How the discovery of Cold Noise delayed the production of ATLAS ITk strip tracker modules by a year

Ian Dyckes[1] and Matthew Kurth[2] on behalf of the ATLAS Collaboration

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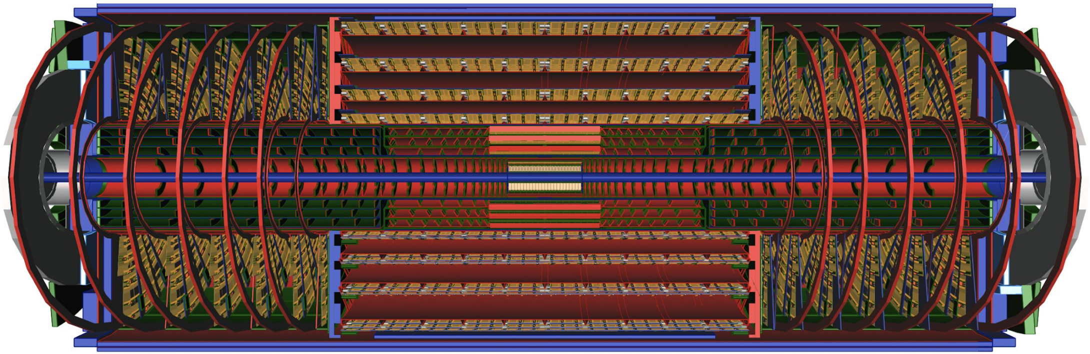
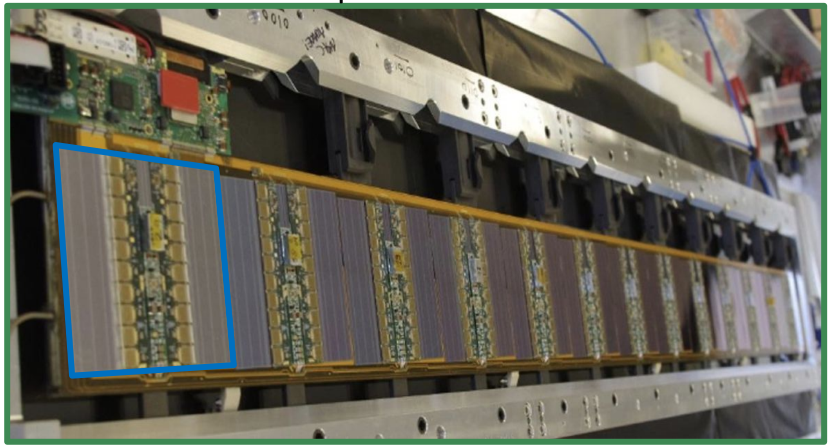
[2]Brookhaven National Laboratory, USA

ITk Strip Detector

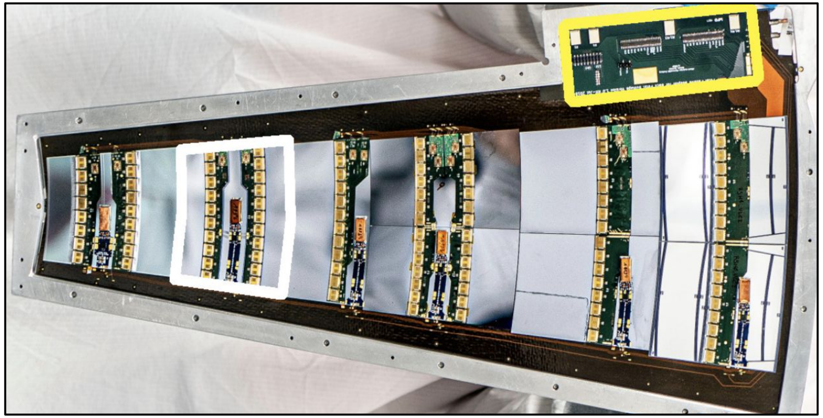
- ATLAS detector is receiving multiple upgrades for the HL-LHC.
  - More interactions per bunch crossing ($\langle \mu \rangle \approx 50 \rightarrow 200$).
  - Higher trigger rate (100 kHz → 1 MHz).
  - Worse radiation damage (up to 2×10^{16} n_{eq}/cm^2).
- Installing new, all silicon Inner Tracker (ITk).
  - Pixel modules for inner layers.
  - Strip modules for outer layers.



Strip Barrel Stave



Strip Endcap Petal



ITk Strip Barrel Module

Silicon sensor:

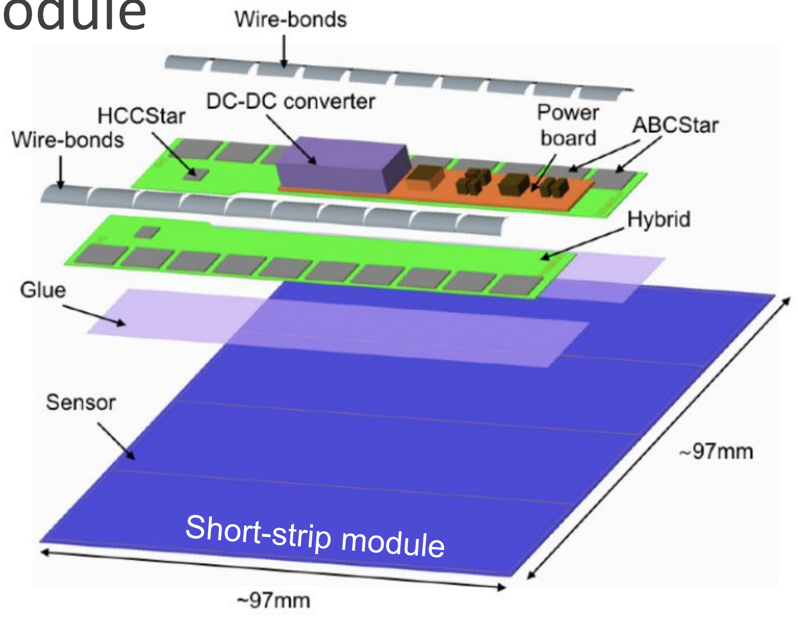
- AC-coupled, n^+-in-p sensor with a 75 µm strip pitch.
  - Long strip sensor → 2 rows, strip length ≈ 5 cm.
  - Short strip sensor → 4 rows, strip length ≈ 2.5 cm.

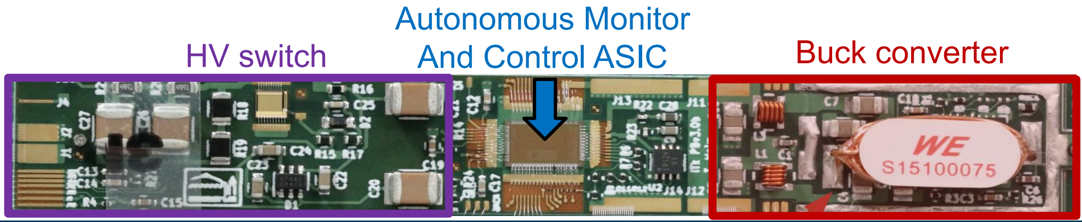
Hybrid:

- Flexible printed circuit board holding readout ASICS.
  - 10 ABCs: amplify and discriminate signal.
  - 1 HCC: interface between ABCs and backend electronics.

Powerboard:

- ASIC power, monitoring & interlock, HV switching for sensor biasing.





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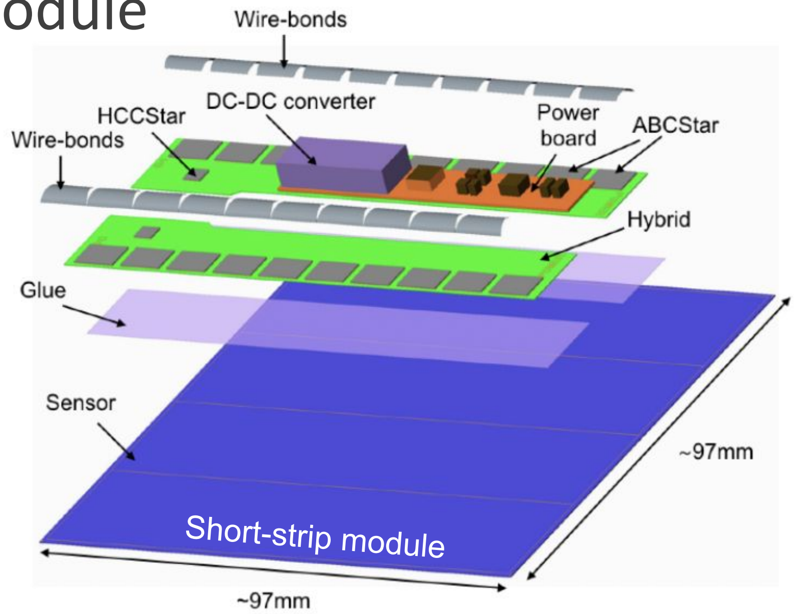

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- Frontend chips require 1.5V, but distribute 11V to modules.
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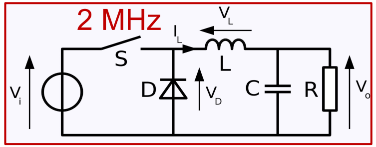
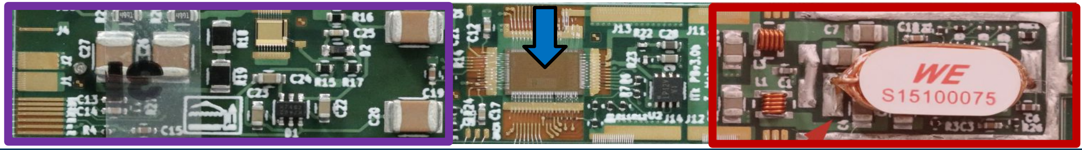
    - Mitigate by aluminum shield box.





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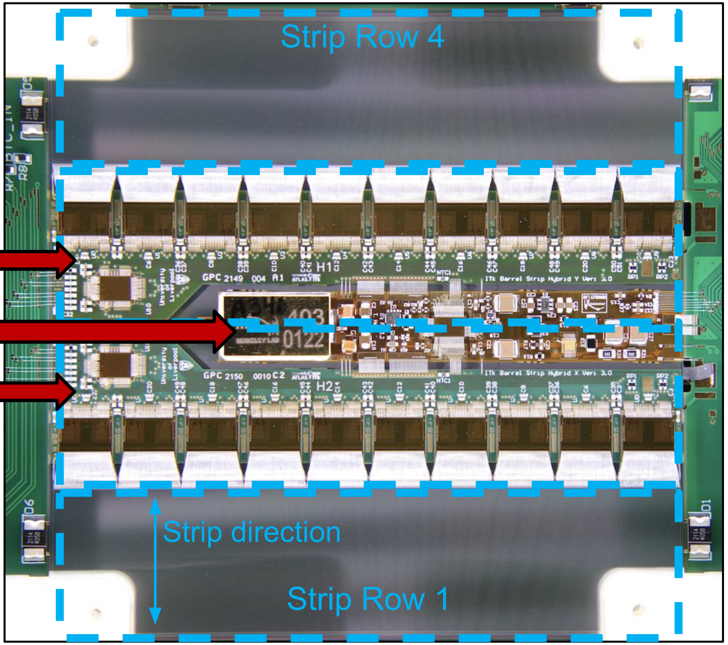
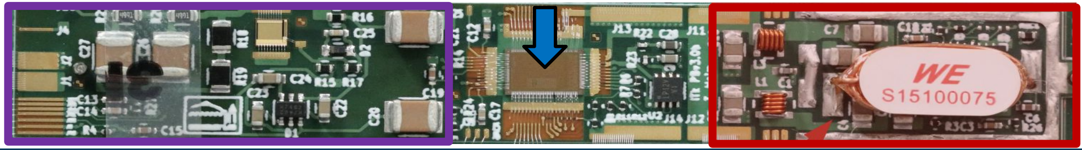


Short-strip module



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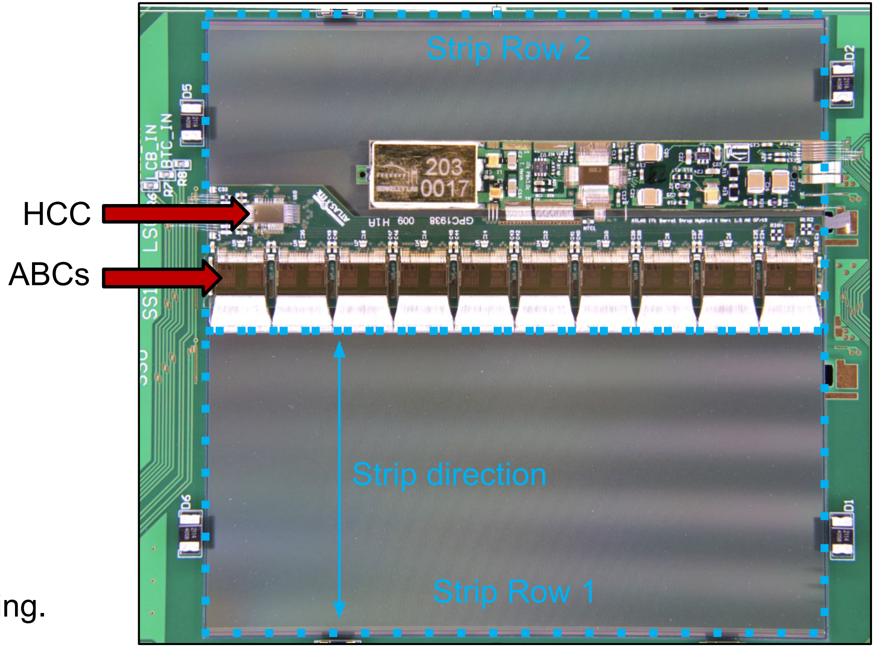
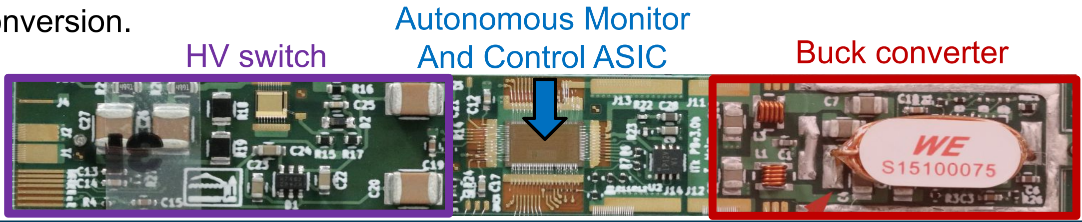


Long-strip module

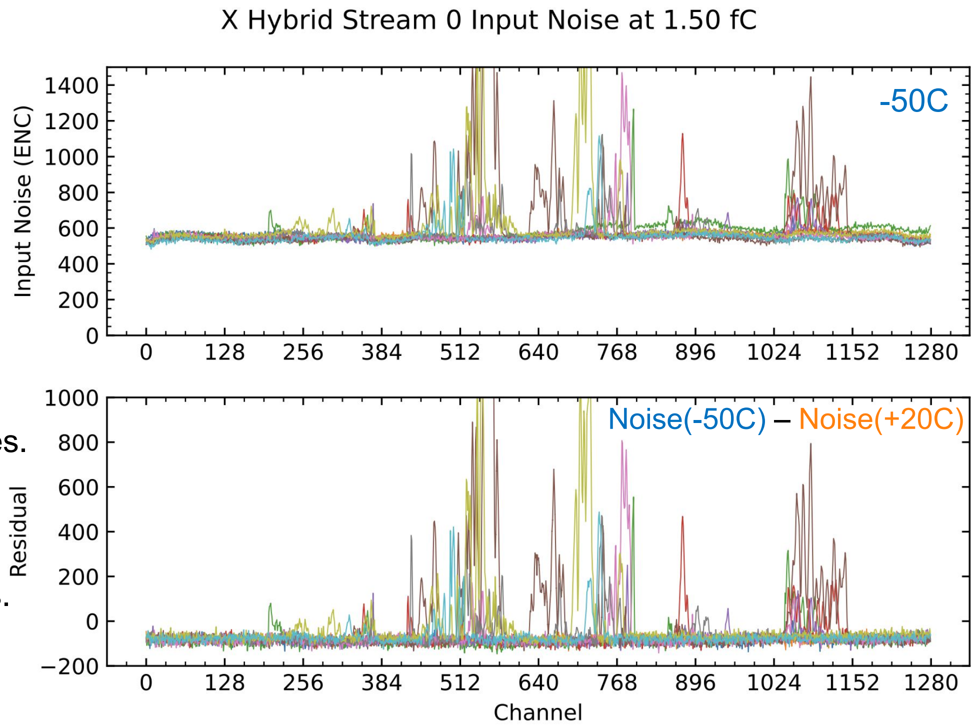


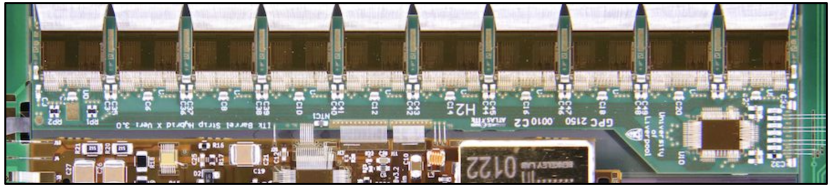
Introduction to cold noise

Cold Noise Intro

Background:

- In early 2022, observed high noise channels appearing when testing modules at cold temperatures.
- Usually disappears upon returning to room temp.
- This "cold noise" is now only seen on barrel modules.
  - Previously observed on older versions of endcap modules.
- Eventually decided to pause pre-production to investigate.
- Inspired a long campaign of custom builds & imaginative tests.
  - Will only highlight a few insightful studies here.

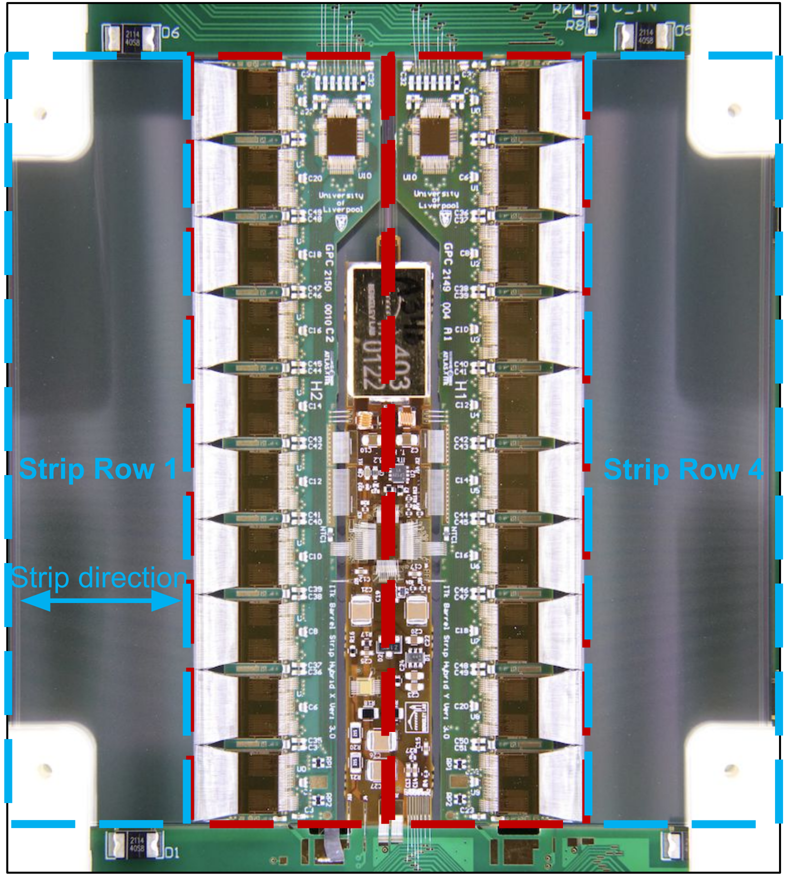




Cold Noise Observations

Early Observations:

- Only appears on the strip rows under the hybrids & PB.



Short-strip module

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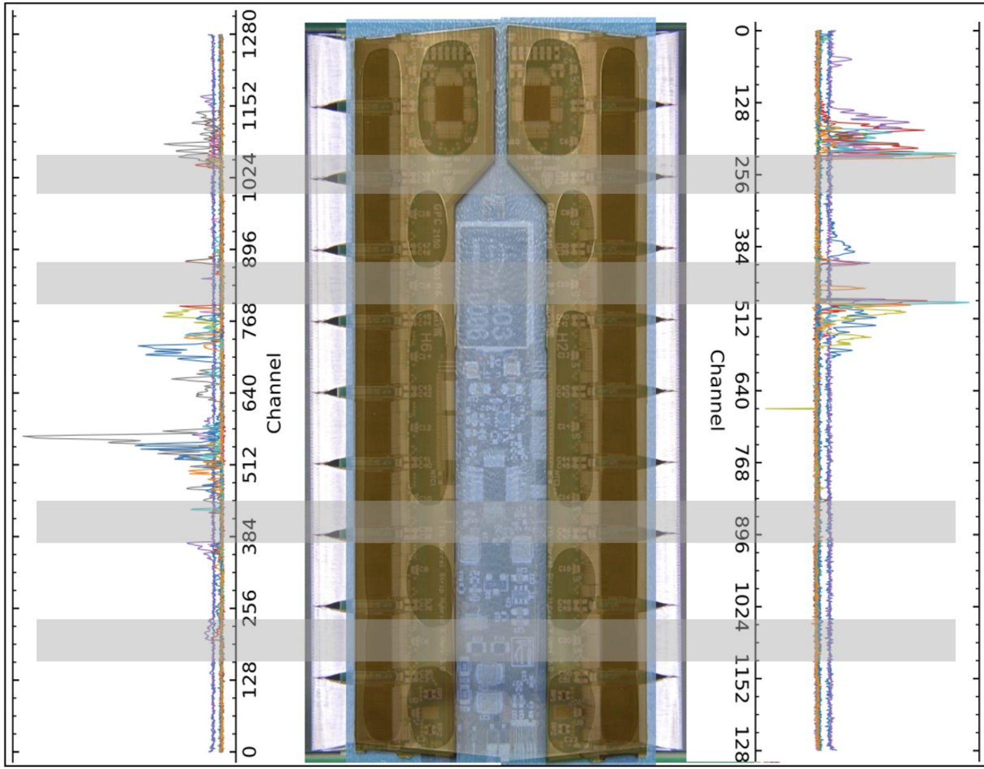

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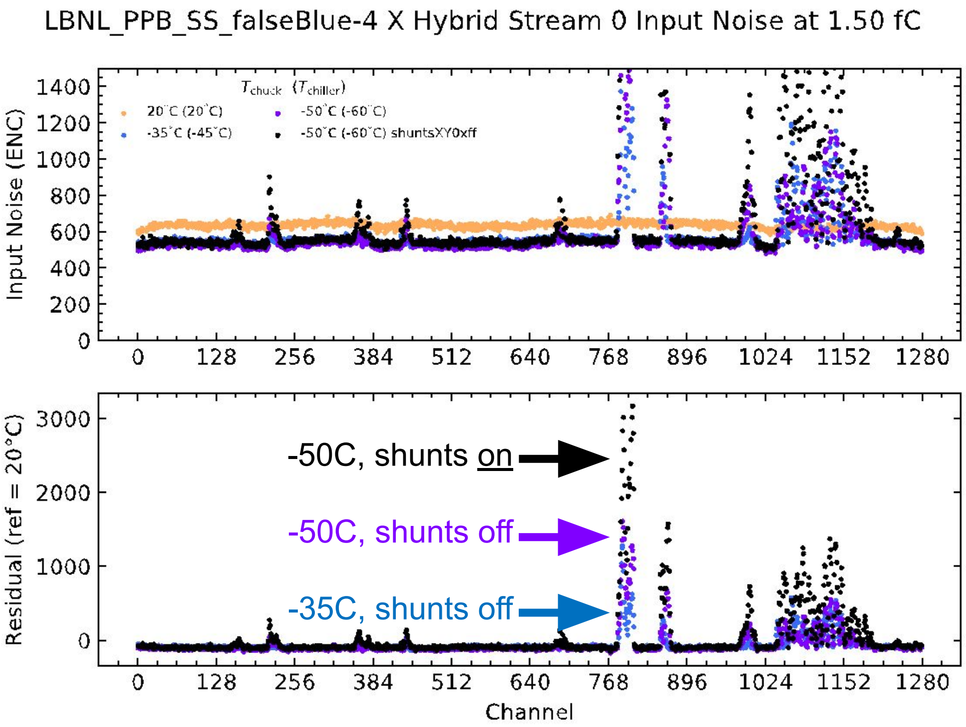

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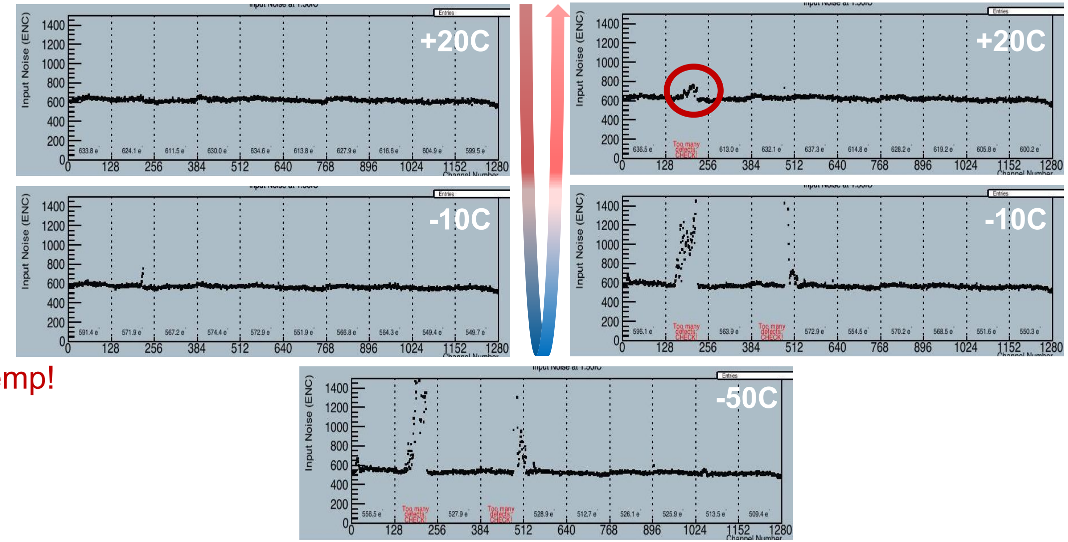
  - Persists while warming.
  - Occasionally have residual “cold” noise at room temp!

