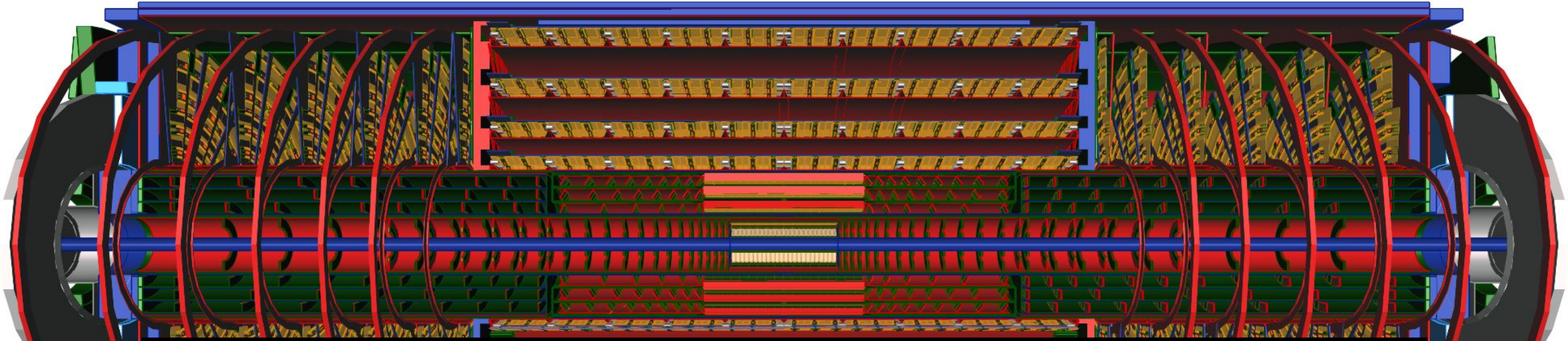

Characterization of Pre-Production Petals for the ATLAS Inner Tracker Strip Detector

Production, Testing and Reliability Parallel, TWEPP 2024,
Glasgow, October 4, 2024

Matthew Basso (TRIUMF/SFU),
On behalf of the ATLAS Collaboration

ATLAS EXPERIMENT
ATLAS ITk
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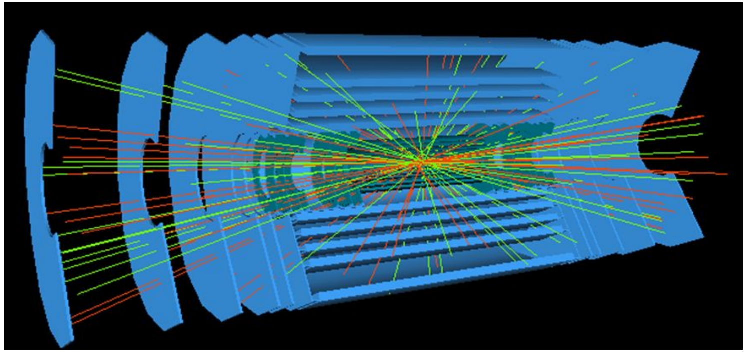
https://indico.cern.ch/event/1381495/contributions/5988722/

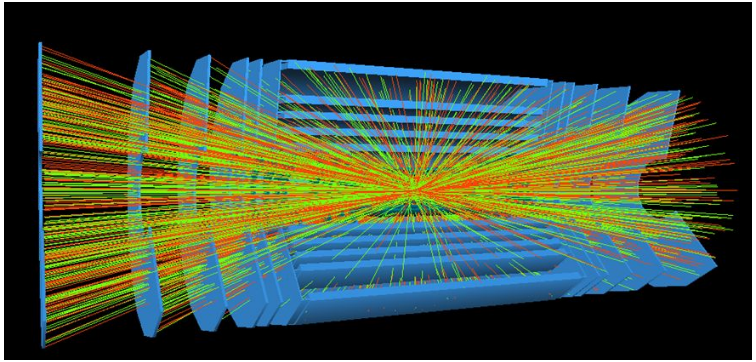
ATL-UPGRADE-PROC-2012-003

Introduction: HL-LHC and ITk

- High-Luminosity LHC (HL-LHC) will enable collisions at **~10 × rate of LHC**
  - Will provide **3000 fb^{-1} of data by its end-of-life**, enabling precision tests of physics
- To accommodate the increased complexity of collisions, ATLAS is upgrading its inner detector: **Inner Tracker (ITk) Upgrade**
  - **All silicon** with improved radiation hardness and less material
  - Higher granularity: 100M → 5000M channels
  - Improved $|\eta|$ coverage: 2.5 → 4.0
  - Faster response

