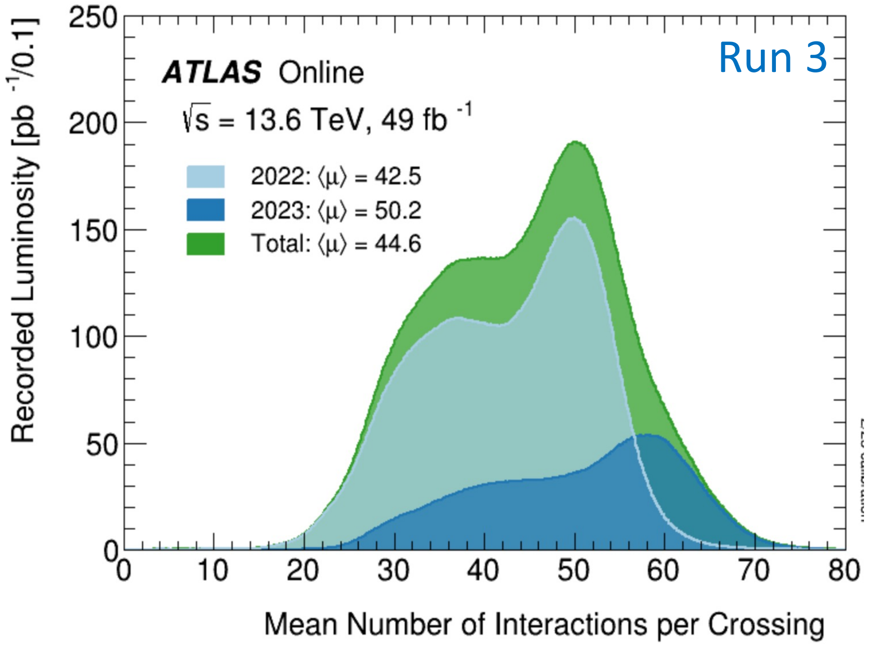
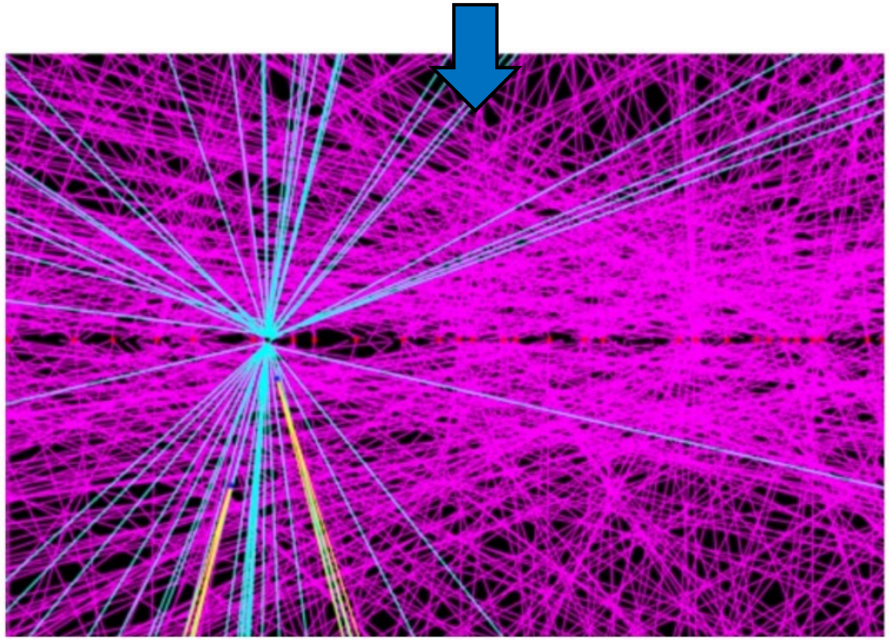
The Mystery of *Cold Noise* in ATLAS ITk Strip Modules

ITk Upgrade

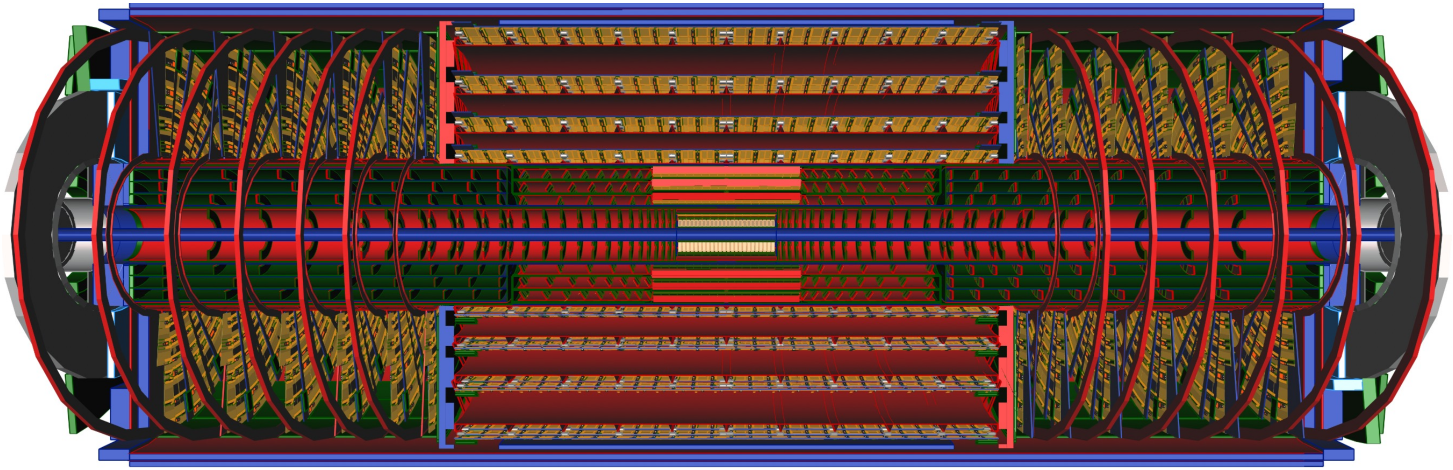
- ATLAS is replacing its inner detector for the High-Luminosity LHC.
  - More interactions per bunch crossing ($\langle\mu\rangle \approx 50 \rightarrow 200$).
  - Higher trigger rate (100 kHz → 1 MHz).
  - Worse radiation damage (up to $2{\times}10^{16}\ n_{\mathrm{eq}}/\mathrm{cm}^2$).

- Installing new, all silicon Inner Tracker (ITk).
  - Pixel modules for inner layers, strip modules for outer layers.
  - LBNL heavily involved in both pixels & strips.
    - Plus global mechanics & integration.





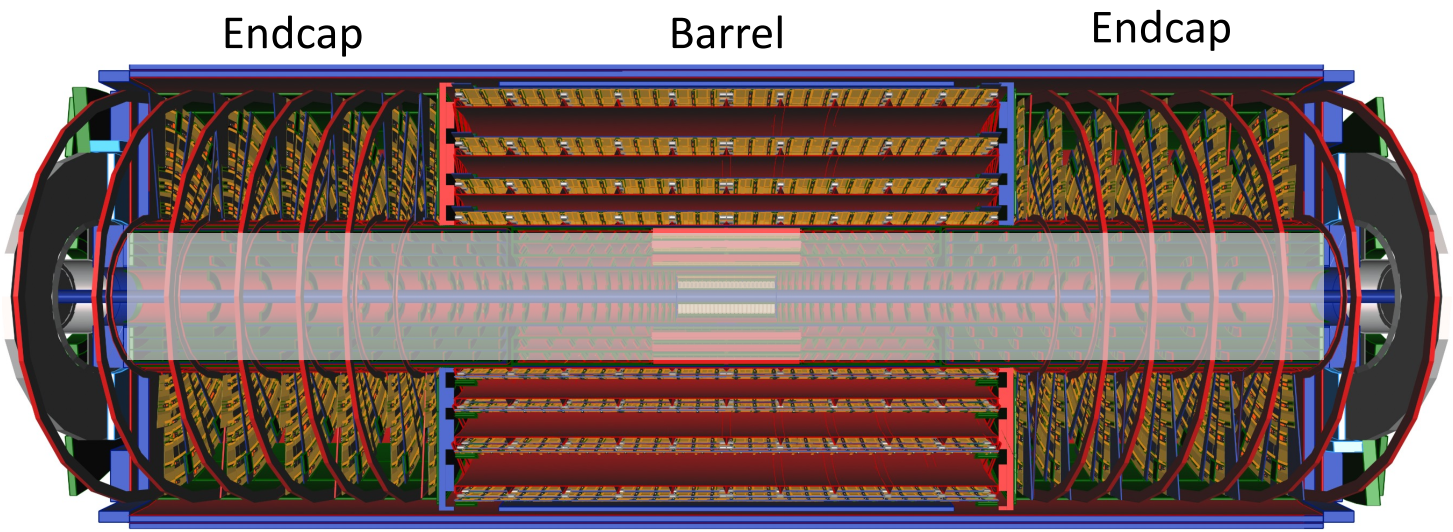
$t\bar{t}$ *event at* $\mu = 200$

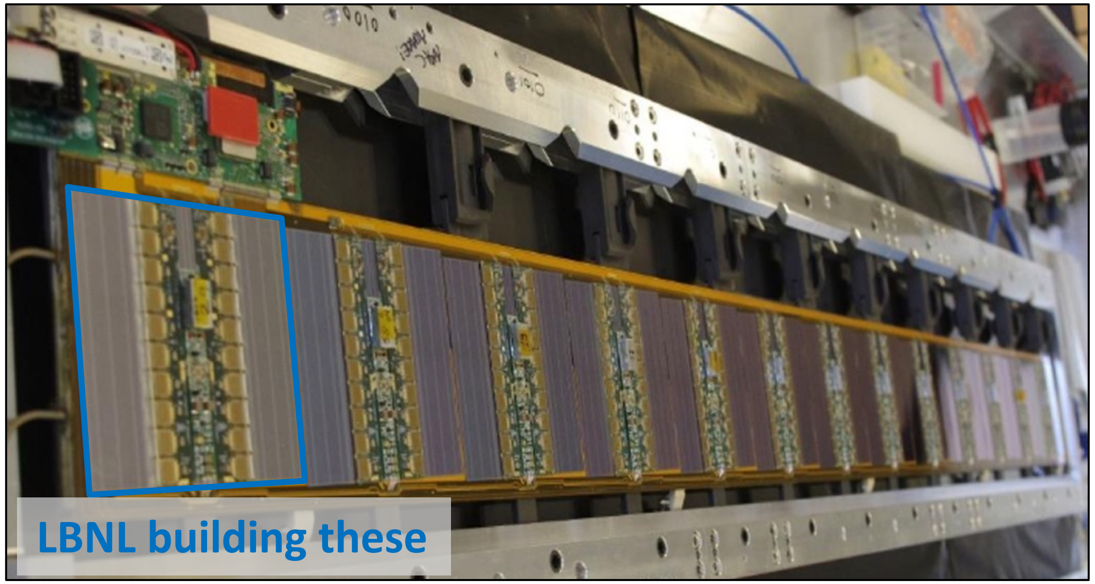


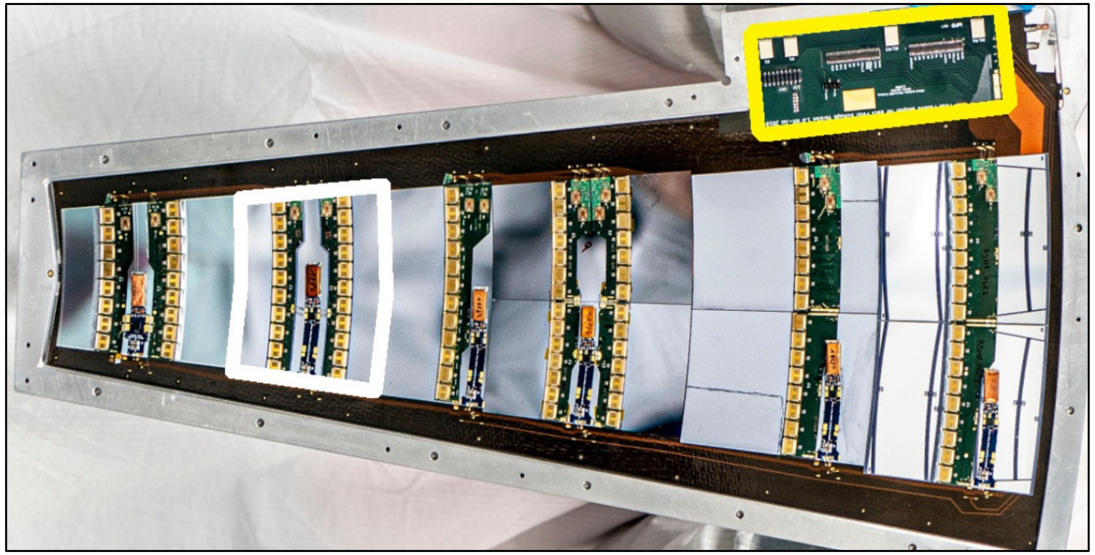
ITk Strip Detector

- Barrel composed of rectangular staves.
  - Assembled in 4 concentric cylinders around interaction point.
  - 14 identical modules on each side.

- Endcaps composed of petals.
  - 32 petals form a disk, 6 disks per endcap.
  - 6 different module geometries.







ITk Strip Barrel Module

Silicon sensor:

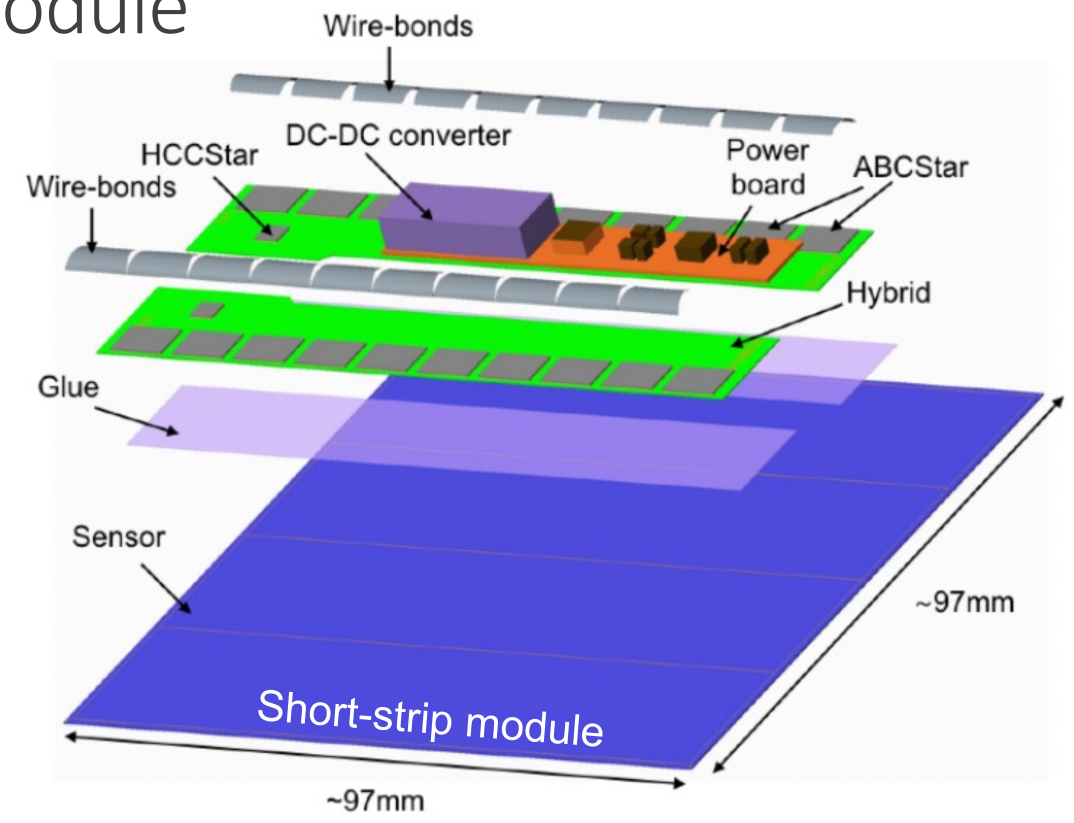
- Multiple rows of 1280 strips with a $75\ \mu m$ pitch.
    - Long-strip sensor → 2 rows, strip length ≈ 5 cm.
    - Short-strip sensor → 4 rows, strip length ≈ 2.5 cm.

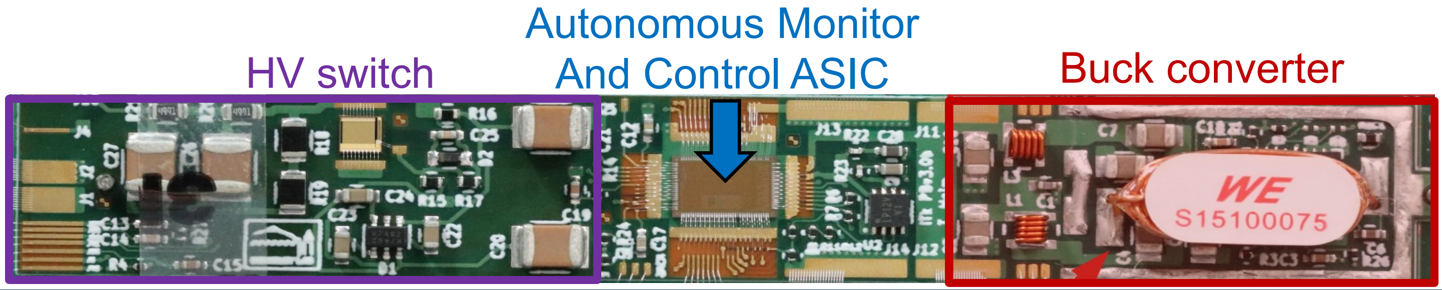
Hybrid:

- Printed circuit board holding the read-out ASICs.
    - 10 ABCs: amplify and discriminate signal.
    - 1 HCC: interface between ABCs and back-end electronics.

Powerboard:

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





ITk Strip Barrel Module

Silicon sensor:

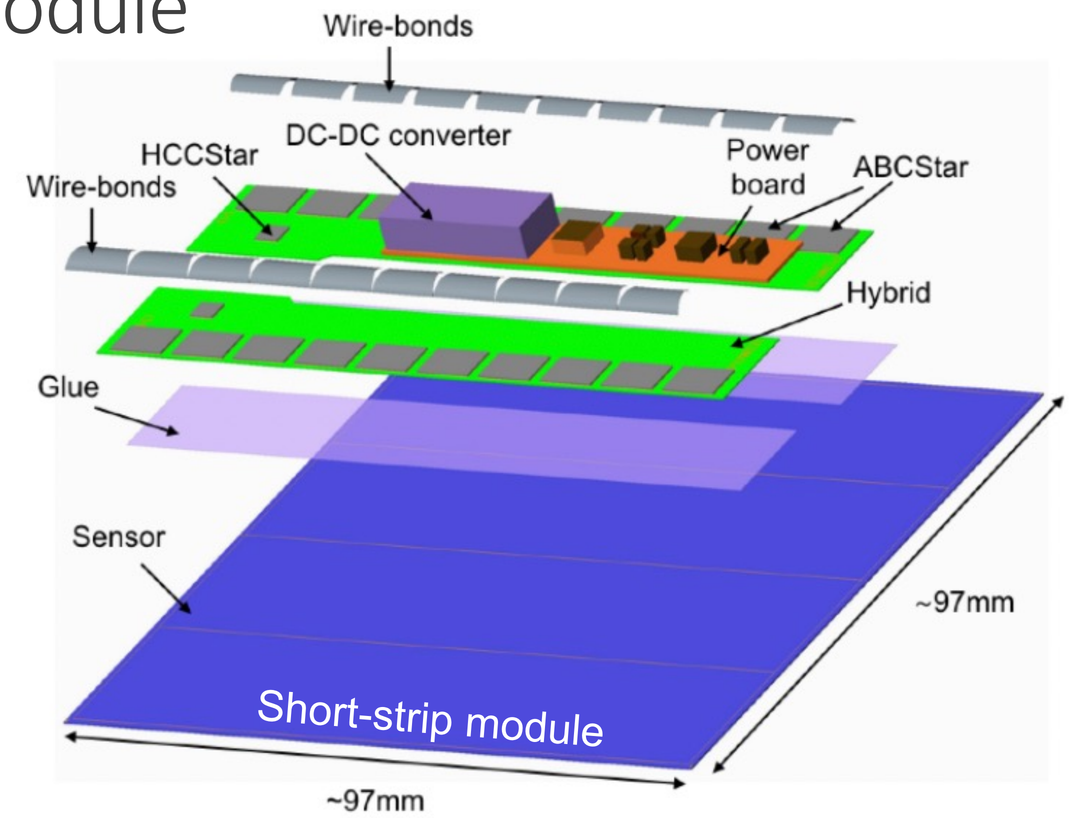
- Multiple rows of 1280 strips with a $75\ \mu m$ pitch.
  - Long-strip sensor → 2 rows, strip length ≈ 5 cm.
  - Short-strip sensor → 4 rows, strip length ≈ 2.5 cm.

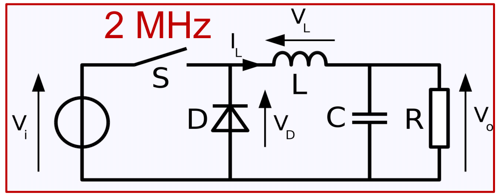
Hybrid:

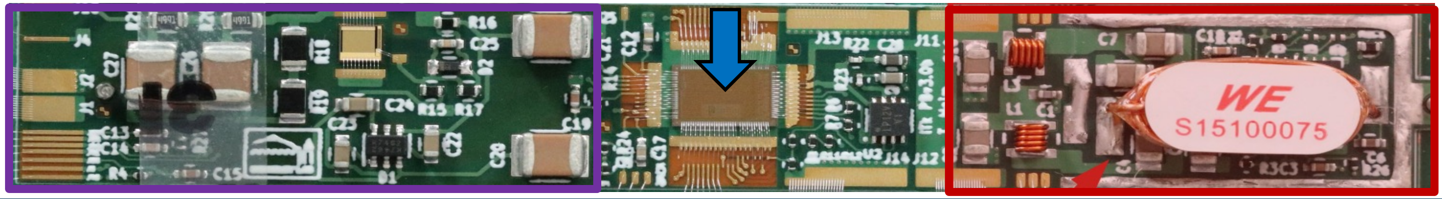
- Printed circuit board holding the read-out ASICs.
  - 10 ABCs: amplify and discriminate signal.
  - 1 HCC: interface between ABCs and back-end electronics.

Powerboard:

- ASIC power, monitoring & interlock, HV-switching for sensor biasing.
- Front-end chips require 1.5V, but distribute 11V to modules.
  - Use buck converter w/ air-core coil for DC-DC conversion.
  - 2 MHz switching → EMI → noise in silicon strips.
    - Mitigated by aluminum shield box.







ITk Strip Barrel Module

Silicon sensor:

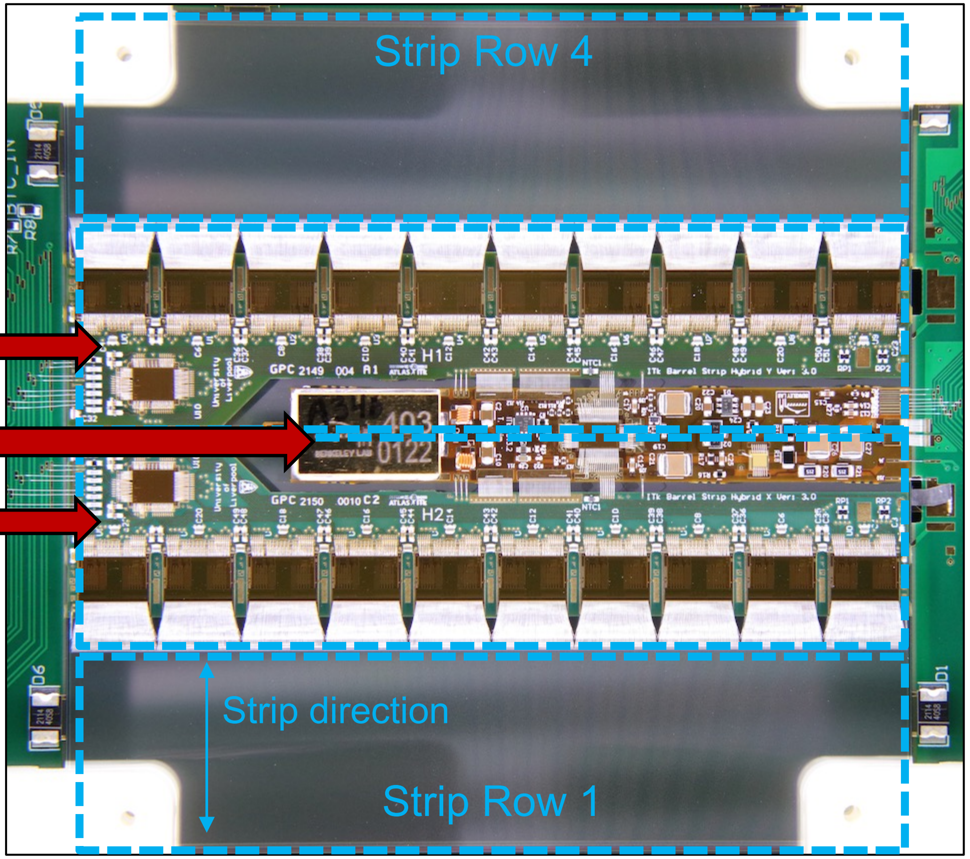
- Multiple rows of 1280 strips with a $75\ \mu\text{m}$ pitch.
  - Long-strip sensor → 2 rows, strip length ≈ 5 cm.
  - Short-strip sensor → 4 rows, strip length ≈ 2.5 cm.

Hybrid:

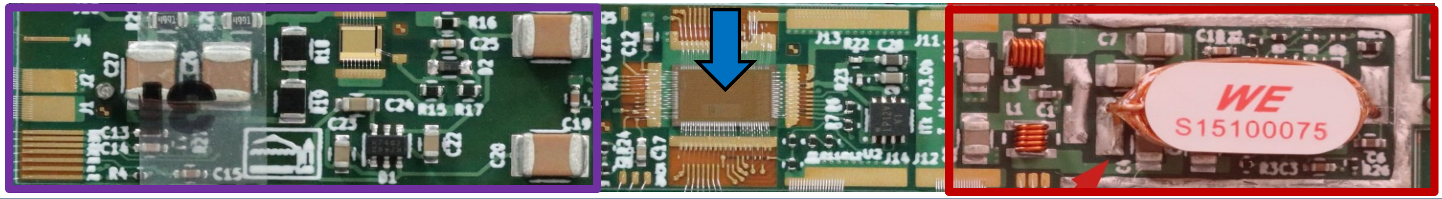
- Printed circuit board holding the read-out ASICs.
  - 10 ABCs: amplify and discriminate signal.
  - 1 HCC: interface between ABCs and back-end electronics.

Powerboard:

- ASIC power, monitoring & interlock, HV-switching for sensor biasing.
- Front-end chips require 1.5V, but distribute 11V to modules.
  - Use buck converter w/ air-core coil for DC-DC conversion.
  - 2 MHz switching → EMI → noise in silicon strips.
    - Mitigated by aluminum shield box.



Short-strip module



ITk Strip Barrel Module

Silicon sensor:

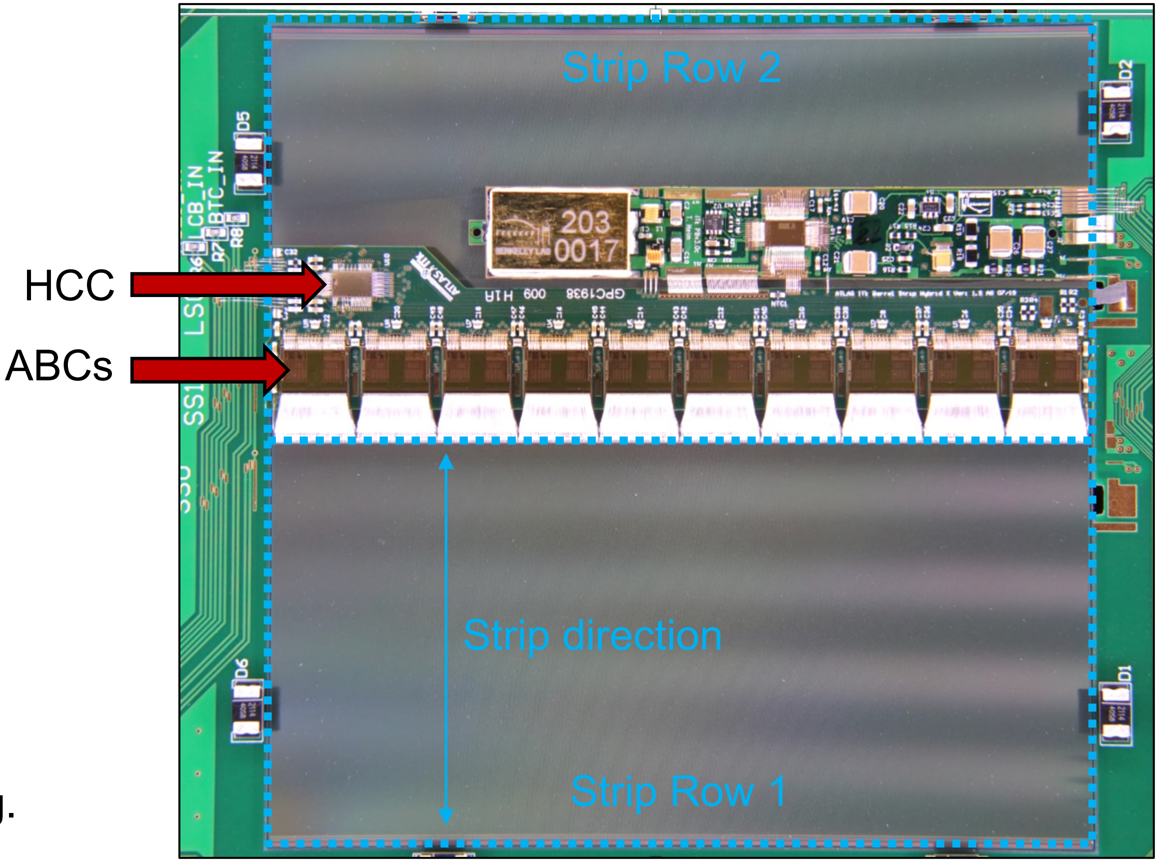
- Multiple rows of 1280 strips with a $75\ \mu m$ pitch.
    - Long-strip sensor → 2 rows, strip length ≈ 5 cm.
    - Short-strip sensor → 4 rows, strip length ≈ 2.5 cm.

Hybrid:

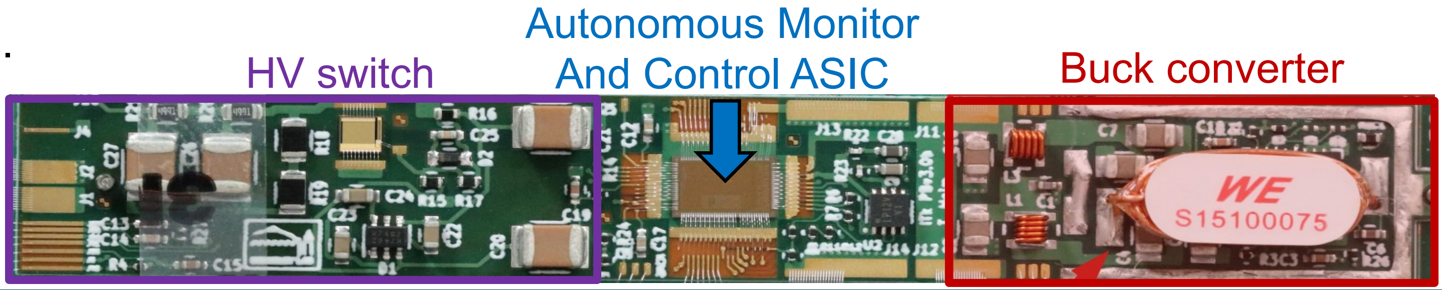
- Printed circuit board holding the read-out ASICs.
    - 10 ABCs: amplify and discriminate signal.
    - 1 HCC: interface between ABCs and back-end electronics.

Powerboard:

- ASIC power, monitoring & interlock, HV-switching for sensor biasing.
- Front-end chips require 1.5V, but distribute 11V to modules.
    - Use buck converter w/ air-core coil for DC-DC conversion.
    - 2 MHz switching → EMI → noise in silicon strips.
        - Mitigated by aluminum shield box.

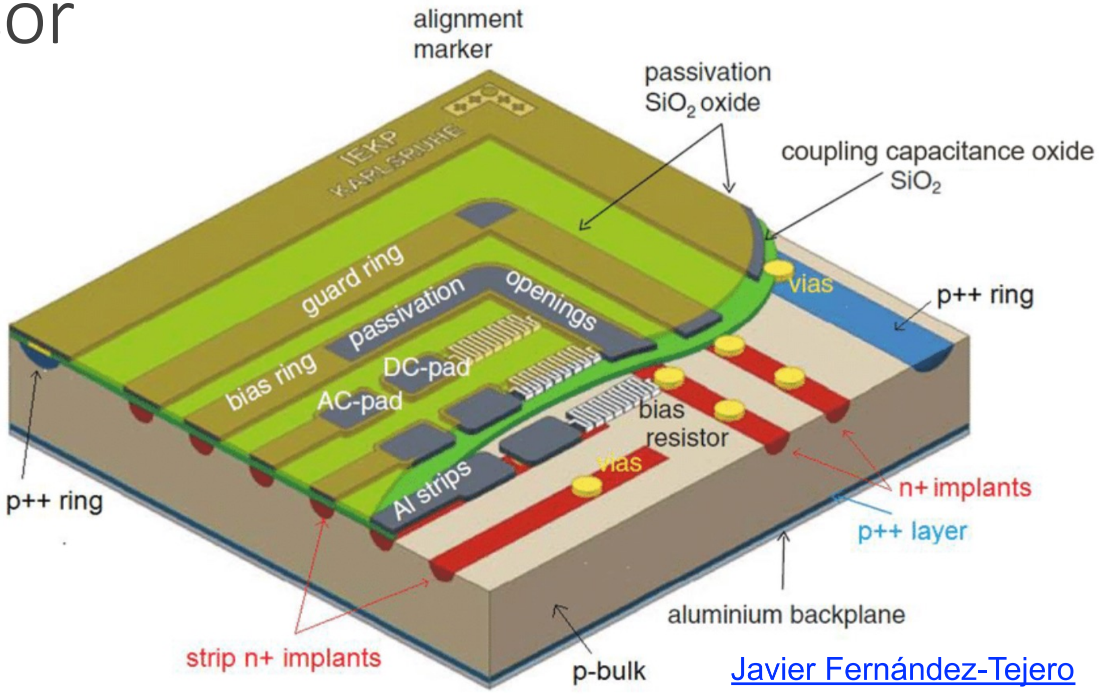


Long-strip module



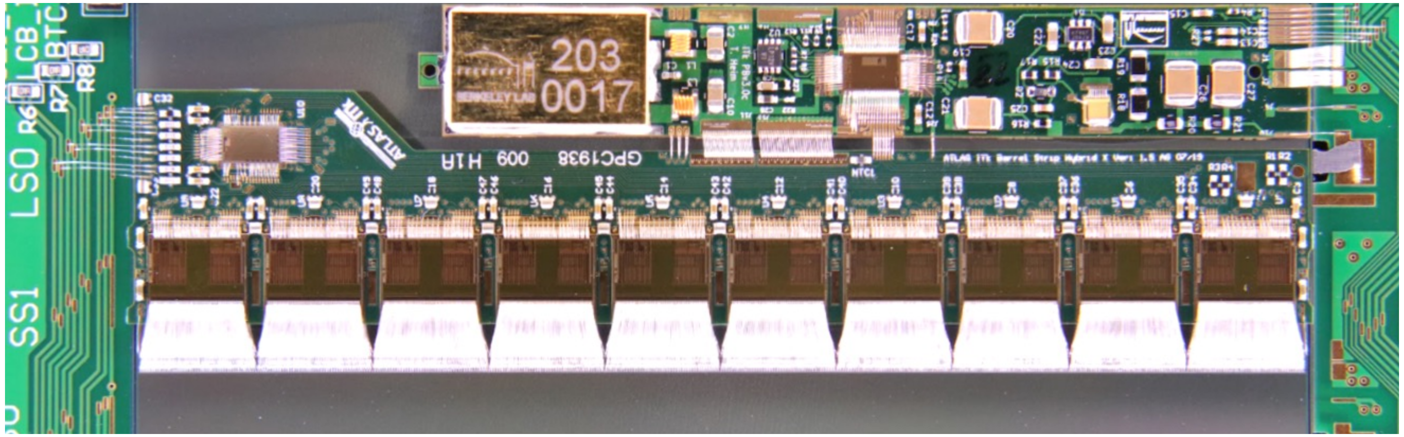
ITk Strip Sensor

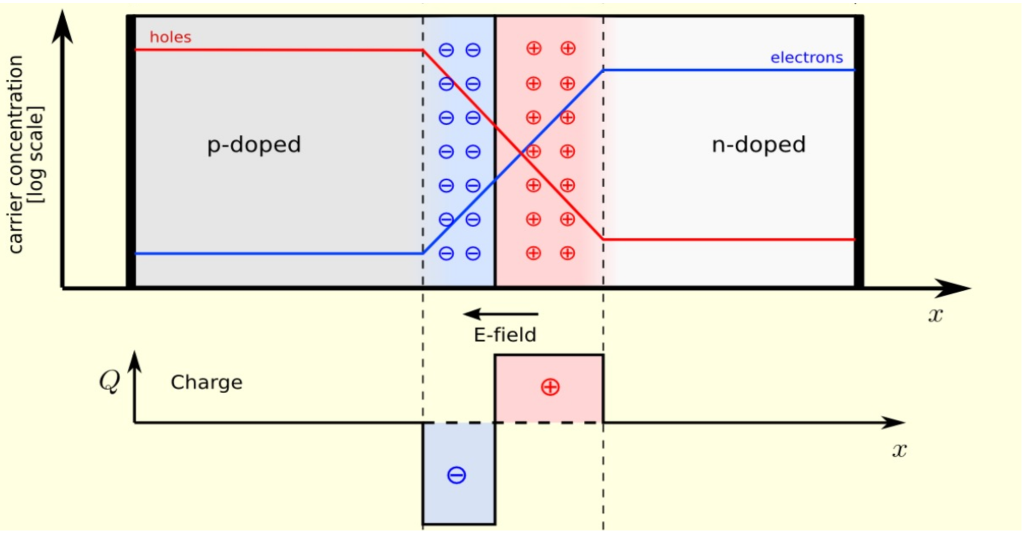
Silicon sensor:
- n-type Si strips implants on p-type Si bulk → p-n junction.
- Apply -350V reverse bias between implants and aluminum backplane.
  - Depletion zone grows as charge carriers removed from bulk.
- Charge particles passing through will ionize Si in depletion zone.
  - Electrons drift to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



[Javier Fernández-Tejero](#)

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



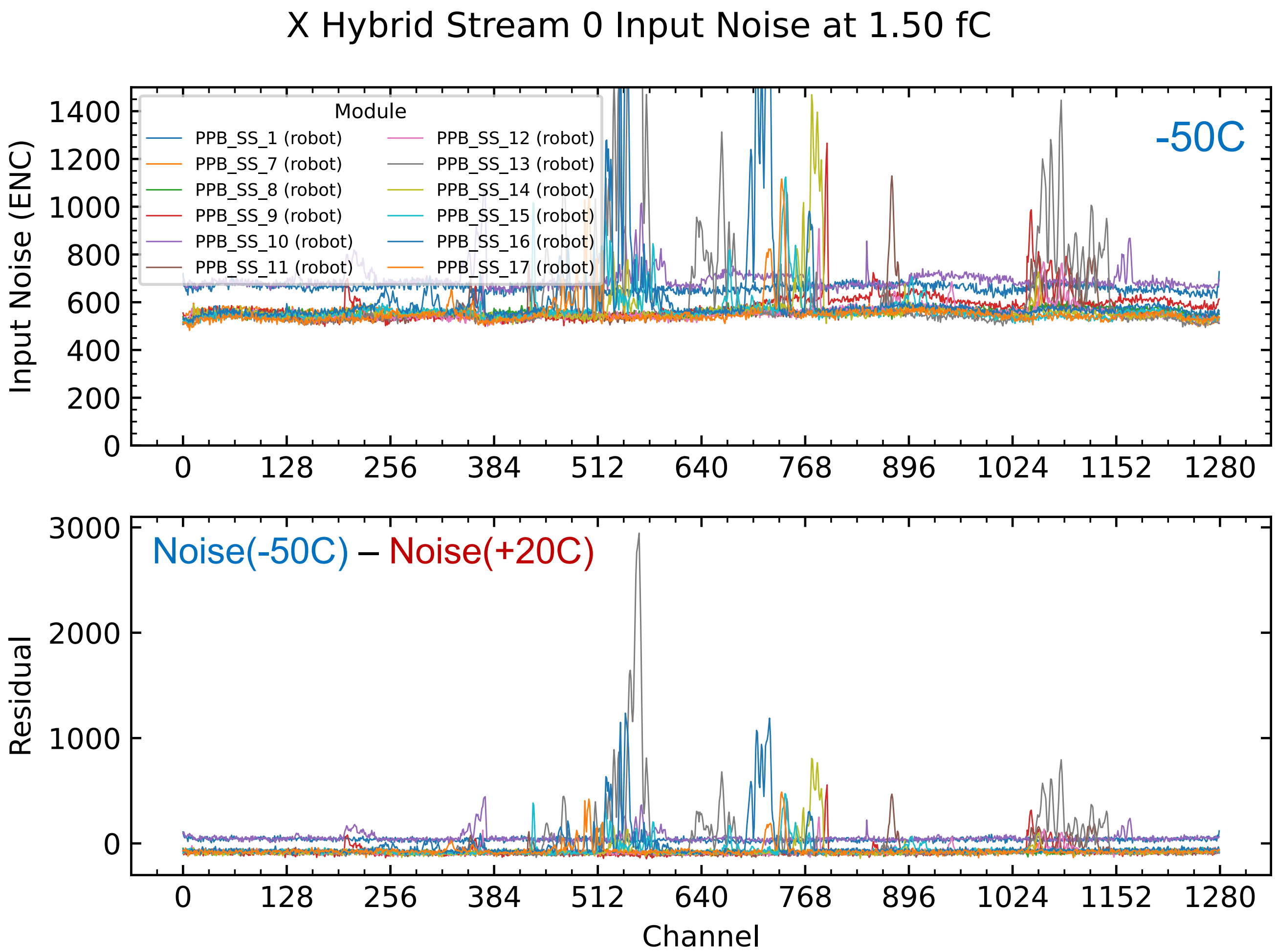


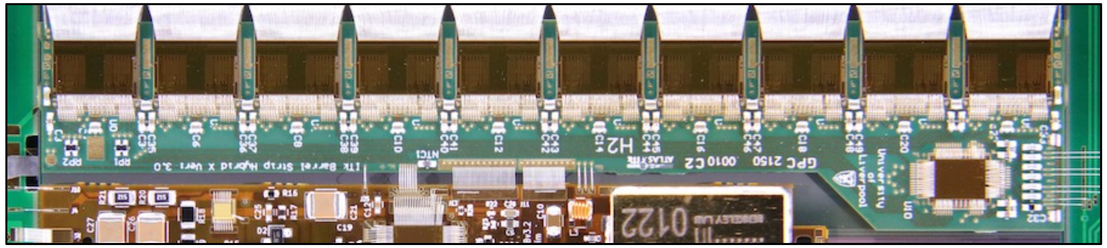
Introduction to cold noise

Cold Noise Intro

Background:

- Early last year, observed high noise channels appearing when testing modules at cold temperatures.
- Generally reversible by returning to room temp.
- This “cold noise” is now only seen on barrel modules.
    - Was seen on earlier versions of endcap modules.
- Eventually decided to pause pre-production to investigate.
- Long campaign of custom builds and imaginative tests.
    - Will only highlight the most interesting studies here.





Measuring Noise

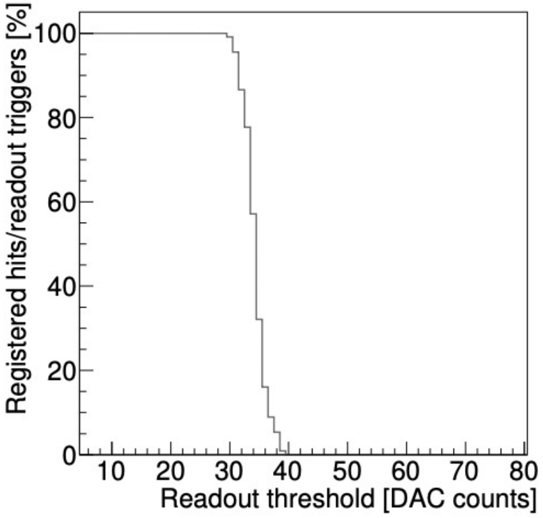
Binary Readout:

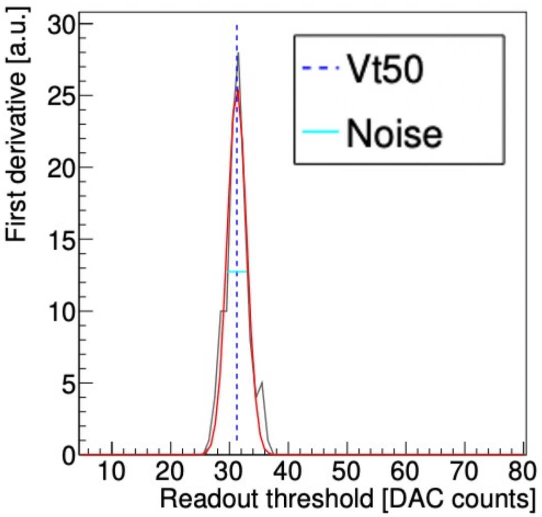
- ABCs amplify & discriminate signal from strips.
  - 1 bit per LHC BX indicating if strip above threshold.
  - Tune to balance signal efficiency vs. noise.