1st thermal cycle



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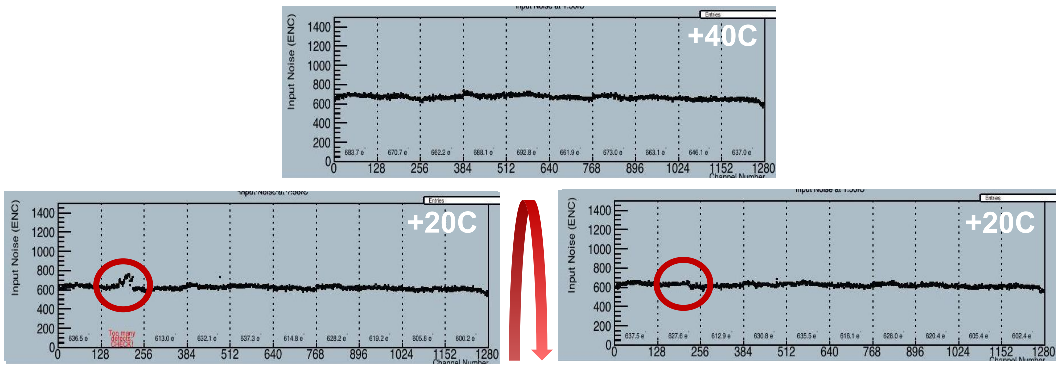
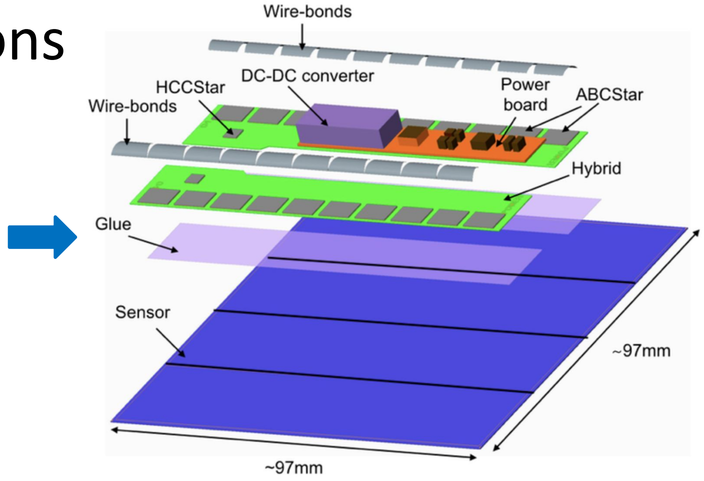


Bake-out

Cold Noise Observations



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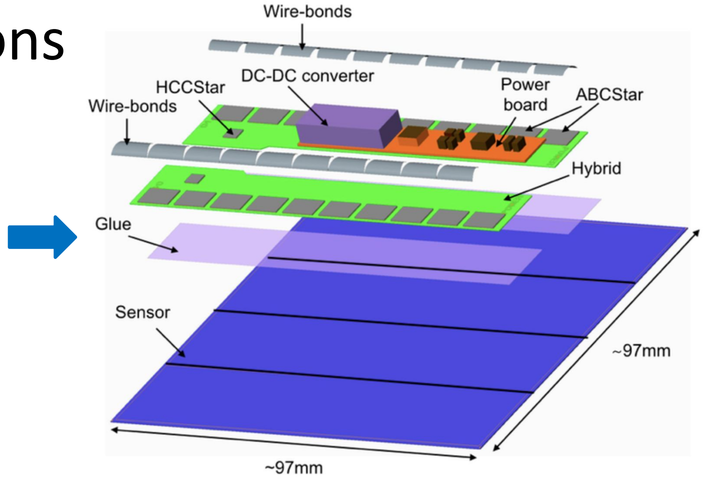
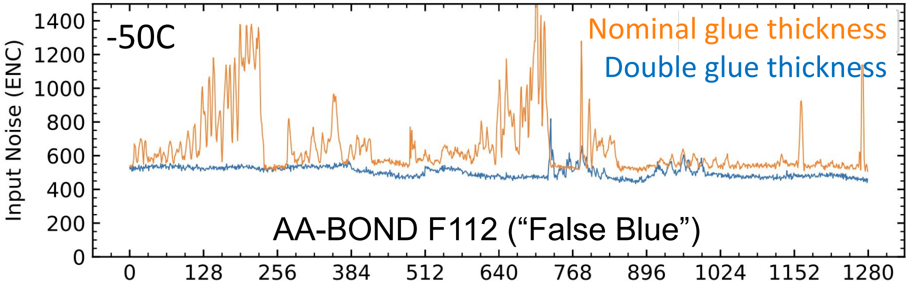
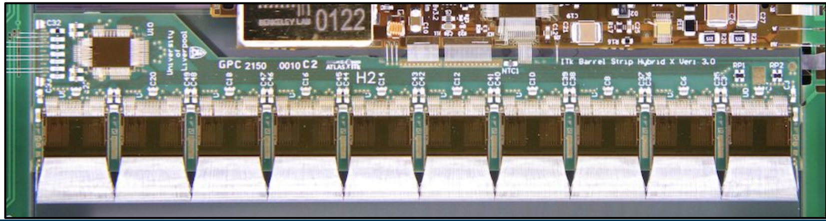
Glue dependence:

- Severity varies greatly among "nearly identical" epoxies.
  - Unable to correlate with any info in data sheets…
- Thicker glue layers under PB and hybrid(s) can reduce CN.
- Softer "glues" (Sylgard encapsulant, SE-4445 gel) remove CN.
  - Only diagnostic, not suitable for detector.





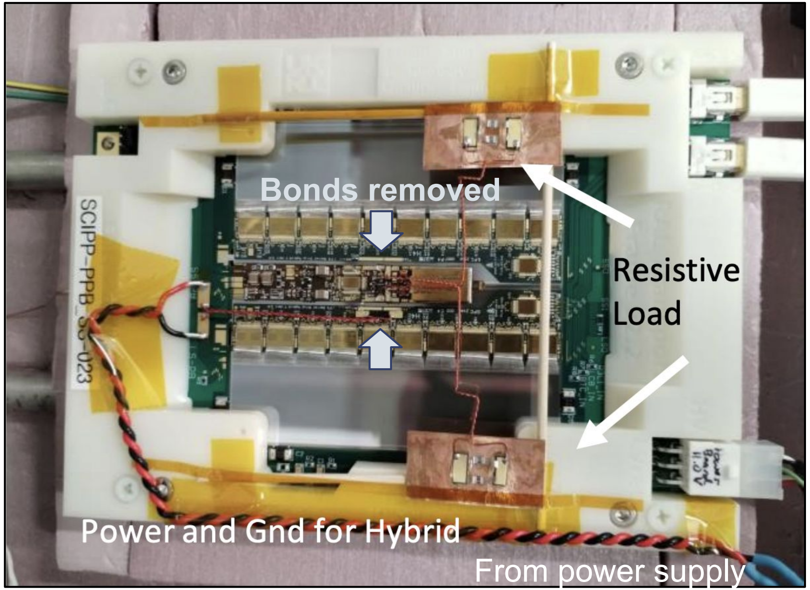


Highlighting the most insightful studies

Bypassed Powerboard

Motivation:

- Is the source of cold noise on the hybrid or powerboard?
- We can factor the two by bypassing the PB for hybrid power.
  - Remove low voltage power bonds between PB & hybrids.
  - Power hybrids directly with power supply.



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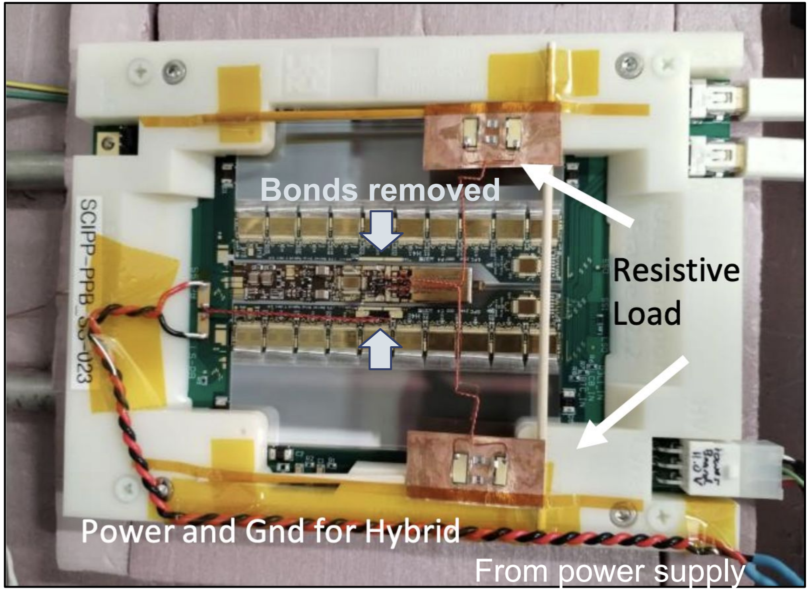

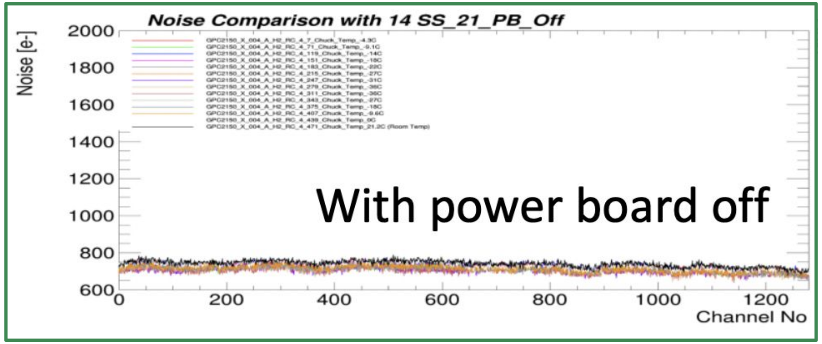

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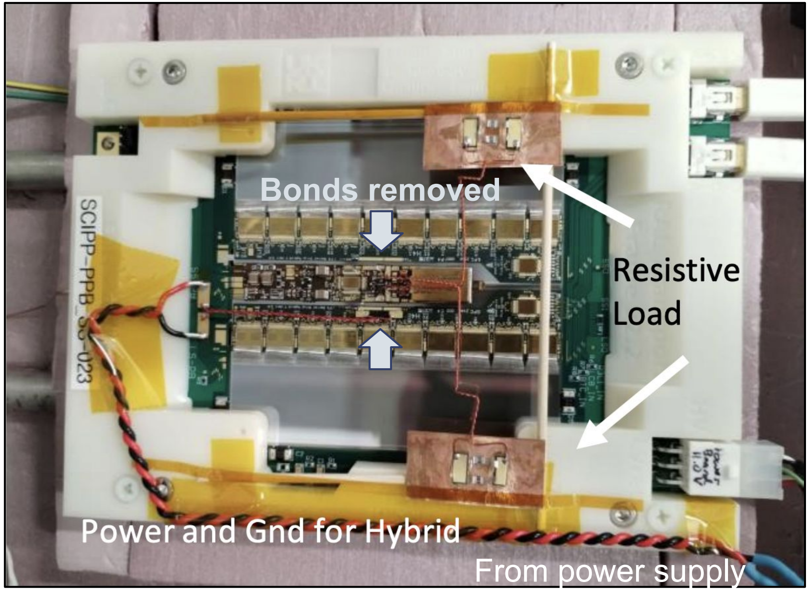

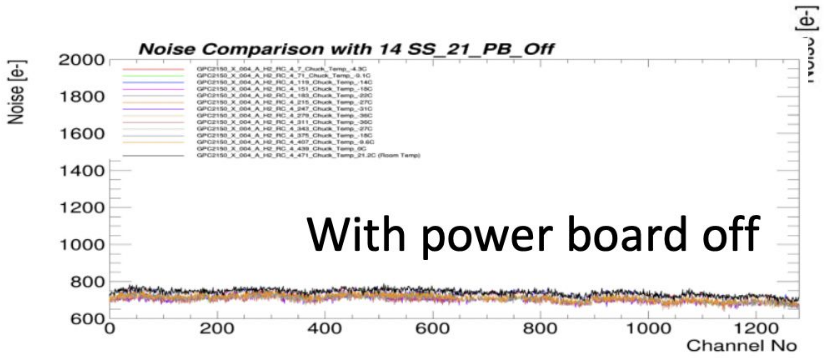

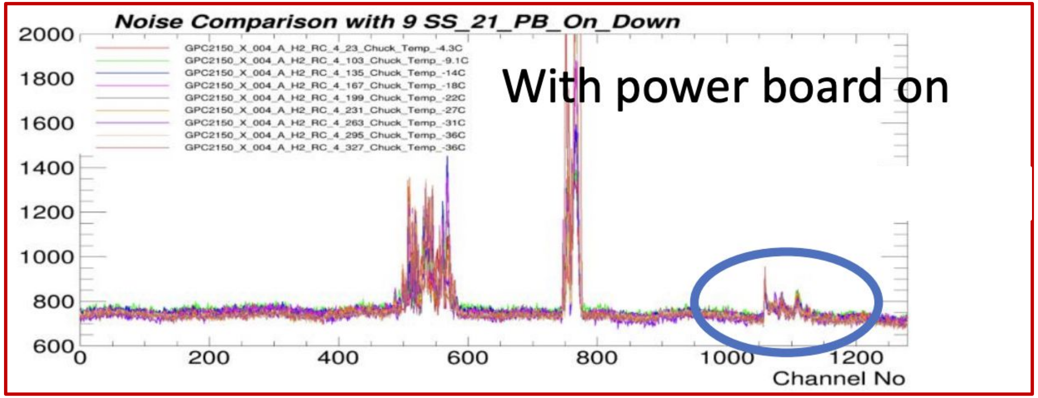

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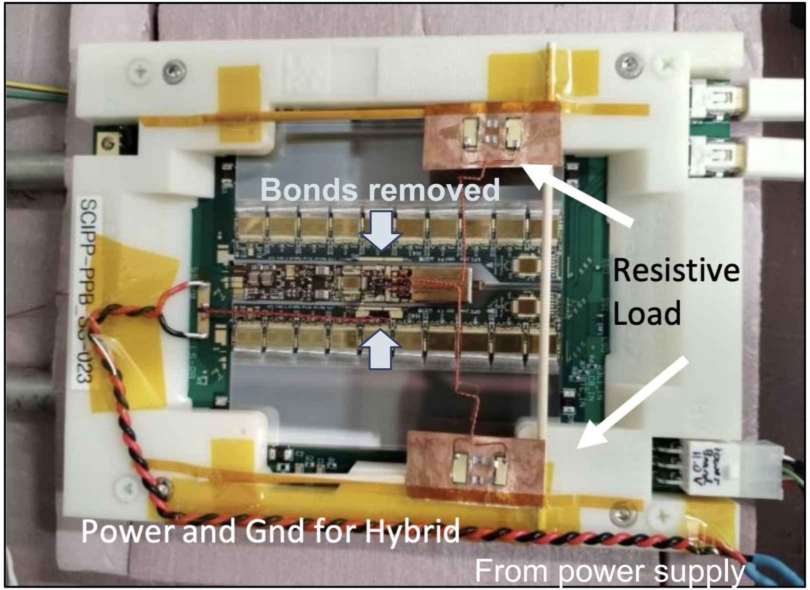
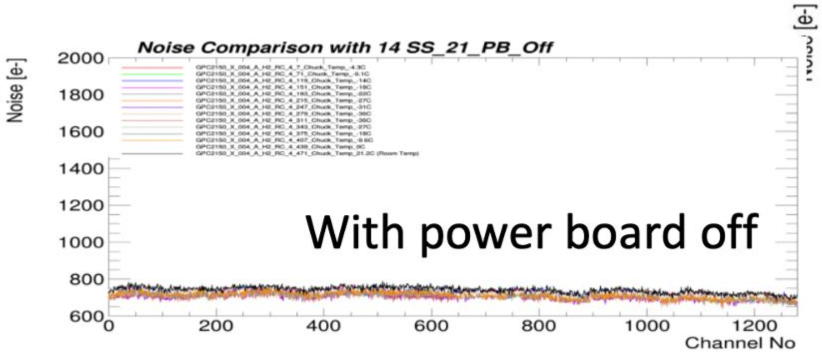
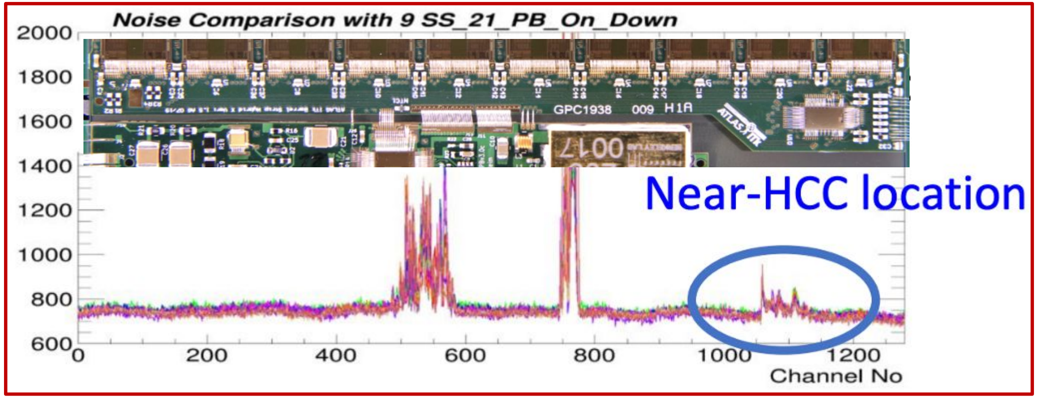
3. PB on with resistive load on DC-DC emulating hybrids → cold noise!
   - Even appears near HCC, far from PB!



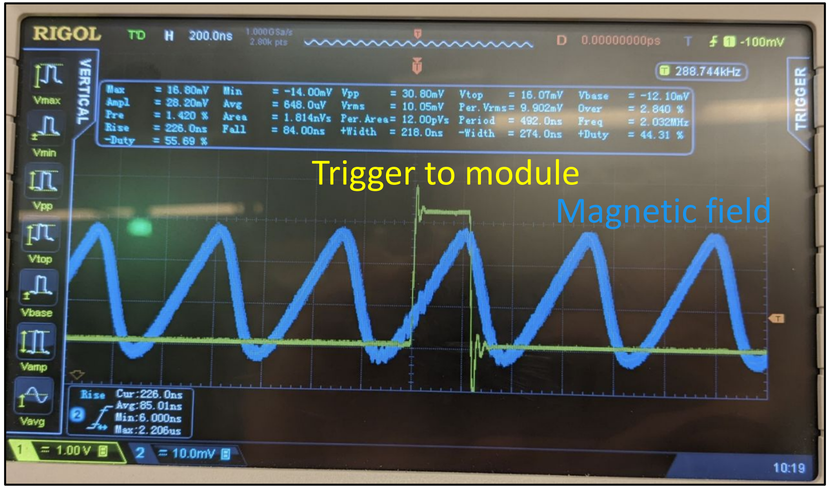




DCDC-Synchronous Triggering

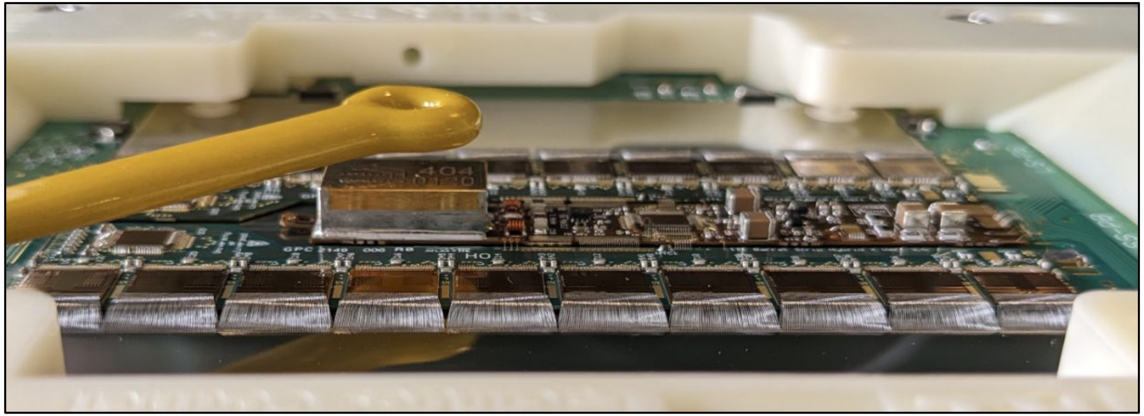
Motivation:

- DC-DC on powerboard switches at 2 MHz → measurable EMI.
  - Mitigated by shield box.
- PB appears to be (at least partially) responsible for CN.
  - Perhaps CN is somehow related to the DC-DC switching?



Setup:

- Place a magnetic field probe over PB shield box → 2 MHz signal.
- Use magnetic field to trigger module readout.
  - Scan over the trigger delay → noise occupancy vs DC-DC phase.
- Perform on warm and cold modules.

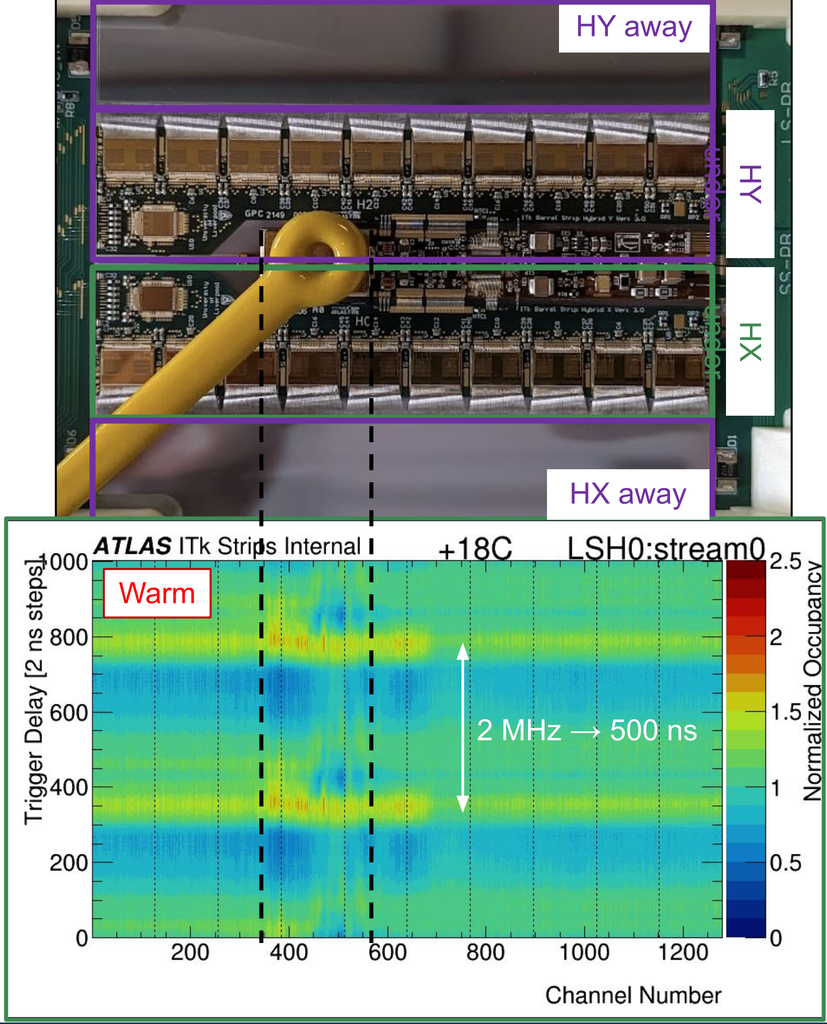


DCDC-Synchronous Triggering

Warm Results:

- Showing occupancy of each channel vs trigger delay [ns].
  - Focusing on row of strips under PB & X-hybrid.

- As expected, observe:
  - Higher noise on strips near DC-DC.
  - Higher noise when in phase with DC-DC.
    → Horizontal bars spaced by 500ns.



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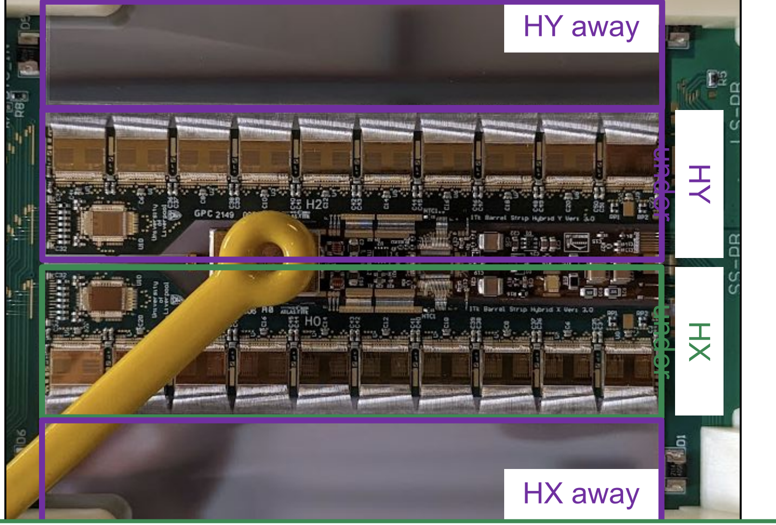
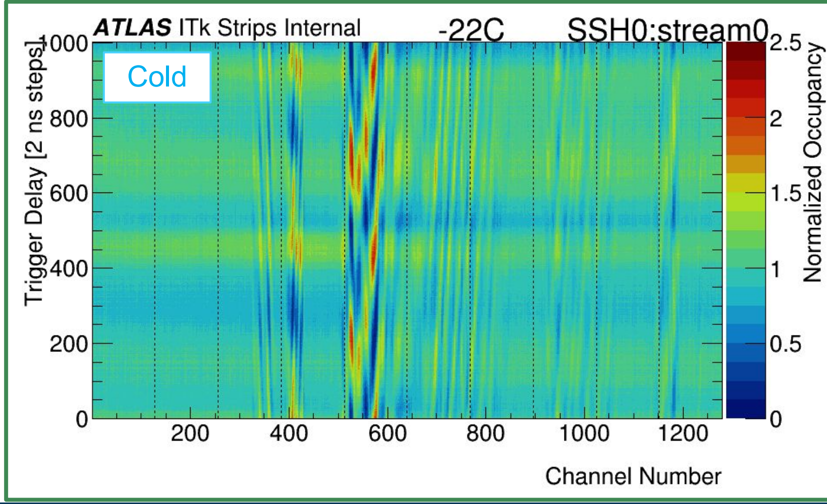


Cold Results:

- In addition to the expected effects, see diagonal bands.
  - Coincide with channels exhibiting cold noise!
- Looks like a wave of noise is traveling across sensor!
- Is something vibrating on the powerboard?
  - At DC-DC switching frequency (2 MHz)?
- Is a mechanical wave coupling into sensor & traveling?
  - If so, what are its properties?