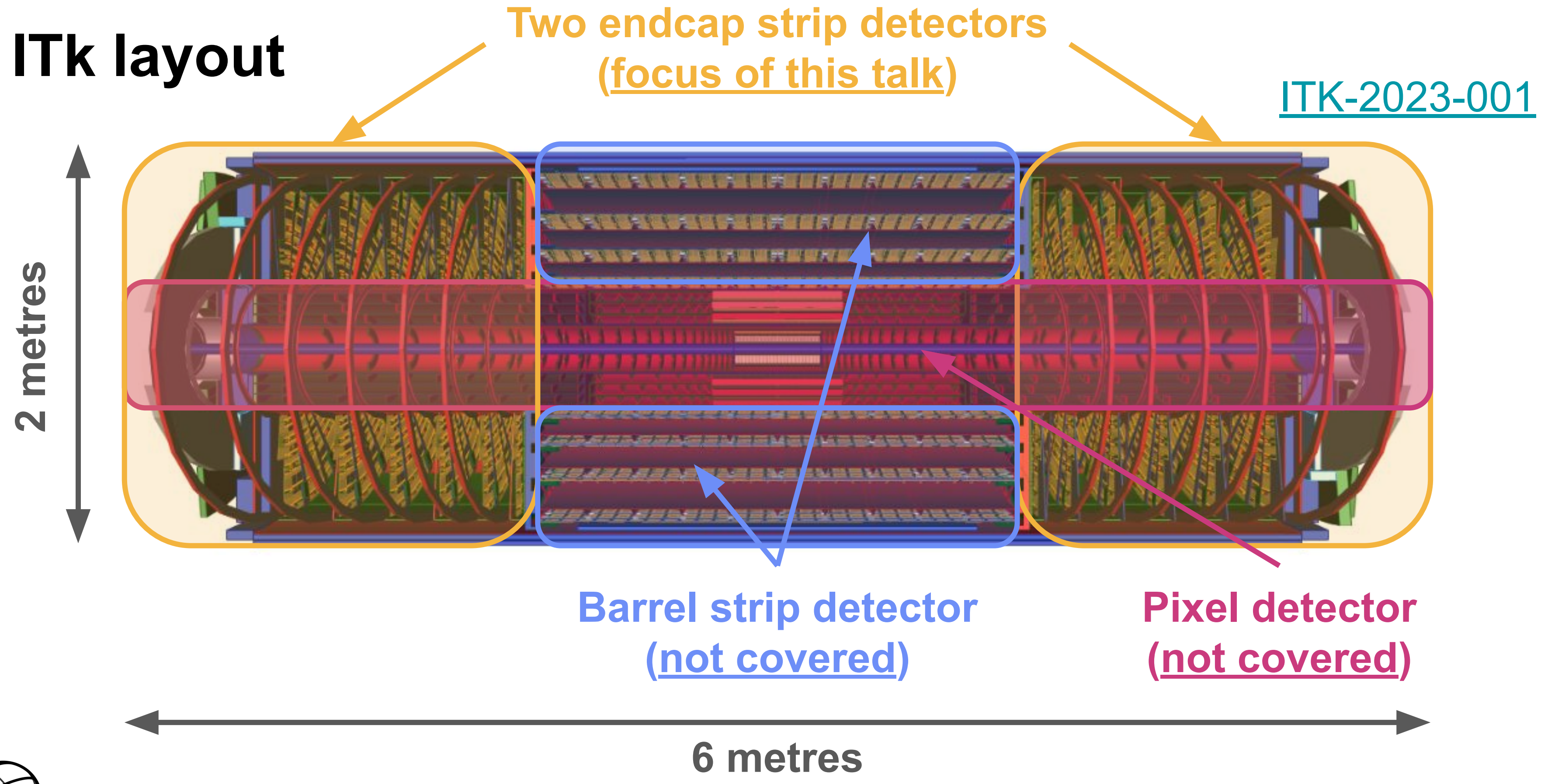


23 collisions per BC (LHC)



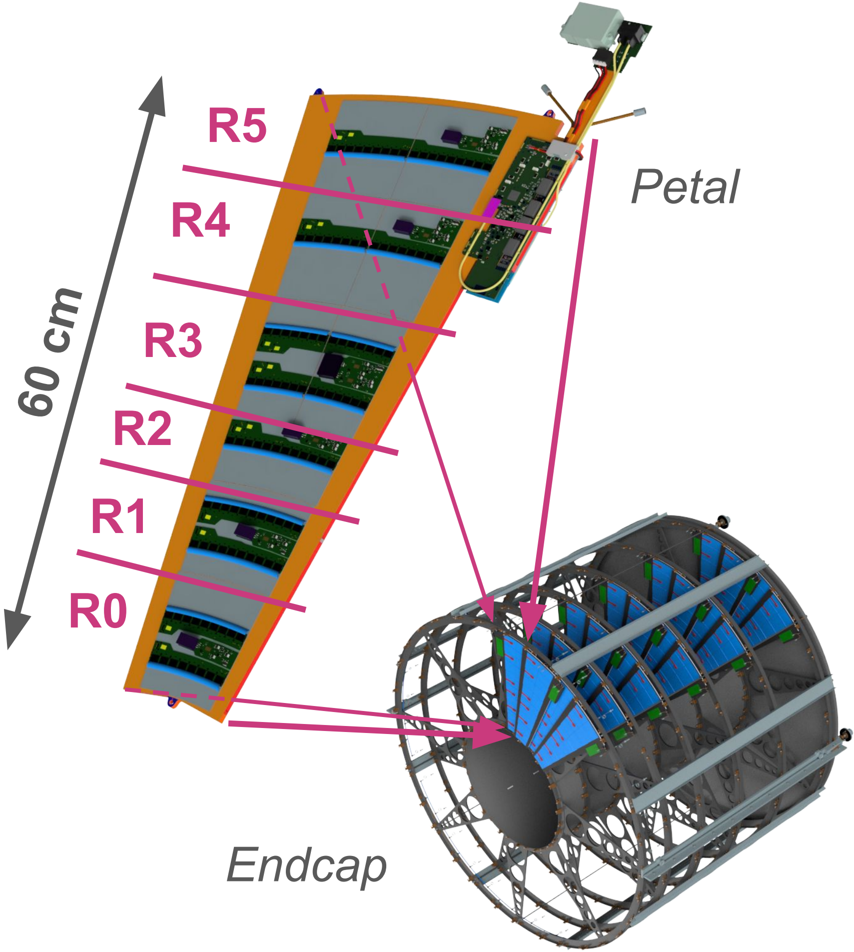
230 collisions per BC (HL-LHC)

ITk layout


Two endcap strip detectors
(focus of this talk)
ITK-2023-001
2 metres
Barrel strip detector
(not covered)
Pixel detector
(not covered)
6 metres

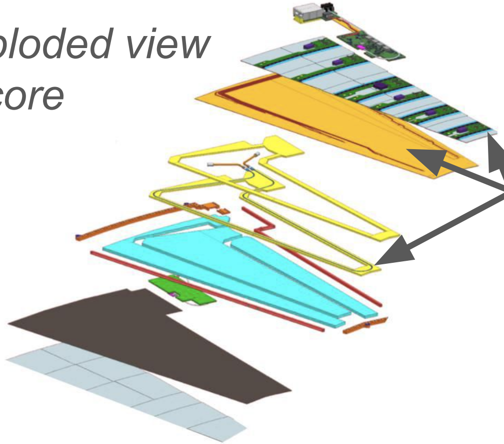
What makes up an endcap?

- Each endcap consists of **6 disks** along the beam (*z*) axis
- Each disk consists of **32 double-sided petals**
- Each side of a petal is composed of **9 silicon strip sensors**, grouped into **6 modules**
- Each module consists **PCB flexes** providing readout and power which are glued and bonded to a **silicon strip sensor**
    - Labelled R0 to R5 in order of increasing radius (4K–7K channels per module)
- This talk will focus on how we **assemble** and **characterize** petals



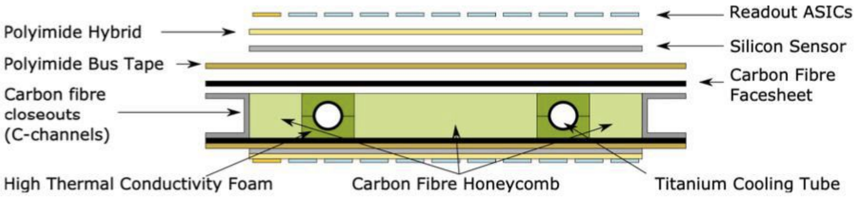
A closer look at petals

Exploded view of core



- Carbon-fibre “**core**” provides a scaffold for modules
  - **Ti cooling pipes** embedded in core’s thermally conductive foam (**end-of-life operating temperature: −35 °C**)
- Copper-on-polyimide “**bus tapes**” route data and power
- Modules are glued to the core and bonded to the bus tape

Petal cross section



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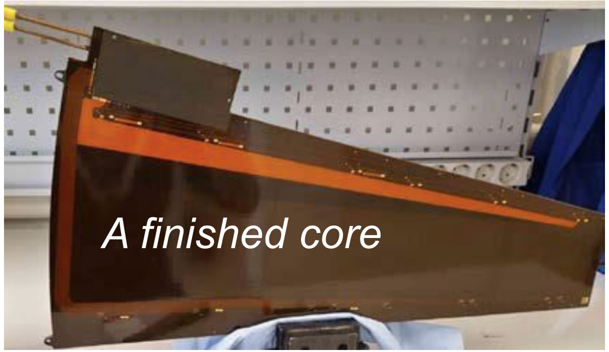