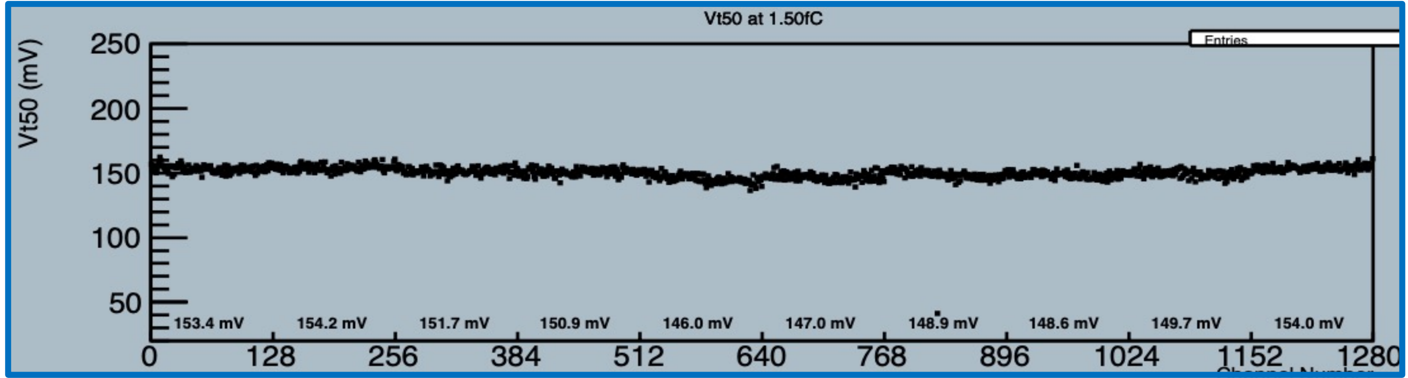
Noise metric:

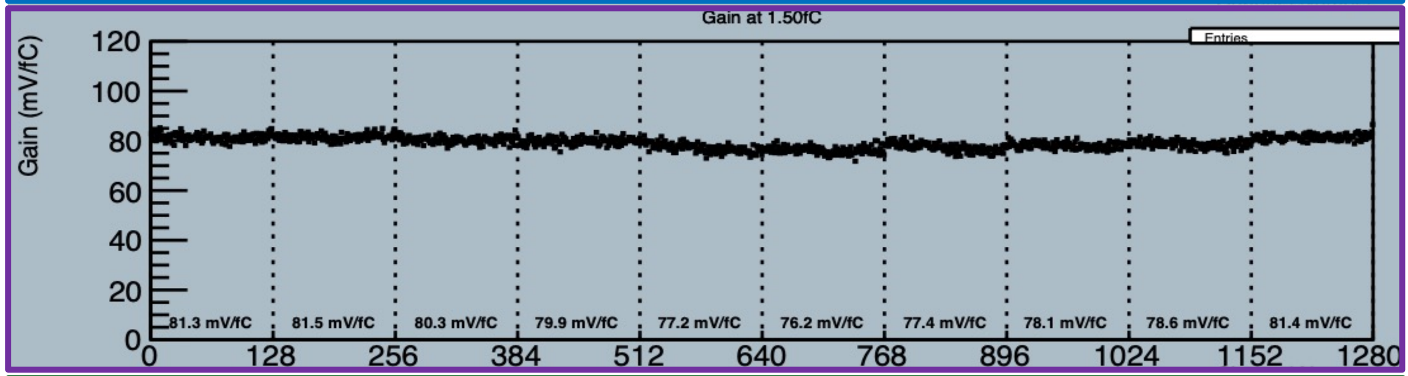
- Scan threshold & measure occupancy → S-curve.
  - Error function → derivative is a gaussian.
  - Mean → vt50, width → output noise.

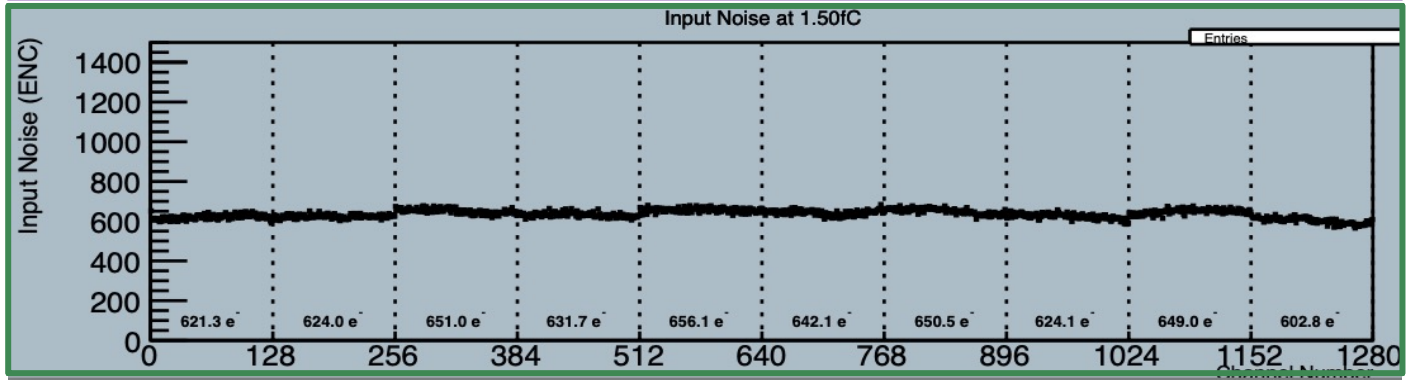
- Input noise [ENC] =
  output noise [voltage] / CSA gain [voltage / charge]

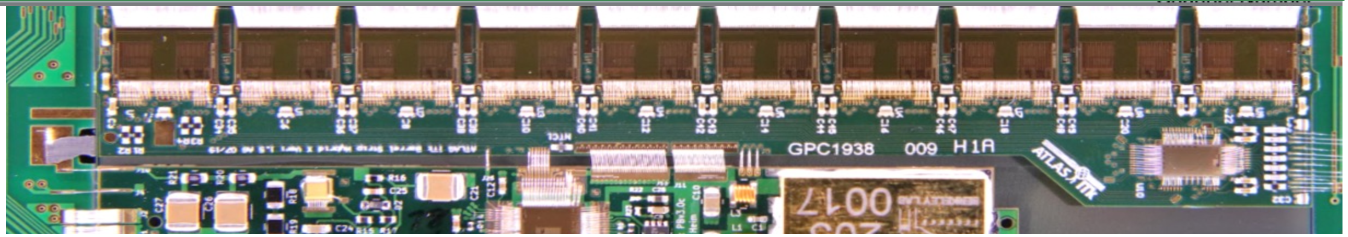






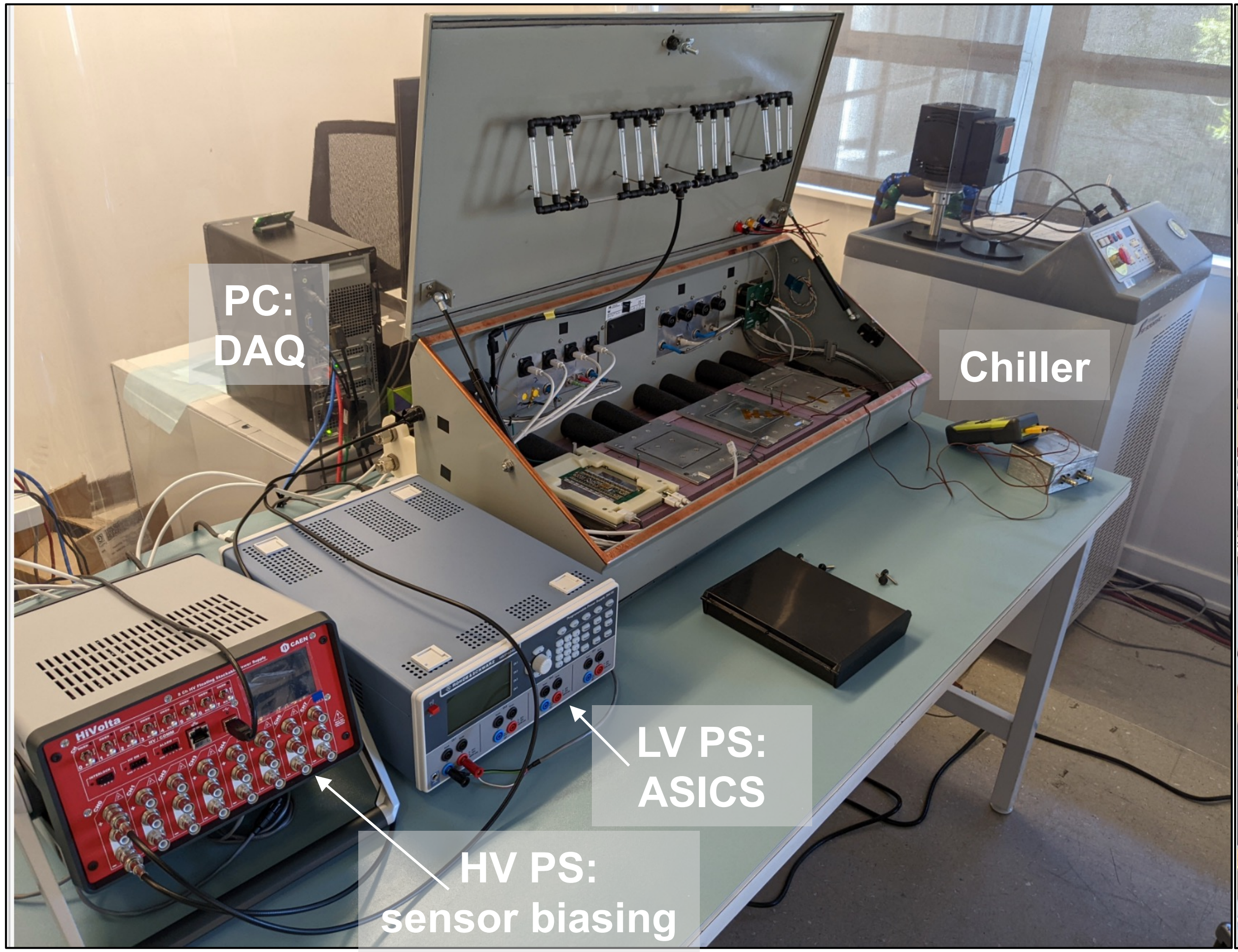


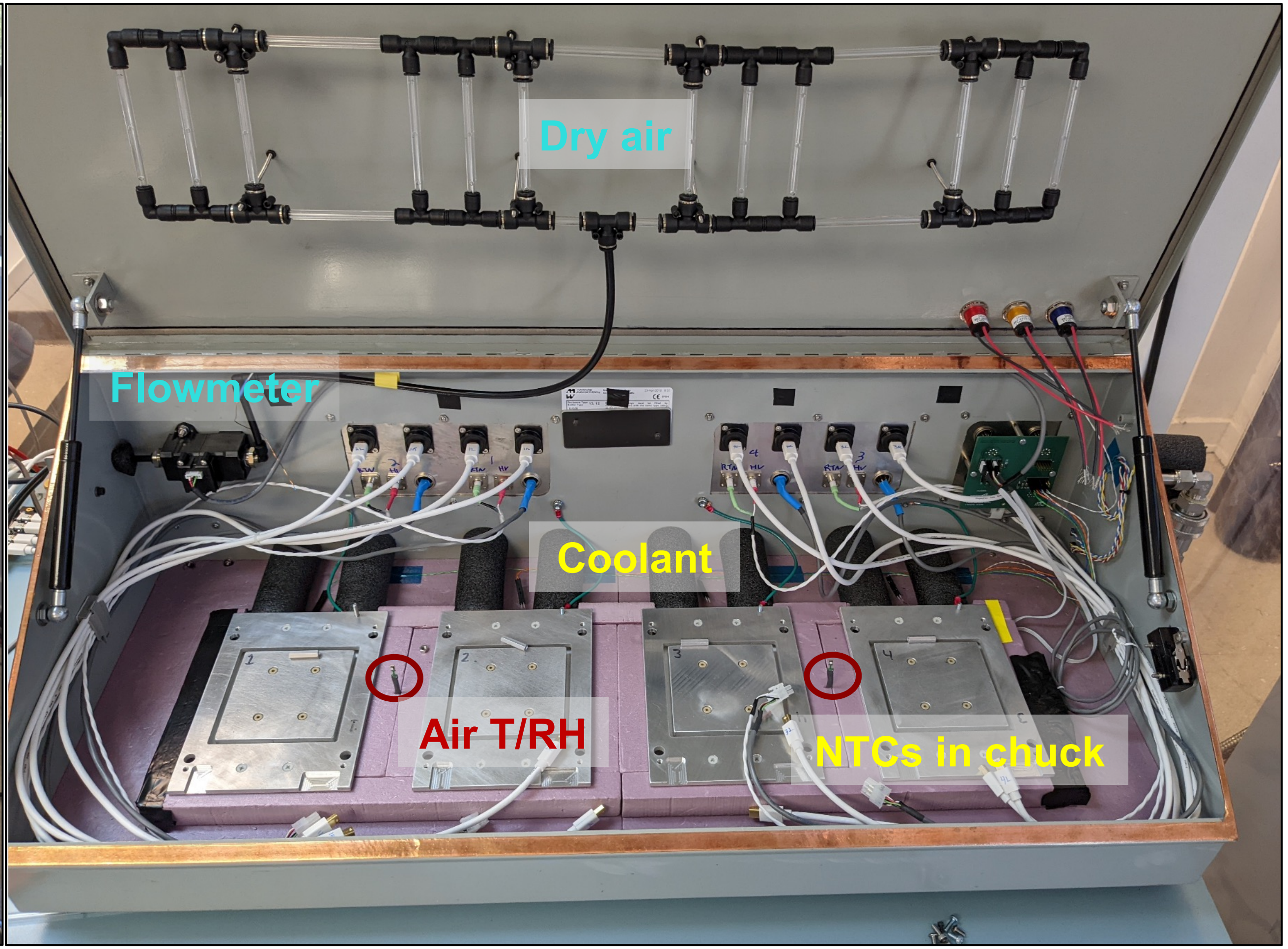




Thermal Cycling Setup

- Can electrically test up to 4 modules simultaneously.
- Nominal module QC: thermal cycle each module $10\times$ from $-35\mathrm{C}$ to $+40\mathrm{C}$ (chuck temp).
  - Diagnostic stress tests: can reach -50C (and probably even colder).

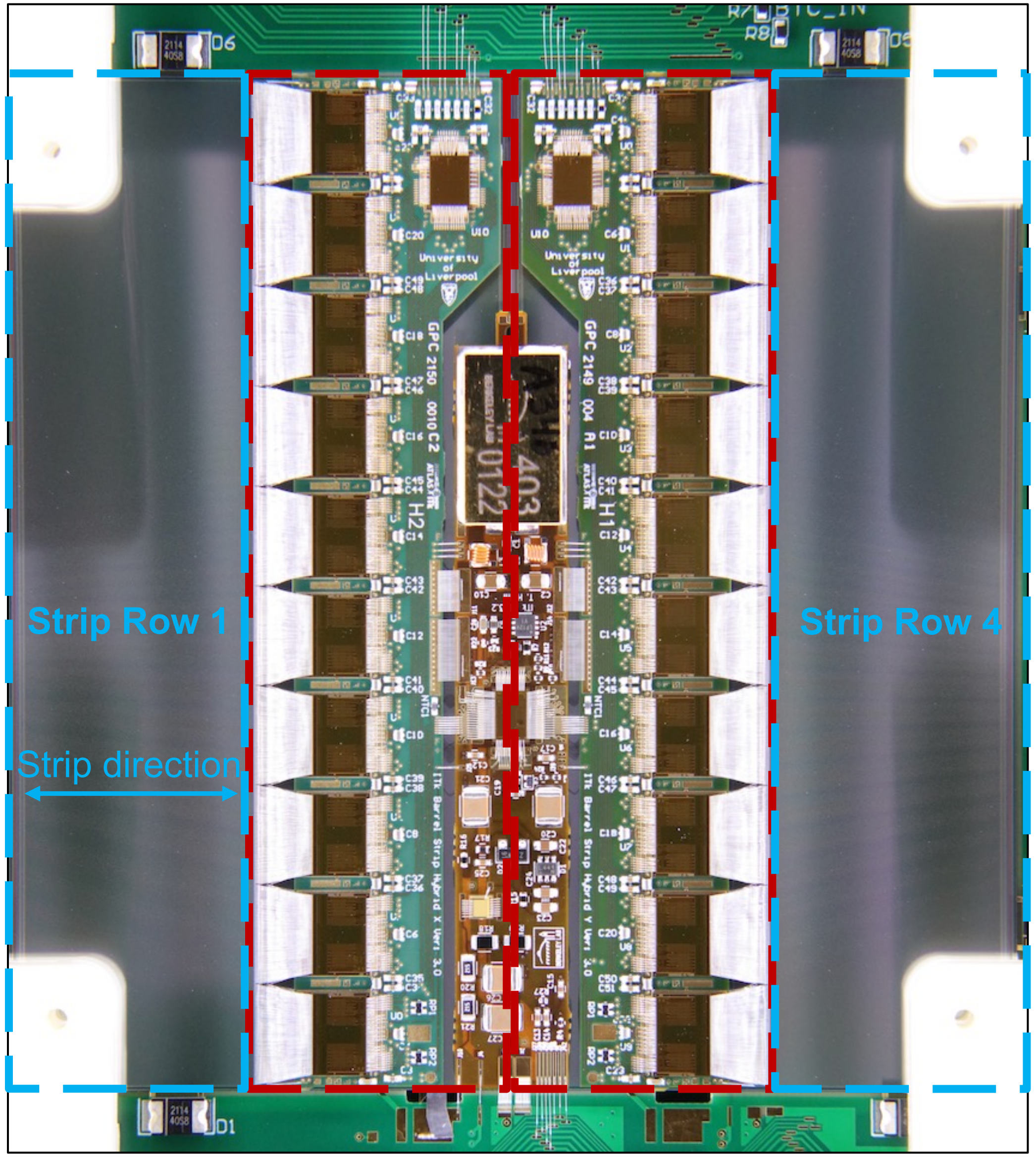




Cold Noise Observations

Early Observations:

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



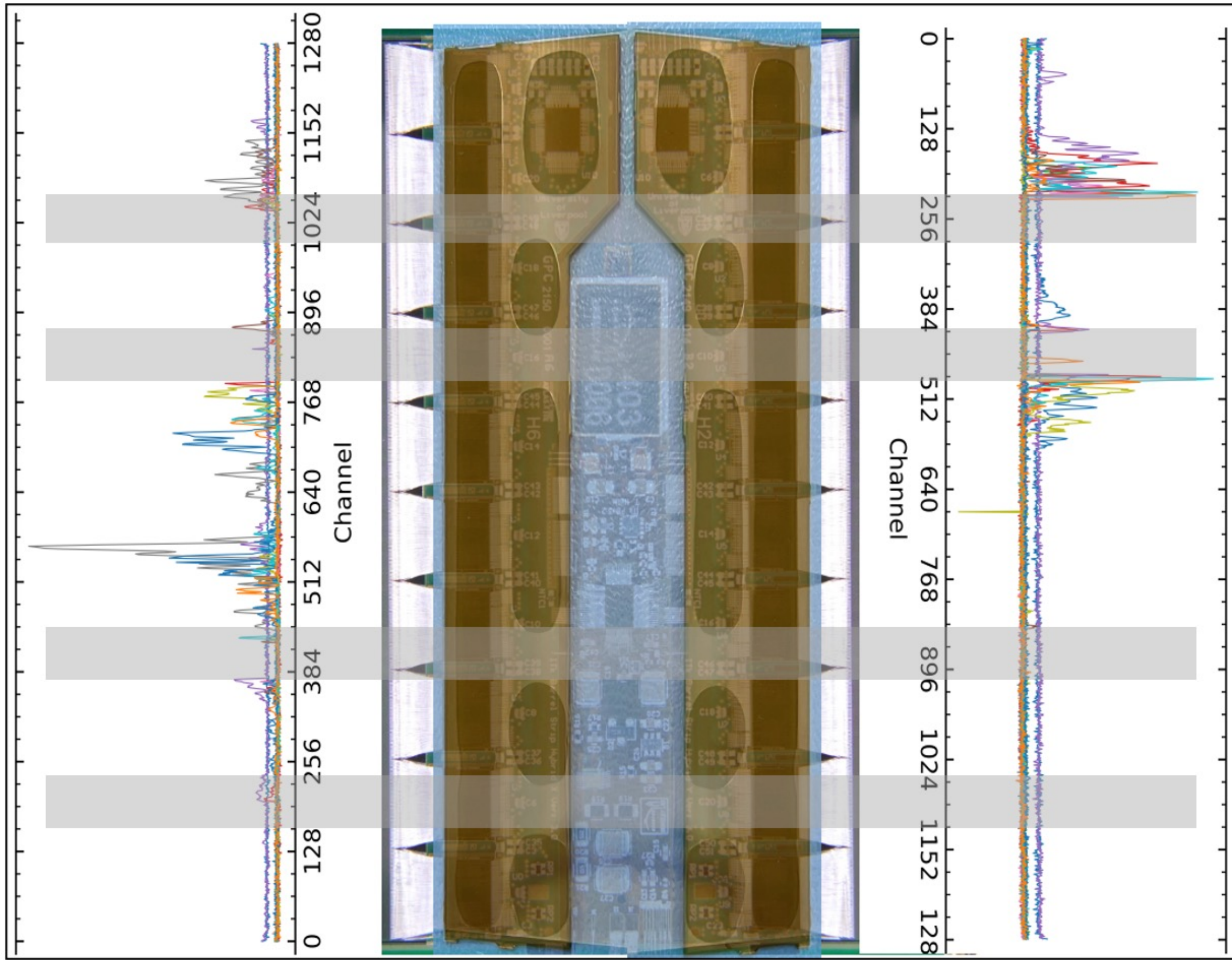
Short-strip module

Cold Noise Observations

Early Observations:

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

- Tends to appear in certain regions.
  - Correlated with glue under hybrids.

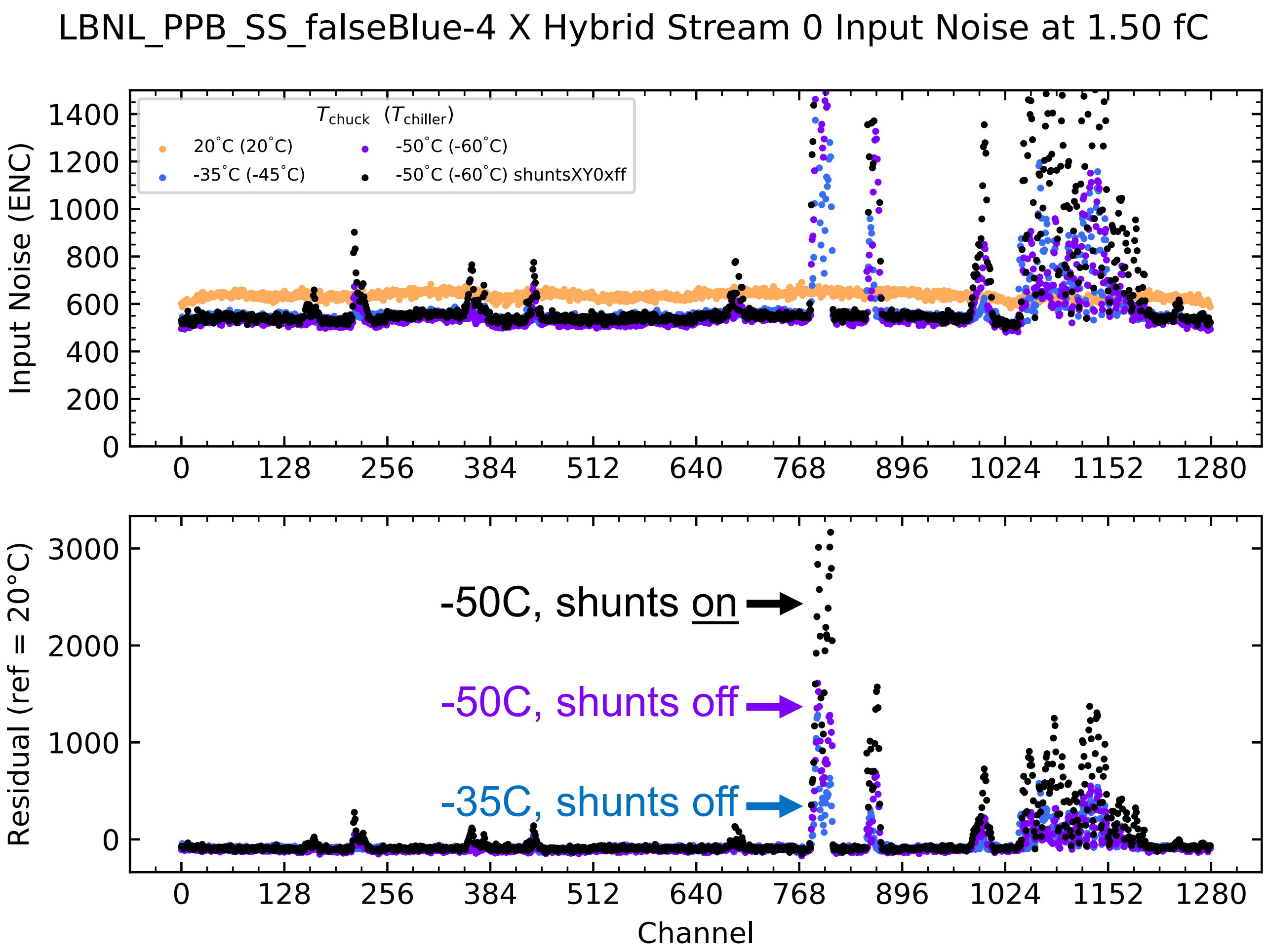


Short-strip module

Cold Noise Observations

Early Observations:

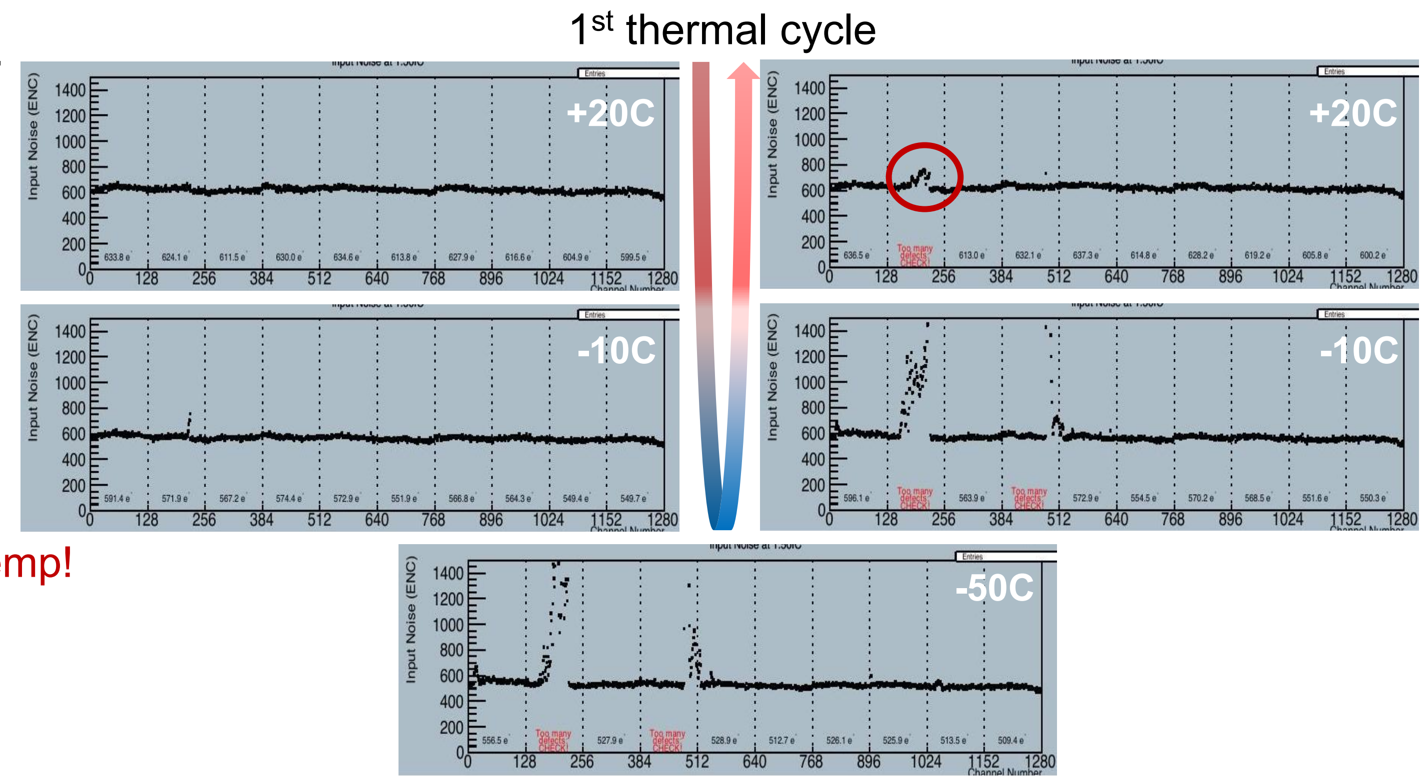
- Only appears on the strip rows under the hybrids & PB.
- Tends to appear in certain regions.
  - Correlated with glue under hybrids.
- Worsens with load on DC-DC converter.
  - Can increase load by shunting current on ABCs.



Cold Noise Observations

Early Observations:

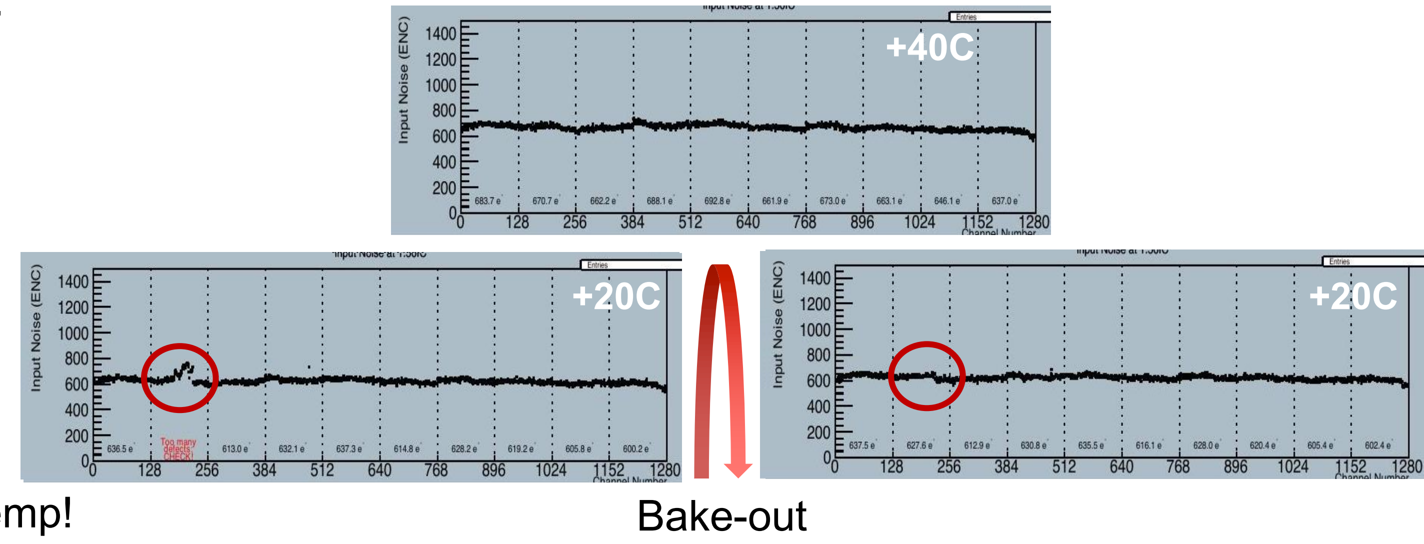
- Only appears on the strip rows under the hybrids & PB.
- Tends to appear in certain regions.
  - Correlated with glue under hybrids.
- Worsens with load on DC-DC converter.
  - Can increase load by shunting current on ABCs.
- Noise “freezes-in” during 1st thermal cycle.
  - Persists while warming.
  - Occasionally have residual “cold” noise at room temp!



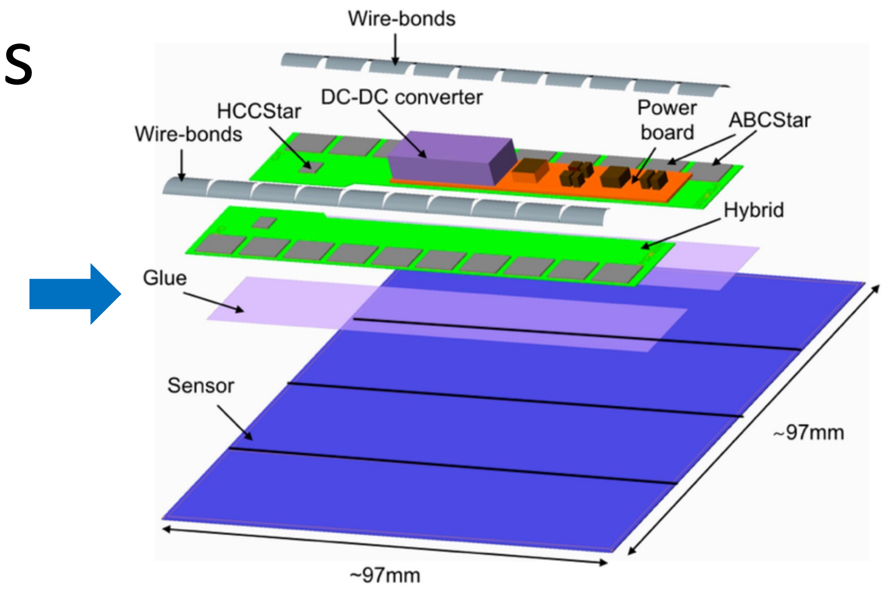
Cold Noise Observations

Early Observations:

- Only appears on the strip rows under the hybrids & PB.
- Tends to appear in certain regions.
  - Correlated with glue under hybrids.
- Worsens with load on DC-DC converter.
  - Can increase load by shunting current on ABCs.
- Noise “freezes-in” during 1st thermal cycle.
  - Persists while warming.
  - Occasionally have residual “cold” noise at room temp!
    - But can “bake-out” by going warmer.



Cold Noise Observations



Early Observations:

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

- Tends to appear in certain regions.
  - Correlated with glue under hybrids.

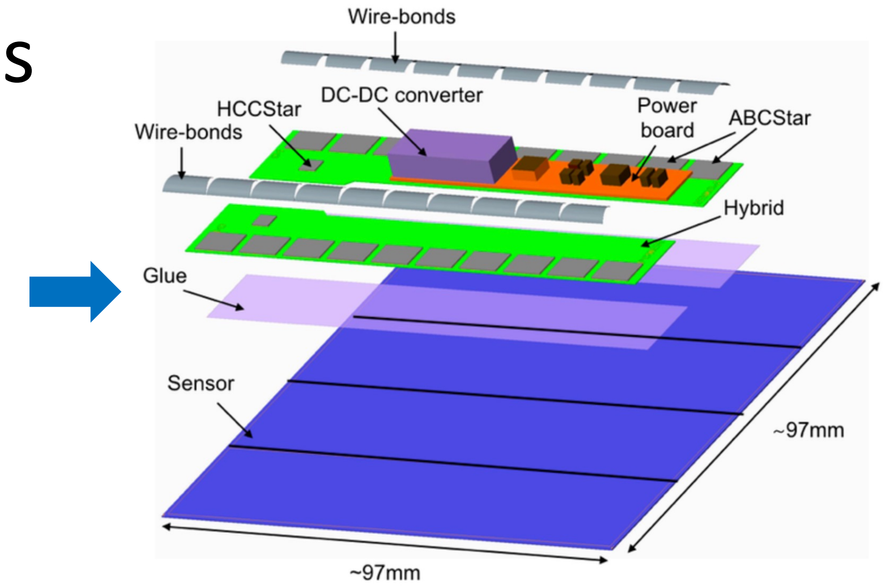
- Worsens with load on DC-DC converter.
  - Can increase load by shunting current on ABCs.

- Noise "freezes-in" during 1st thermal cycle.
  - Persists while warming.
  - Occasionally have residual "cold" noise at room temp!
    - But can "bake-out" by going warmer.

Glue dependence:

- Severity varies greatly among "nearly identical" epoxies.
  - Unable to correlate with any info in data sheets…

Cold Noise Observations

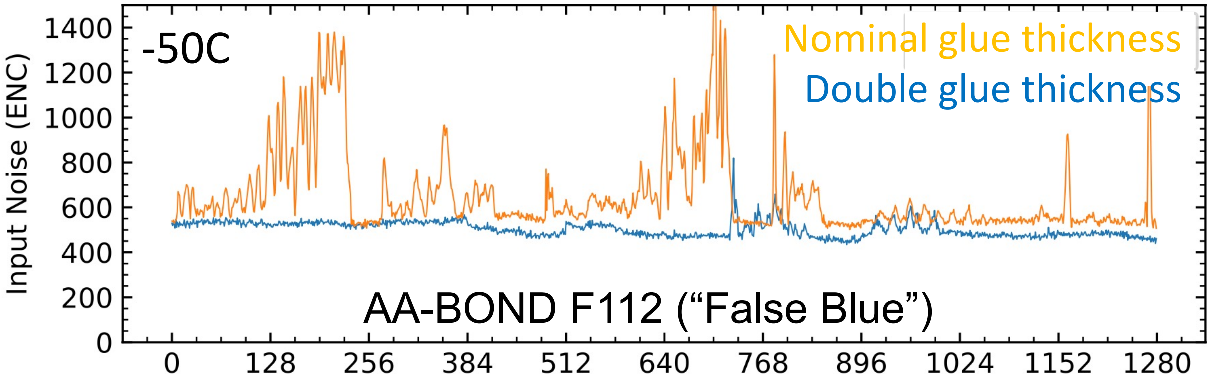


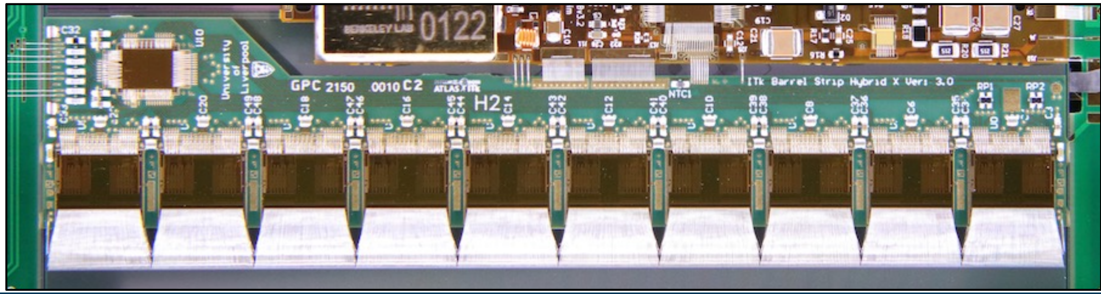
Early Observations:

- Only appears on the strip rows under the hybrids & PB.
- Tends to appear in certain regions.
  - Correlated with glue under hybrids.
- Worsens with load on DC-DC converter.
  - Can increase load by shunting current on ABCs.
- Noise "freezes-in" during 1st thermal cycle.
  - Persists while warming.
  - Occasionally have residual "cold" noise at room temp!
    - But can "bake-out" by going warmer.

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.



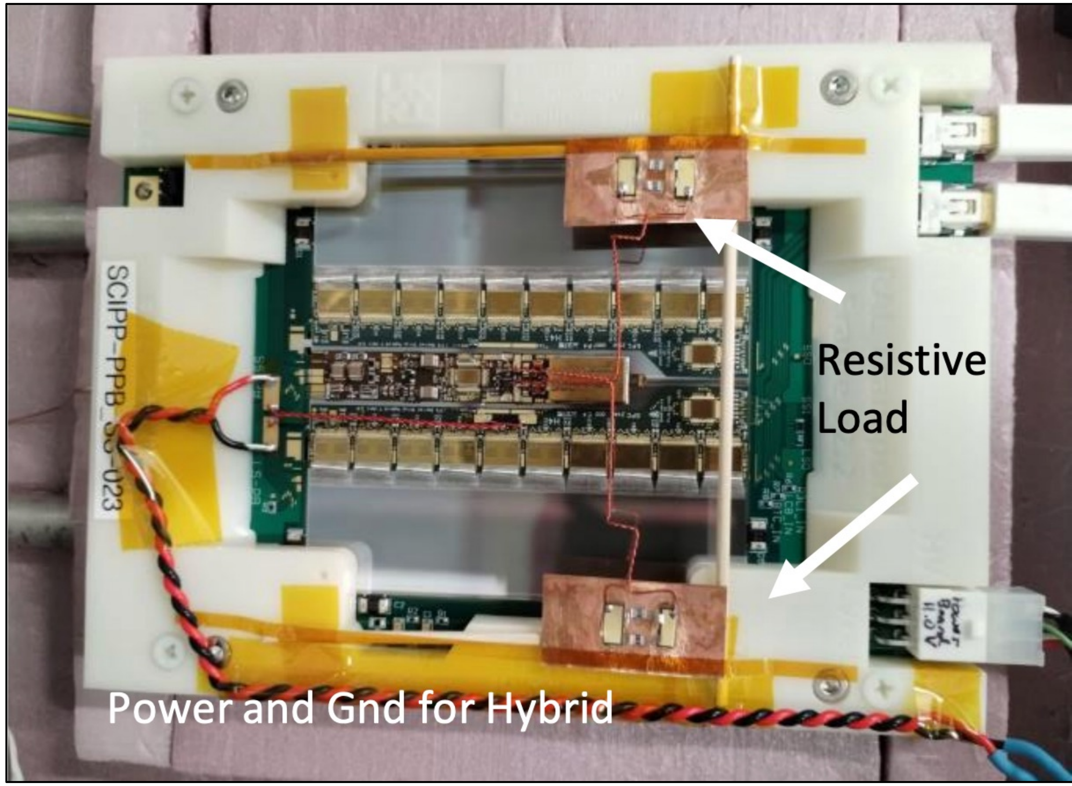


Highlighting the most insightful studies

Bypassed Powerboard (SCIPP)

Motivation:

- Is the source of cold noise on hybrid or powerboard?
- 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.

