Preliminary insights on coldnoise testbeam data

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SiDet meeting
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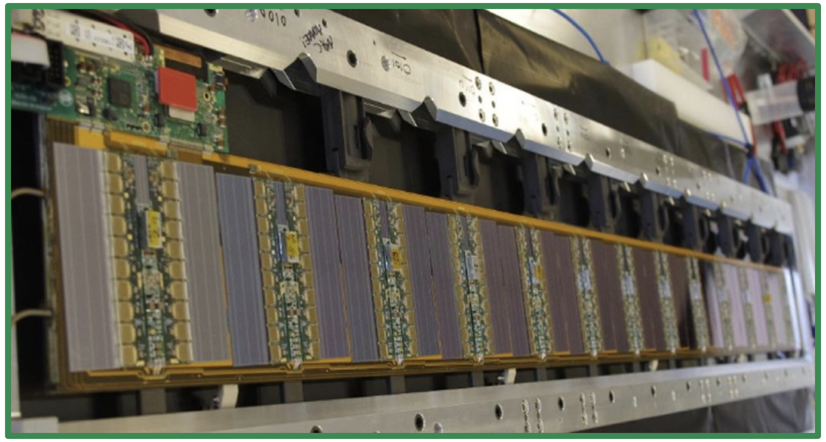
HELMHOLTZ

Introduction

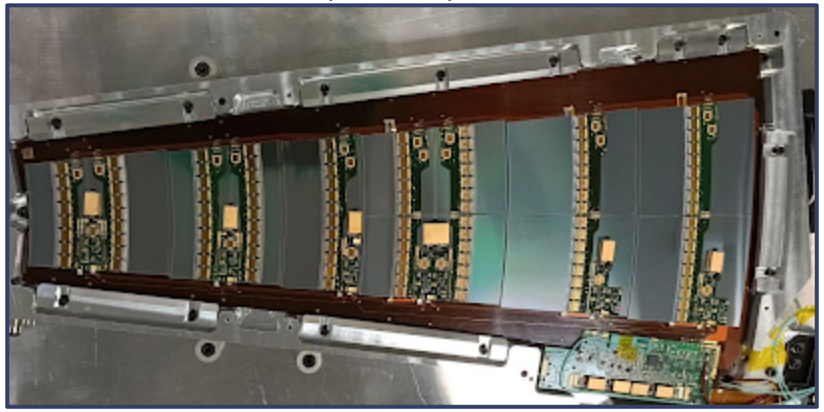
- ATLAS detector for the HL-LHC:
  - More interactions per bunch crossing ($\langle\mu\rangle \approx 50 \rightarrow 200$).
  - Higher trigger rate (100 kHz → 1 MHz).
  - Worse radiation damage (up to 2×10^{16} n_{eq}/cm^2).

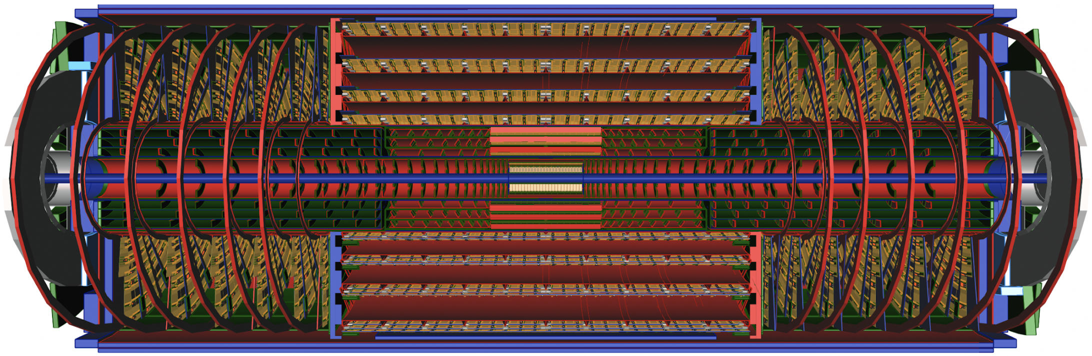
- Installing new, all silicon Inner Tracker (ITk).
  - Pixel modules for inner layers.
  - Strip modules for outer layers.