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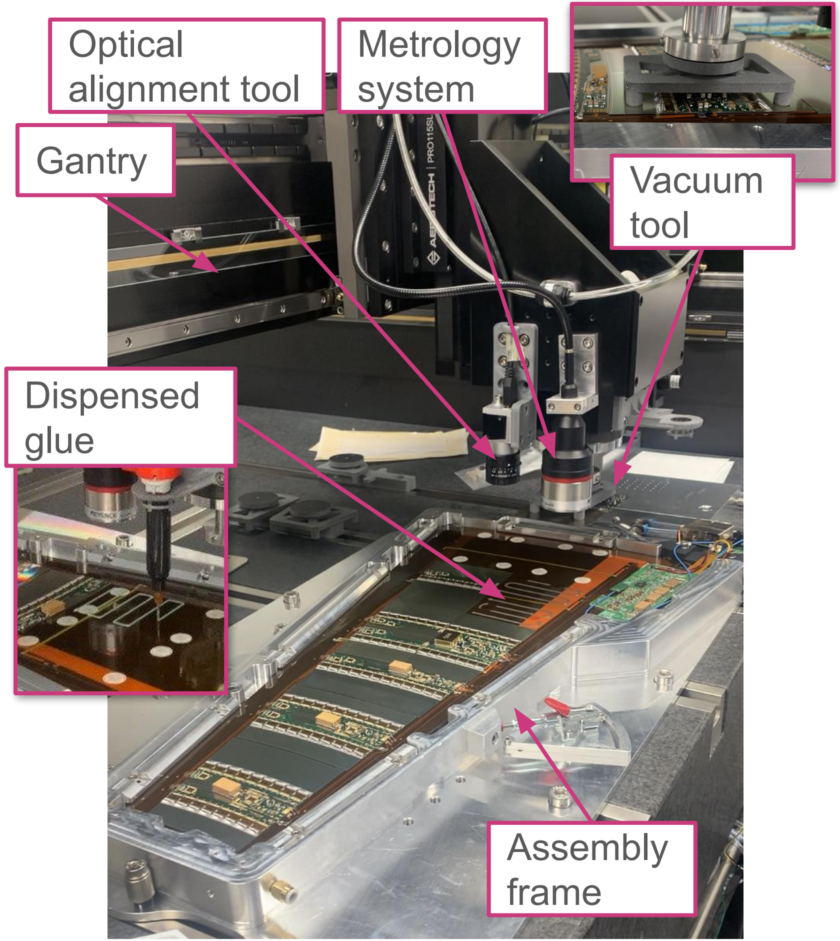
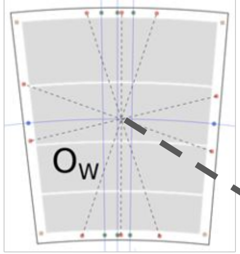
Automated loading of petals

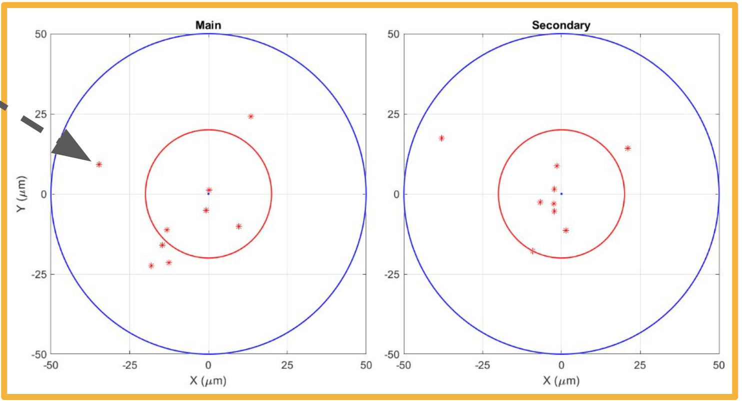
- **Loading** ≔ mounting modules onto petals
  - Loading occurs at several international sites (Canada, Germany, and Spain)
- For **uniformity** and **simplicity** of production, an **automated loading system** has been developed, consisting of a robot gantry capable of:
  - Dispensing adhesive
  - Placing modules with micron-level precision using custom vacuum tools
  - Performing post-loading visual capture, module accuracy, and metrology surveys