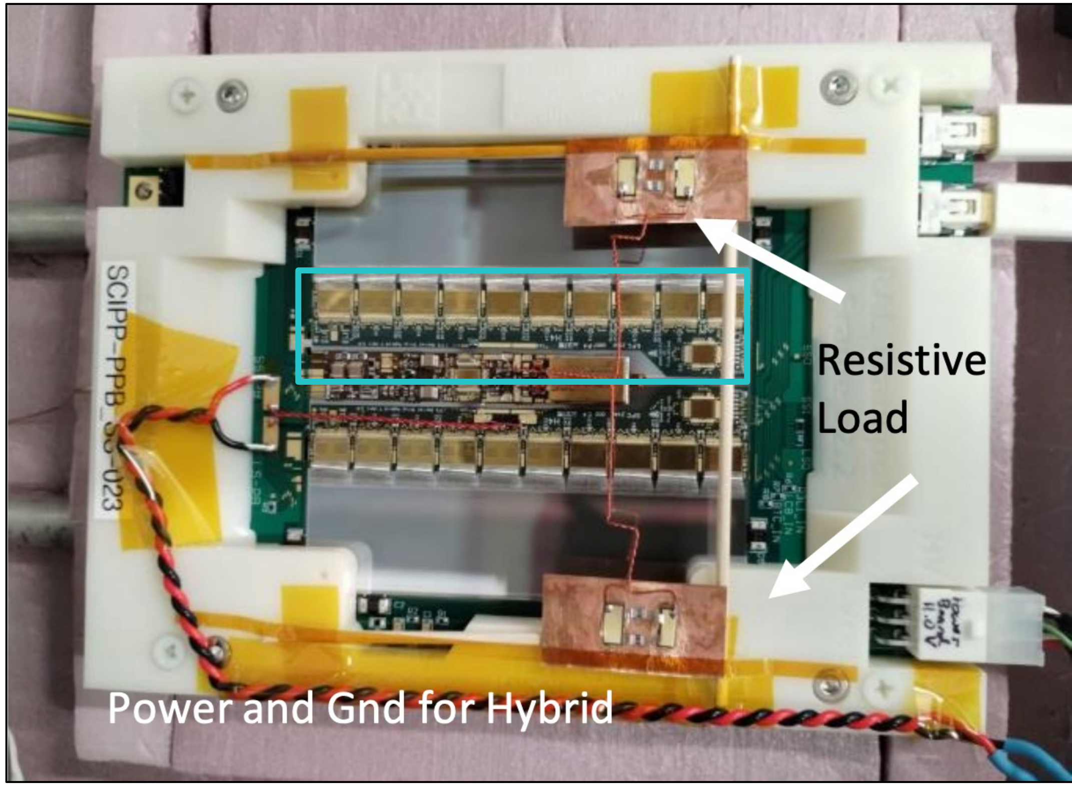


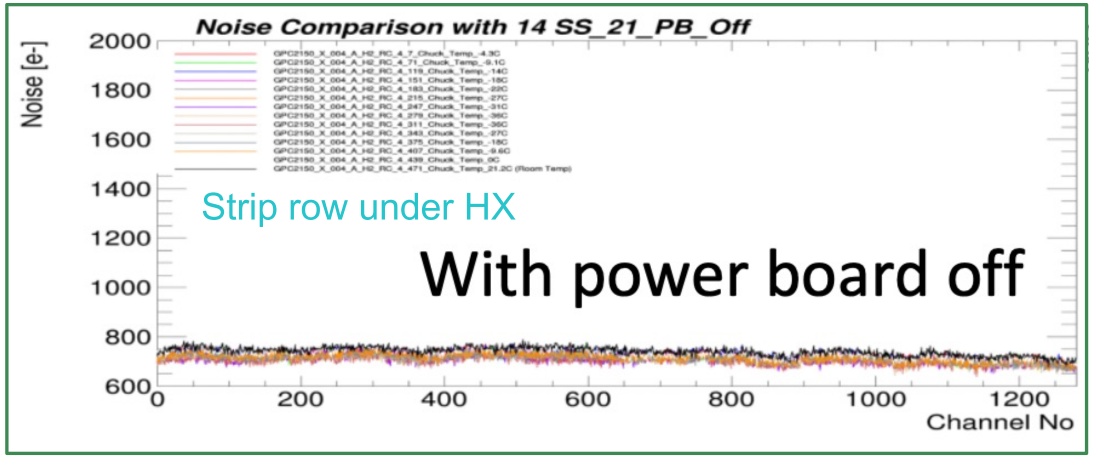
Bypassed Powerboard (SCIPP)

Motivation:
- Is the source of cold noise on hybrid or powerboard?

- 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.

Tests:
1. PB off → no cold noise.
2. PB on, but no load on DC-DC→ still no cold noise.





Bypassed Powerboard (SCIPP)

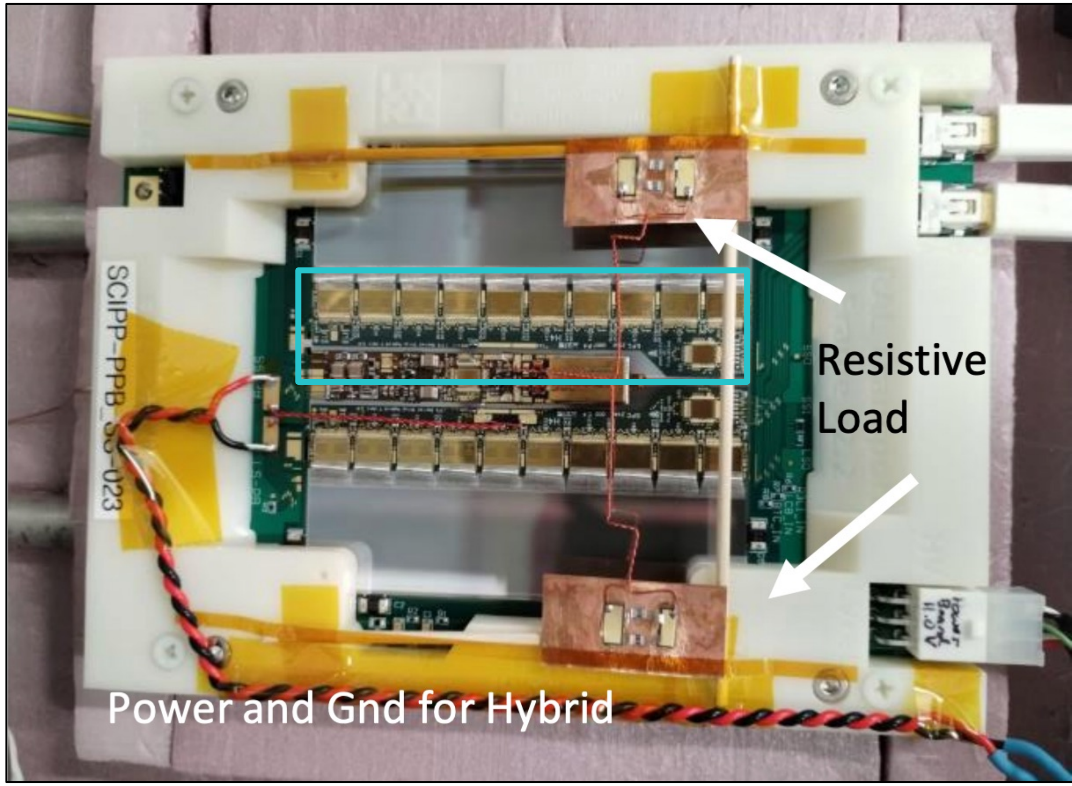
Motivation:

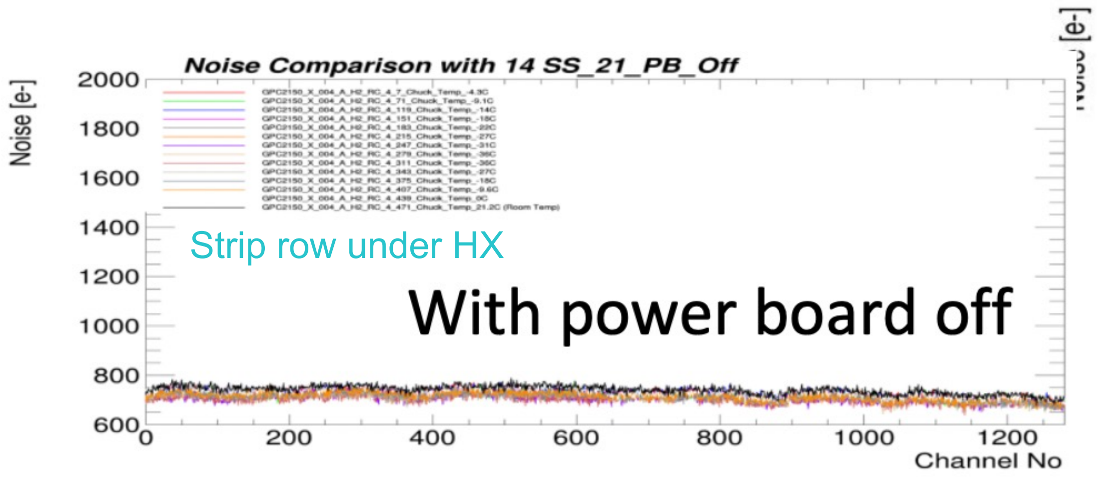
- Is the source of cold noise on hybrid or powerboard?

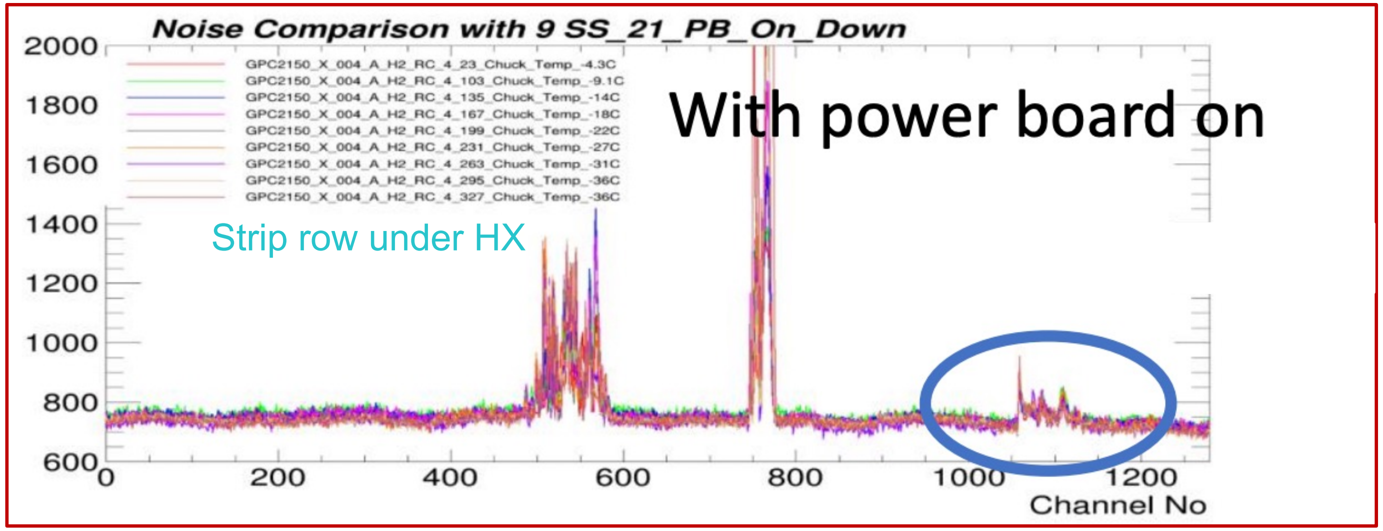
- Can factor the two by bypassing the PB for hybrid power.
  - Remove low voltage power bonds between PB & hybrids.
  - Power hybrids directly with power supply.

Tests:

1. PB off → no cold noise.
2. PB on, but no load on DC-DC→ still no cold noise.
3. PB on with resistive load on DC-DC emulating hybrids → cold noise!





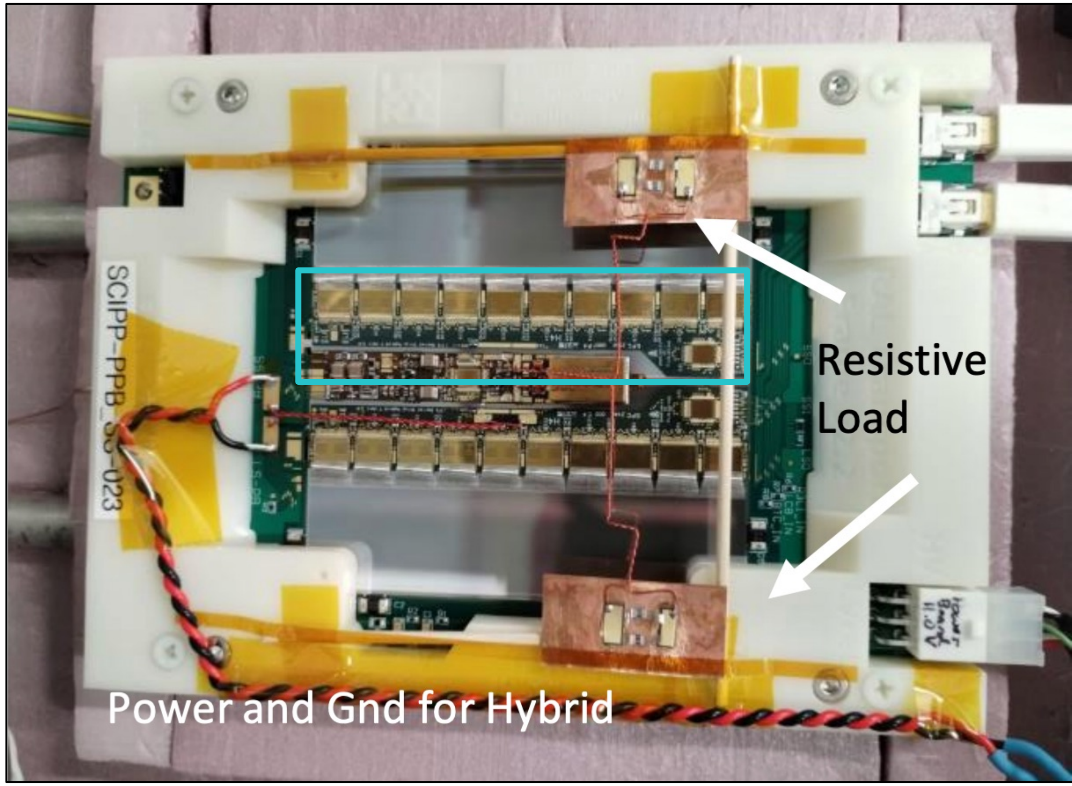


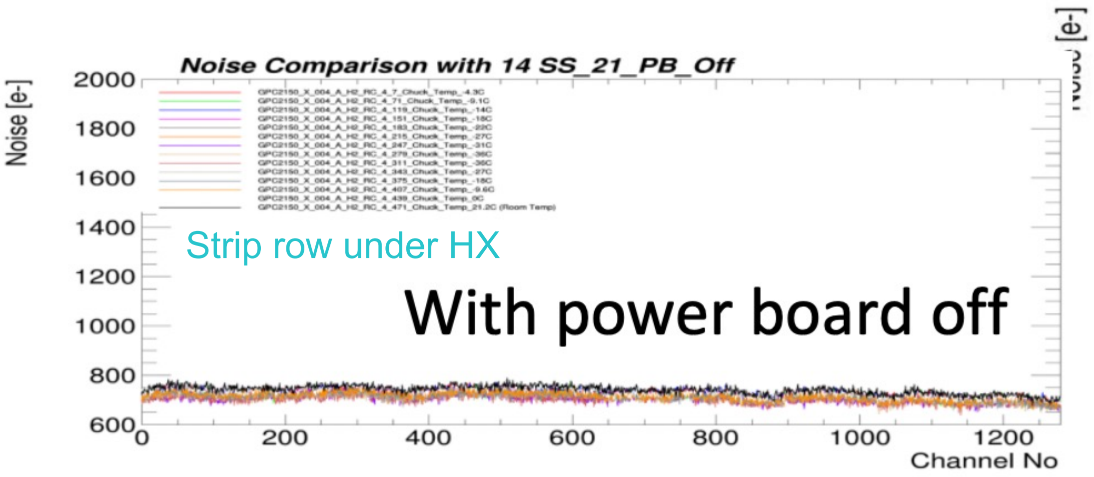
Bypassed Powerboard (SCIPP)

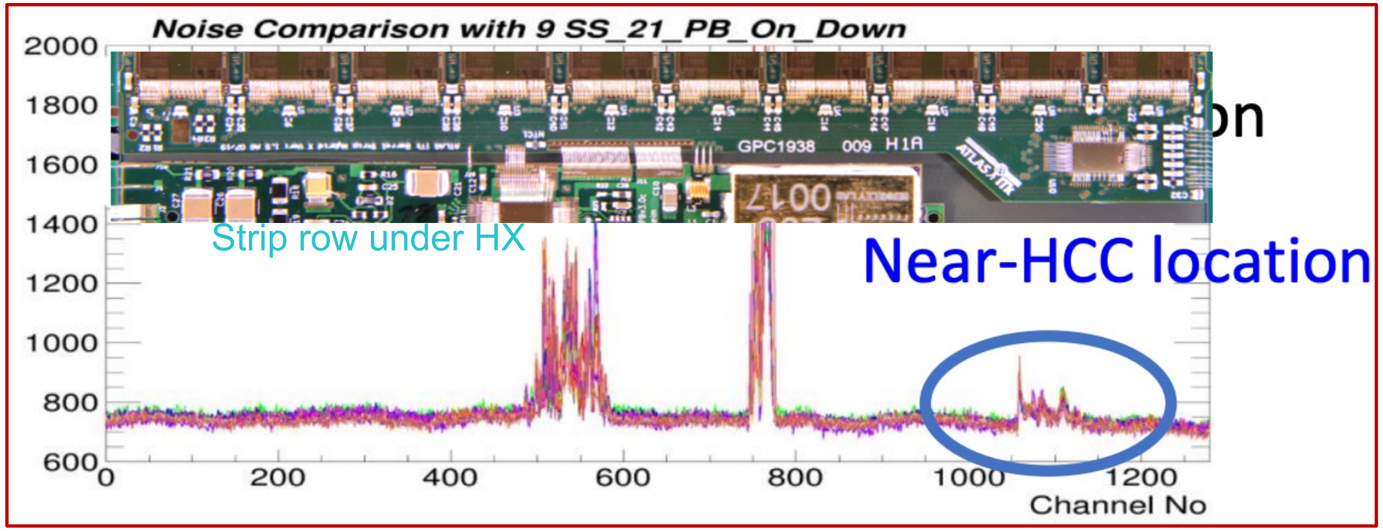
Motivation:
- Is the source of cold noise on hybrid or powerboard?

- 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.

Tests:
1. PB off → no cold noise.
2. PB on, but no load on DC-DC→ still no cold noise.
3. PB on with resistive load on DC-DC emulating hybrids → cold noise!
   - Even appears near HCC, far from PB!

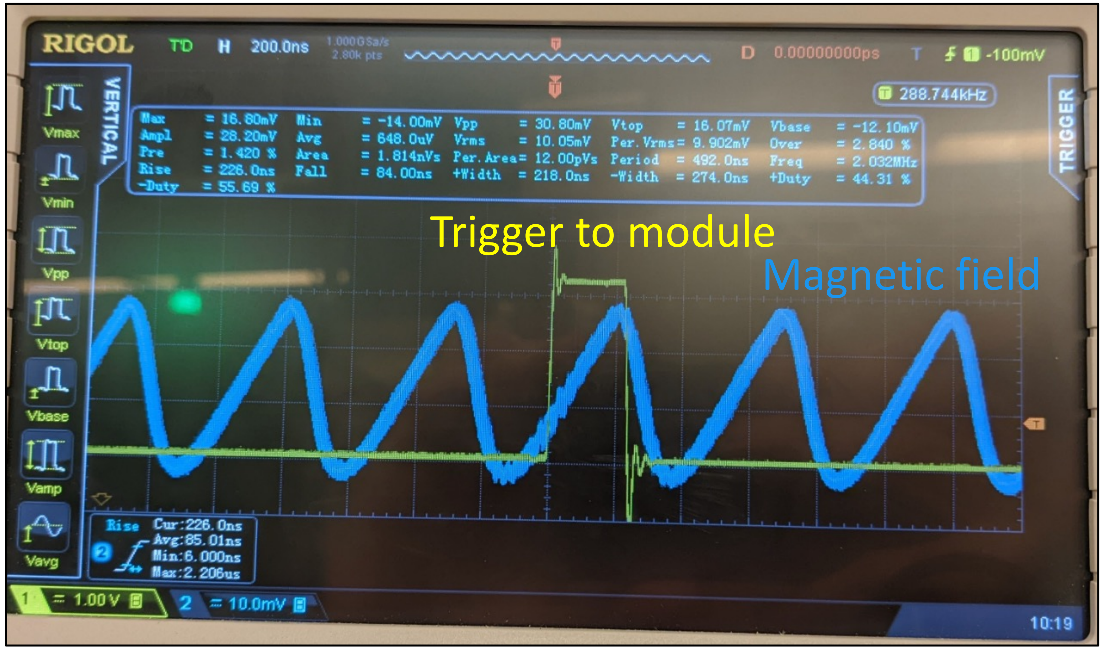




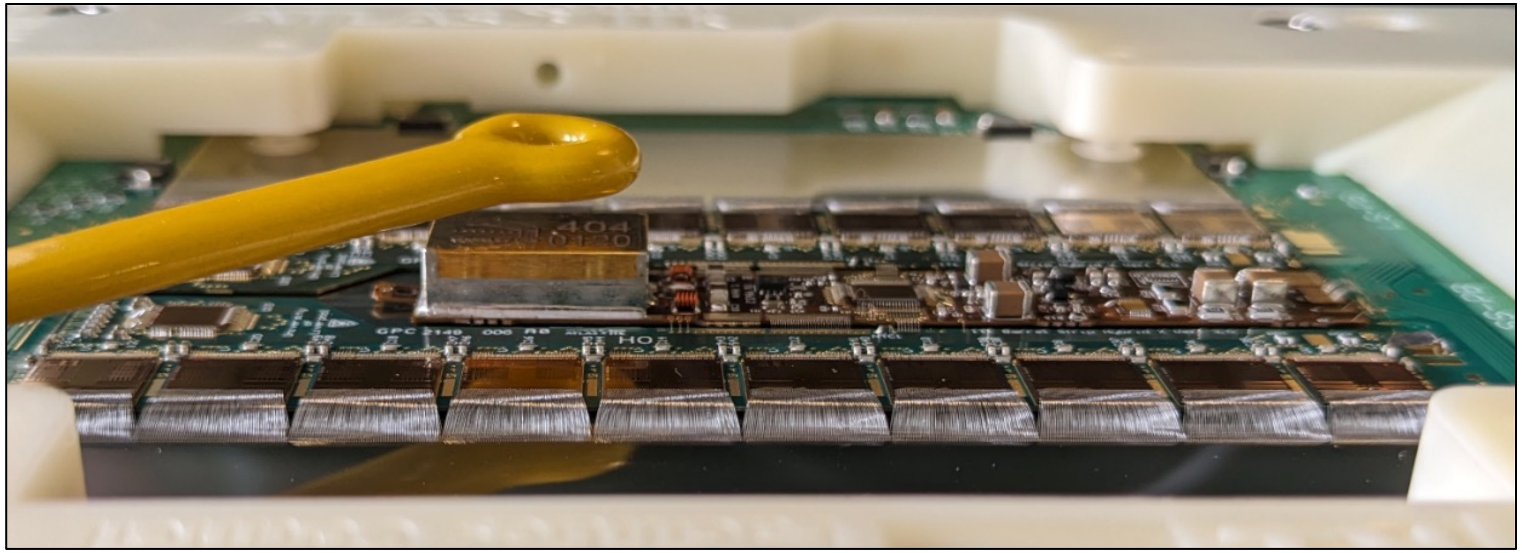


DCDC-Synchronous Triggering (UBC, LBL, RAL)

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.

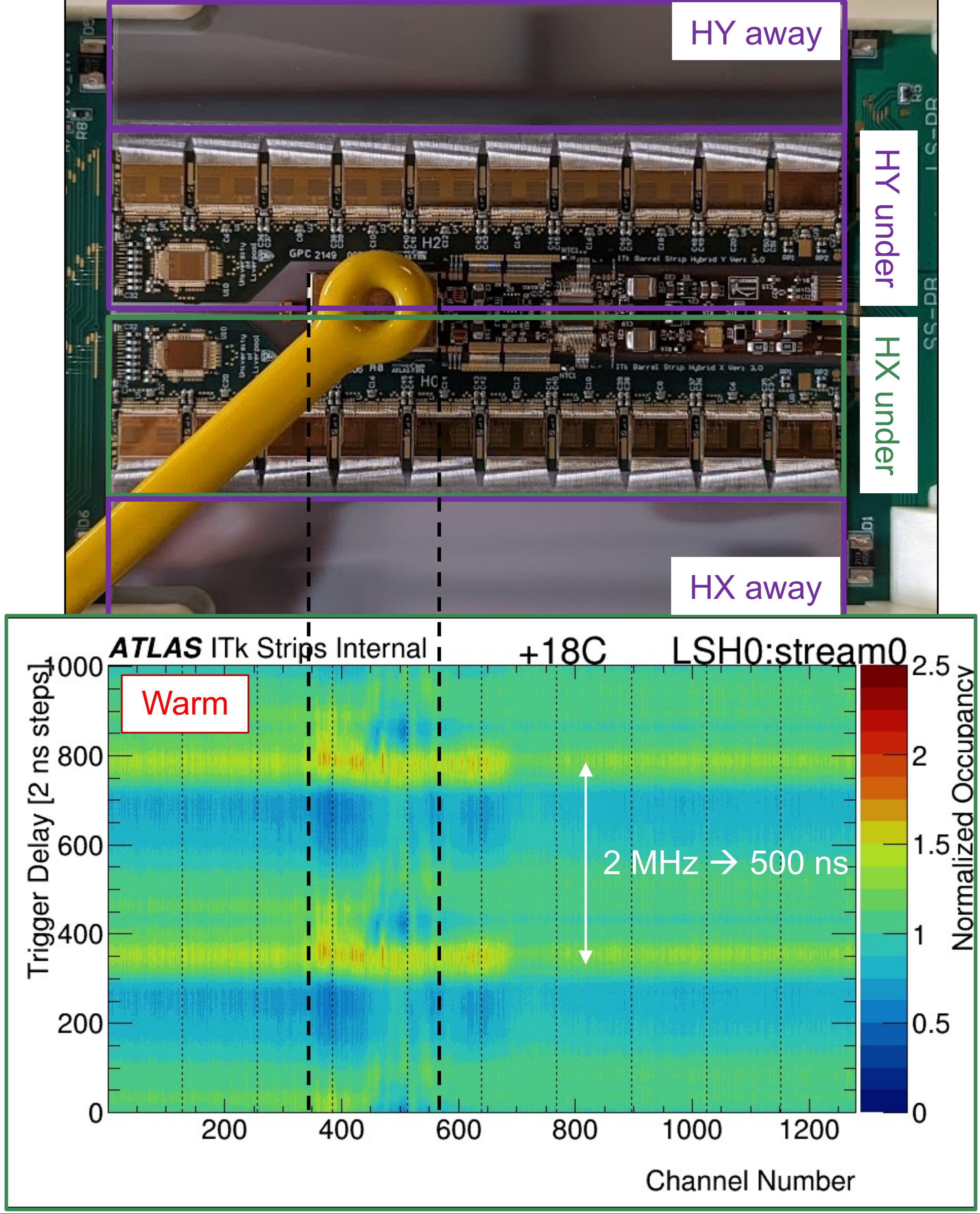


DCDC-Synchronous Triggering

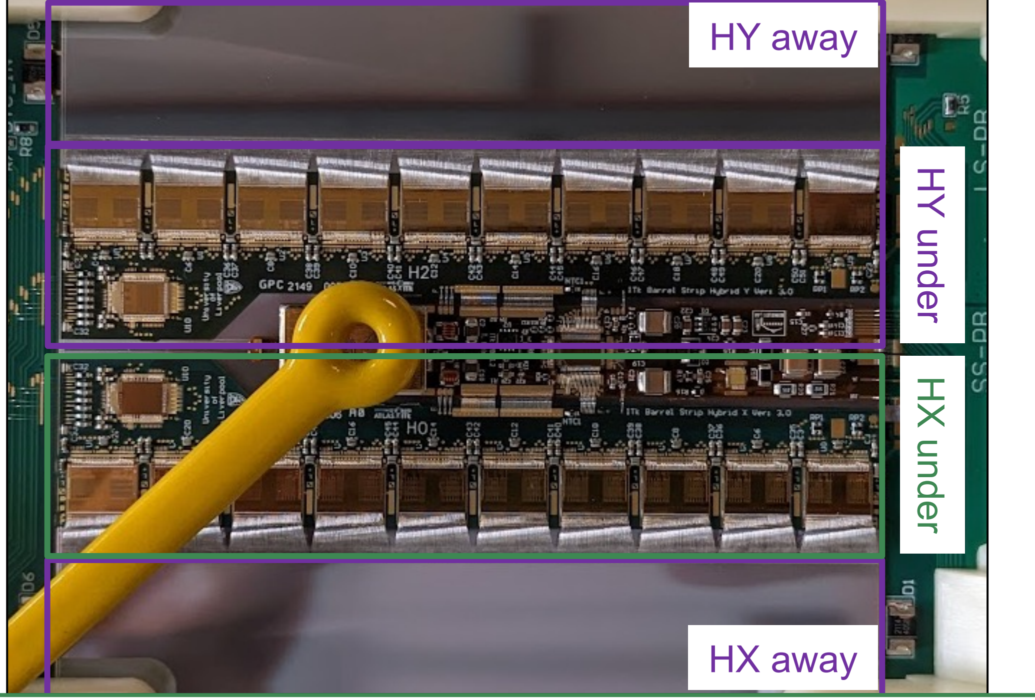
Warm Results:

- 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.



DCDC-Synchronous Triggering

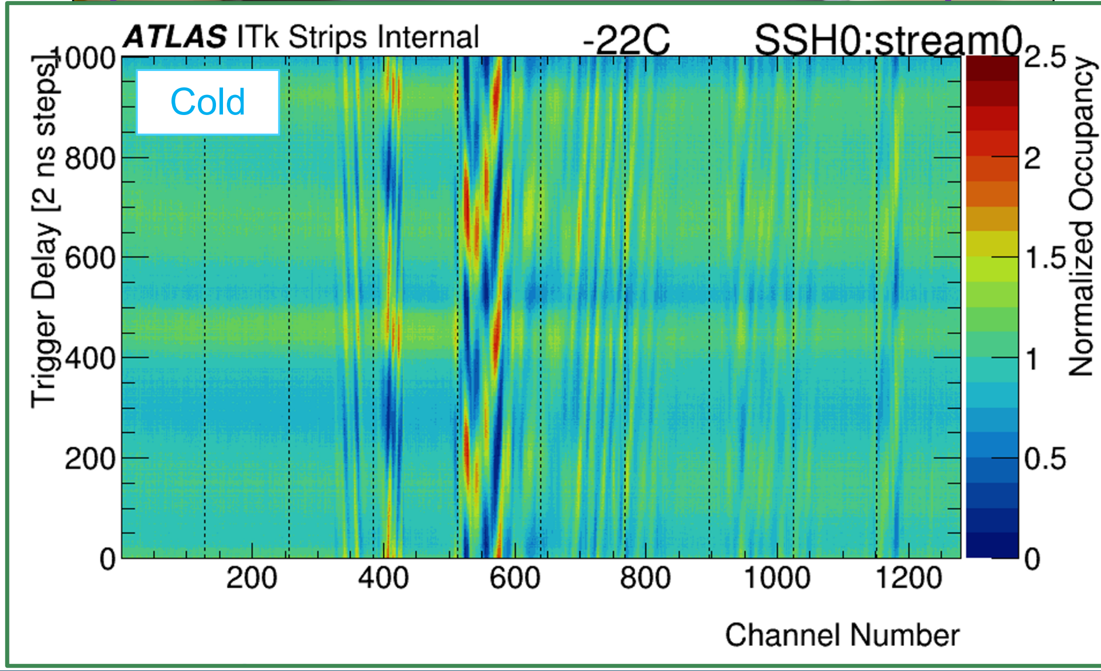


Warm Results:

- 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.

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 to 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

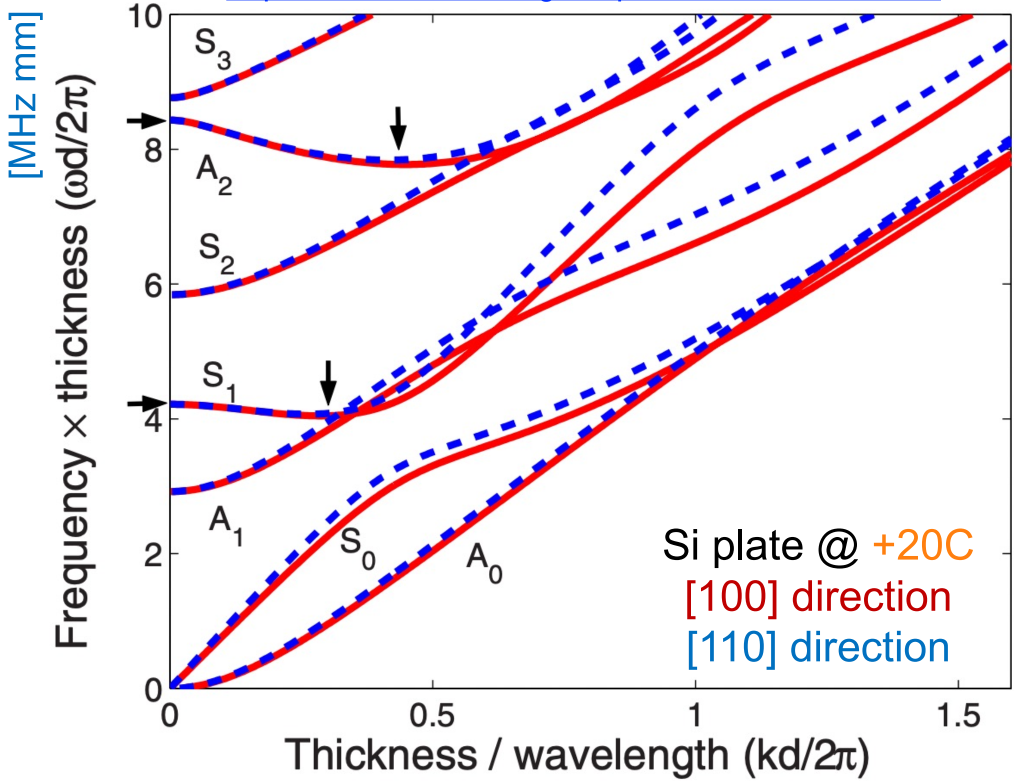
Brief Introduction:

- Sinusoidal solutions to wave equation in flat plates.
  - Family of symmetric (S_n) and anti-symmetric (A_n) solutions.

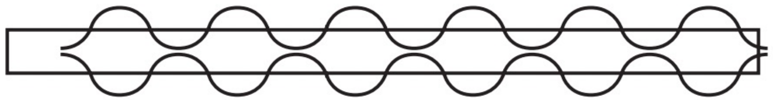
- Only S_0 and A_0 at low frequencies.
  - Higher order modes have cut-off frequencies $\gtrsim 10$ MHz.
  - S_0 and A_0 most important when $\lambda \gg$ plate thickness.

- 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.

https://asa.scitation.org/doi/pdf/10.1121/1.3167277



(a) S_0



(b) A_0

Lamb Waves

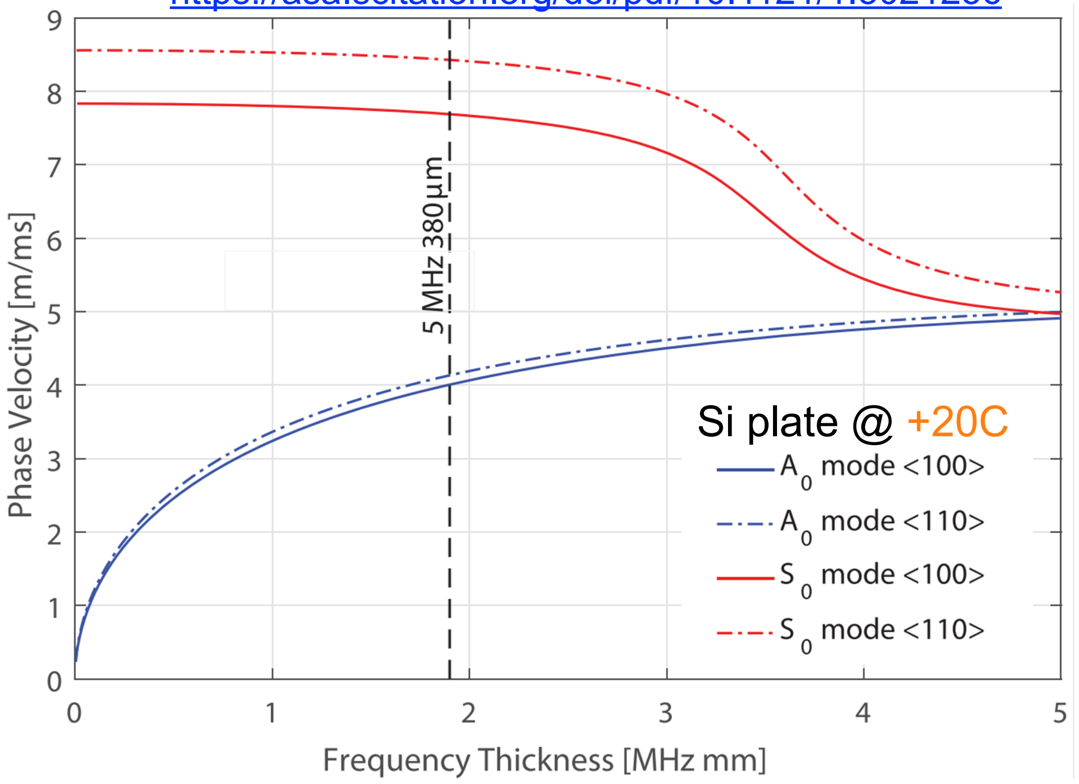
Brief Introduction:

- 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.

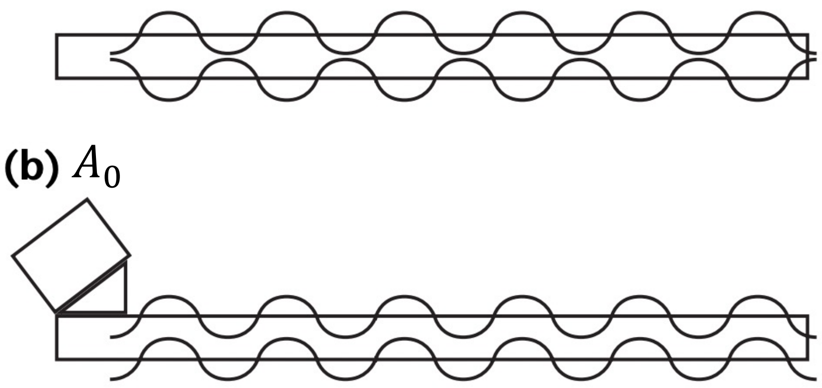
- Suspect we are seeing A_0.
  - A_0 (flexural mode) → particles move perpendicular to sensor plane.
  - S_0 (extensional mode) → particles move parallel to plane.

https://asa.scitation.org/doi/pdf/10.1121/1.5021256



(a) S_0

(b) A_0



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.

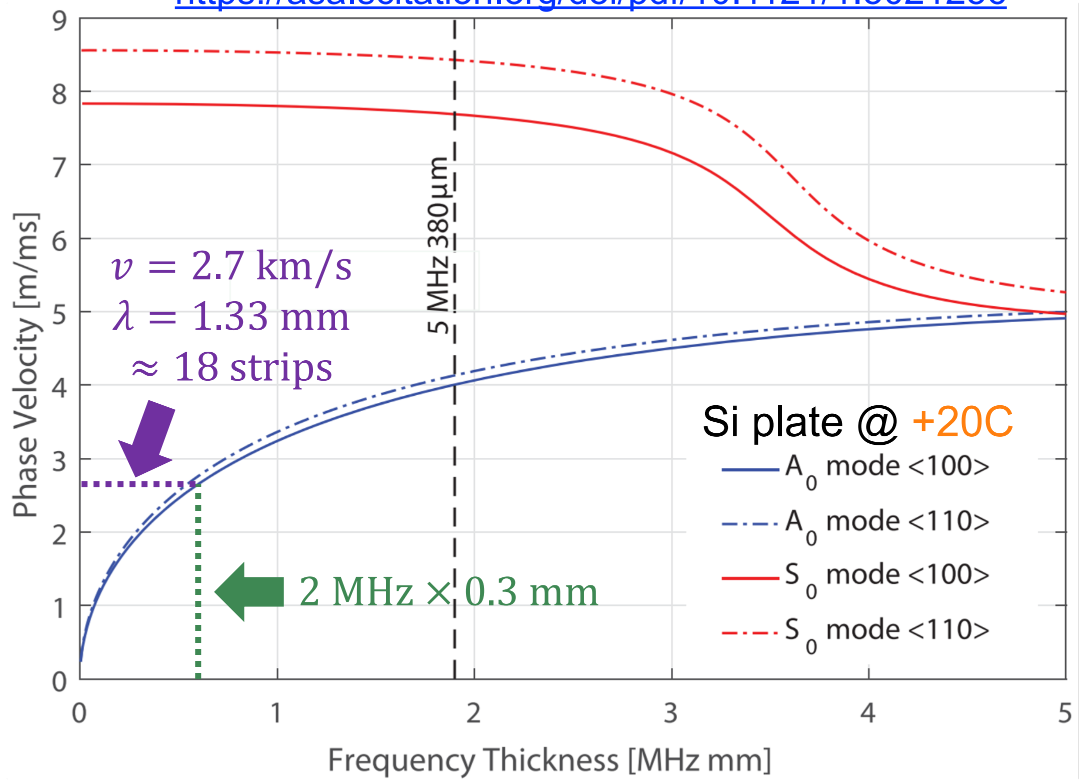
- Suspect we are seeing A_0.
  - A_0 (flexural mode) → particles move perpendicular to sensor plane.
  - S_0 (extensional mode) → particles move parallel to plane.

Plugging in some numbers:

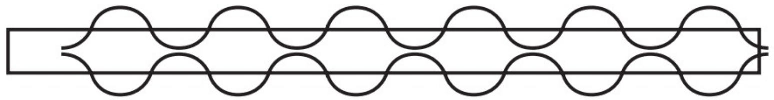
- $f_{\mathrm{DCDC}} = 2\ \mathrm{MHz},\ \mathrm{thickness} = 0.3\ \mathrm{mm}$ → $v = 2.7\,\frac{\mathrm{km}}{\mathrm{s}}, \lambda = 18\ \mathrm{strips}$.

- Does this agree with our data?

https://asa.scitation.org/doi/pdf/10.1121/1.5021256



(a) S_0

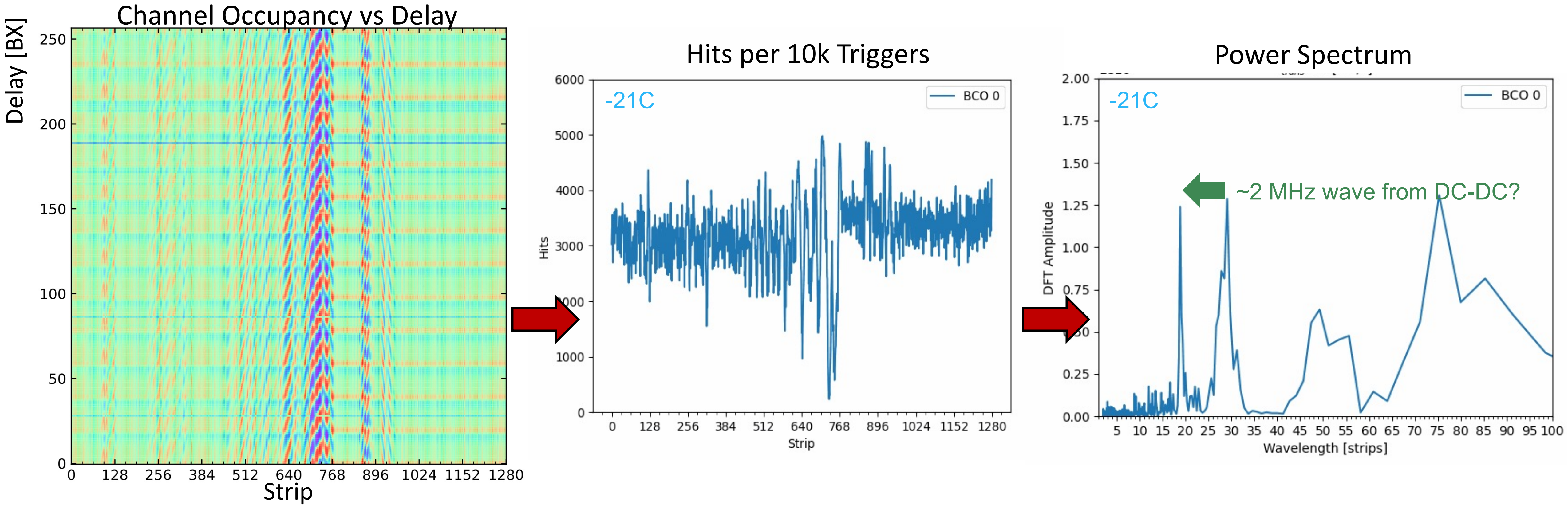


(b) A_0

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

$T_{\mathrm{DCDC}} = 20\ \mathrm{BX}$

DCDC-Synchronous Delay Scan (Revisited)



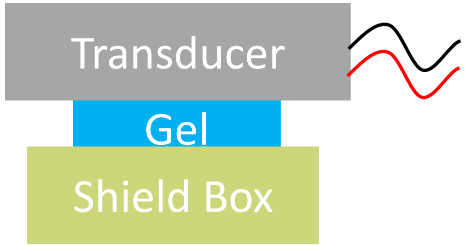
- Calculated power spectrum for every step in a delay scan (step size = 1 LHC bunch crossing = 25 ns).
- Suspect something is vibrating at the DC-DC switching frequency, $f_{\mathrm{DCDC}} \approx 2\ \mathrm{MHz}$.
  - Dispersion plot (at +20C) → $v \approx 2.7$ km/s, $\lambda \approx 18$ strips.
  - See a peak near here in the spectrum!
- Maybe vibrations really are the source of cold noise.

