Beam Testing of ATLAS ITk Strip Module

ATLAS ITk Strip Detector, DESY Test Beam, Corryvreckan, Operating Window

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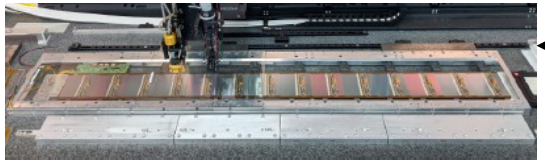
On Behalf of **China ATLAS ITk Group**

Contents

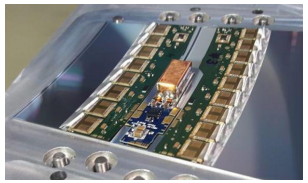
ATLAS All-Silicon Inner Tracker

ATLAS ITk System

- HL-LHC: instantaneous $\mathcal{L} \rightarrow$ **5 to 7.5** larger (than nominal).
- Such *high-radiation* condition calls for new ITk.
- 1400M (59.9M) channels of Si pixel (strip) detectors over 12.7 (165) m^2.

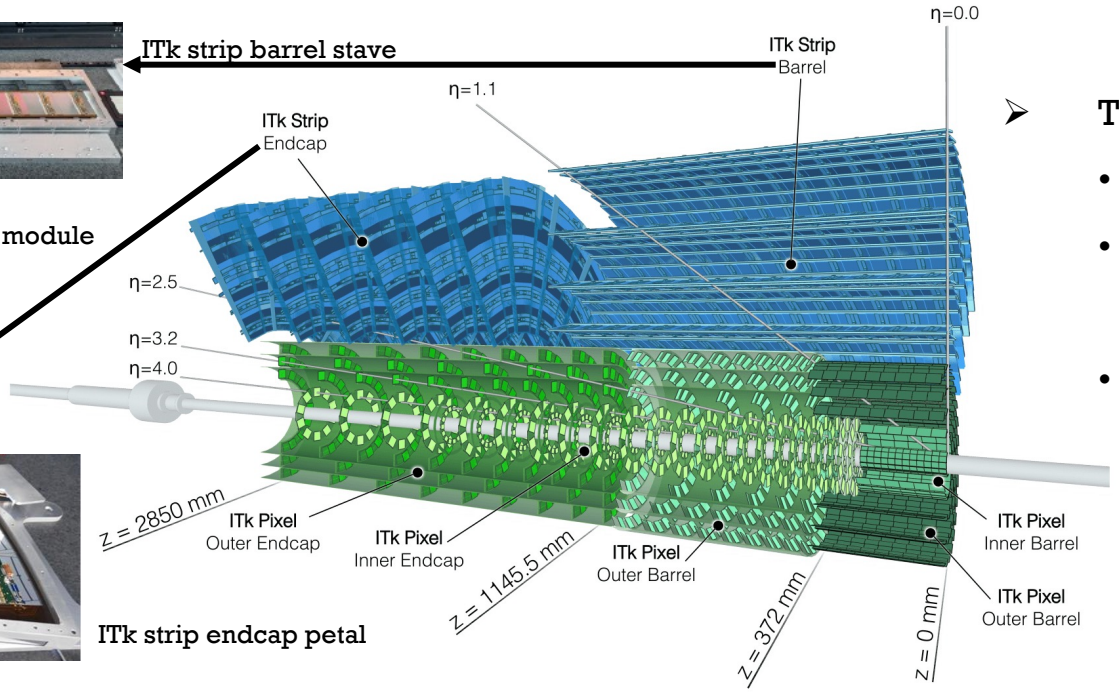


ITk strip barrel stave



ITk strip module

ITk strip endcap petal



ITk Strip Detector

➢ Central *barrel* sector

- 4 layers of ***staves*** (10976 rectangular modules);
- 24 **Short Strip** (48 **Long Strip**) mm in the inner (outer) two;
- 75.5 μm strip pitch and a **26 mrad** stereo angle.

➢ Two *end-cap* sectors

- each with 6 disks composed of ***petals***:
- 6912 trapezodial-shaped modules of 6 different geometric flavours (**R0-R5**);
- Strips, have a built-in stereo angle of **20 mrad**.

ITk Strip-Module Test-Beam Workflow

Online (Data Taking)

Test-Beam Facility & Beam
- DESY II: 1-6 GeV $e^{\pm}$, TB21, TB22 and TB24
- CERN SPS North Area: 400 GeV p^{+}, H2/H4/H6/H8

Assemble Experimental Line
- ADENIUM-type Tracking Telescope
- DUT: ITk Strip Module (sensor + ABCStar/HCCStar)
- Mechanics: cold box, rotation stage, cooling

Trigger & Timing
- Scintillators/PMTs
- AIDA-2020 Trigger Logic Unit (TLU)

DAQ & Run Control
- EUDAQ2 linking telescope, TLU, DUT
- DUT readout (ITSDAQ / Star chipset; FELIX in system tests)
- Clock/trigger distribution & event building

Run Plan & Scans
- Charge collection threshold, timing-delay
- HV/temperature, angle scans
- Online monitoring: hit maps, rates, sync, noise

Data Quality & Bookkeeping
- Run numbers, geometry, voltages, temps, humidity
- Telescope, DUT and beam positions

Offline (Data Analysis)

Event Loading
- EUDAQ2: Convert telescope/DUT/TLU outputs to Corry format

Event Building
- Match by TLU trigger ID / timestamps

Geometry & Telescope Alignment
- Define telescope/DUT geometry
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DUT Aignment
- Project tracks to DUT
- Clustering & track finding according to spatial residuals

Performance Extraction
- Hit detection efficiency vs threshold
- Noise occupancy from pedestal scans
- Cluster size/charge sharing; intrinsic resolution

Hunt For Detector Operating Window
- Find a (threshold, HV, charge) region with efficiency > 99% and noise occupancy < 0.001 – primary goal of test beam campaigns