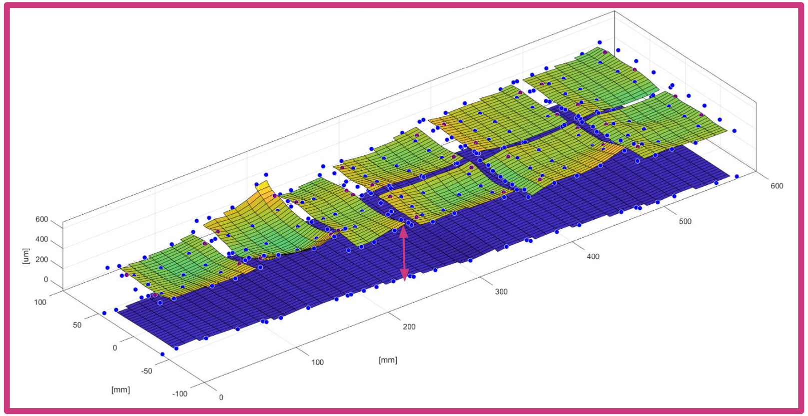
Also see B. Stelzer's talk at ICHEP2024

Quality metrics for petal loading

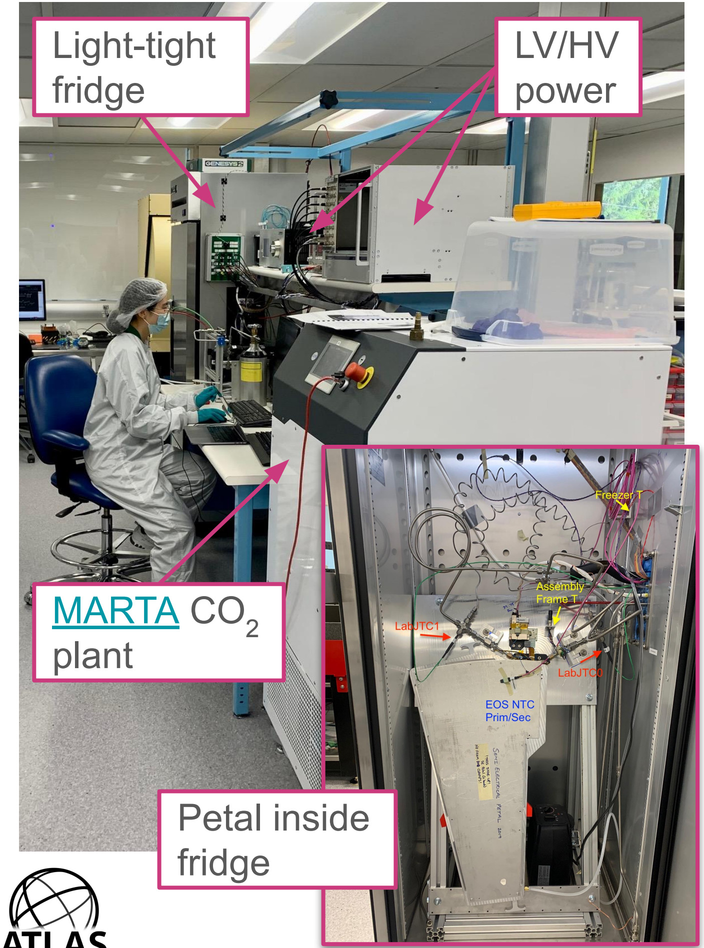




- **Placement accuracy** based on 10 sensor fiducials, allowing its centre and angle to be determined
    - Specification: **±50 µm**
    - Most modules are placed within **±20 µm**!
- **Out-of-plane metrology** performed using confocal displacement sensor (or similar means)
    - Height set by adhesive, 110 µm, and sensor thickness, 300 µm
    - Verifies petals are ready for endcap insertion
- **Nearly* all petals met specifications** ✅



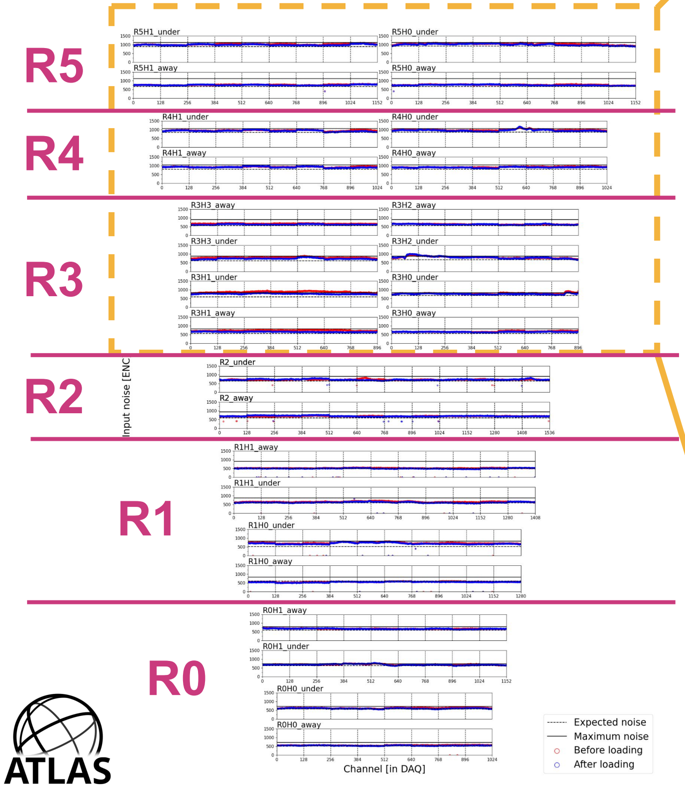
** Nearly, as a few are out-of-spec, but for known reasons*



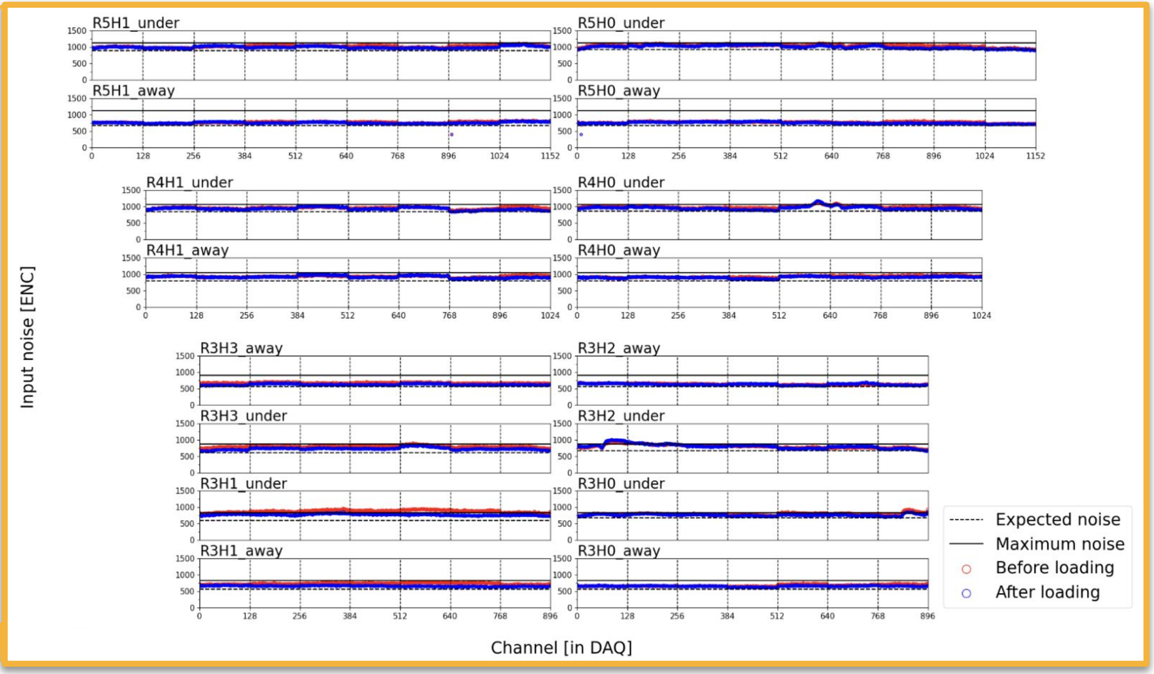
Electrical characterization

- Includes measurements of the **HV sensor current (IV)** as well as **per-channel input noise** for each module
  - Current should be < 10 uA @ 550 V bias, noise should be low enough @ 350 V bias to ensure signal-to-noise is high enough at end-of-life
    - **Breakdown voltage** ≔ voltage at which an **immediate** and **held** increase in current occurs
  - Should ***not*** be impacted by loading
- Petals are tested in a light-tight fridge with controlled a temperature and humidity
  - CO_2 or ethanol coolant flowed through petal core
- Measurements performed using the ITk's data acquisition (DAQ) software