Vibrating Transducer Studies:

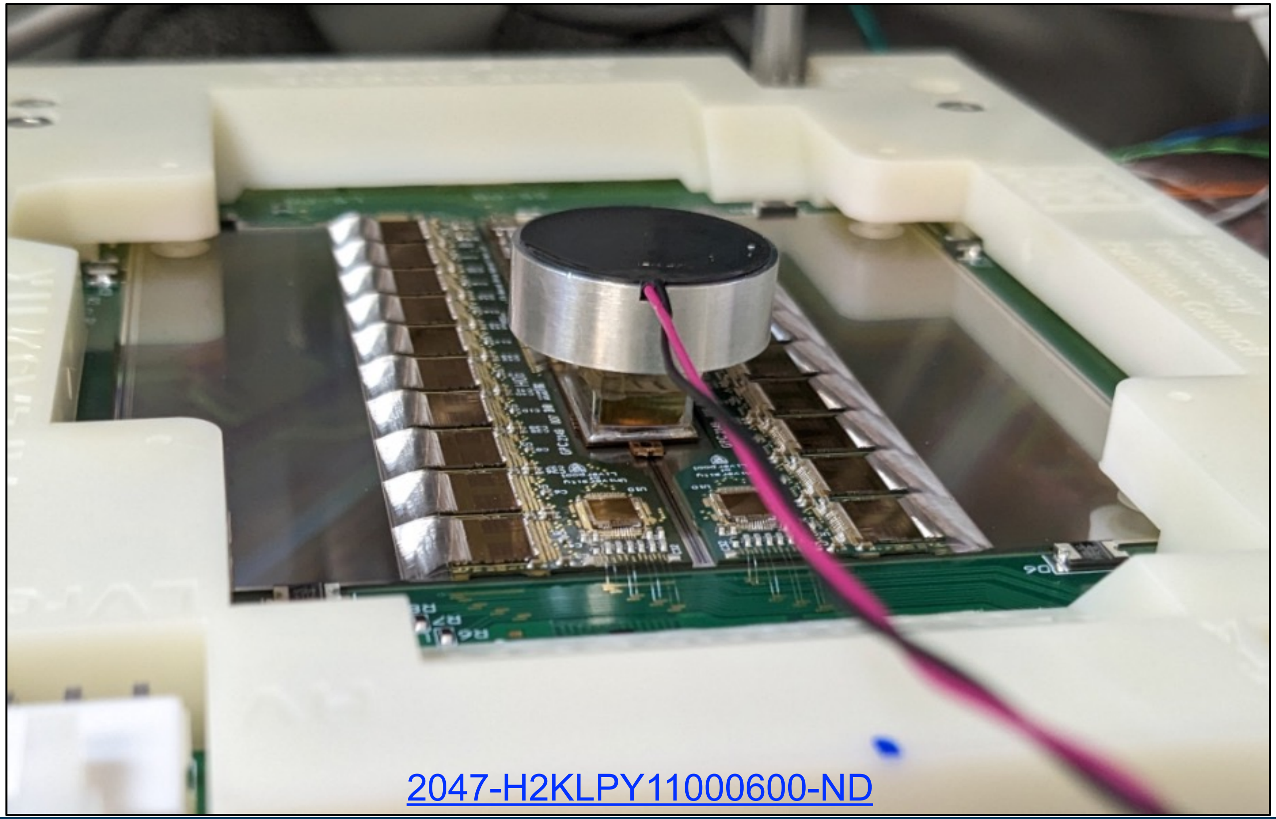
Building confidence in the vibration theory

Intentionally Vibrating Modules

Motivation:
- Suspect powerboard is producing vibrations.
  - Somehow mechanical waves → electrical noise.
- Suspect module is vibrating at all temperatures.
  - Then something changes at cold temperatures (stress?)
    → cold noise turn-on.
- Maybe we can induce “cold” noise at room temperature…



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.

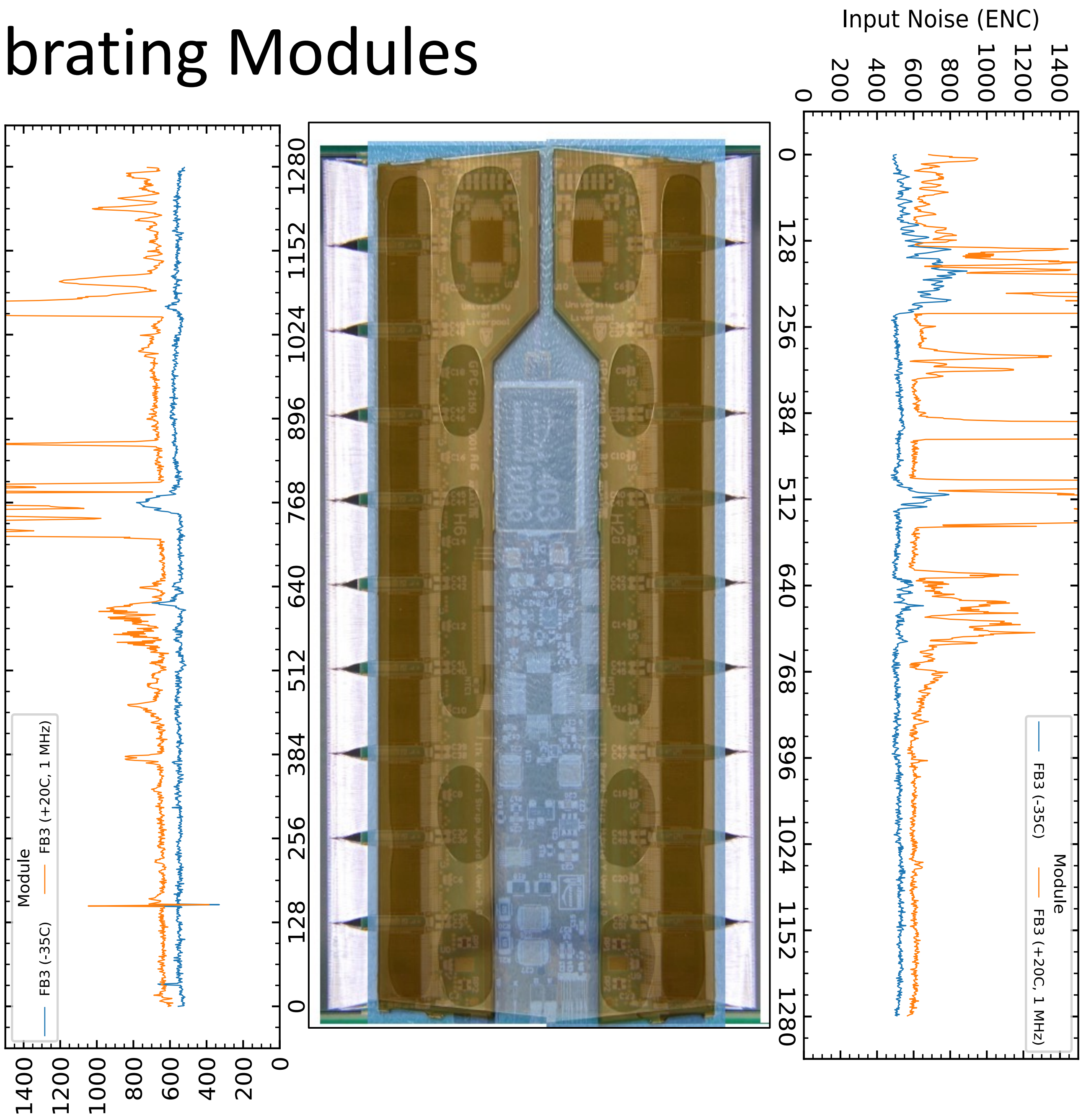


Intentionally Vibrating Modules

Motivation:
- Suspect powerboard is producing vibrations.
  - Somehow mechanical waves → electrical noise.
- Suspect module is vibrating at all temperatures.
  - Then something changes at cold temperatures (stress?)
    → cold noise turn-on.
- Maybe we can induce "cold" noise at room temperature…

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.

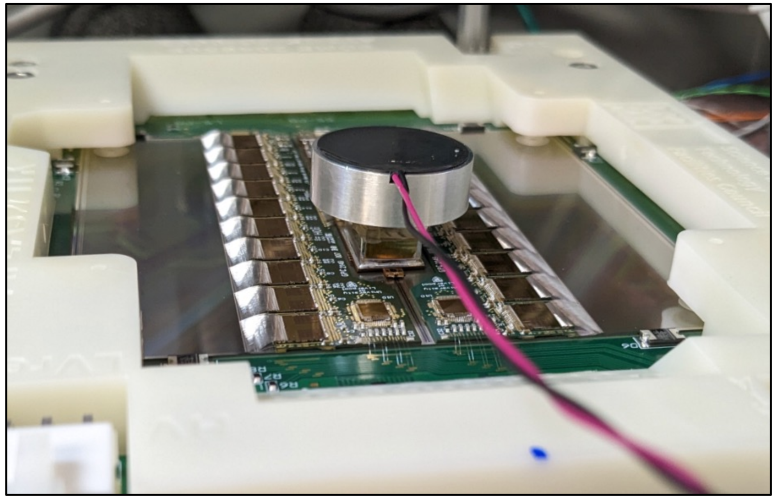
Results:
- Noise pattern @ +20C w/ transducer looks like CN pattern @ -35C (w/out transducer), but worse.

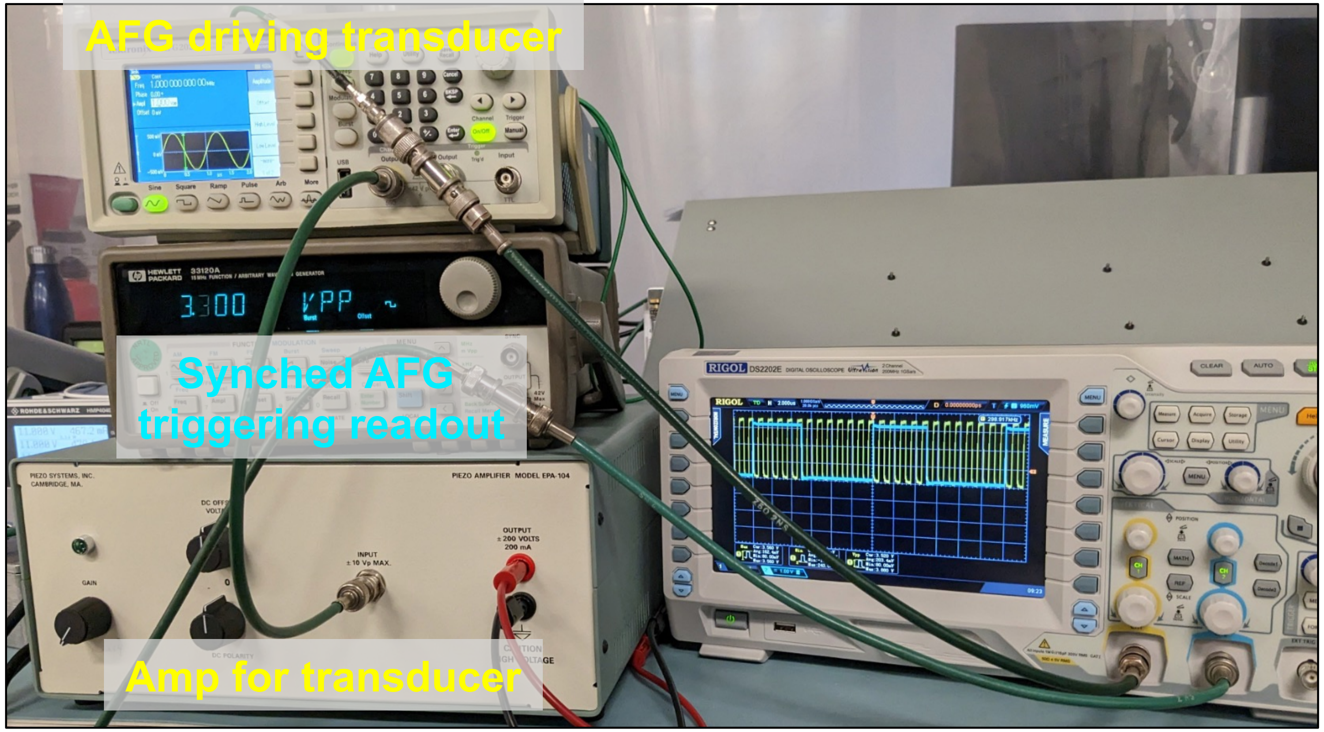


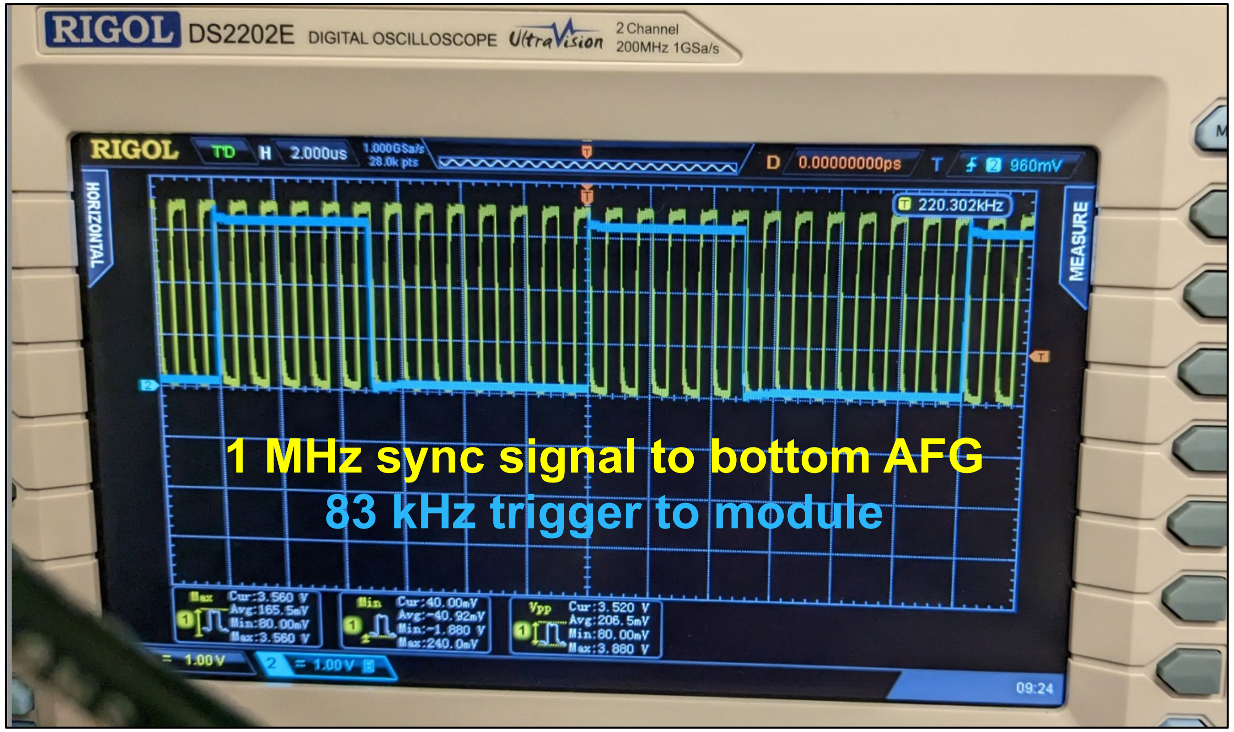
Transducer-Synchronous Triggering

Next step:

- Instead of triggering randomly (previous slide), <u>synch trigger with transducer</u>.
- 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.



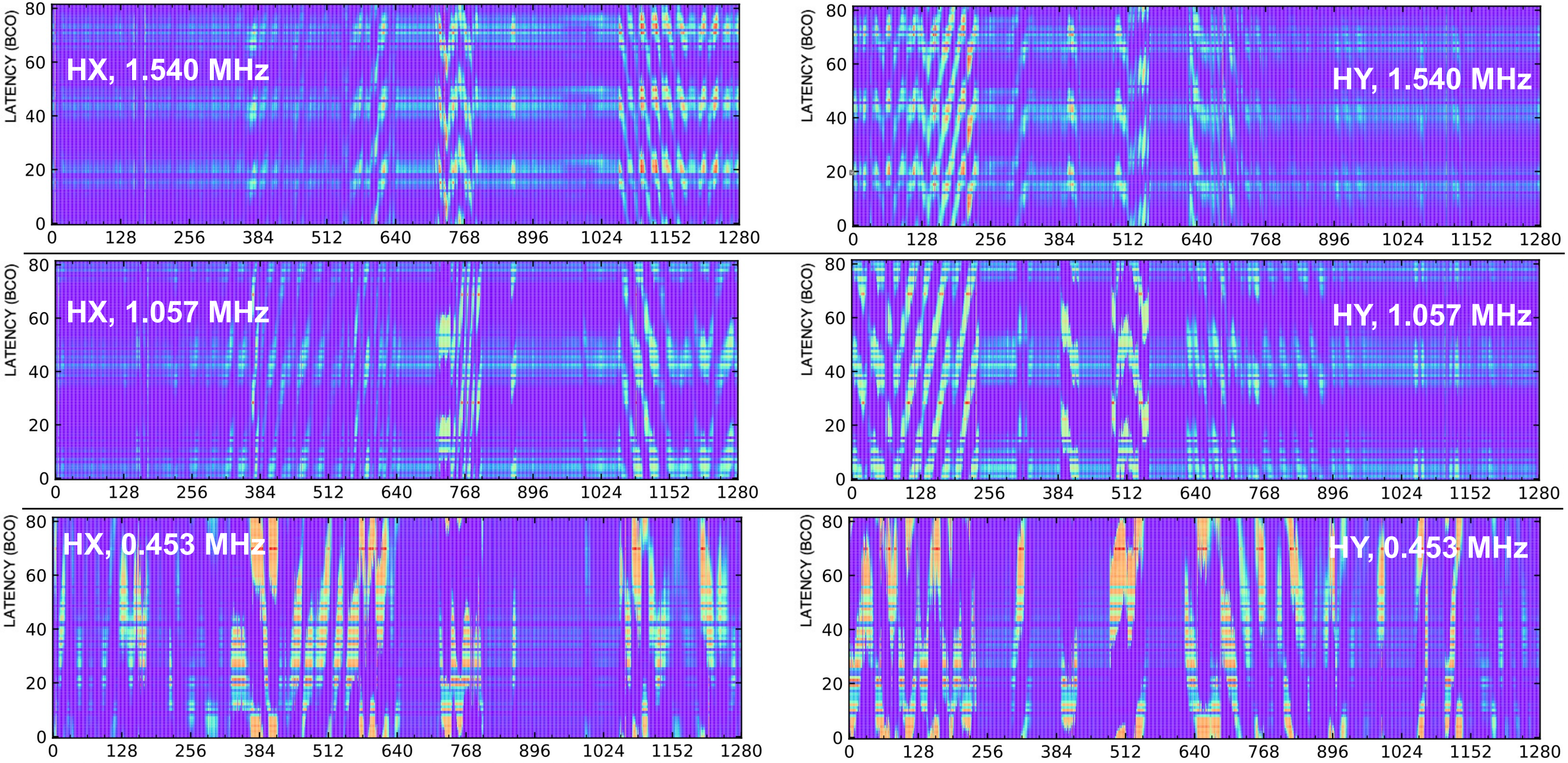




x-axis: strip number
y-axis:1 BCO → 25 ns
z-axis: noise occupancy

Transducer-Synchronous Triggering

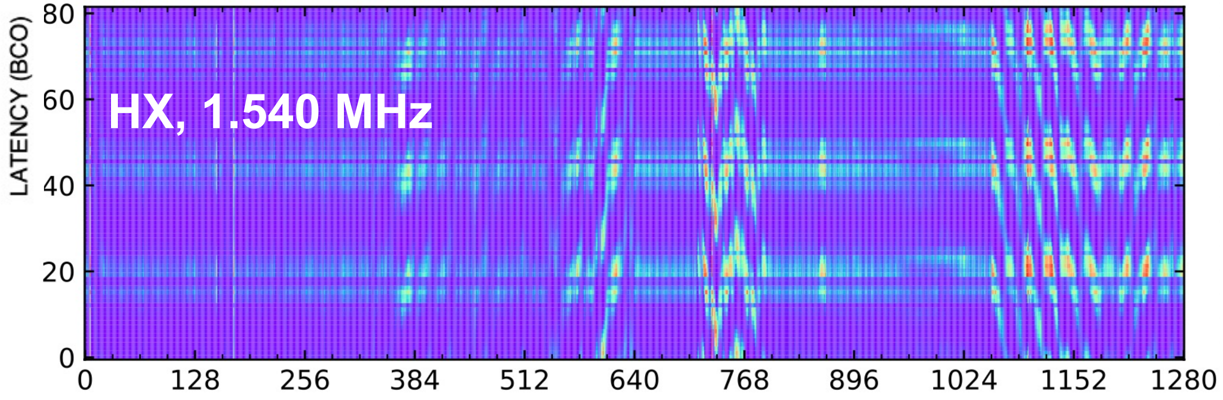
Showing only strip rows covered by hybrids and PB.

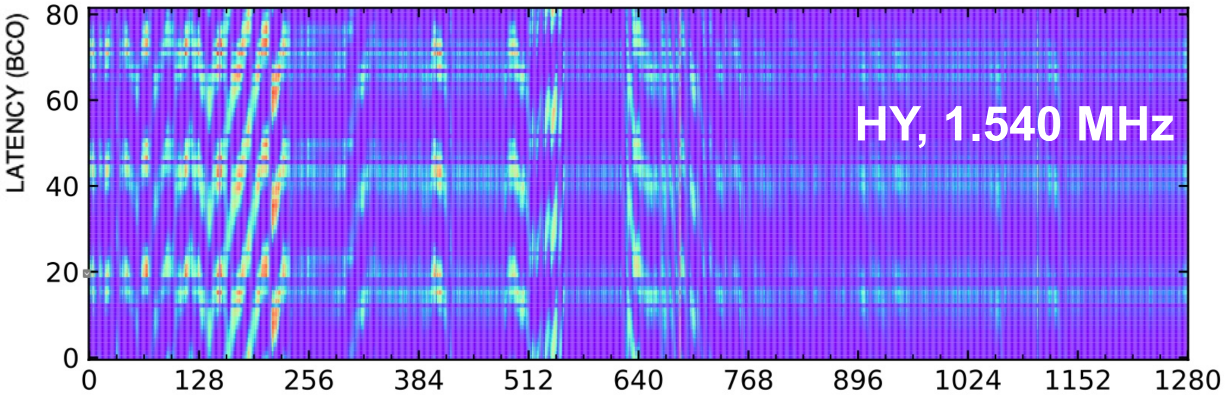


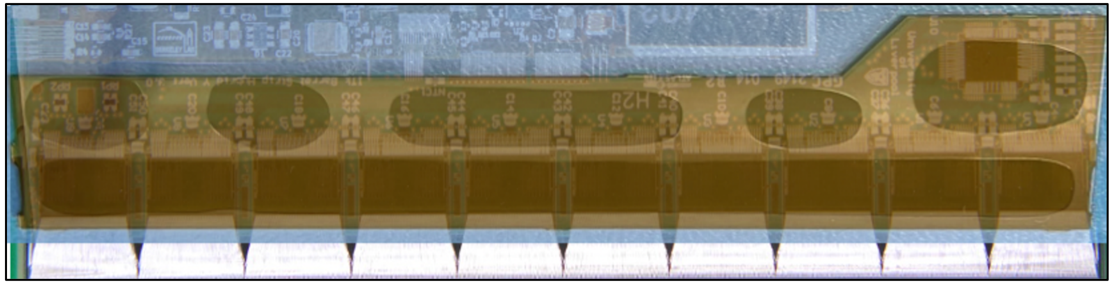
x-axis: strip number
y-axis:1 BCO → 25 ns
z-axis: noise occupancy

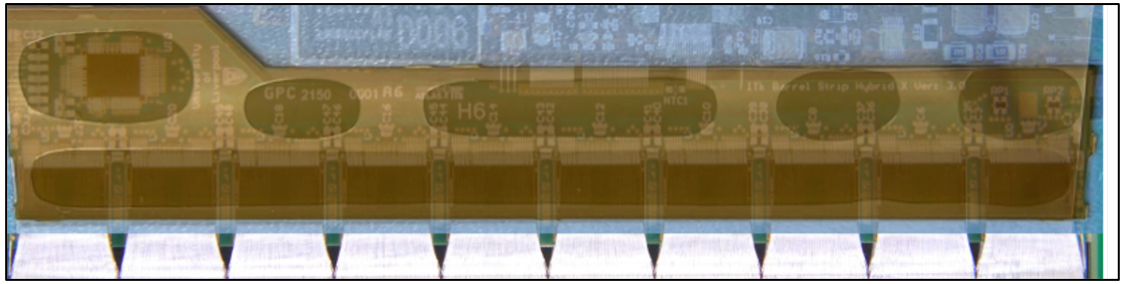
Transducer-Synchronous Triggering

Showing only strip rows covered by hybrids and PB.





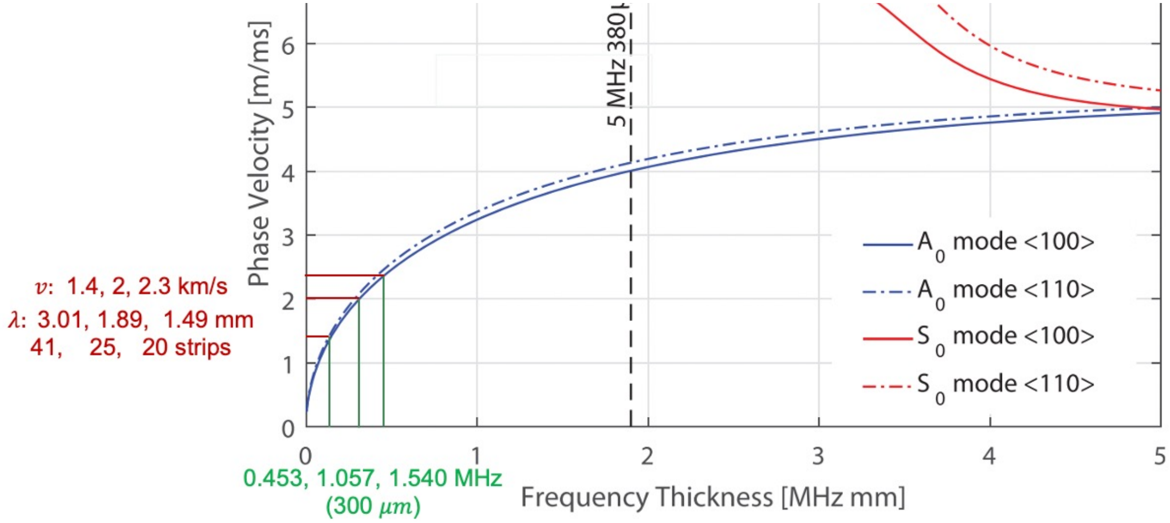




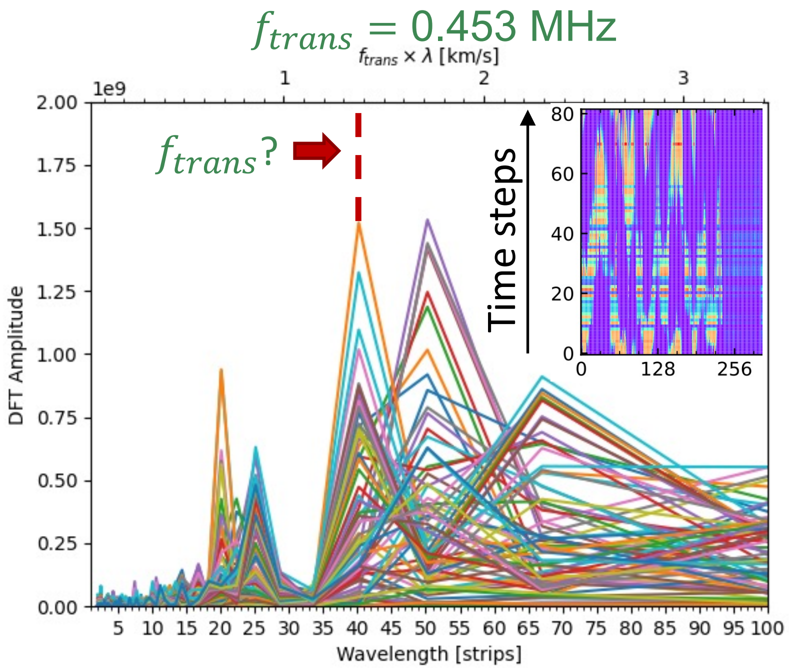
A_0 wave properties:

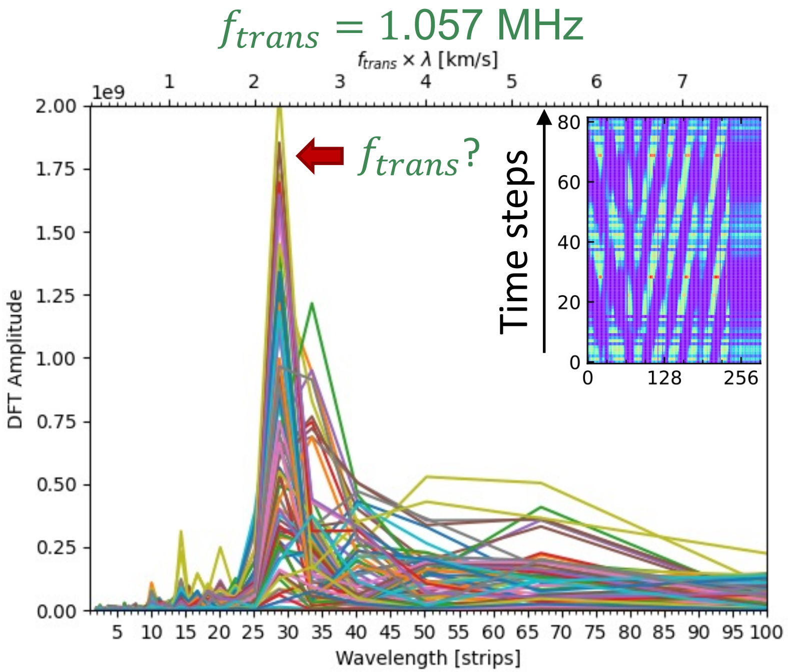
- $v_p \approx \frac{1}{2} v_g \sim \sqrt{f}$ for low f ($\lambda \gg$ plate thickness).

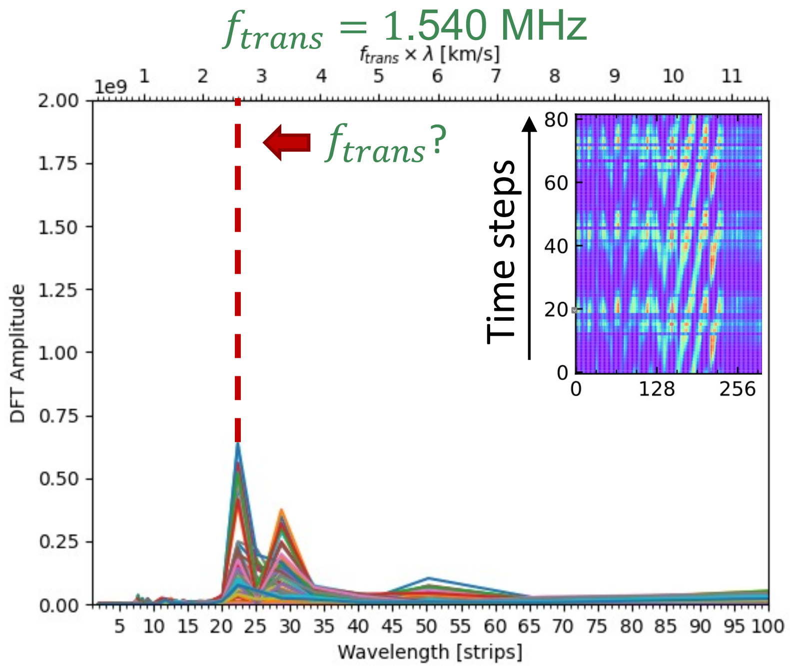
- Can we see $v \sim \sqrt{f}$ dependence?



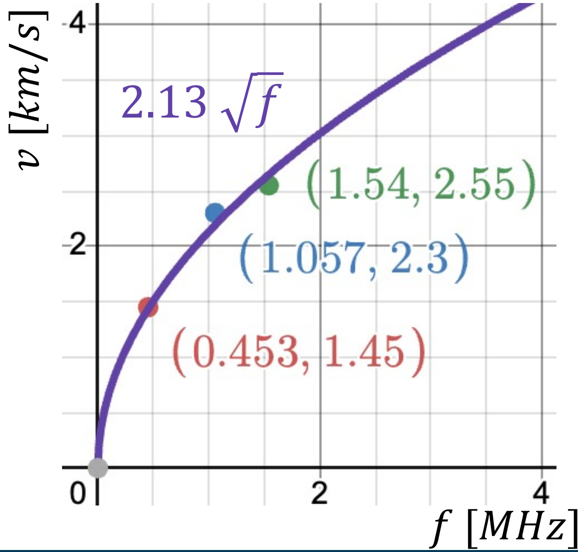
HY HCC Spectrum (Channels 0-200) @ -35C







- 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.



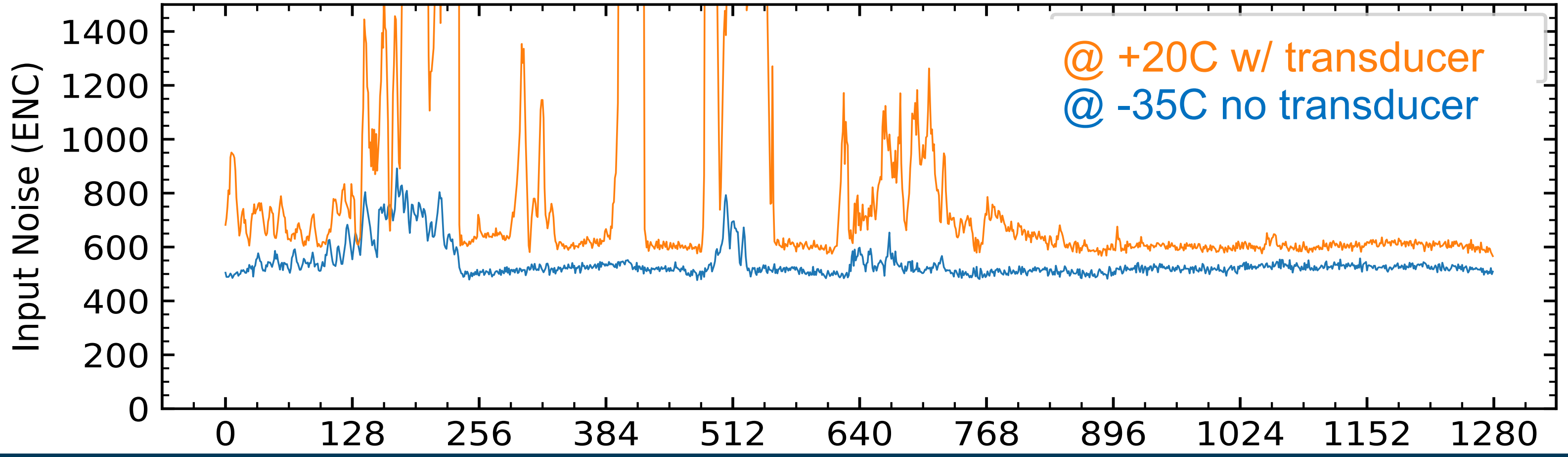
Vibration Summary

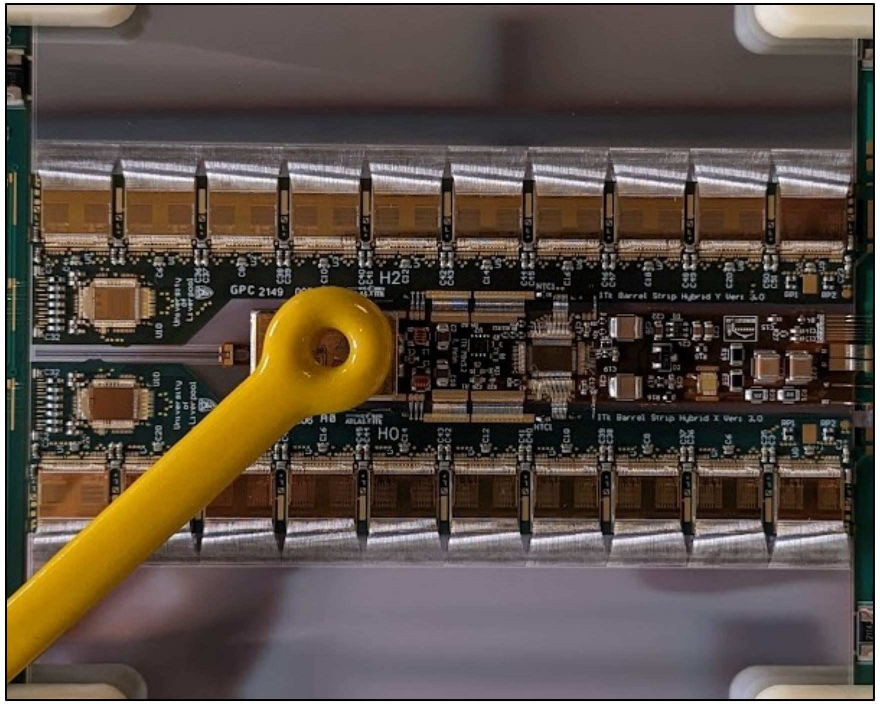
Summary:

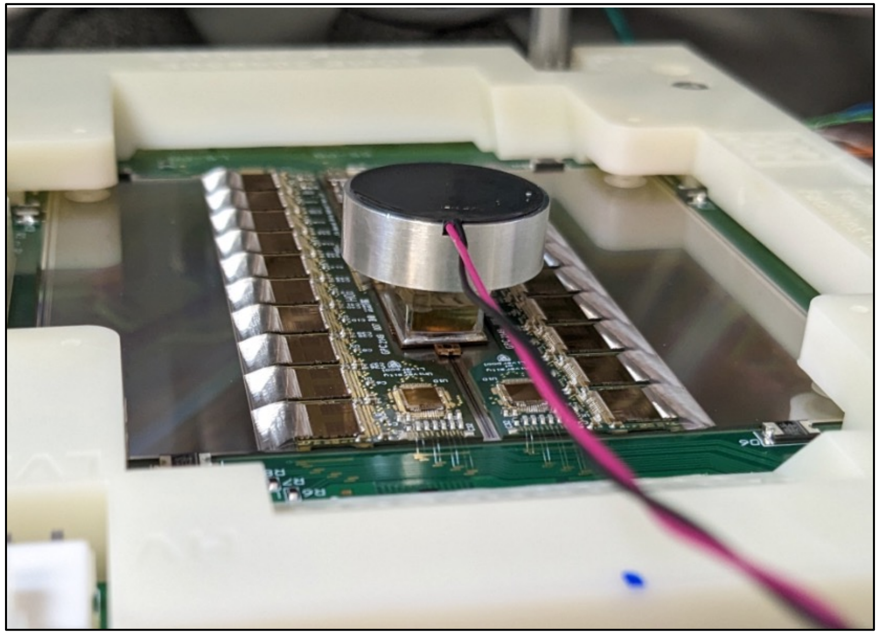
- Fairly confident something is vibrating on the powerboard at $f_{\mathrm{DCDC}} \approx 2\ \mathrm{MHz}$.
    - Likely vibrating at all temperatures.
    - But something changes when cold (stress?) → cold noise turn-on.
- "Cold" noise pattern reproduced at room temp by vibrating module with transducer.
- Mechanical wave couples into sensor & travels → noise on strips far from PB.
    - Velocity and wavelength consistent with A_0 Lamb wave.

Questions:

- What component is vibrating?
- How do mechanical waves produce electrical noise?





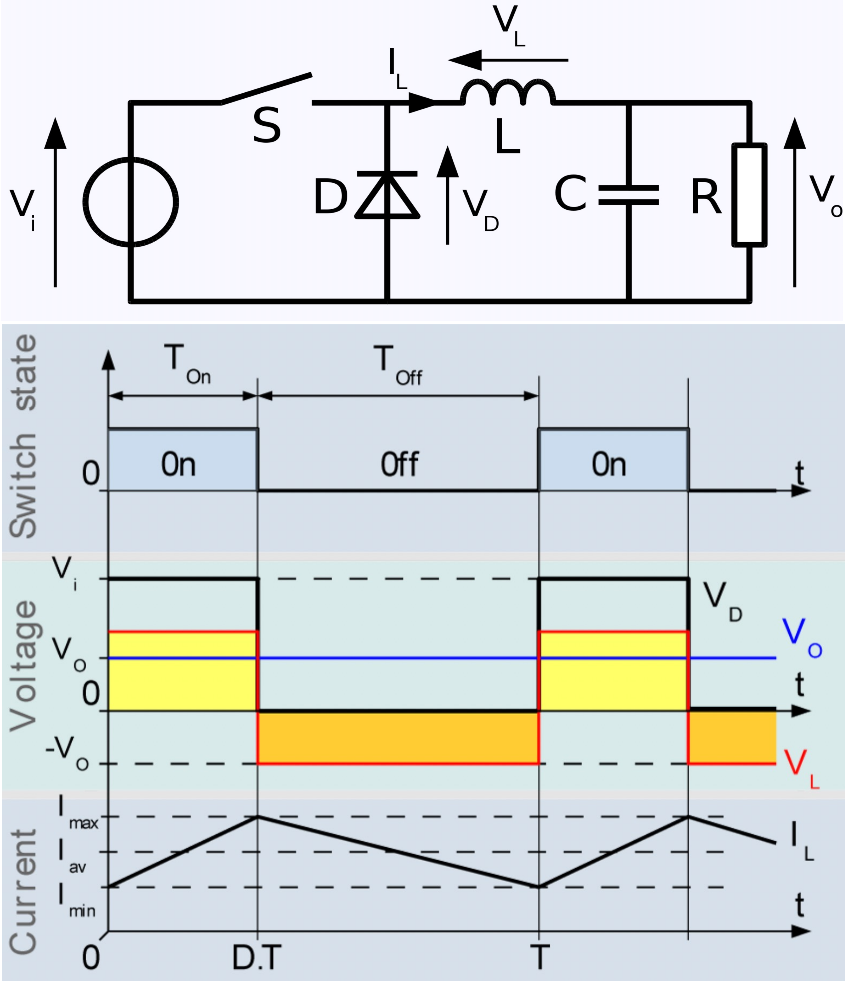


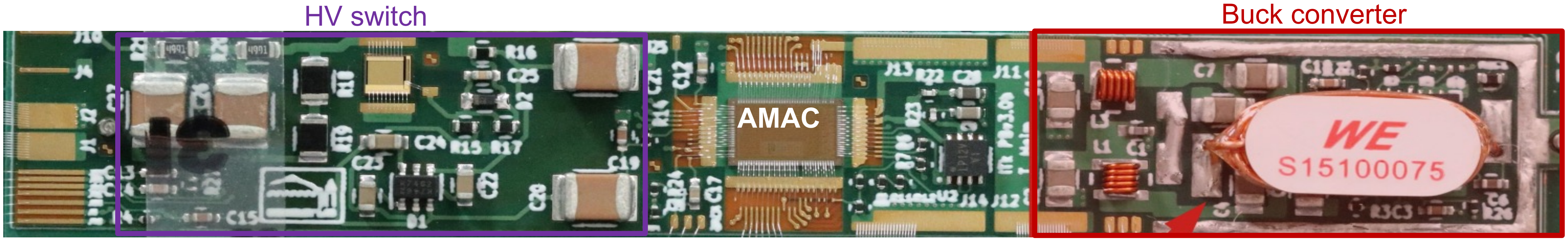
The Powerboard: A Closer Look

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).





The Powerboard: A Closer Look

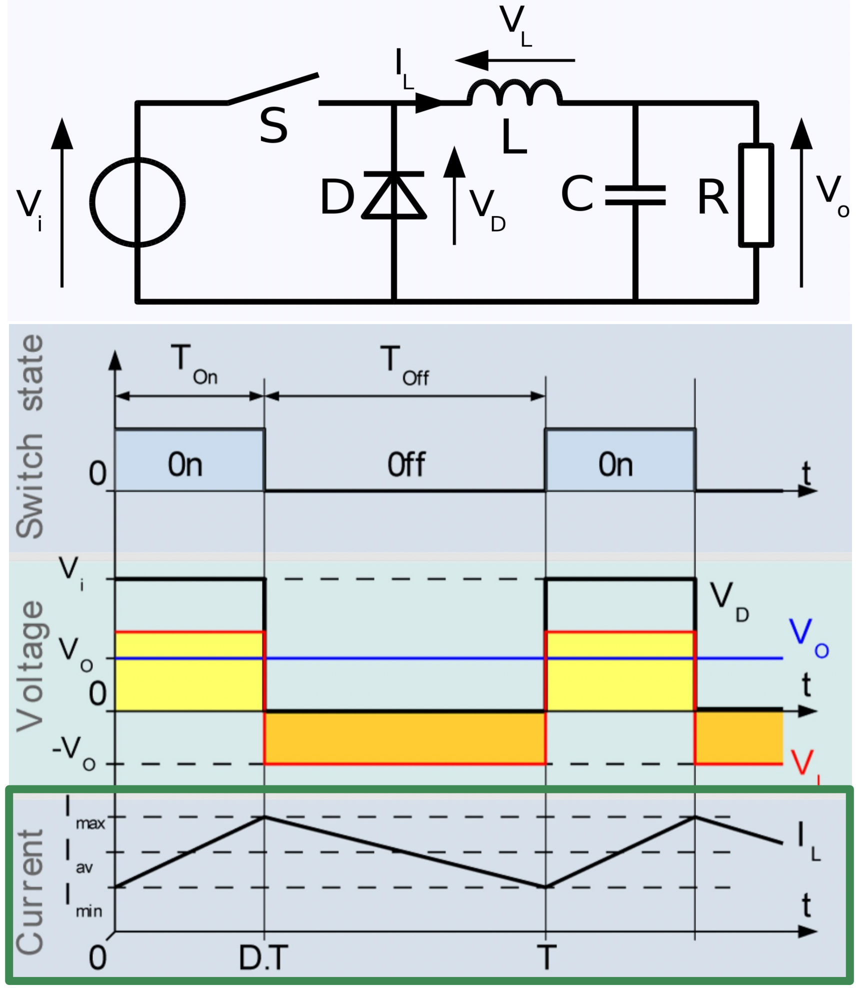
Voltage Stepdown:

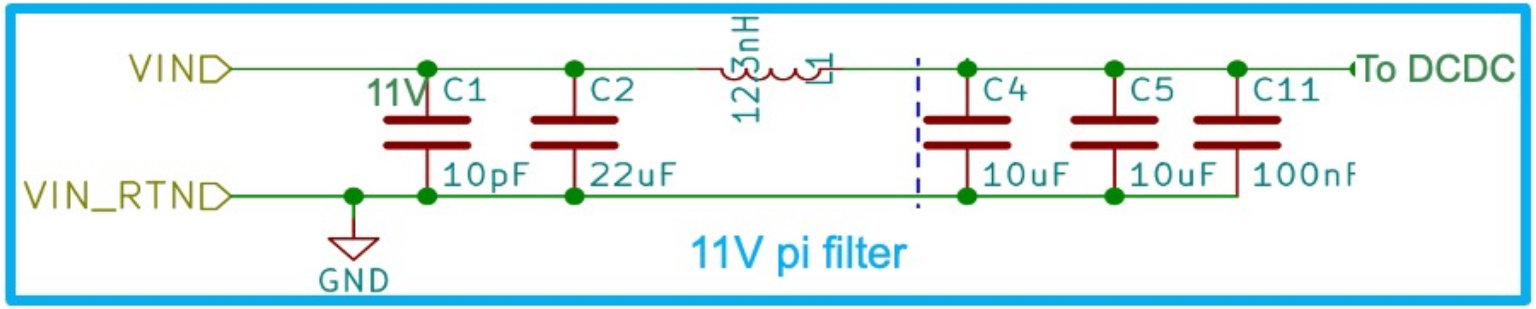
- Front-end ASICs need 1.5V.
  - But distribute 11V to modules & use DC-DC conversion.
  - Reduces ohmic losses in cables & traces.