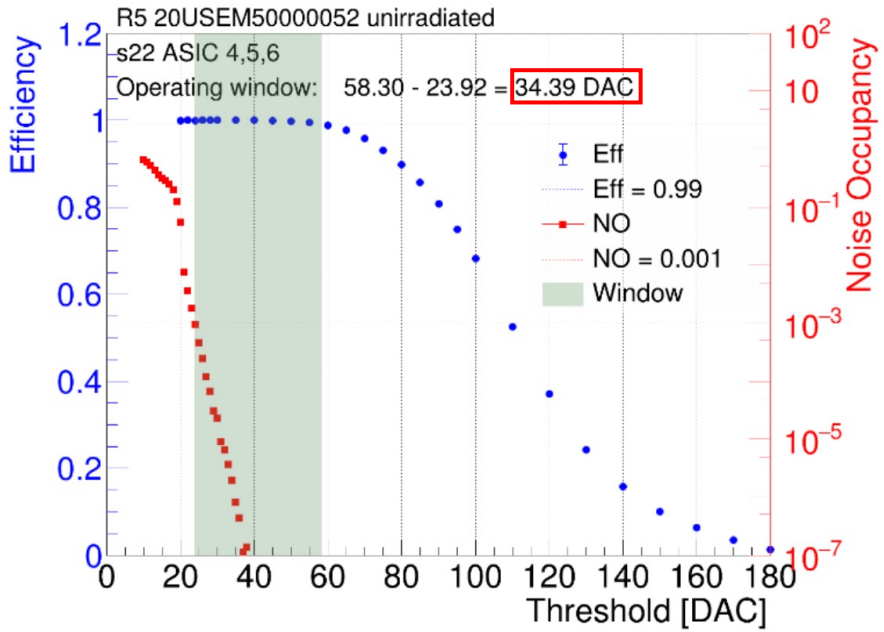
Reporting & Cross-Checks
- Report module performance both before- and after- irradiation
- Optimization of data-taking settings

Beam Testing Studies

Motivation

- Demonstrating module performance in **close-to-real** conditions with beams of **different particle types**.
- Measurements were performed for
  - charge collection
  - hit detection efficiency
  - noise occupancy and
  - tracking performance

  in various sensor regions.



Calculating Detection Efficiency

- Reconstruction is done in a four-step process:
  1. Re-synchronising DUT and telescope.
  2. Masking of noisy channels.
  3. Alignment of the beam telescope and construction of tracks.
  4. Alignment of DUT and search for associable hits to the telescope
  5. Track fit - which is based on a simple distance-to-nearest-cluster cut.
- Hit detection efficiency is then calculated as:

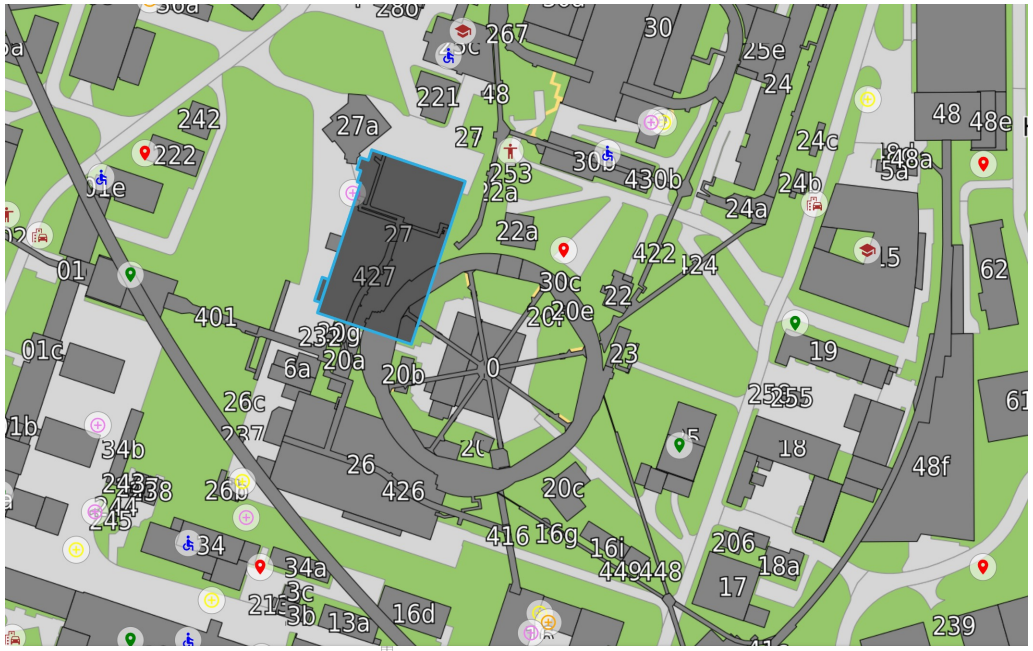
$$\epsilon = \frac{tracks_{with\ DUT\ cluster}}{tracks_{telescope+timing\ plane}}$$

Hunt For An Operational Window

- Primary goal of test beam campaigns.
- Hit detection efficiency > 99% to maintain tracking performance of ITk modules.
- Noise occupancy < 0.1% to manifest pile-up events.