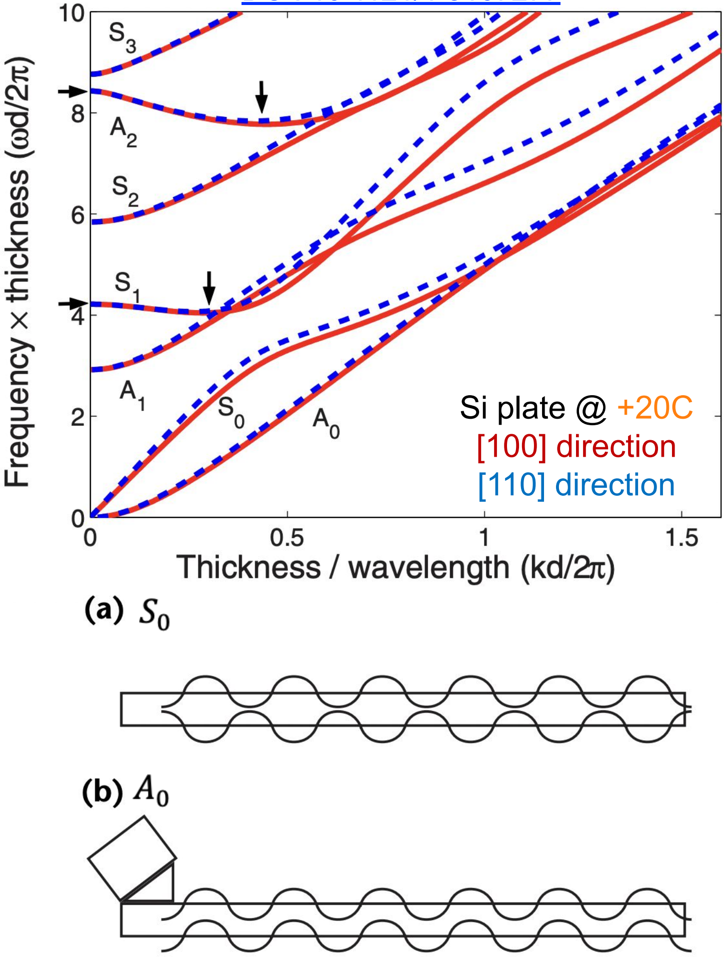


Lamb Waves

Brief Introduction:

- Sinusoidal solutions to wave equation in flat plates.
  - Family of symmetric (S_n) and anti-symmetric (A_n) solutions.
- Only S_0 and A_0 at low frequencies.
  - Higher order modes have cut-off frequencies $\gtrsim$ 10 MHz.
  - S_0 and A_0 most important when $\lambda \gg$ plate thickness.
- Suspect we are seeing A_0.
  - A_0 (flexural mode) → particles move perpendicular to sensor plane.
  - S_0 (extensional mode) → particles move parallel to plane.

DOI: 10.1121/1.3167277



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  - A_0 (flexural mode) → particles move perpendicular to sensor plane.
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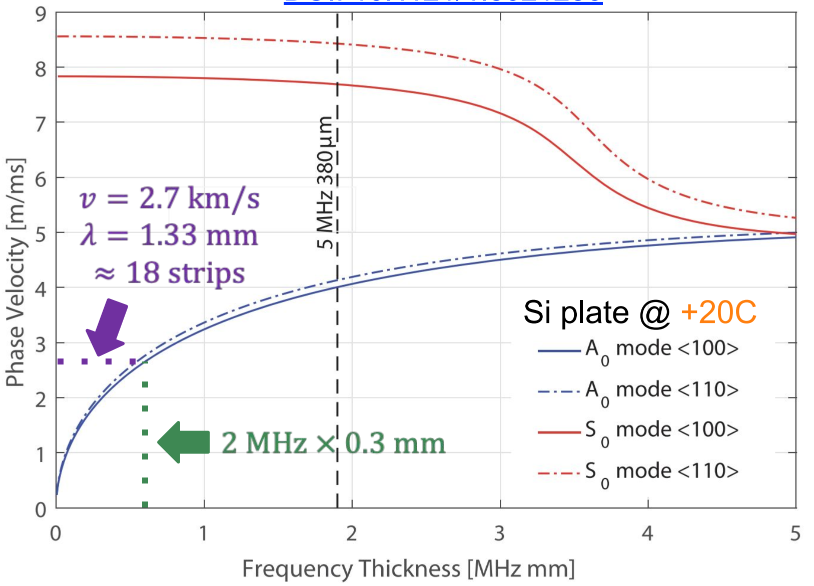
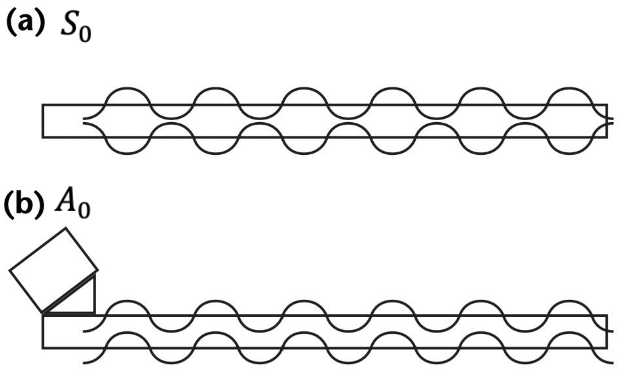
Plugging in some numbers:
- $f_{\mathrm{DCDC}} = 2\ \mathrm{MHz},\ \mathrm{thickness} = 0.3\ \mathrm{mm}$ → $v = 2.7\frac{\mathrm{km}}{\mathrm{s}}, \lambda = 18\ \mathrm{strips}$.

- Does this agree with our data?

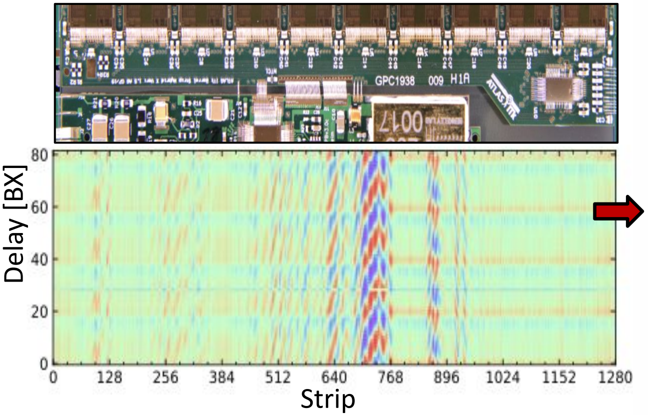




NB: dispersion plots here are for simple silicon wafers at +20C.

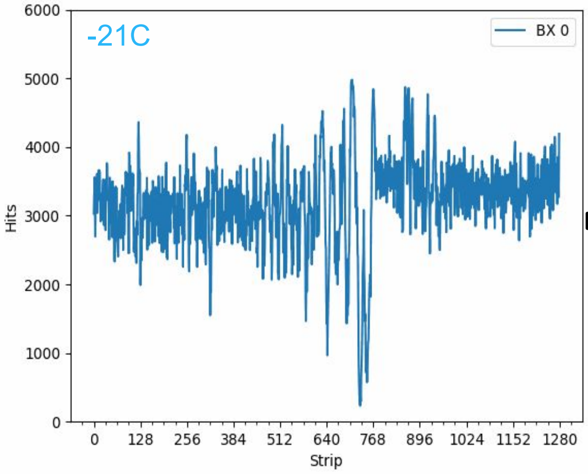
DCDC-Synchronous Triggering (Revisited)

Channel Occupancy vs Delay

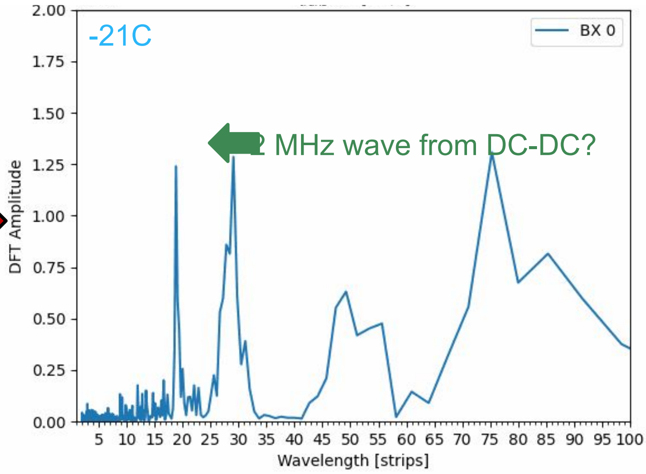


T_{DCDC} = 500 ns = 20 BX

Hits per 10k Triggers



Power Spectrum



- Calculated power spectrum for every step in a delay scan (step size = 1 LHC bunch crossing = 25 ns).

- Suspect something is vibrating at the DC-DC switching frequency, $f_{DCDC} \approx 2$ MHz.
  - Dispersion plot (at +20C) → $v \approx 2.7$ km/s, $\lambda \approx 18$ strips.
  - See a peak near here in the spectrum!

- Suggests that the PB is vibrating → mechanical wave in the sensor → electrical noise (mechanism unknown).

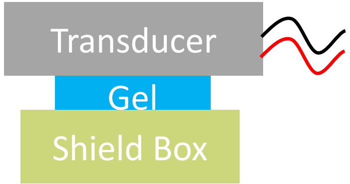
Vibrating Transducer Studies:

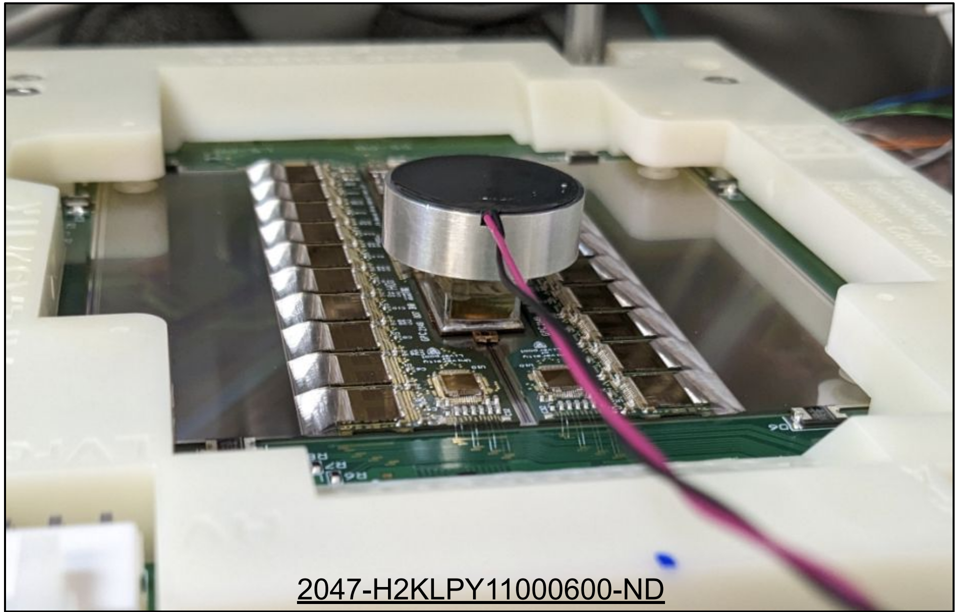
Building confidence in the vibration theory

Intentionally Vibrating Modules

Motivation:
- Suspect the powerboard is producing vibrations.
  - Somehow mechanical waves → electrical noise.
- Suspect the PB is vibrating at all temperatures.
  - Something changes at cold temperatures → cold noise turn-on.
- Maybe we can induce "cold" noise at room temperature…
  - By vibrating the module harder.

Test:
- Placed transducer on PB shield box w/ coupling gel.
  - No conductive path from transducer to shield box.
- Drove transducer at resonant frequency (1 MHz) with AFG.
- Performed electrical characterization at +20C.





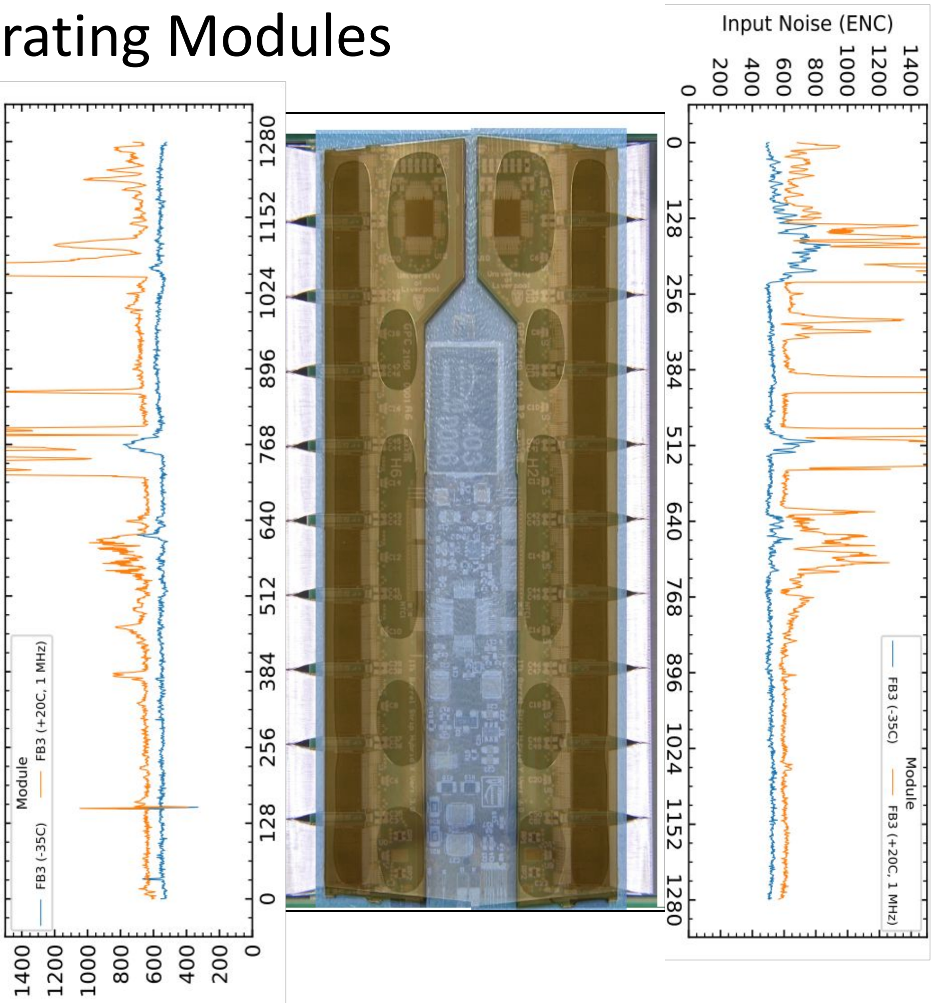
2047-H2KLPY11000600-ND

Intentionally Vibrating Modules

Motivation:
- Suspect the powerboard is producing vibrations.
  - Somehow mechanical waves → electrical noise.
- Suspect the PB is vibrating at all temperatures.
  - Something changes at cold temperatures.
    → cold noise turn-on.
- Maybe we can induce “cold” noise at room temperature…
  - By vibrating the module harder.

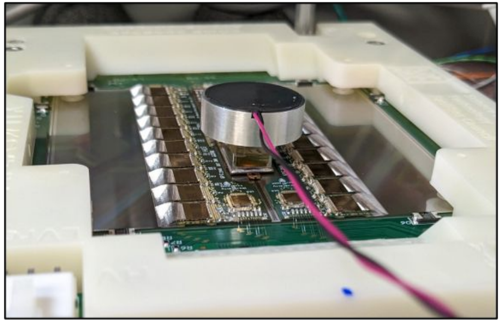
Test:
- Placed transducer on PB shield box w/ coupling gel.
  - No conductive path from transducer to shield box.
- Drove transducer at resonant frequency (1 MHz) with AFG.
- Performed electrical characterization at +20C.

Results:
- Noise pattern @ +20C w/ transducer looks like CN pattern @ -35C (w/out transducer), but worse.



Transducer-Synchronous Triggering

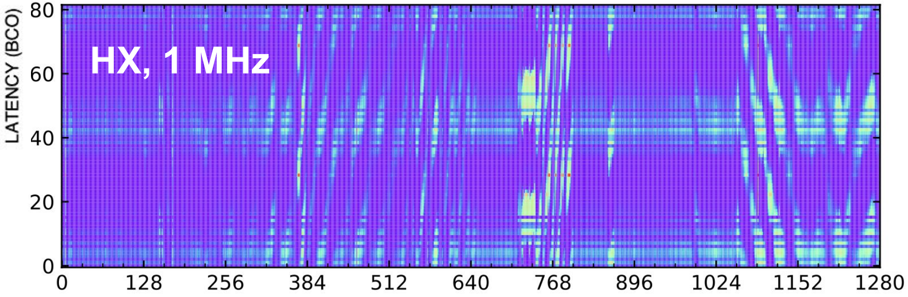
- Triggering on AFG signal to transducer.
  - Scan over trigger delay → noise occupancy vs transducer phase.
  - Again, see diagonal bands in channels with “cold” noise.
- Can vary transducer frequency and calculate resulting power spectrum.
  - Check if velocity & wavelength are consistent with A_0 wave dispersion relation ($v \sim \sqrt{f}$).
  - See backup for more info.

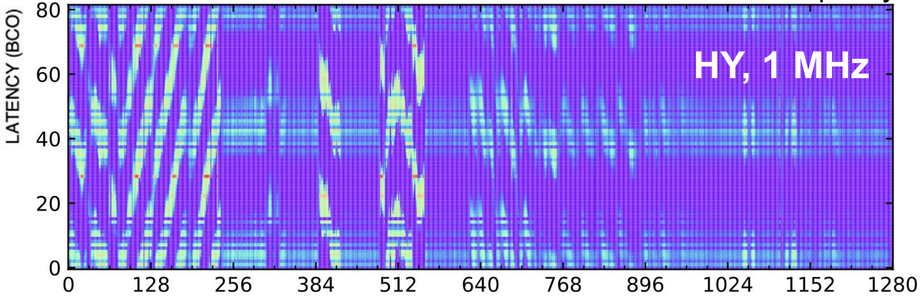


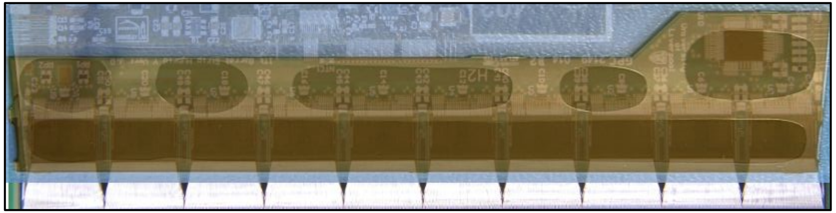
Noise occupancy vs trigger latency (1 MHz transducer)

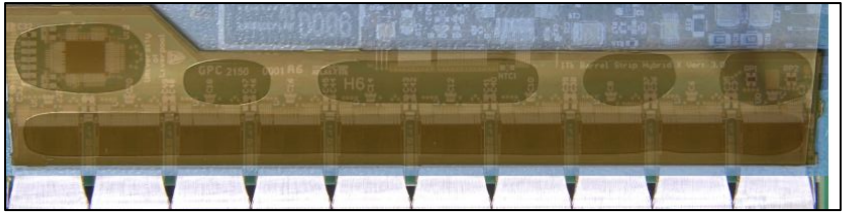
1 BCO = 25 ns

z-axis: noise occupancy









Where do we stand?

Summary:

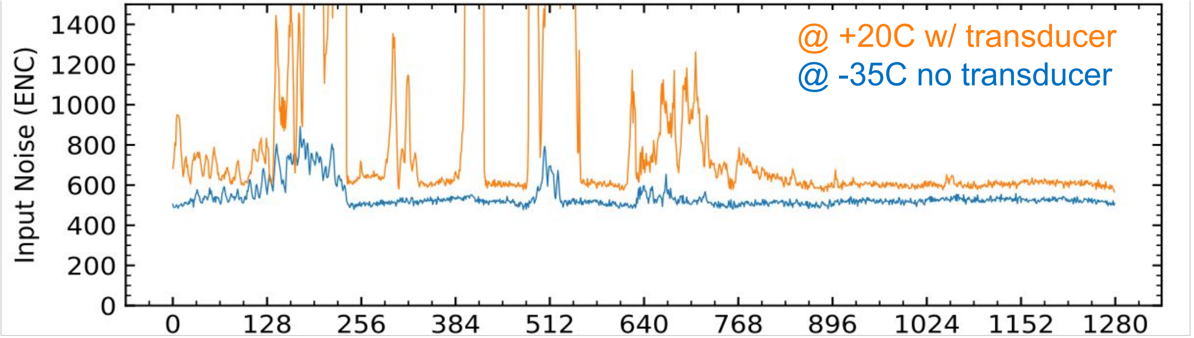
- Fairly confident something is vibrating on the powerboard at $f_{DCDC} \approx 2$ MHz.
  - Likely vibrating at all temperatures.
  - But something changes when cold (stress?) → cold noise turn-on

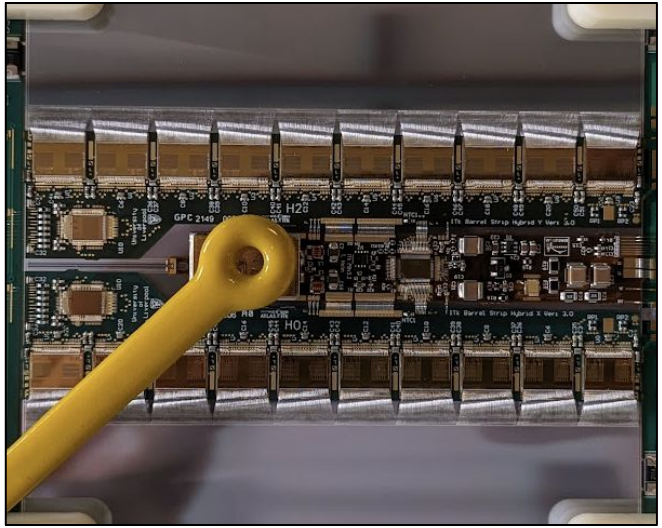
- "Cold"-noise pattern reproduced at room temp by vibrating module with transducer.

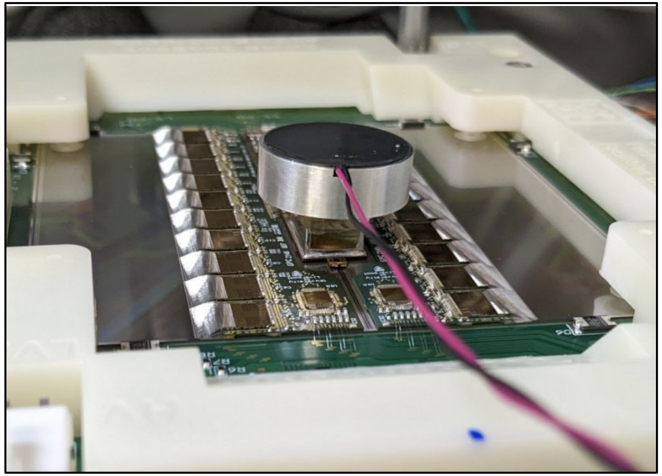
- Mechanical wave couples into sensor & travels → noise on strips far from PB.
  - Velocity & wavelength are consistent with A_0 Lamb waves.

Questions:

- Which component is vibrating on the powerboard?
- How do mechanical waves produce electrical noise?







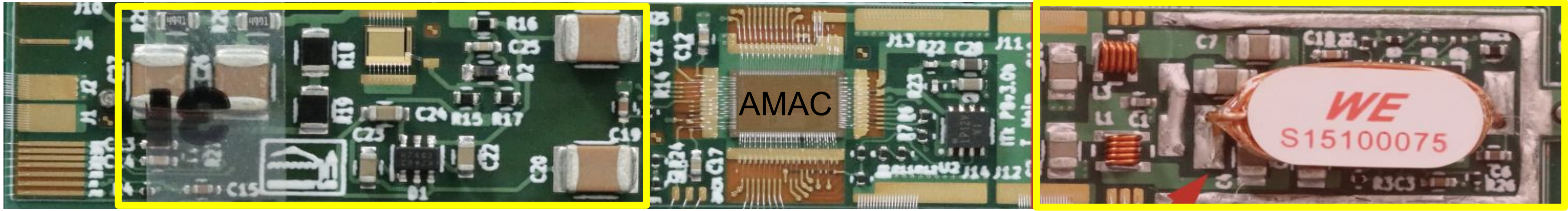
Finding the source of vibrations

Cold Noise *Instigator*

Powerboard

HV switch

Buck converter



Autonomous Monitor and Control (AMAC)

Powerboard is instigator of Cold Noise
- Powerboard electrically bypassed - CN is removed

Mechanically detaching the power board but still powered also removes the CN
- Power board peeled off, replaced same height, small dots glue on edges
- If EMI source CN, would persist - vibration is source of CN

Component on board producing vibration

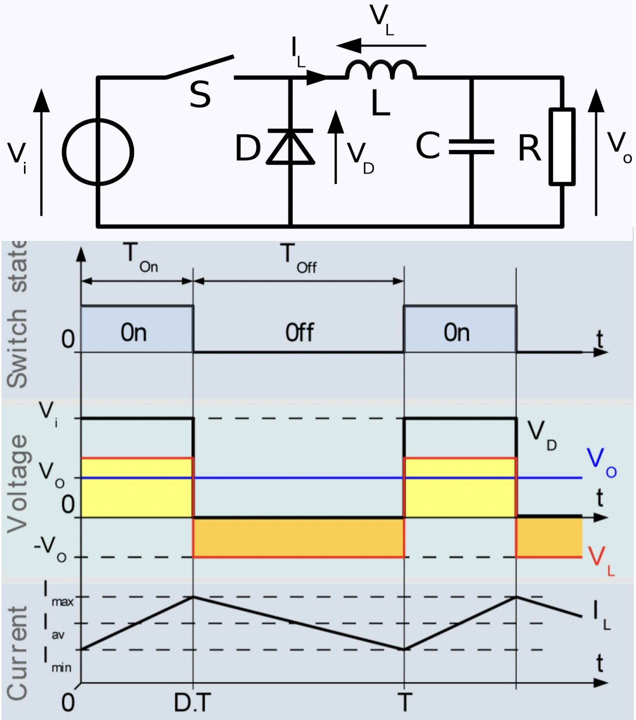
“Singing” capacitors known phenomenon when dielectric used in capacitor has piezoelectric effect
- Occurs with a oscillating voltage on capacitors
- Buck converter a potential candidate for singing capacitors

The Powerboard: A Closer Look

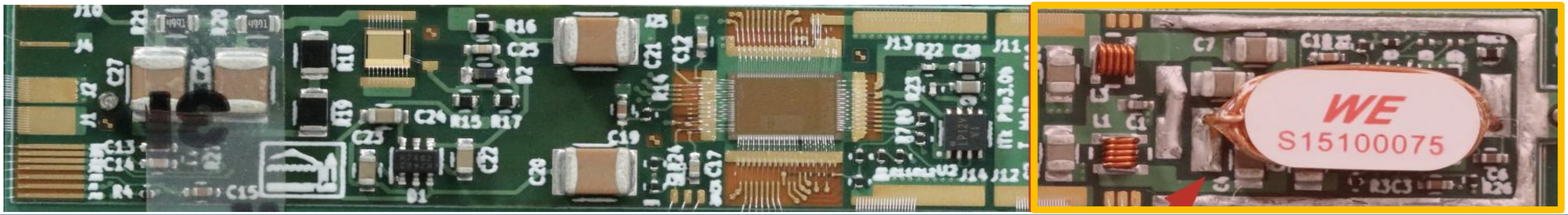
Voltage Stepdown:

- Front-end ASICs need 1.5V.
  - But distribute 11V to modules & use DC-DC conversion.
  - Reduces ohmic losses in cables & traces.