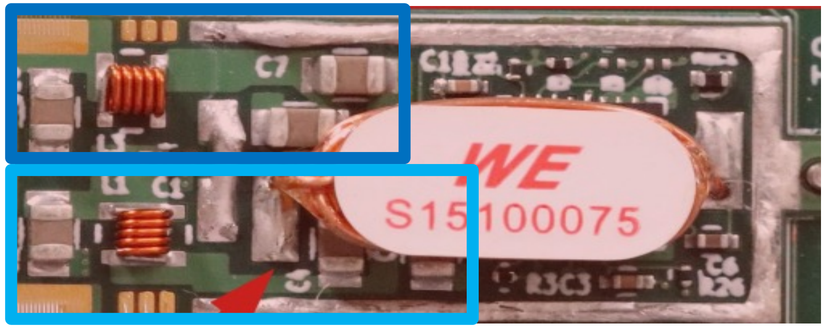
- Use a buck converter (bPOL) w/ air-core coil on powerboard.
  - More efficient than a linear regulator → less heat.
  - But 2 MHz switching → EM noise (hence shield box).

Filtering:

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







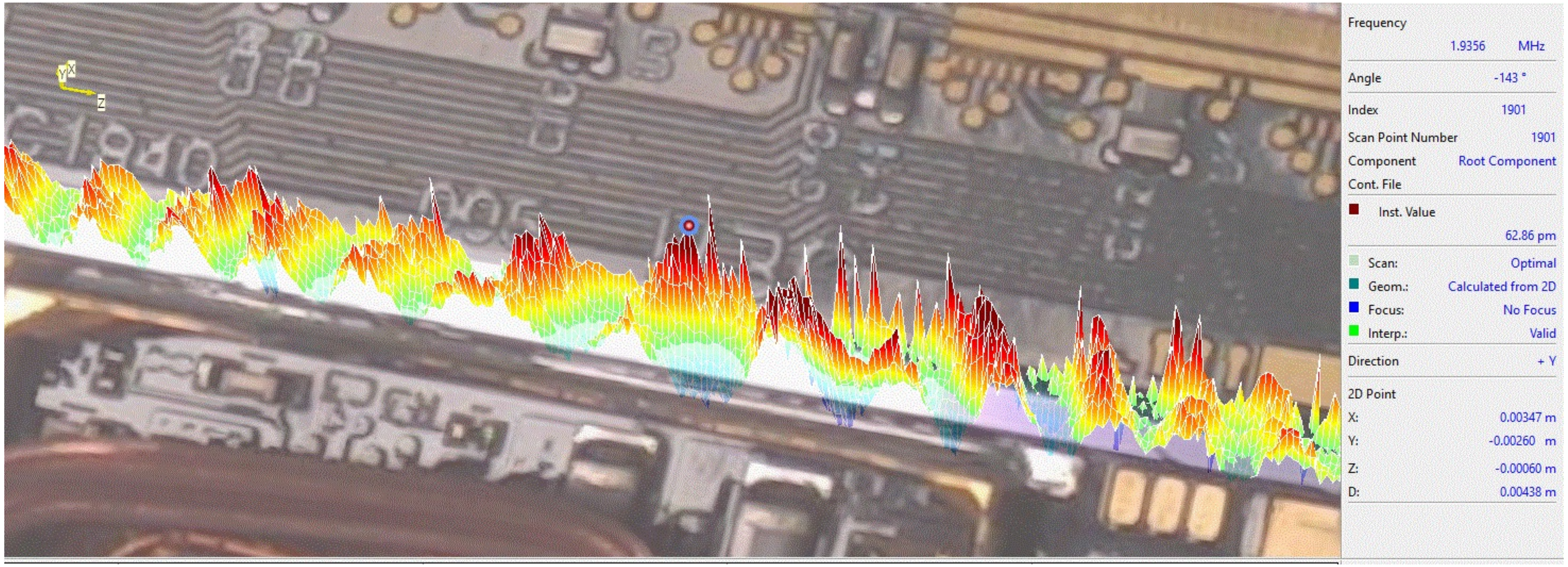
Vibrometer Measurements (RAL)

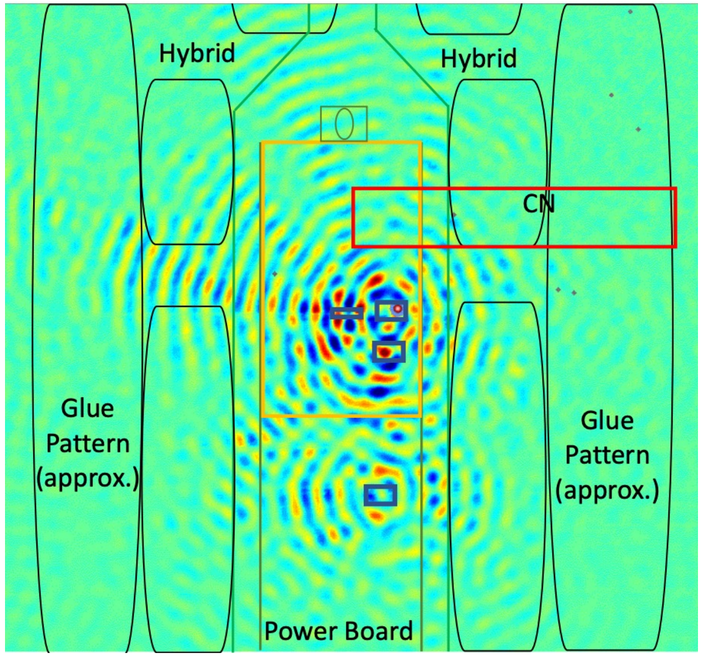
- Vibrations confirmed using laser doppler vibrometer at RAL.
  - See $\mathcal{O}(10\ \mathrm{pm})$ - $\mathcal{O}(1\ \mathrm{nm})$ vibrations, depending on location on module.

- 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.



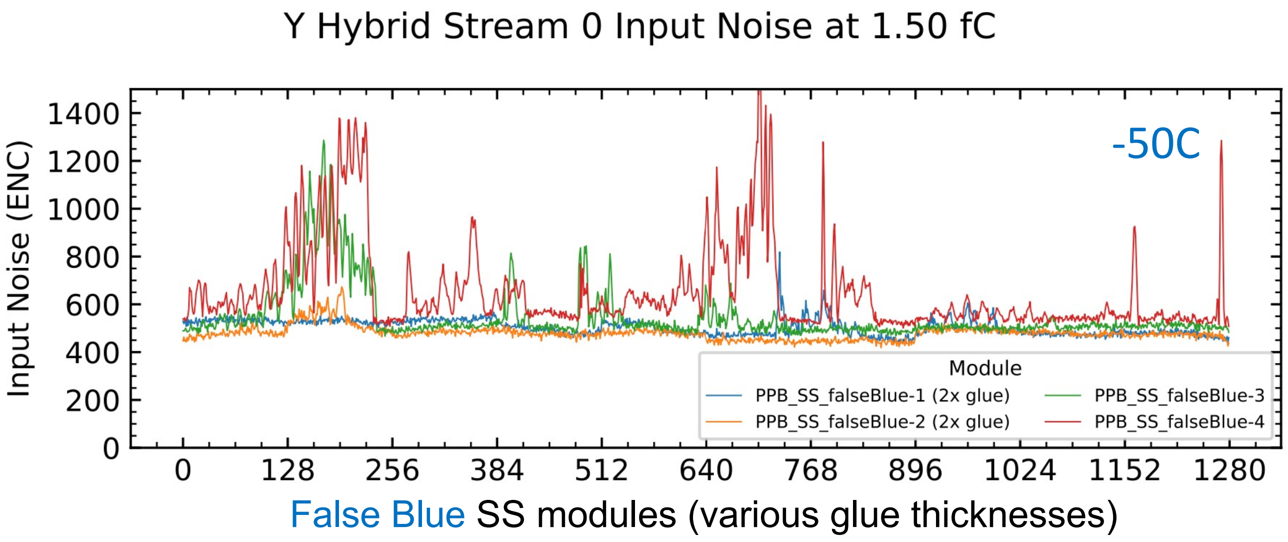


Mitigations Strategies

Strategy #1: Picking the right glue & glue thickness

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

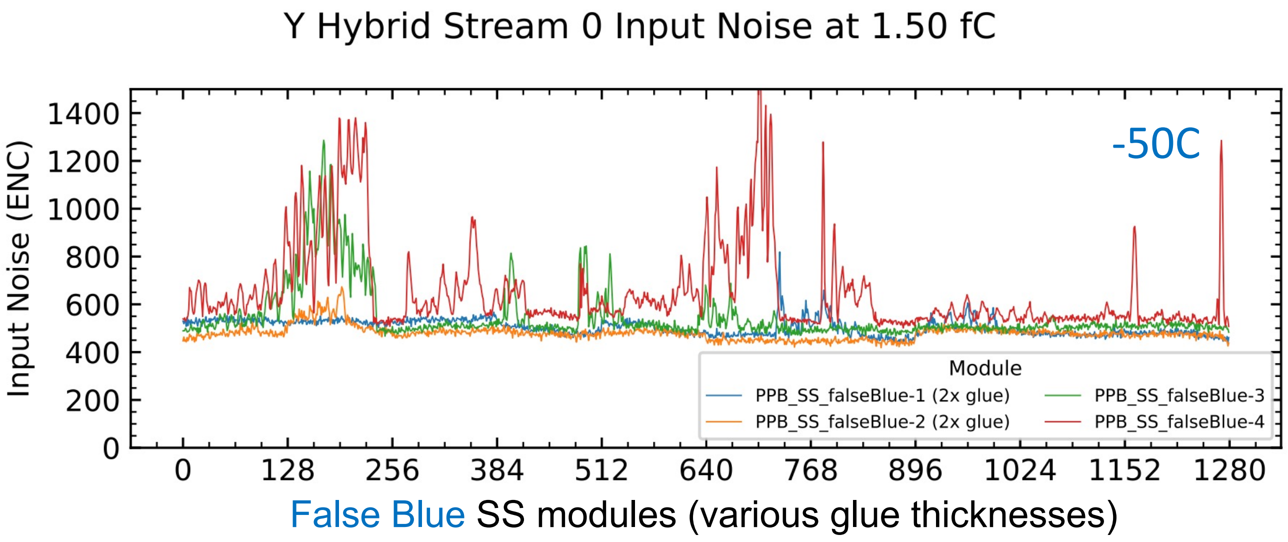
Evaluated epoxies:
- Polaris PF-7006 2-part epoxy
  - Previous baseline, no longer available.
  - Discovered CN with this glue.
- Loctite Eccobond F112 (“True Blue”)
  - Previous backup, new baseline.
  - Better CN performance than Polaris.
- AA-BOND F112 (“False Blue”)
  - Should be very similar to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

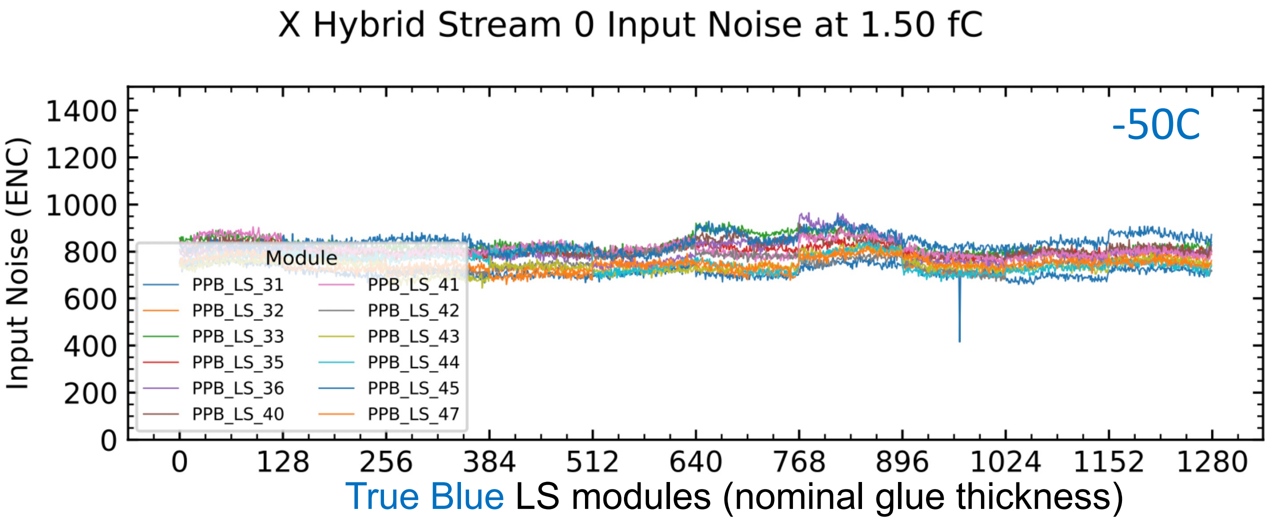


Strategy #1: Picking the right glue & glue thickness

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.





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

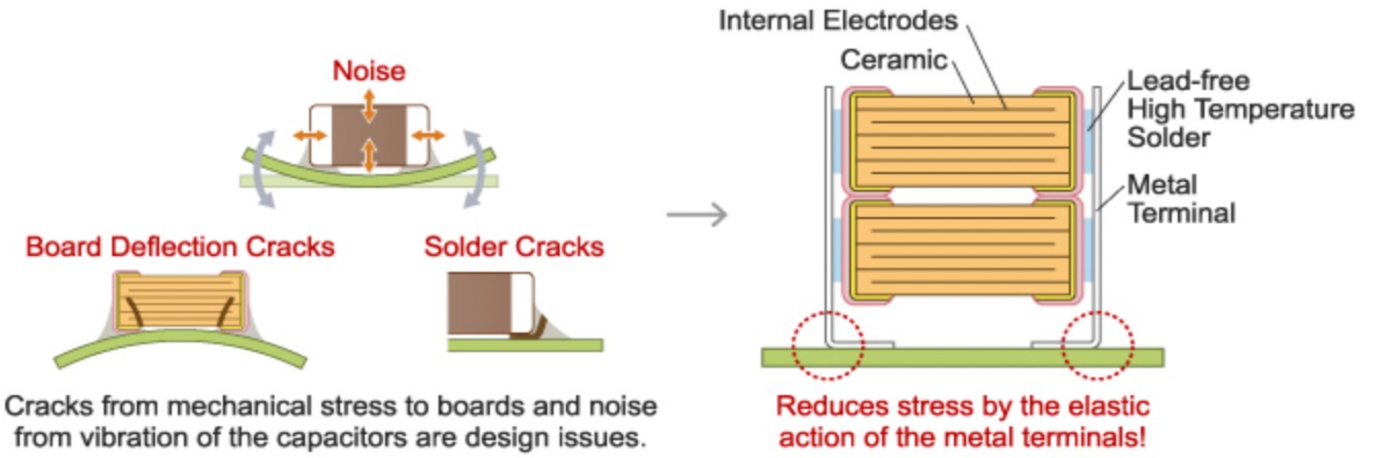
Strategy #2: Modifying the powerboard

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.

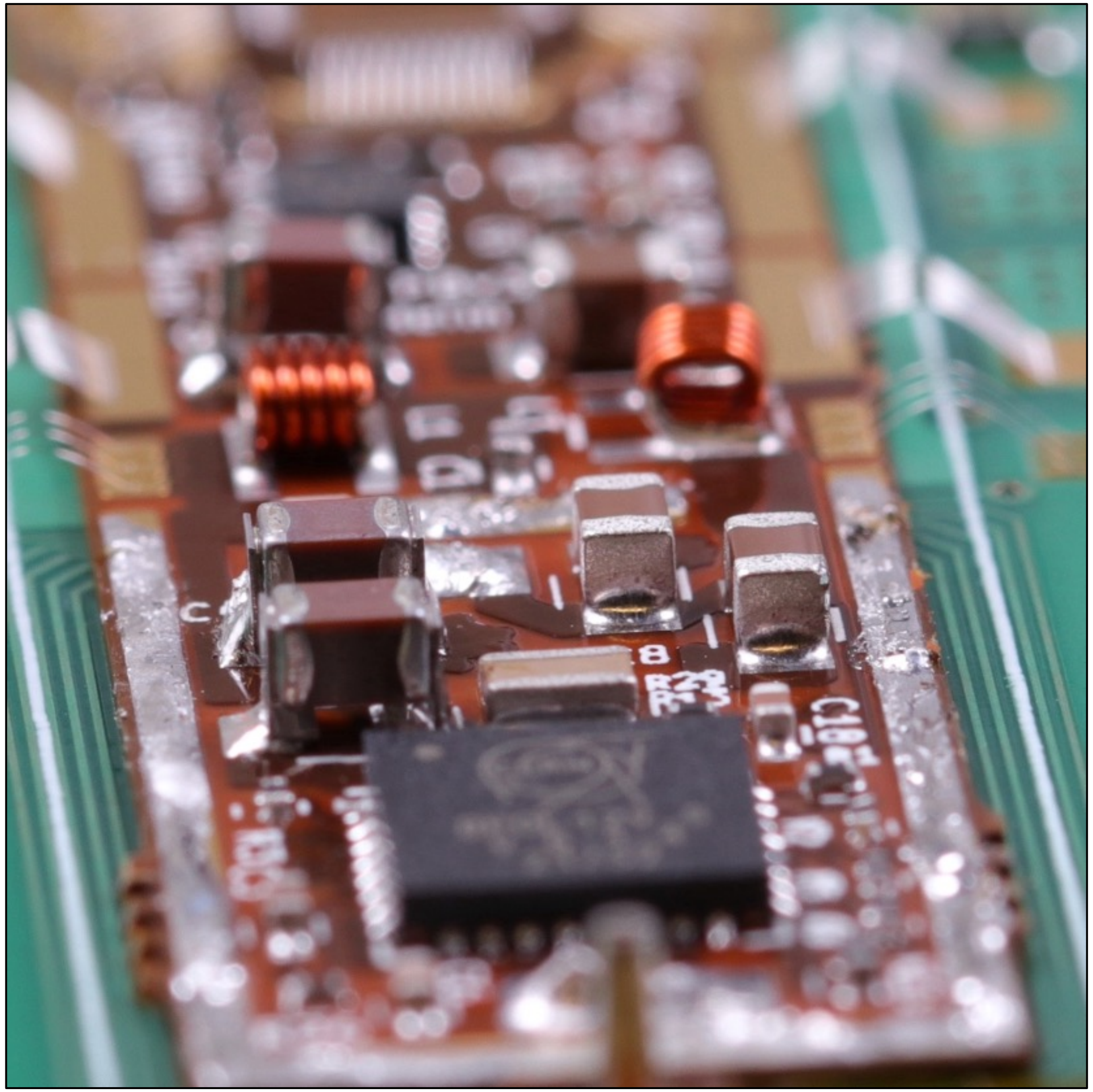
1. Bond metal terminals to the external electrodes of chips.

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



Strategy #2: Modifying the powerboard

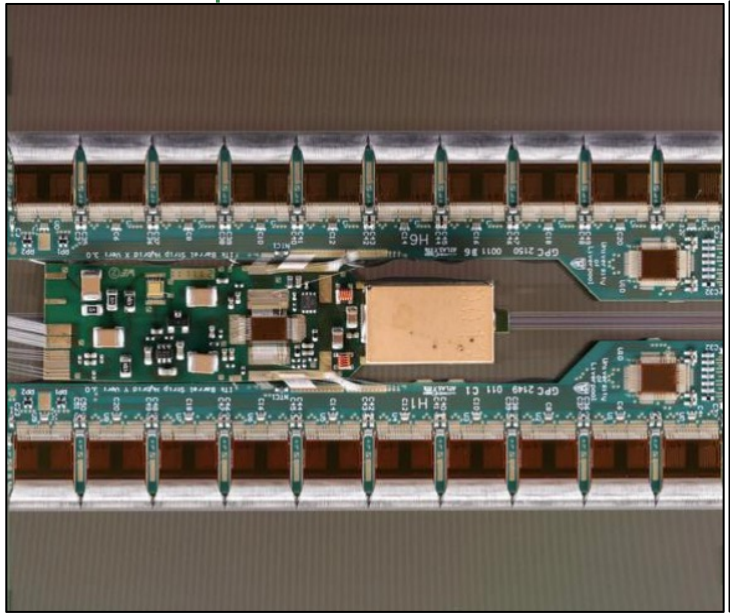
Swapping components:

- 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.

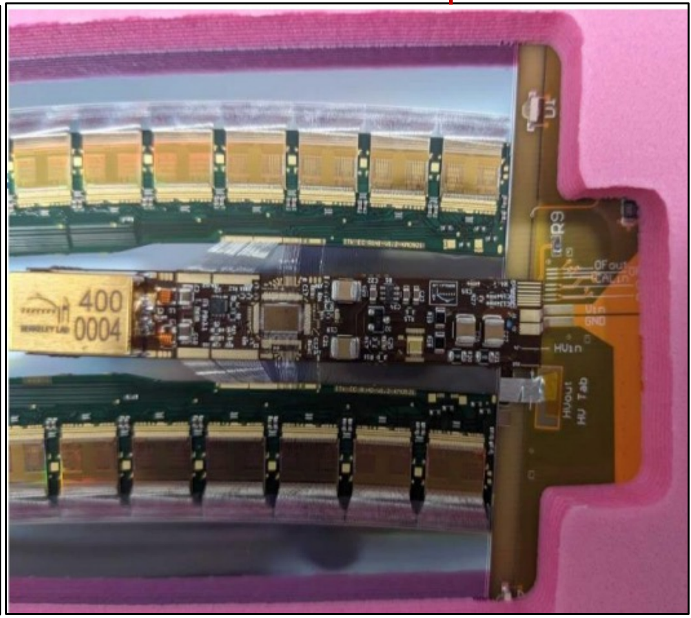
Changing the substrate:

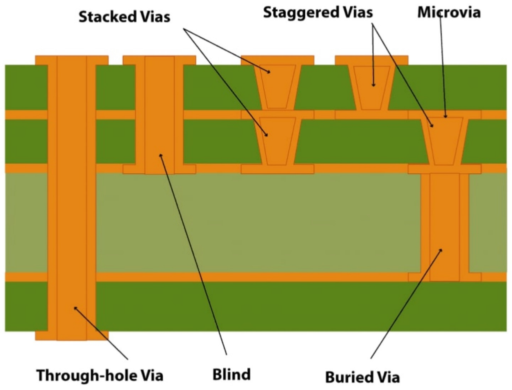
- Recent endcap modules do **not** have CN.
- Inspired some special builds:
  - Barrel PB on endcap module → CN.
  - Endcap PB on barrel module → no CN.
- Endcap has different powerboard flex PCB manufacturer (Würth).
  - Thinner & more flexible than barrel PBs.
  - Different stack-up & vias (barrel = 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



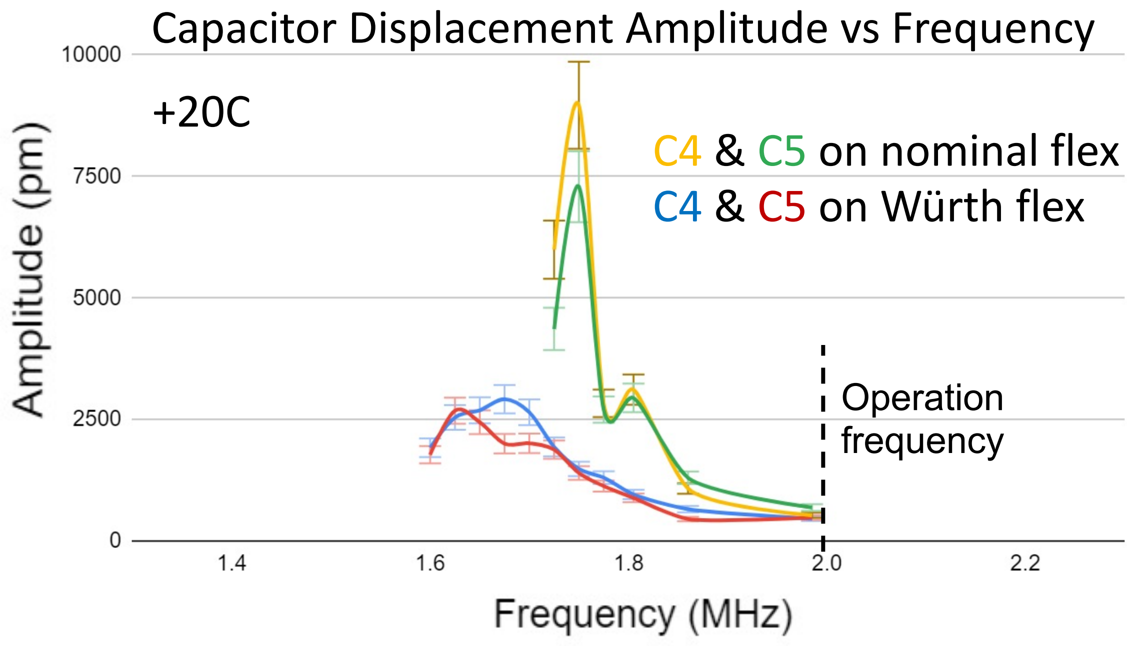
Barrel PB on endcap module





Strategy #2: Modifying the powerboard

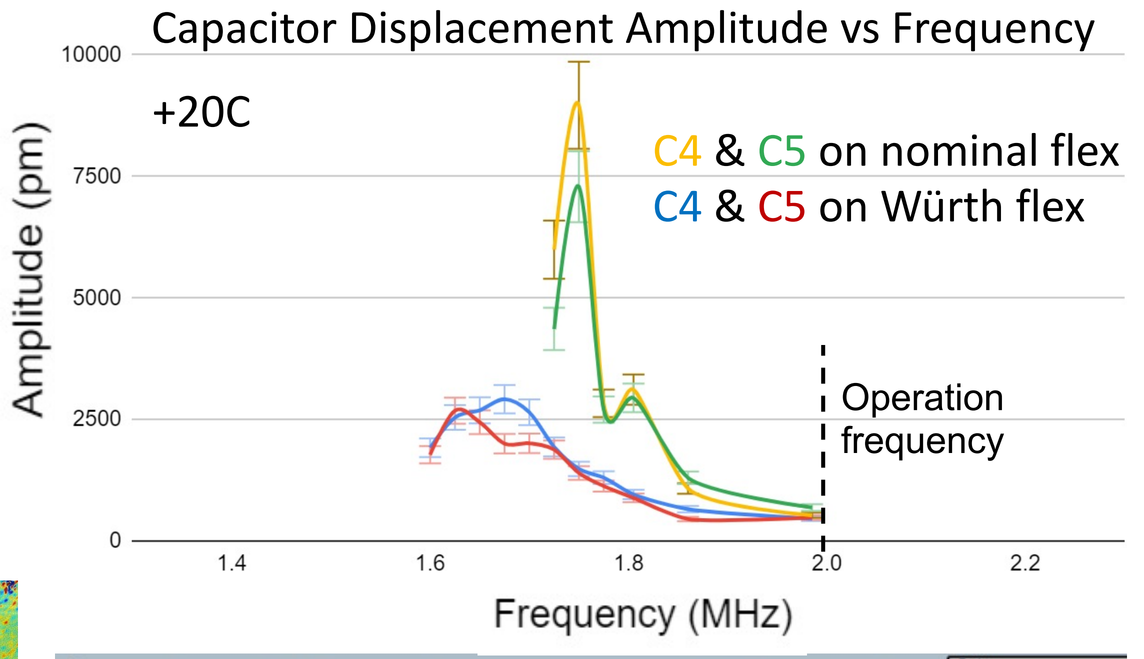
Barrel PBs in endcap process:
- Vibrometer tests of standalone PBs were encouraging.
  - Caps vibrate much less than on nominal barrel PB flexes.
  - Although the difference is small at 2 MHz…



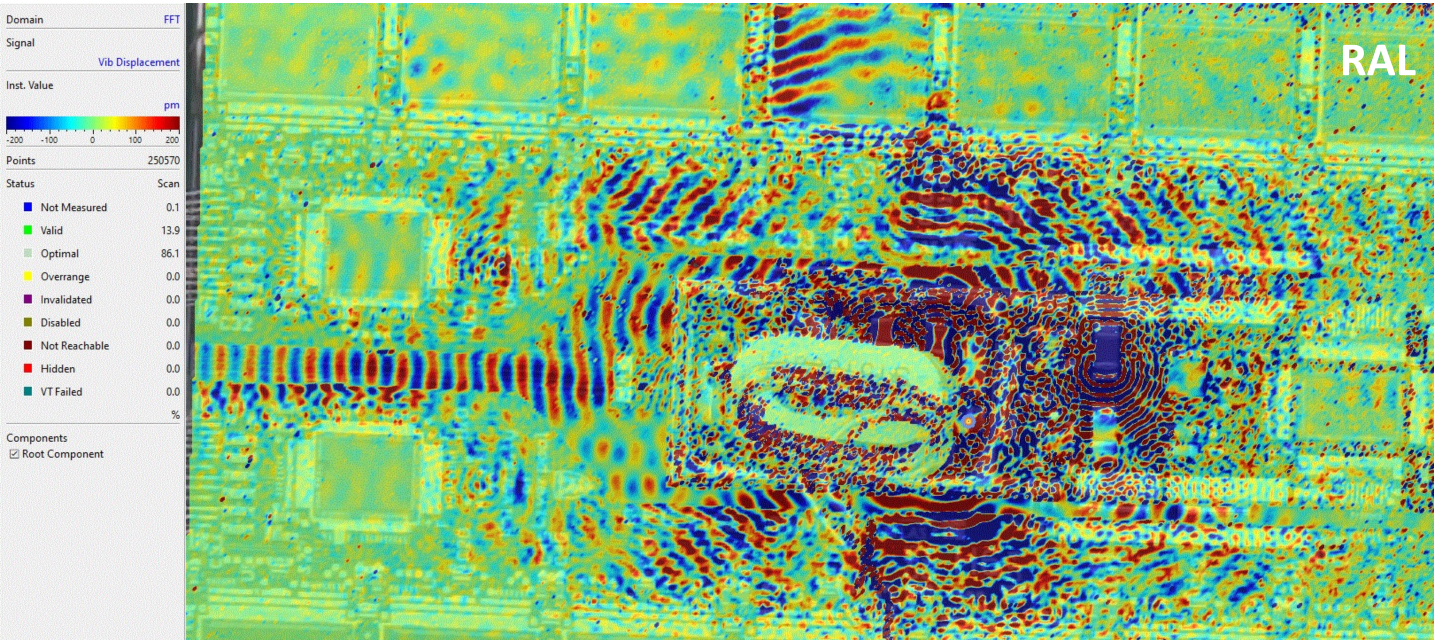
Strategy #2: Modifying the powerboard

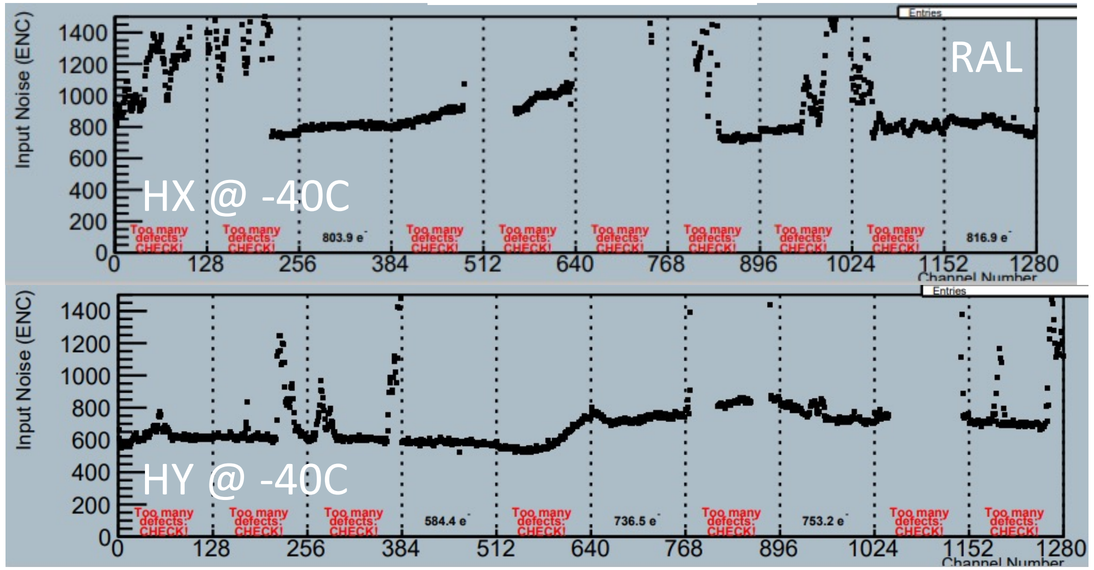
Barrel PBs in endcap process:

- 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



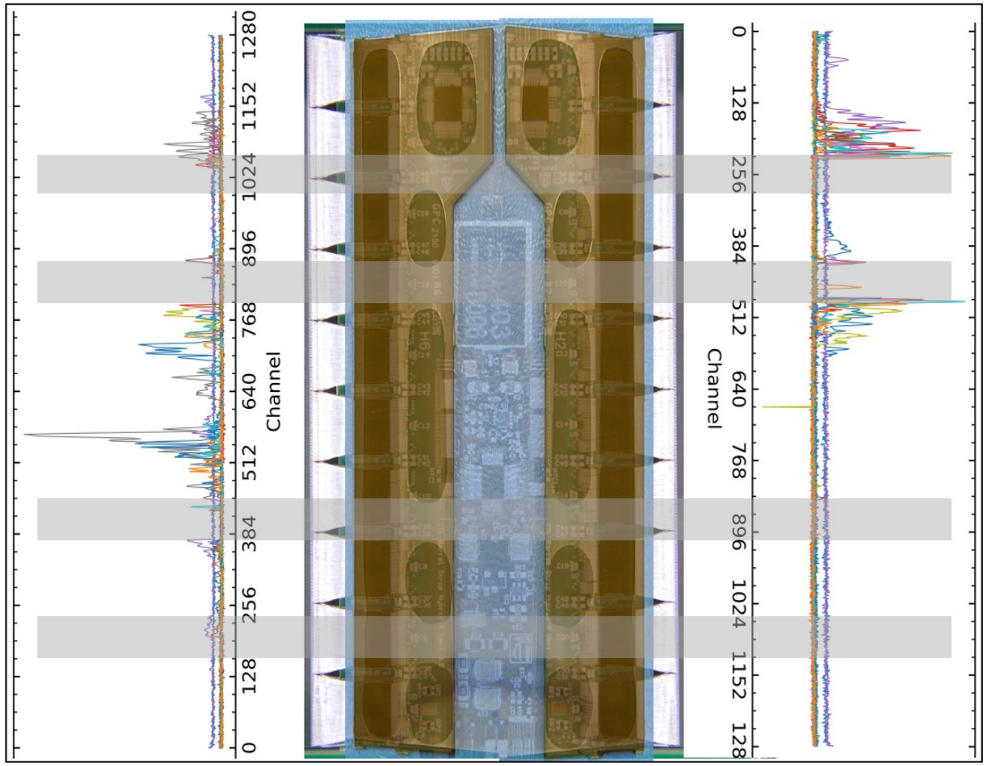


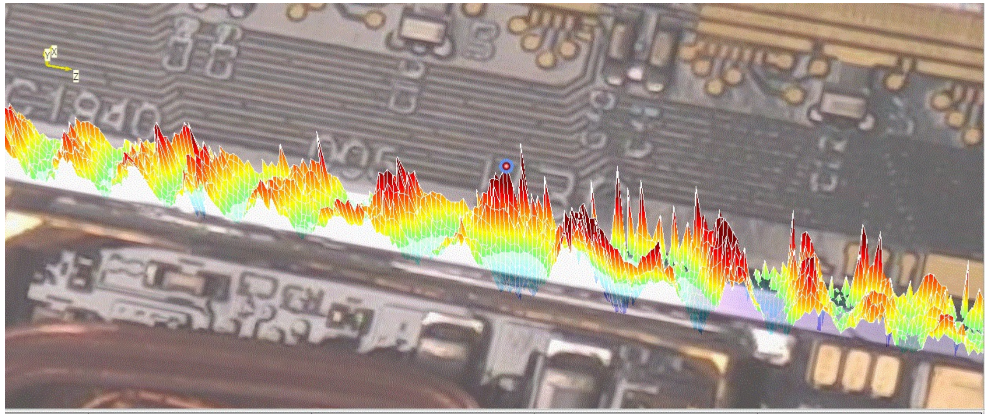
Strategy #3: Filling in the gaps

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.





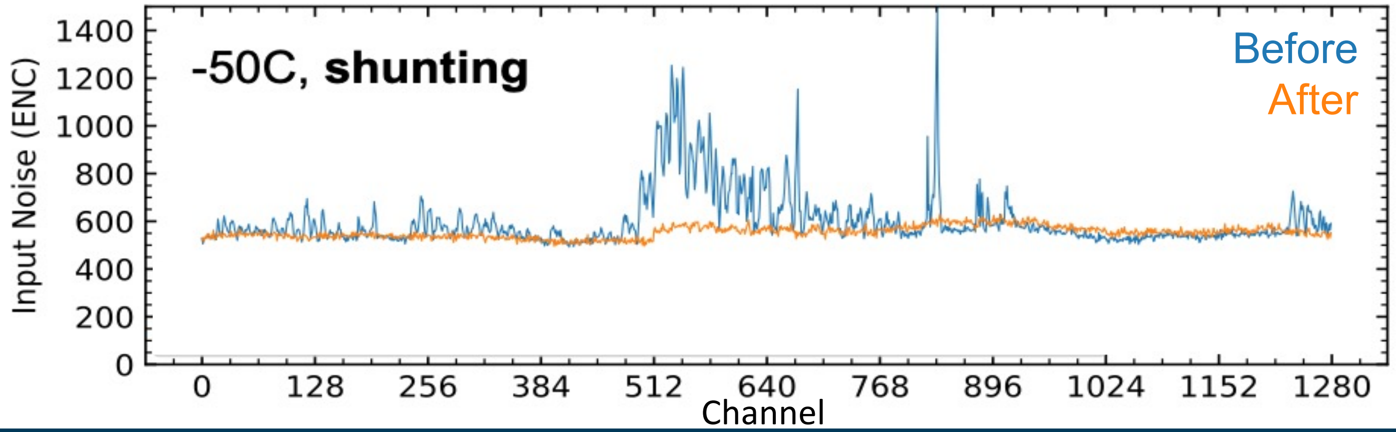
Strategy #3: Filling in the gaps

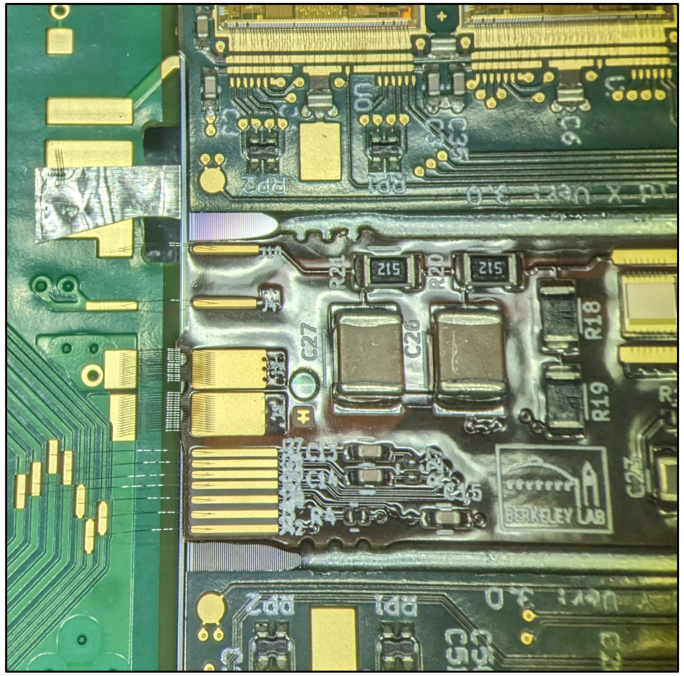
Procedure:
- Filled in gaps between hybrids and PB on existing module.
  - Originally built with worst glue (False Blue) → severe cold noise.
  - Filled gaps with more False Blue.

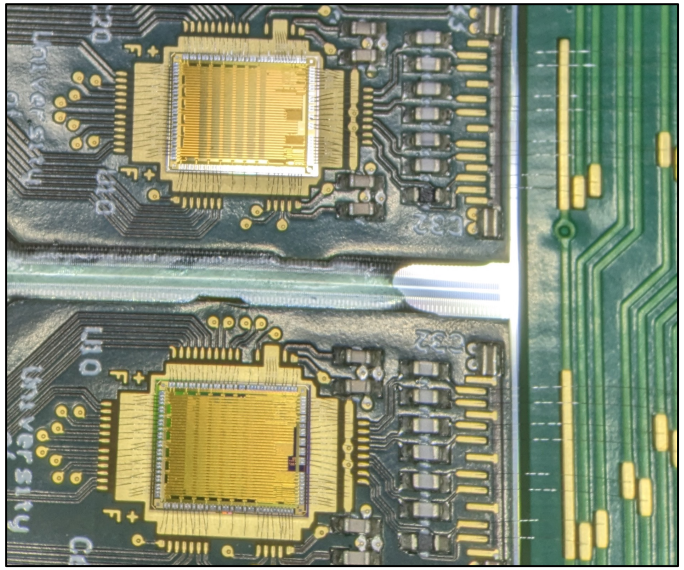
Results:
- Almost completely removed the cold noise!

- 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.





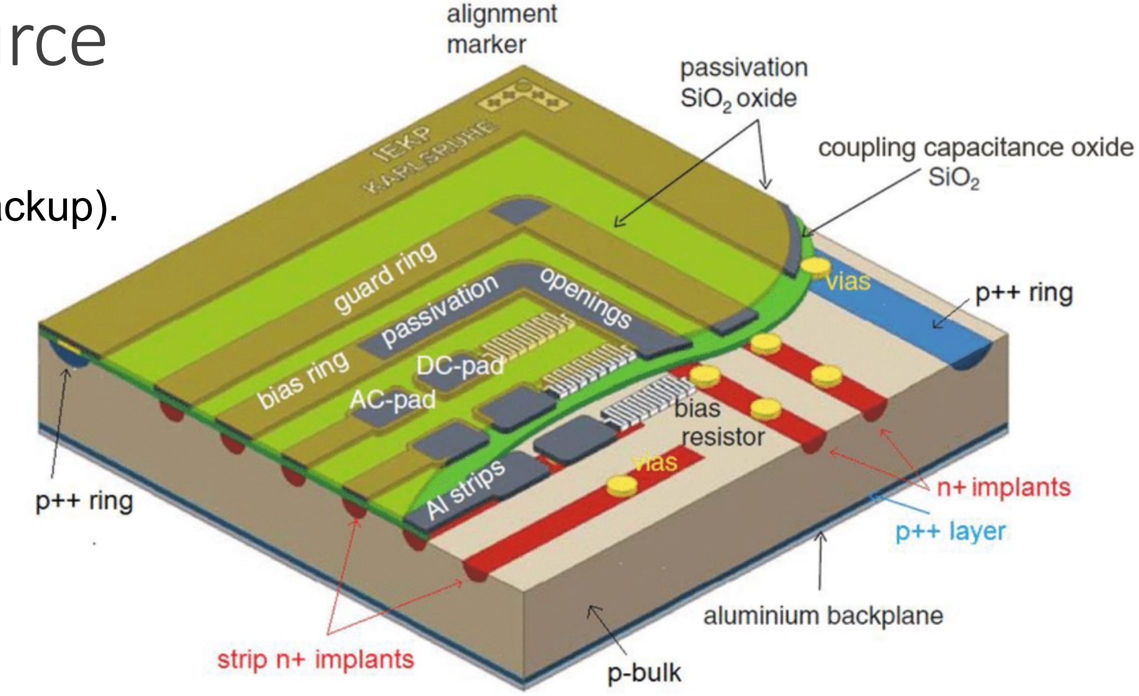


Mechanical Wave → Electrical Signal Mechanism

Voltage Source

Speculation:

- Have evidence suggesting cold "noise" is <u>not</u> Gaussian noise (see backup).
- Appears vibrations produce AC voltage between strips and hybrid.
    - Causes *effective* discrimination threshold to oscillate.
- How is this AC voltage produced from mechanical waves?
- SiO_2 and Si_3N_4 in passivation & dielectric known to be piezoelectric...
    - Module built using old sensor w/ less passivation → less CN.
    - CN appears to be independent of bias voltage.