Example of input noise before and after loading



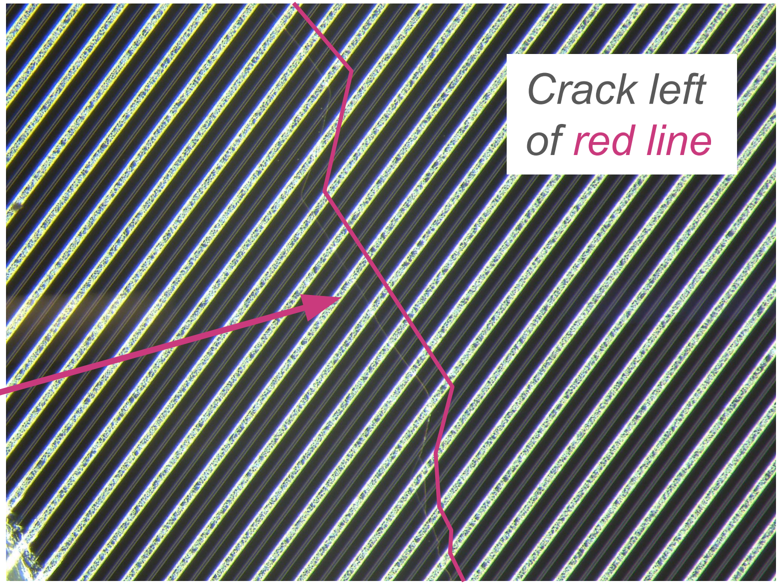
Exploded view of "petal" plot
(ENC ≔ electron noise charge)

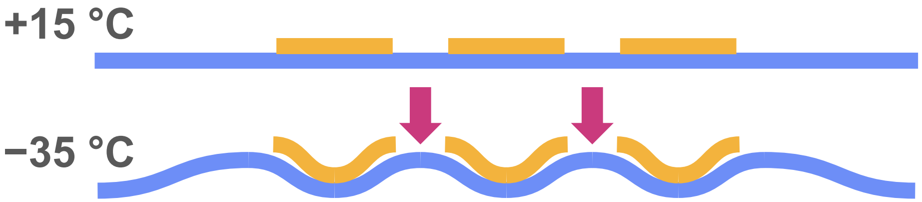


Noise before and after loading are consistent ✅

Sensor cracking

- ~10% of all sensors on cores exhibited HV breakdown (< 100 V) in the relevant QC temperature range, −35 °C or colder
- Found to be a result of **sensor cracks**, typically in the sensor areas between flexes
- Mismatch in coefficients of thermal expansion (CTE) of the **sensor** and the **copper in the flexes**, resulting in **localized stress** at cold temperatures



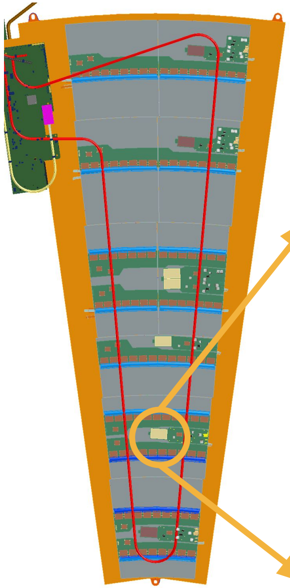


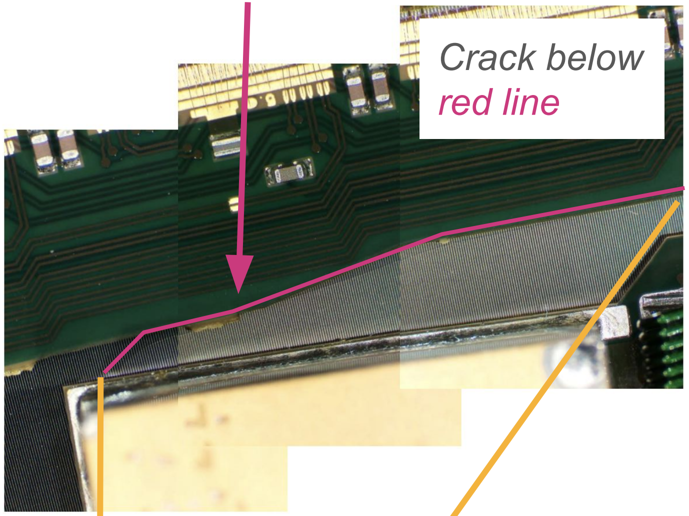
Also see S. Diez's poster at PM2024 and A. Tishelman-Charny's poster at LHCP2024

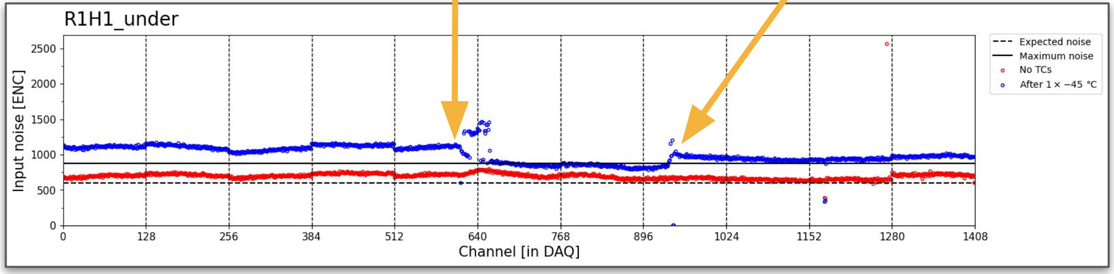
Initial cracking signatures on petals

- Cracking on any sensor at any temperature ≳ −55 °C is considered **problematic**
  - To test for cracks, petals have been thermal cycled (TC-ed) from −35 °C to progressively colder temperatures
- Cracks also result in regions of **low/high input noise**
- First petal TC-ed exhibited **cracks** already at −40 °C → **campaign to explore mitigation strategies**

__Crack__ occurred in the space between flexes

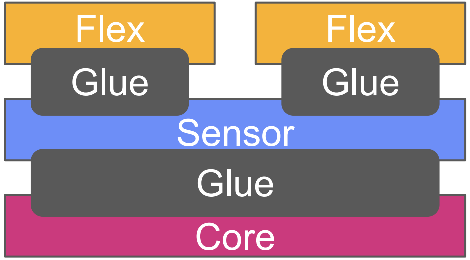


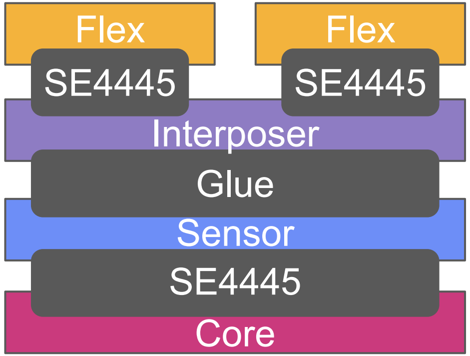




Mitigation strategies

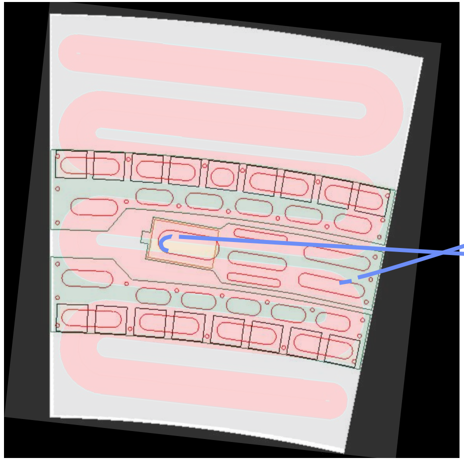
- Mechanical simulations have corroborated cracks as locations of high physical stress
  - Also confirmed the importance of the choice of adhesive and its pattern
- Mitigation strategies:
  - **Choice of sensor-core adhesive**: a stiffer glue (Hysol) instead of a softer glue (SE4445) can reduce stress by 50%
  - **Pattern of sensor-core adhesive**: improved glue coverage to better support regions of high stress
  - **Interposer**: inclusion of a Kapton layer between the flexes and the sensor can reduce stress by 95%
- We'll present results for the **first two**

