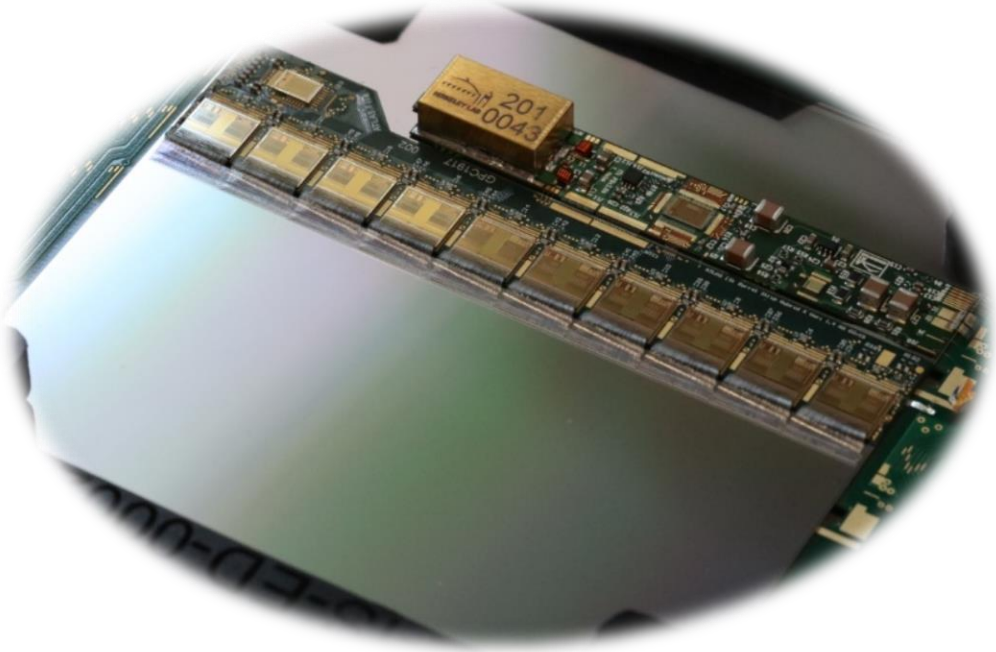
Cold Noise on ATLAS ITk Strip modules

Sergio Díez Cornell, summarizing the work of the ATLAS ITk Collaboration



Silicon Detector R&D meeting,
06.06.2023

Disclaimer: this is mostly a repeat of Tony Affolder's talk at the ITk strips module Production Readiness Review (May 2023), with a few added extra slides and some material extracted from Matt Kurth's AUW talk (May 2023)

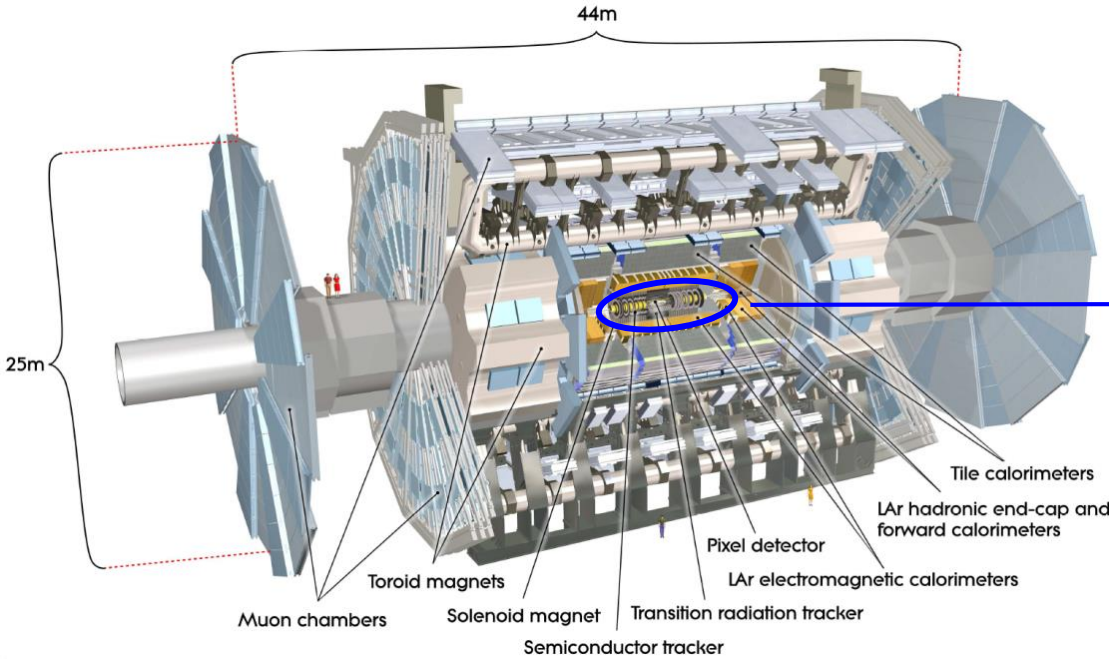
HELMHOLTZ

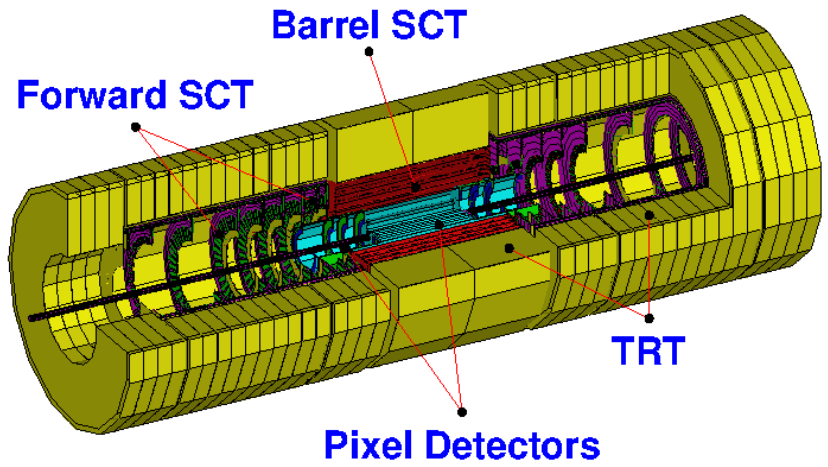
ATLAS ITk

DESY.

The new silicon tracker

Replacing the old Inner Detector by a new all-silicon Inner Tracker (ITk)





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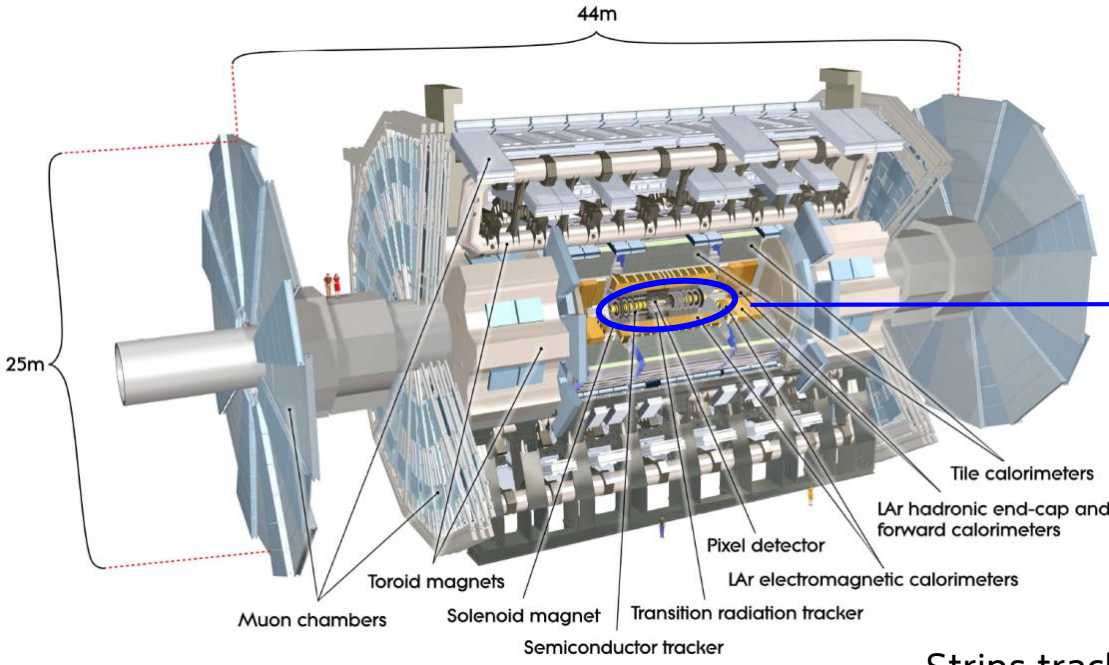
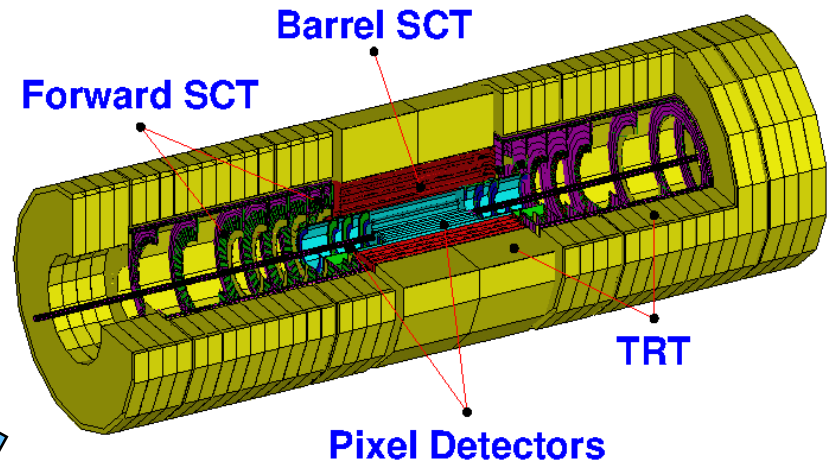
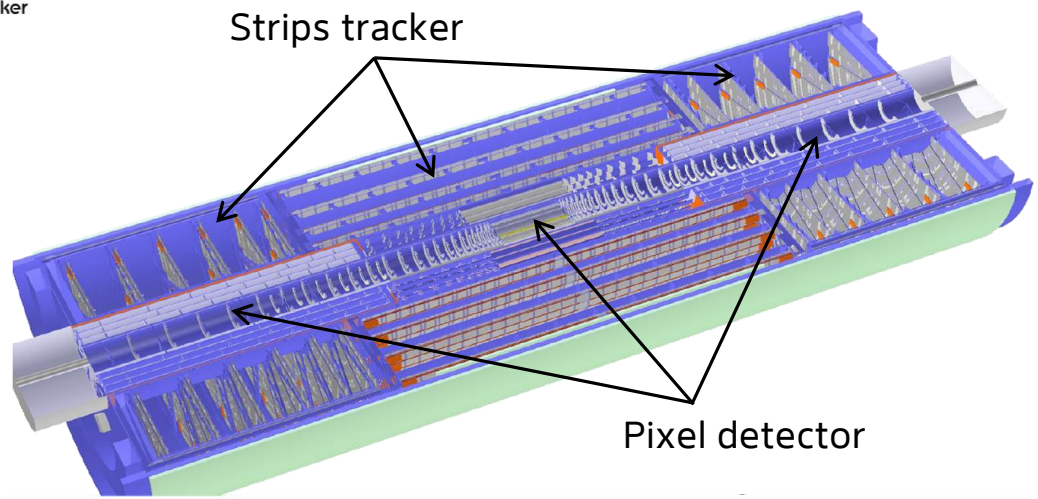
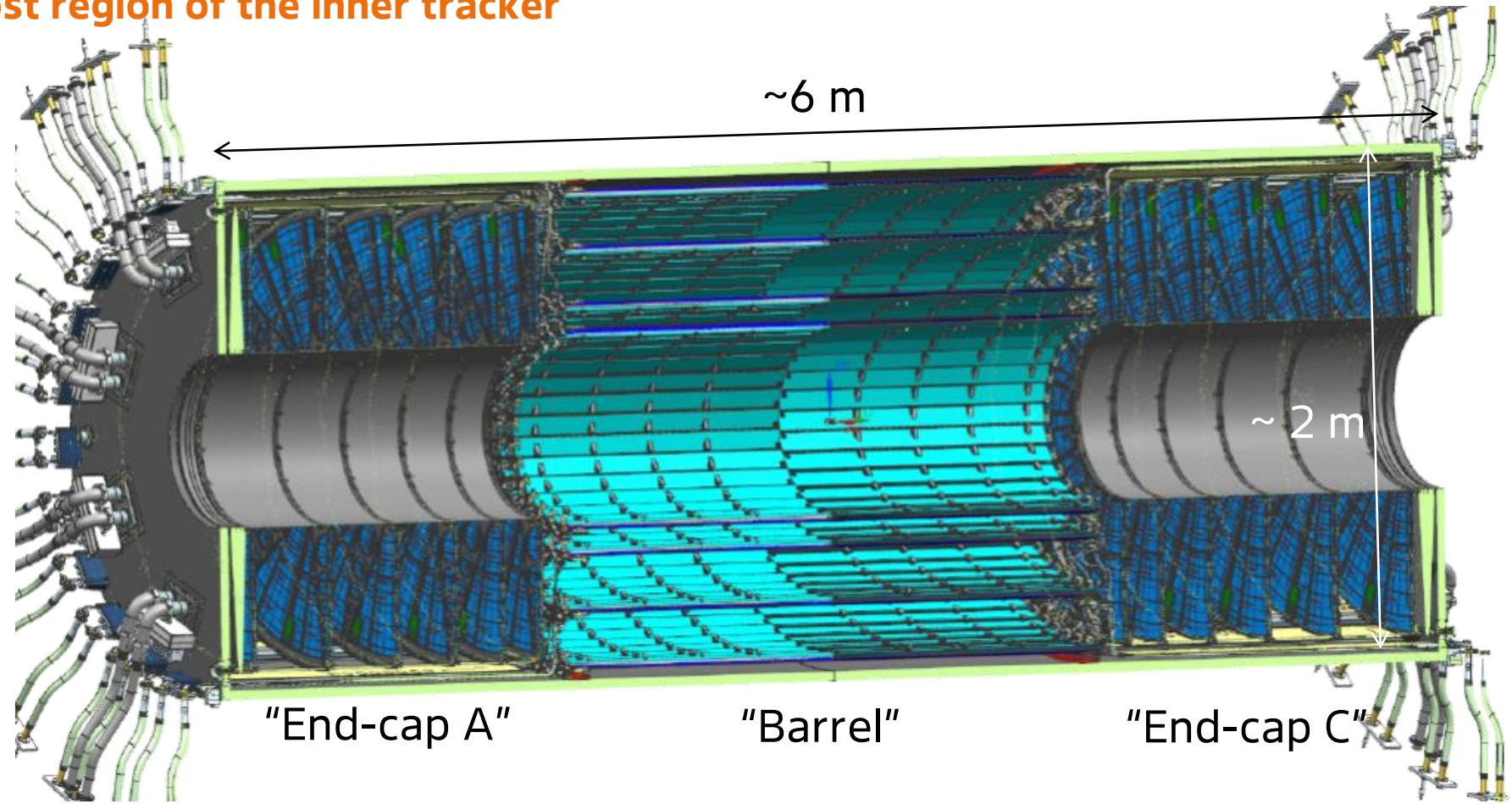






