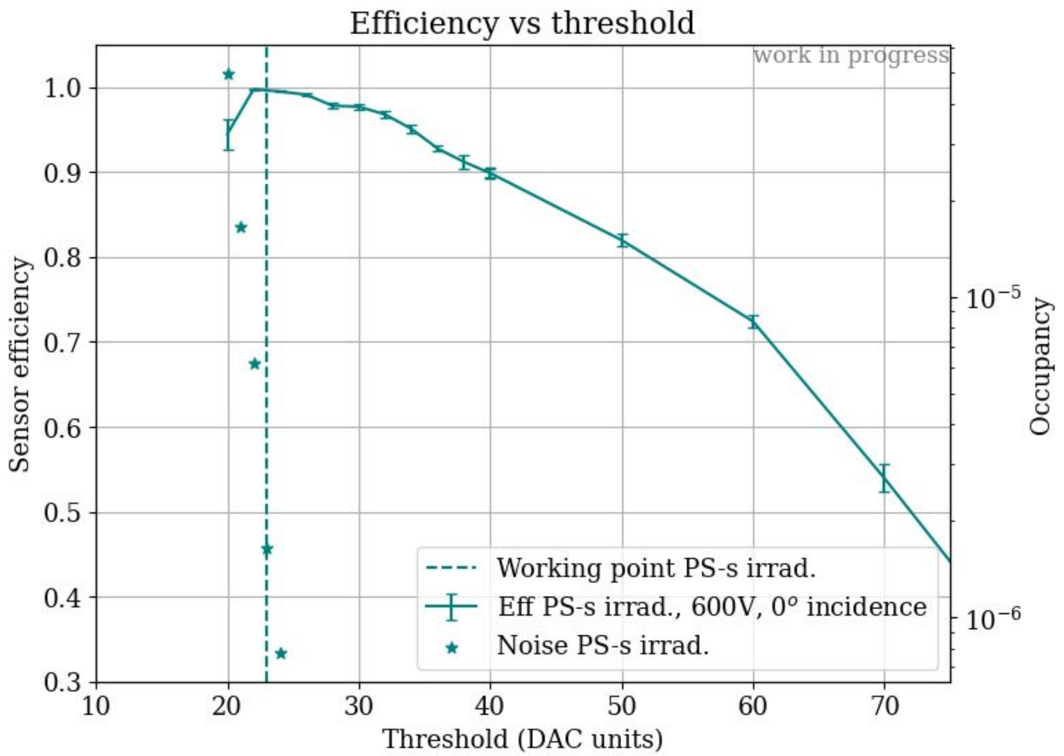


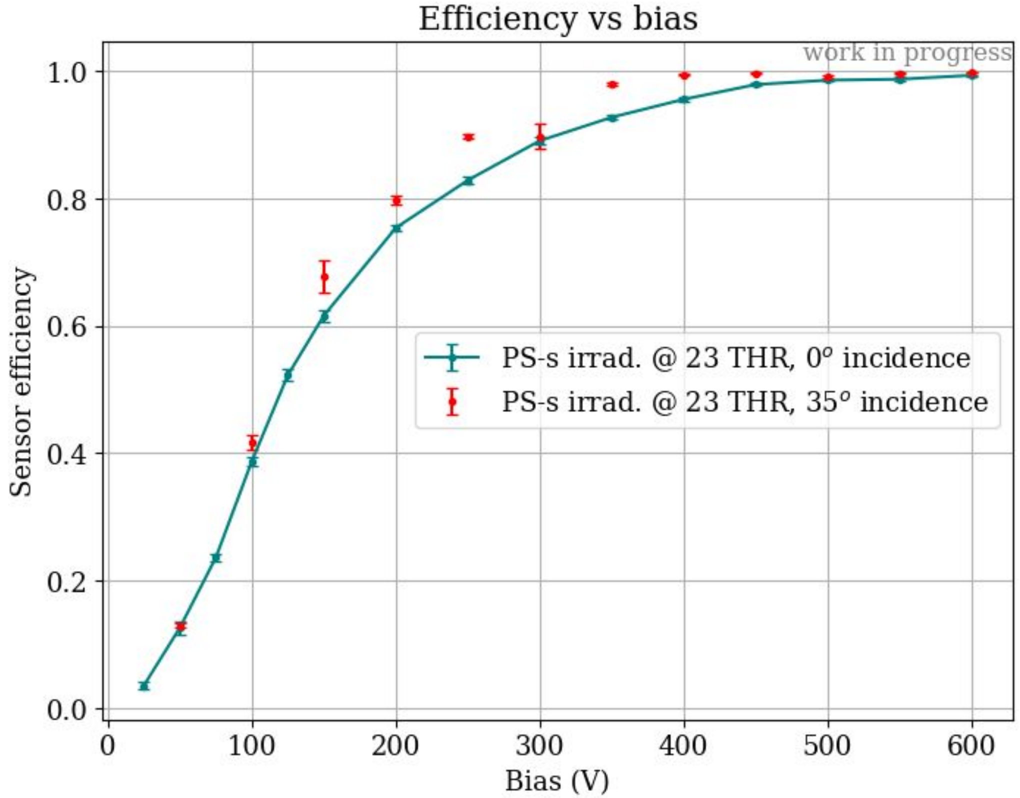
Cooling system (inside)