- Use a buck converter (bPOL) w/ air-core coil on powerboard.
  - More efficient than a linear regulator → less heat.
  - But 2 MHz switching → EM noise (hence shield box).



Buck converter



The Powerboard: A Closer Look

Voltage Stepdown:

- Front-end ASICs need 1.5V.
    - But distribute 11V to modules & use DC-DC conversion.
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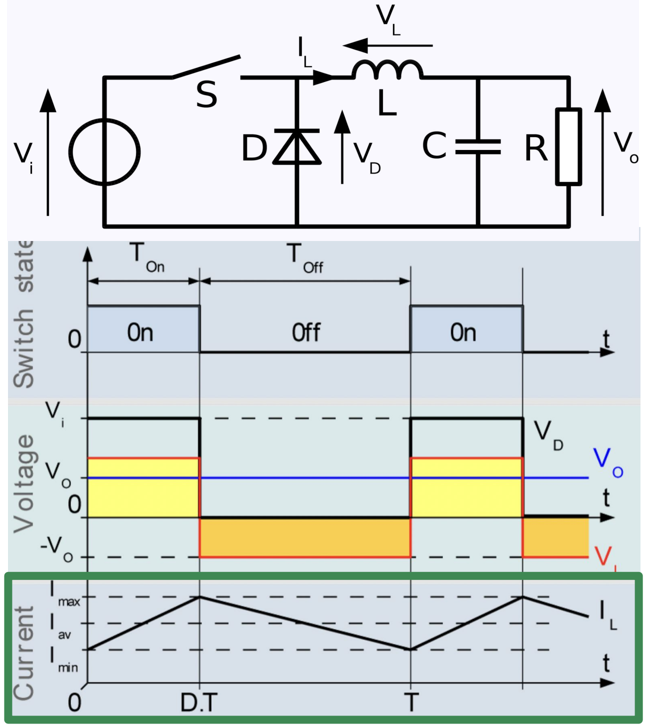
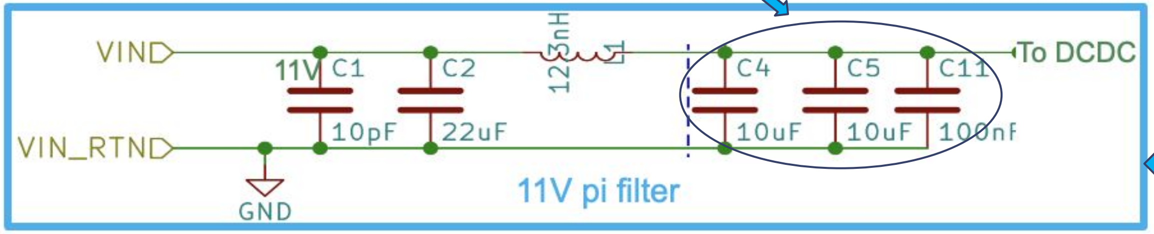
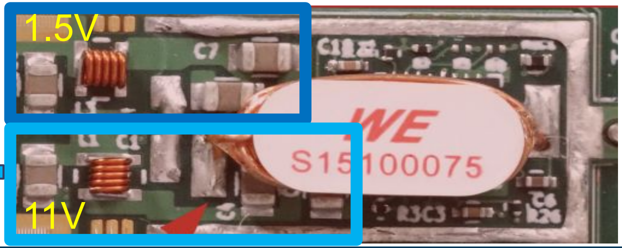
- Use a buck converter (bPOL) w/ air-core coil on powerboard.
    - More efficient than a linear regulator → less heat.
    - But **2 MHz** switching → EM noise (hence shield box).

Filtering:

- Output of buck converter has some ripple.
    - Smooth with pi filters on both 11V & 1.5V lines.
    - Caps are piezoelectric! Are they vibrating?





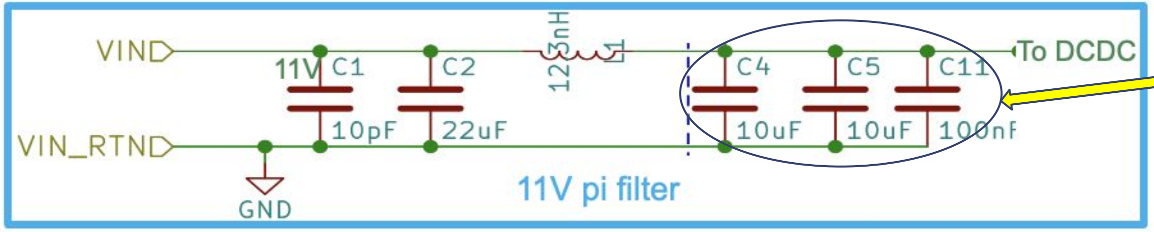


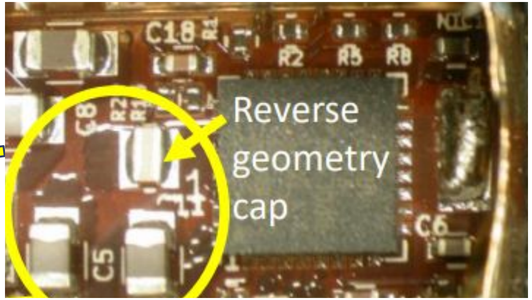
Replace Suspected Capacitors

- Replaced with tantalum capacitors
  - Tantalum not piezoelectric - no vibration
  - Not suitable for production but good diagnostic

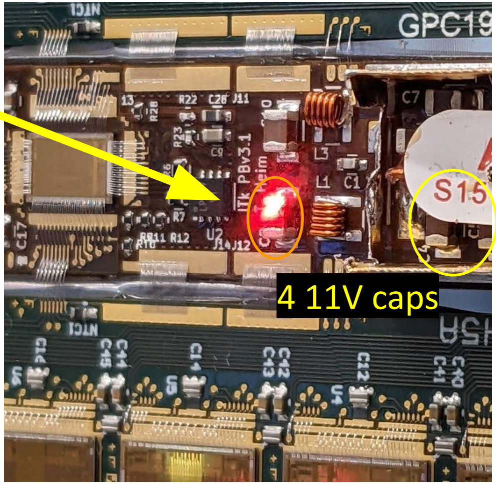
- Cold Noise slightly decreased but persistent
  - unexpected

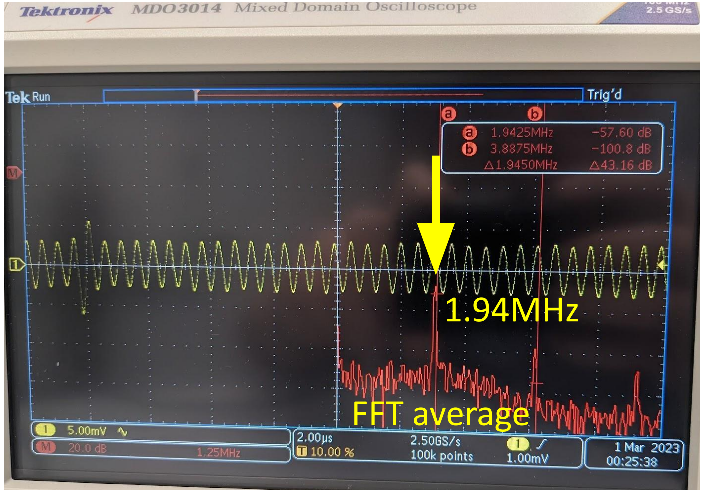
- Motivation to start looking for the “right tool” to identify individual vibrating components
  - Attaching transducers to small components not ideal





Right Tool for the Job - Vibrometer





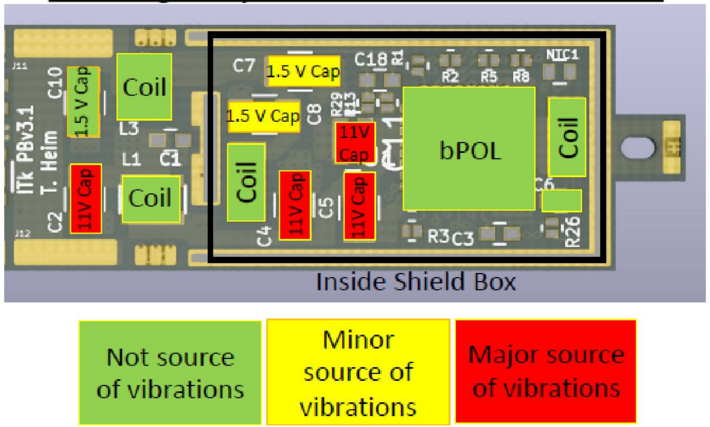
- Laser doppler Vibrometer used to measure frequency and amplitude of vibrations
  - Non-contact measurement
  - No mass loading
  - Laser spot 40 μm
  - Sensitive to MHz range

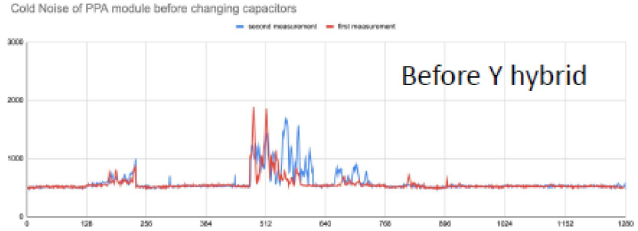
- Spot measurements of different components
- Identified vibrating capacitors at frequency of buck converter
- Unexpected capacitor vibrating

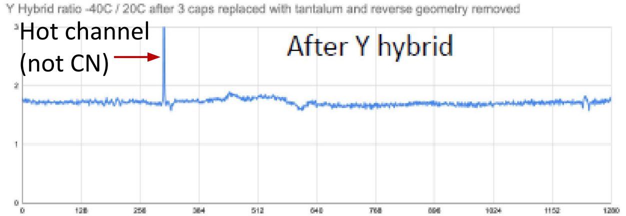
Identified Vibrating components

- The barium titanate in parallel plate capacitors expand and contract according to voltage across them
- 4 11V caps are the **primary sources of vibrations**
- The 11V capacitor after the pi filter has a significant vibration especially with increased power to module – **unexpected**
- 1.5V caps dV and vibration an order of magnitude less
- When all 4 11V capacitors were replaced or removed then the Cold Noise disappeared

Vibrating Components on Barrel Power Board



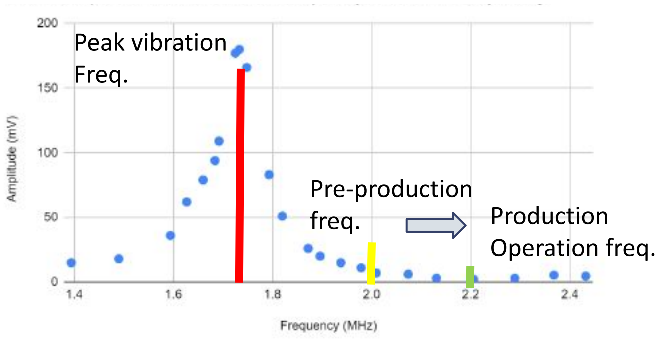




Frequency Dependance

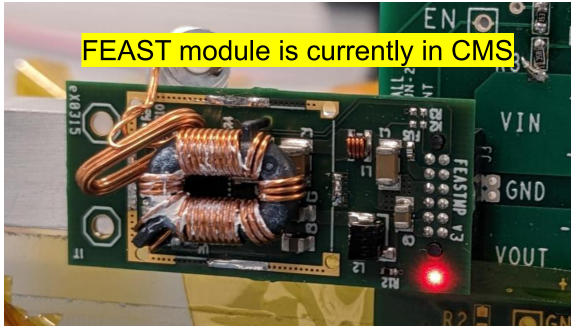
- The capacitor’s amplitude of vibration is also dependant on frequency
- Capacitor amplitude about 1 nm at 2MHz
- The Barrel power board increases its vibrations by an order of magnitude at 1.7MHz compared to 2MHz
- The production frequency of 2.2MHz will be far from this peak
- Vibration propagates across module - detected on sensor

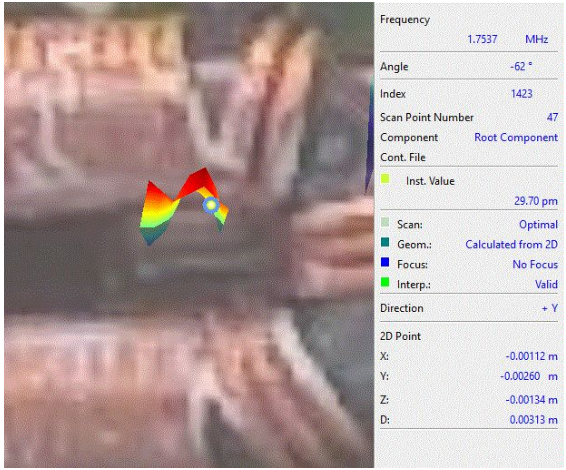
Capacitor Vibration



We Are Not Alone

- FEAST has been running in CMS for over a year
- 0.5nm vibrations seen on CERN's FEAST module
- CERN's bPOL modules also show a similar amplitude
- These capacitor vibrations are the same as our module
- Source and scale vibrations not unique to ATLAS ITk





Stop at the Source

Swapping components:

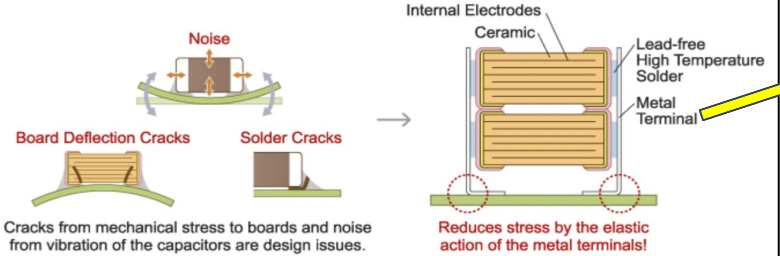
- Attempts to solve CN by modifying components on PB have failed.
  - Caps on stilts (smaller vibrations).
  - 0805 → 0603 (different frequency response).
  - Removed caps completely.
  - And more…

- Barium Titanate caps allows us to achieve the radiation tolerance, reliability, and capacitance we require

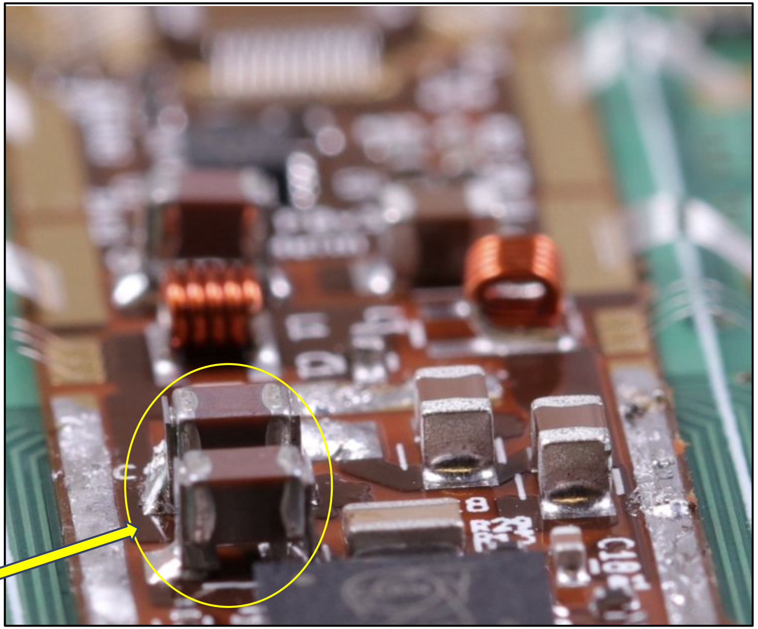
- Alternative caps do not achieve those requirements

1. Bond metal terminals to the external electrodes of chips.

The stress applied to the chip is relieved by the elastic action of the metal terminal.



2. Substantially reduces noise, board deflection cracks and soldering cracks.

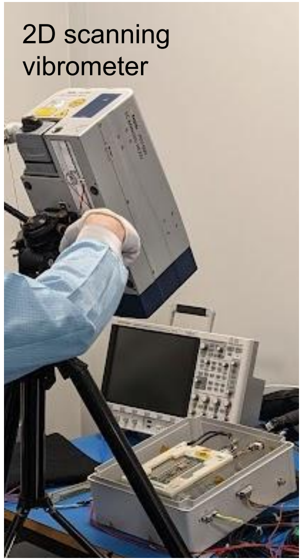


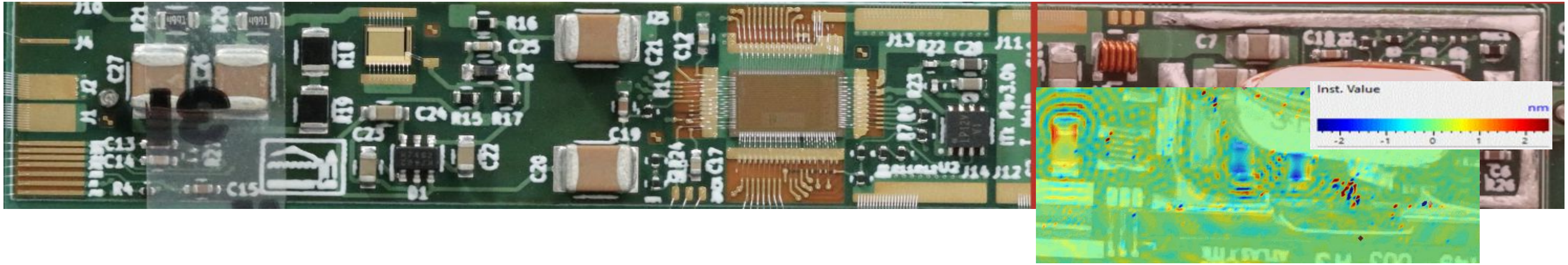
Murata KRM series

Propagating wave

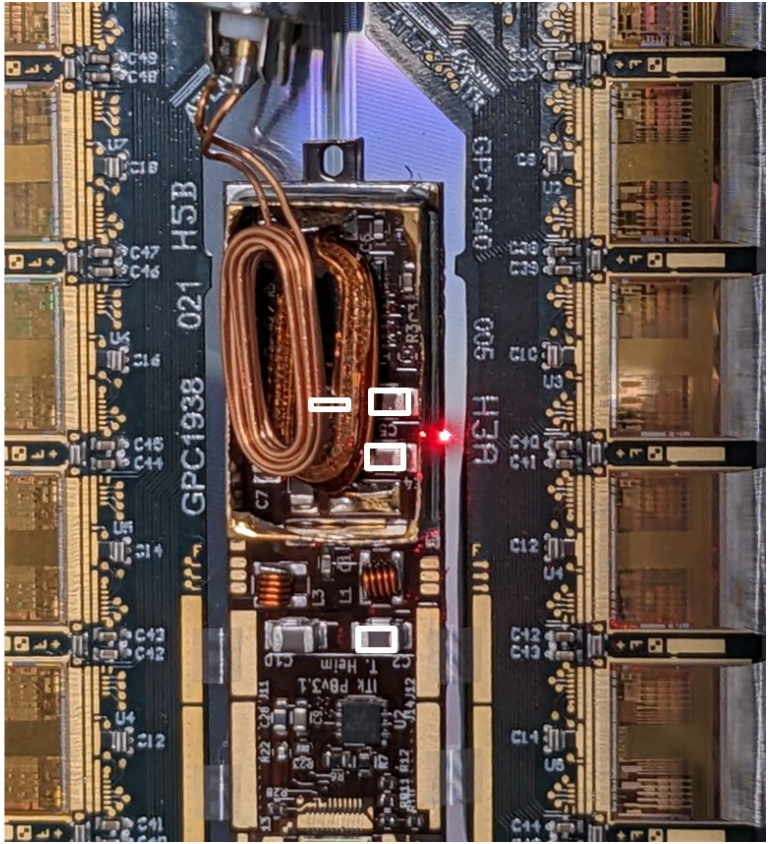
- Cant remove the source of vibration
- Need to understand how vibration is propagating
- Upgraded Vibrometer with 2D scanning
  - Single point measurements across module
  - Stitched together measurements in phase
    - Magnetic trigger on buck converter as reference

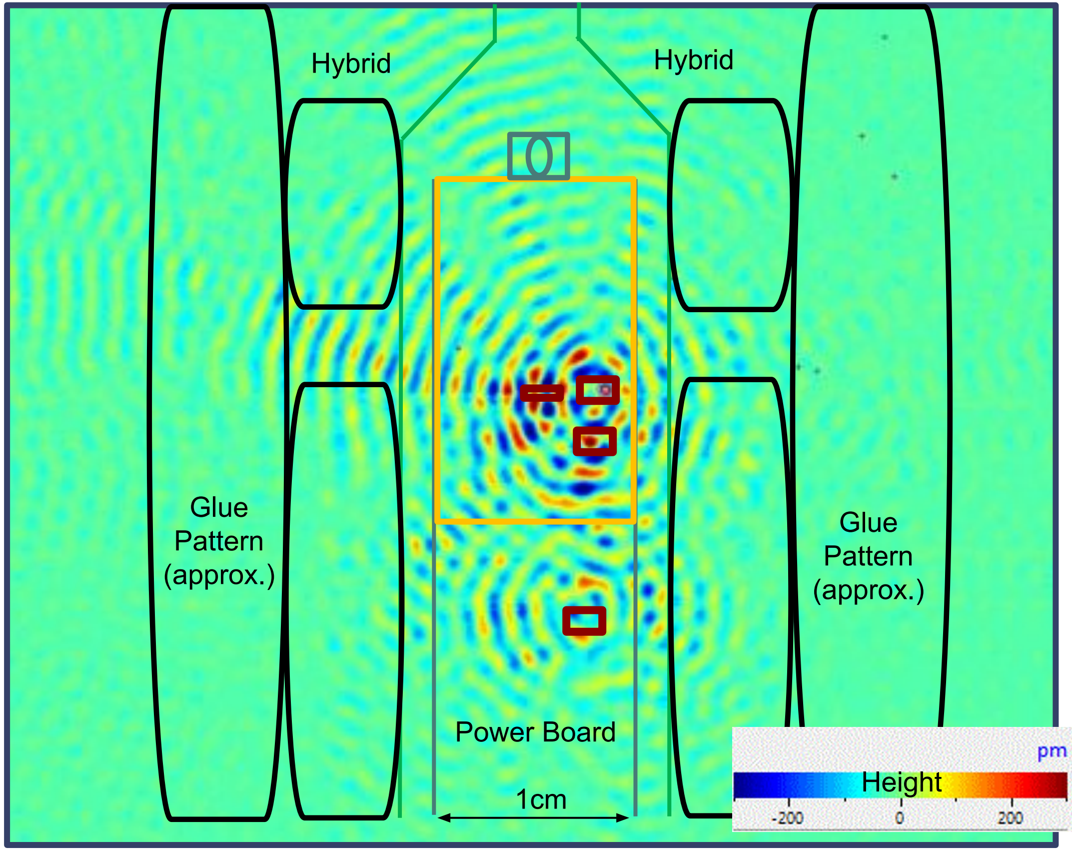
- Capacitor amplitude around 1 nm
  - Amplitude is dependent on power draw of powerboard
- Vibrations propagate across sensor at same wavelength as calculated ~1.3 mm
- The wavelength on the PCB is ~200 μm
- CN connected to wavelength in Silicon so interested in scan of back side of module