The strips tracker

The outermost region of the Inner tracker

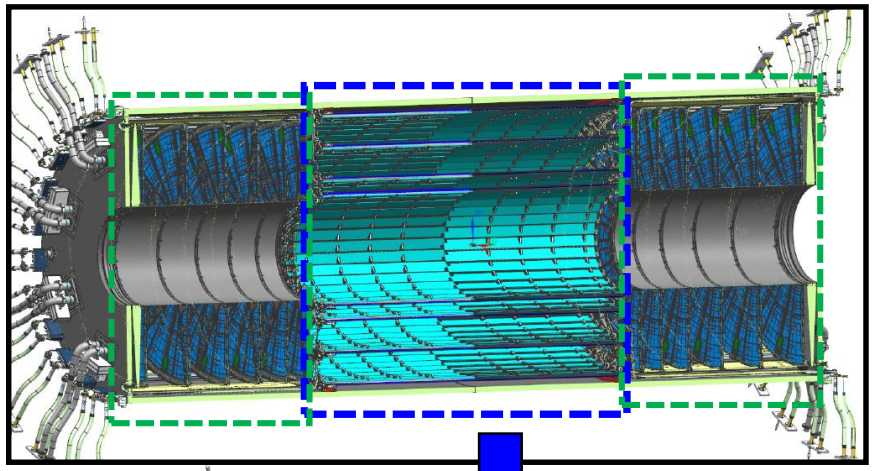


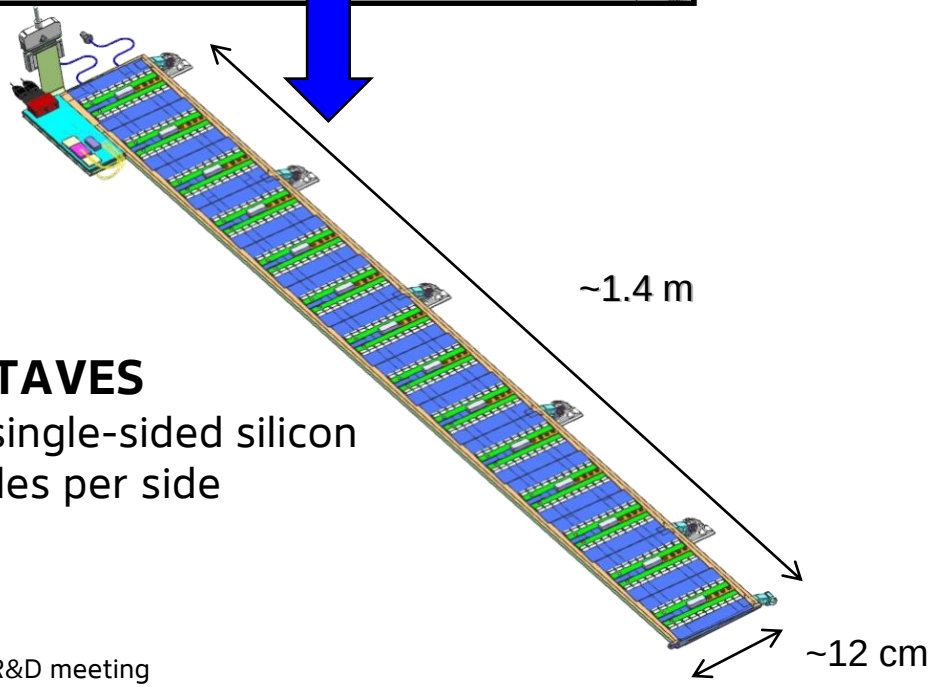
4 barrel cylinders, 6 EC disks per side

180 m^2 of silicon, 15584 silicon "modules", 60 M channels

The strips tracker

"Stave" and "petal" concept



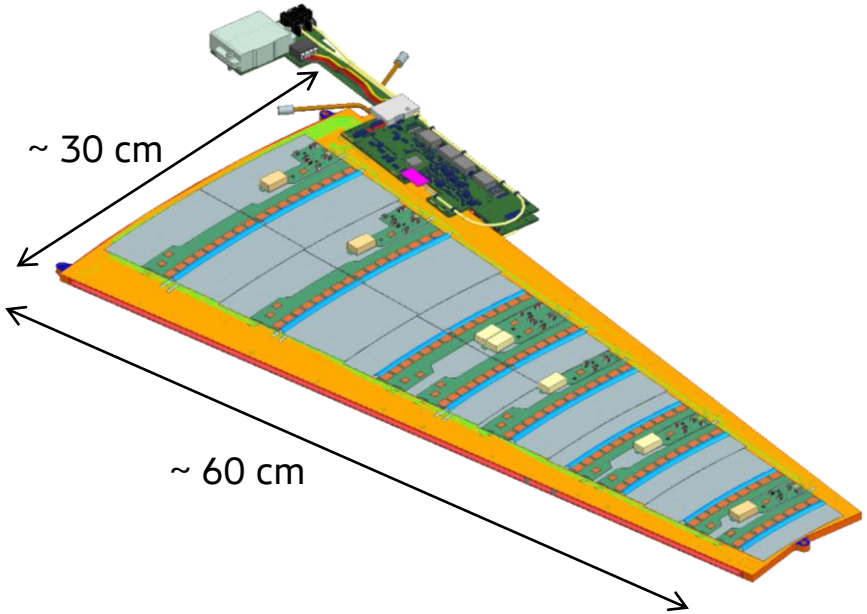


STAVES

14 identical single-sided silicon modules per side

PETALS

6 types of single-sided silicon modules per side

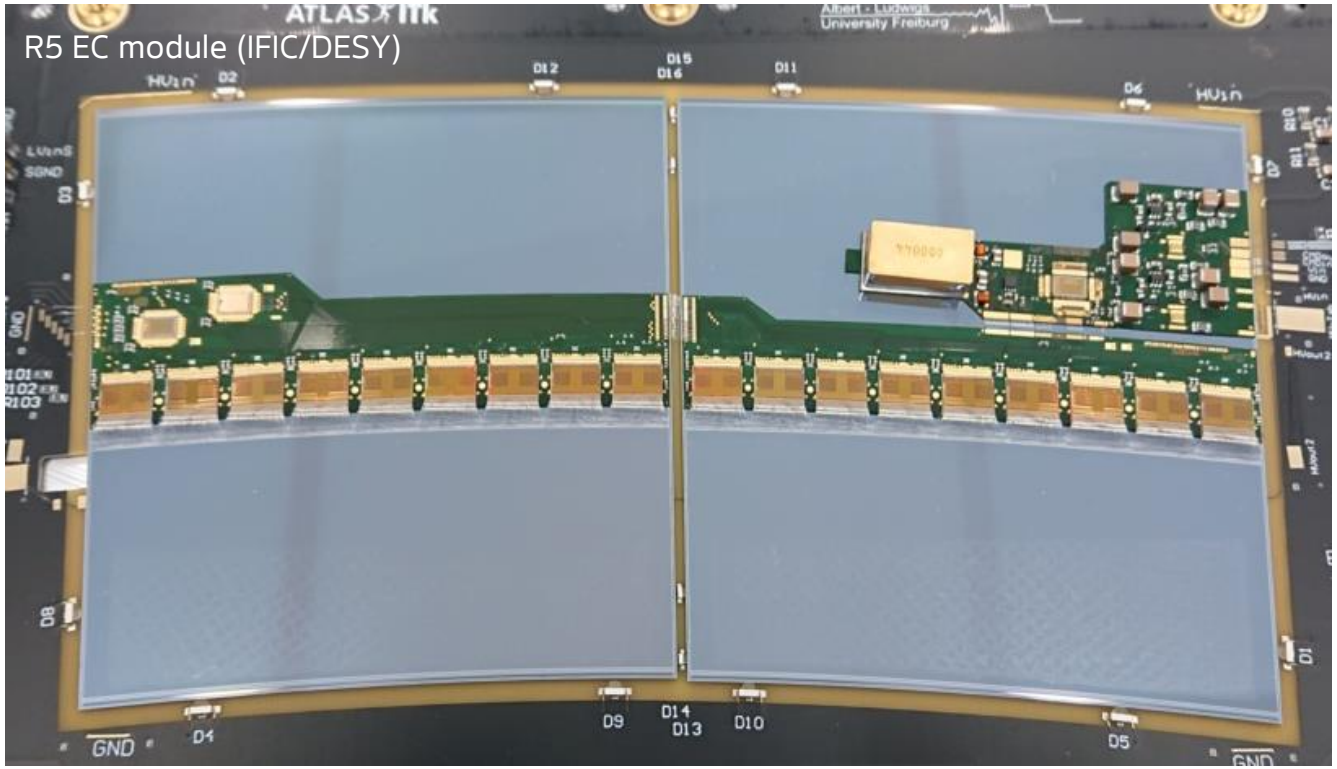


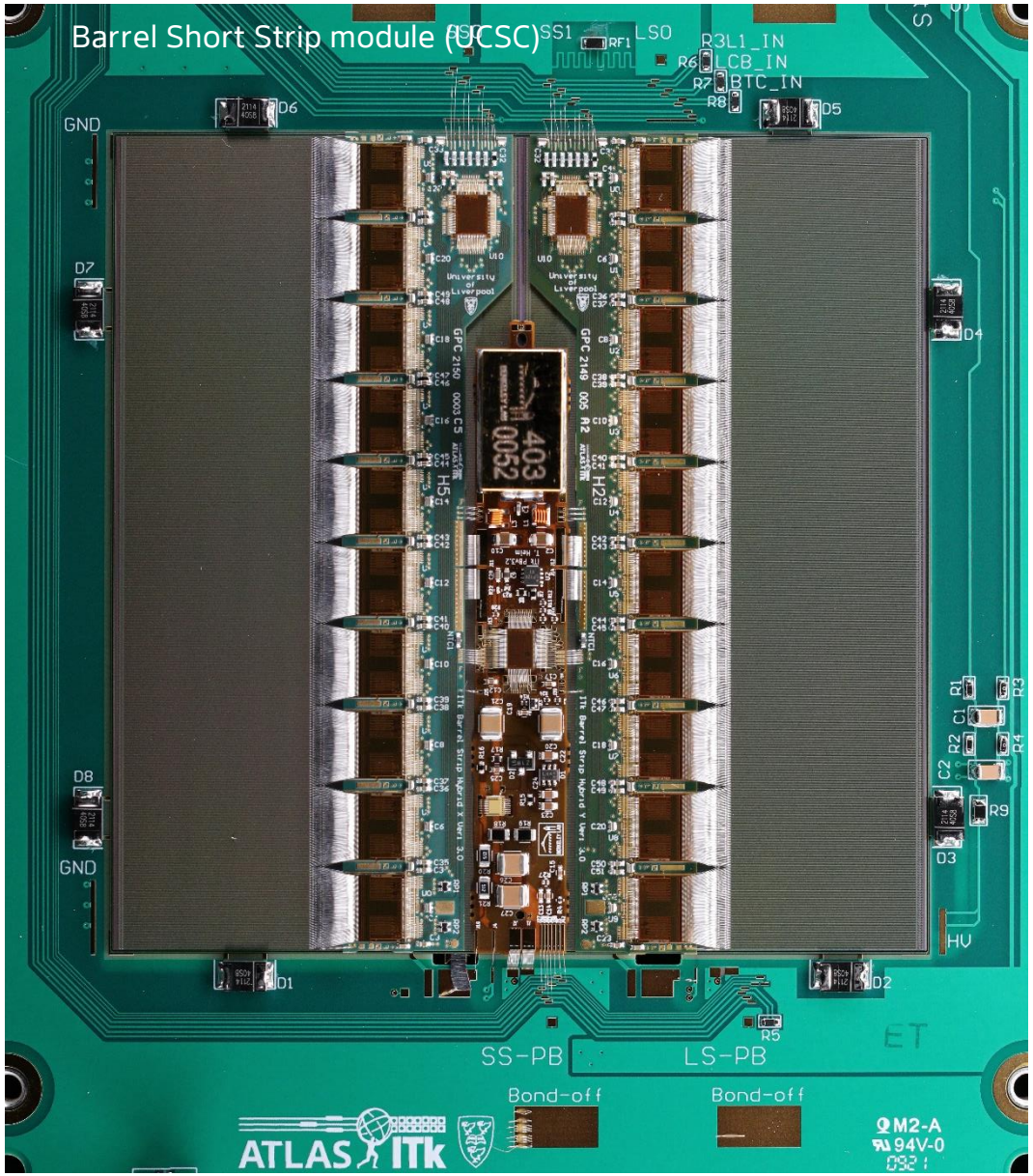
Carbon fiber "sandwich" structures supporting multiple strip silicon modules inside the tracker

Modules are directly glued onto the structures

Single power/data cable per stave/petal side

The strips modules





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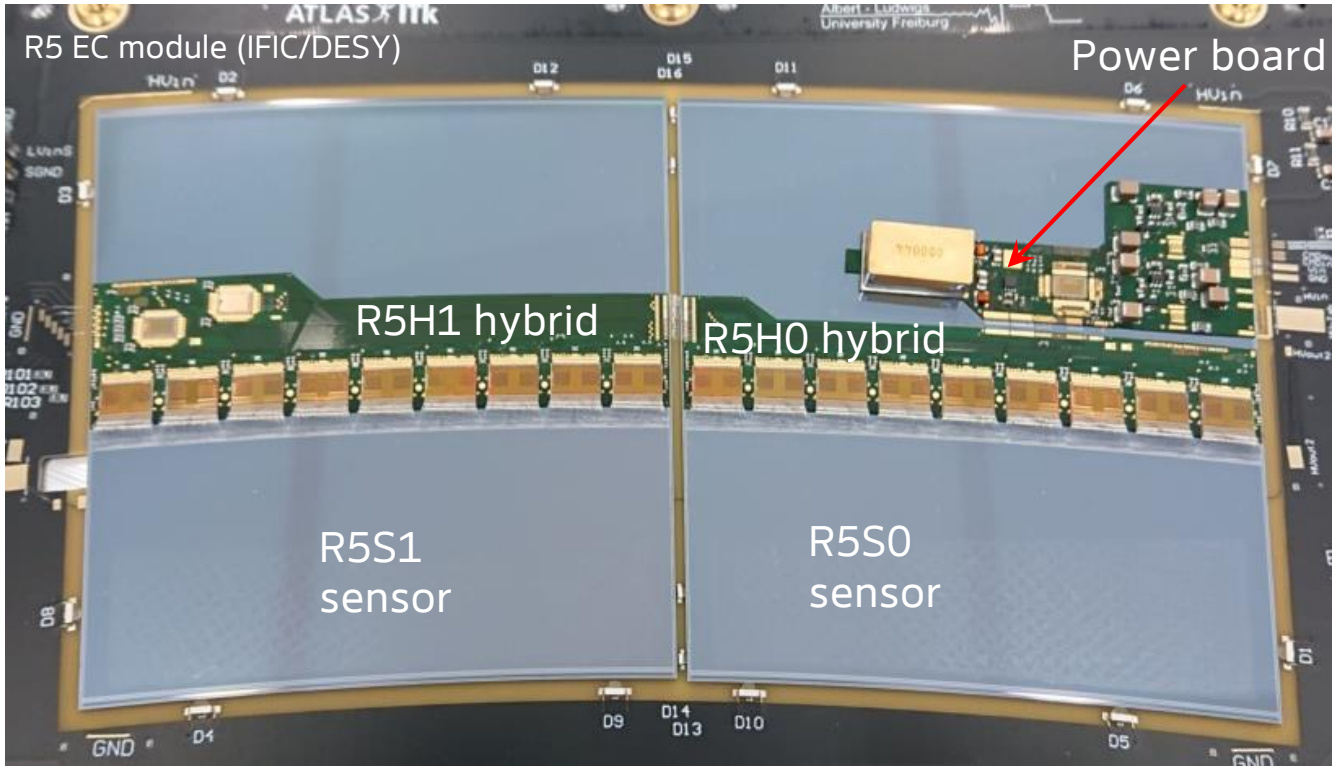