Strip Barrel Stave

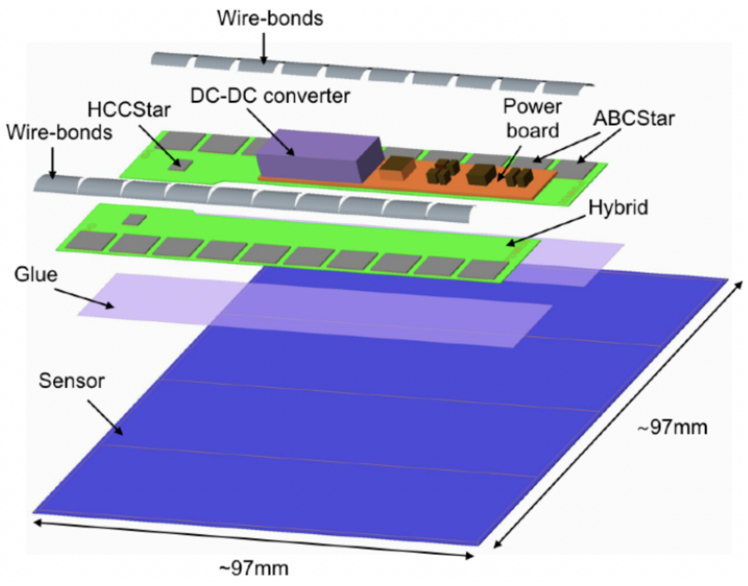


Strip Endcap Petal





Short strip barrel module



Silicon sensor:

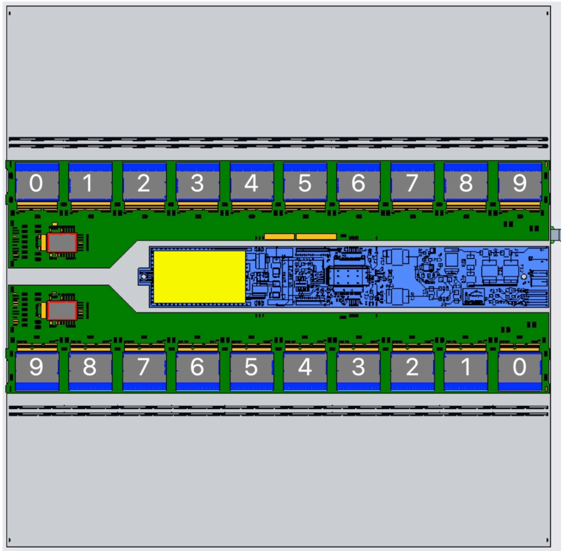
- AC-coupled, n^+-in-p sensor
- 75 µm strip pitch
- 24.1 mm strip length
- 300 µm thickness

Hybrid:

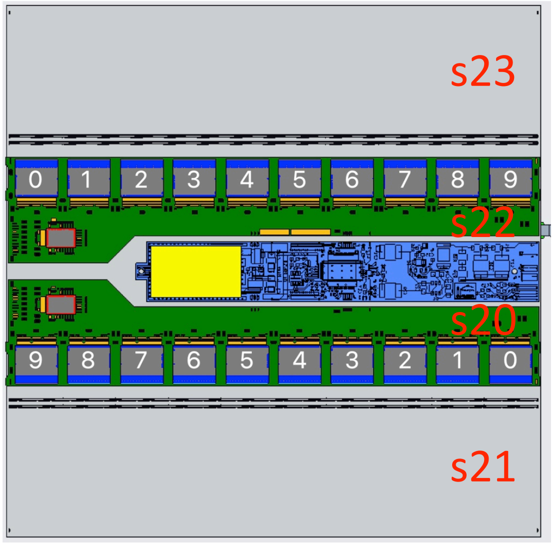
- Flexible printed circuit board holding readout ASICS.
  - 10 ABCs: amplify and discriminate signal, 256 strips/ABC.
  - 1 HCC: interface between ABCs and backend electronics