Propagating Wave in Silicon Sensor

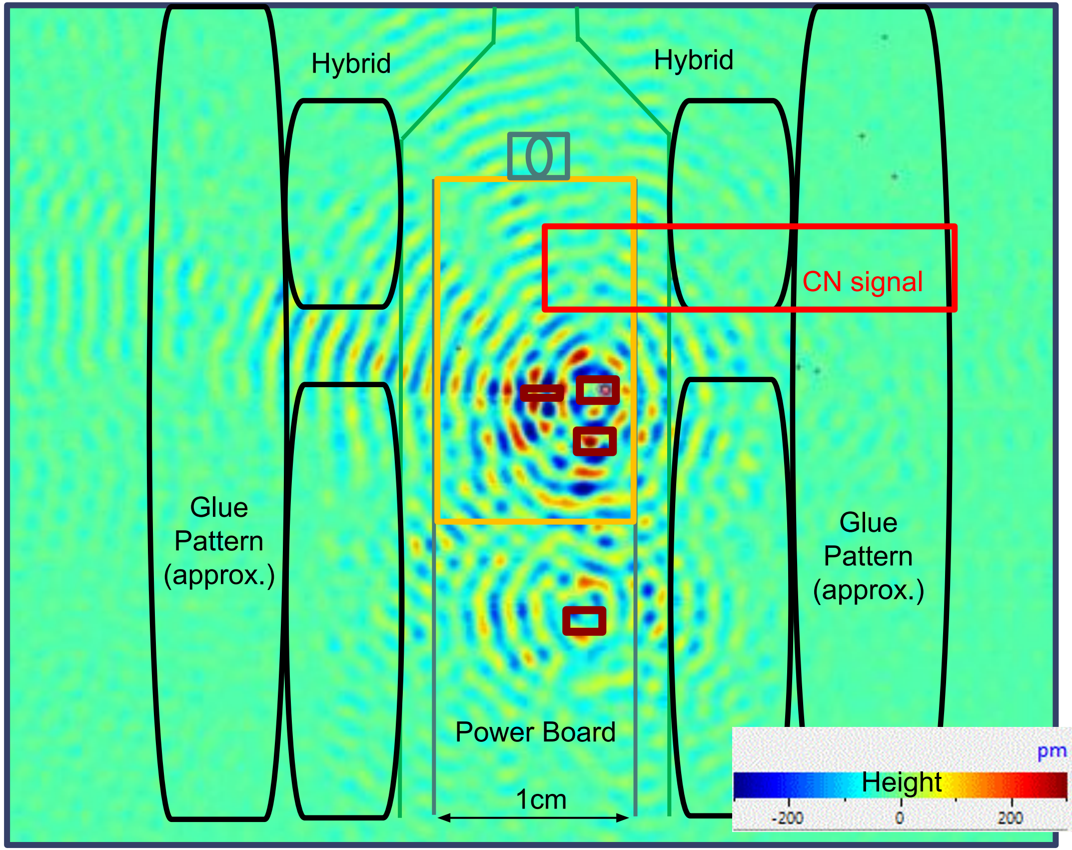




Vibrometer scan of Silicon sensor from the back of module while in climate chamber at -60C

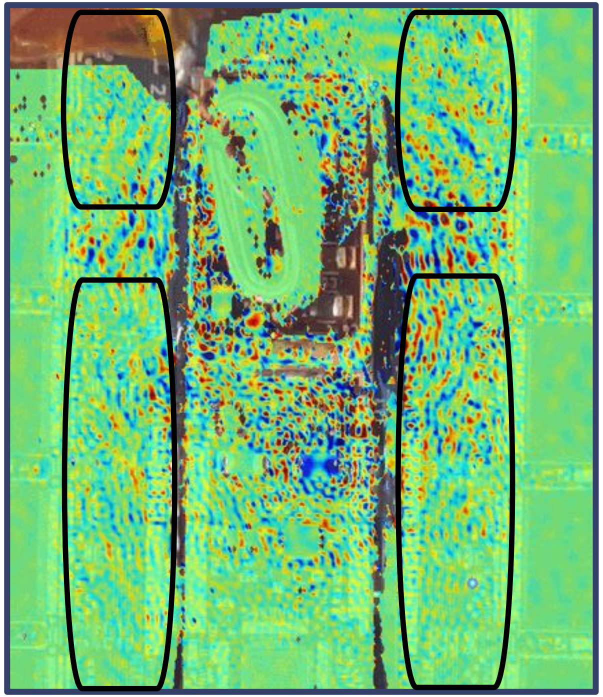
Propagating Wave in Silicon Sensor

- The glue gaps allow the waves to pass through
- The glue under the hybrids dampens the vibrations
- There is an interference pattern between the caps
- The C2 cap has strong oscillations when at full power
- The location of CN readout is not clearly correlated to the wave pattern



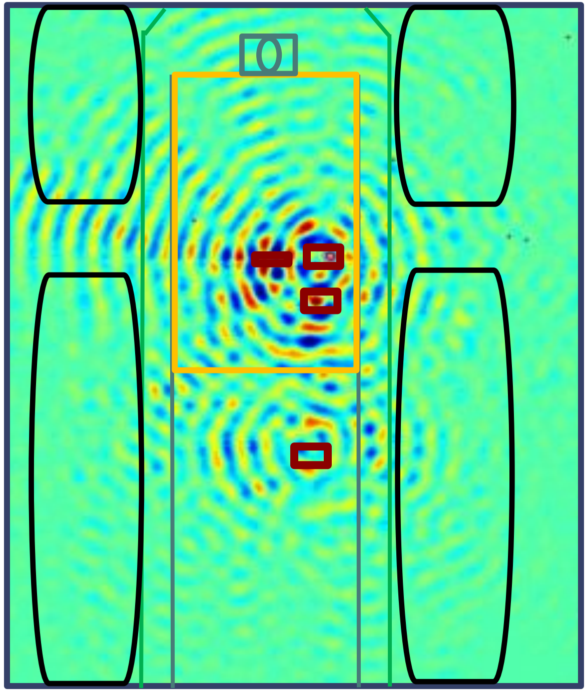
Propagating Wave in Silicon Sensor

Scan from above



-25C

Scan from below

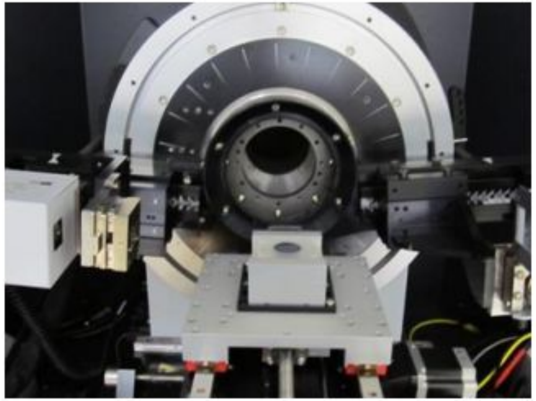


-60C

- Wave propagates in Silicon at wavelength ~1.3 mm
- The plastic composite power board and hybrids have a lower speed of sound and hence a shorter wavelength ~0.2 mm
- The CN signal corresponds to the wave traveling through the Silicon as seen in mag triggering wavelength measurement of 1mm
- Vibration seen on sensor at same level for all glues - **unexpected**
- Vibration amplitude relatively constant with temp - **unexpected**

Readout of Vibration

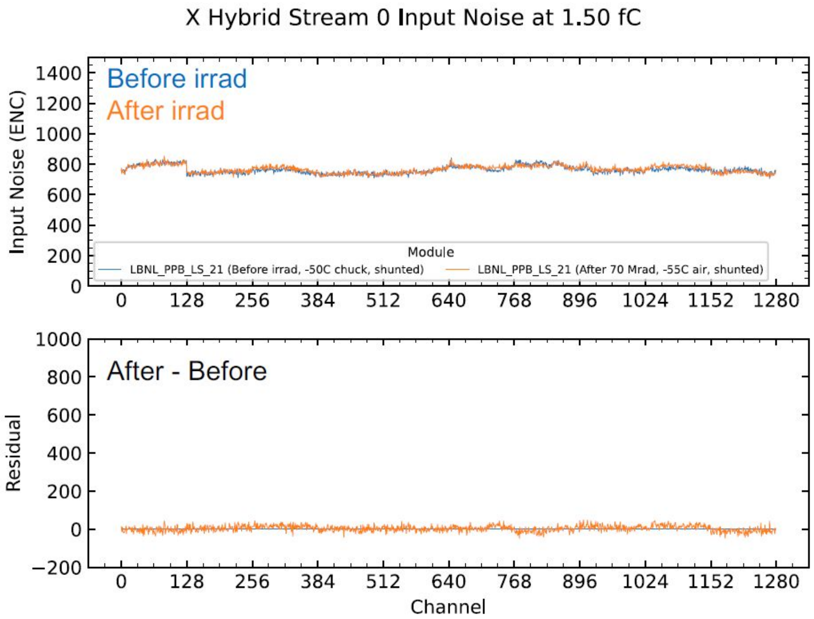
- Mechanical vibration is converted back to electrical signal to be read out
- Possible mechanisms:
  - Piezoelectric effect from the glue, passivation layer, or dielectric
  - Oscillating fixed surface charge
- Some polymers can have piezoelectric effect – glues piezo-properties unknown
  - X-ray diffraction tests of 3 types of glue extracted from CN regions of modules
  - No crystalline-like structure identified that would support the piezoelectric effect
- Passivation layer Silicon Nitride is piezoelectric but expect as amorphous layer – no expected piezoelectric effect
- Surface charge from coupling capacitor for strip readout might be measurable
  - Change in capacitance as compressed induce signal
  - Would expect to see increase with irradiation

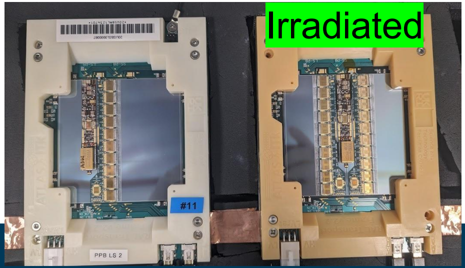


X-ray Diffraction glues

Gamma Irradiation

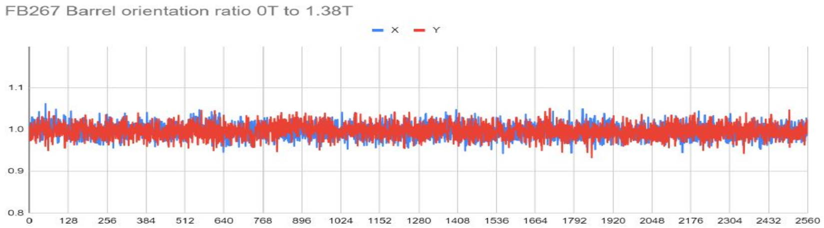
- Polymer glues are susceptible to change from gamma irradiation
- Fixed surface charge on silicon will increase with gamma irradiation
- 14 modules irradiated with Co_{60} source at Sandia National laboratory
  - 3 different module types tested
  - 3 different glues tested
- 70 Mrad dose - safety factor 1.5
- **No change** in Cold Noise for the modules irradiated

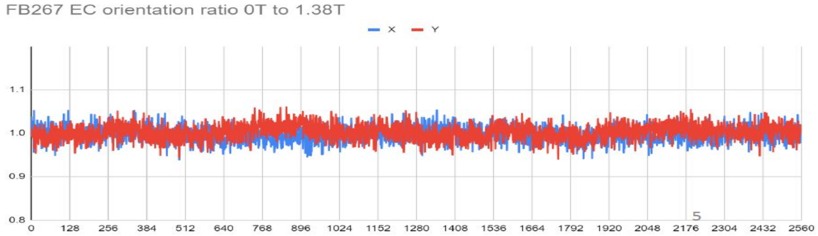


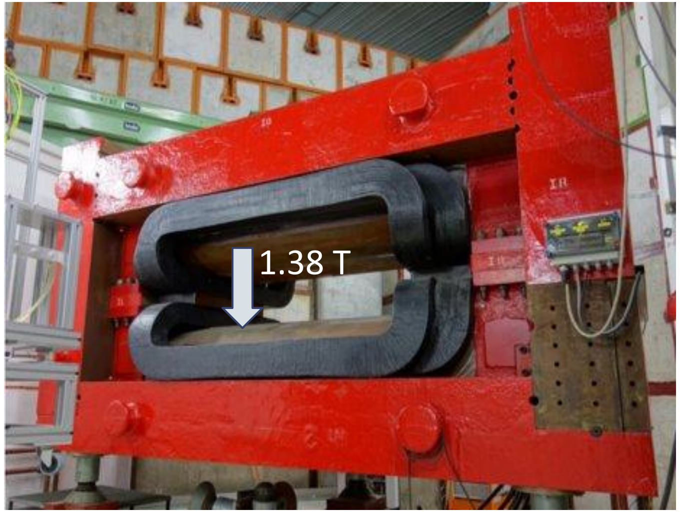


Magnetic Field

- ATLAS solenoid 2T magnetic field
- Motivated to see if any change in Cold Noise in high magnetic fields
- Large volume magnet used to allow for module's cold box
- DESY's 1.38T dipole used
- Modules tested with different glues, types, and field orientations
- **No change** in Cold Noise for any of the modules

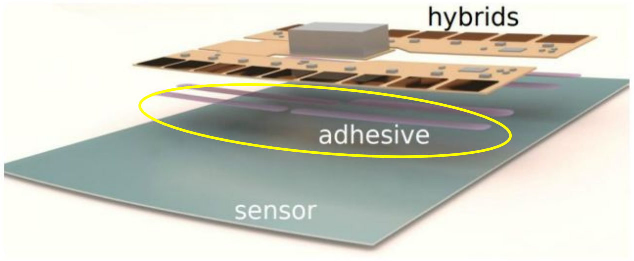


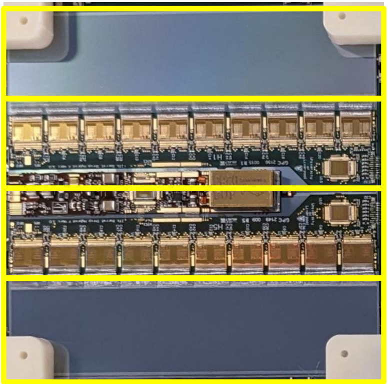




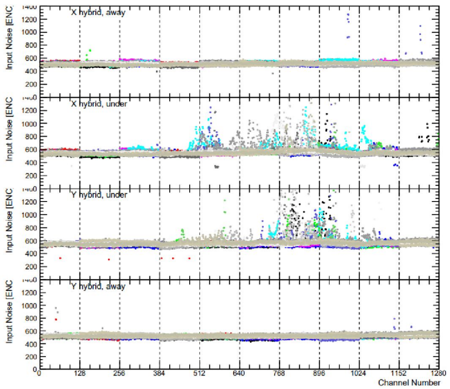
Glue Choice

- Several years of testing dozens of glues to qualify for the senor surface
- 3 glues were acceptable for use before considering Cold Noise levels
- The backup glue turned out to be the best with respect to Cold Noise
- Only the short strip type module has Cold Noise with the backup glue
- First 2 years of production are non-short strip module types
- Production has begun using the backup glue

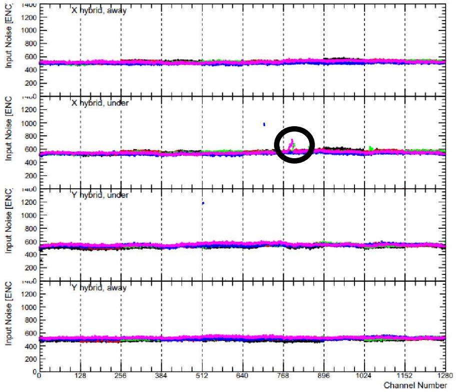




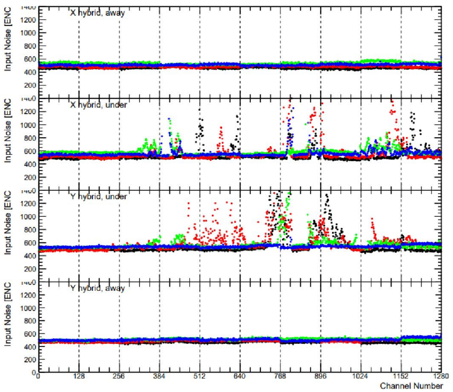
Original Glue



Backup Glue



2^{nd} Backup



Mitigation Strategy

Procedure:

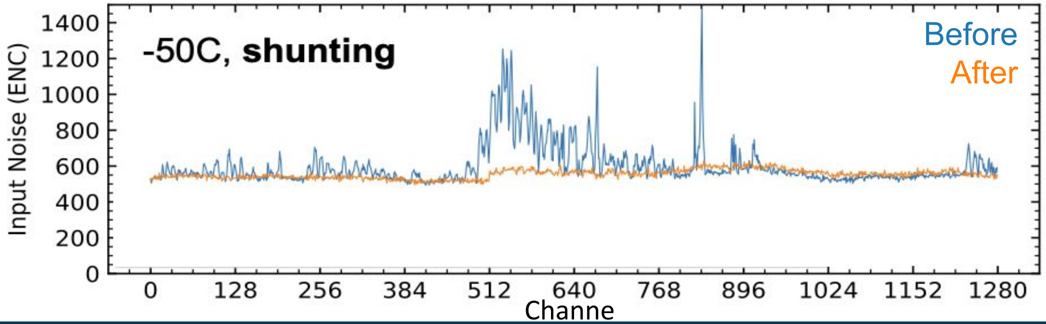
- Filled in gaps between hybrids and PB on existing module.
  - Originally built with worst glue (AA-Bond F112) → severe cold noise.
  - Filled gaps with more of the same glue.

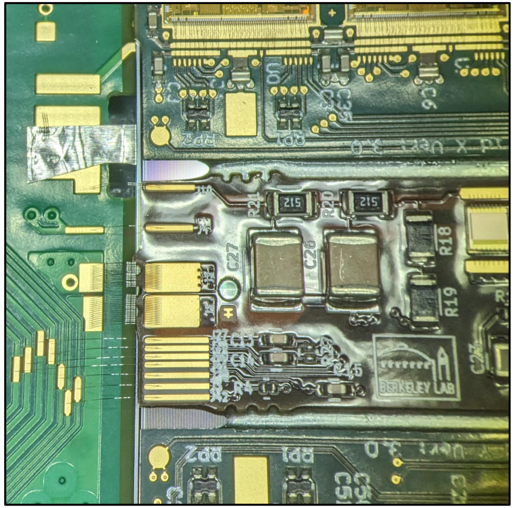
Results:

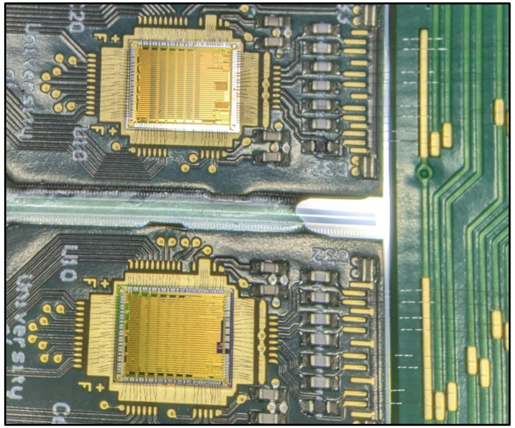
- Almost completely removed the cold noise!

- Repeated w/ more modules and other glues → similar improvements!
  - Results hold up over 50+ (extra stressful) thermal cycles!

- Need to develop a production friendly process & better understand the stress.
  - Filling gaps with a glue syringe is too tedious.







Summary

Cold noise

- In early 2022, we observed very noisy channels when testing modules at cold temperatures.
  - Decided to pause pre-production to investigate.

- Capacitors on the powerboard are vibrating at the DC-DC converter frequency (2 MHz).
  - Produces mechanical waves that travel through the sensor.
  - Confirmed by vibrometer measurements.

- Mechanical vibrations appear to be producing a voltage → effective discrimination threshold oscillates.
  - Exact mechanism not yet understood.

- Mechanism doesn't change in magnetic fields or with irradiation.
  - Builds confidence in stability of mechanism even if not understood

Mitigation strategies:

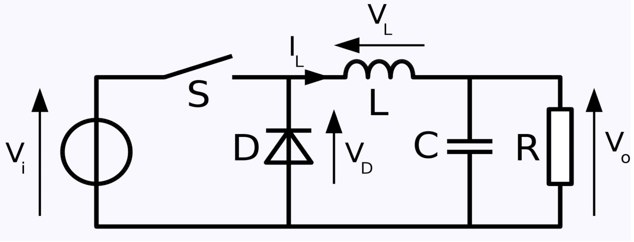
1. Using backup glue (True Blue = Loctite Eccobond F112) for all module types except short strip
   Do not understand why this helps.

2. Doubling glue thickness for short strip modules
   - Very encouraging results, tests ongoing

3. Filling in the gaps between the hybrids & PB with more glue.
   - Very encouraging results, but need to develop a production-friendly process

Backup

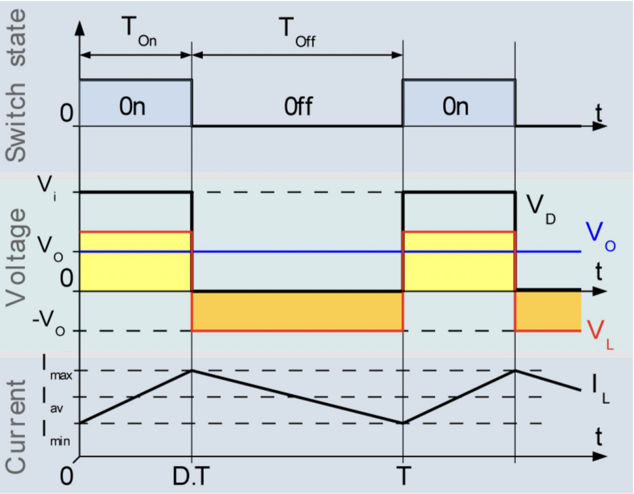
The Powerboard: A Closer Look



Voltage Stepdown:

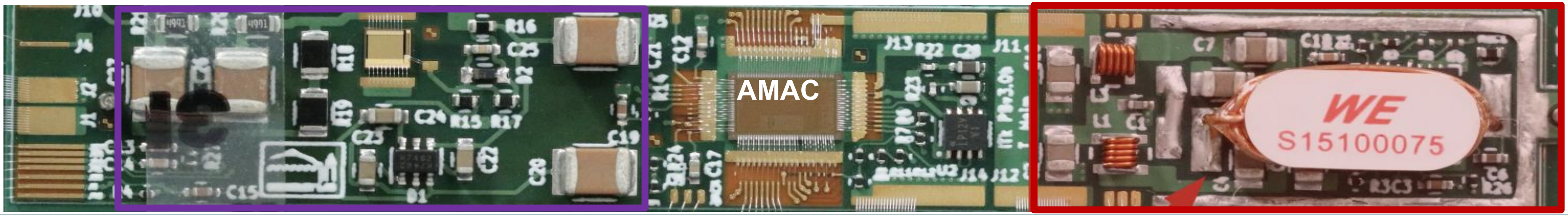
- Front-end ASICs need 1.5V.
  - But distribute 11V to modules & use DC-DC conversion.
  - Reduces ohmic losses in cables & traces.

- Use a buck converter (bPOL) w/ air-core coil on powerboard.
  - More efficient than a linear regulator → less heat.
  - But 2 MHz switching → EM noise (hence shield box).



HV switch

Buck converter



The Powerboard: A Closer Look

Voltage Stepdown:

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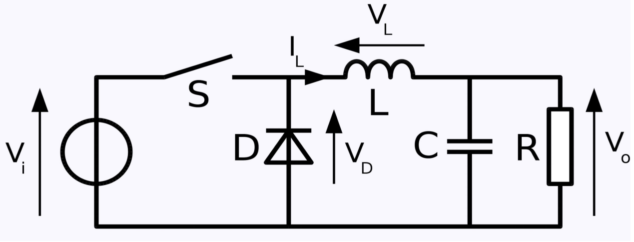
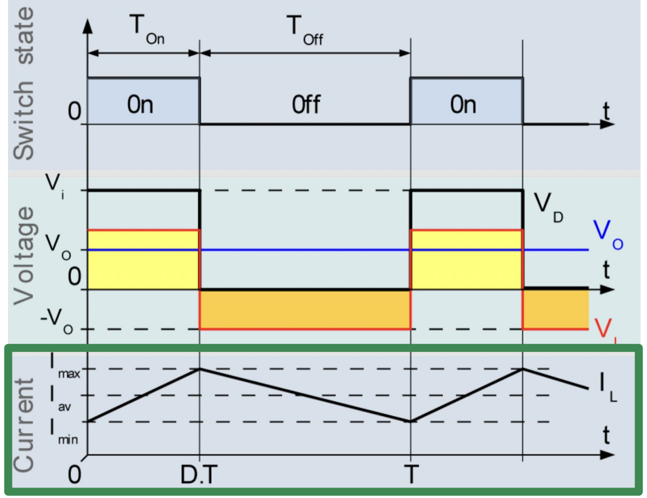
    - But distribute 11V to modules & use DC-DC conversion.
    - Reduces ohmic losses in cables & traces.

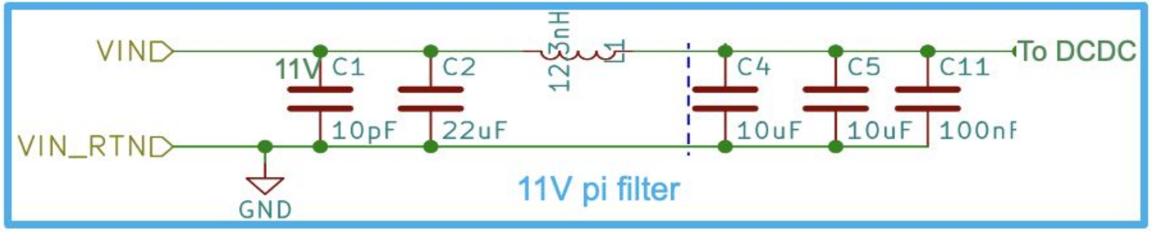
- Use a buck converter (bPOL) w/ air-core coil on powerboard.
    - More efficient than a linear regulator → less heat.
    - But 2 MHz switching → EM noise (hence shield box).

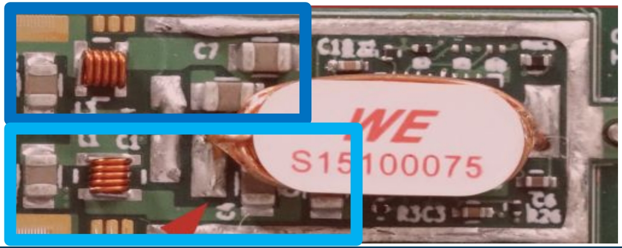
Filtering:

- Output of buck converter has some ripple.
    - Smooth with pi filters on both 11V & 1.5V lines.
    - Caps are piezoelectric! Are they vibrating?