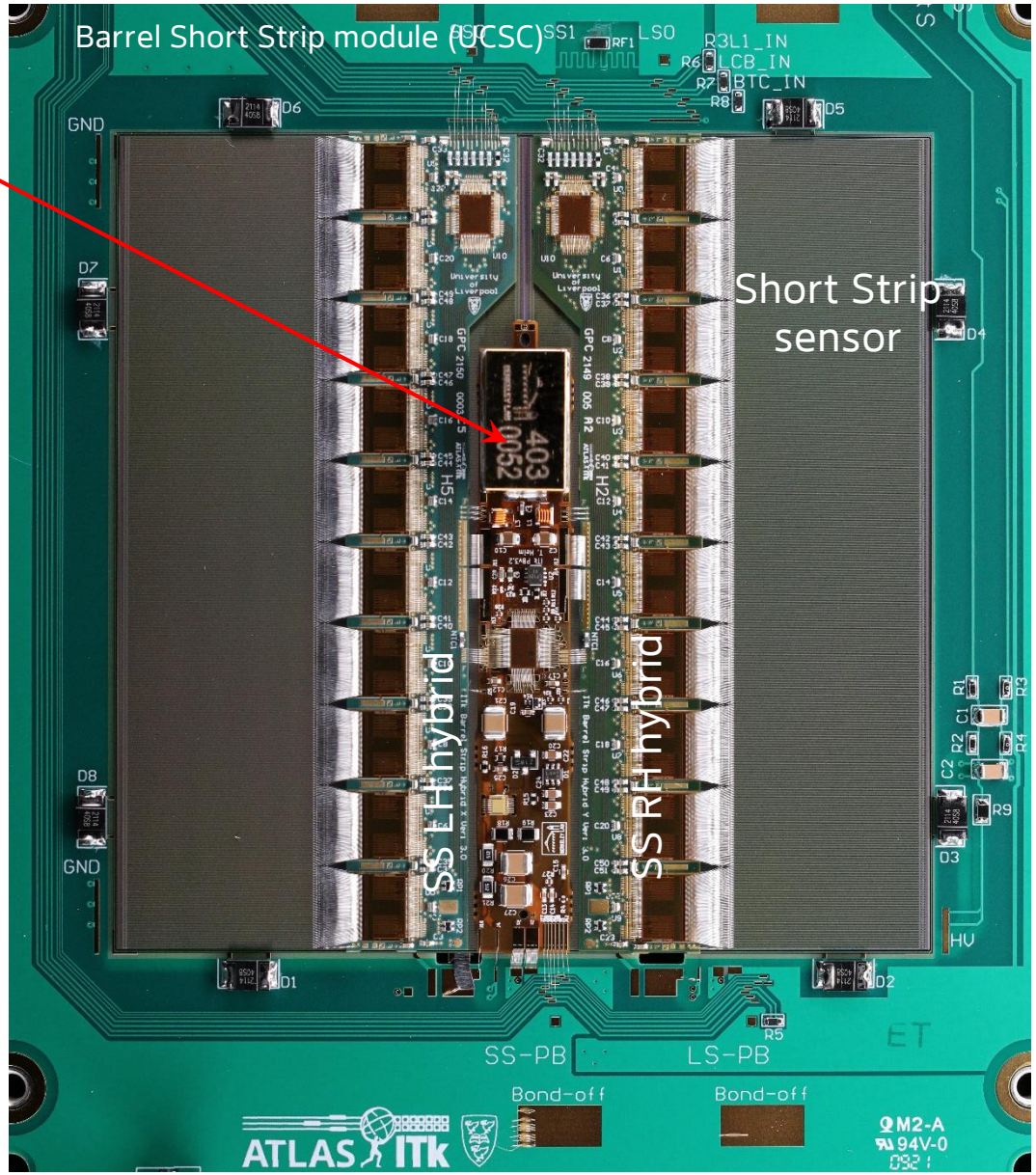

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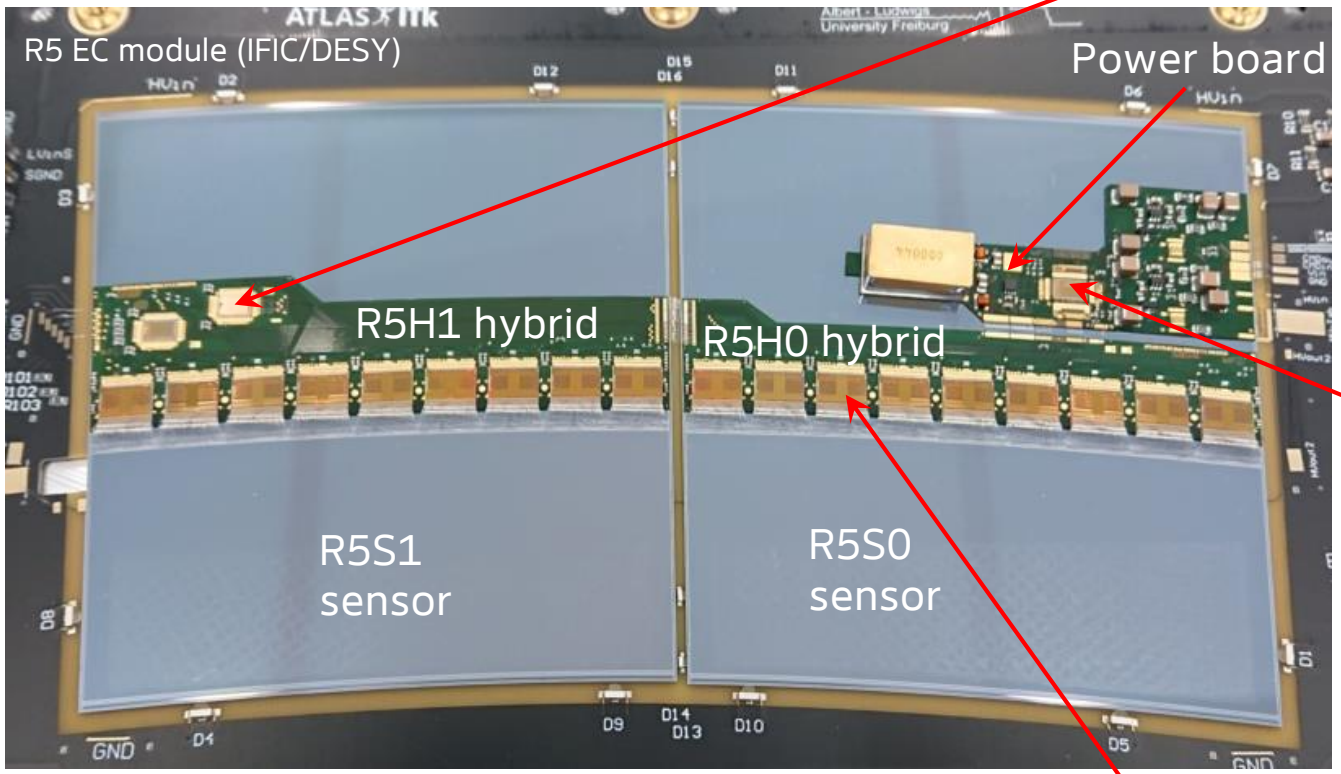
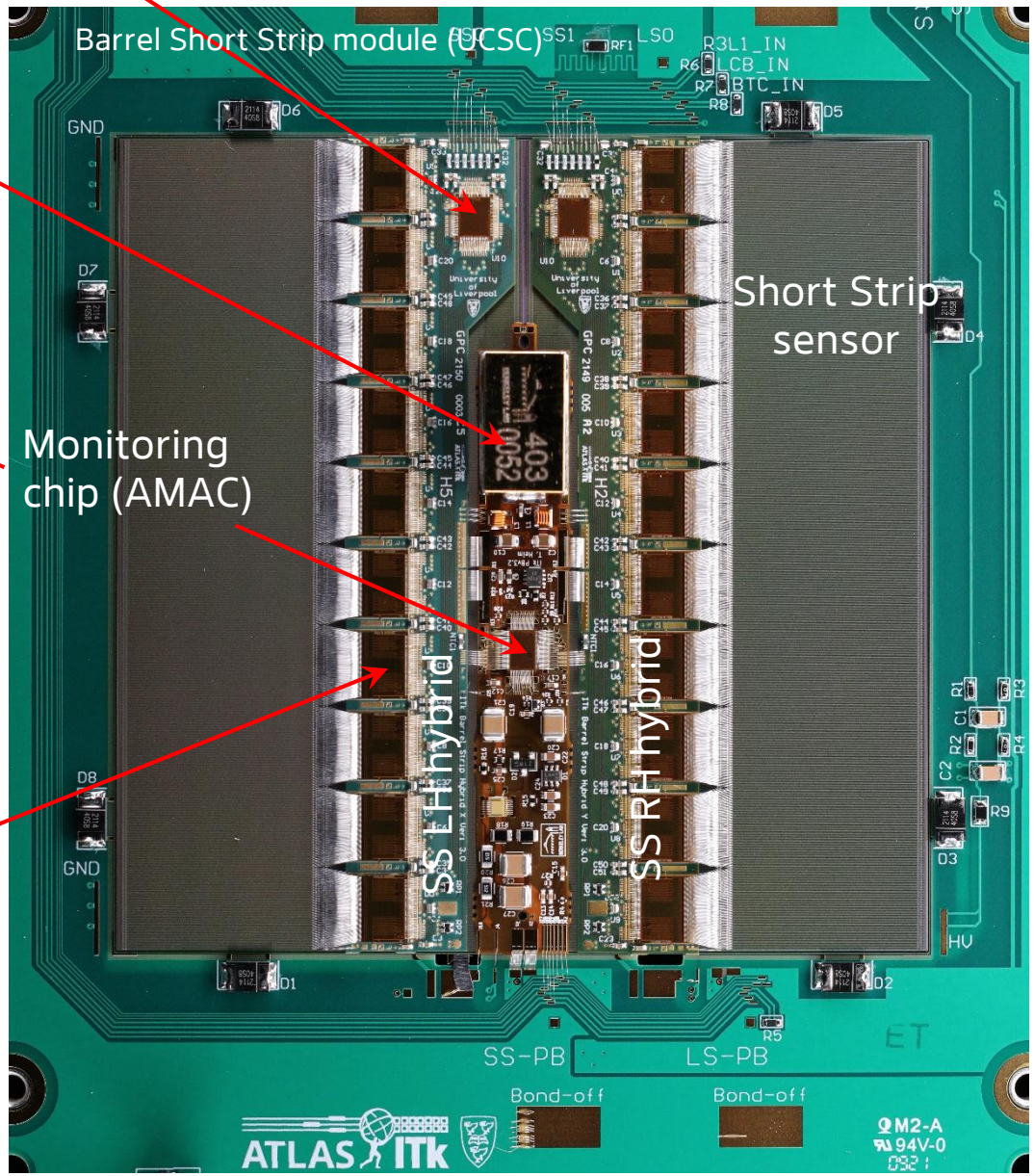


Hybrid controller chips (HCCs)

Front-End chips (ABCStar)



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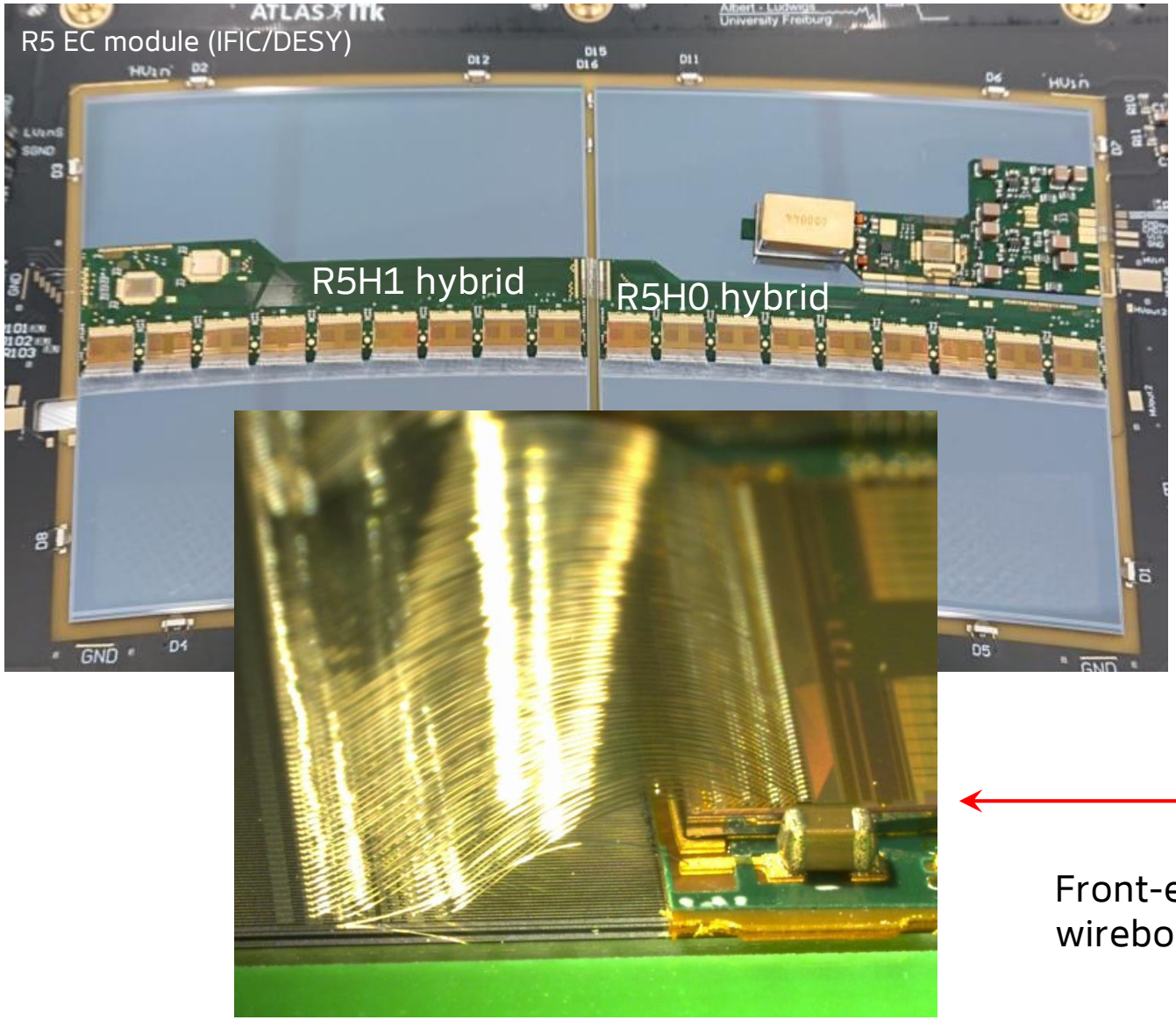
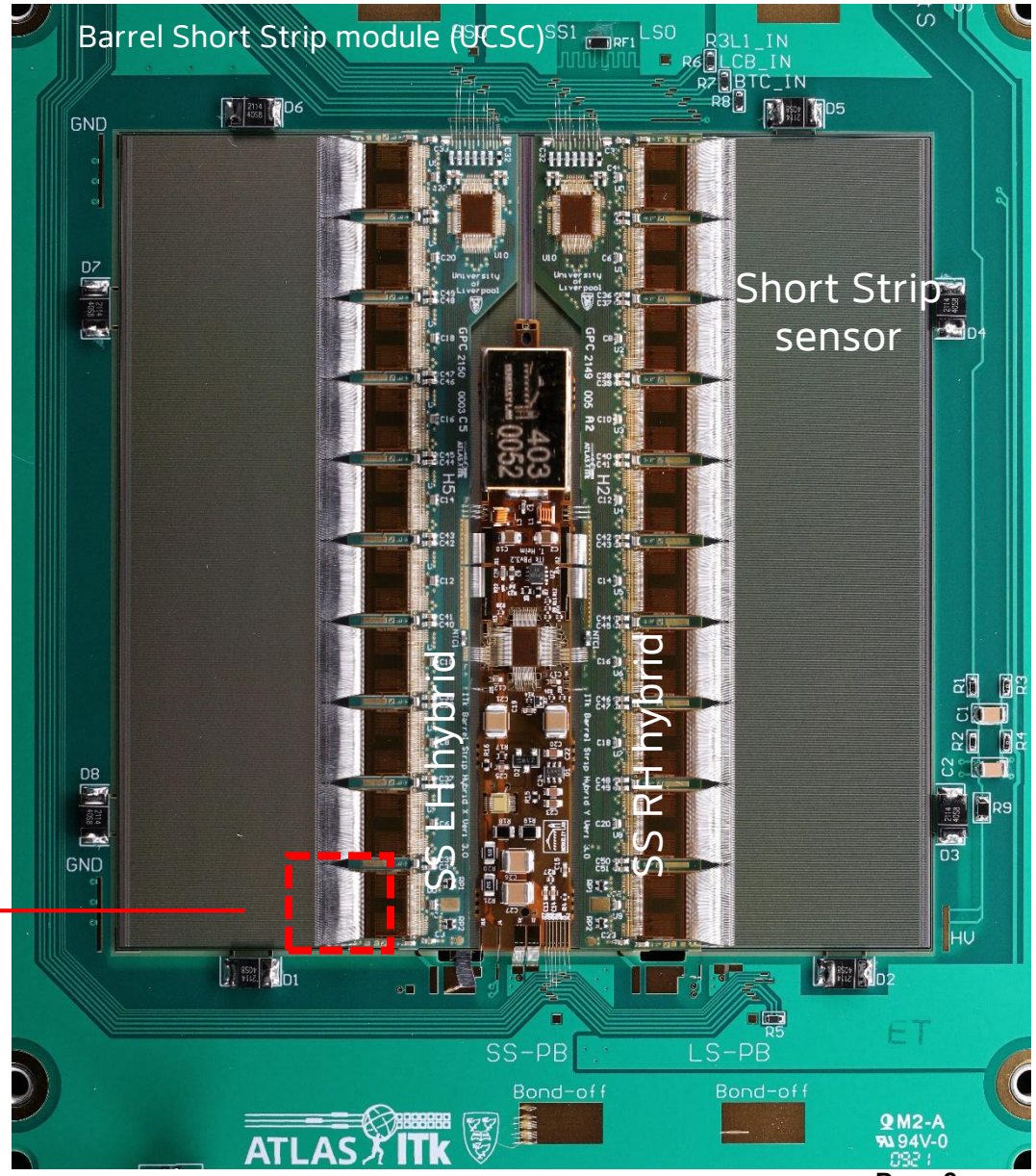
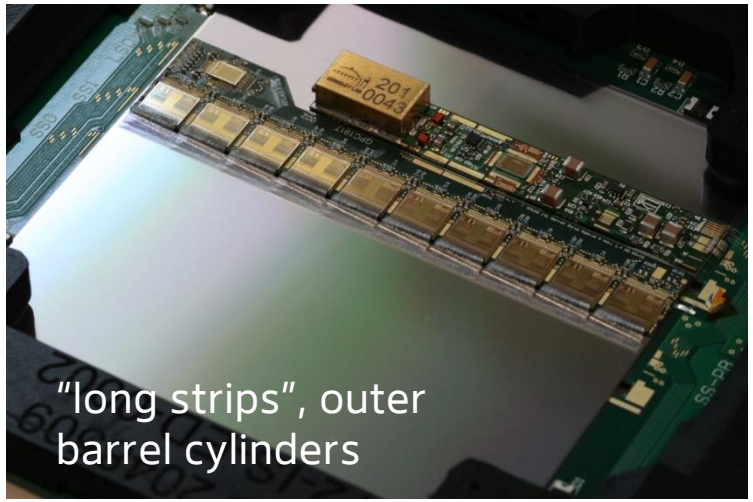