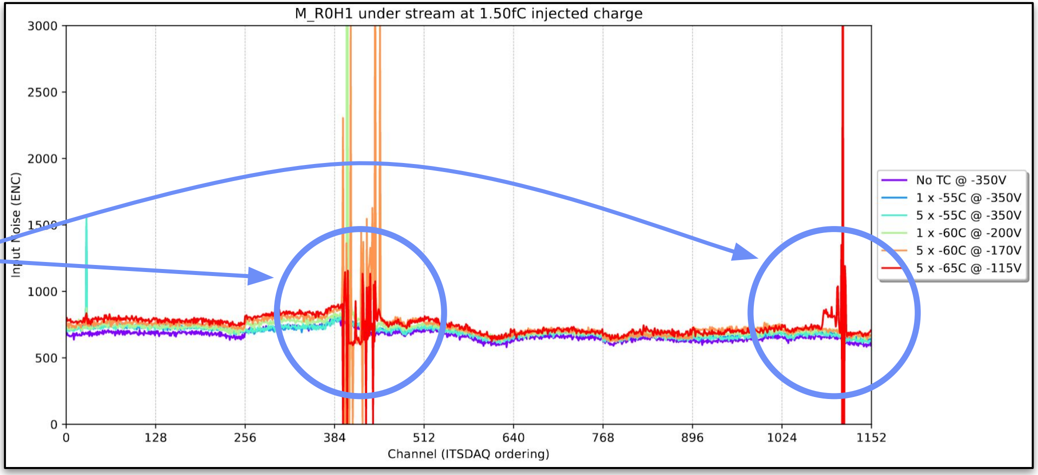




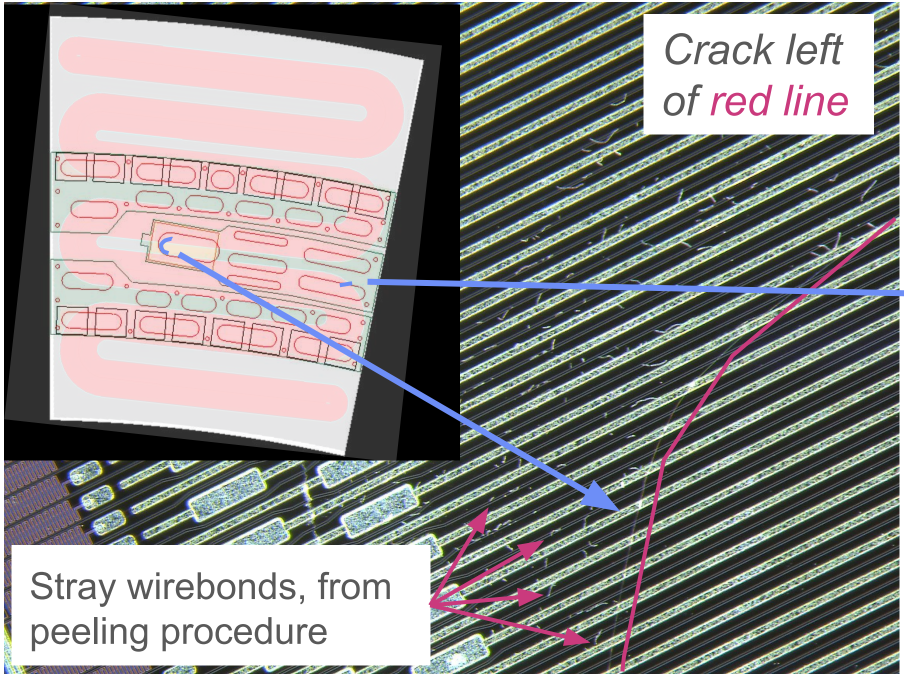
Choice of adhesive: Hysol

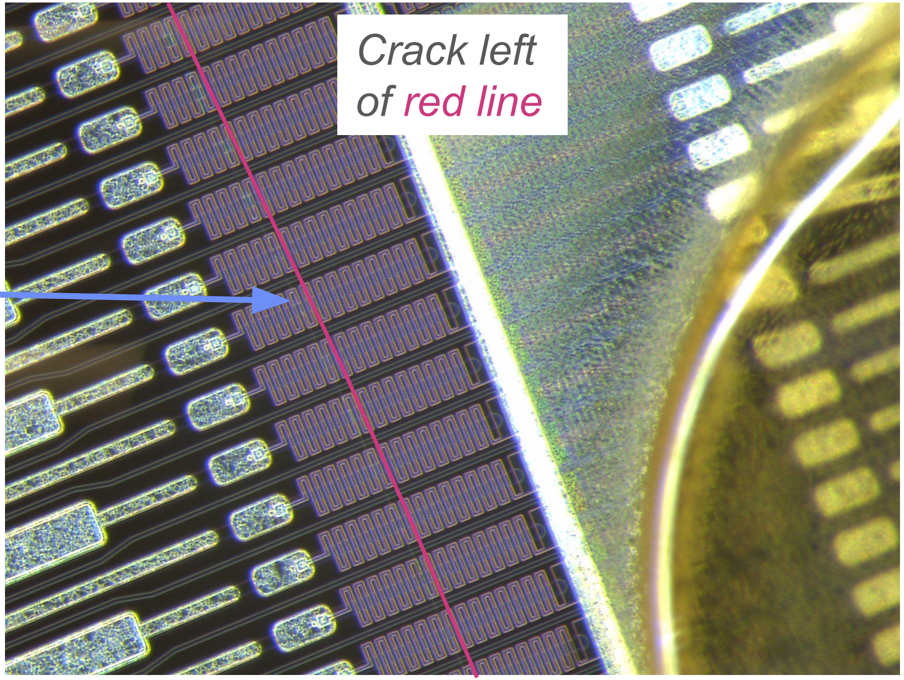
- Instead of SE4445 in a “snake-like” pattern, a petal was loaded using Hysol in the same pattern and TC-ed from −35 to −70 °C in −5 °C steps
- **20 cracks observed** (out of 23 suspected), the first at −35 °C... **why?**