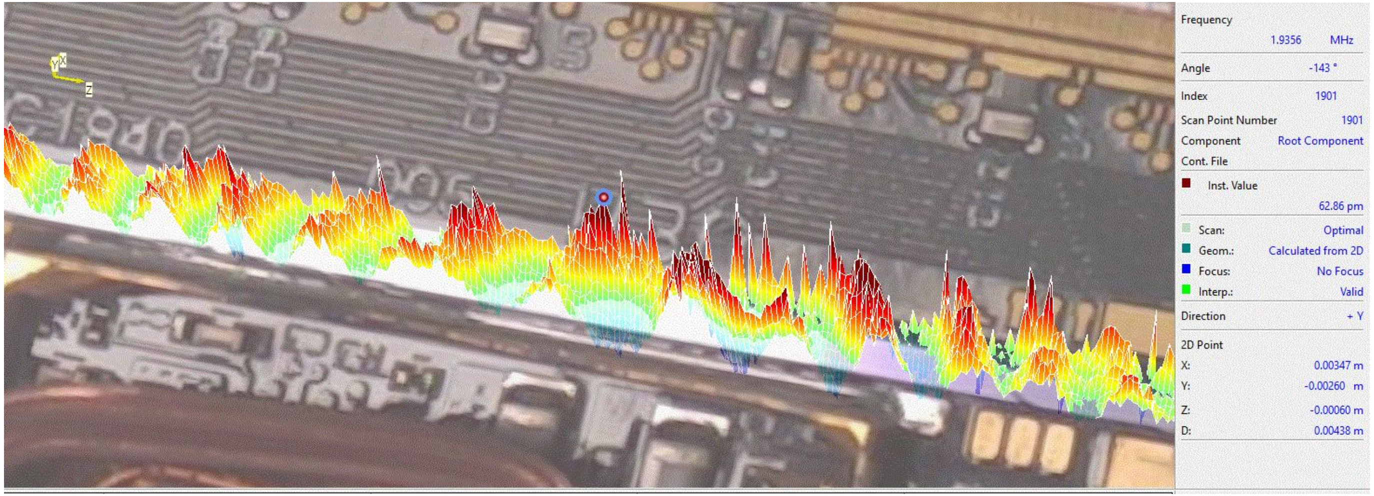


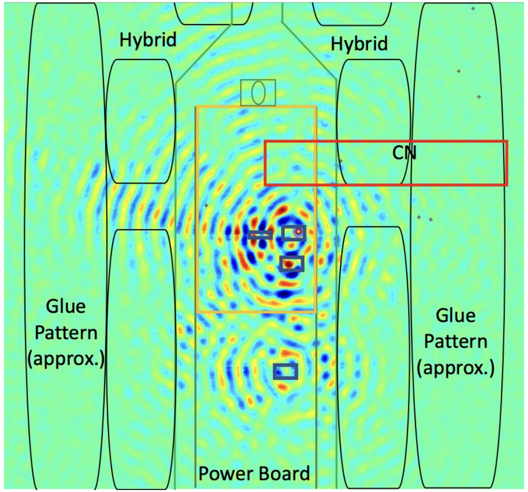




Vibrometer Measurements

- Vibrations confirmed using laser doppler vibrometer at RAL.
  - See $\mathcal{O}(10\ \mathrm{pm})$ - $\mathcal{O}(1\ \mathrm{nm})$ vibrations, depending on location on module.
- Caps on pi filters are driving vibrations, with 11V caps having ~10x larger amplitude compared to 1.5V caps (higher dV/dt).
- Vibrations are coupling into sensor.
  - Amplitude is fairly independent of temperature, but the propagation changes (standing waves when cold).
- We're not alone – also see vibrations on DC-DC converter boards currently installed in CMS.





Mitigations Strategies

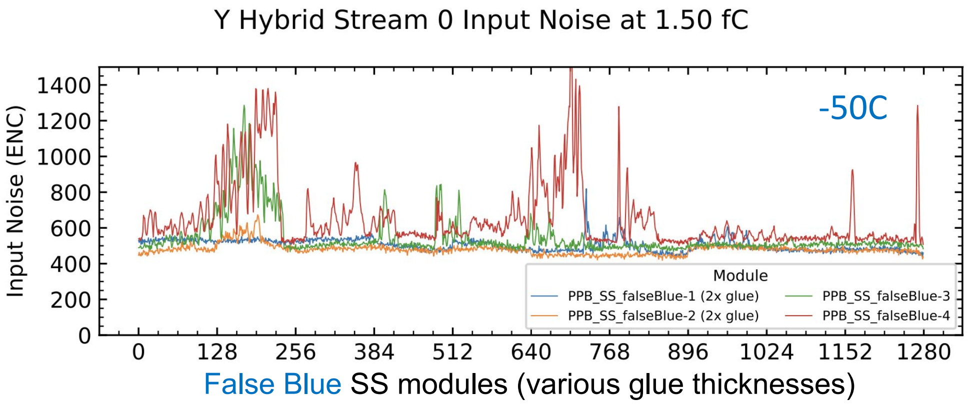
Strategy #1: Picking the right glue & glue thickness

Observations:

- CN severity varies greatly with glue type.
- Generally, thicker glue layers reduce CN.

Evaluated epoxies:

- Polaris PF-7006 2-part epoxy
  - Previous baseline, no longer available.
  - Discovered CN with this glue.
- Loctite Eccobond F112 (“True Blue”)
  - Previous backup, new baseline.
  - Better CN performance than Polaris.
- AA-BOND F112 (“False Blue”)
  - Should be very similar to True Blue.
  - But observe much worse CN.



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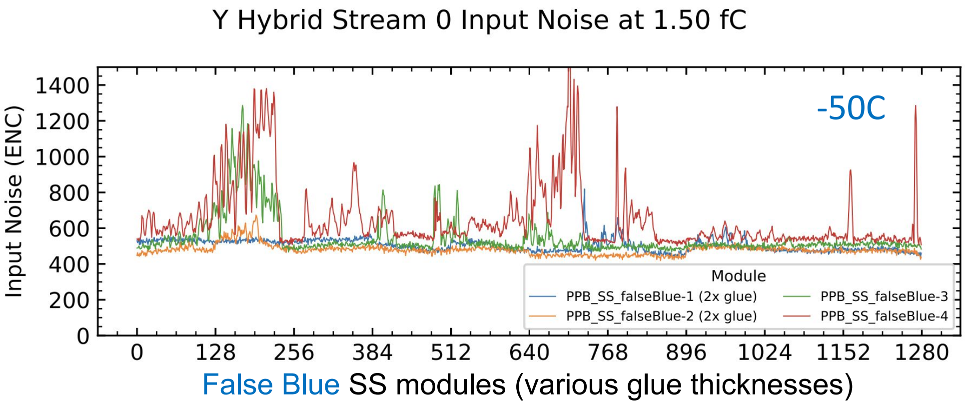
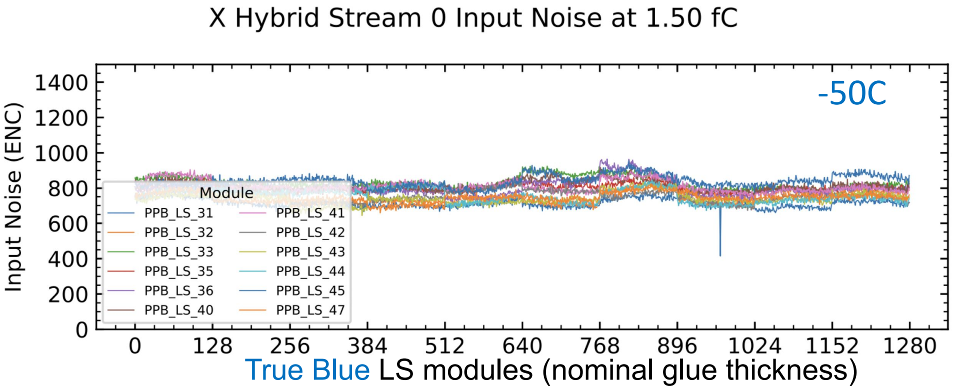




Mitigation plan:
- True Blue with the nominal thickness (120 μm) is good enough for LS modules.
  - Can double the glue thickness for SS modules.

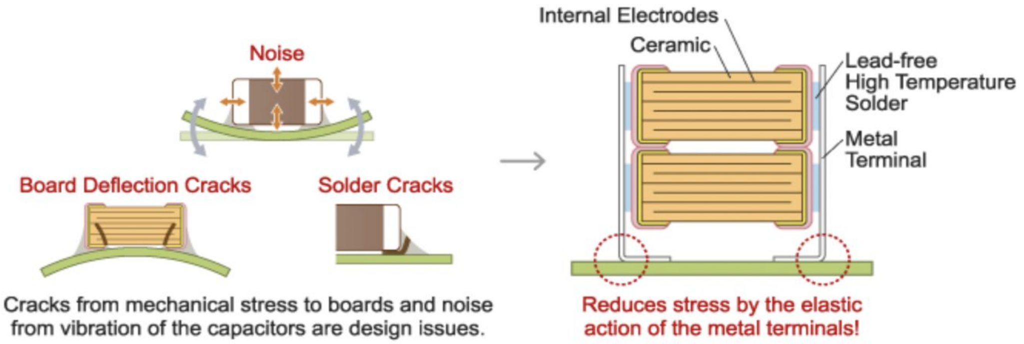
Strategy #2: Modifying the powerboard

Swapping components:

- Attempts to solve CN by modifying components on PB have failed.
  - Caps on stilts (smaller vibrations).
  - 0805 → 0603 (different frequency response).
  - Removed caps completely.
  - And more…
- Using tantalum capacitors helps (not piezoelectric).
  - But not radiation hard.

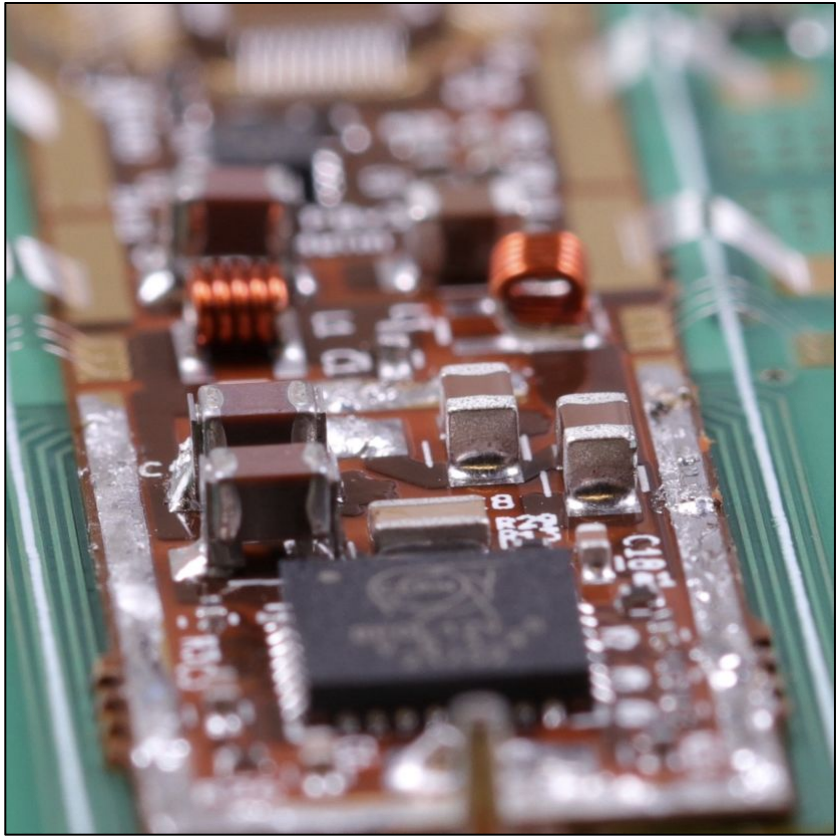
1. Bond metal terminals to the external electrodes of chips.

The stress applied to the chip is relieved by the elastic action of the metal terminal.



2. Substantially reduces noise, board deflection cracks and soldering cracks.

Murata KRM series



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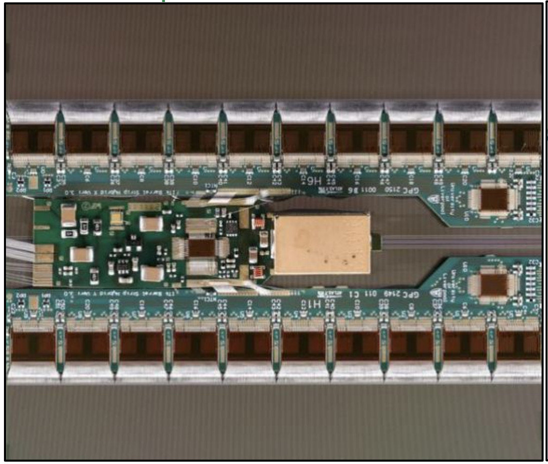
  - And more…
- Using tantalum capacitors helps (not piezoelectric).
  - But not radiation hard.

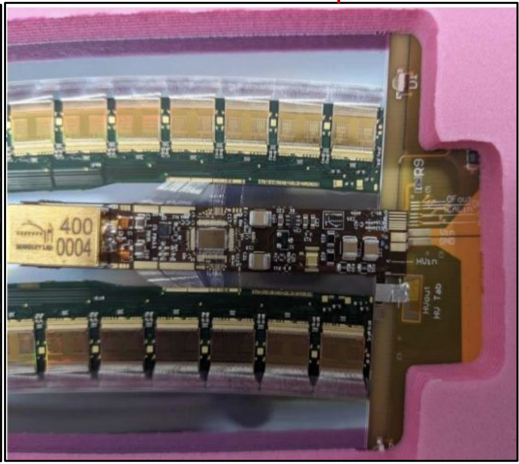
Changing the substrate:

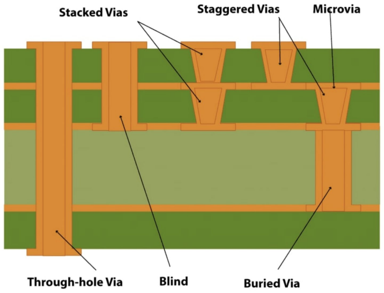
- Recent endcap modules do **not** have CN.
- Inspired some special builds:
  - Barrel PB on endcap module → CN.
  - Endcap PB on barrel module → no CN.
- Endcap has different powerboard flex PCB manufacturer (Würth).
  - Thinner & more flexible than barrel PBs.
  - Different stack-up & vias (barrel = through hole, endcap = staggered microvias).
  - Acrylic instead of epoxy.
- Ordered PB flexes from Würth using barrel layout but endcap process (so stacked microvias).

Endcap PB on barrel module



Barrel PB on endcap module

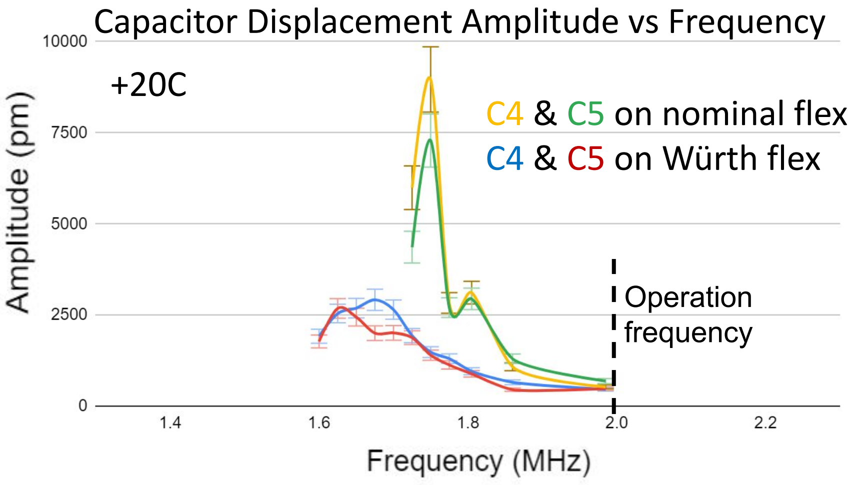




Strategy #2: Modifying the powerboard

Barrel PBs in endcap process:

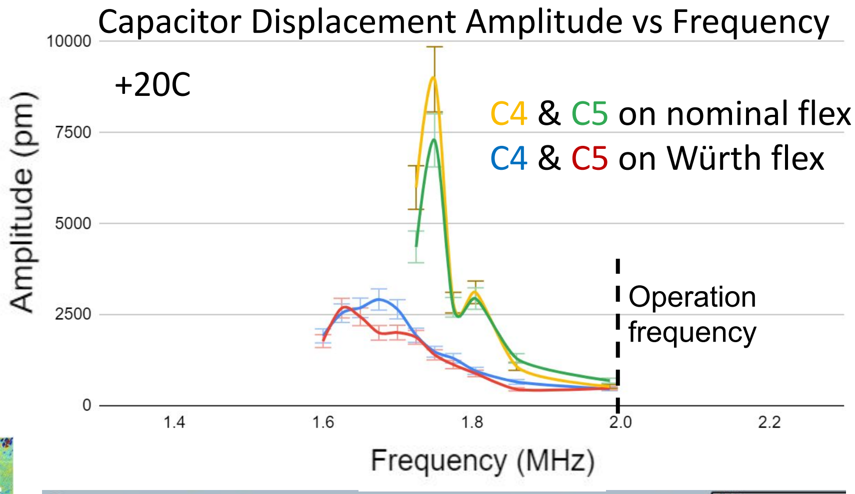
- Vibrometer tests of standalone PBs were encouraging.
  - Caps vibrate much less than on nominal barrel PB flexes.
  - Although the difference is small at 2 MHz…



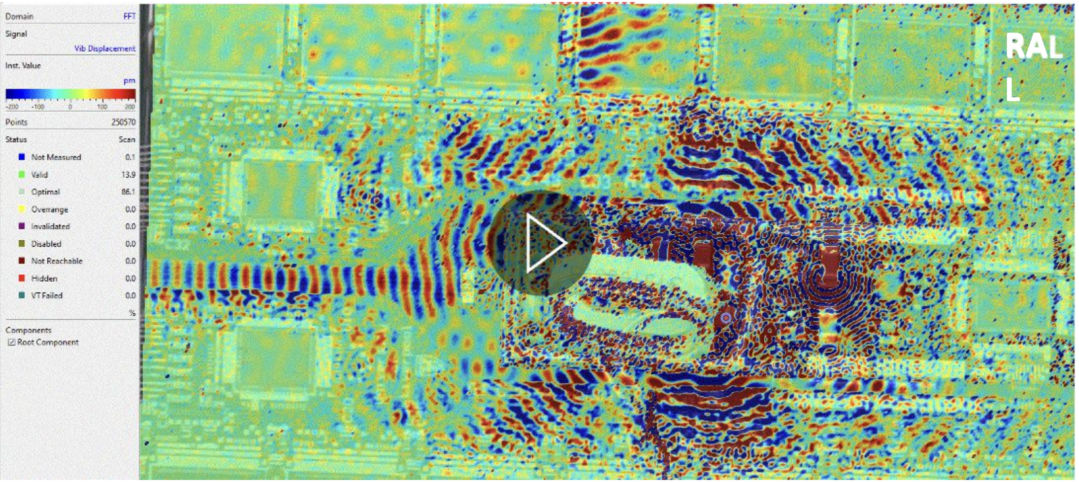
Strategy #2: Modifying the powerboard

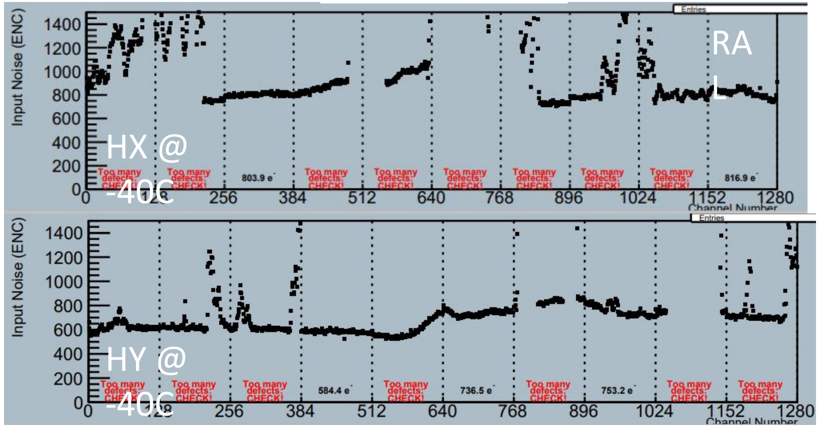
Barrel PBs in endcap process:

- Vibrometer tests of standalone PBs were encouraging.
    - Caps vibrate much less than on nominal barrel PB flexes.
    - Although the difference is small at 2 MHz…
- But severe CN observed on modules with Würth PB.
    - Will try again with staggered microvias like endcap…



Module with new Würth barrel PB



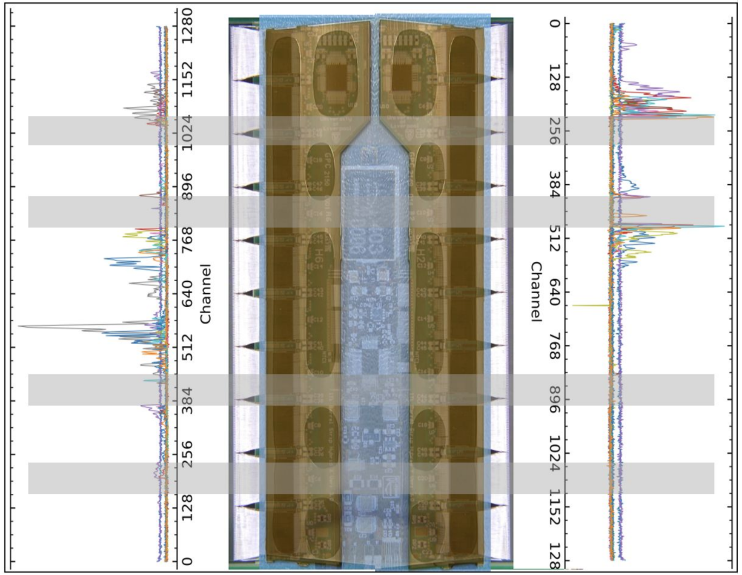


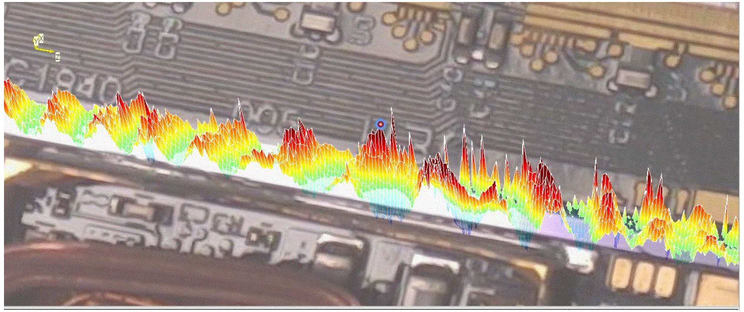
Strategy #3: Filling in the gaps

Observation:
- CN channels are correlated with glue dots & dashes on hybrid back-end.

Speculation:
- Maybe PB & hybrid glue form resonant cavity → waves reflecting back and forth.
- Perhaps glue is undergoing some transition that affects reflectivity → CN turn-on.

Possible fix:
- Fill the gaps between hybrids and PB with the same glue to reduce reflections.
  - Important to use glue with same "index of refraction".
- Waves must then travel farther before reflecting.





Strategy #3: Filling in the gaps

Procedure:

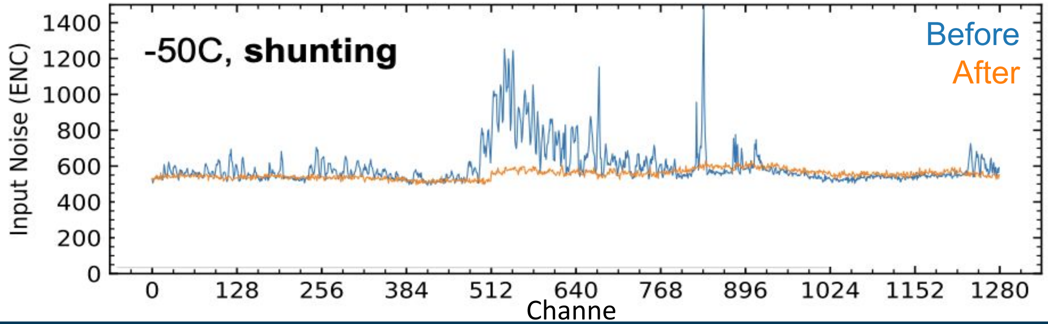
- Filled in gaps between hybrids and PB on existing module.
  - Originally built with worst glue (False Blue) → severe cold noise.
  - Filled gaps with more False Blue.

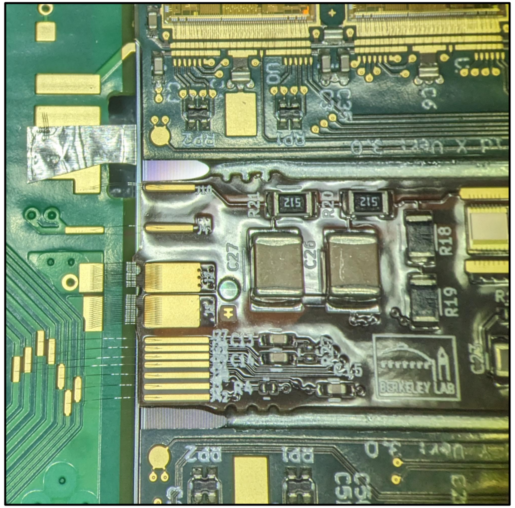
Results:

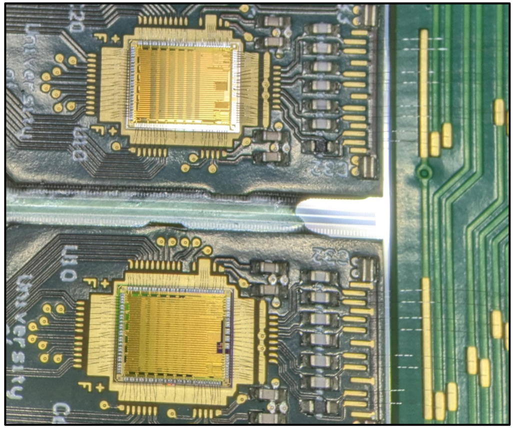
- Almost completely removed the cold noise!

- Repeated w/ more modules and other glues → similar improvements!
  - Results hold up over 50+ (extra stressful) thermal cycles!

- Need to develop a production friendly process & better understand the stress.
  - Filling gaps with a glue syringe is too tedious.