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

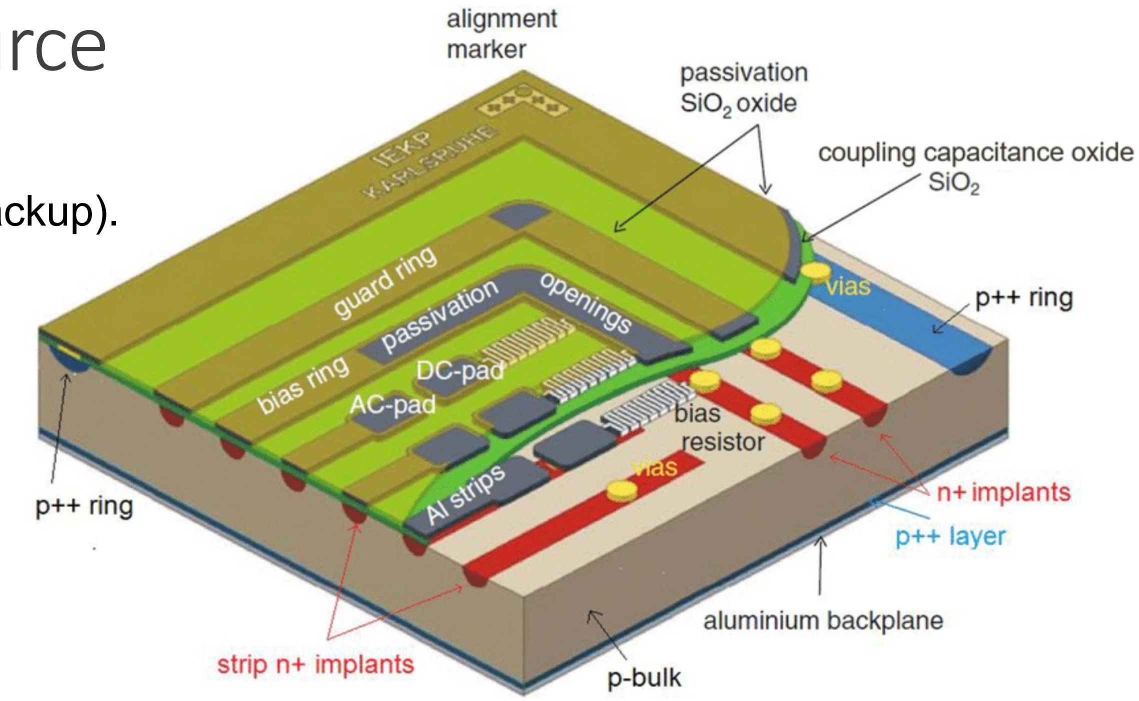
Voltage Source

Speculation:
- Have evidence suggesting cold "noise" is not Gaussian noise (see backup).

- Appears vibrations produce AC voltage between strips and hybrid.
  - Causes *effective* discrimination threshold to oscillate.

- How is this AC voltage produced from mechanical waves?

- SiO_2 and Si_3N_4 in passivation & dielectric known to be piezoelectric...
  - Module built using old sensor w/ less passivation → less CN.
  - CN appears to be independent of bias voltage.

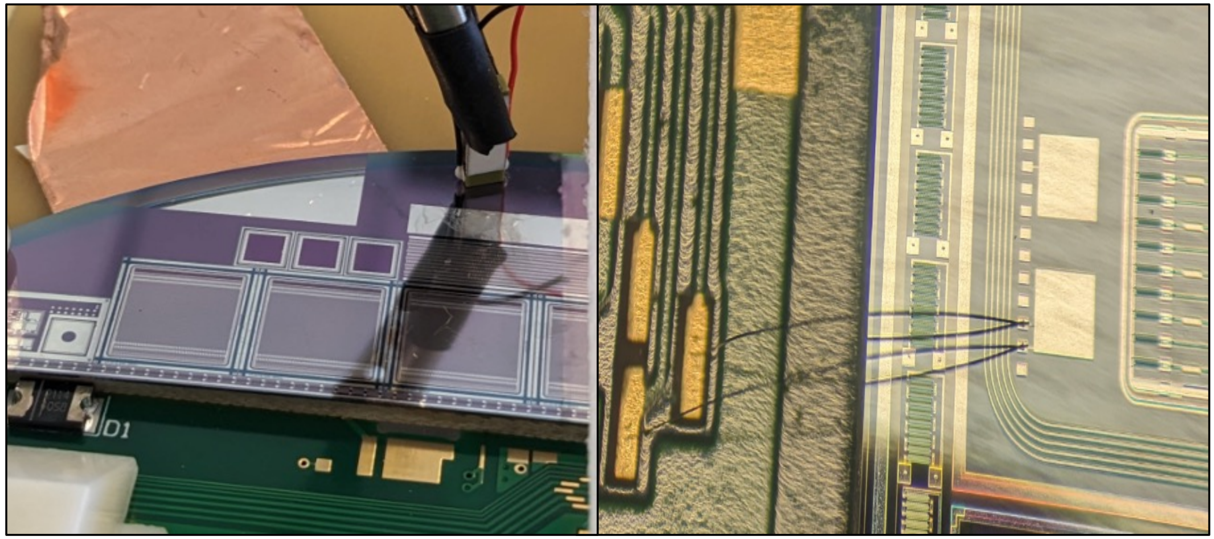


1: Schematic representation of a n-on-p AC-coupled silicon strip detector. Figure adapted from [27].

Javier Fernández-Tejero

Test for (inverse) piezoelectricity:
1. Vibrate a sensor and look for signs of piezoelectricity.
   - Drive a piezoelectric actuator to vibrate a sensor.
   - Measure voltage between AC pad & implant.
   - *Hard to control electrical noise from actuator…*

2. Do the opposite.
   - Apply AC voltage between AC pad & implant.
   - Look for vibrations using a laser vibrometer.
   - *Not clear if vibration amplitudes will be large enough…*



Concluding Thoughts

Putting It All Together (Speculative)

Vibrations:

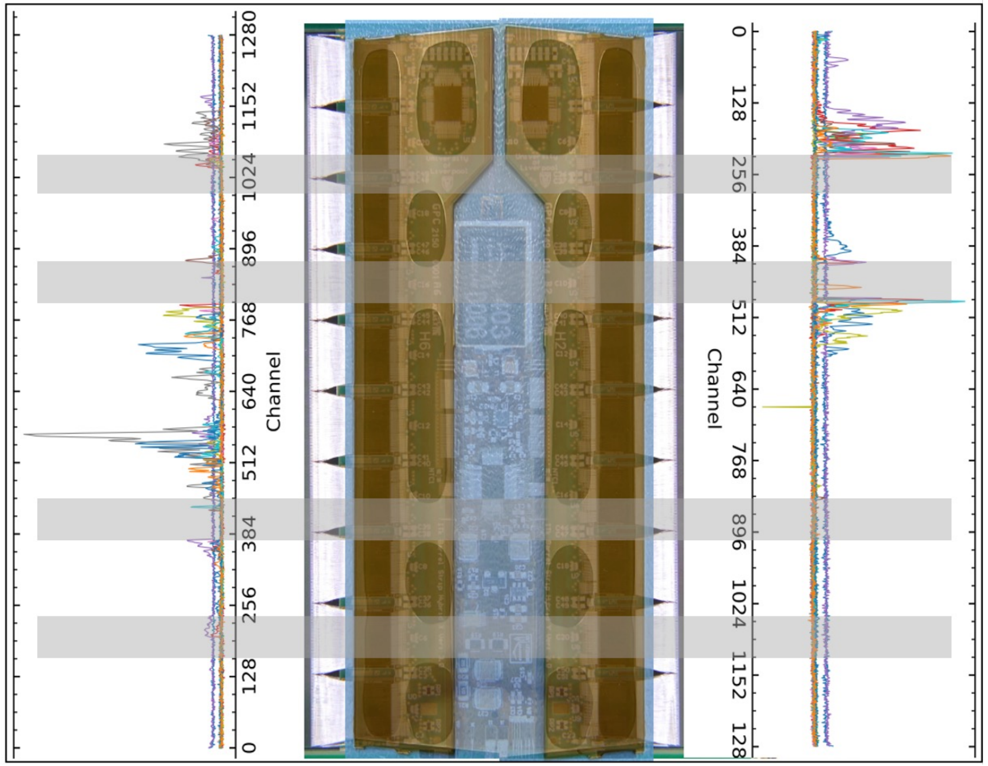
- PB is always vibrating, at all temperatures.
  - Waves reflecting off glue-sensor interfaces.
  - Resonant cavities forming between hybrid and PB glue lines?

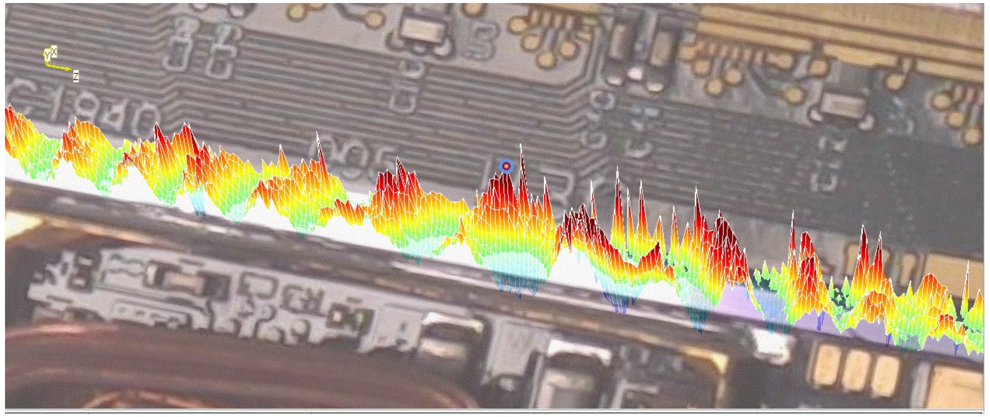
Phase transition:

- 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

- Early last year, 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) & 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.

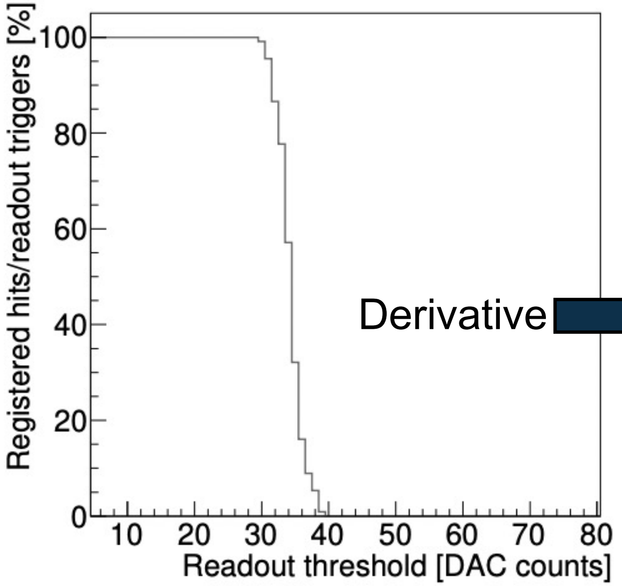
3. Filling in the gaps between the hybrids & PB with more glue.
   - Very encouraging results, but need to develop a production-friendly process

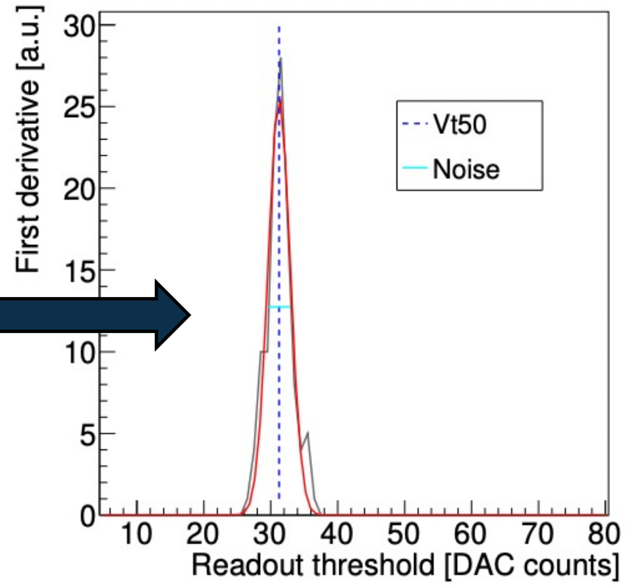
Backup

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.

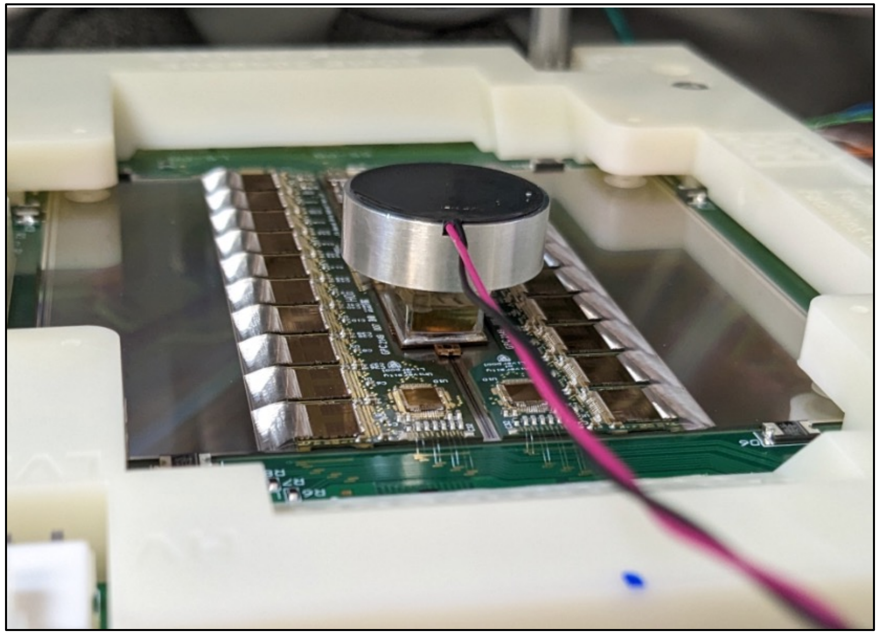




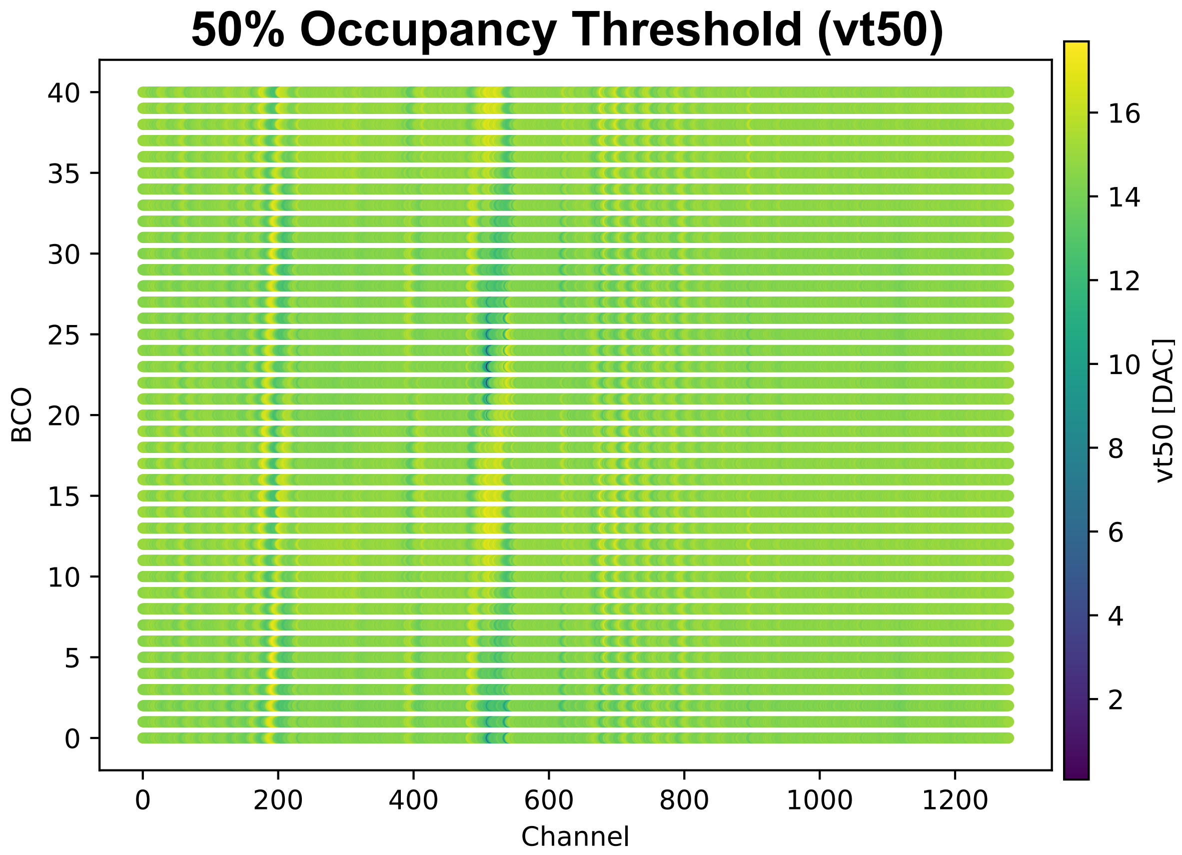
Simultaneous trigger delay & threshold scan:
- Vibrate module with 1 MHz transducer.

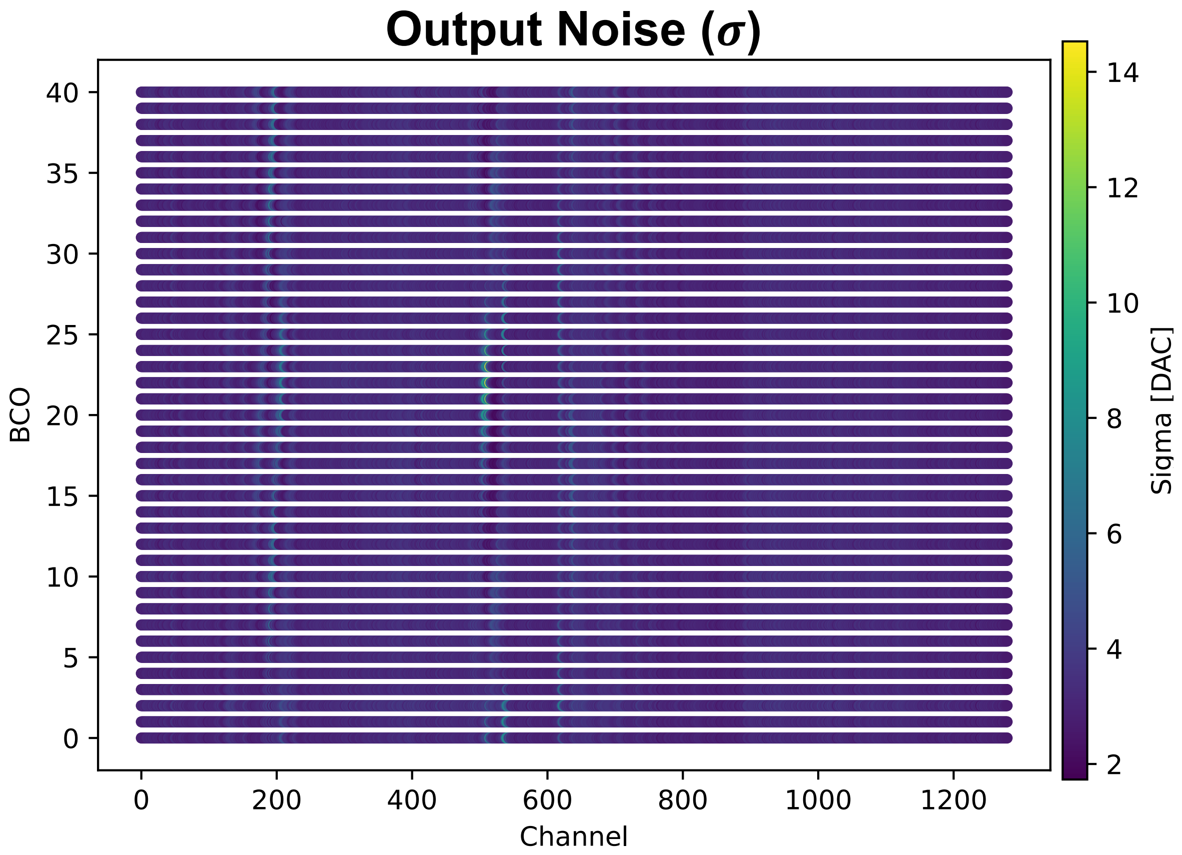
- Trigger module readout synchronous with transducer
  - Scan over trigger delay & discrimination threshold.

- 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?

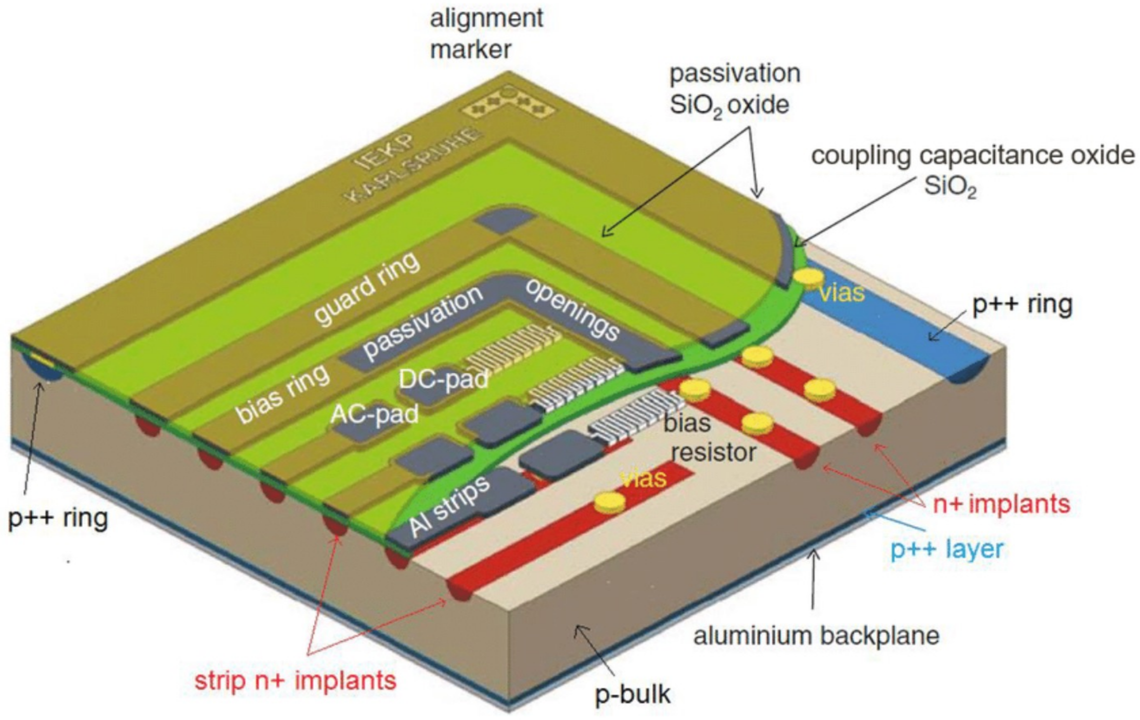
Mechanical Wave → Voltage Mechanism

Overview:

- Magnetic triggering & transducer tests → CN is the result of vibrations.
  - Fourier analysis → consistent with Lamb waves.
  - Vibrations confirmed & studied with vibrometer.
- Not Gaussian noise, but instead a DCDC-synchronous voltage → oscillating vt50.
- Do not understand how vibrations produce this voltage.
  - Piezoelectricity in the glue?
  - Piezoelectricity in the passivation/dielectric?
  - Electrostriction in the Silicon bulk?

Speculation:

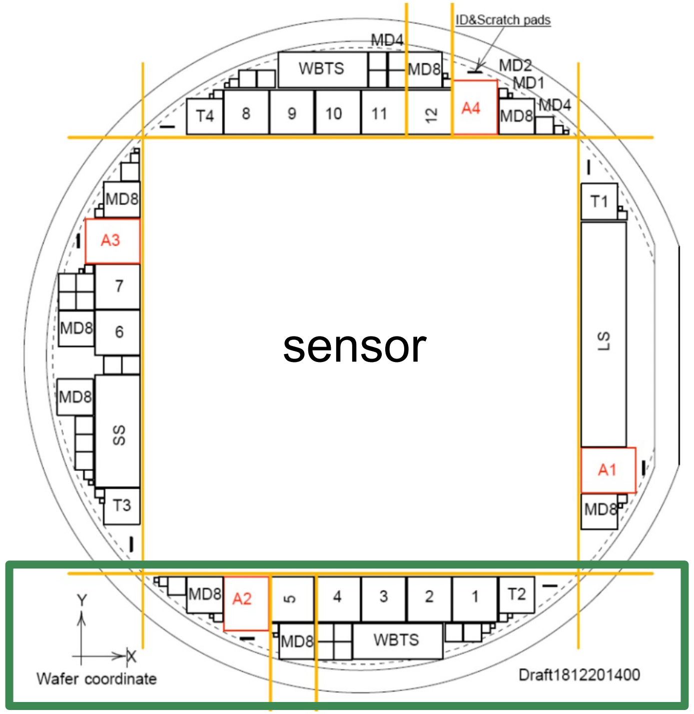
- SiO_2 and Si_3N_4 is passivation & dielectric known to be piezoelectric...
  - Expect to be amorphous…
- Personally lean towards piezoelectricity in the passivation/dielectric.
  - CN appears to be independent of bias voltage.
  - Module built using old sensor w/ less passivation → less CN.



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

Javier Fernández-Tejero

Test Idea

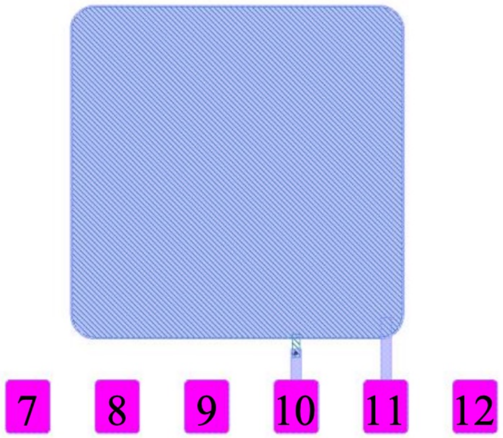


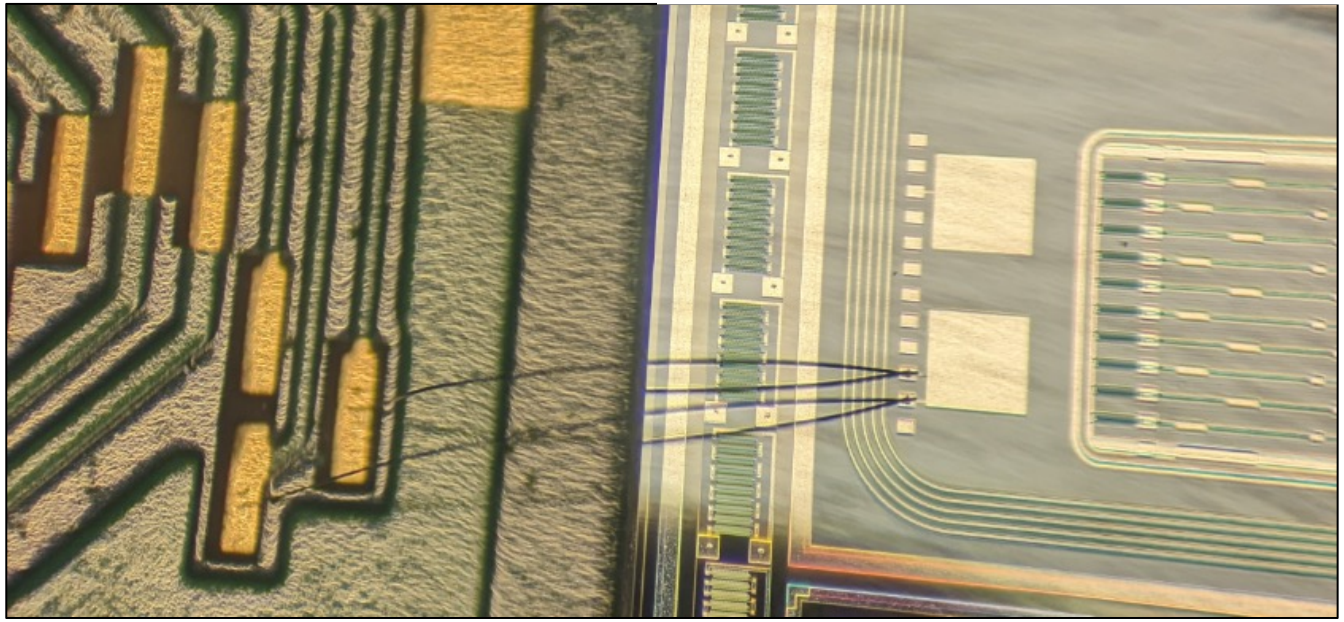
Inverse piezoelectricity in dielectric:

- Vibrate the coupling capacitor test structure on a halfmoon.
  - Square metal pad & implant separated by dielectric.
  - Simpler than sensor.
  - Size (~0.7 mm)$^2 \ll \lambda_{Si}$ of mechanical wave.

- Bond AC (10) & DC (11) pads to differential pair pads on frame.
  - Frame → mini displayPort → spy board → diff probe → amp → scope.

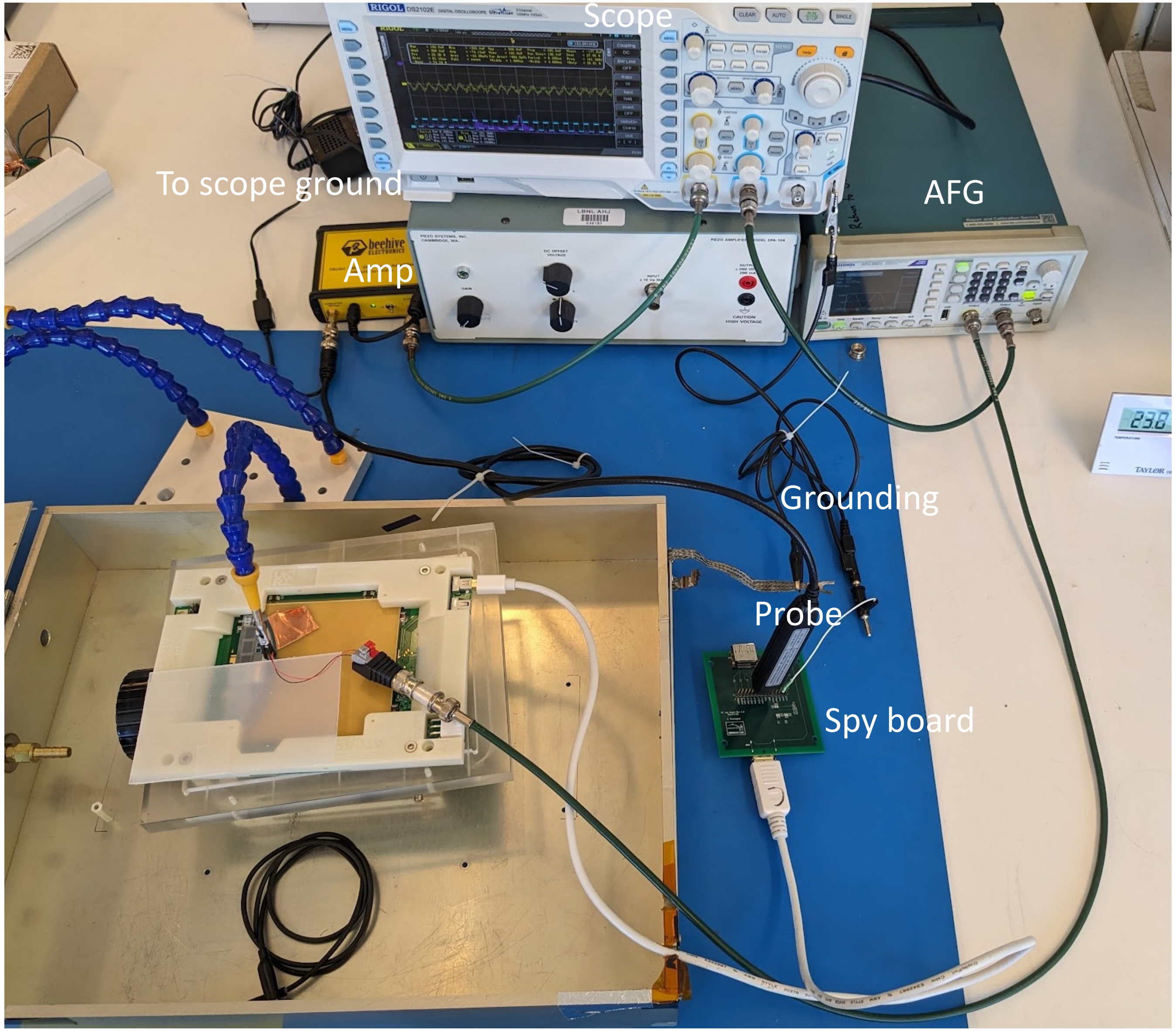
- Look for periodic signal with $f = f_{trans}$.





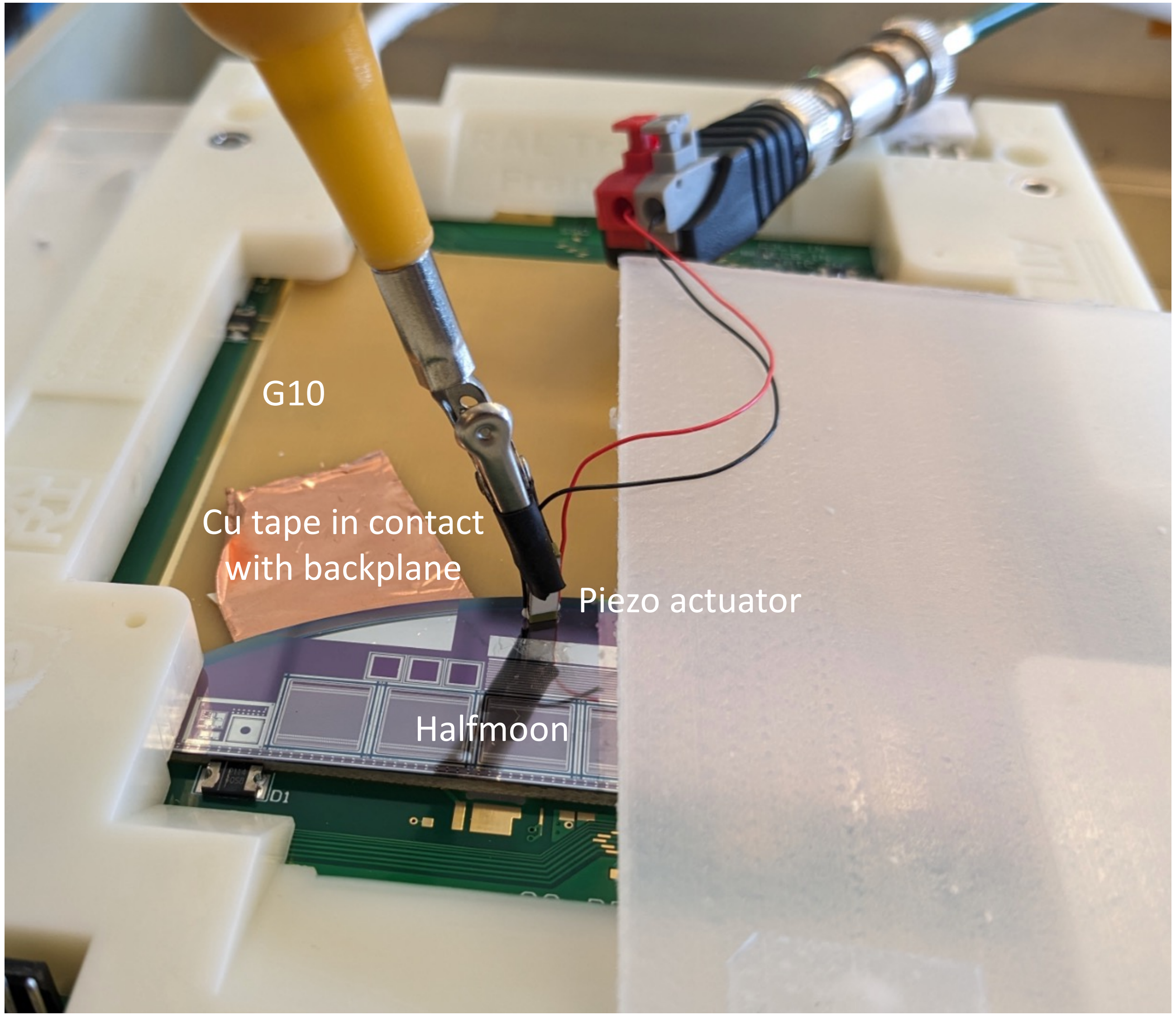
Setup

- Halfmoon held to test frame by spacer w/ suction cups.
- Layer of rigid G10 between halfmoon & test frame pad.
  - Electrically isolating halfmoon backplane.
- Driving 152 kHz piezo with AFG at 10 Vpp (~0.5 μm).
  - $\lambda_{Si} \gg$ coupling cap test structure → mechanical wave amplitude is ~constant over structure.
  - Low frequency → less radiative pickup.
- AC & DC pads bonded to differential pair pads on frame.
- Mini DP → spy board → diff. probe → amp → scope.
- Grounding & shielding important for controlling EMI.

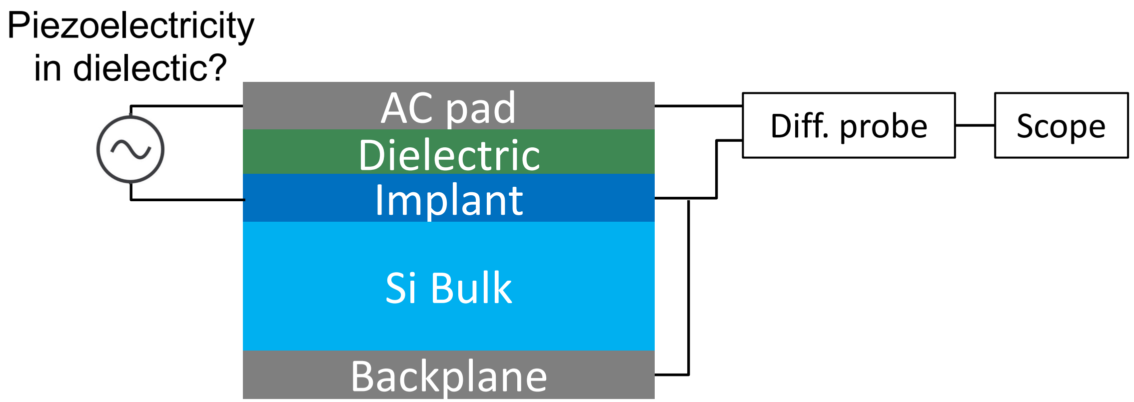


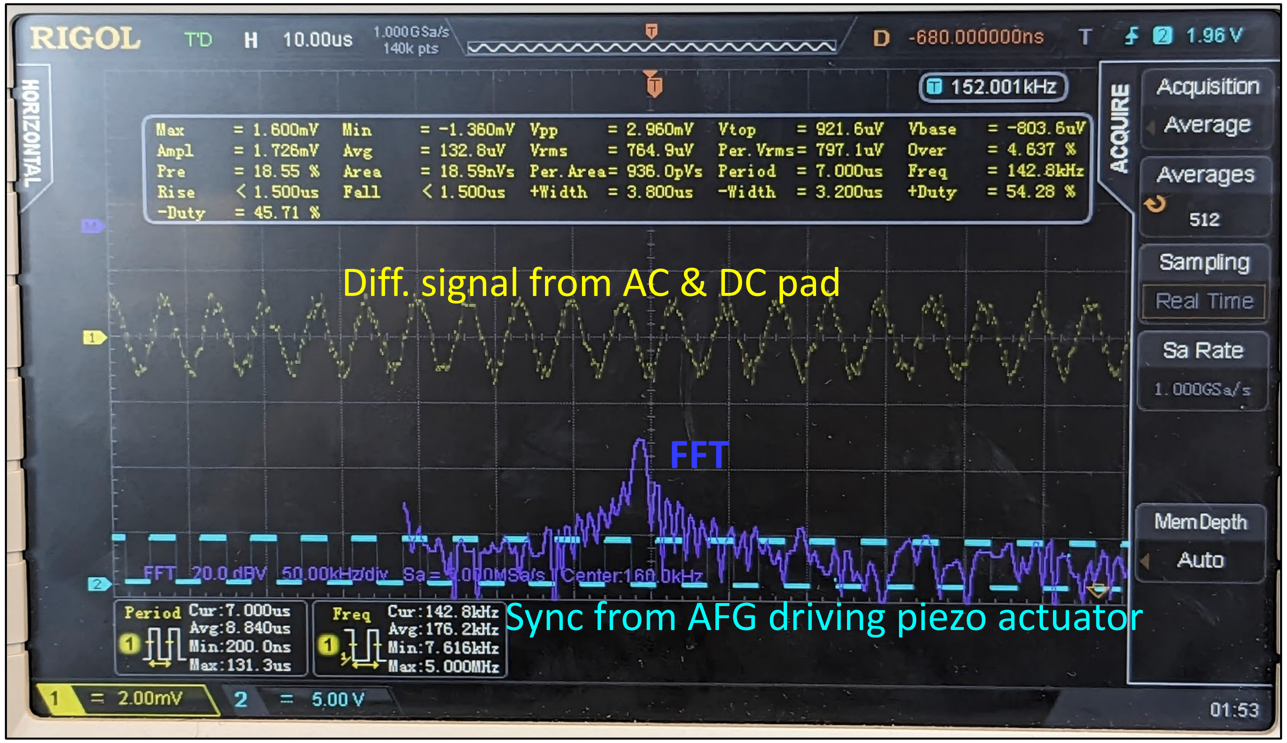
Setup

- Halfmoon held to test frame by spacer w/ suction cups.
- Layer of rigid G10 between halfmoon & test frame pad.
  - Electrically isolating halfmoon backplane.
- Driving 152 kHz piezo with AFG at 10 Vpp (~0.5 μm).
  - $\lambda_{Si} \gg$ coupling cap test structure → mechanical wave amplitude is ~constant over structure.
  - Low frequency → less radiative pickup.
- AC & DC pads bonded to differential pair pads on frame.
- Mini DP → spy board → diff. probe → amp → scope.
- Grounding & shielding important for controlling EMI.



Backplane Shorted to Implant





- Shorting aluminum backplane to the n^+ implant.
- Triggering on sync signal from AFG that's driving the piezo.
- Performing FFT (centered at 152 kHz).
- Differential signal is DC coupled into scope, averaging.
  - See signal matching piezo frequency!
- Could be EMI… Still investigating…
- Maybe easier to turn this process around:
  - Produce an AC voltage across the AC pad & implant → mechanical deformation?
  - Look for vibrations with laser vibrometer.

$$C_{coupl} = \frac{C_{meas}}{l_{5-strip}} = \frac{C_{meas}}{3.4\ \text{cm}} \geq 20\ \text{pF/cm}.$$

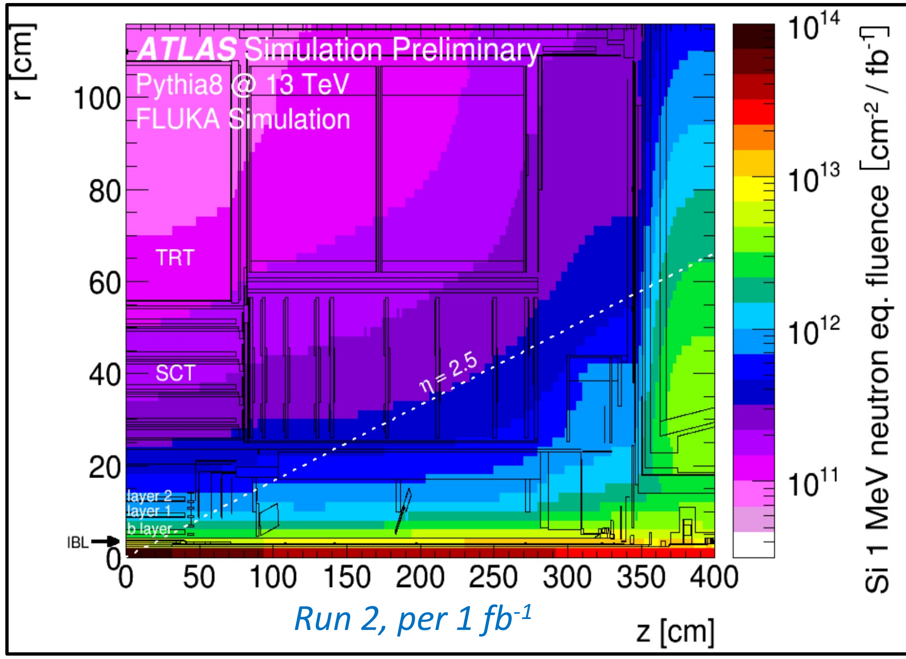
Unbiased Si → built-in depletion region → parallel plate cap with small d → large C_{bulk}.