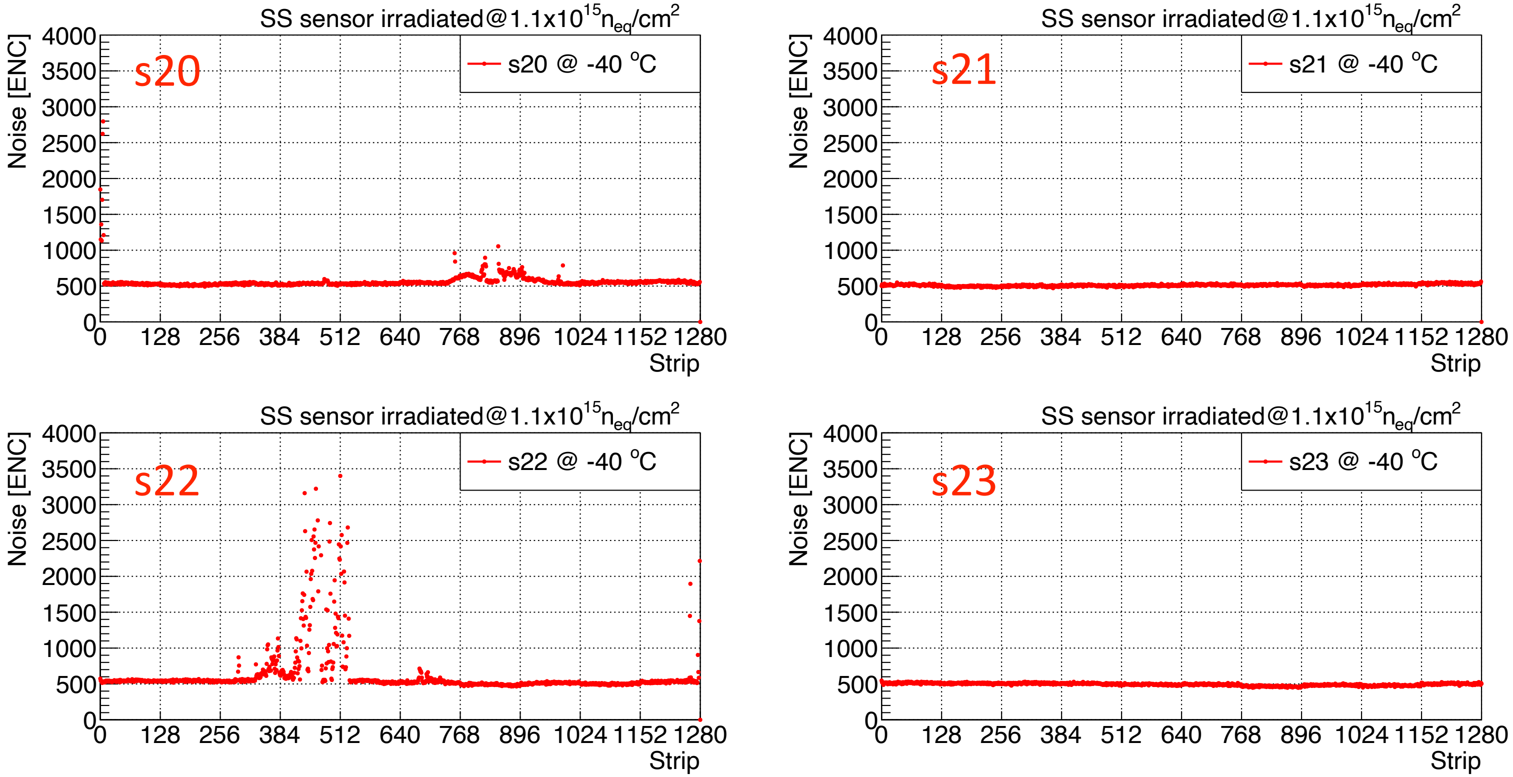
Powerboard:

- ASIC power, monitoring & interlock, HV switching for sensor biasing.
- Frontend 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 strips.
    - Mitigate by aluminum shield box.