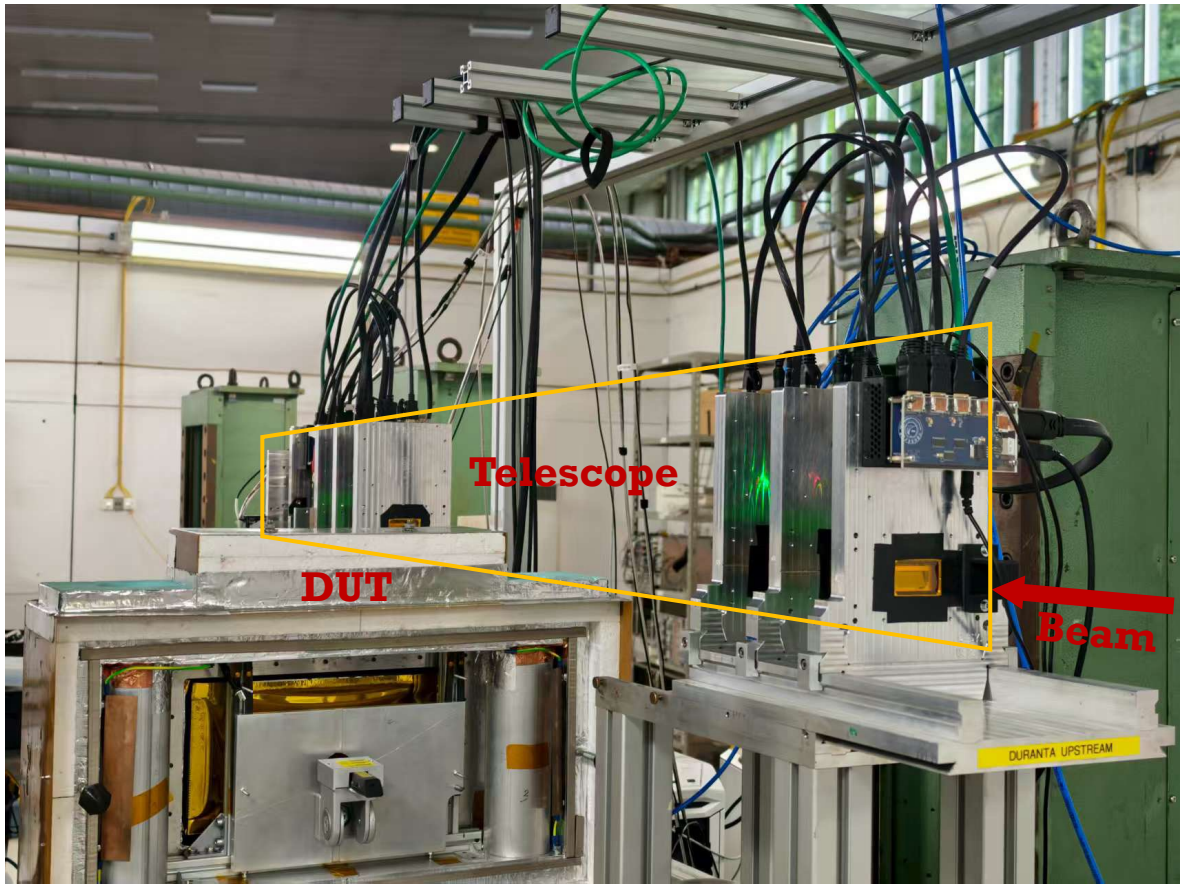
DESY-II Test Beam Location

Hamburg Bahrenfeld Campus



- Experimental Hall 2 (building 27)
  - three beam lines: TB21, **TB22** and TB24.
  - γ beams in e^-/e^+synchrotron DESY II
  - hitting **carbon fibre targets** (thickness of 7 µm)
  - converted into **bremsstrahlung e^-/e^+** beams
  - with up to **1000 particles per cm²** and
  - energies from **1 to 6 GeV**
  - an energy spread of ~**5%** and a divergence of ~**1mrad**.

ADENIUM-Type Telescope & DUT Cold Box



- ADENIUM Telescope:
  - Serve as spatial reference plane
  - 6 **ALPIDE** Si sensor pixel plane with 1*2 cm^2 active area
  - Intrinsic patial resolution <3 μm
  - 1 TelePix2 timing plane with <4 ns time resolution.

- Device Under Test (DUT)
  - Placed in the center of the telescope
  - Placed in a -40 ℃ cooling box
  - High bias voltage
  - Temperature and humidity sensors

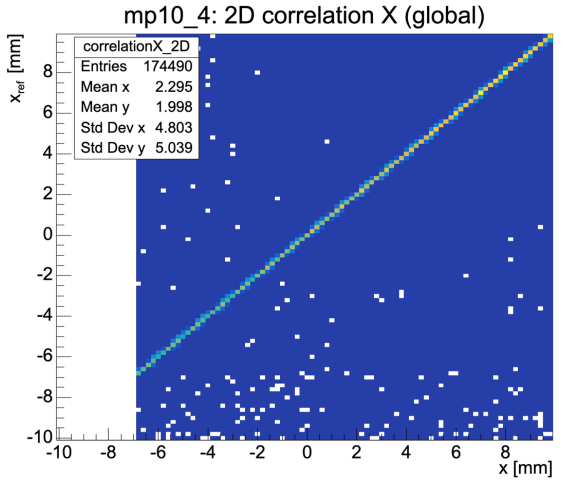
Test Beam Data Analysis Framework

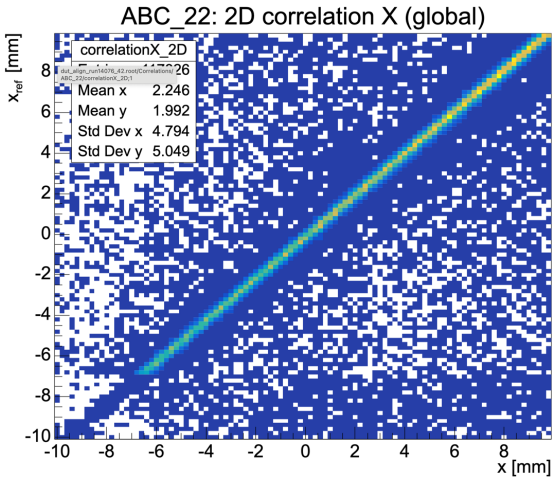
Corryvreckan

- The **main** test beam data analysis framework:
  - **Modular concept** of the reconstruction chain;
  - Combining detectors with very **different readout architectures**.
  - Centrally provided functionality: coordinate transformations, input and output, parsing of user input, and configuration of the analysis.

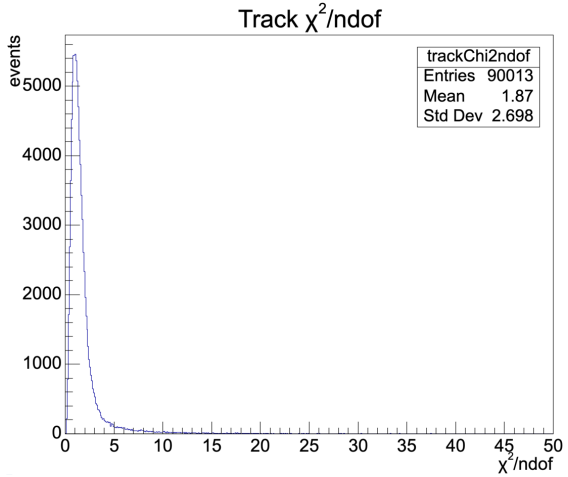
- **Both online and offline** core functionalities include:
  - track association and clustering algorithm,
  - telescope and DUT alignment with spatial correlation and residuals,
  - visualization of hit and calculation of hit detection efficiency.