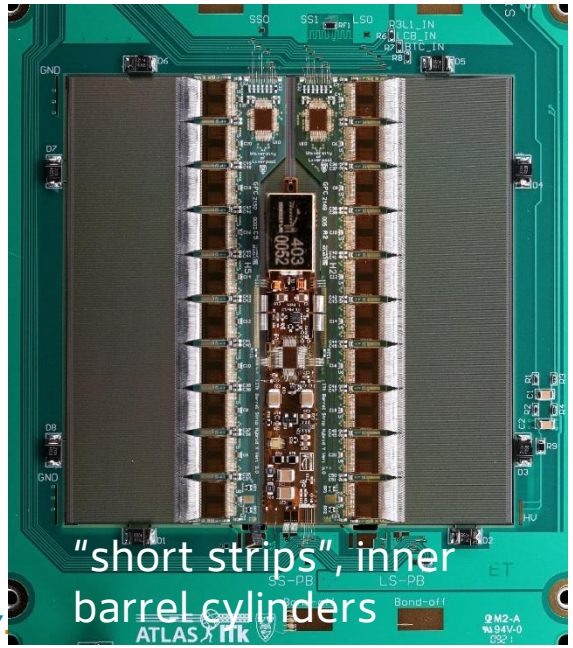
Front-end wirebonds

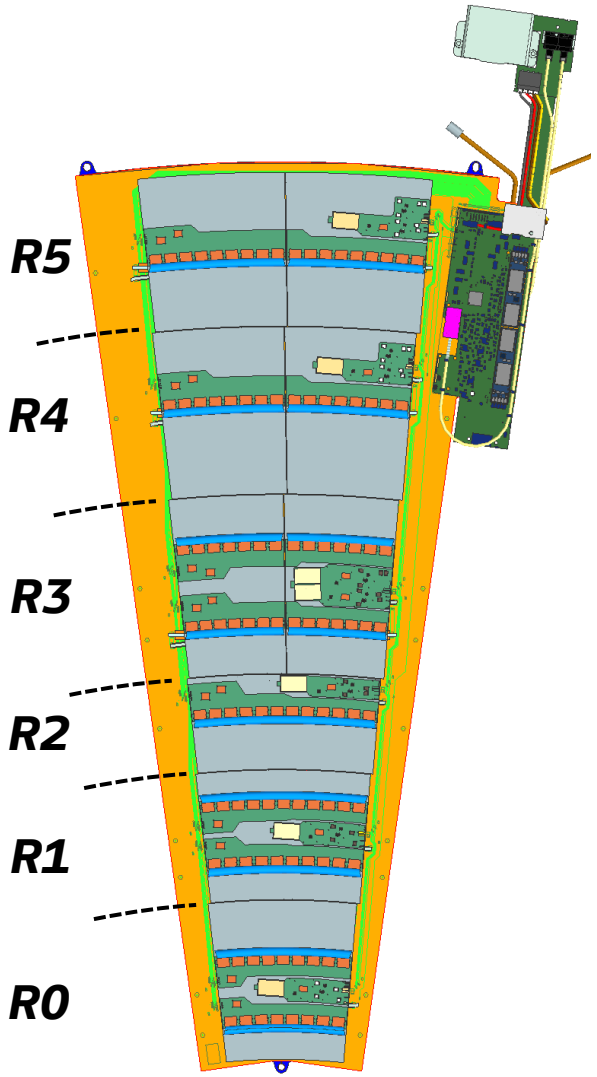


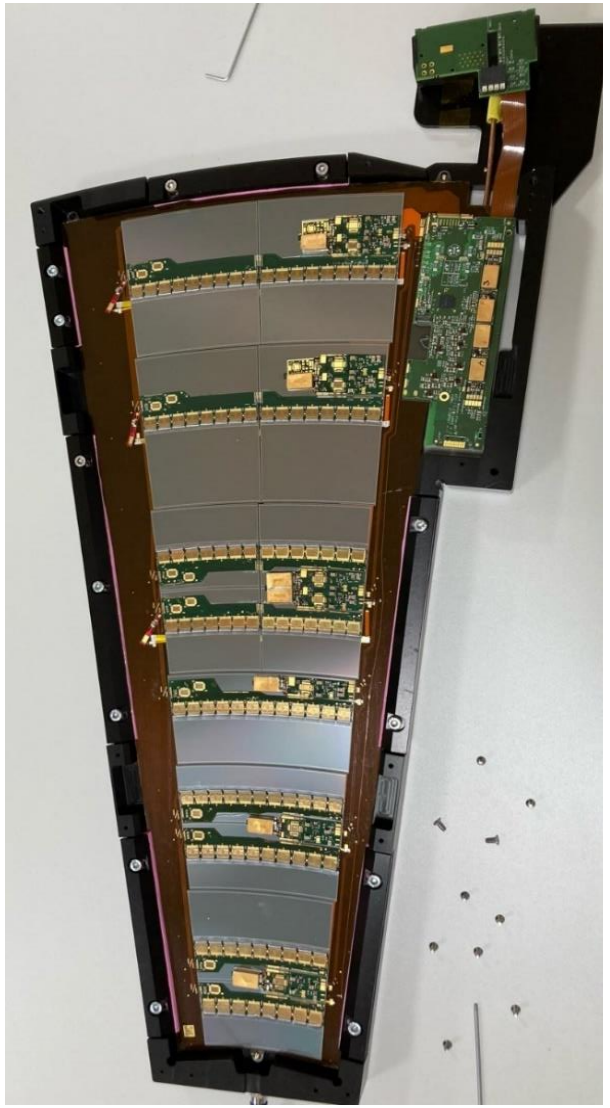
Module flavors

2 module flavors in the barrel, 6 in the ECs









Appearance of cold noise

Beginning of pre-production (May 2022)

Prototyping was a success, modules for multiple staves have been built, a couple of fully loaded staves were available, pre-production started for the barrel…

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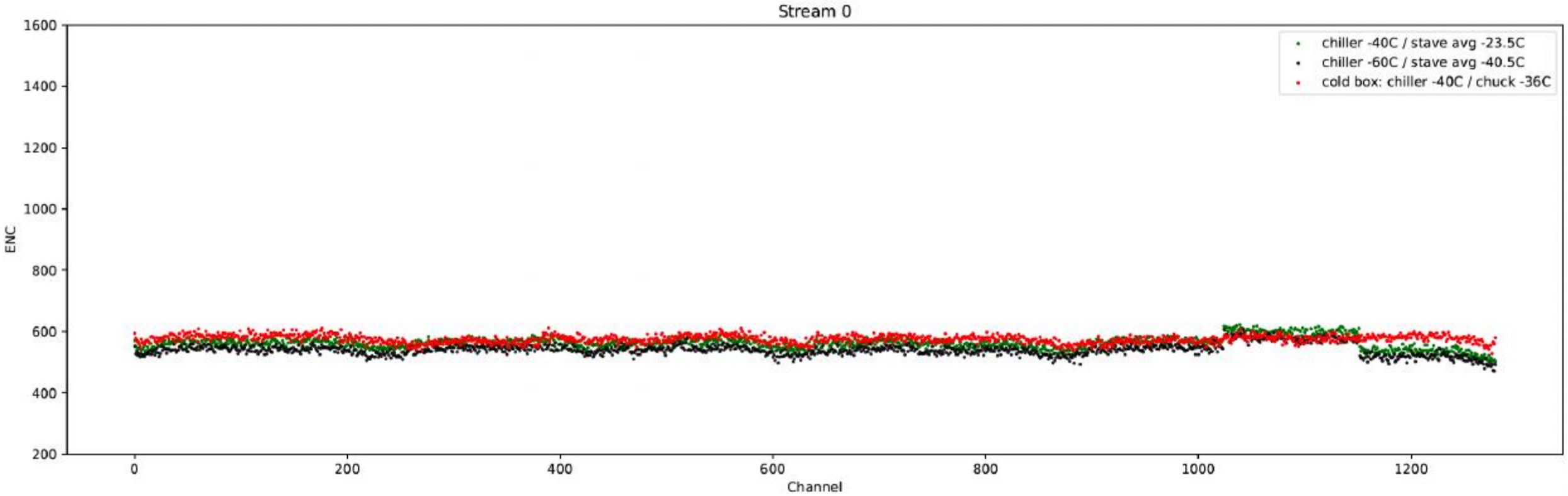

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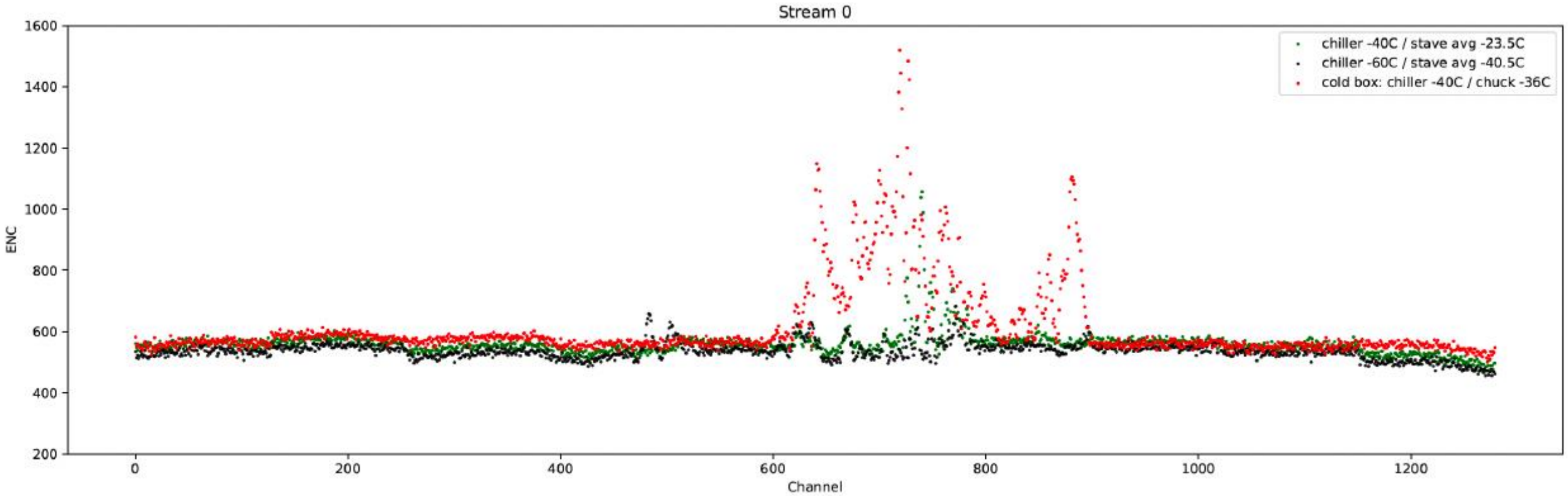