Cold noise

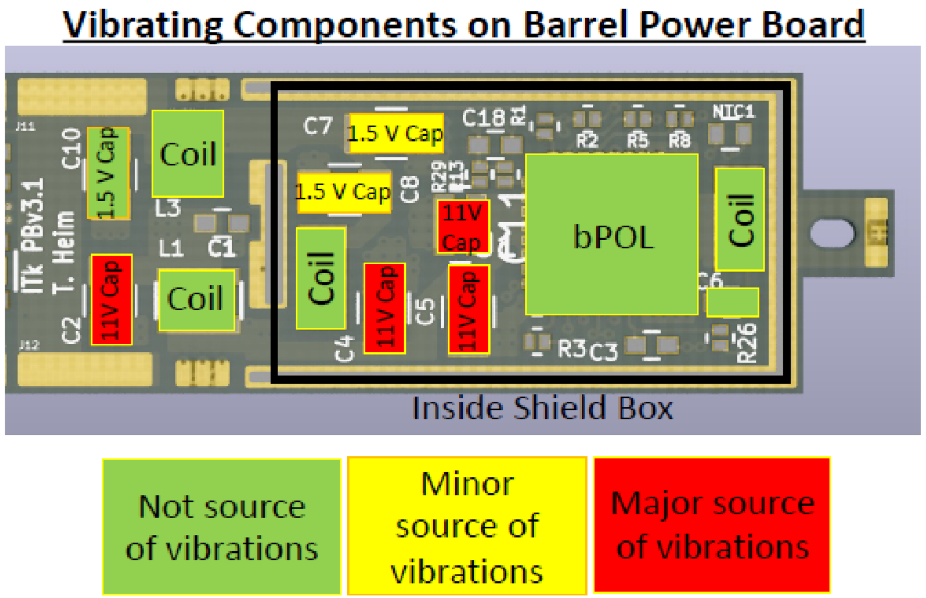




- Noise level growing at low temperature under hybrids & PB.
- Correlated with glue under hybrids.
- Correlated to the DC-DC converter: switching @ 2MHz.
  - **We have confirmed that mechanical wave couples into sensor (via glue) & travels. But who and how?**
- Mechanism doesn’t change in magnetic fields or with irradiation.

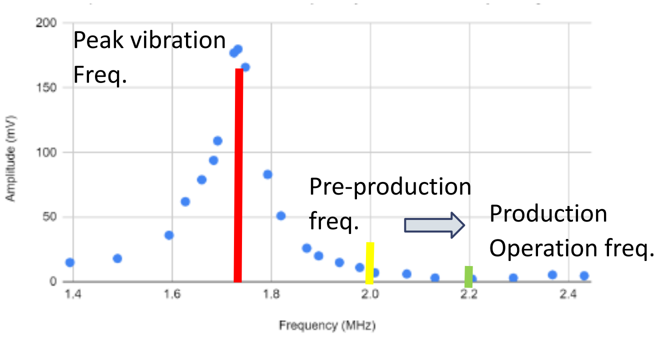
Who is vibrating?

Ian Dyckes and Matthew Kurth

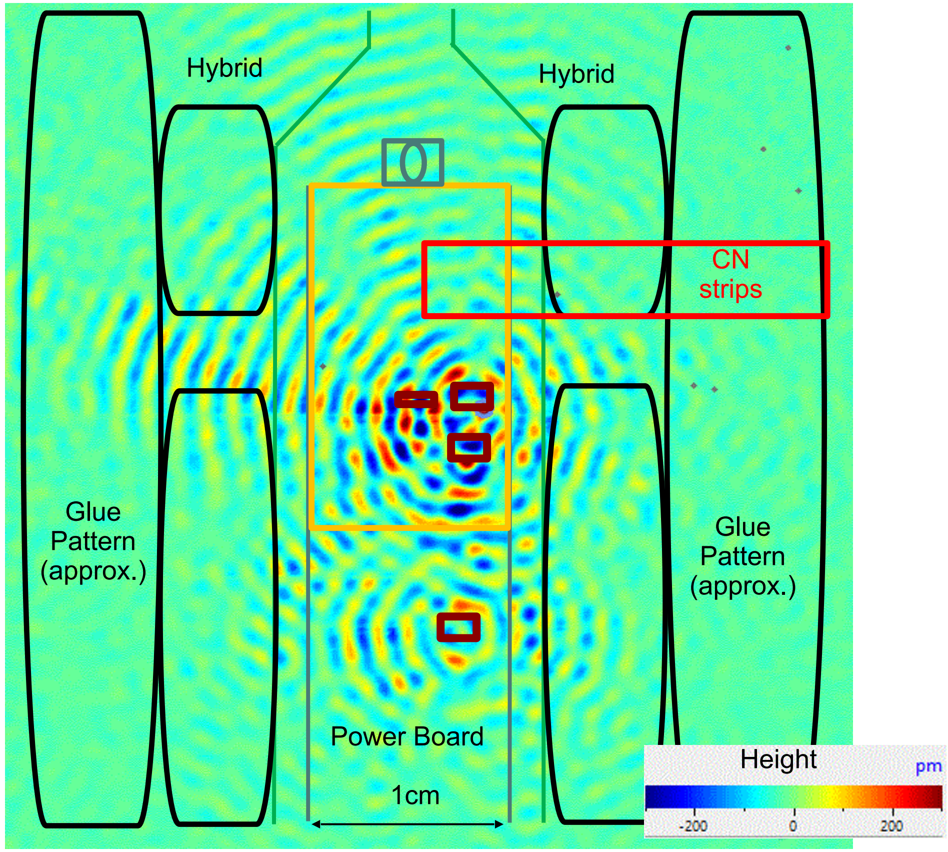


Barium Titanate caps

Capacitor Vibration



Alternative caps do not achieve the radiation tolerance, reliability, and capacitance.