Cooling system (outside)

BRN_009 irradiated PS-s (2/2)

efficiency study





Working point:

- Threshold SSA = **23 DAC units ≈ 6 ke$^-$**
- Bias = **– 600 V**

→ ε(PS-s) = **99.5±0.1%**

Inclined incidence:
slightly higher efficiency for lower bias

Rationale:
under-depletion ⇒ thinner effective layer
⇒ increasing angle yields more charge *per channel*

IPG_103 at 10 Gbps

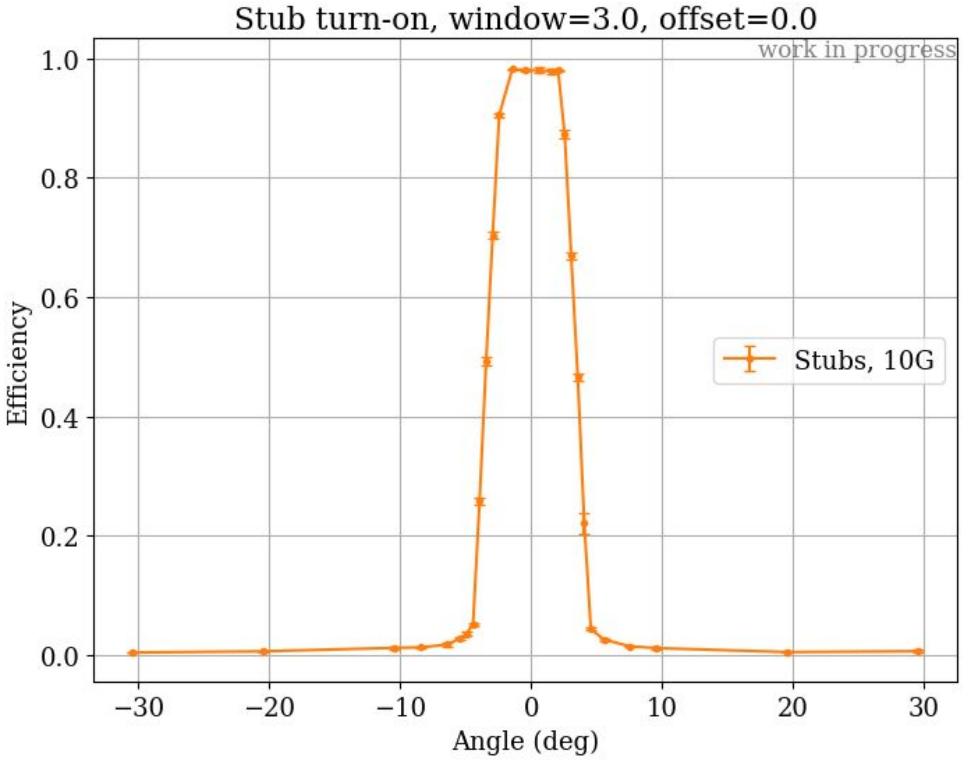
stub readout works now!

Trivia:

- Depending on expected hit rates, modules have either 5 Gbps or 10 Gbps readout
- 10G was not fully operational

With all the issues fixed,
10G readout has proven to work under test-beam conditions!