ITk Upgrade

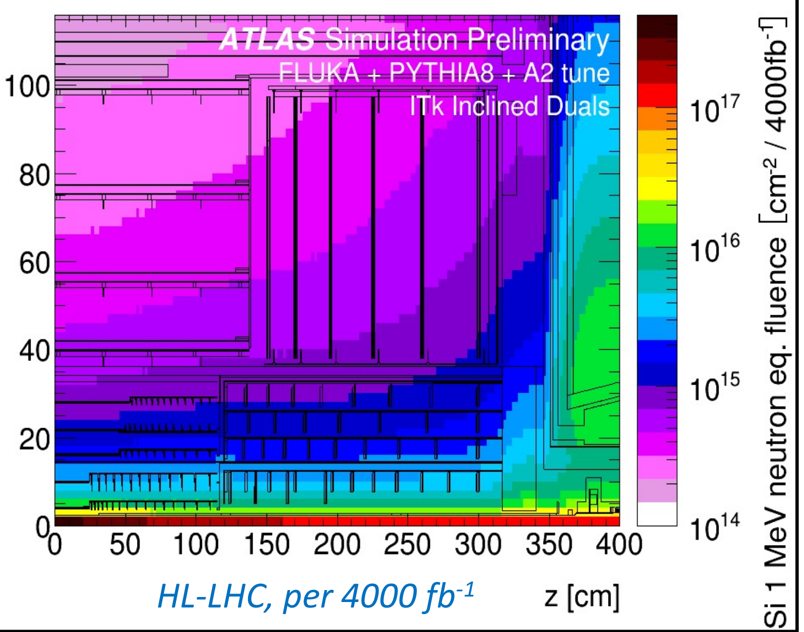
ITk Upgrade:

- ATLAS is replacing its inner detector for the High-Luminosity 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 $2\times10^{16}\ n_{\text{eq}}/\text{cm}^2$).

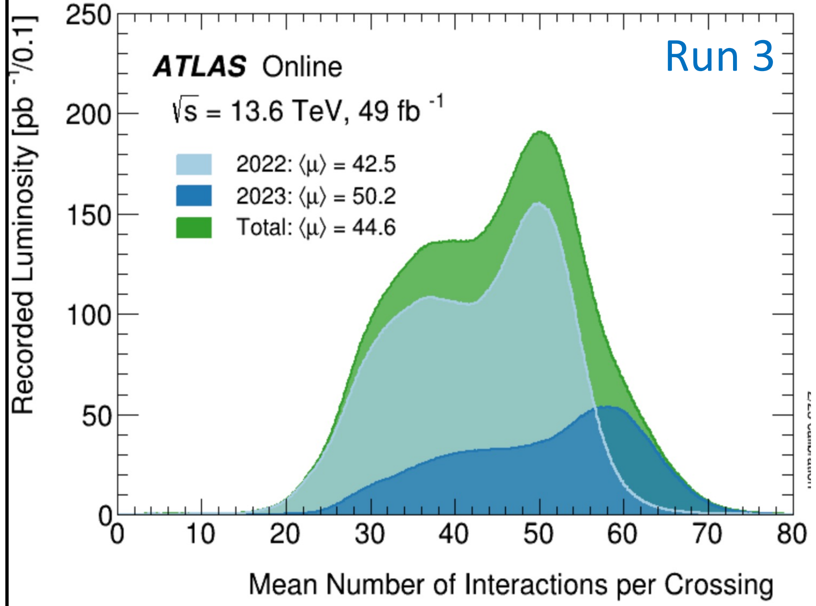
- Installing new, all silicon Inner Tracker (ITk).
    - Pixels modules for inner layers, strip modules for outer layers.
    - LBNL heavily involved in pixels & strips, plus global mechanics & integration.

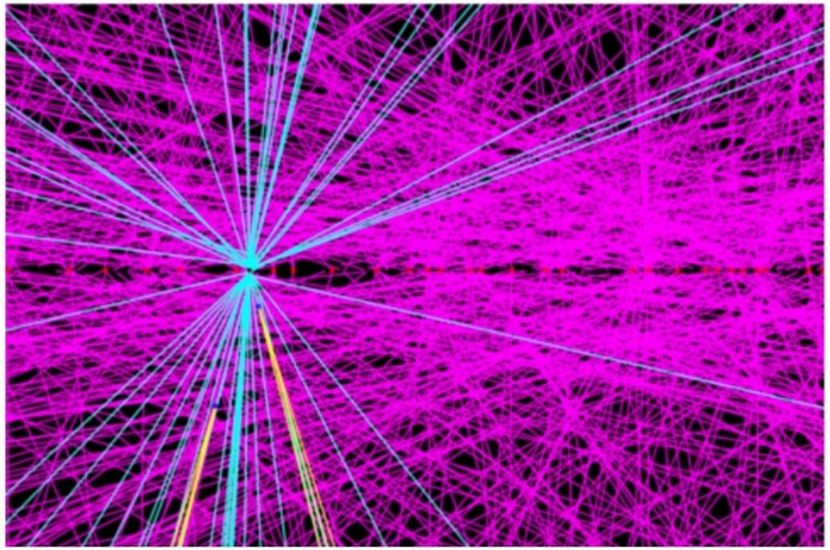


Run 2, per 1 fb^{-1}



HL-LHC, per 4000 fb^{-1}



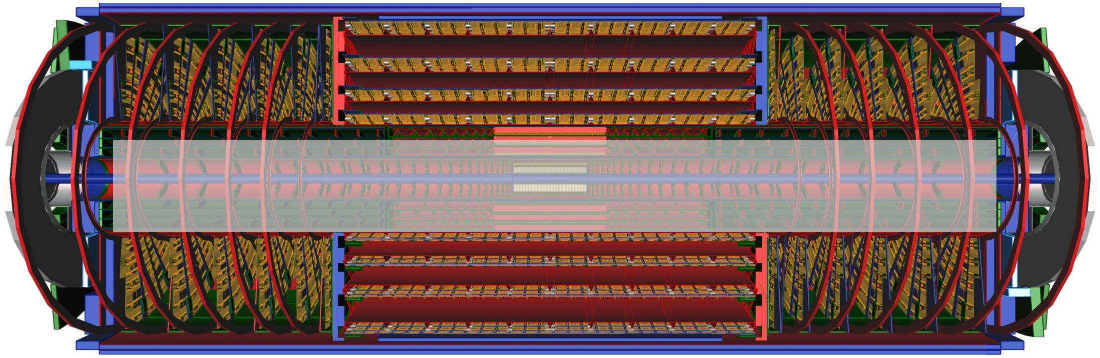


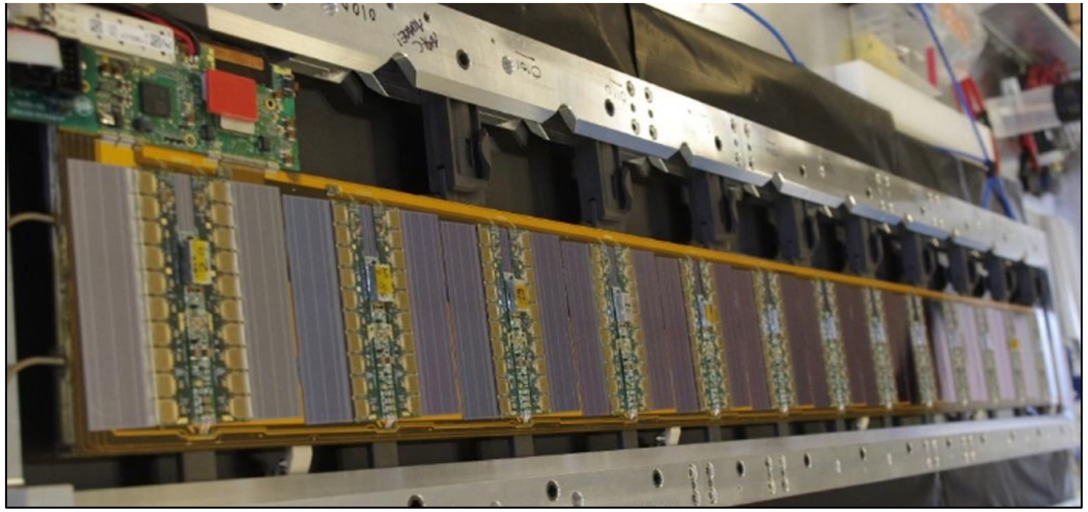
$t\bar{t}$ event at $\mu = 200$

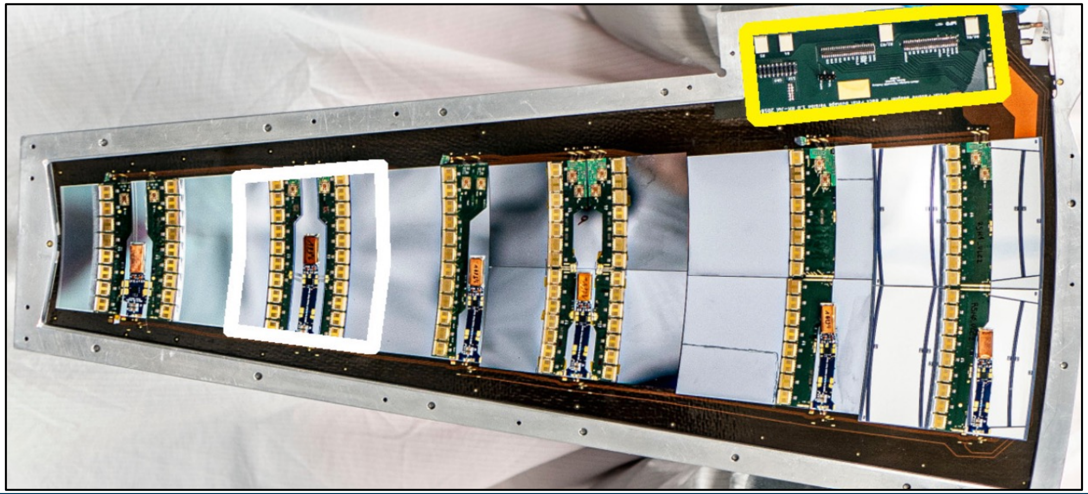
ITk Strip Detector

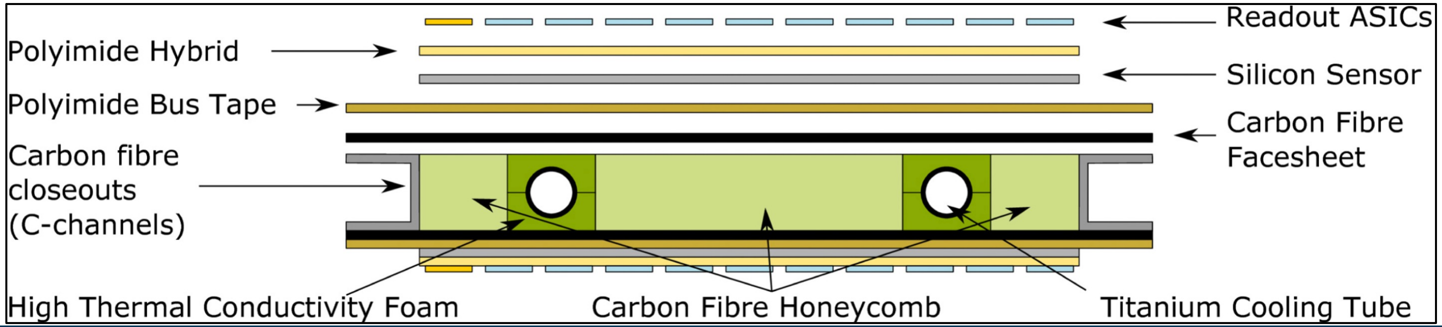
Strip detector:

- Barrel composed of rectangular staves.
    - Assembled in 4 concentric cylinders.
    - 14 identical modules on each side.
- Endcaps composed of petals.
    - 32 petals form a disk, 6 disks per endcap.
    - 6 different module geometries.
- Staves & petals constructed from carbon fiber.
    - Each side covered with a “bus tape”.
        - TTC/DCS/data transmission.
        - Power for ASICs & HV for sensor biasing.

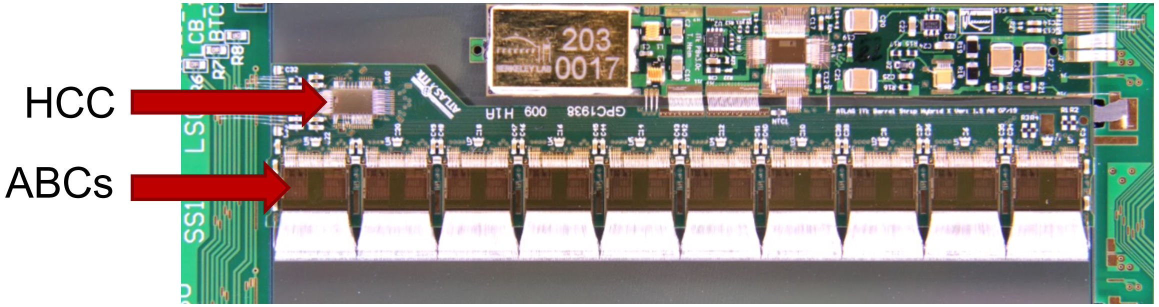






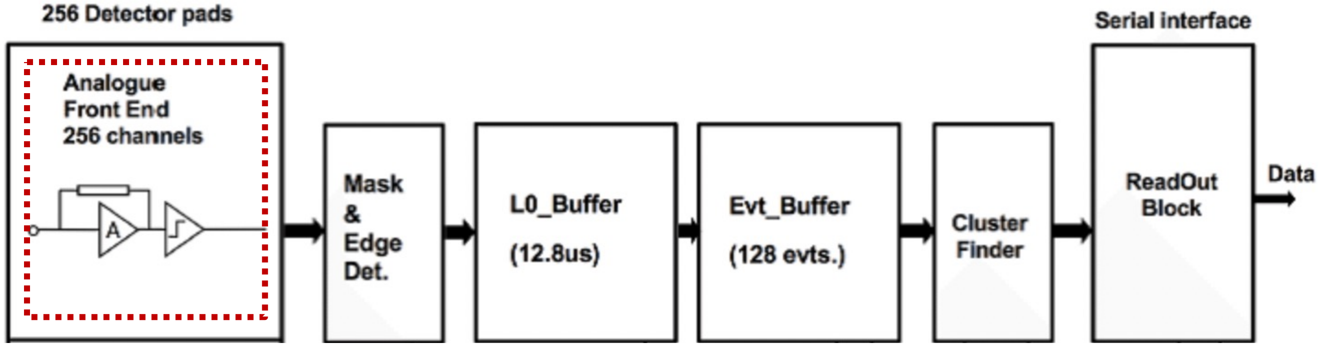


Threshold Scans



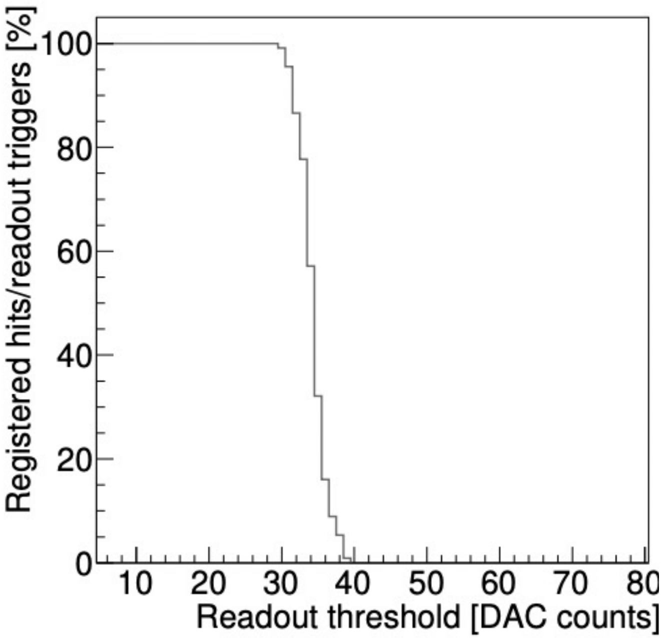
Binary Readout:

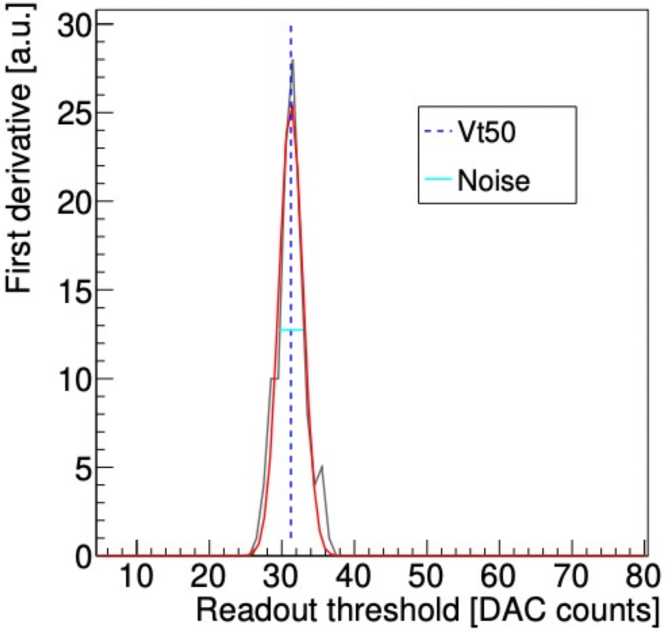
- ABCs amplify & discriminate signal from strips.
  - Discriminated signal sampled once per 25ns BX → 1 bit indicating if above threshold.
- Discriminator threshold can be tuned.
  - Balancing signal efficiency vs. noise.
  - Spec: >99% efficiency, <0.1% noise occupancy.



S-curves:

- Scan over threshold, triggering N times at each step.
  - With or without charge injection.
- Plot occupancy vs. threshold → S-curve (error function).
  - Derivative is a gaussian.
  - Mean → vt50, width → <u>output</u> noise.





Response Curves, Gain, and Input Noise

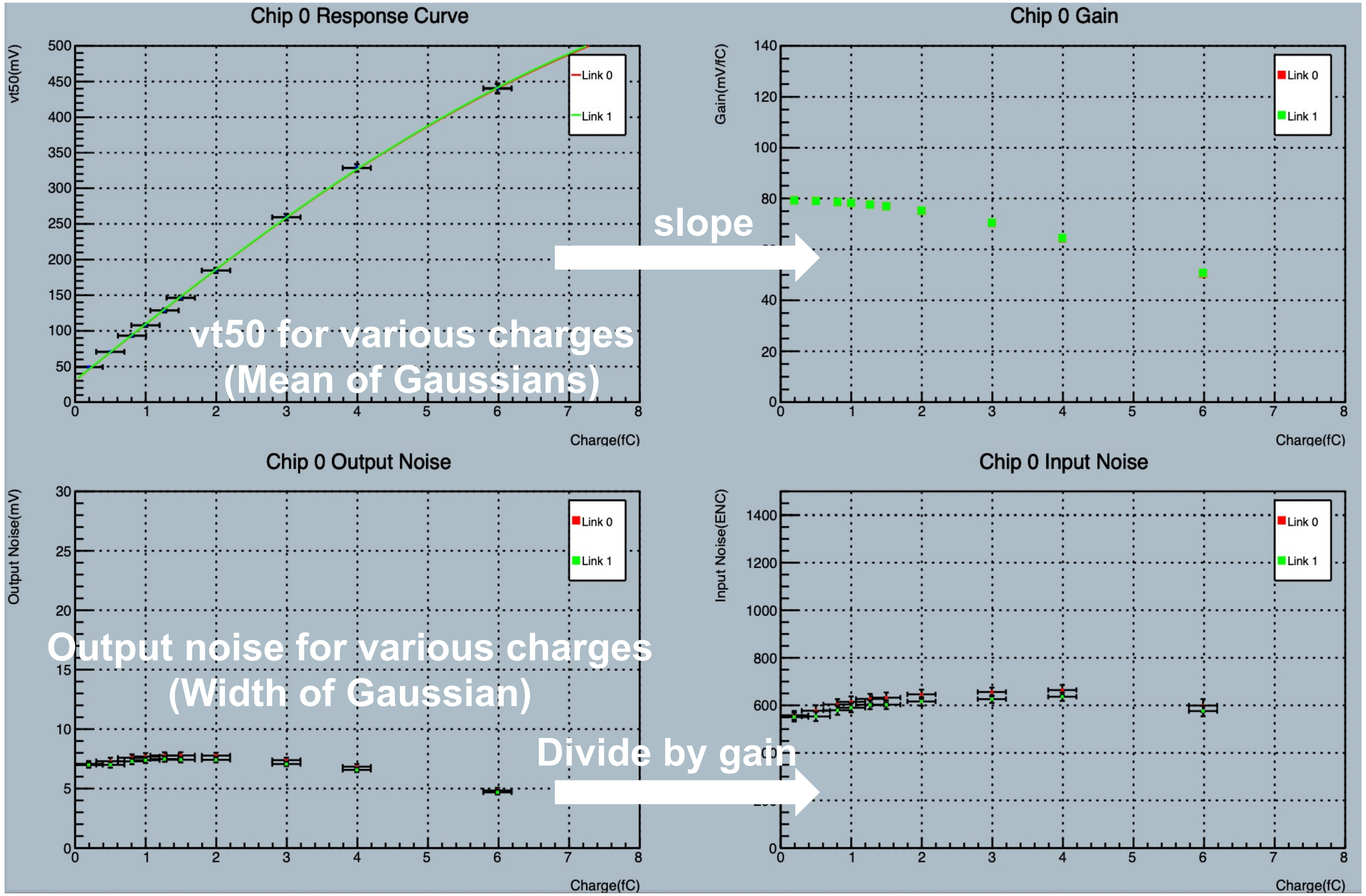
Response Curve:

- Perform threshold scans while injecting charge.
  - Repeat for 10 different charges.

- For each charge injected, get s-curve.
  - Mean → vt50.
  - Width → output noise.

- Plot vt50 vs. injected charge → response curve.
  - Slope → gain.

- Input noise = output noise / gain.
  - Most useful metric.



Input Noise

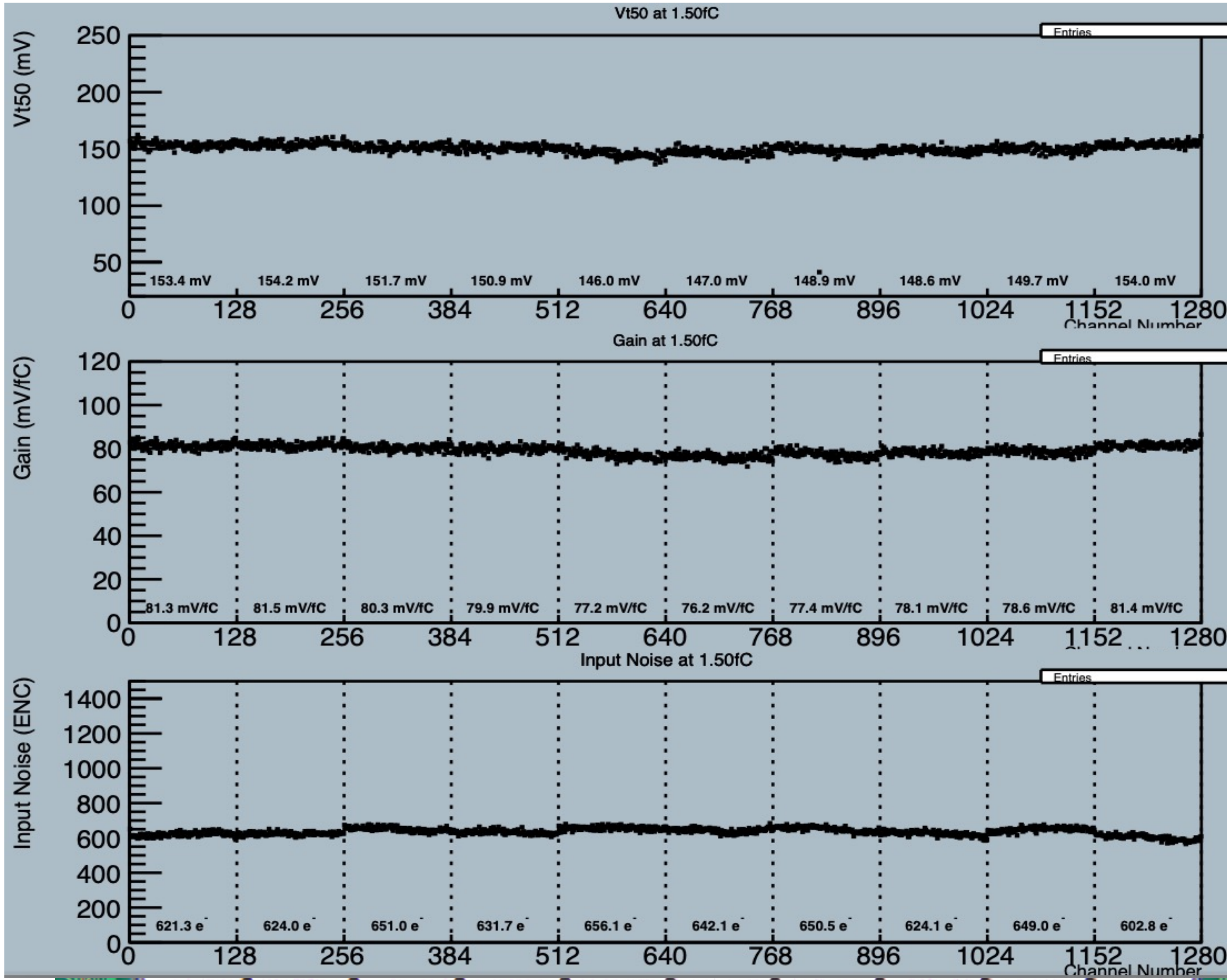
Response Curve:

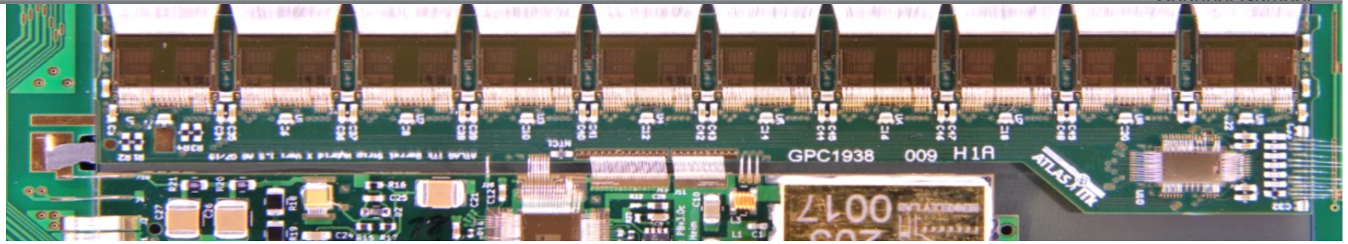
- Perform threshold scans while injecting charge.
  - Repeat for 10 different charges.

- For each charge injected, get s-curve.
  - Mean → vt50.
  - Width → output noise.

- Plot vt50 vs. injected charge → response curve.
  - Slope → gain.

- Input noise = output noise / gain.
  - Most useful metric.





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.

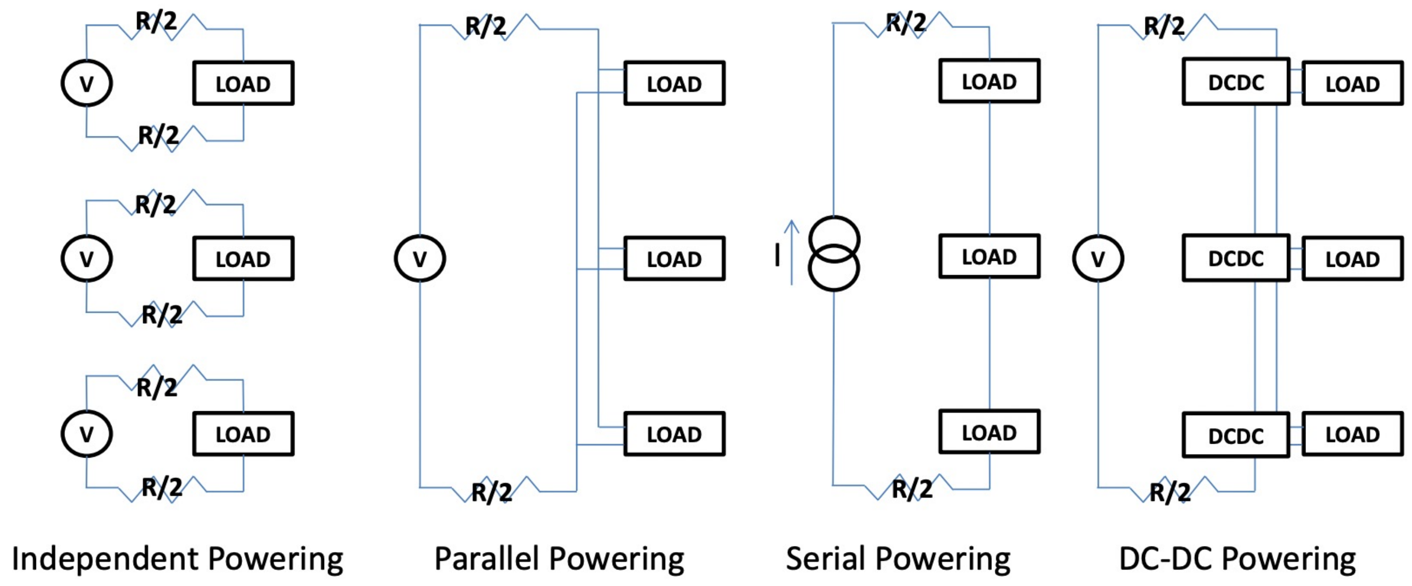
Parameter	Value (range: tolerance)
Initial	(measured at RT)
Interstrip resistance (R_{int})	$>10 \times R_b$ at 300 V
Interstrip capacitance (C_{int})	<1 pF/cm at 300 V measured at 100 kHz
Number of defects[a]	<1% per row, <1% per sensor <8 consecutive bad strips
Leakage current	<0.1 $μA/cm^2$ at 700 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/cm^2
Ionizing dose (γ's)	Up to 60 Mrad.
Micordischarge onset voltage	> 700V or $>V_{FD} + 50$ V (if $V_{MD} < 700$ V)
Interstrip resistance	$>10 \times R_b$ at 400 V
Collected charge (per MIP)	> 7500 electrons at 500 V

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).

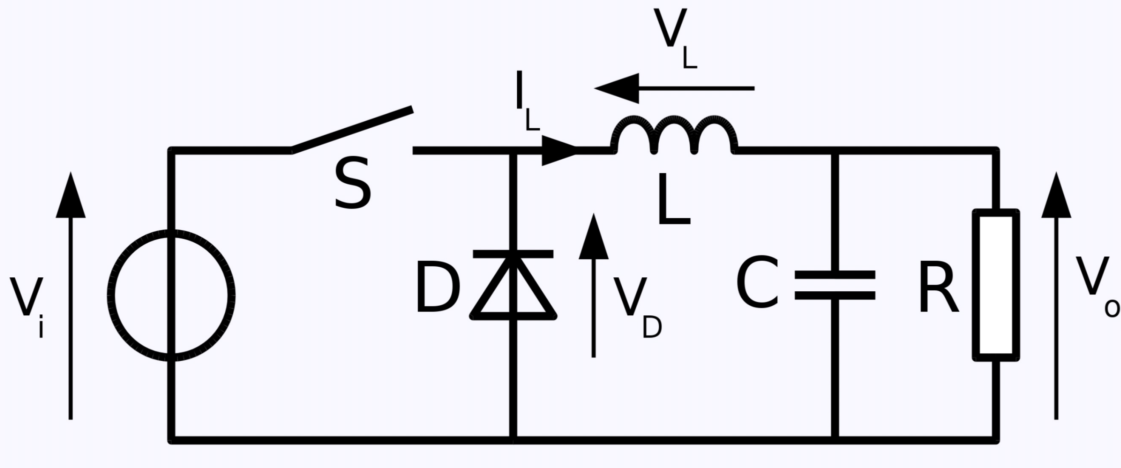


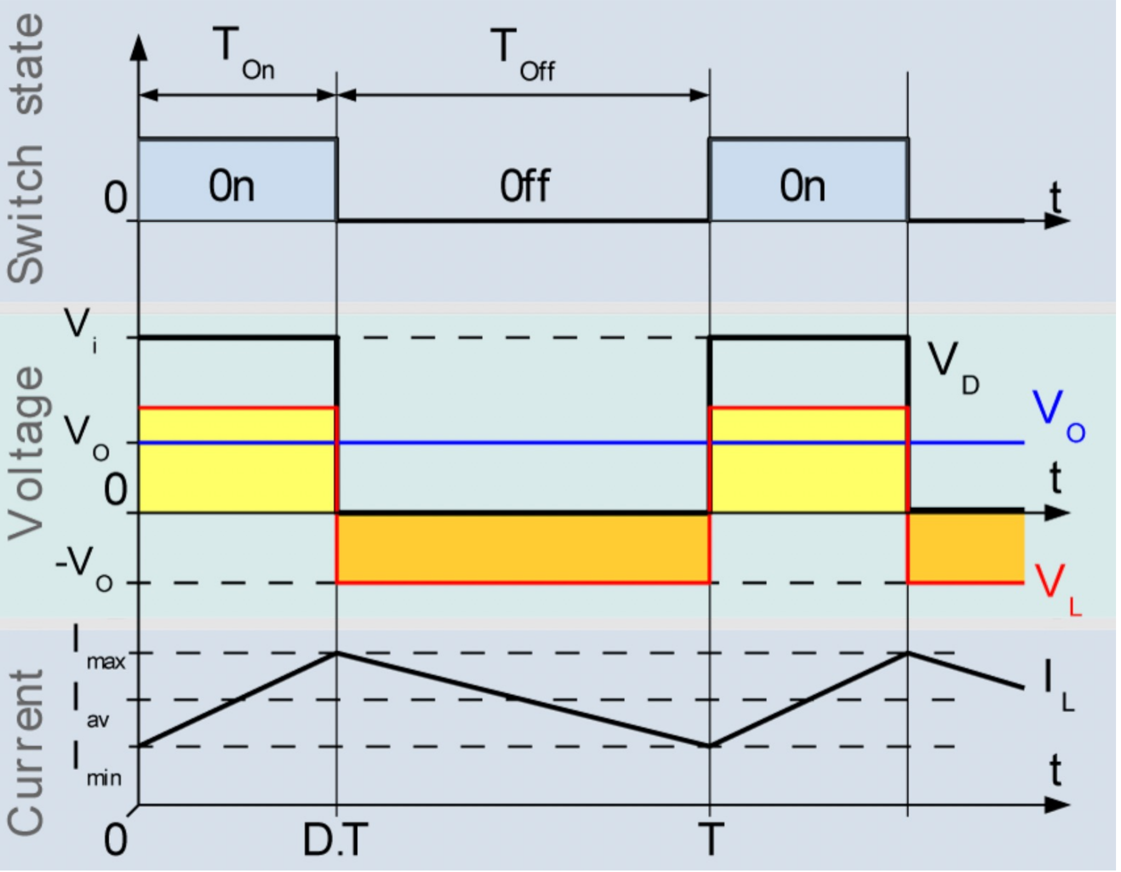
Losses in off-detector cabling of total resistance R for n loads drawing current I:

$P = nI^2R$ | $P = n^2I^2R$ | $P = I^2R$ | $P = n^2I^2R / r^2$

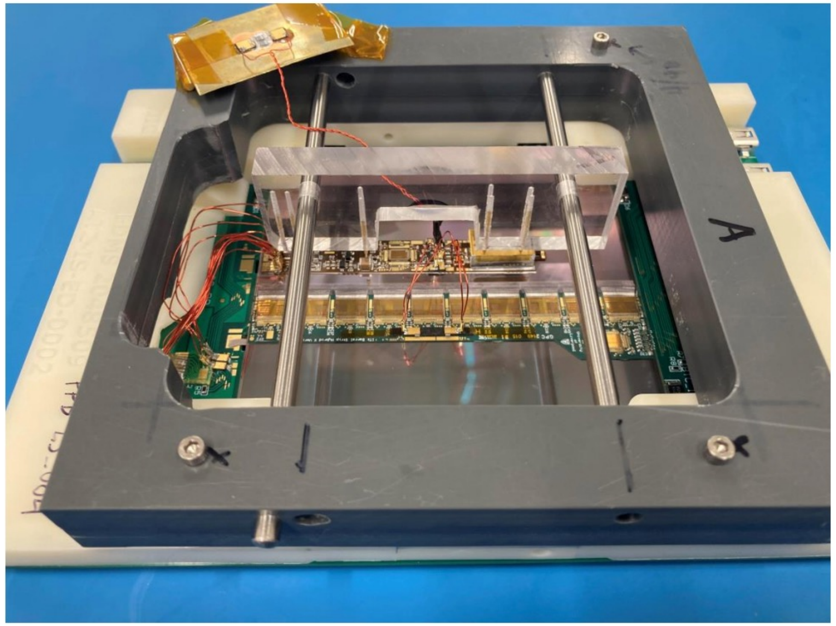
where ratio r = Vin/Vout

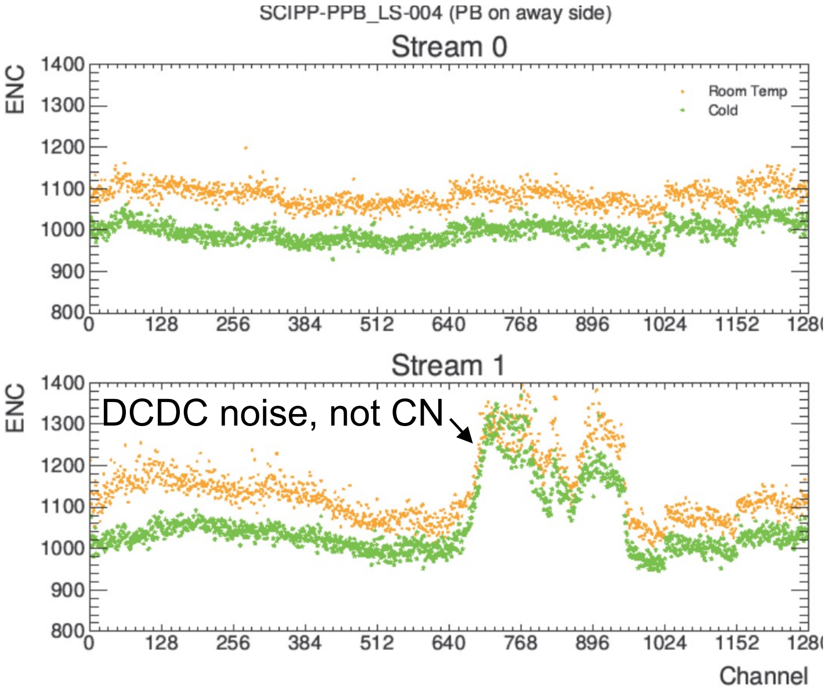
Powering modules on stave (from Peter Phillips)



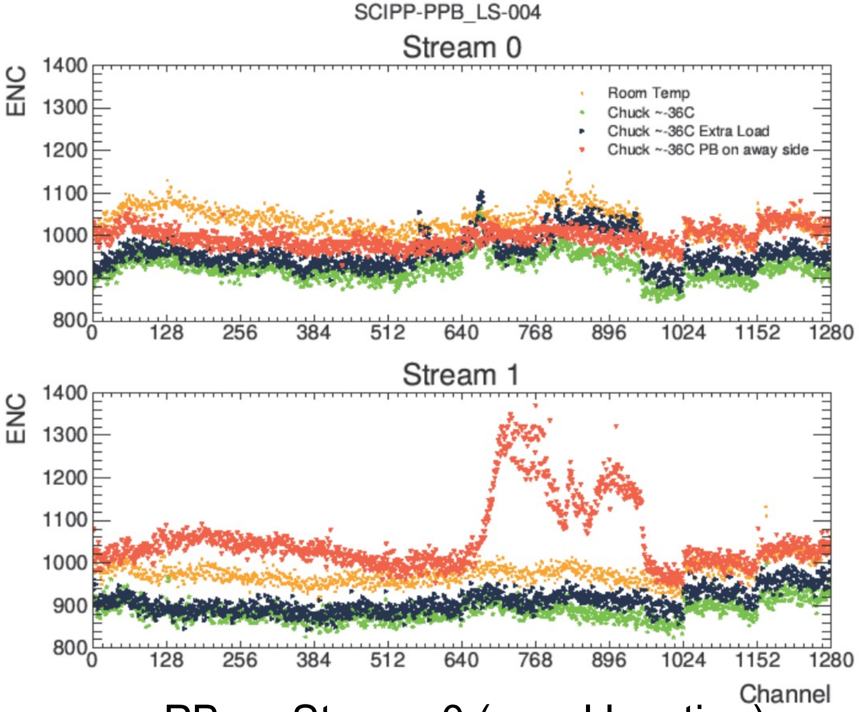


Moveable PB





PB on Stream 1 (not hybrid segment)
→ <u>no cold noise anywhere</u>!



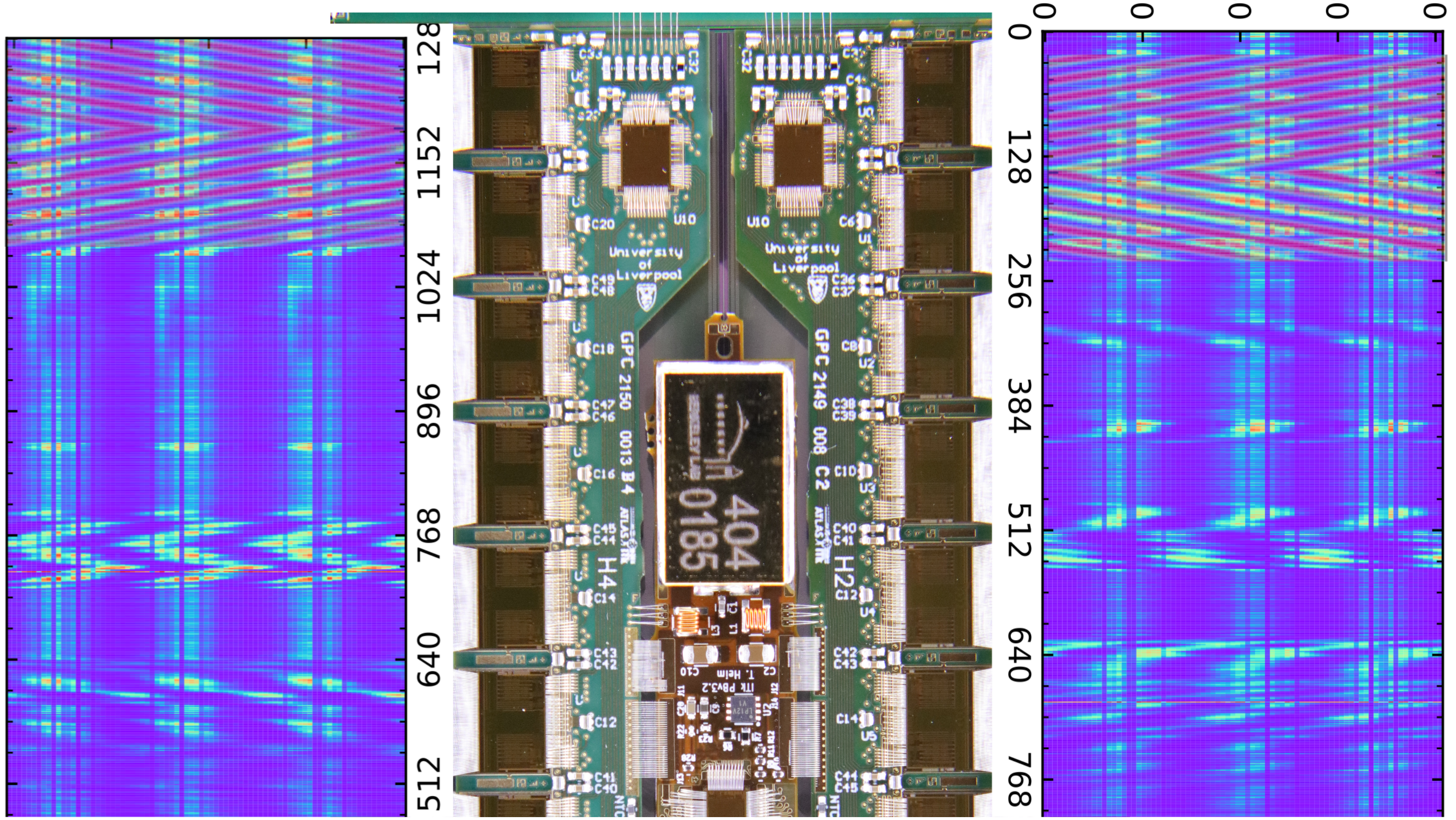
PB on Stream 0 (usual location)
→ cold noise on Stream 0!