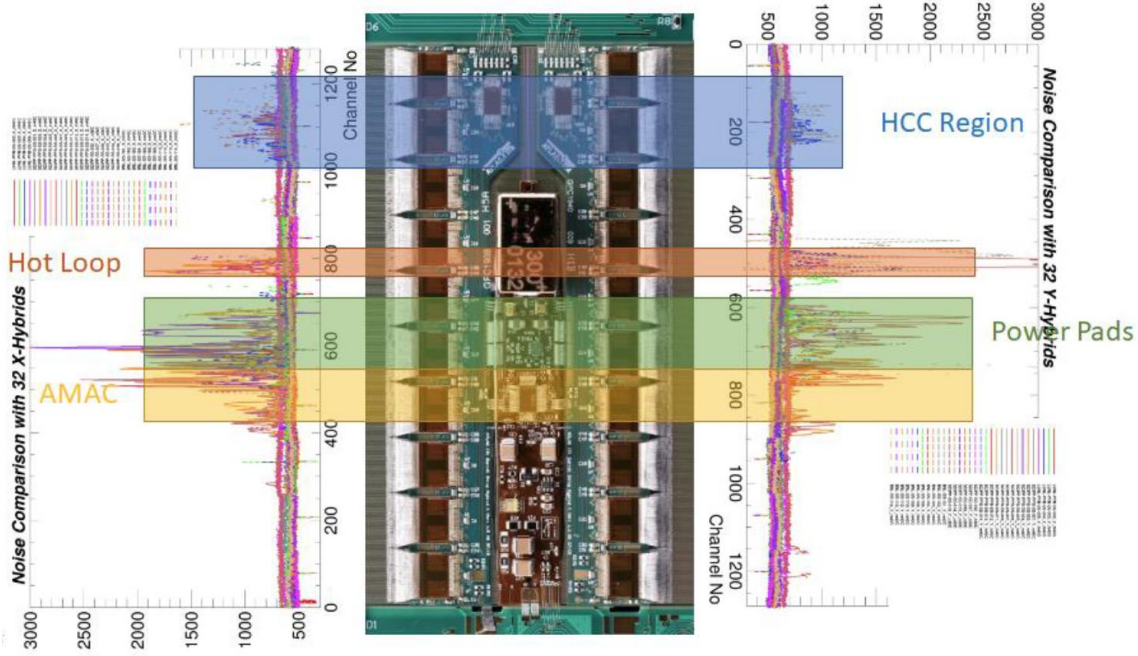
Cold noise on modules

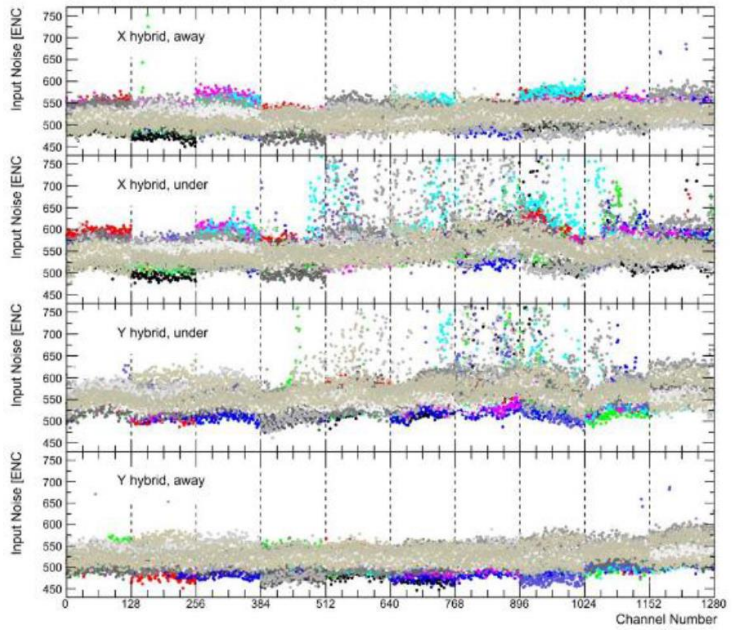
Main observations

When cooled down, noise peaks occur in different areas of the module

On discovery a task force was convened to work on this (meeting bi-weekly since July 22)

- Turns on at different temperatures (typically -10 C)
- Affects specific sections of modules
- Typically reversible when module warmed again
- Increasing power leads to increasing effect
  - Short strip modules more prone to cold noise
- Observed on single modules as well as staves
- It was not observed on prototype modules





New glues

Impact of glue choice

Almost coincidentally, and without warning, Polaris, the glue chosen for the hybrids and power boards interface to sensors, was discontinued by the manufacturer

We had to veer towards our backup options

Modules were built with alternative glues ….with interesting results

- Polaris+, Sylgard, SE-4445, Eccobond F112 (True Blue), Atom Adhesives F112 (“False” Blue)

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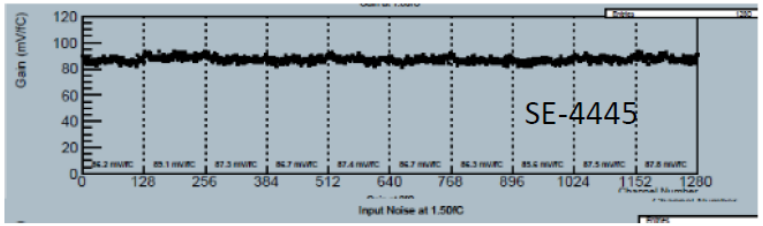
Sylgard and SE-4445 do not exhibit cold noise!

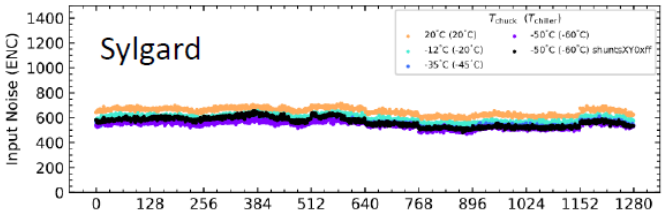
- Sylgard → not rad hard, SE4445 → poor IV characteristics

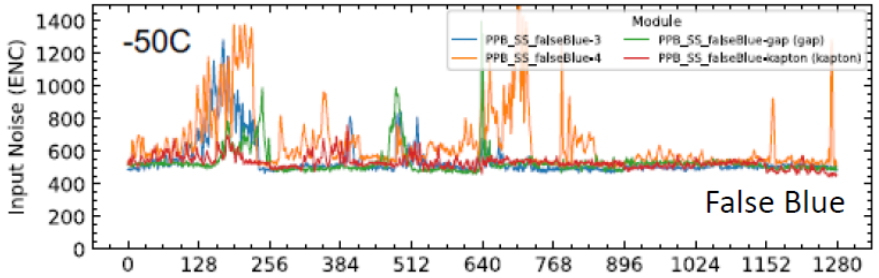
Electronics grade epoxies had different performance

- **True Blue modules show little cold noise**
- Polaris+ modules shows cold noise
- False blue modules showed significant cold noise

For a given blue, cold noise is reduced as you increase its thickness



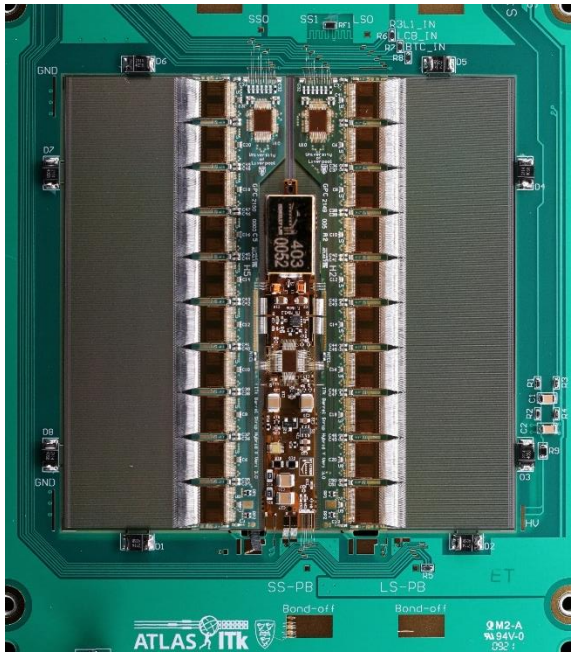




*This was one of the indicators that cold noise could be related to **mechanical stress** on sensor surface*

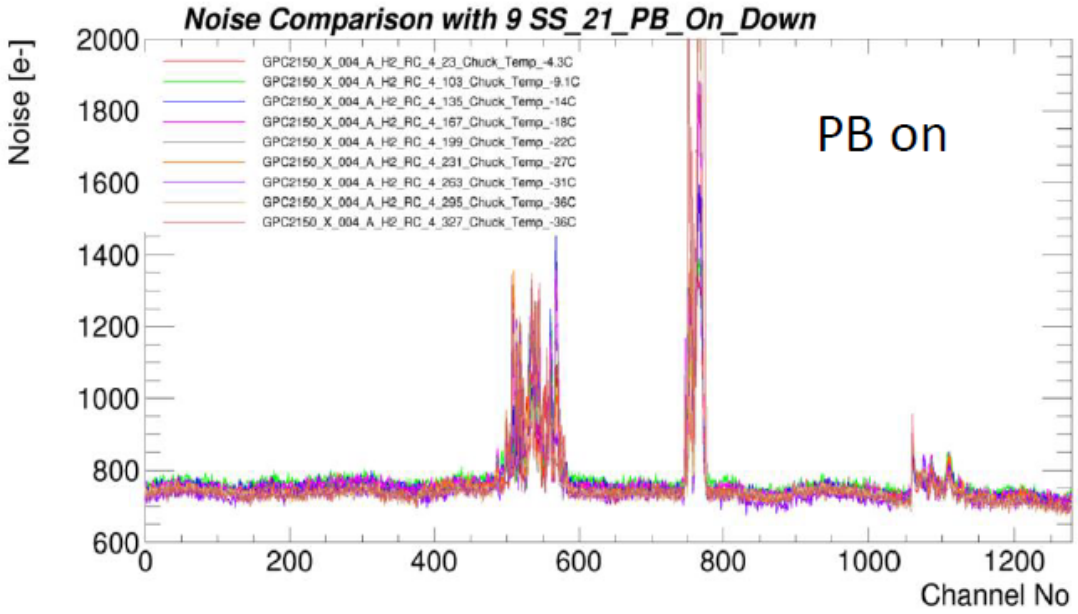
No power board – no problem

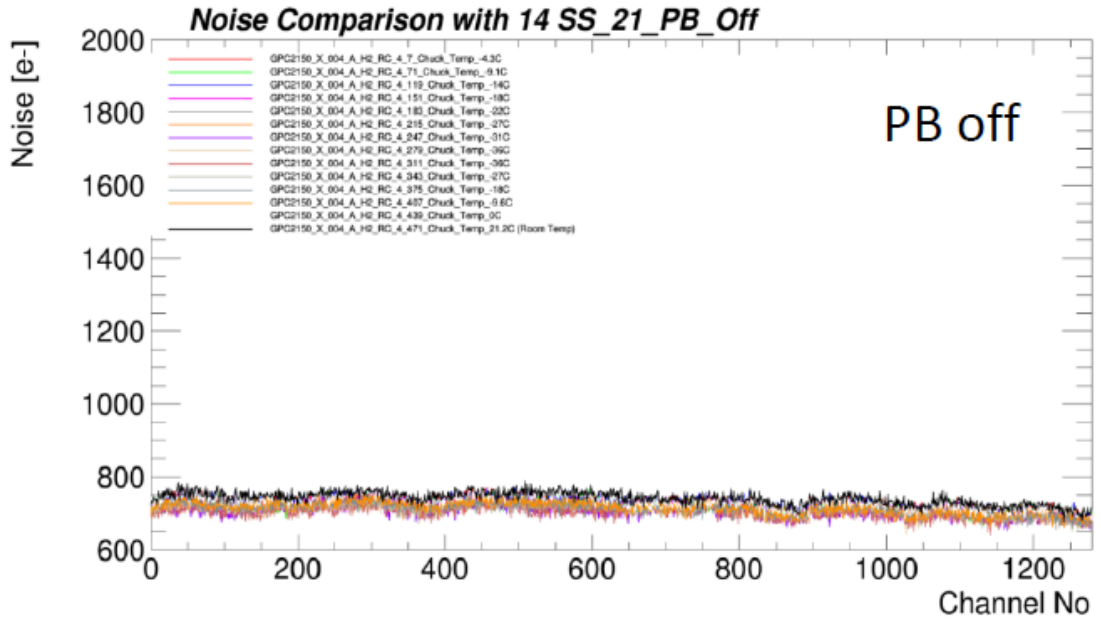
Identifying the source



Quickly isolated the source of the noise to the power board

- By powering hybrids externally on modules with known cold noise we were able to turn cold noise on/off via the power board





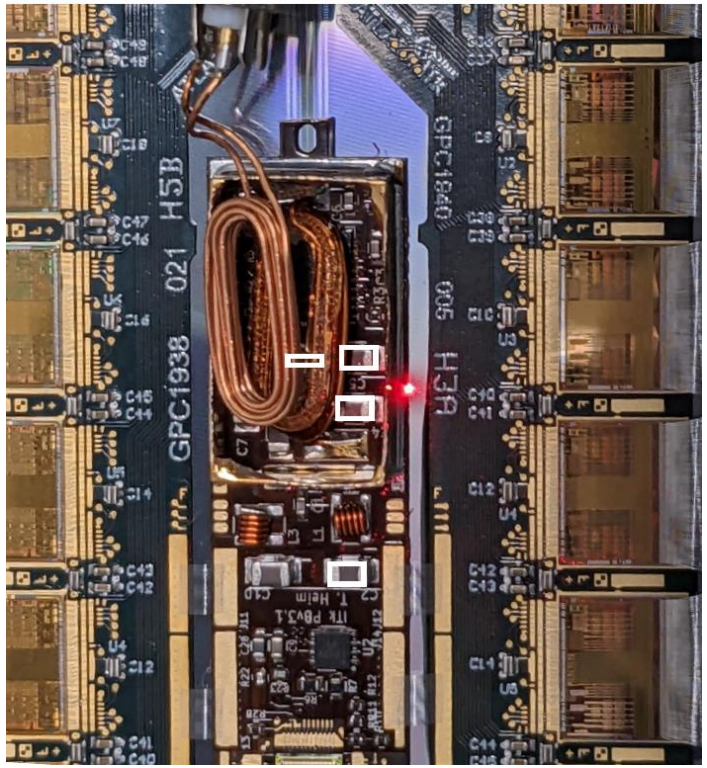
Magnetic triggering

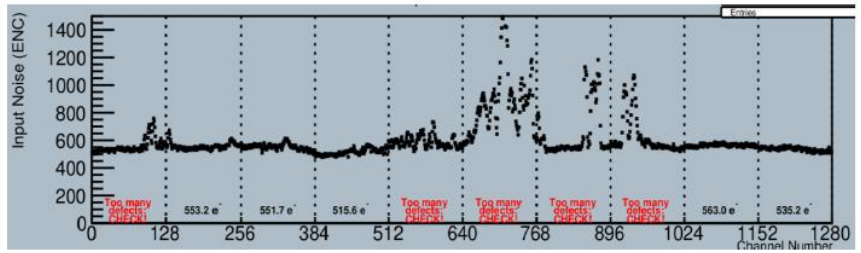
The big breakthrough

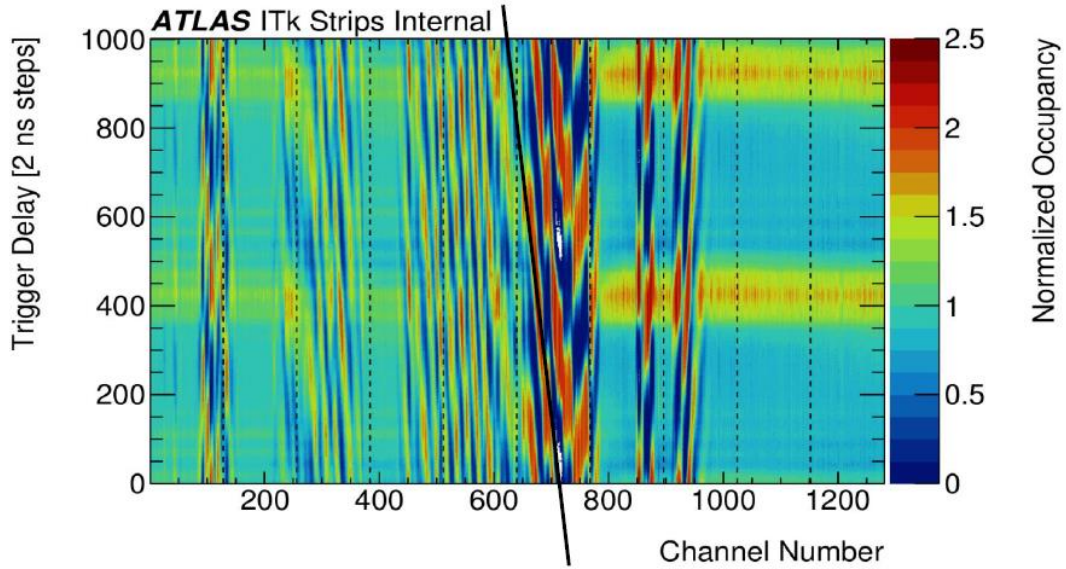
A hint: while operating the power board without shielding, a tiny movement of the coil was detected