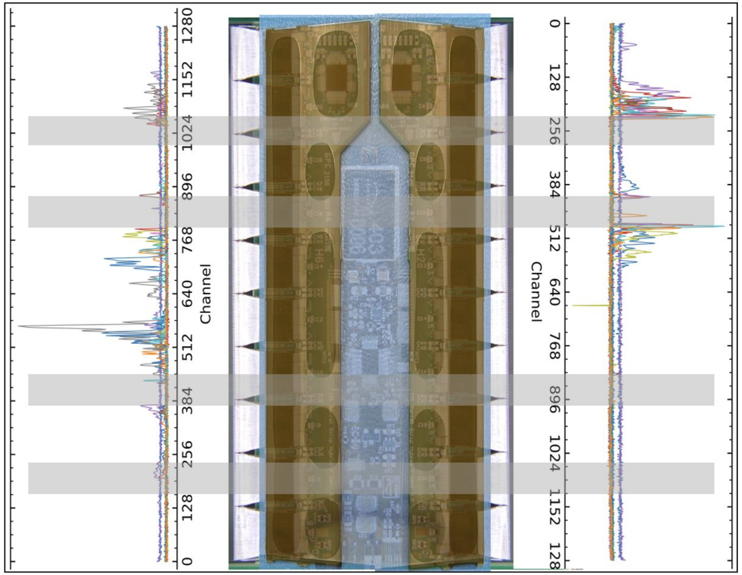
Concluding Thoughts

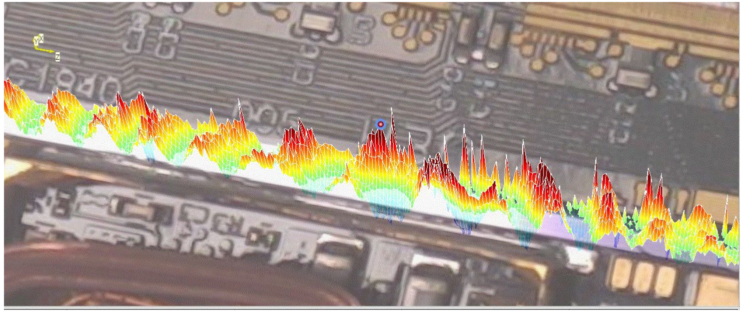
Putting It All Together (Speculative)

Vibrations:
- PB is always vibrating, at all temperatures.
  - Waves reflecting off glue-sensor interfaces.
  - Resonant cavities forming between hybrid and PB glue lines?

Phase transition:
- When cold, module undergoes phase transition.
  - Related to stress from CTE mismatch?
- Somehow affects how waves propagate and produce noise?
  - Mechanical impedance of glue changes?

Mechanical waves → electrical signal:
- Vibrations produce time-dependent voltage.
  - Possibly between strip implants and ASIC ground.
  - Piezoelectricity in AC coupling dielectric? Or in the glue?
- *Effective* discrimination threshold oscillates in phase with DC-DC converter.
  - Looks like gaussian noise when triggering asynchronously.





Summary

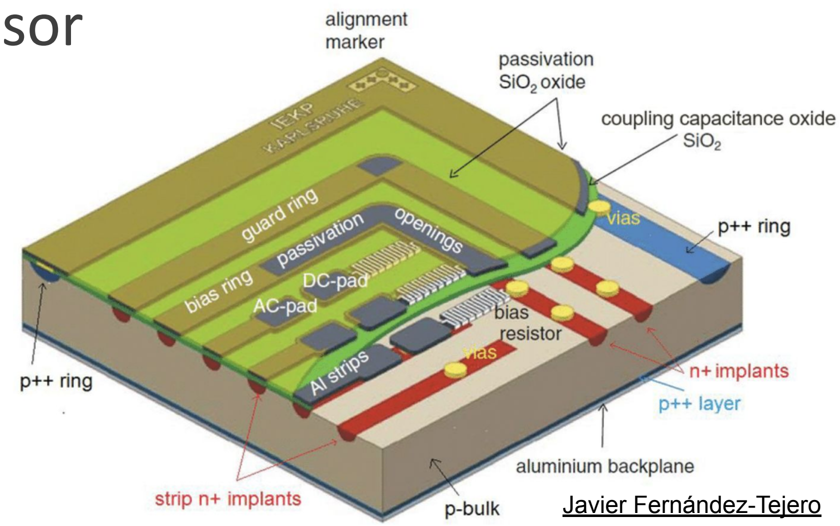
Cold noise

- In early 2022, we observed very noisy channels when testing modules at cold temperatures.
  - Decided to pause pre-production to investigate.
- Capacitors on the powerboard are vibrating at the DC-DC converter frequency (2 MHz).
  - Produces mechanical waves that travel through the sensor.
  - Confirmed by vibrometer measurements.
- Mechanical vibrations appear to be producing a voltage → effective discrimination threshold oscillates.
  - Exact mechanism not yet understood.

Mitigation strategies:

1. Using a particular glue (True Blue = Loctite Eccobond F112) & possibly doubling its thickness.
   - Do not understand why this helps.
2. Redesigning the powerboard flex to more closely match the endcap.
   - Early results are discouraging, but we're trying new layout with staggered microvias.
3. Filling in the gaps between the hybrids & PB with more glue.
   - Very encouraging results, but need to develop a production-friendly process

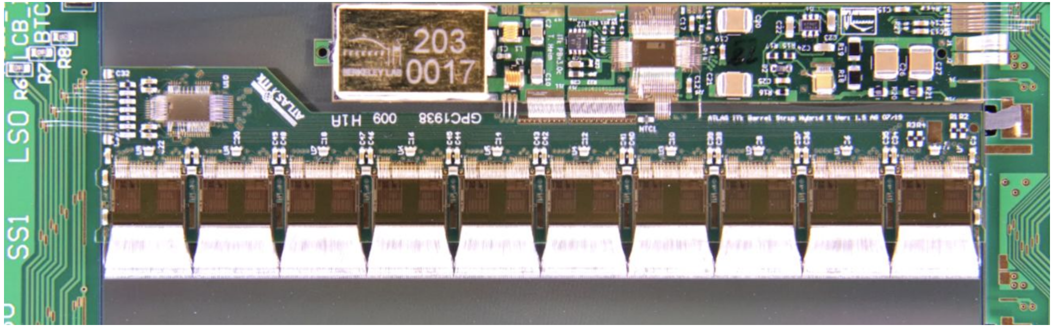
ITk Strip Sensor

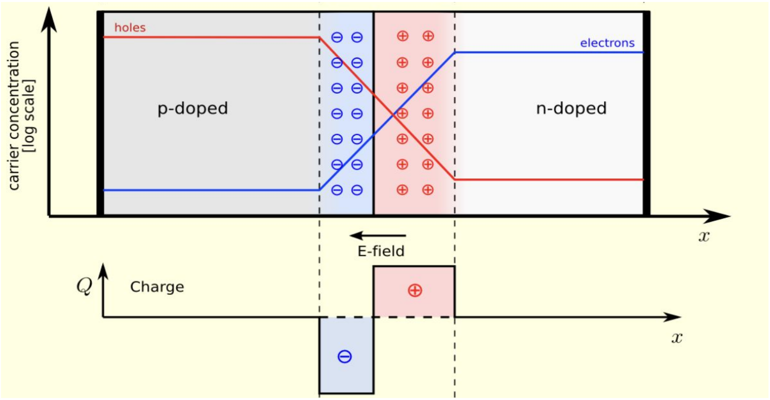


1: Schematic representation of a n-on-p AC-coupled silicon strip detector. Figure adapted from [27].

Silicon sensor:

- n-type Si strips implants on p-type Si bulk → p-n junction.
- Apply -350V reverse bias between implants and aluminum backplane.
  - Depletion zone grows as charge carriers removed from bulk.
- Charge particles passing through will ionize Si in depletion zone.
  - Electrons drift to n^+ strip implant.
  - Holes drift to sensor backplane.
- Aluminum bond pads are AC coupled to each strip.
  - Pads are wire bonded to ABC chips.





Measuring Noise

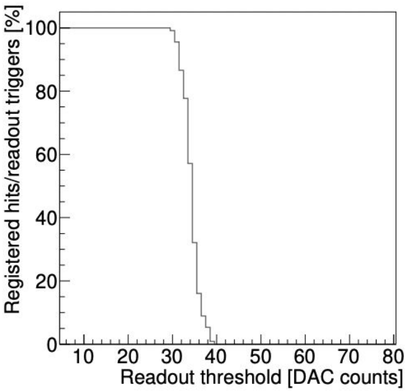
Binary Readout:

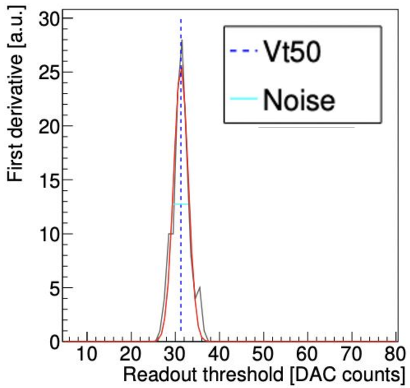
- ABCs amplify & discriminate signal from strips.
  - 1 bit per LHC BX indicating if strip above threshold.
  - Tune to balance signal efficiency vs. noise.

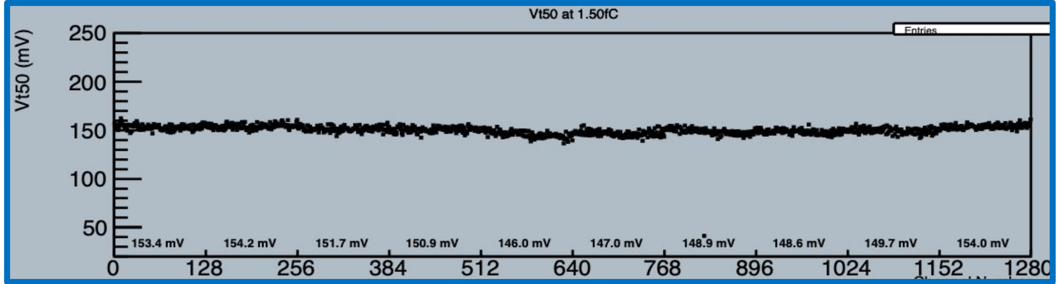
Noise metric:

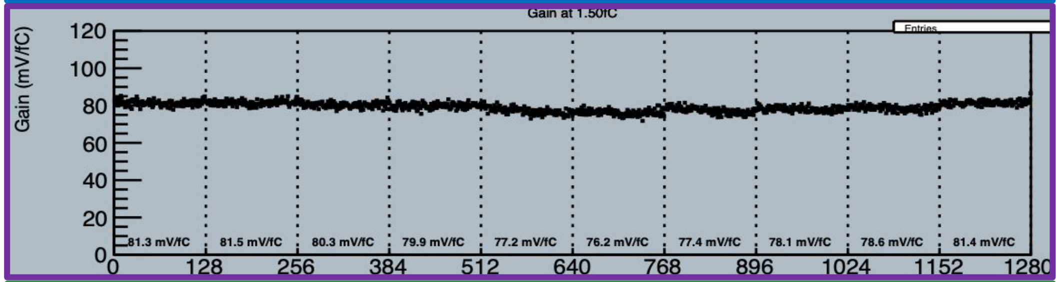
- Scan threshold & measure occupancy → S-curve.
  - Error function → derivative is a gaussian.
  - Mean → vt50, width → output noise.

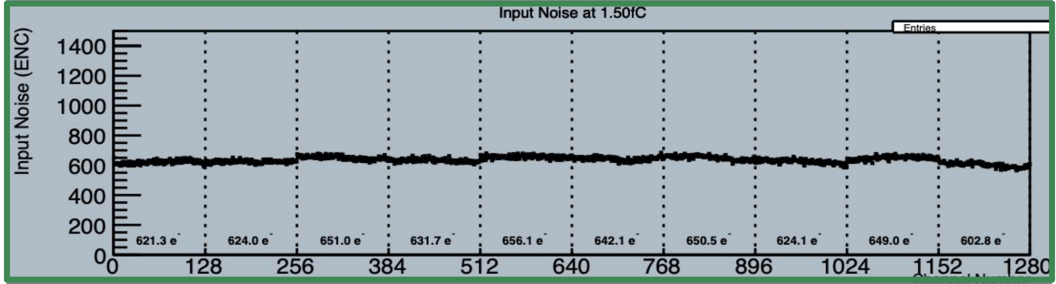
- Input noise [ENC] =
  output noise [voltage] / CSA gain [voltage / charge]

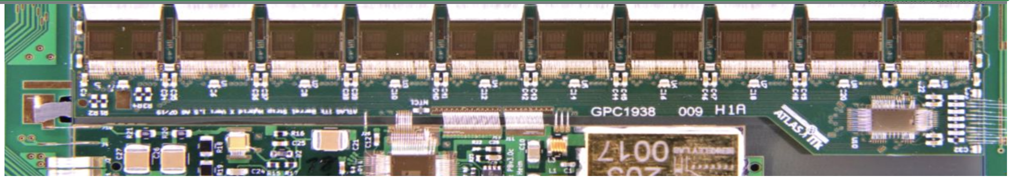








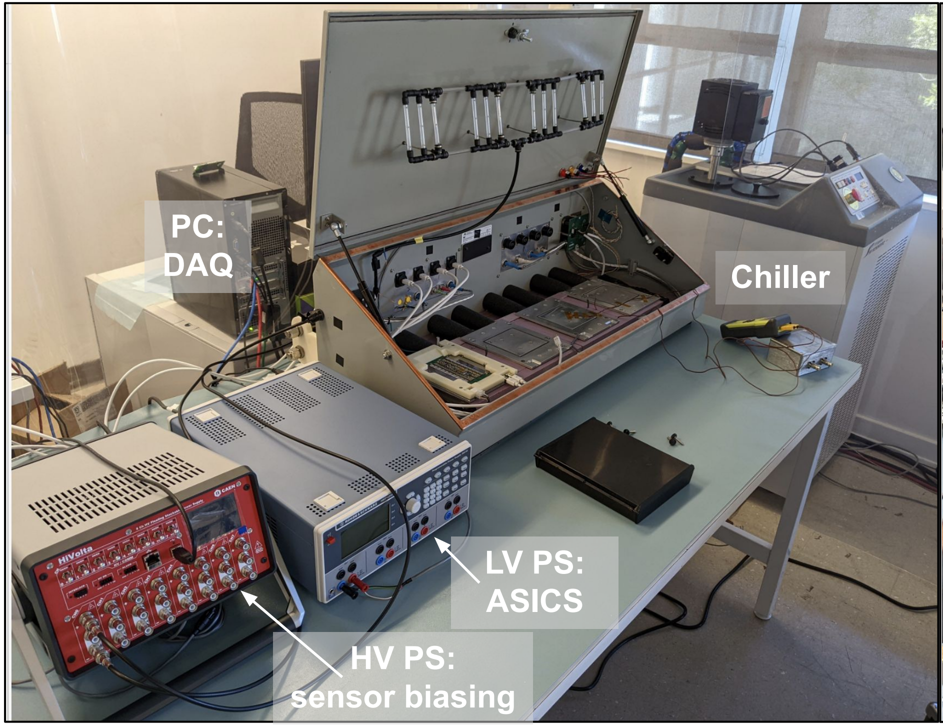


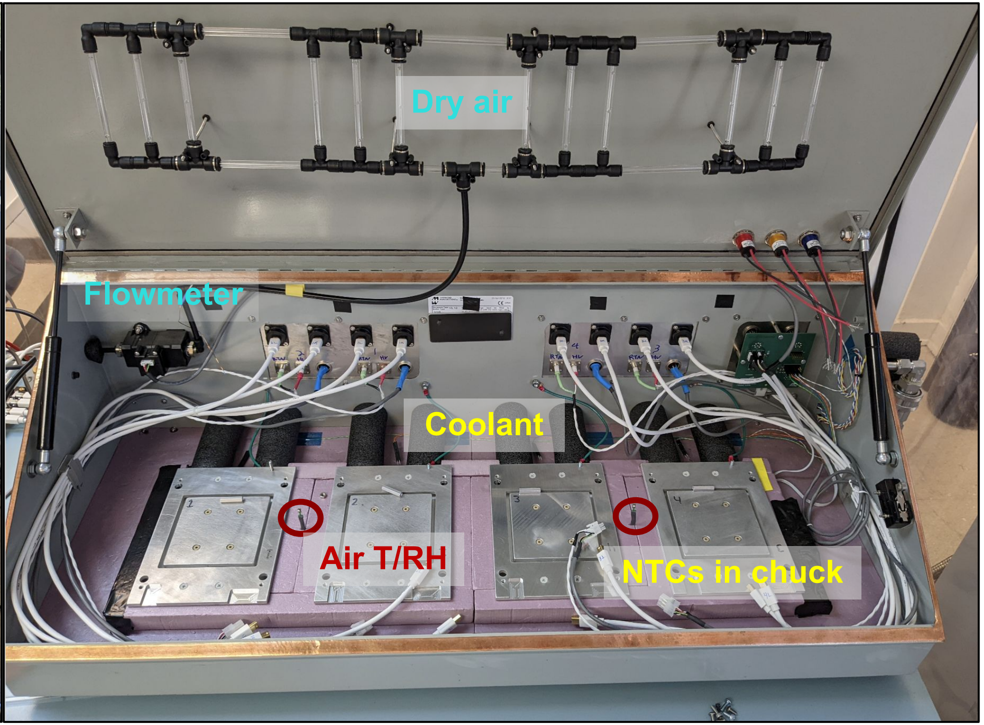


Thermal Cycling Setup

- Can electrically test up to 4 modules simultaneously.

- Nominal module QC: thermal cycle each module $10\times$ from -35C to $+40\text{C}$ (chuck temp).
  - Diagnostic stress tests: can reach -50C (and probably even colder).

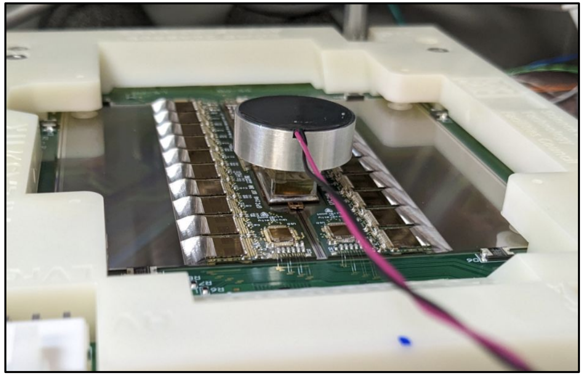


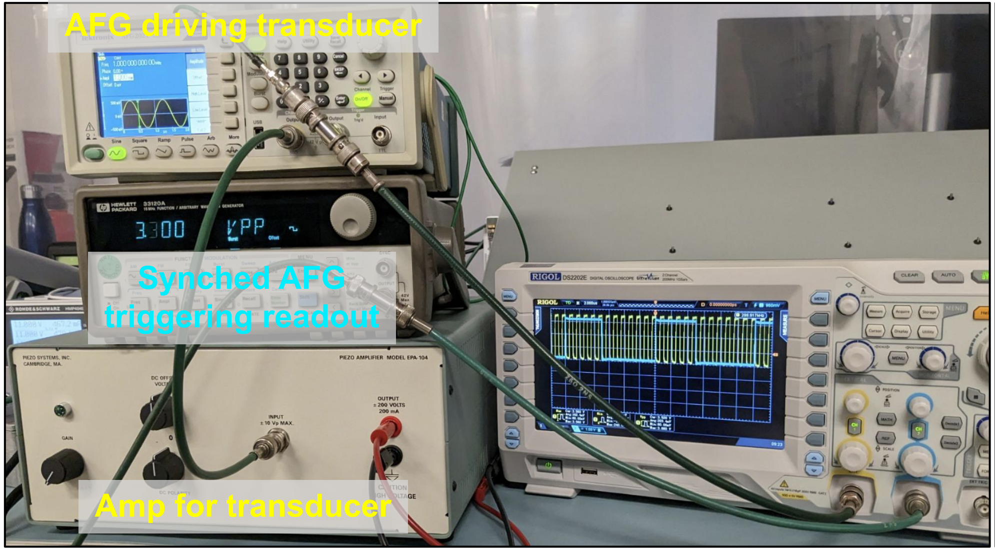


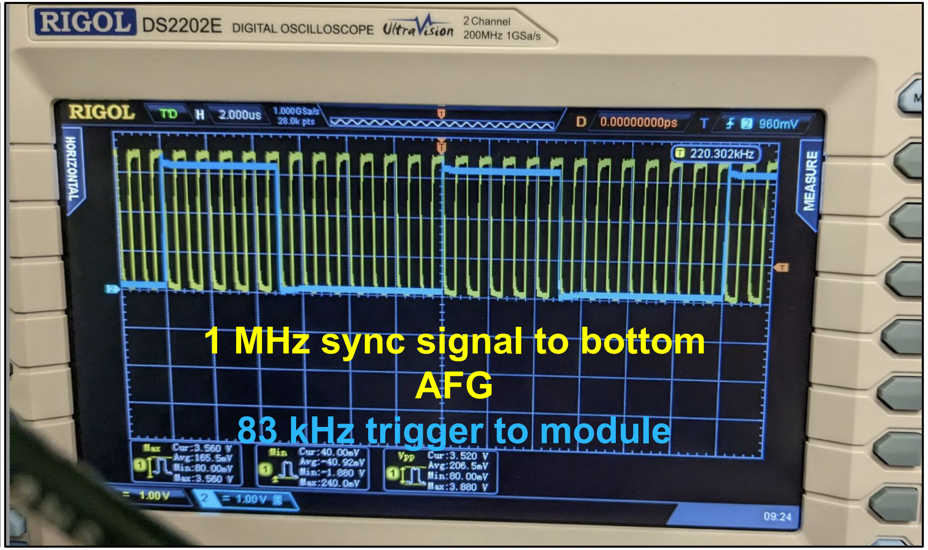
Transducer-Synchronous Triggering

Next step:

- Instead of triggering randomly (previous slide), synch trigger with transducer.
- Synchronized 2 waveform generators.
  - Top AFG drives transducer at 3 different frequencies (resonant at 1 MHz).
  - Bottom AFG sends trigger to module at ~80 kHz.
- Scanned trigger delay → noise occupancy vs. transducer phase.



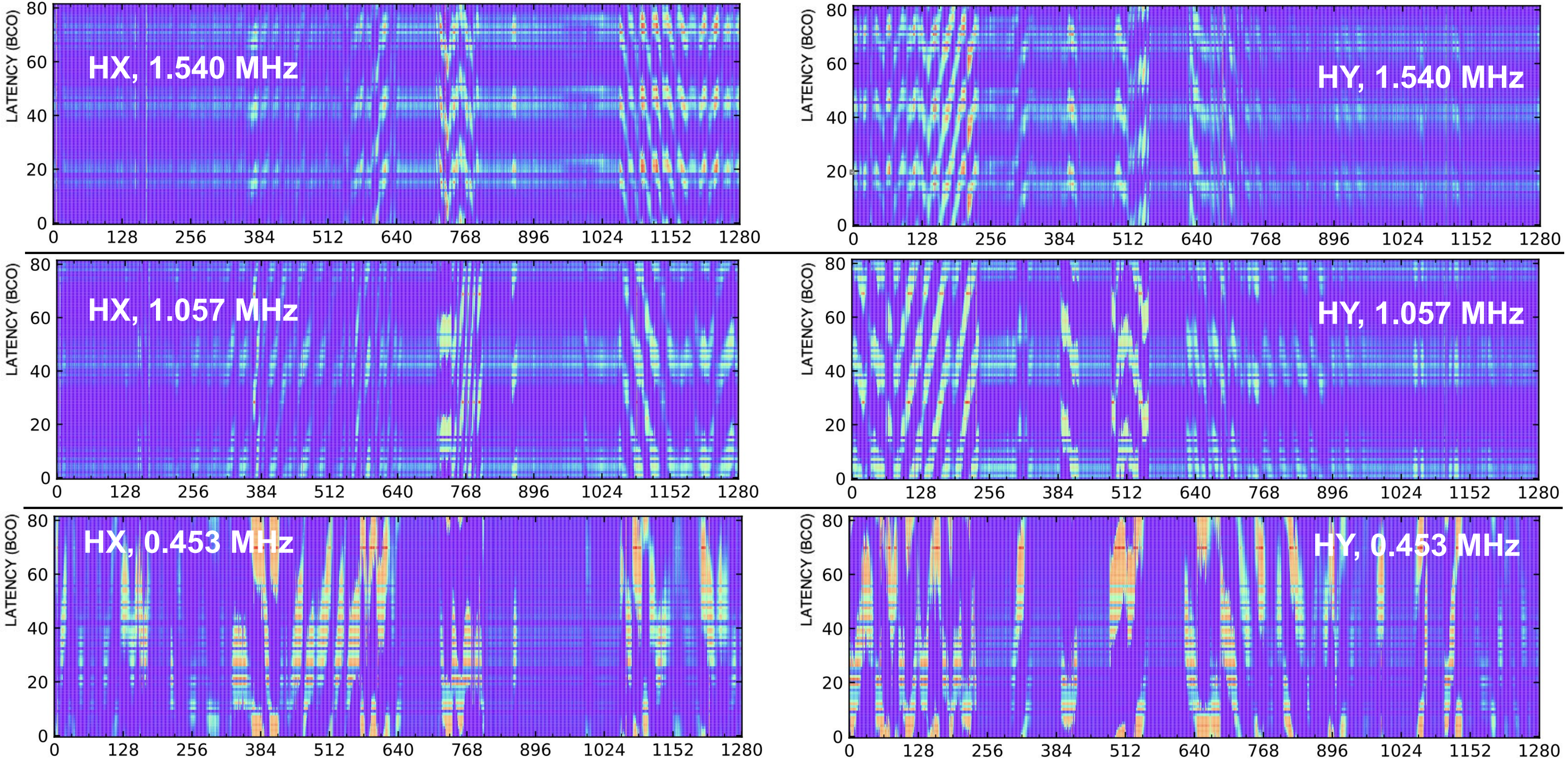




x-axis: strip number
y-axis:1 BCO = 25 ns
z-axis: noise occupancy

Transducer-Synchronous Triggering

Showing only strip rows covered by hybrids and PB.