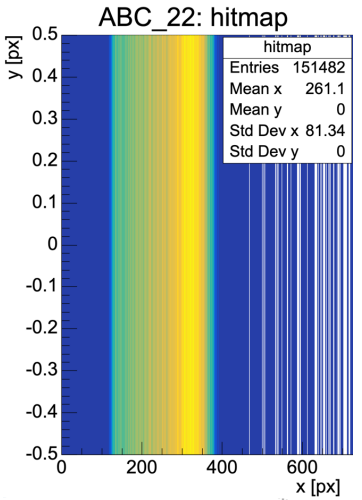
- Correlation Plots



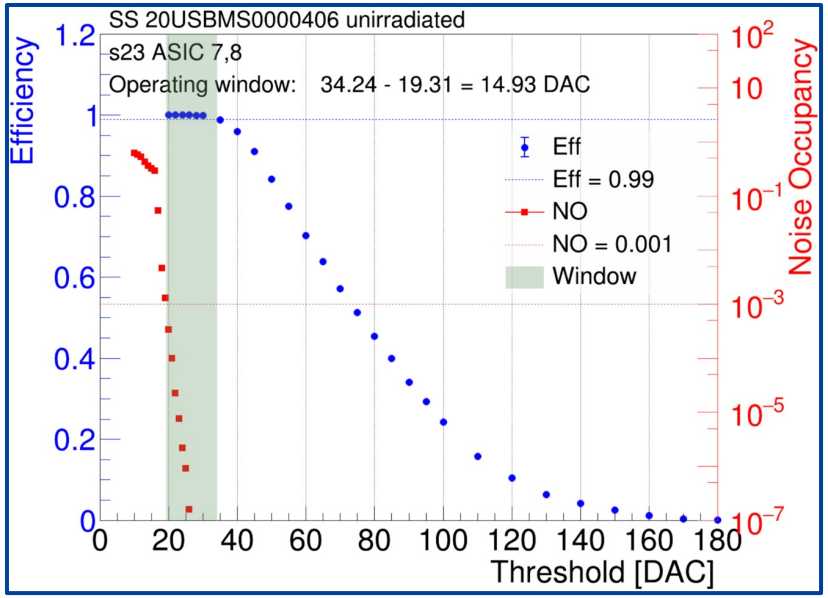


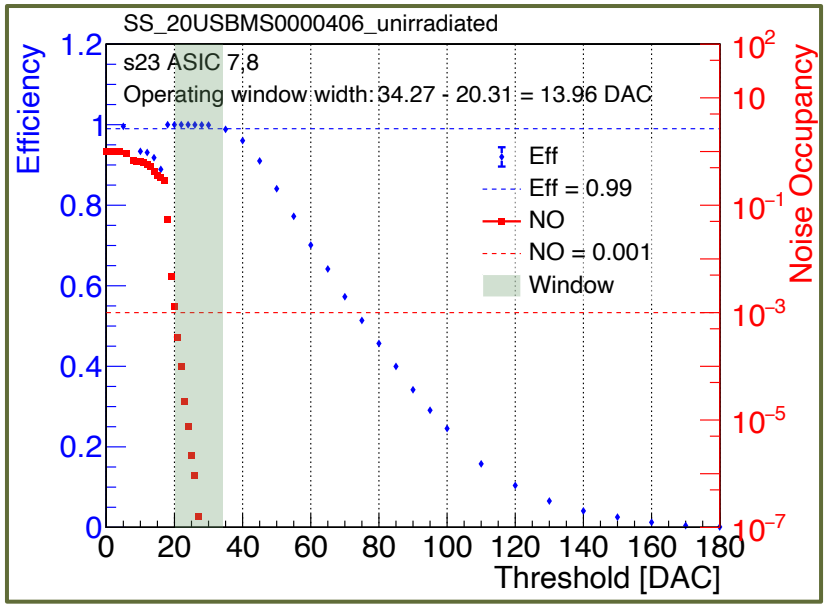
- Spatial Residuals & Hit Map





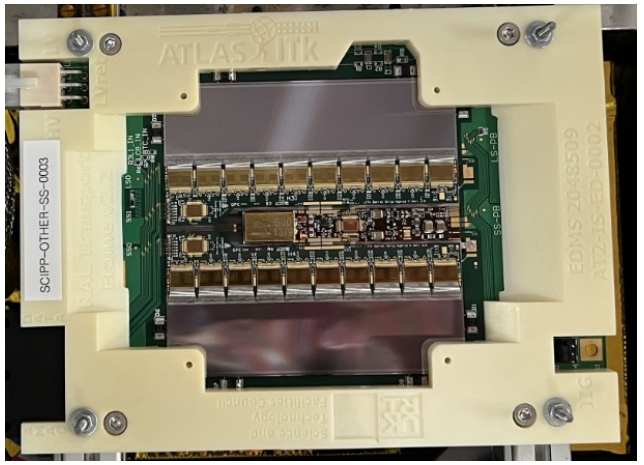
Test Beam Data Analysis – Cross-Check Results



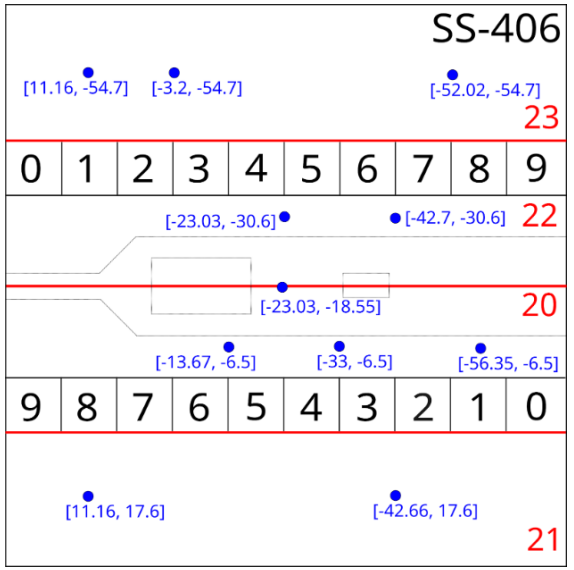


SS_406 Module

- Motivation
  - Gain familiarity with Corryvreckan
  - Confirm the ”half-window” issue
- Module information
  - Canonical ID: SS_20USBMS0000406
  - Manufacture ID: SCIPP-OTHER_SS-0003
  - Unirradiated module
  - With interposed layer
  - Assembly: true blue.
- Upper-Left Plot
  - Reported analysis result
- Lower-Left Plot
  - Cross-check analysis: consistent result