- SCIPP built module with moveable PB.
  - No glue, shunts hardwired on, hybrid powered by PS, resistive load on PB emulating hybrids.
- PB in usual location on same strip segment as hybrid (stream 0) → cold noise.
- PB on opposite strip segment (stream 1) → <u>no</u> cold noise.
- Maybe hybrid and PB have to be on same segment?
  - PB vibrates segment → wave travels to hybrid glue → piezo effect → voltage between strips and hybrid ground plane?

[Jacob Johnson, SCIPP]

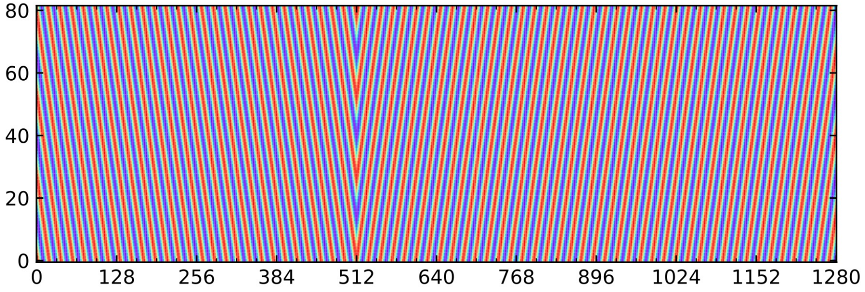
Geography

- Does pattern point to specific features?
- Point source near HCC?
- What about near DCDC?
    - See “W”s, not ”V”s…

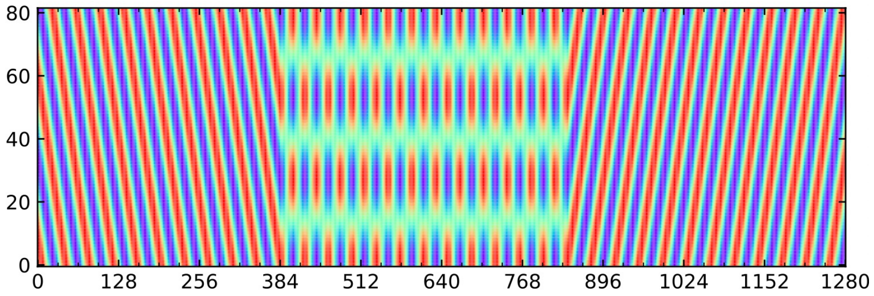


Toy model:
- Point source.
- Undamped sine waves traveling perpendicular to strips at 2.2 km/s.
- Plotting amplitude.

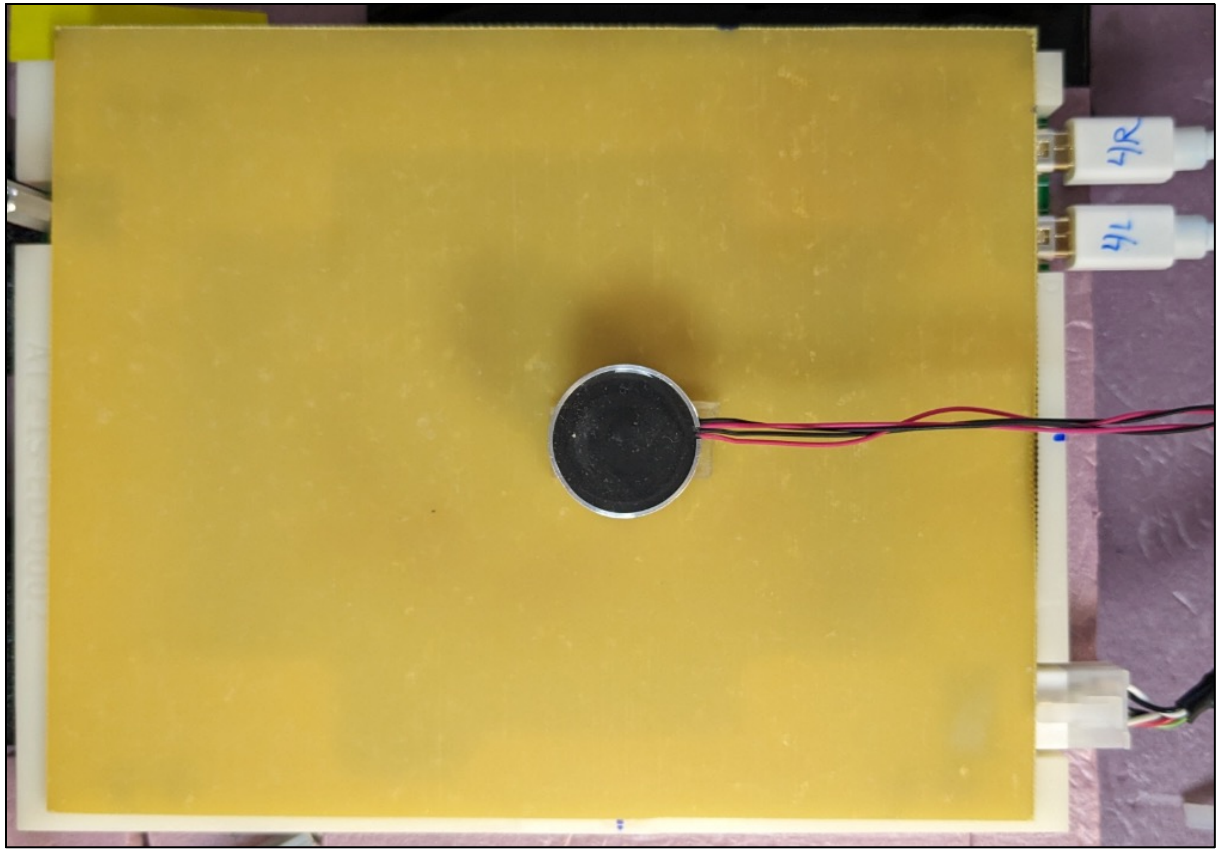
1.540 MHz

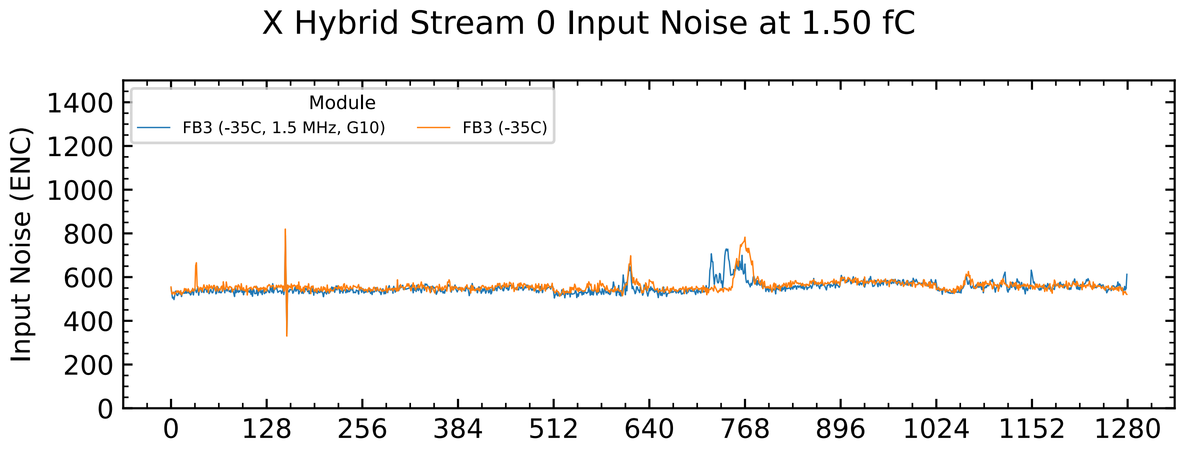


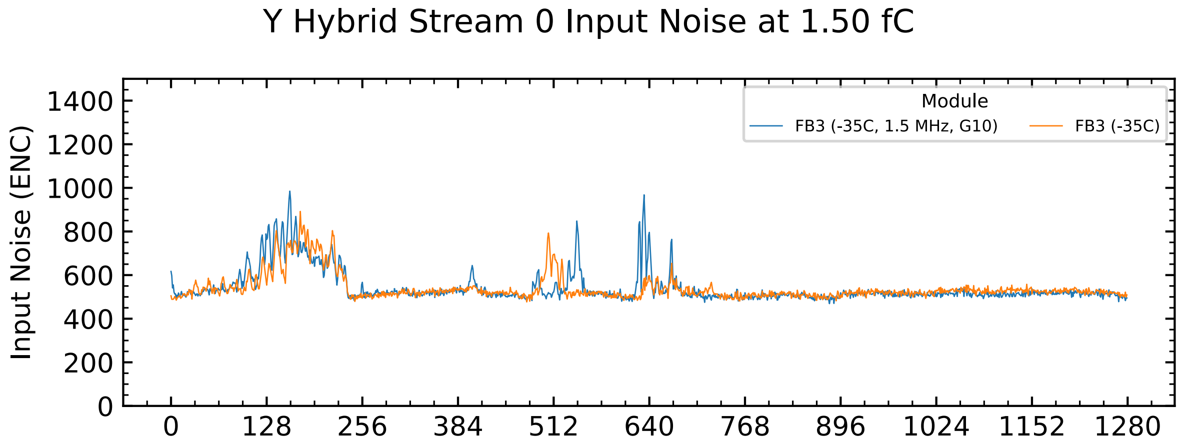
1.540/2 MHz + 1.540/2 MHz



G10 Cover





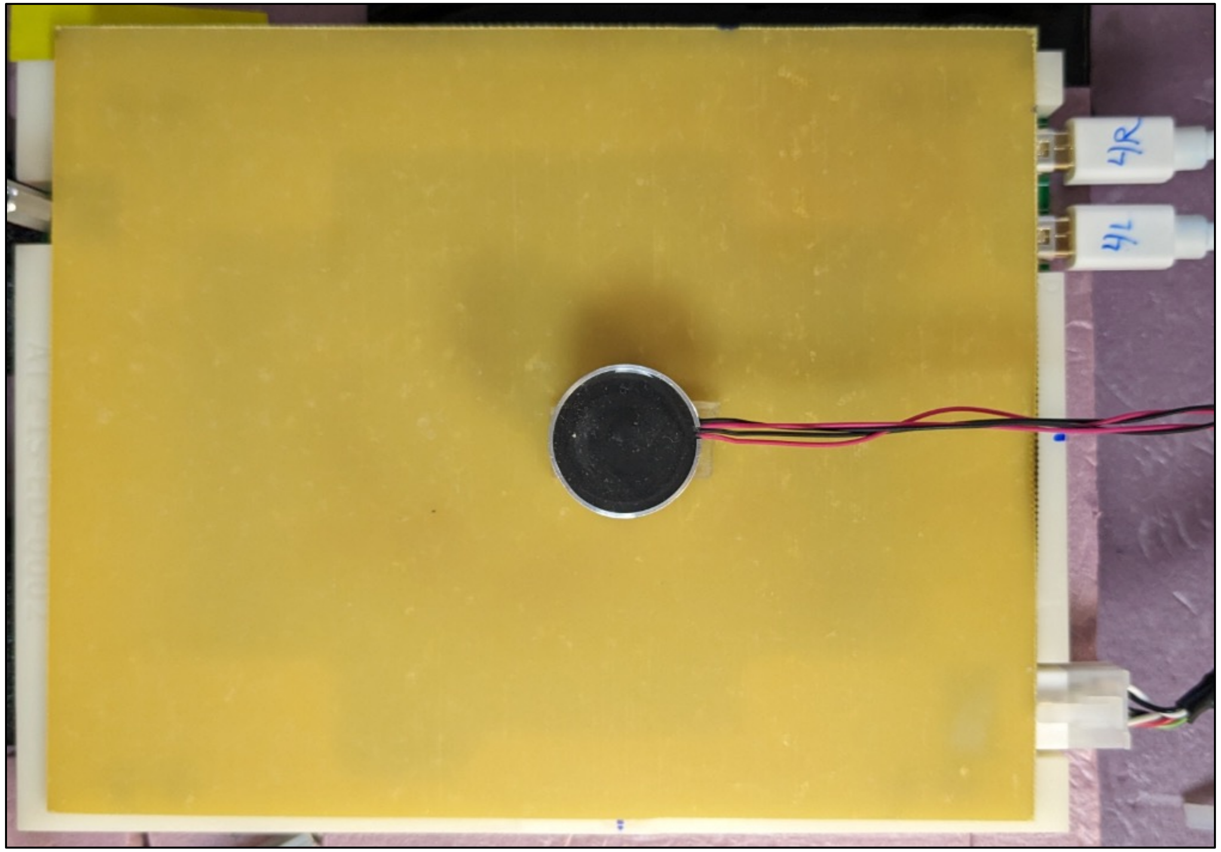


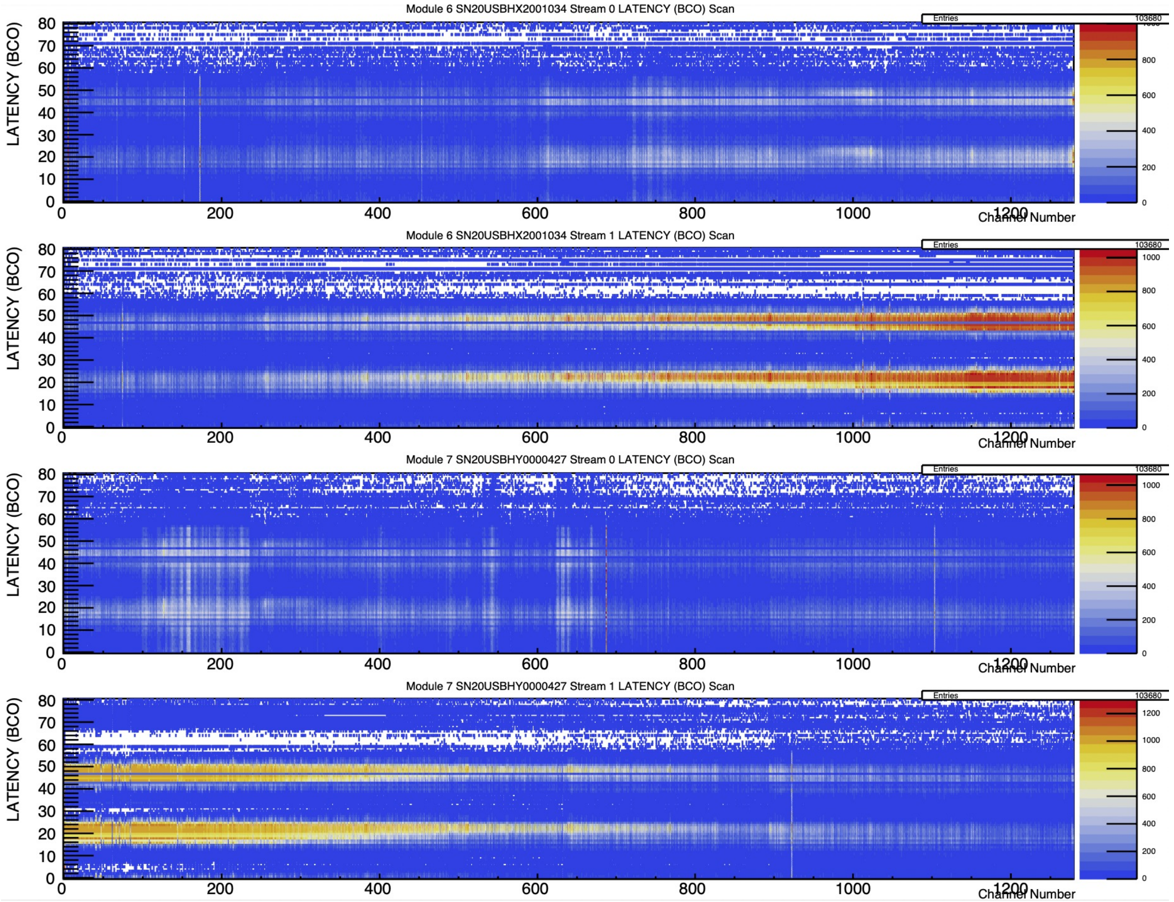
Creating an air gap:

- Placed transducer on G10 module cover, centered over shield box.
  - Not physically touching module (4 mm air + 2 mm G10) → helps separate out EM noise from transducer.

- Noise pattern at -35C with transducer on G10 bridge is consistent with usual CN.
  - Not much EM noise on the under streams (plenty on away streams).

G10 Cover



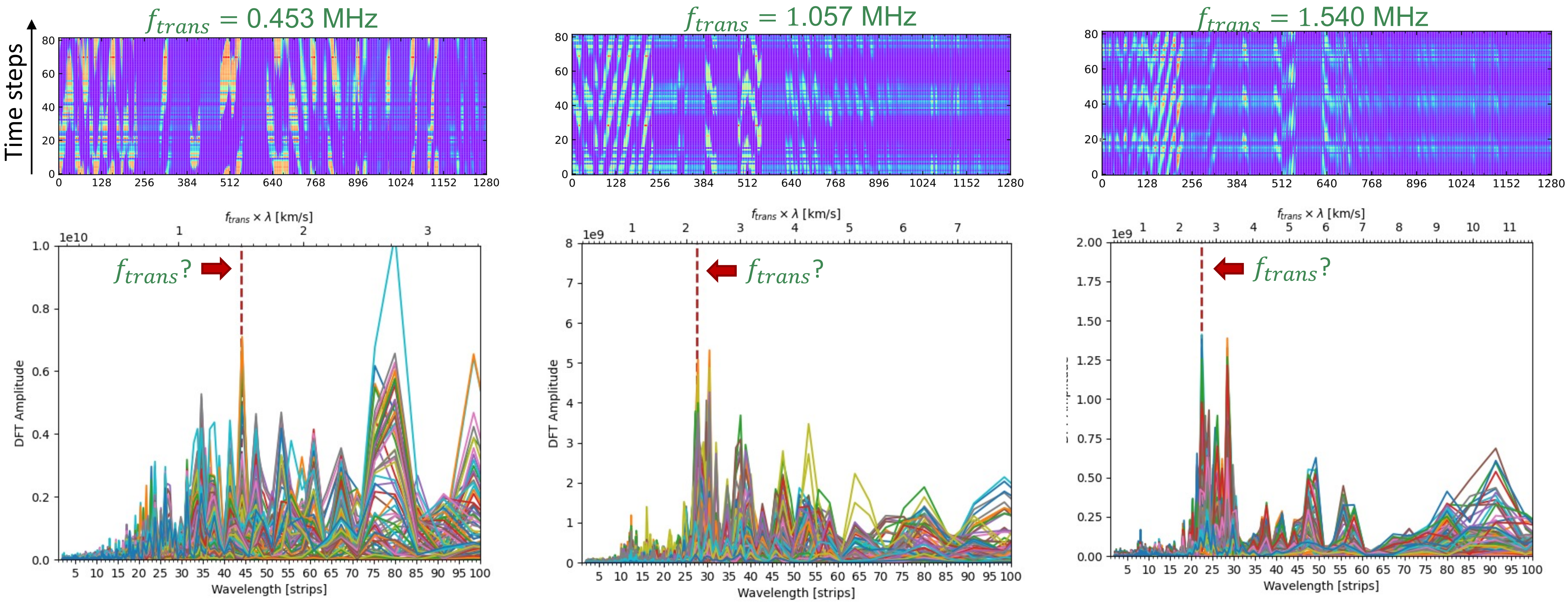


Creating an air gap:

- Placed transducer on G10 module cover, centered over shield box.
  - Not physically touching module (4 mm air + 2 mm G10) → helps separate out EM noise from transducer.

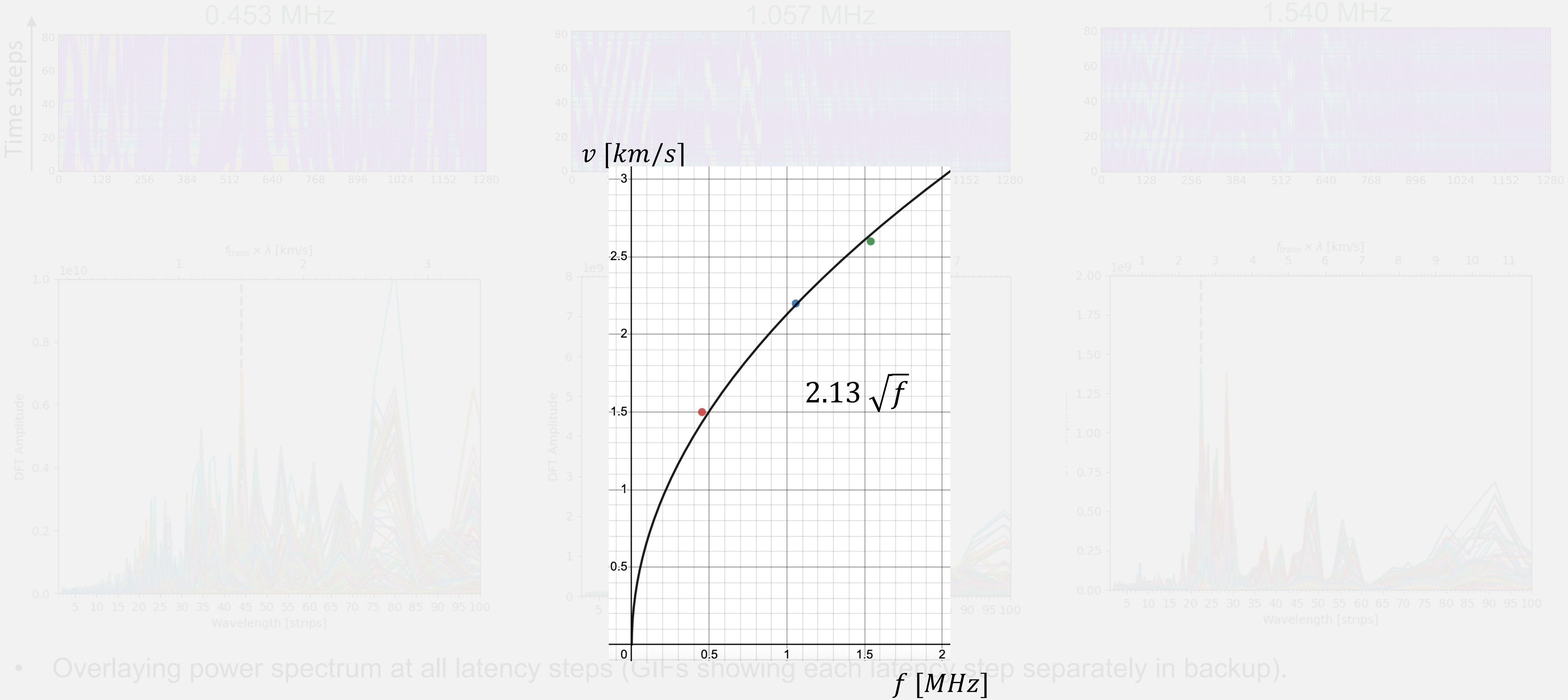
- See lots of EM noise on away streams when in phase with transducer.
  - Not much on the under streams.

HY Spectrum (All Channels) @ -35C



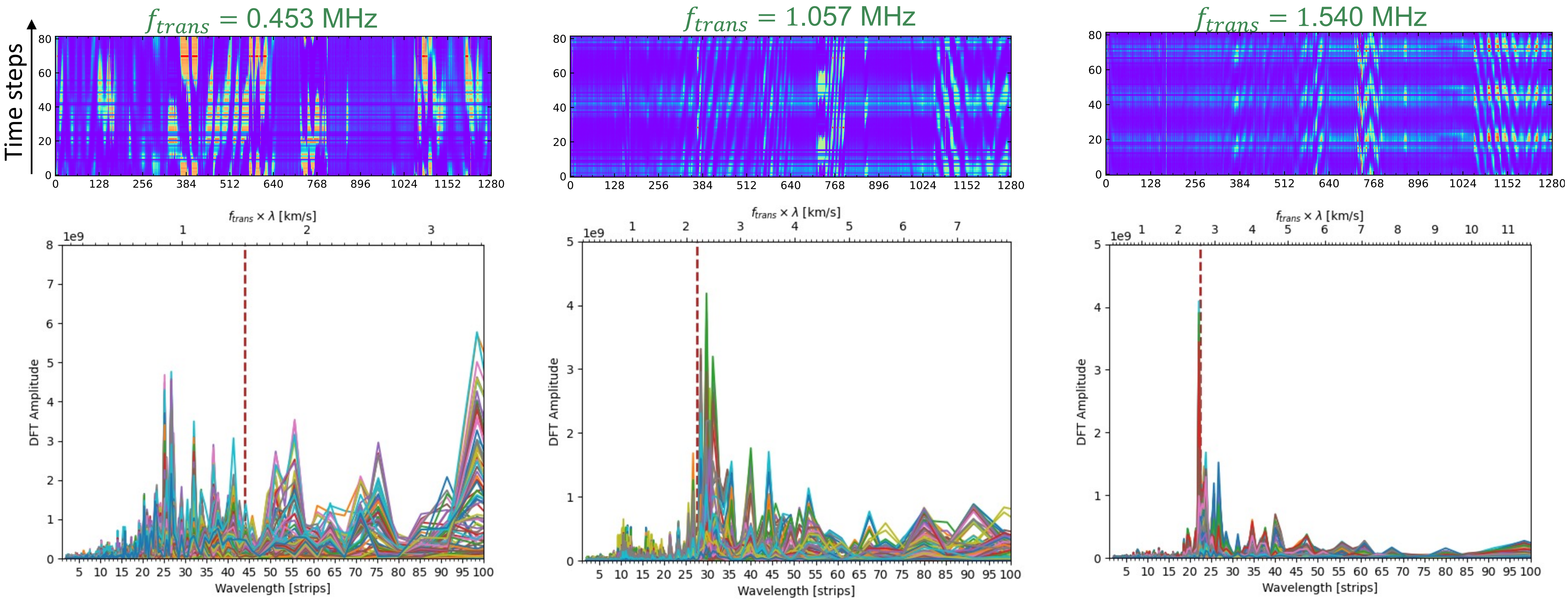
- Overlaying power spectrum at all 80 latency steps (GIFs showing each latency step separately in backup).
- Guessing which peak corresponds to a wave traveling at f_{trans} → can calculate $v(f) = \lambda(f)\times f$.
- Other peaks? Flexural waves traveling at other frequencies (harmonics of f_{trans})? Artifact of complex sensor/module structure?
  - Recall, speed is frequency dependent. So $2f \nRightarrow \lambda/2$.

HY Spectrum (All Channels) @ -35C



- Overlaying power spectrum at all latency steps (GIFs showing each latency step separately in backup).
- Red dashed line marks guess peak I think corresponds to the transducer frequency.
  - Can read off corresponding velocity from top axis.

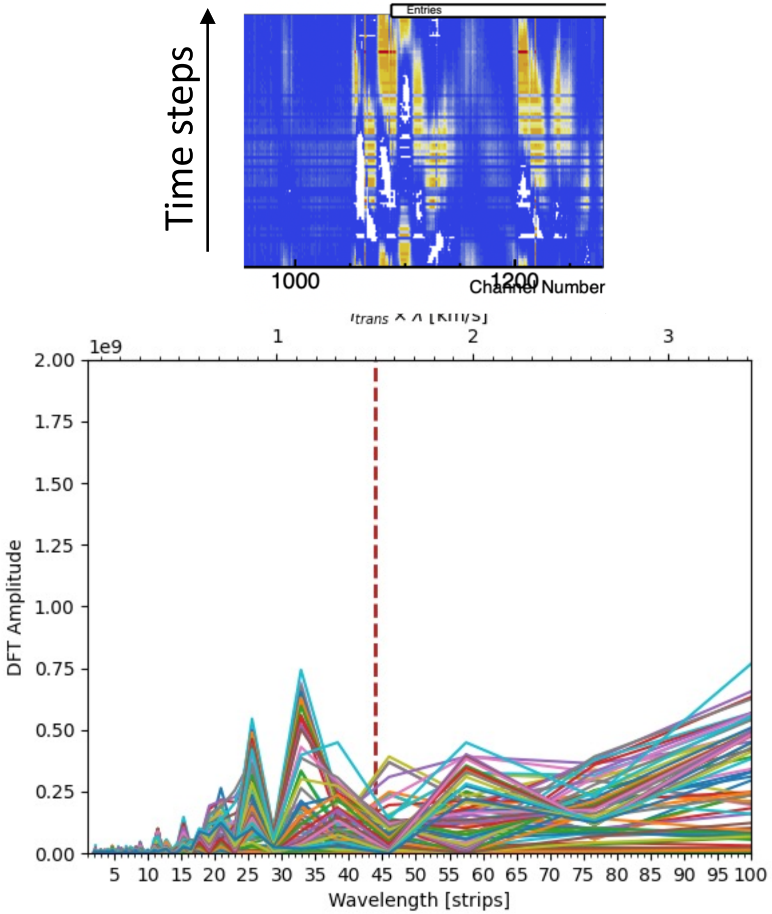
HX Spectrum (All Channels) @ -35C



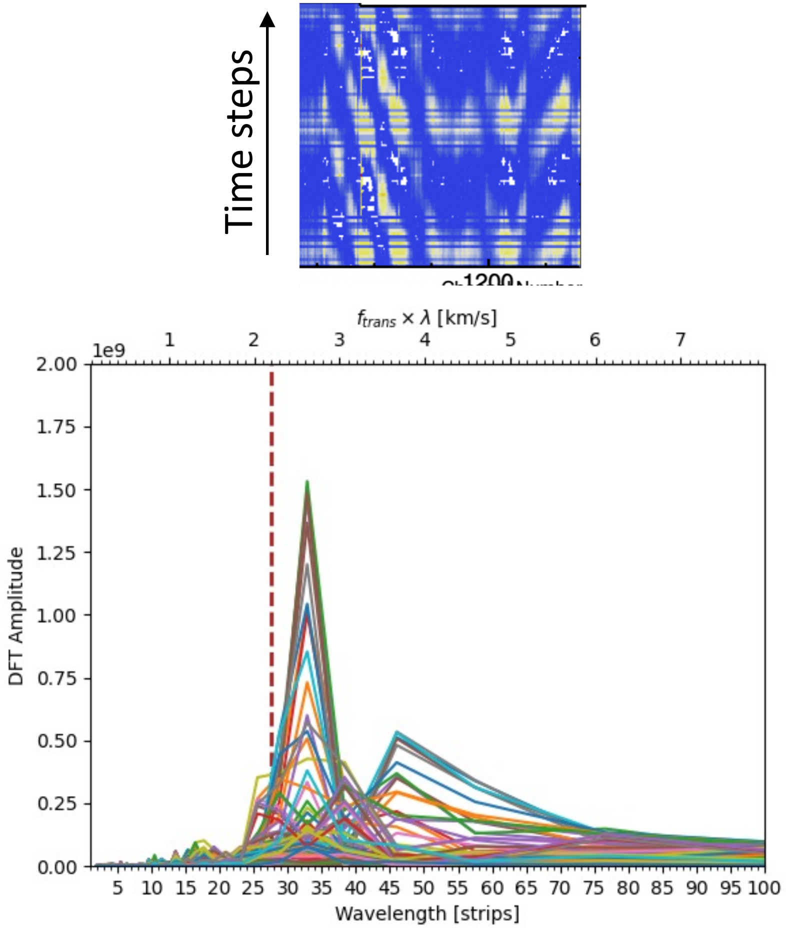
- Cleanest signal at 1.540 MHz → peak agrees well with Y hybrid.
- Less convincing at lower f_{trans}, but less clean signal.

HX HCC Spectrum (Channels 1050-1280) @ -35C

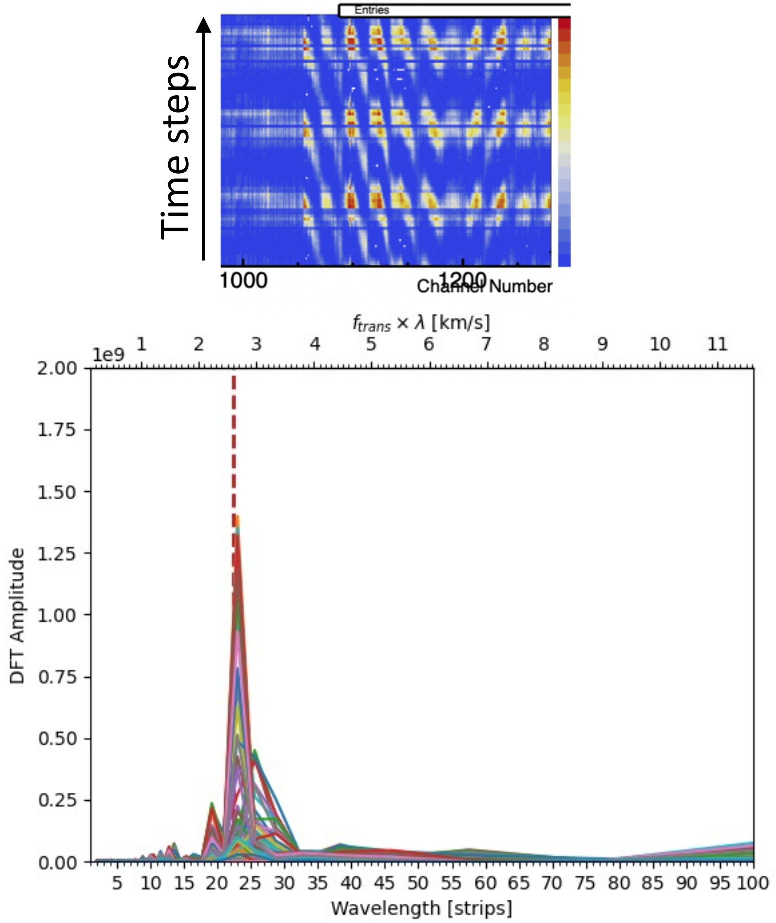
$f_{trans} = 0.453$ MHz



$f_{trans} = 1.057$ MHz



$f_{trans} = 1.540$ MHz



- Now focusing on HCC of HX, using same $v(f)$ as HY ("fitted" to HY power spectrum).
- 1.540 MHz spectrum matches well, but 0.453 MHz and 1.057 MHz do not.
  - Lower frequencies have less clean signal in latency scan and fewer wavelengths for the DFT.

Phase and Group Velocity of Lamb Waves in Aluminum Plate

A_0 properties*:*

- $v_p \approx \frac{1}{2} v_g \sim \sqrt{f}$ for low f $(\lambda \ll t)$.
- As λ approaches plate thickness, $v_p \rightarrow$ Rayleigh speed.
  - Rayleigh speed close to shear (AKA transverse) speed.
- v_g hits max just above v_T when $\lambda \approx$ plate thickness
  - Then decreases to Rayleigh speed.

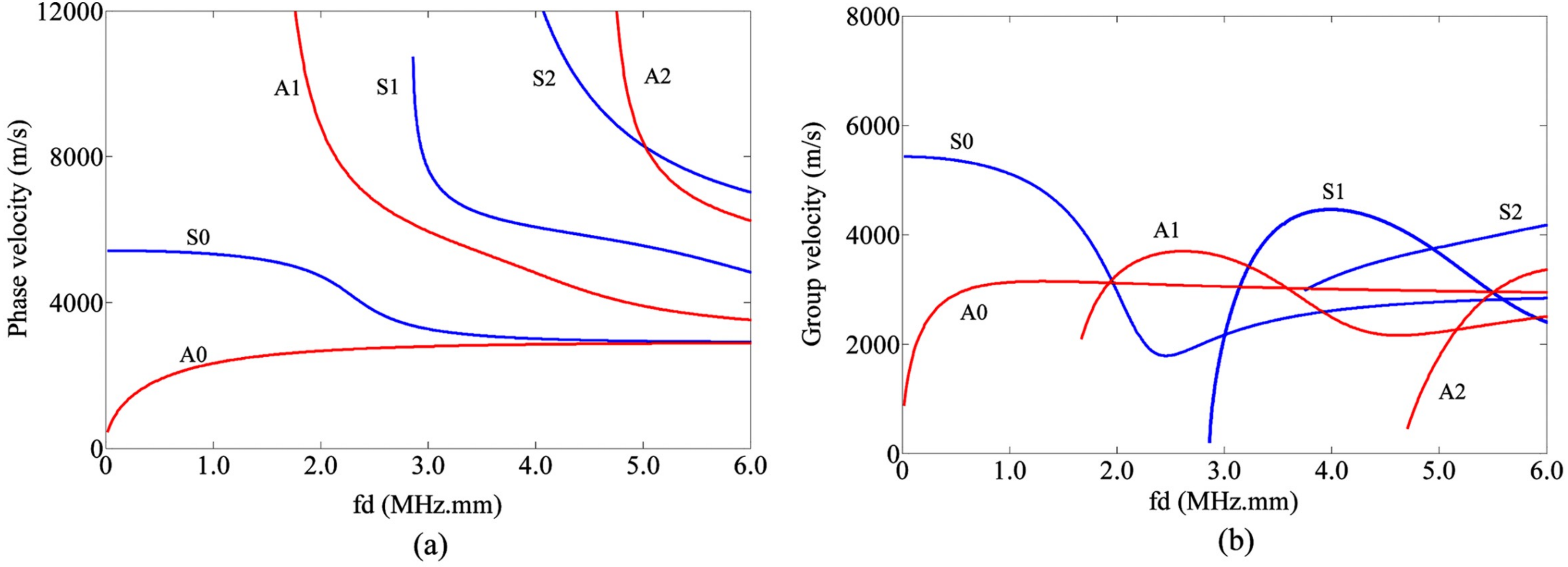
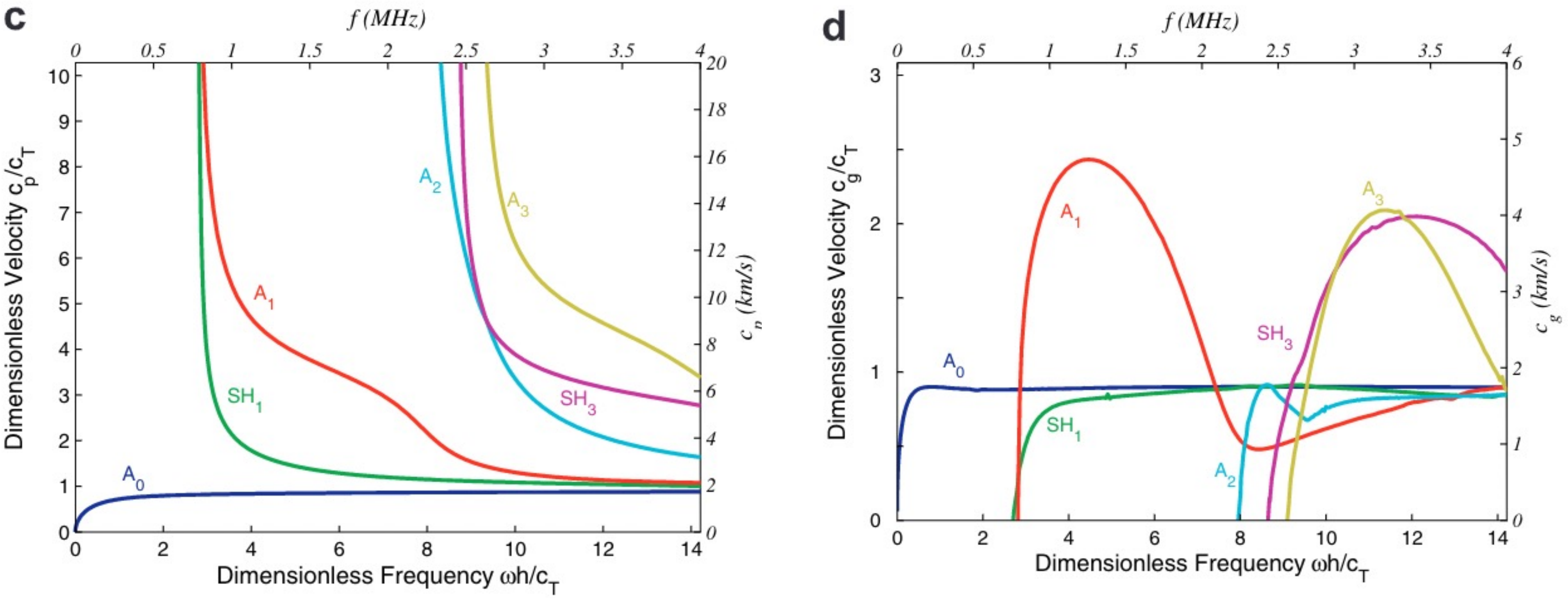


Fig. 1 Dispersion curves of Lamb waves: (a) phase velocity and (b) group velocity

https://www.researchgate.net/publication/264031140_Damage_localization_in_plate-like_structure_using_built-in_PZT_sensor_network

Group velocity and characteristic wave curves of Lamb waves in composites: Modeling and experiments



https://www.sciencedirect.com/science/article/pii/S0266353806003630

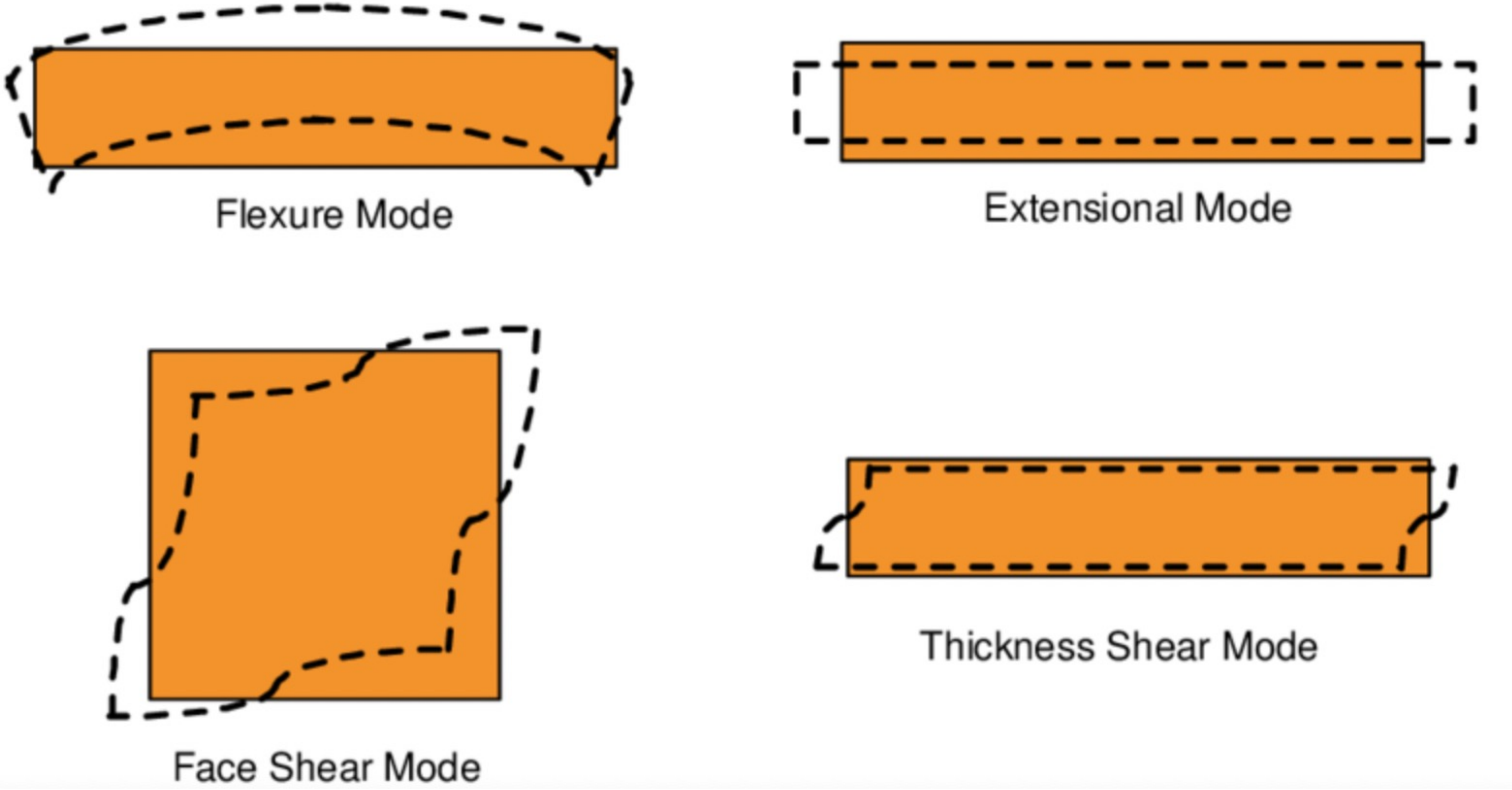


Figure 50. Lamb wave propagating in plate: (a) symmetric; (b) antisymmetric.