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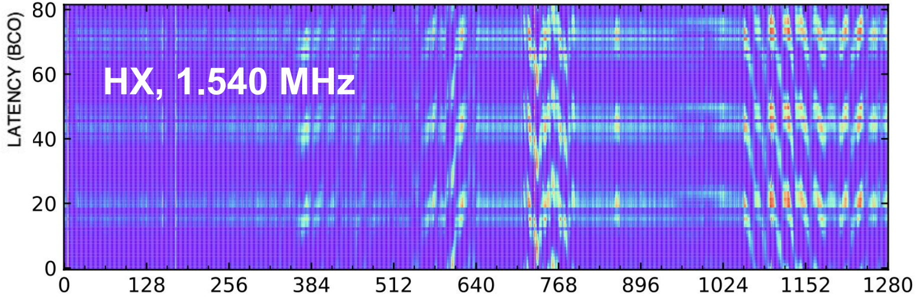
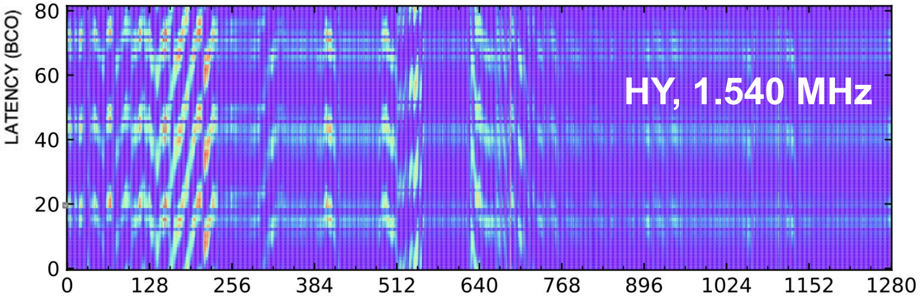
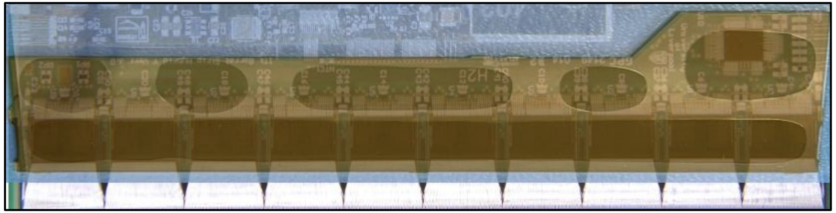
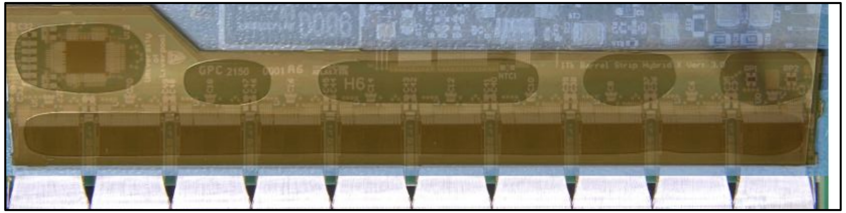


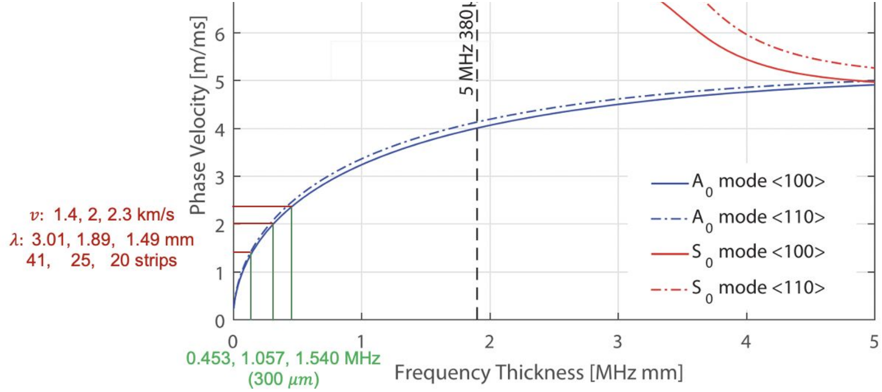




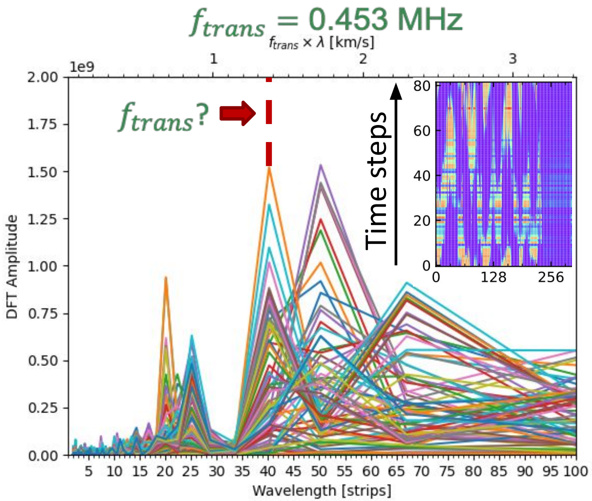


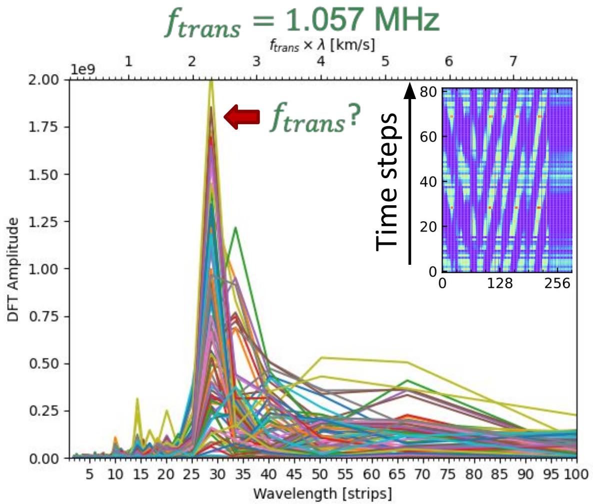
A_0 wave properties:

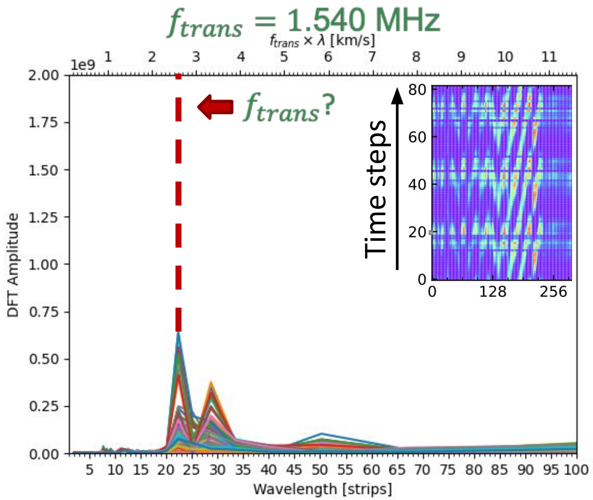
- $v_p \sim \sqrt{f}$ for low f ($\lambda \gg$ plate thickness).
- Can we see this dependence?



HY HCC Spectrum (Channels 0-200) @ -35C

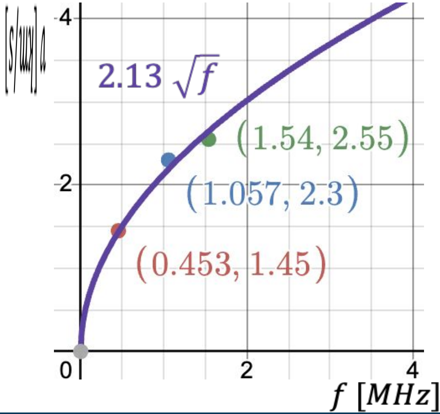






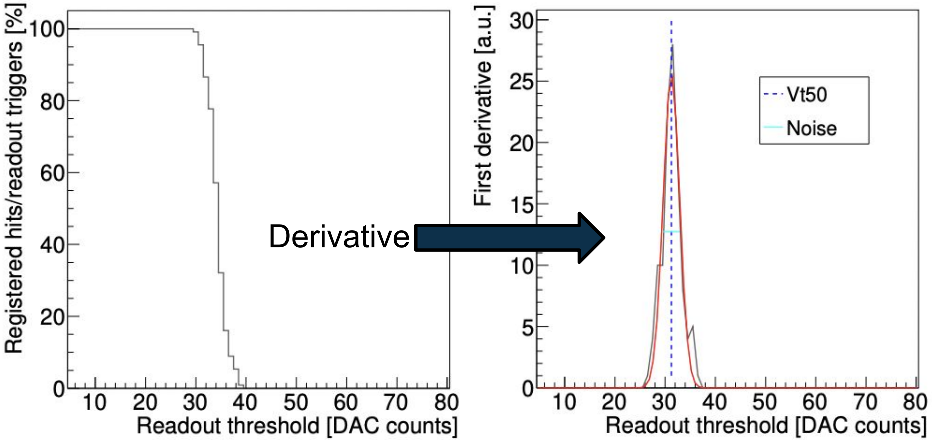
- For calculating power spectrum, zoomed in on HCC region on the Y-hybrid.
  - Cleanest signal, especially at higher frequency.

- Can guess which peak corresponds to a wave traveling at f_{trans} → can calculate $v(f) = \lambda(f) \times f$.
  - Only three points, but roughly follows expected $v \sim \sqrt{f}$ behavior for A_0 wave.

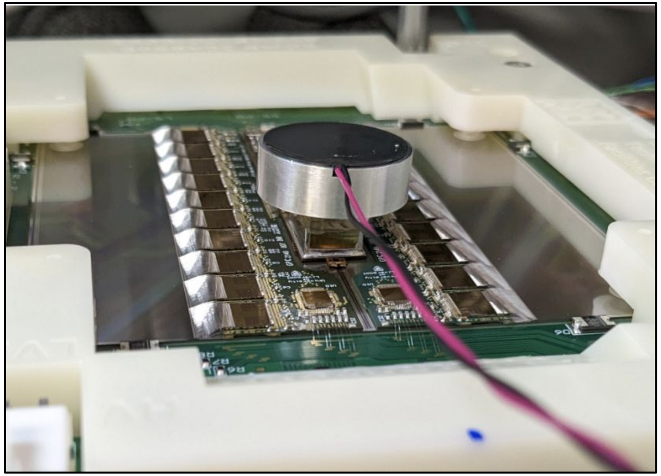


Simultaneous Delay & Threshold Scan

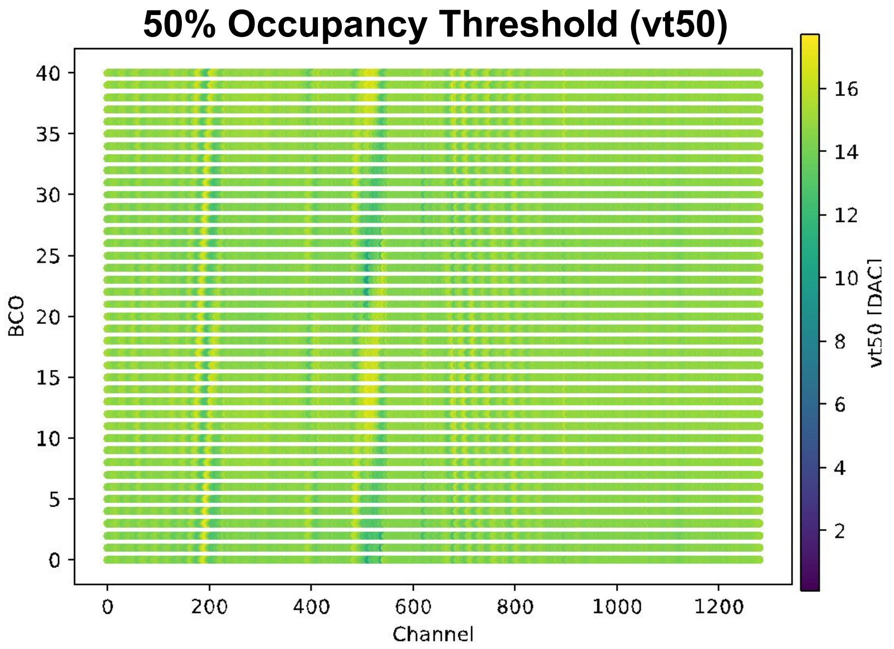
Threshold scans:
- ATLAS Binary Chips amplify and discriminate strip signal.
  - Tunable threshold.
  - Balancing signal efficiency vs. noise rejection.
- Measure strip occupancy vs threshold → S-curve.
  - Mean: 50% occ. threshold (vt50).
  - Width: output noise.

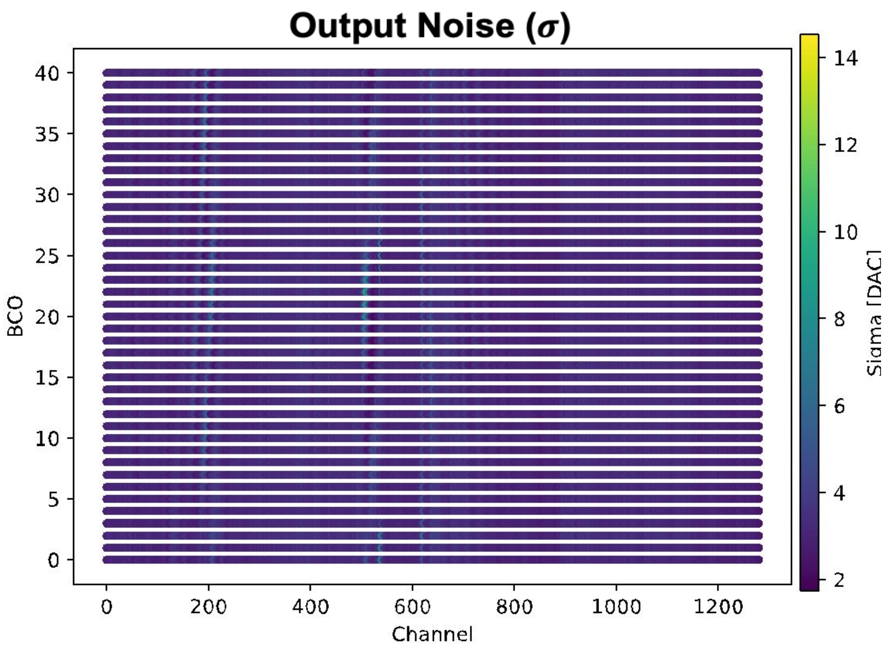


Simultaneous trigger delay & threshold scan:
- Vibrate module with 1 MHz transducer.
- Trigger module readout synchronous with transducer
  - Scan over trigger delay & discrimination threshold.
- Produce a vt50 & noise measurement for each trigger delay step.



Simultaneous Delay & Threshold Scan





- Observe more variation in the 50% occupancy threshold (vt50) than the output noise (σ).
  - S-curves are shifting left and right with transducer.

- As if the "effective" threshold is shifting up and down in phase with the transducer.
  - Not some Gaussian noise source with a varying width.

- Time-dependent voltage difference between implant and hybrid/ASIC ground?

Required Performance

8.5 Expected End-of-Lifetime Performance

At the end-of-lifetime, modules are required to have greater than 99% detection efficiency at thresholds that allow for operation with less than 1×10^{-3} channel noise occupancy. It has been shown that requiring a signal-to-noise ratio of 10:1 will simultaneously satisfy these efficiency and noise occupancy requirements. For this signal-to-noise ratio calculation, the signal is defined to be the sum over a number of strips using a cluster algorithm and analogue read-out electronics operating at HL-LHC speeds and the noise is the average single-channel noise. Previous sections in this chapter have shown the signal, the hit

Table 8.2: Estimated signal-to-noise at the end-of-lifetime for all module types of the ITk Strip Detector. Maximal values of the Fluence include a safety factor of 1.5

Module Type	Fluence $10^{14} n_{eq} cm^{-2}$	Charge ke^- 500 V	Charge ke^- 700 V	Noise e^-	S/N 500 V	S/N 700 V
SS	8.1	13.7	16.1	630	21.8	25.6
LS	4.1	17.3	19.5	750	23.1	26.0
R0	12.3	11.5	14.0	650	17.7	21.5
R1	10.1	12.5	15.0	640	19.6	23.4
R2	8.7	13.3	15.7	660	20.3	23.9
R3	8.0	13.8	16.2	640	21.4	25.1
R4	6.8	14.6	17.0	800	18.4	21.3
R5	6.0	15.3	17.6	840	18.3	21.1

1 Femtocoulombs

= 6241.5091258833 Electron Charge

Table 1
Sensor specifications.

Parameter	Value (range: tolerance)
Wafer	
Diameter	6-in. (150 mm)
Type	p-type FZ
Crystal orientation	⟨100⟩
Thickness (physical)	320 ± 15 μm
Thickness uniformity	±10 μm
Thickness (active)	>270 μm
Resistivity	>3.5 kΩ cm
Oxygen concentration	0.8×10^{16} to 7×10^{17} cm^{-3}
Full depletion voltage	V_{FD}< 330 V
Maximum operation voltage	V_{OP} = 700 V
Outer dimension	(after process/dicing)
Width ×Length	97.950 × 97.621 μm^2
Dicing tolerance	±20 μm
Bow	<200 μm
Strips	
Implant	N
Rows of strip segments	2
Length of segment	48.306 mm (approx.)
Pitch (round of 0.5 μm)	75.5 μm
Implant width	16 μm
Readout coupling	AC
Readout metal and width	Pure Aluminum, 22 μm
AC coupling capacitance	>20 pF/cm
Resistance of N-implant strips	<50 kΩ/cm
Resistance of readout metals	<30 Ω/cm
Bias resistor	Polysilicon
Bias resistance (R_b)	1.5 ± 0.5 MΩ
N-strips isolation	Common p-stop
Surface passivation	Strip-side passivated

Table 2
Sensor performance specifications.

Parameter	Value (range: tolerance)
Initial	(measured at RT)
Interstrip resistance (R_{int})	>10 × R_b at 300 V
Interstrip capacitance (C_{int})	<1 pF/cm at 300 V measured at 100 kHz
Number of defects[a]	<1% per row, <1% per sensor <8 consecutive bad strips
Leakage current	<0.1 μA/cm² at 700 V
Leakage current stability[b]	<15% for 24 h at RH < 5%, at V_{FD} + 50 V
Microdischarge onset voltage	V_{MD} > 700 V
After irradiation	(measured at −20 °C)
Fluence (of particles)	Up to 2×10^{15} neq/cm²
Ionizing dose (γ's)	Up to 60 Mrad.
Micordischarge onset voltage	> 700V or >V_{FD} + 50 V (if V_{MD} < 700 V)
Interstrip resistance	>10 × R_b at 400 V
Collected charge (per MIP)	> 7500 electrons at 500 V

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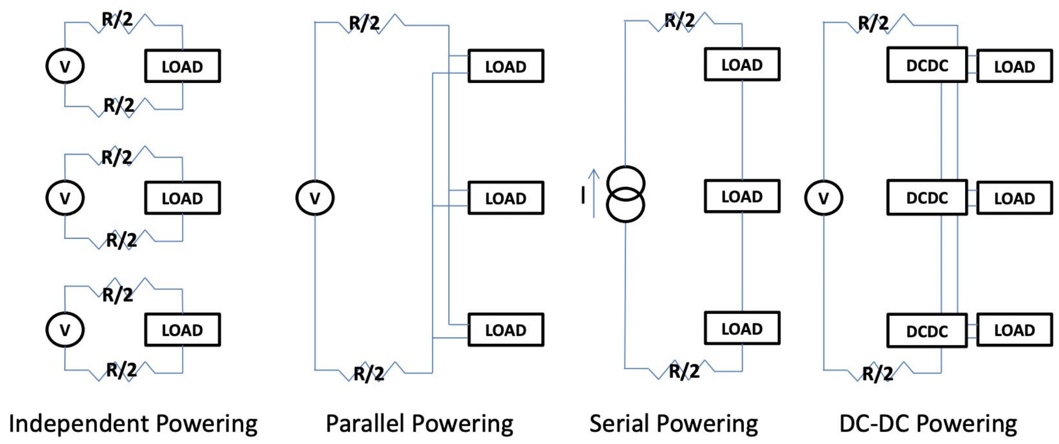
The Powerboard: A Closer Look

Voltage Stepdown:

- ABCs and HCC need 1.5V.
  - But distribute 11V to modules & use DC-DC conversion.
  - Reduce ohmic losses.

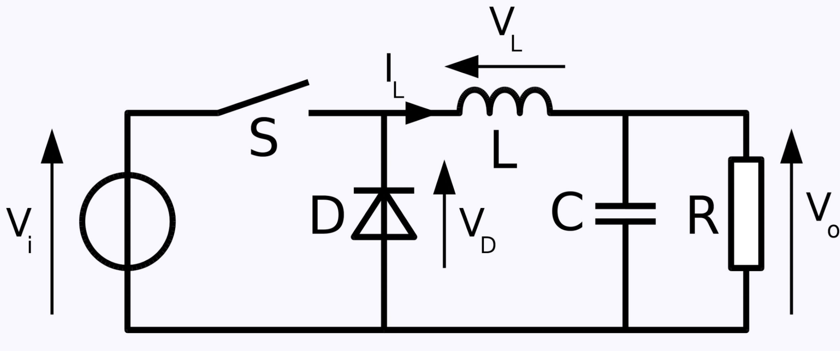
- Use a buck converter (bPOL) & air-core coil on powerboard.
  - More efficient than a linear regulator → less heat.
  - But 2 MHz switching → EM noise (hence shield box).

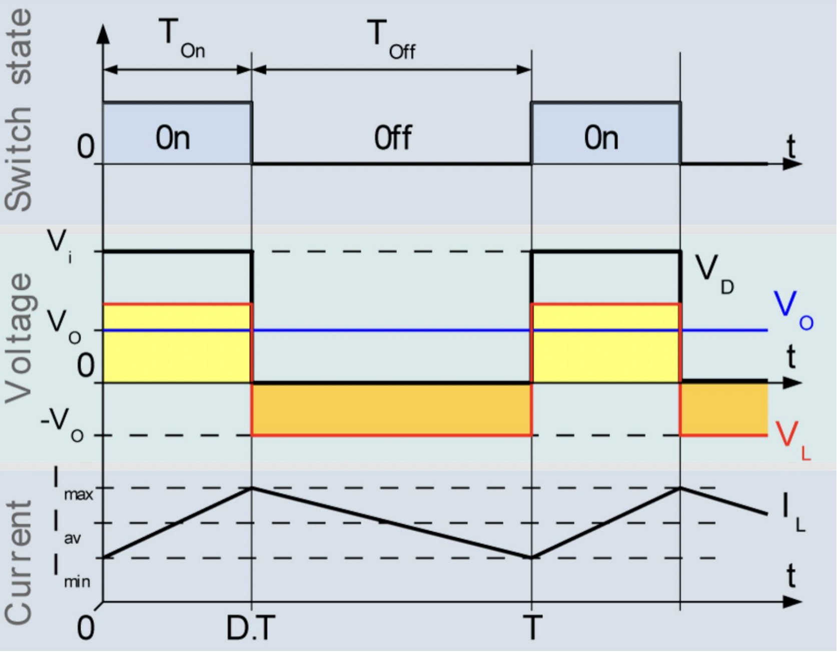


Losses in off-detector cabling of total resistance R for n loads drawing current I:

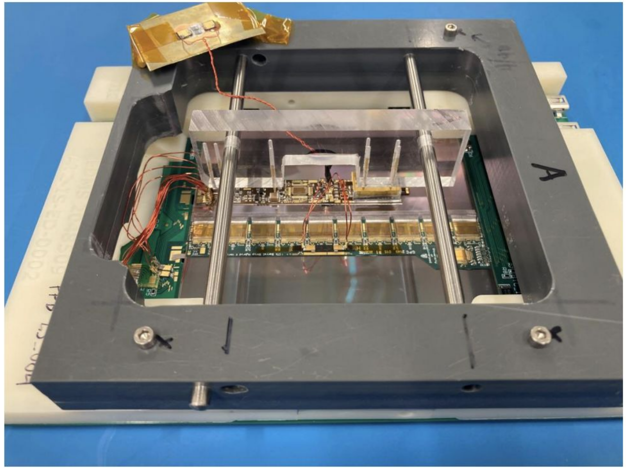
Independent Powering	Parallel Powering	Serial Powering	DC-DC Powering
$P = nI^2R$	$P = n^2I^2R$	$P = I^2R$	$P = n^2I^2R / r^2$ where ratio r = Vin/Vout

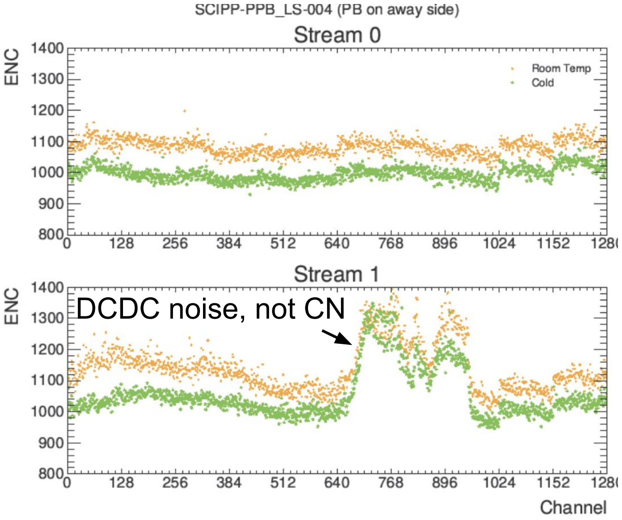
Powering modules on stave (from Peter Phillips)



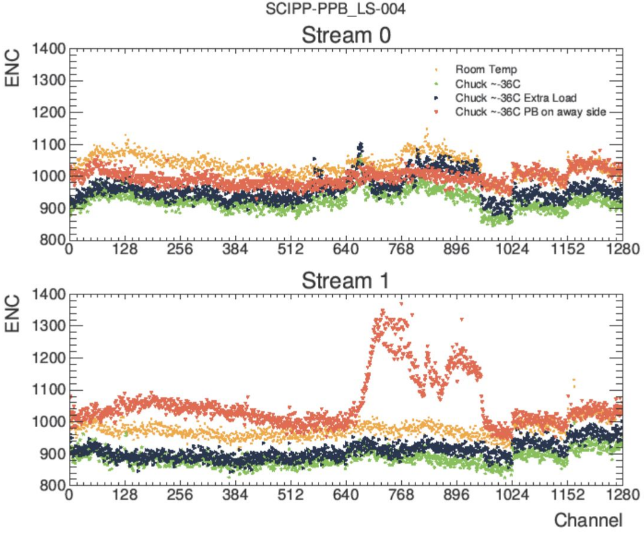


Moveable PB





PB on Stream 1 (not hybrid segment)
→ no cold noise anywhere!



PB on Stream 0 (usual location)
→ cold noise on Stream 0!

- Built LS module with moveable PB:
  - No glue (held down with weights)
  - Hybrid powered by PS,
  - Resistive load on PB emulating hybrids.
- PB in usual location (i.e. same row of strips as hybrid = stream 0) → cold noise.
- PB on opposite row of strips (stream 1) → no cold noise.
  - Maybe hybrid and PB have to be on same row of strips?