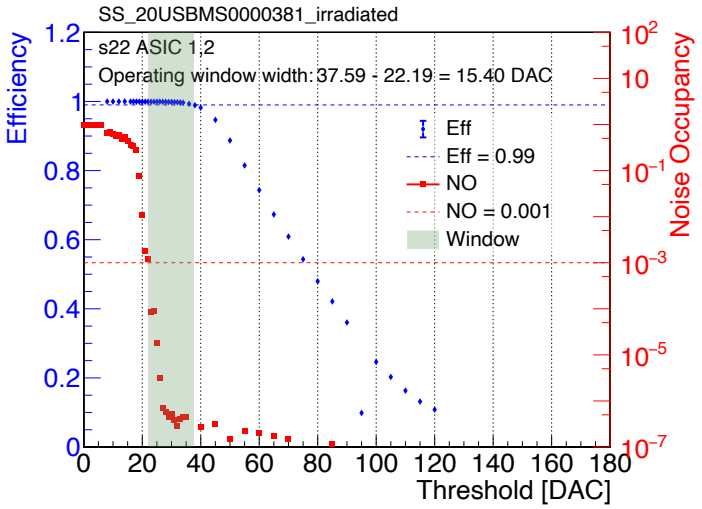


A Photograph of SS_406 Module in DUT Cold Box



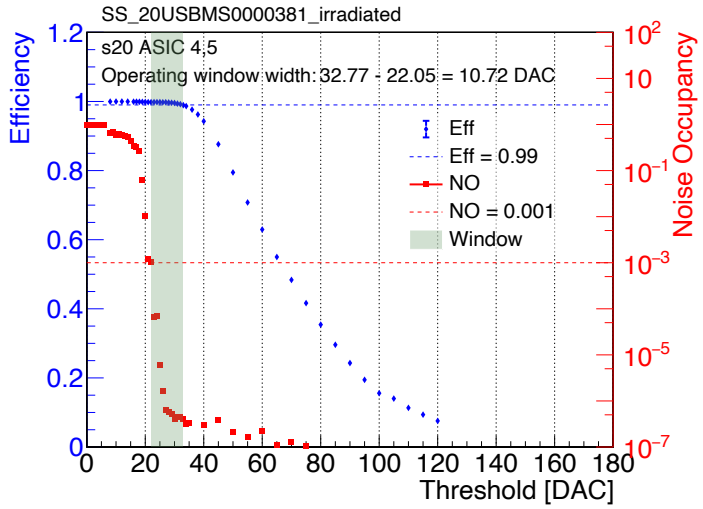
Beam Test Coordinate Map

Test Beam Data Analysis – Our Contributions

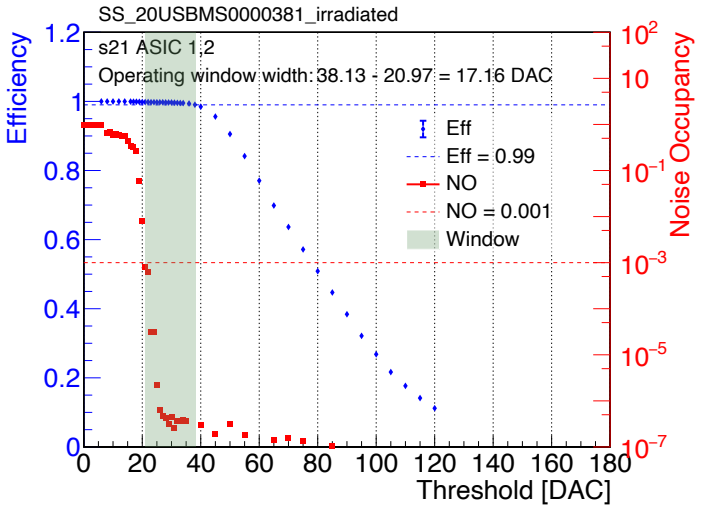


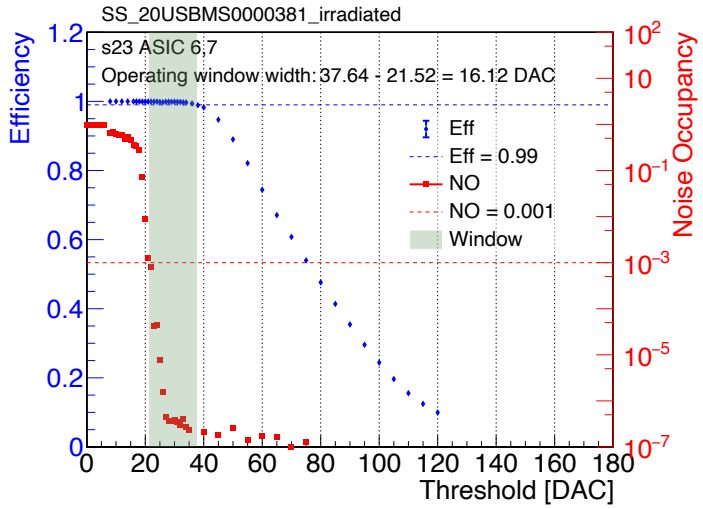
SS_381 Module

- Single-stream window width
  - S20 (top-right): **10.72**
  - S21 (bottom-right): **17.16**
  - S22 (bottom-left): **15.40**
  - S23 (top-left): **16.12**



- Expected features
  - Smooth "S-curve" profile.
  - High efficiency at low thresholds.
  - Steep decline above a particular threshold value.
  - Pedestal runs drop faster.

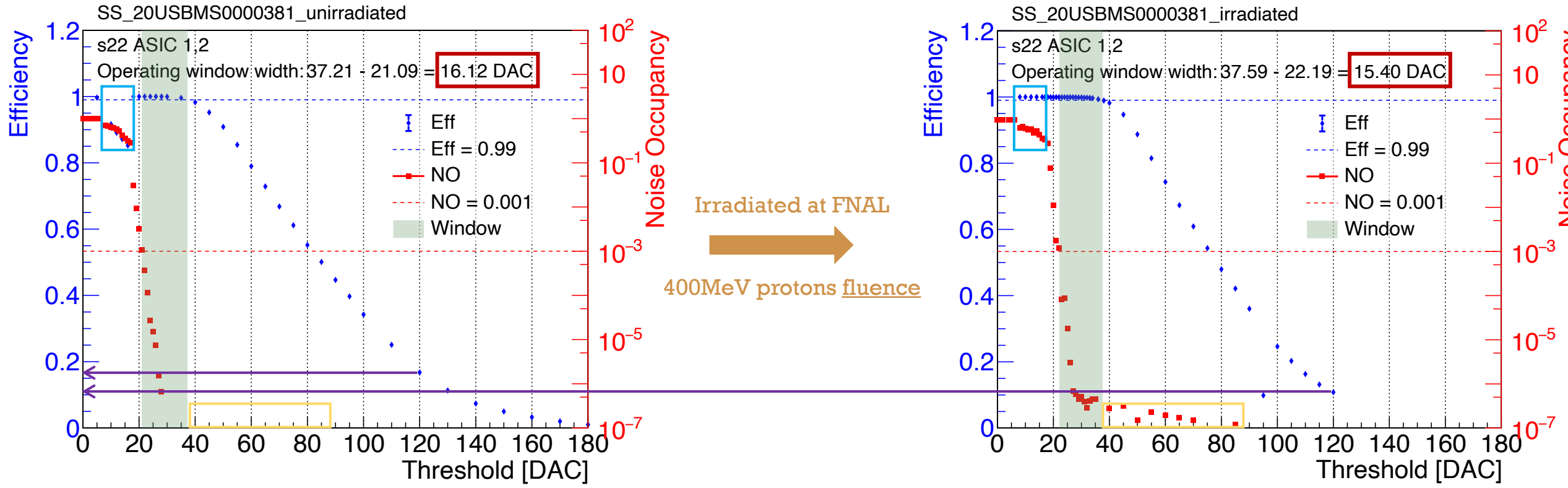




Module Performance Before & After Irradiation

➢ Four interesting features after irradiation:

1. Red box: **50% reduction** in operating window width compared to the **expected** before-irradiation value.
2. Blue box: The "localized dip" below 20 DAC **disappeared**.
3. Purple arrows: Hit detection efficiency shows a **steeper decline** with increasing threshold.
4. Yellow box: Noise occupancy exhibits a new haviour – a **long-tailed decay** to zero above 40 DAC.