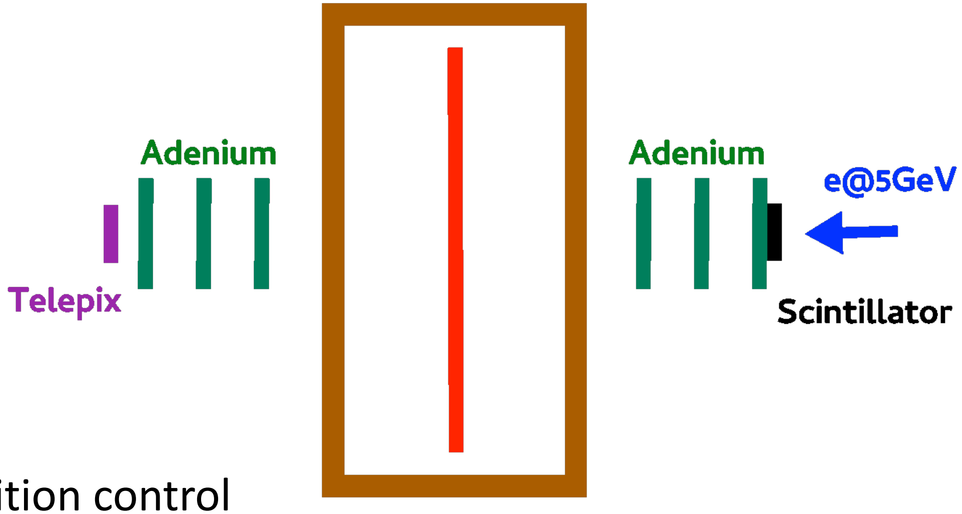


Vibrations seen from backside of the sensor.
But for all types of module.
Why only SS having coldnoise?
How mechanical to electrical?

Ongoing studies.

Test beam setup

[1] j.nima.2018.11.133
[2] 2023 JINST 18 P06025
[3] j.nima.2022.167947

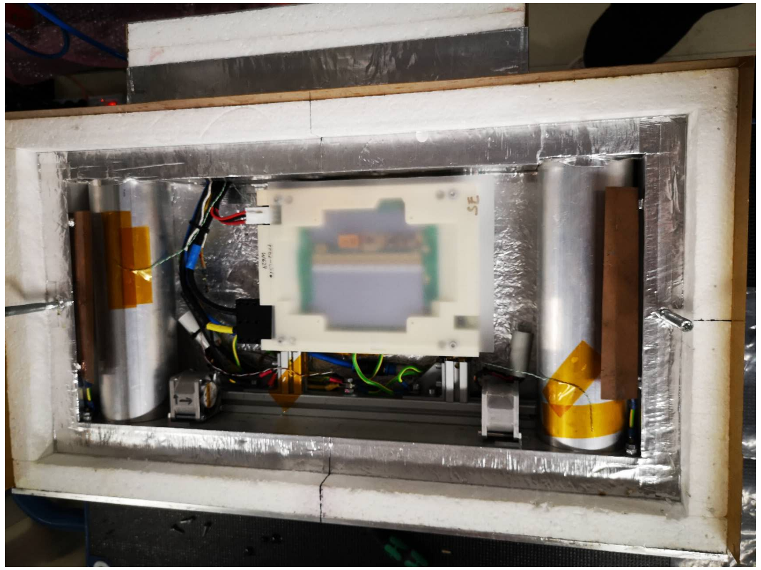


Test beam setup @DESY [1]

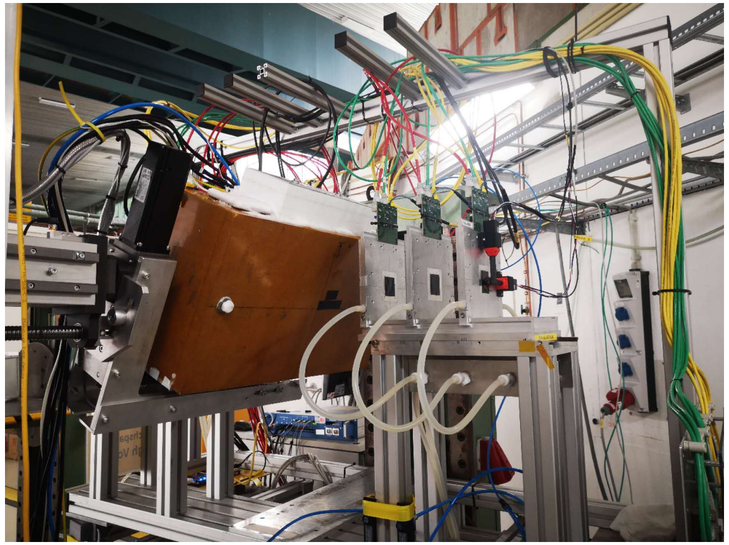
- Adenium telescope [2]
- Telepix timing plane [3]
- Scintillator trigger signal
- DUT cooling box
- DUT