Proper stub turn-on curve with
stub efficiency at flat top of **98.2±0.1%**

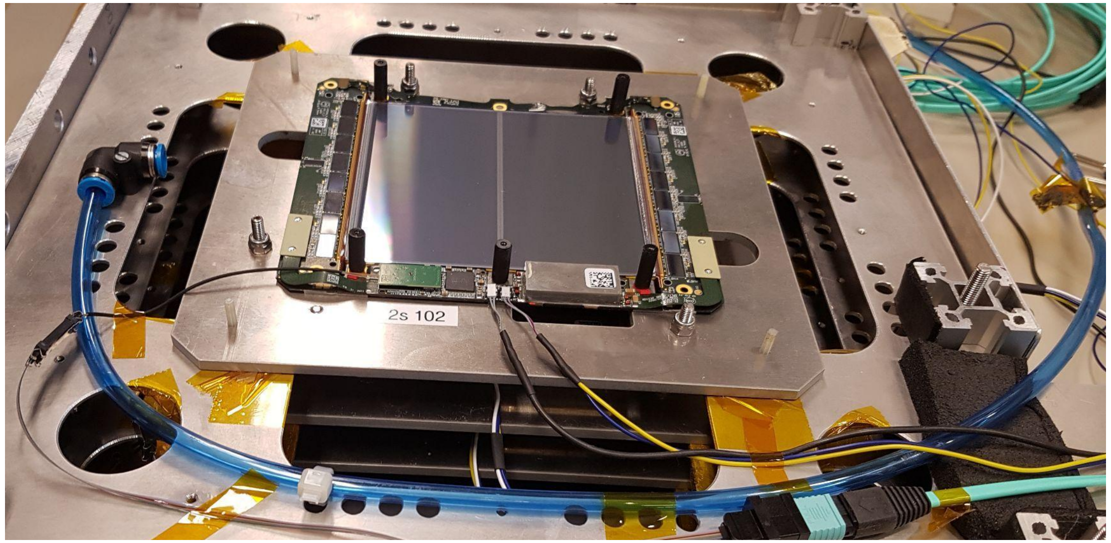


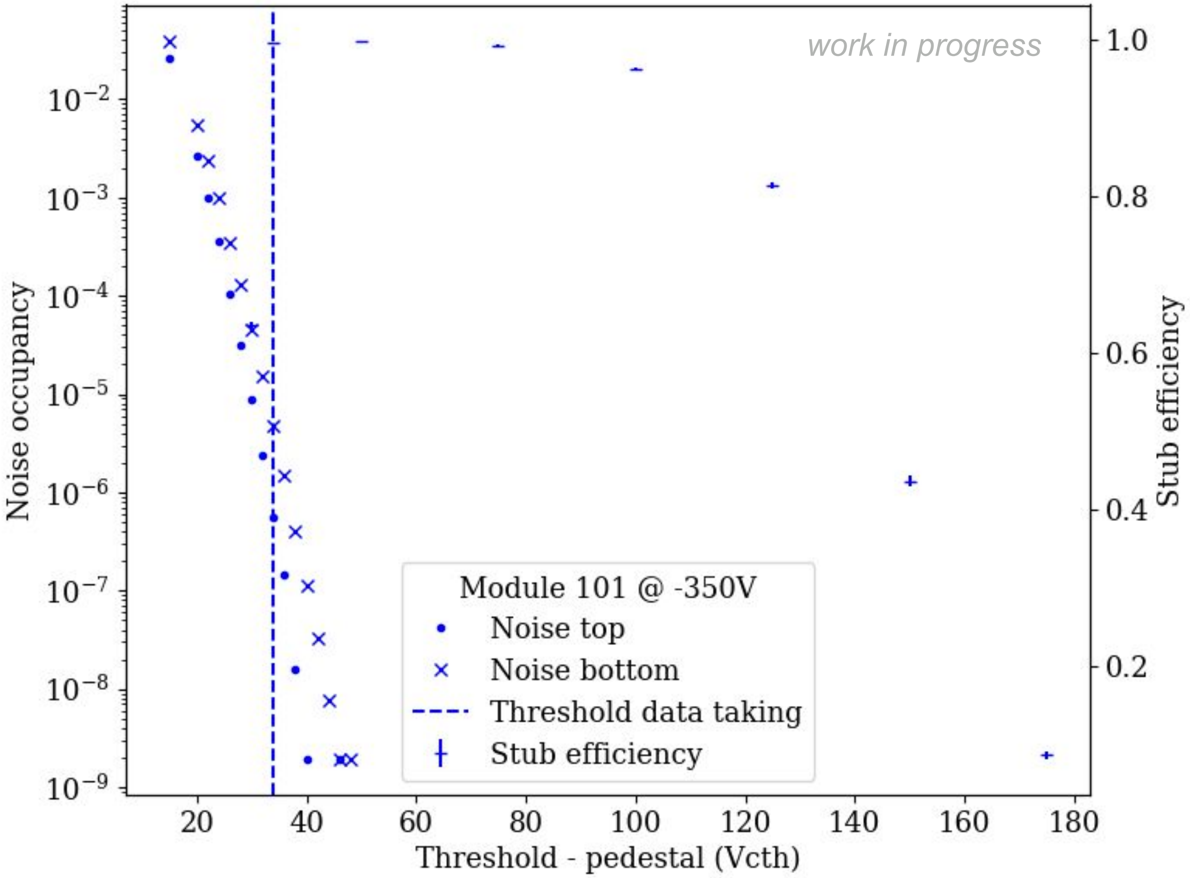
2S modules, multiple!

A sneak peek on results

Measurement programme:

- Threshold study (efficiency, noise occupancy)
- Stub turn-on study (various windows and offsets)
- Simultaneous readout of 3 modules
- Sensor-to-sensor alignment study, track-based





Summary

Things are looking good!

Successful beam time at DESY-II
Completed a dense measurement program on 6 modules:

- Extensive characterization of 5G PS kick-off module
- Stub readout on PS 10G kick-off module
- Efficiency measurements on irradiated PS-s sensor
- Synchronous readout of 3x. 2S kick-off modules

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)

That's it! Thank you for attention!