Summary

Contributions from China ITk Group:

- ✓ Validation of existing results via ITk strip module **SS_20USBMS0000406**.
- ✓ Complete and independent analysis of ITk strip module **SS_20USBMS0000381**, both before and after irradiation.
- ✓ Automated Corryvreckan data analysis program.
- ✓ Person power in the July 2025 test beam campaign.

Special Thanks to **Yajun He** from DESY for consistent guidance and support.

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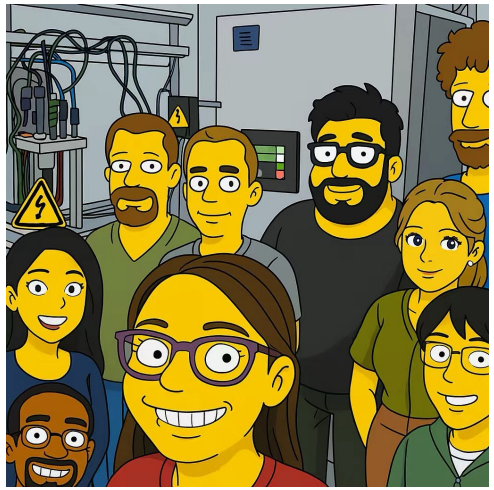

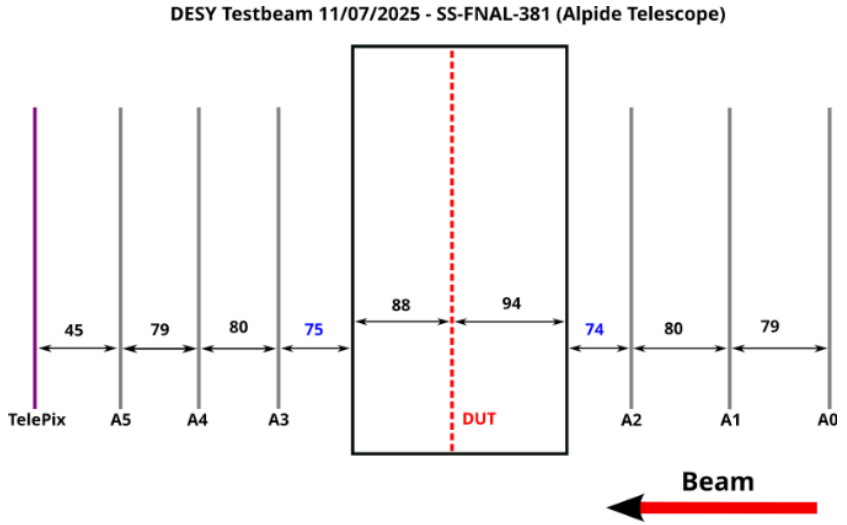

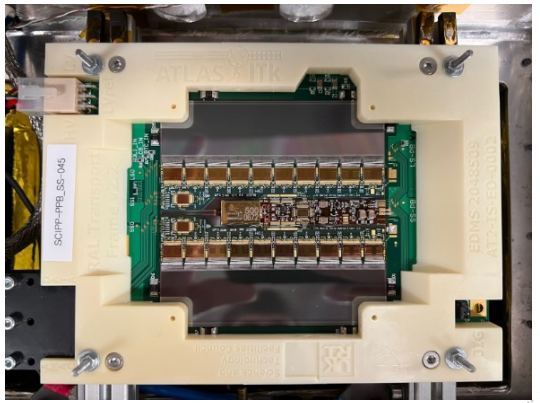

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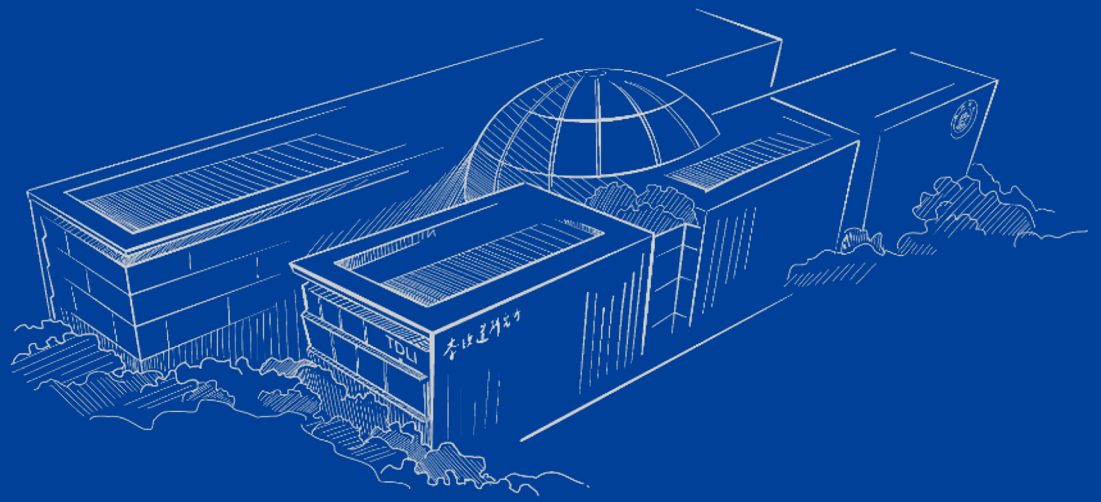
Thank You