Position control

Cooling box down to -50C



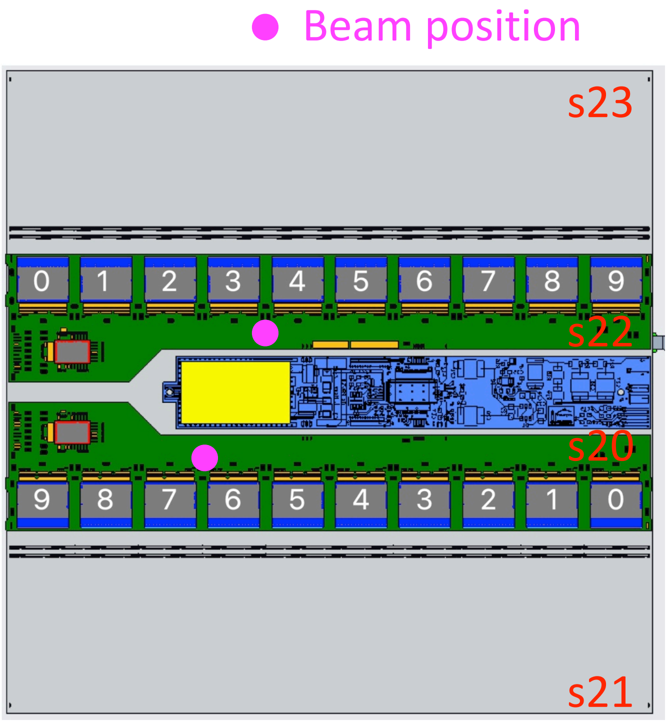
Angle control

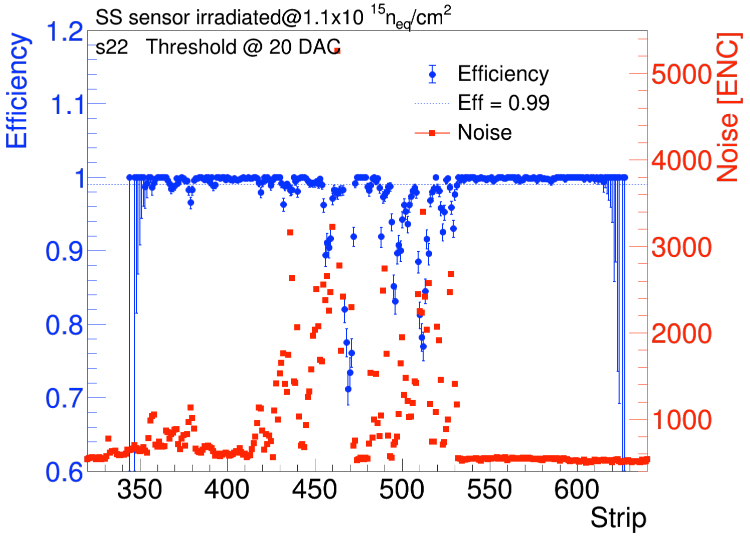


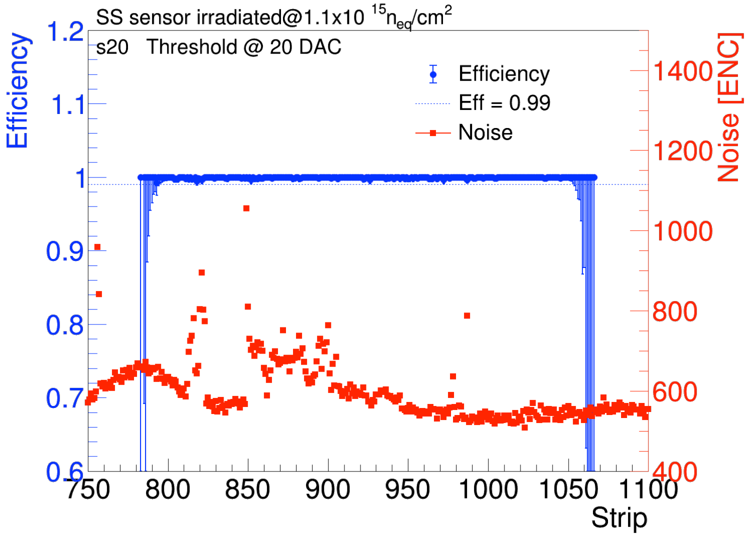
Testbeam - March 2024

20DAC ~1990e

- Irradiated SS with sensor irradiated at $1.1 \times 10^{15}\ n_{eq}/cm^2$.
- Data reconstruction using Corryvreckan [4]