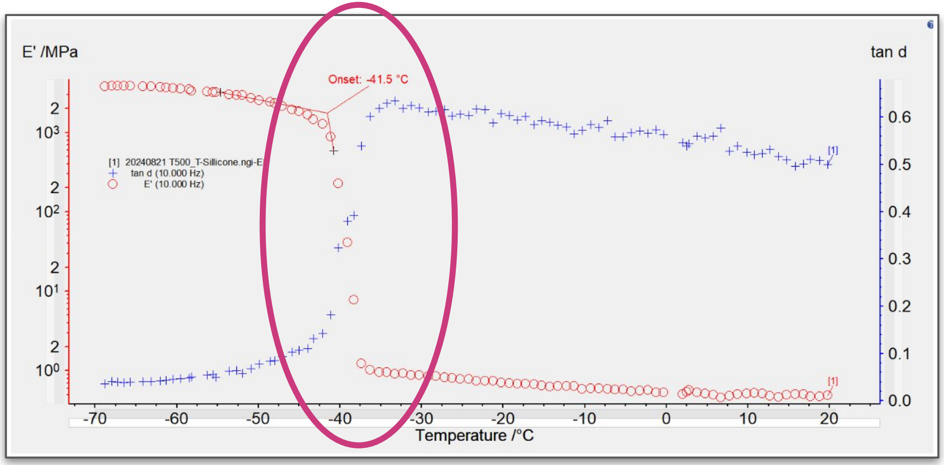
A closer look at the cracks





Understanding Hysol results

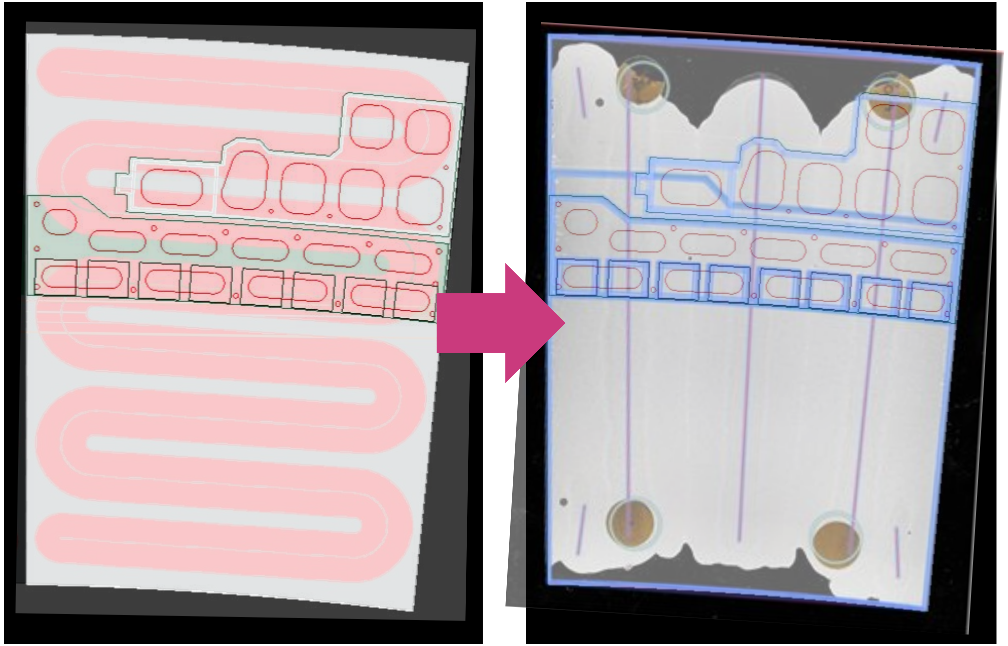
- Simulation informs of the relative (not absolute) change in stress from design choices
  - SE4445 vs. Hysol comparison assumed SE4445 remains softer when cold
- Mechanical analysis revealed SE4445's modulus **increases by 2 orders of magnitude** below **−40 °C**
  - Other studies of silicone-based gels align well with this conclusion
- **Explains why Hysol did not lead to an improvement on its own**



Modulus for SE4445

Pattern of adhesive: Hysol

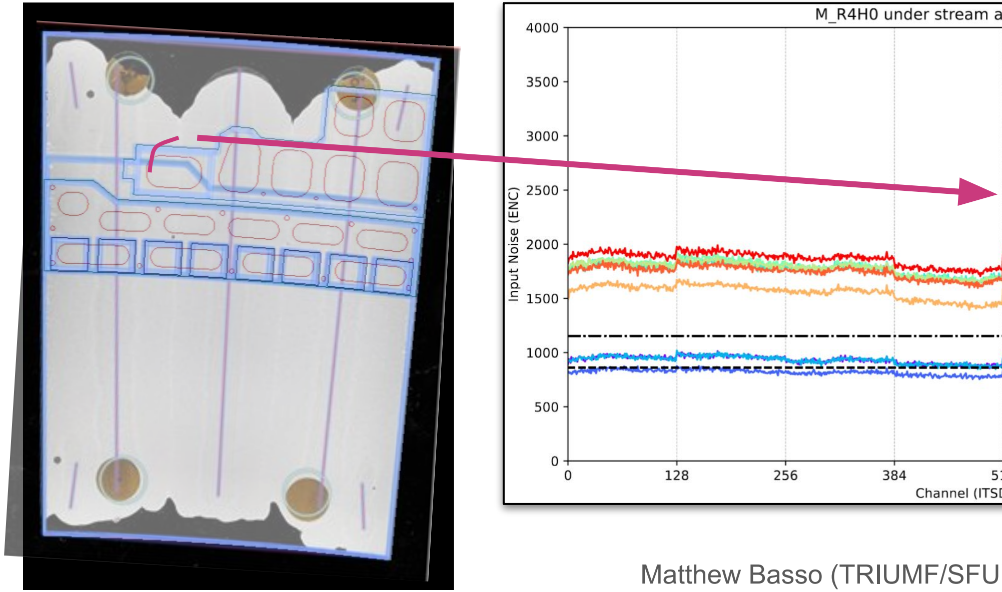
- For the petal with the snake-like Hysol pattern, it was noticed that many cracks occurred along glue edges
  - **Edges are not well supported**
- Next petal utilized a **“full-coverage” glue pattern**, which was optimized to cover as much of the core-sensor interface as possible