Motivated magnetic triggering measurements: measure noise occupancy relative to the phase switching of the buck DC-DC converter in the power board (instead of the bunch crossing frequency)

- Demonstrated that **cold noise is in-phase with the DC-DC converter switching frequency**







Vibration injection

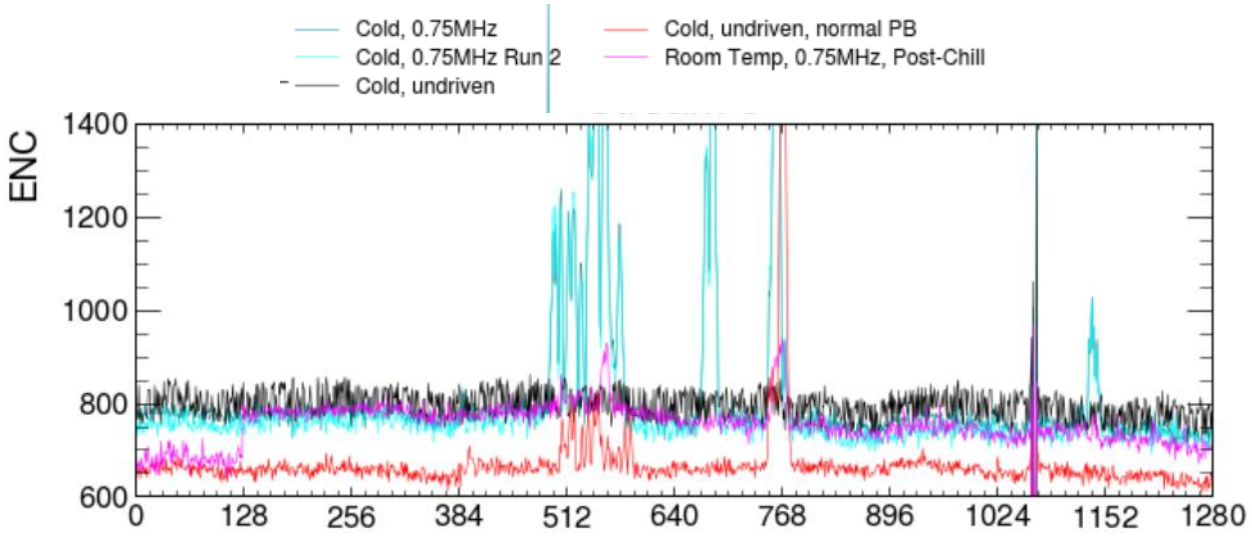
Via transducers

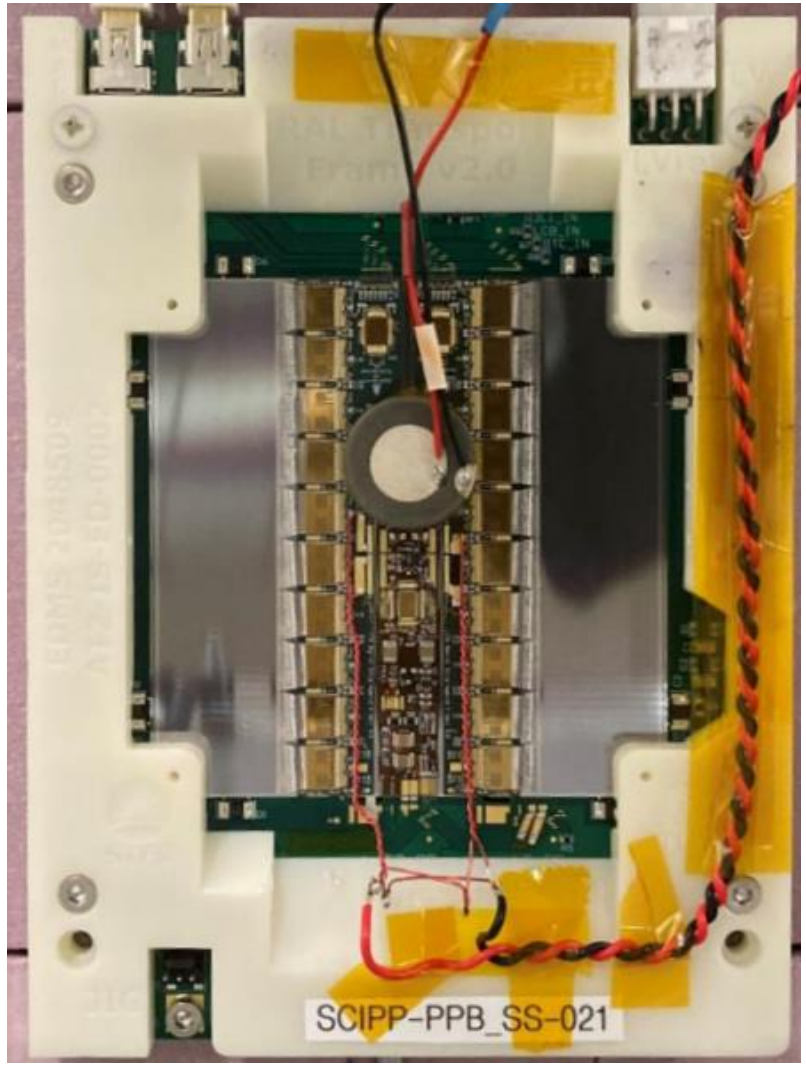
Injected vibrations into the module using transducers on the shield box

Reproduced a cold-noise like signal while power board was switched off

- Even at room temperature!

Unable to generate a cold noise signal on EC modules





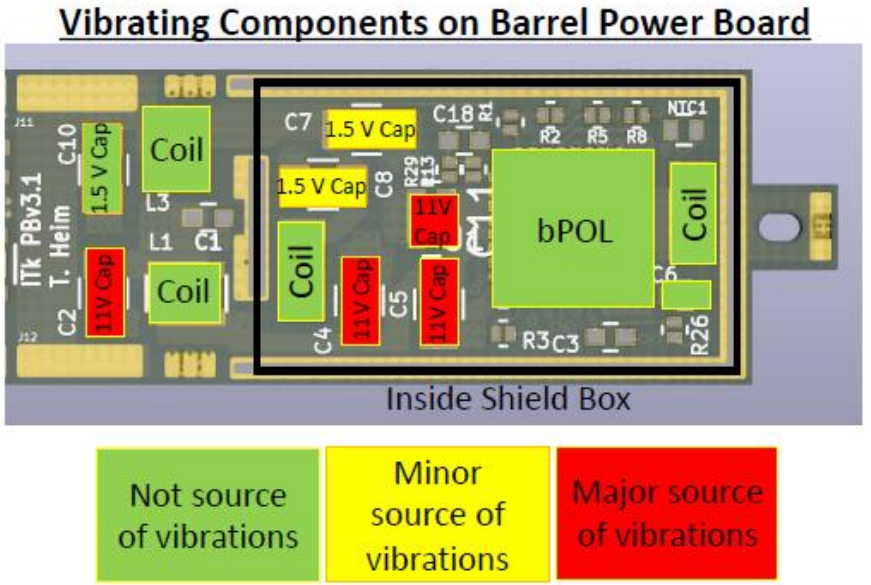
Measuring vibrations

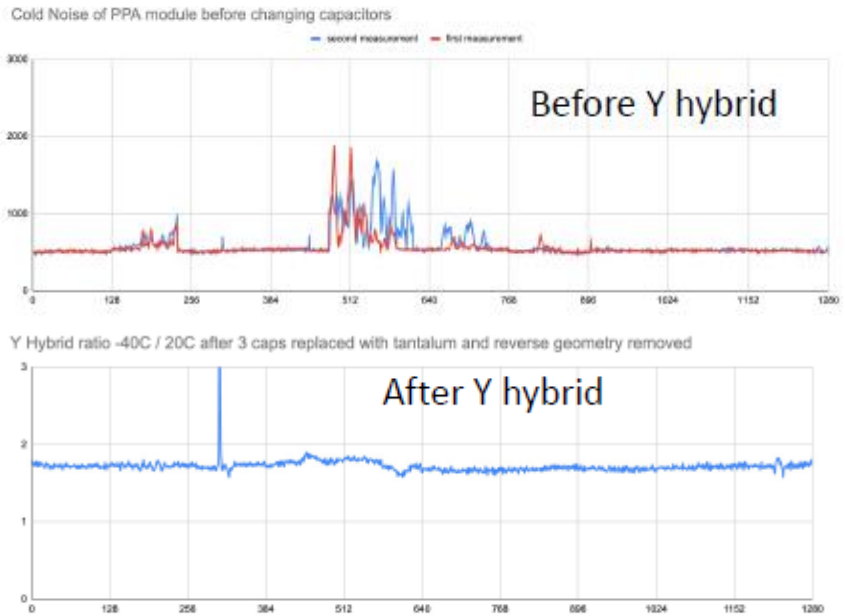
Via laser vibrometer

1-D and 2-D laser vibrometer systems to image power board and sensors

Main findings of 1-D laser vibrometry:

- ❖ **4 capacitors in the power board with relatively large vibrations**
  - 2 nm on 11V caps, 0.2 nm on 1.5 caps
  - 0.02 nm seen on sensor
  - The larger the voltage, the greater the expansion/contraction
- ❖ Capacitors are made with Barium Titanate (BaTiO3), which have a known piezoelectric effect → If AC voltage applied, they vibrate
  - Electro-mechanical vibration in the MHz range was unanticipated
- ❖ Replacing 11 V caps with tantalum caps removes cold noise
  - Helped in insulating the source of CN, but Ta caps are not viable for operation
    - Rad tolerance, reliability, capacitance/size ratio requirements
- ❖ Replacing barrel caps with EC power board caps had no impact
  - Both types are BaTiO3





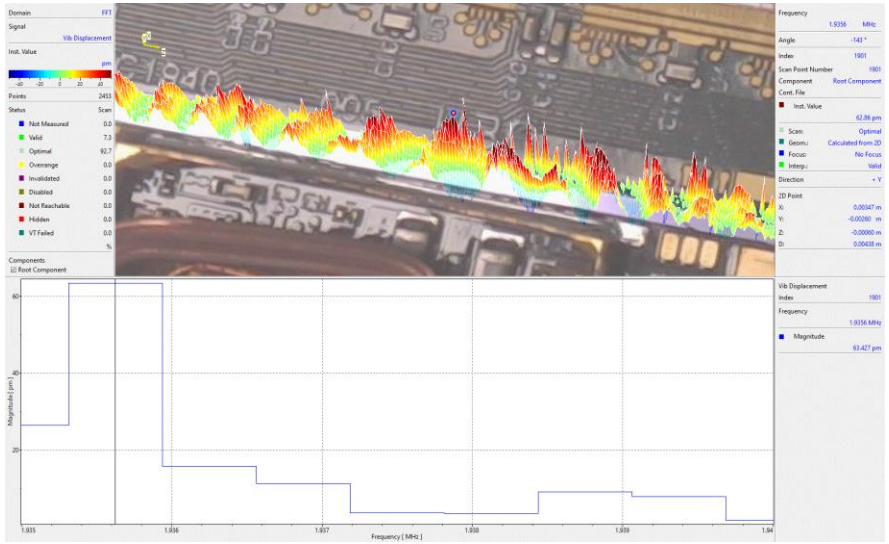
Measuring vibrations

Via laser vibrometer

Most consistent response on reflective surfaces

2-D measurements:

- ❖ Multiple images of the area of the sensor between the hybrid and the power board
  - Vibrations pass to the glues and then propagates through the sensor
  - Oscillations of ~ 100 pm
  - Magnetic triggering first saw this pattern:
    - Both show a wavelength of about 1.3 mm propagating at the speed of sound



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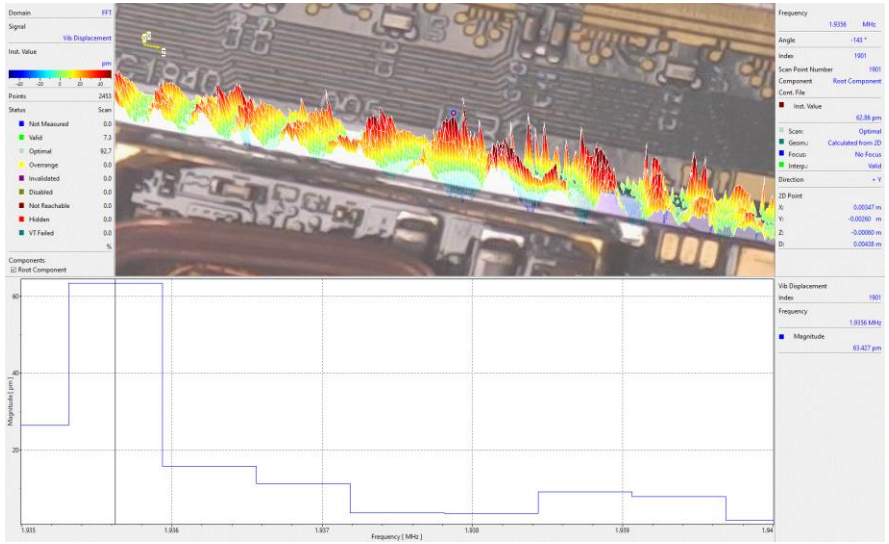
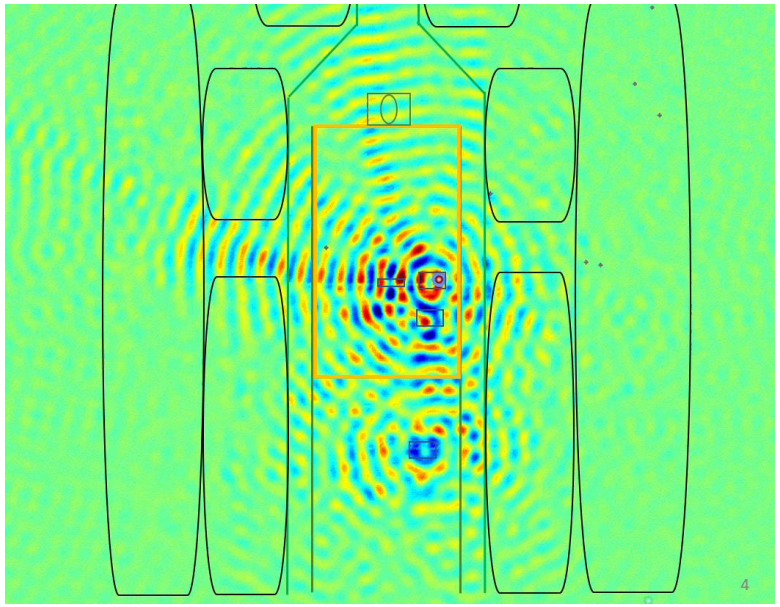
  - Magnetic triggering first saw this pattern:
    - Both show a wavelength of about 1.3 mm propagating at the speed of sound
- ❖ Images of the sensor backside
  - Interference pattern
  - The waves can be seen to be dampened by the glue pattern
  - Evidence of the wave dissipating as it reached the edge of the hybrid glue