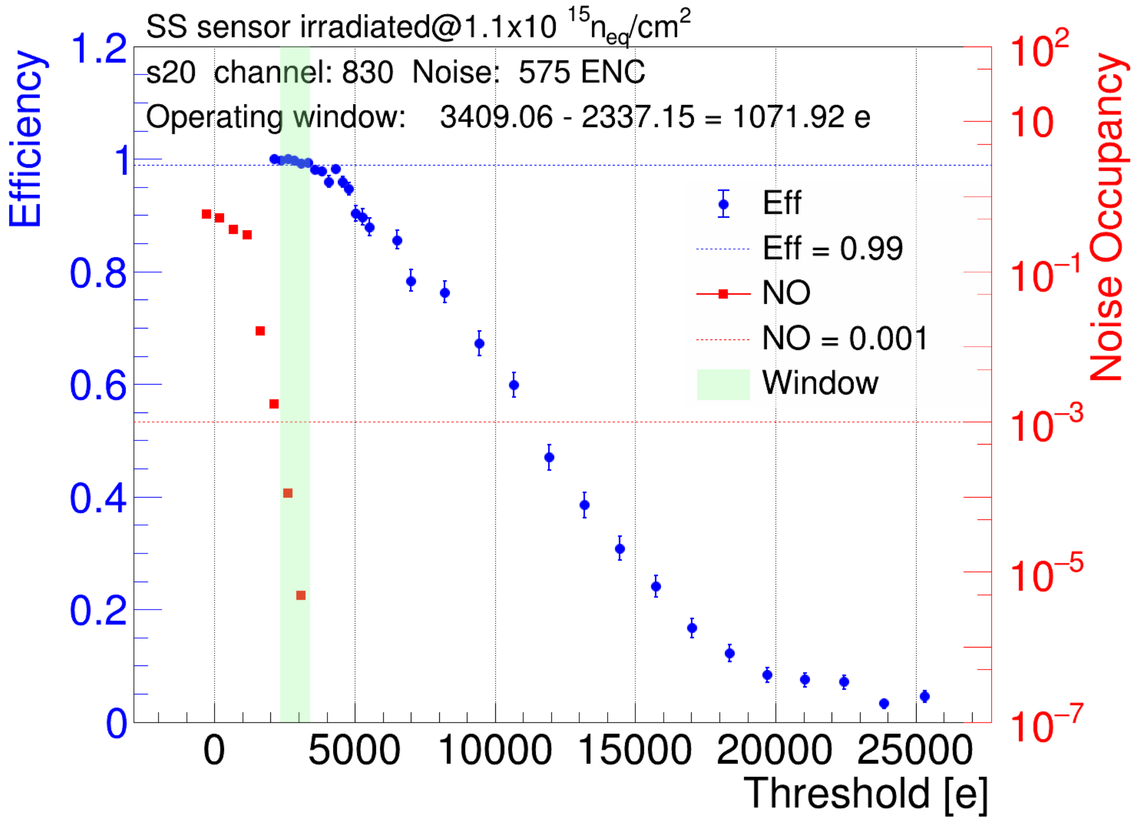


[4] 2021 JINST 16 P03008

Operating window

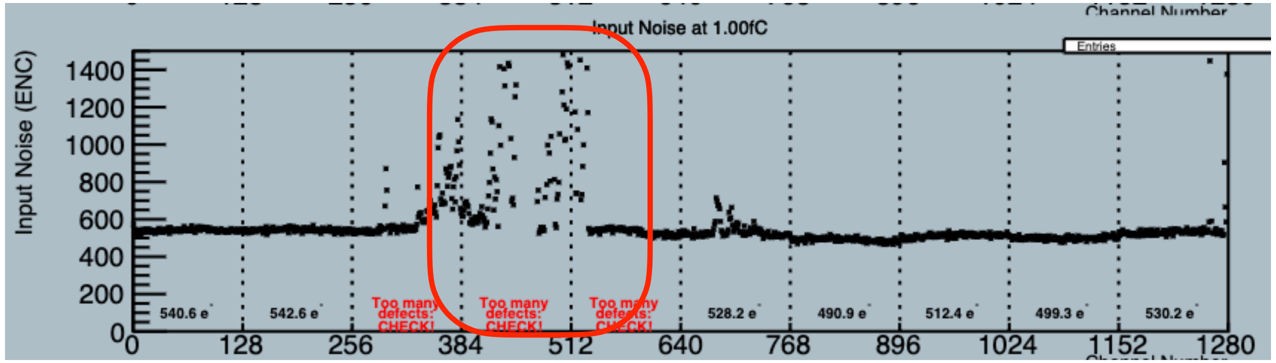
- **Operating window** =
  threshold (efficiency@99%) -
  threshold (noise occupancy@10^{-3})

- If max efficiency < 99%, for plotting use:
  - threshold set as 1500e;
  - operating window set as -2500e.