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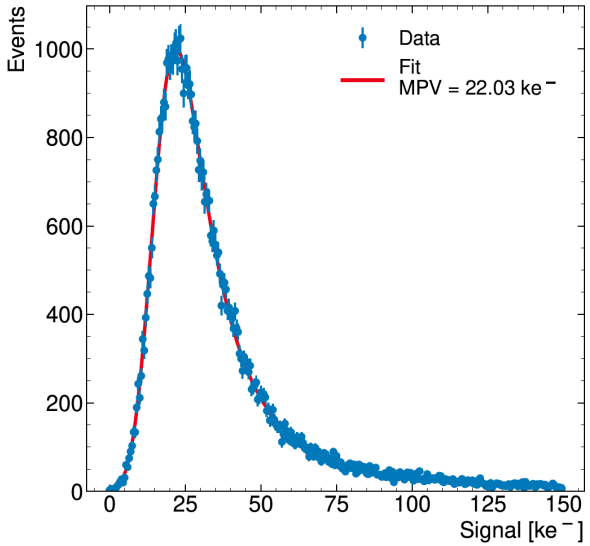
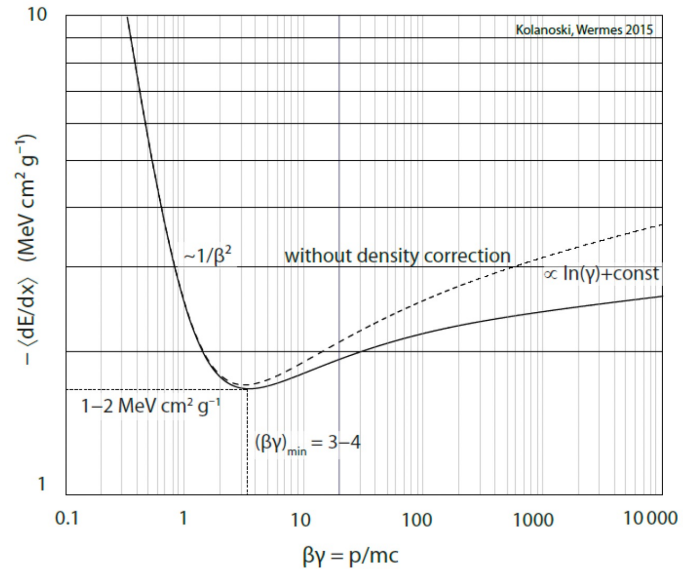
Back-Up Slides

$$L(\lambda) = \frac{1}{\pi}\int_0^\infty e^{-t\ln t - \lambda t}\sin(\pi t)\,\mathrm{d}t$$

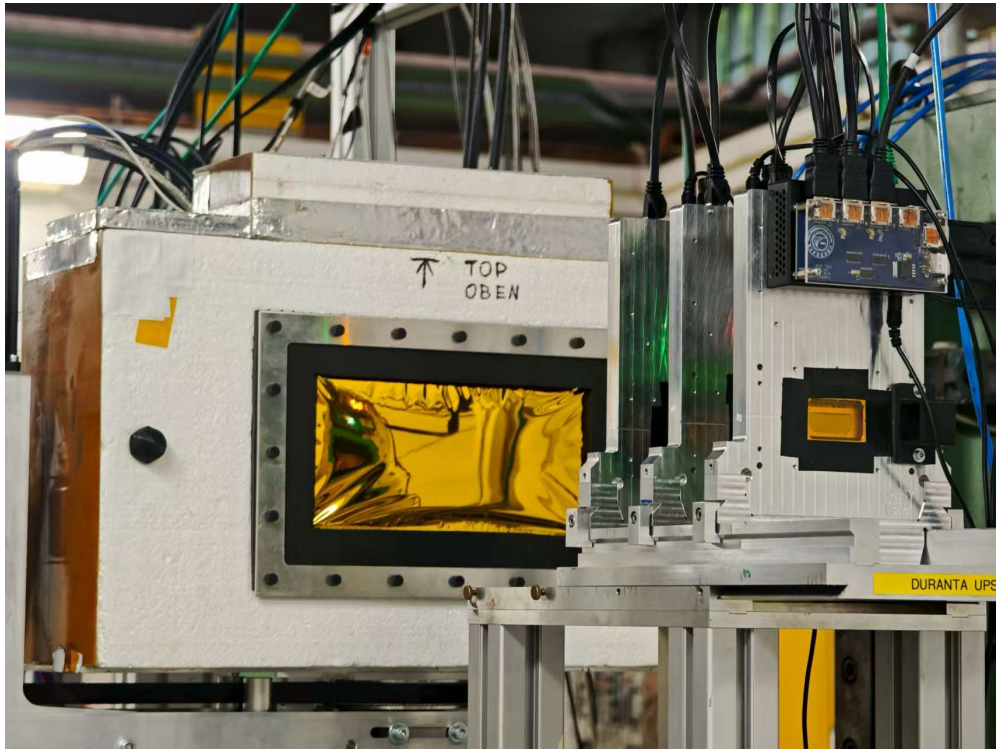
$$\lambda = \frac{\Delta E - (\Delta E)_{\mathrm{m.p.v.}}}{\xi} \quad \text{with} \quad \xi = \frac{1}{2}K\frac{Z}{A}\frac{z^2}{\beta^2}\cdot d$$

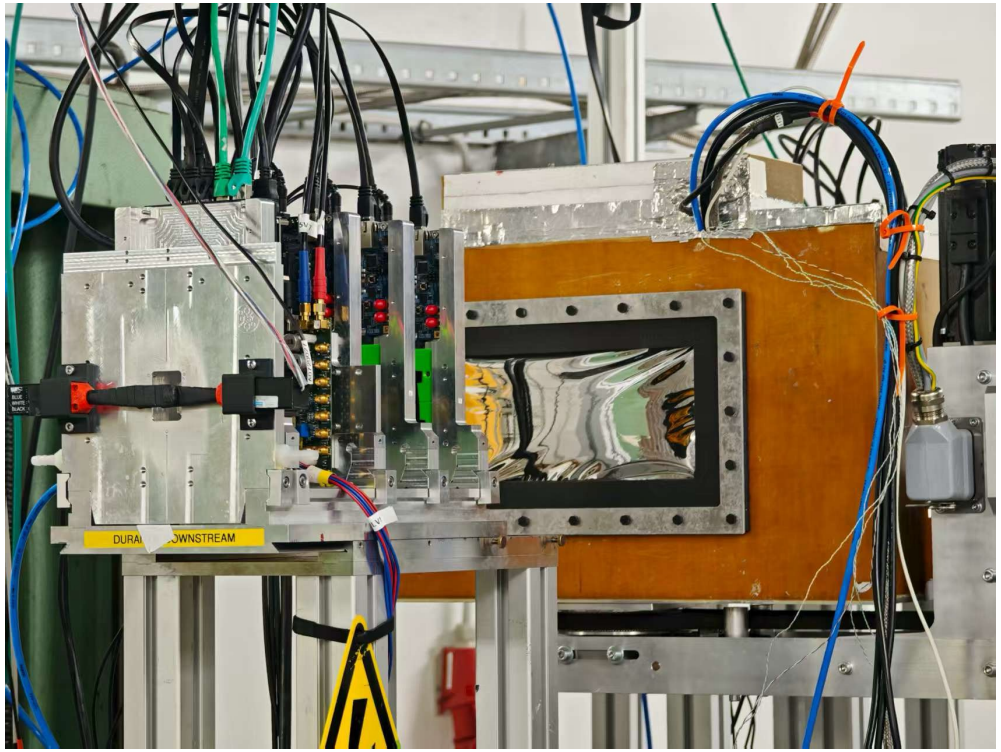


$$\epsilon = \frac{\epsilon_{max}}{2}\cdot erfc\left\{\frac{q_{thr}-\mu}{\sqrt{2}\sigma}\left[1 - 0.6\cdot\tanh\left(\xi\frac{q_{thr}-q_M}{\sqrt{2}\sigma}\right)\right]\right\}$$