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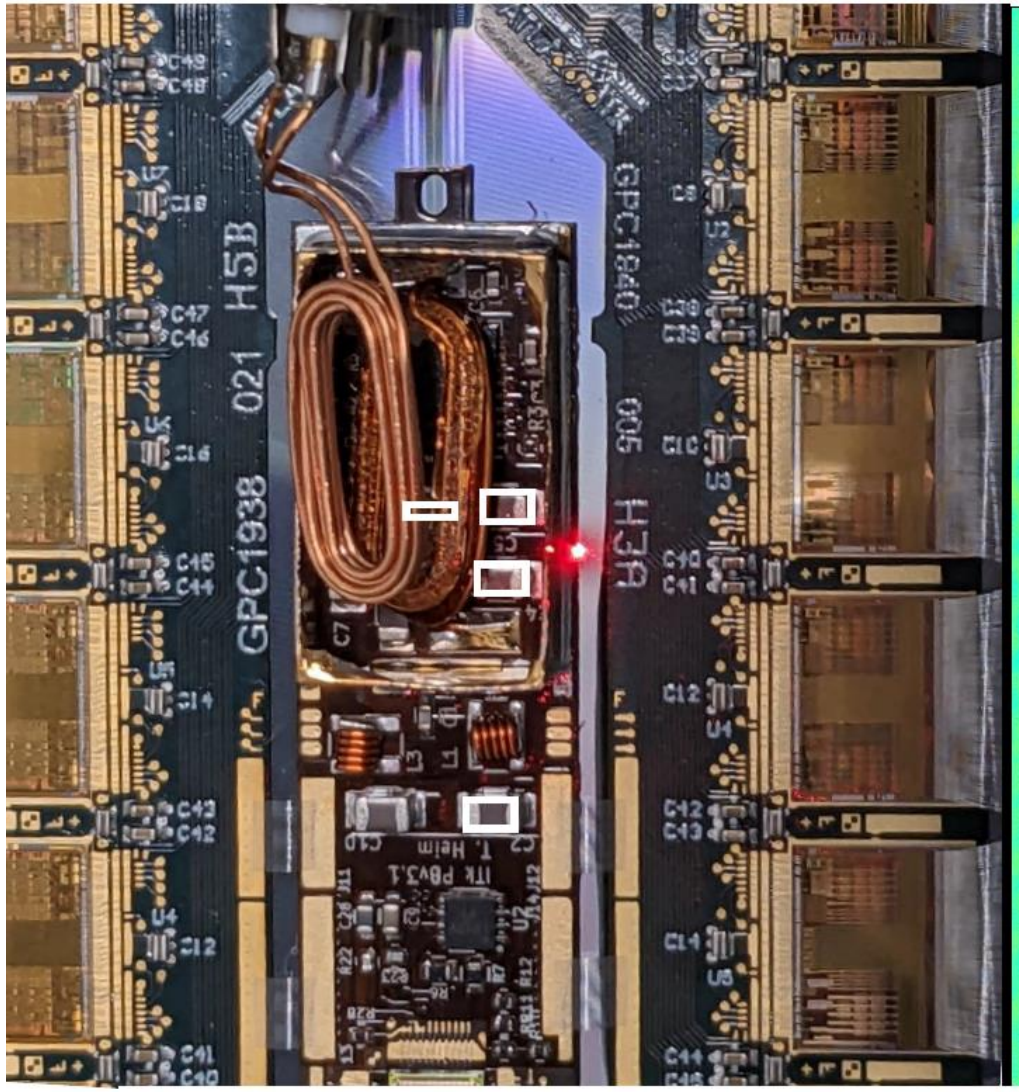
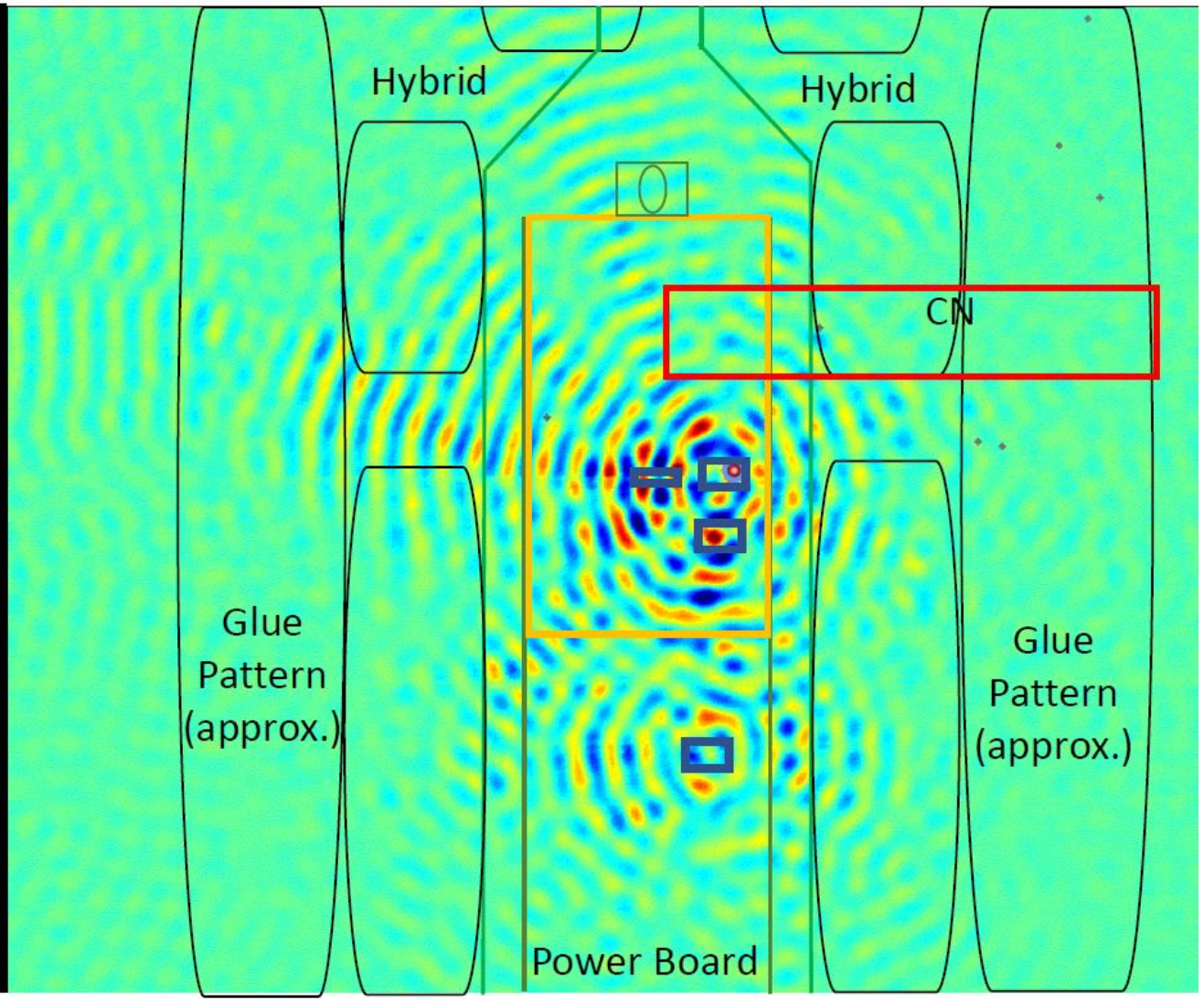
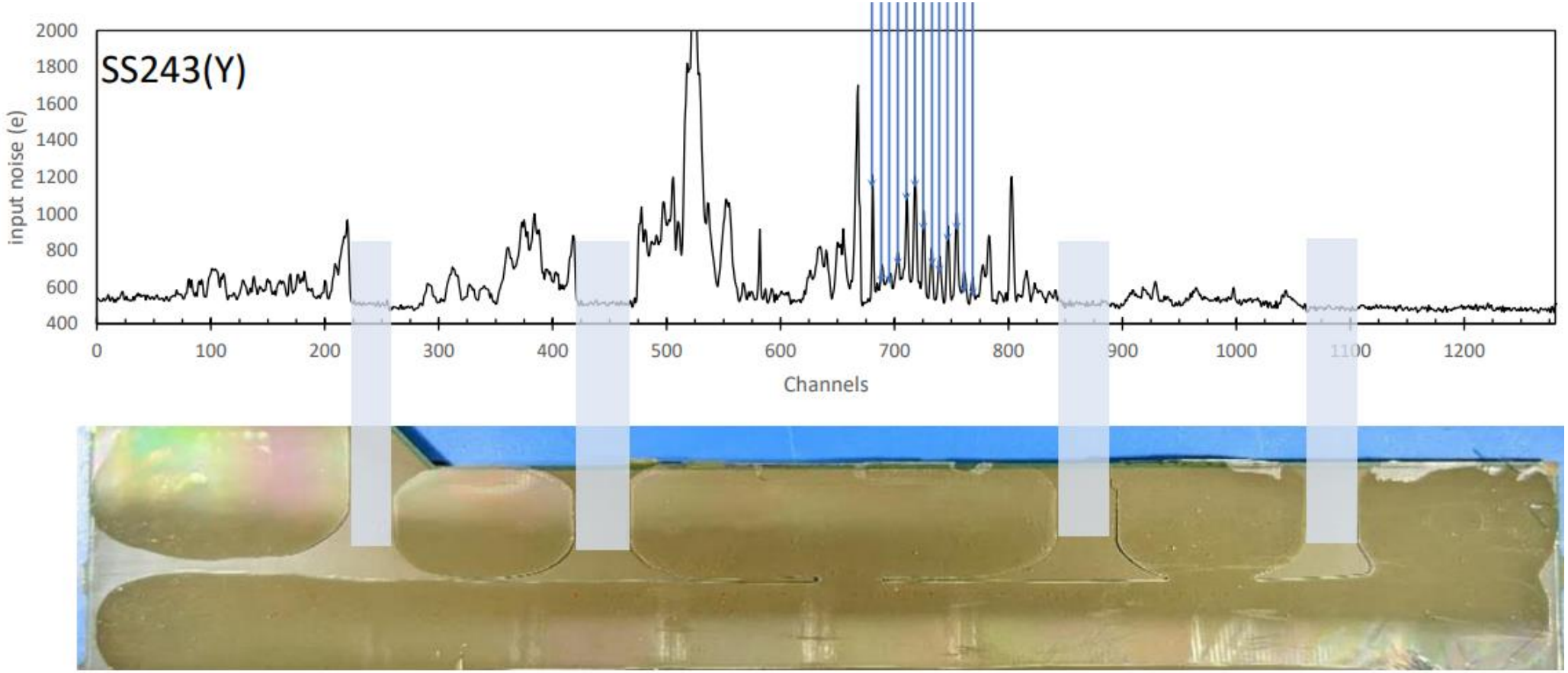




Effect of glue dampening

Another visualization



Temperature effect

How about the “cold” part on cold noise?

Excellent question!

- The vibrations of the capacitors are largely unchanged with temperature
- The size of the vibration in the sensors appears unchanged with temperature

What is left is the **mechanism of the coupling of the vibration into electrical signal in the sensor**

- Thickening glue layer reduces cold noise, but not clear how
- The glue choice impacts the amount of cold noise, but not clear why

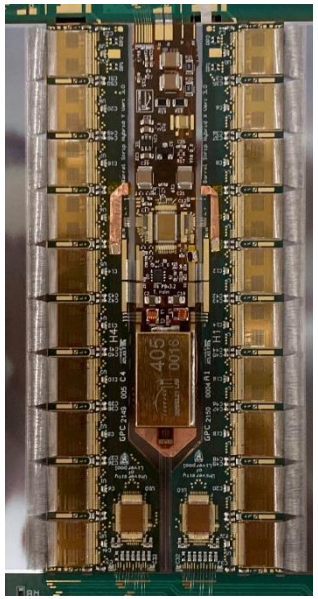
This is still an ongoing investigation in multiple directions: understanding the translation of vibration to electrical signal and how it changes with temperature

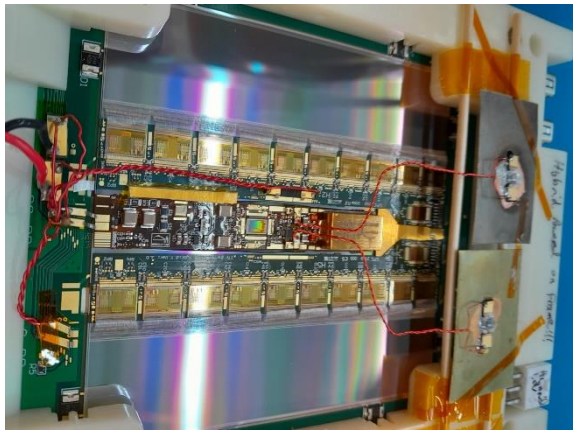
- Studies of vibration with temperature, glue properties, …

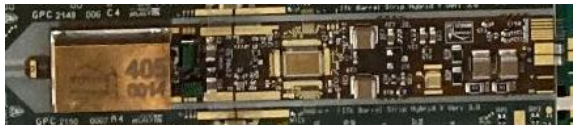
Many other tests that did not work

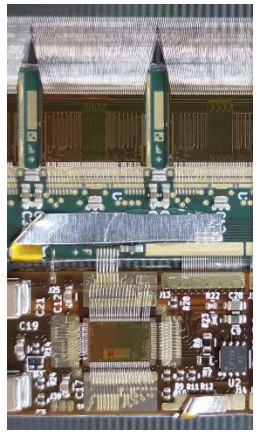
Torturing modules

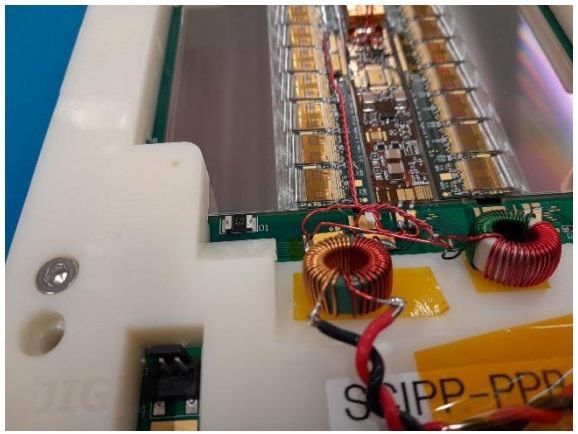
- Added ceramic stiffeners under hybrids/power boards
- Added additional copper and Al shielding under hybrids and/or power boards
- Added Kapton spacers
- Modified pi-filtering
  - Changing capacitors/inductor
- Added chokes in power connections between power board and hybrids
- Alternative shield materials