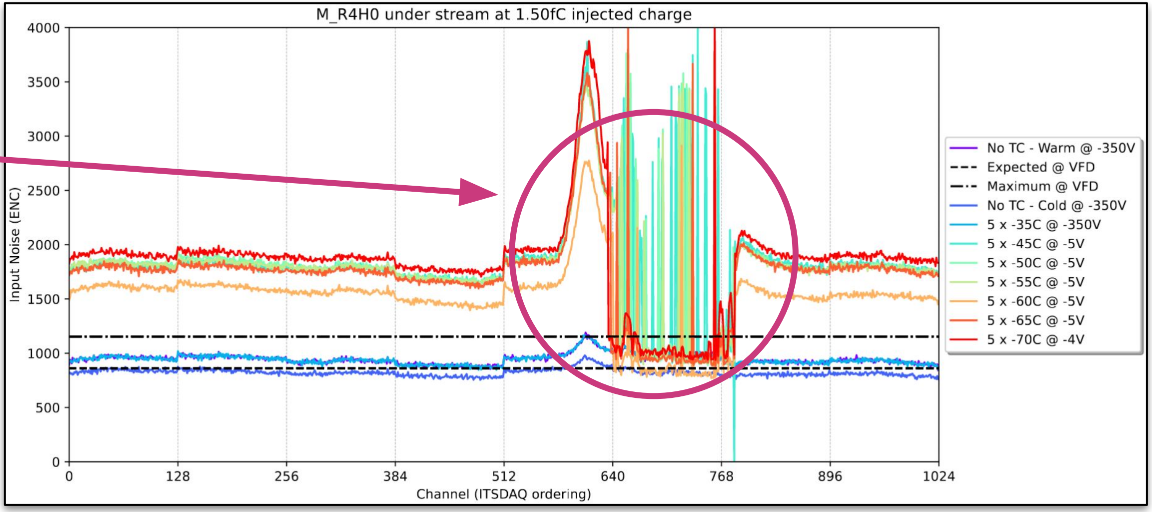


Snake-like *Full-coverage*

Results for full-coverage pattern

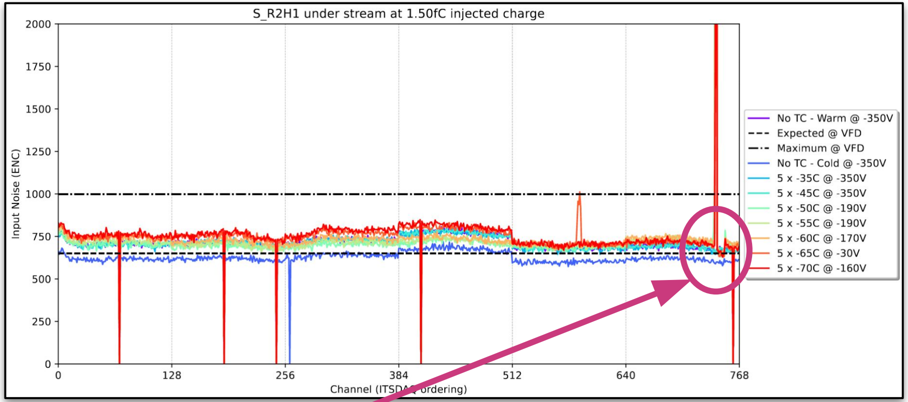
- **Cracks were still observed**: while there were fewer cracks (11) compared to the snake-like Hysol pattern, **one crack** occurred in a region well-supported by glue after the −45 °C TC → **an improvement, but not sufficient**

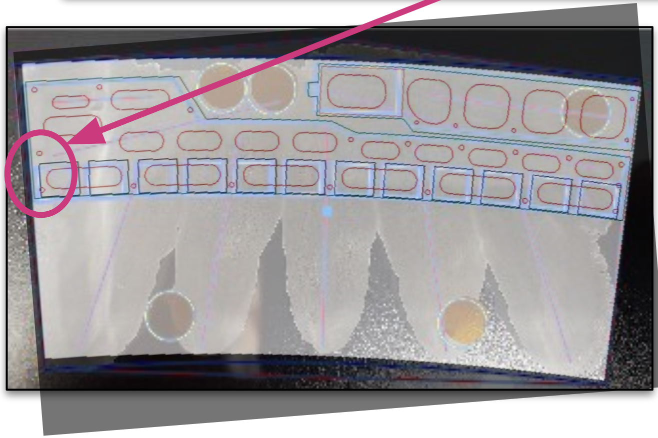


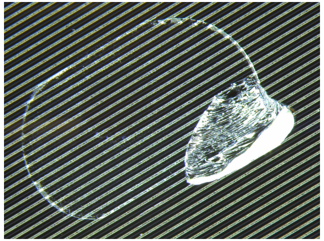


Directions of further study

- Remaining 10 cracks occurred around **“glue-dot” regions**
    - Glue pattern for modules ([“True Blue”](#)) utilizes glue dots throughout → simulation has shown these to be localized regions of stress
    - Will load a petal using SE4445 and modules built **without** glue dots
- Interposers have been shown to be a promising route to prevent cracking down to −70 °C → will also load a petal using **interposed** modules







Picture is for a different petal, but arises from the same mechanism

Summary

- Presented a summary of the **procedures for building and testing petals** for the ATLAS ITk Upgrade
  - Demonstrated that we are building petals which **meet both their mechanical and electrical specifications**
- Also presented a summary of the steps taken thus far to address **sensor cracking on cores**
  - <u>Complex issue</u>: at the intersection of module building and petal loading, mitigation strategies take time to fully realize (need to fully load and test petals cold), etc.
  - Two mitigation strategies shown were not sufficient, but the **issue is well understood** and **we have a promising path forward**

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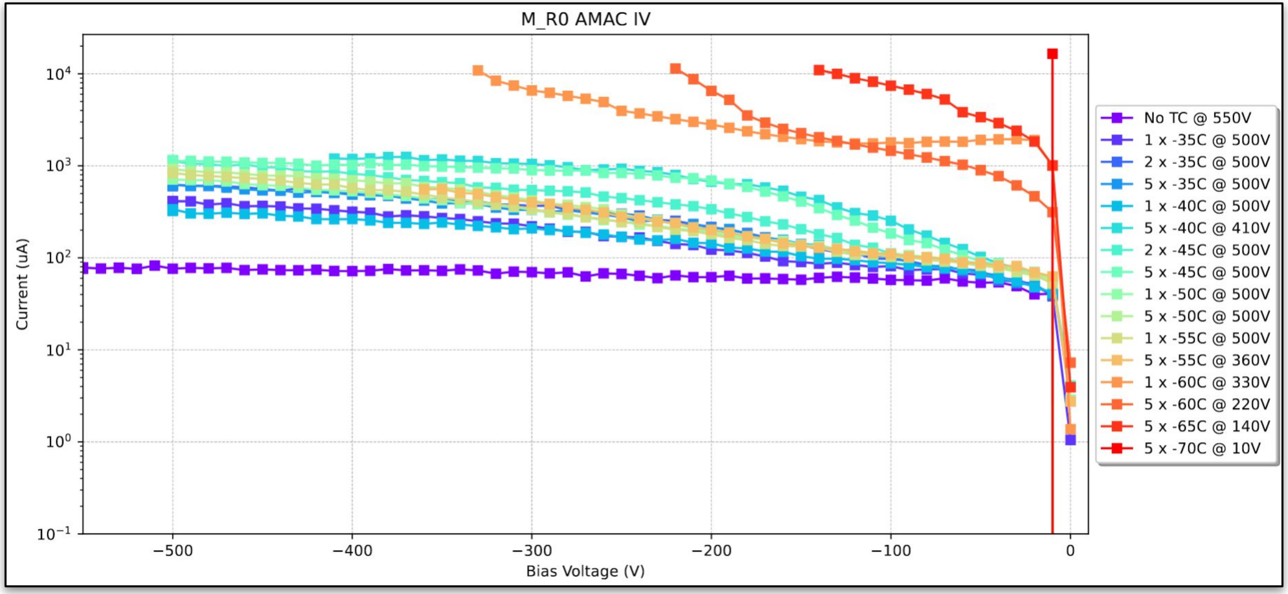
Thank you for listening! Questions?

Backup

Example of HV breakdown



Past the −60 °C cycle, breakdown is visible

Summary of observed cracks