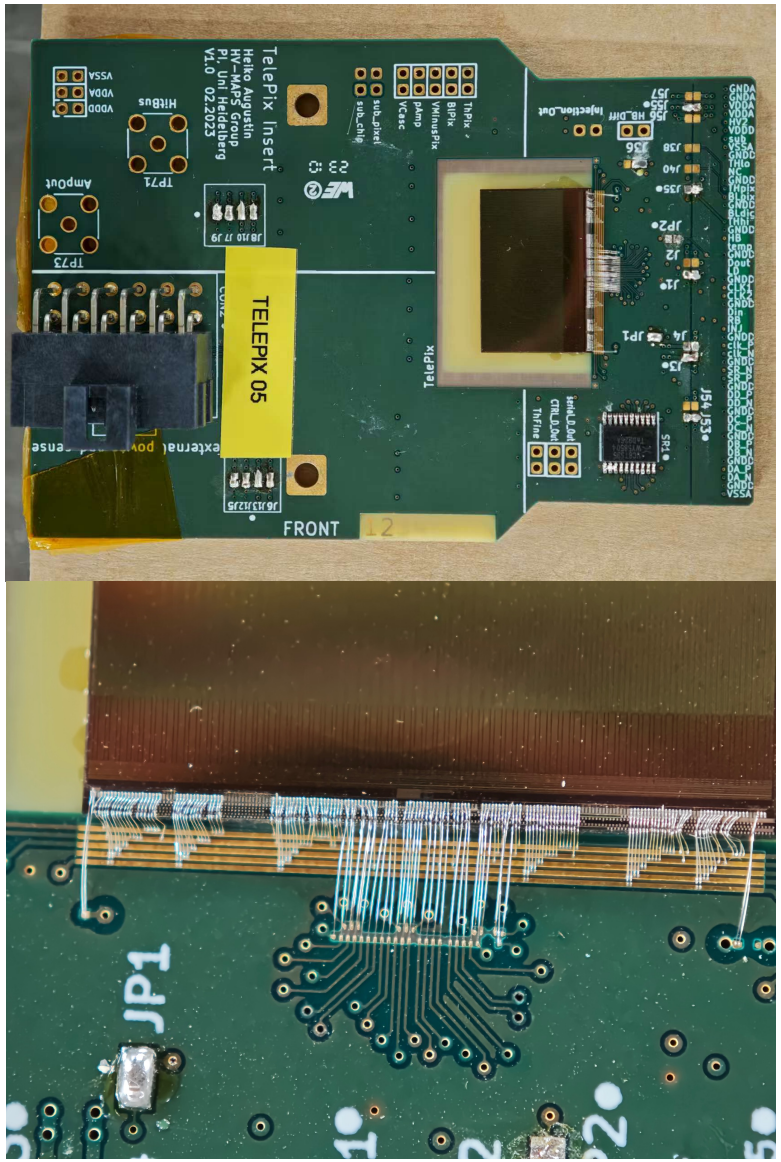
With DUT In Place

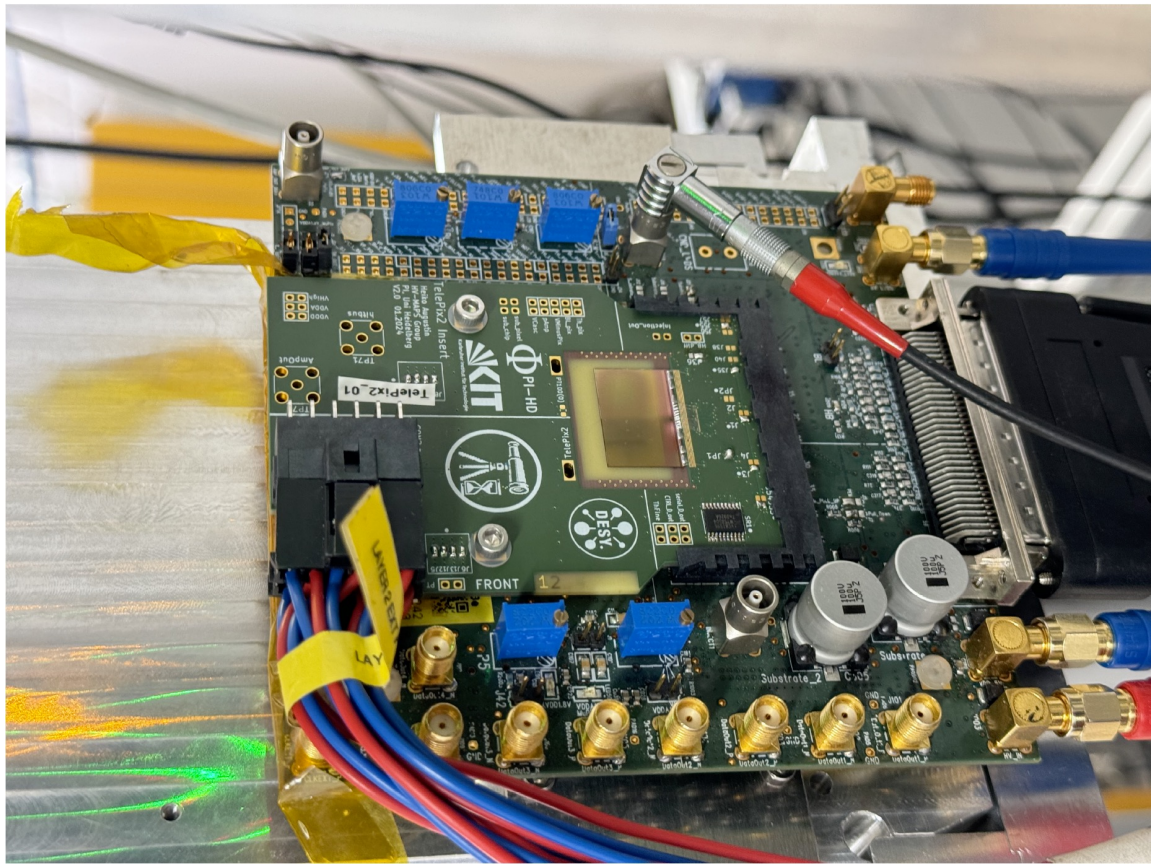




Close-Range Shot of TelePix2 Chipboard

With Power Filtering





ITk SS_20USBMS0000381 Module