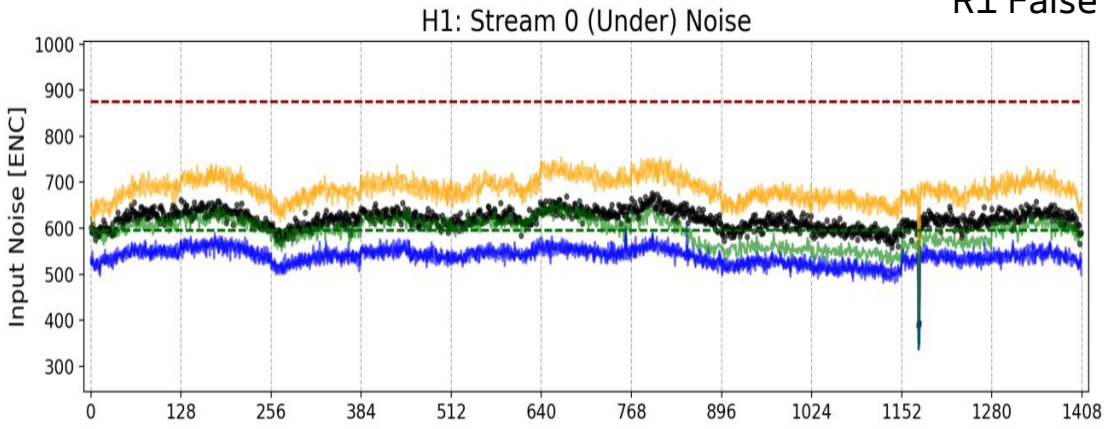
End-cap modules

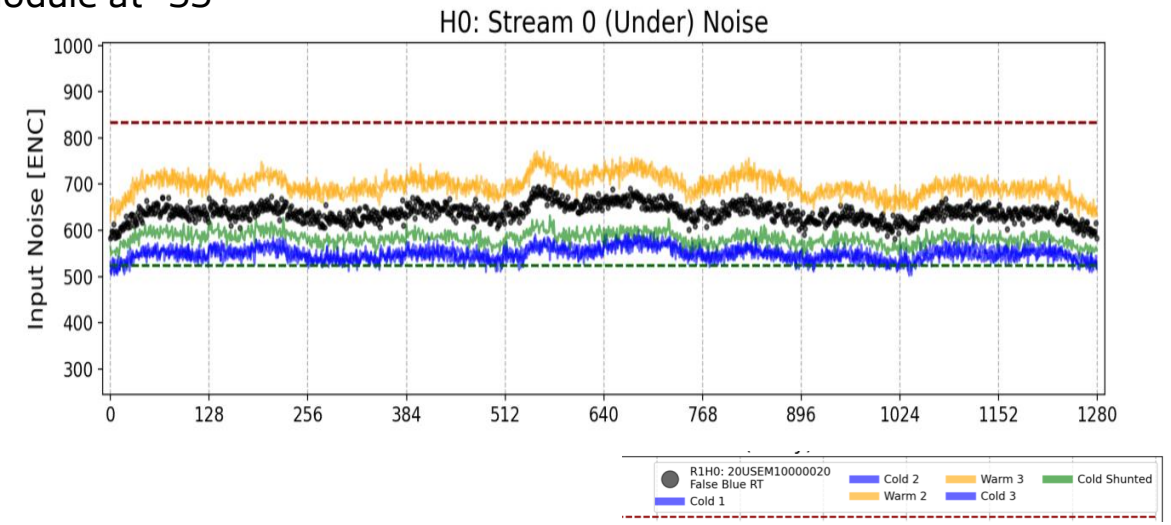
No cold noise!

The final version of the end-cap power boards shows no cold noise on any of the module types tested so far (R0, R1, R4, R5)

Remember: they use the same capacitors as the barrel power boards

R1 False Blue module at -35





Back to laser vibrometry

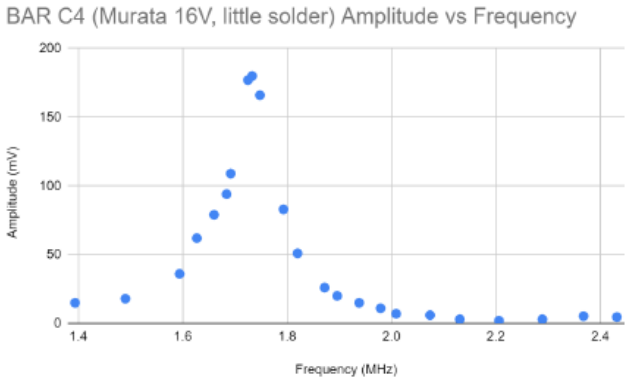
On EC modules

Way less vibration with EC power boards for the same capacitors and similar power draw

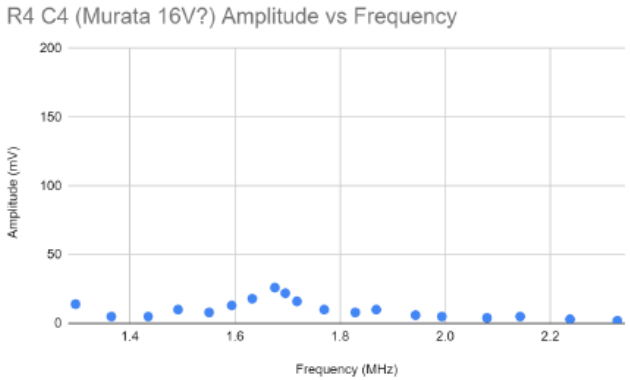
- 10x vibration amplitude for barrel vs EC modules

Cold noise differences are consistent with vibration differences

barrel



end-cap



Back to laser vibrometry

On EC modules

Way less vibration with EC power boards for the same capacitors and similar power draw

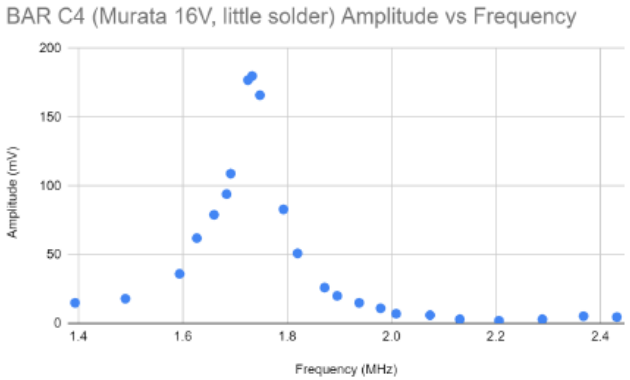
- 10x vibration amplitude for barrel vs EC modules

Cold noise differences are consistent with vibration differences

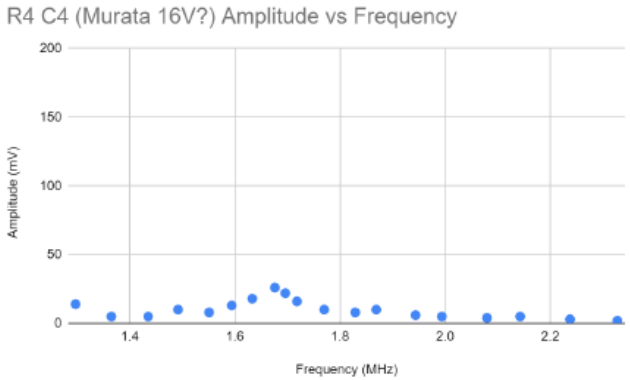
Looking for differences between barrel and EC power board substrates

- Barrel board thicker and stiffer
- Epoxy (barrel) vs. Acrylic (EC) adhesive
- Stacked vias (barrel) vs. staggered vias (EC)

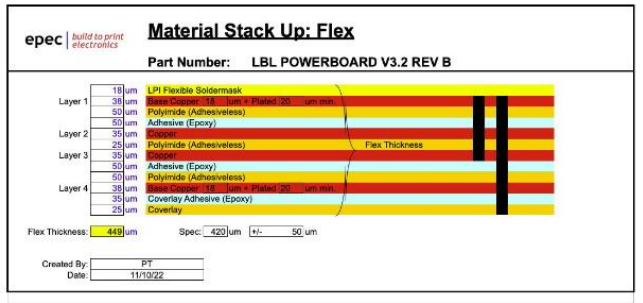
barrel



end-cap



Barrel



Endcap

Layer	Material	Stack-up, thickness	finished thickness
Solder Mask	PSR-9000AC/CA-90AC	SM 25µm	20 µm
Top	Dupont Pyralux AC	(Cu 18µm + Cu Plating) + 25µm PI	50 µm
	Pyralux LF0100	25µm Sheet Adhesive	10 µm
Inner 1 & 2	DuPont Pyralux AP	(Cu:18µm + Plating) + PI:50µm + (Cu:18µm + Plating)	100 µm
	Pyralux LF0100	25µm Sheet Adhesive	10 µm
Bottom	Dupont Pyralux AC	(Cu 18µm + Cu Plating) + 25µm PI	50 µm
PI Coverlay	Pyralux LF Coverlay LF0110	50µm (PI:25µm + Ad:25µm)	35 µm
Solder Mask	PSR-9000AC/CA-90AC	SM 25µm	20 µm
		Board thickness (±20%)	295 µm

Geometry dependency

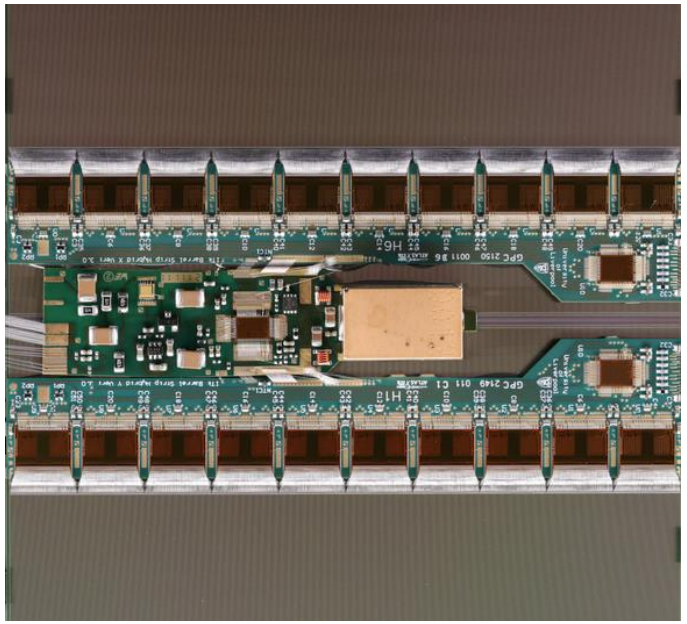
Mixing up module components

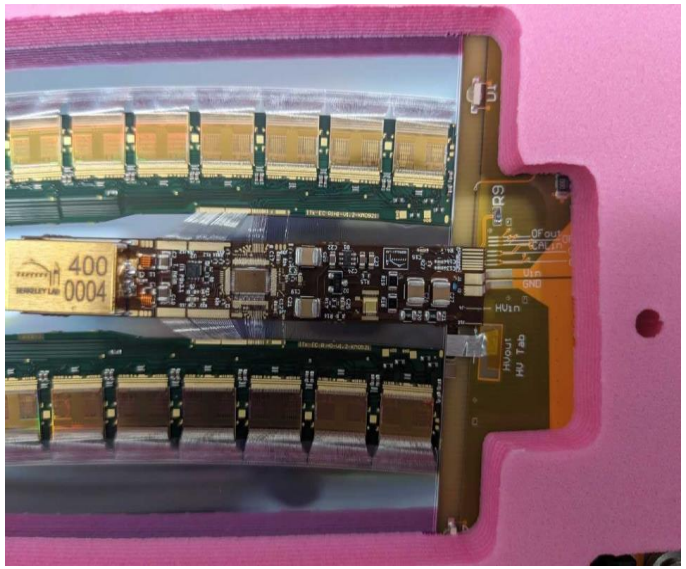
In order to further isolate module geometry from power board substrate manufacturer/layout:

- EC R1 module with barrel power board
- Barrel short strip module with R1 power board

No cold noise in barrel short strip module, cold noise in EC R1 module

- More indications that support the hypothesis that vibration of the capacitors in the barrel power board is the source of cold noise





	Short strip module	R1 module
Barrel power board	Lots of cold noise (FB)	Cold noise (Polaris)
R1 power board	No cold noise (FB)	No cold noise (FB)

Prototype vs. pre-production results

One last question…

5 short strip modules were tested cold in late 2019 and had no CN

- We should expect CN for those… but PB version was different
- Sensor passivation layer changed as well

New module with pre-production parts and old (ATLAS-12) sensor

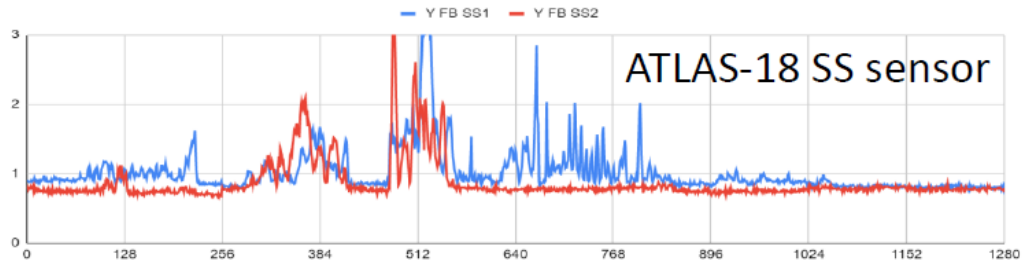
- Used false blue glue to increase CN
- Only difference is the sensor (ATLAS-12 vs. ATLAS-18)
- **Cold noise dramatically reduced**, but still non-zero

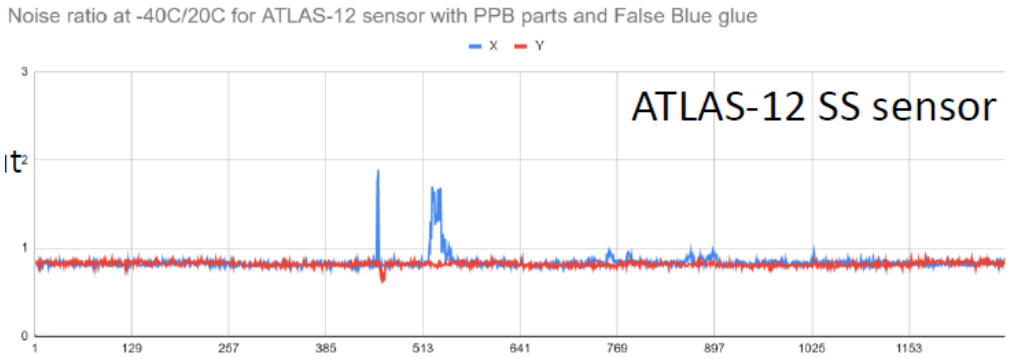
There is a connection between passivation layer and CN

Passivation layer not something that can be changed now, but helps understand why we did not see CN in earlier prototypes

- Really helped in not losing our minds!

Hint?: Silicon Nitride added to ATLAS-18 → piezoelectric, yet amorphous





In summary

Cold noise is driven by the vibration of capacitors on the power boards

It causes vibration on the sensor which injects noise at the regions in which the hybrids are glued

- Translation of vibration to noise believed to be a piezo-electric effect but it is not understood completely

EC modules do not exhibit cold noise

The task force allowed us to discover several mitigation techniques and a path forward for barrel production

- Usage of True Blue, thicker glue layers, power board flex changes

Future ongoing studies

- Reliability with known vibration studies
- Confirm cold noise not influenced by external magnetic field
- Of critical importance is to learn the results from a barrel power board designed at EC vendor with same EC materials
  - Ongoing, results imminent!

In summary

Cold noise is driven by the vibration of capacitors on the power boards

It causes vibration on the sensor which injects noise at the regions in which the hybrids are glued

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EC modules do not exhibit cold noise

The task force allo roduction

- Usage of True

An obvious lesson to learn here: **extensive prototyping is absolutely essential**, even if only minor changes are applied

Future ongoing studies

- Reliability with known vibration studies
- Confirm cold noise not influenced by external magnetic field
- Of critical importance is to learn the results from a barrel power board designed at EC vendor with same EC materials
  - Ongoing, results imminent!

Thank you

Impact of cold noise

As first measured, cold noise would cause most short strip and some long strip modules to fail specifications

- 2% bad channels
- >= 8 consecutive bad channels