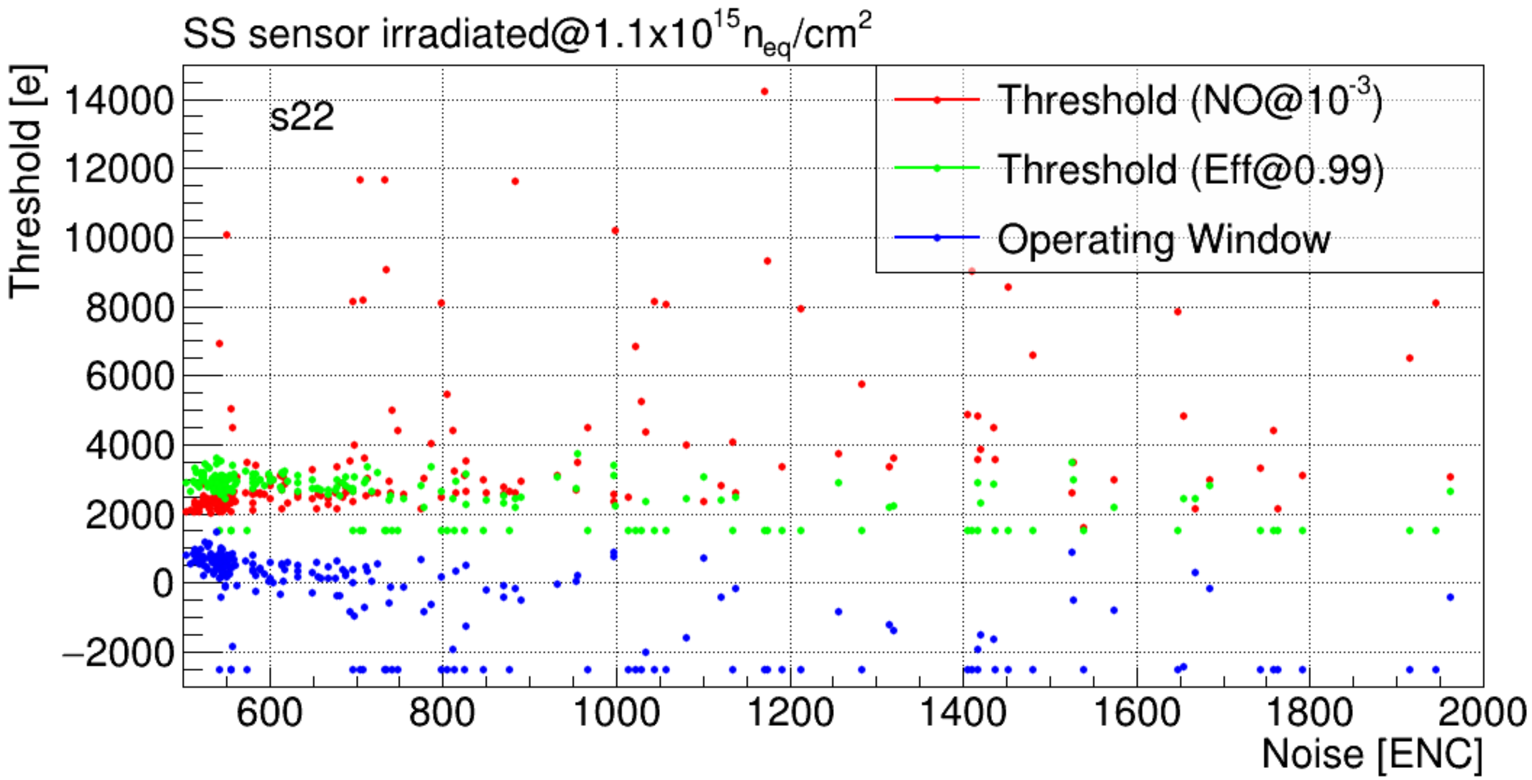
Coldnoise strips (s22)

Scatter plot: each point is a strip.



Strip 360-610

In total: 251 strips



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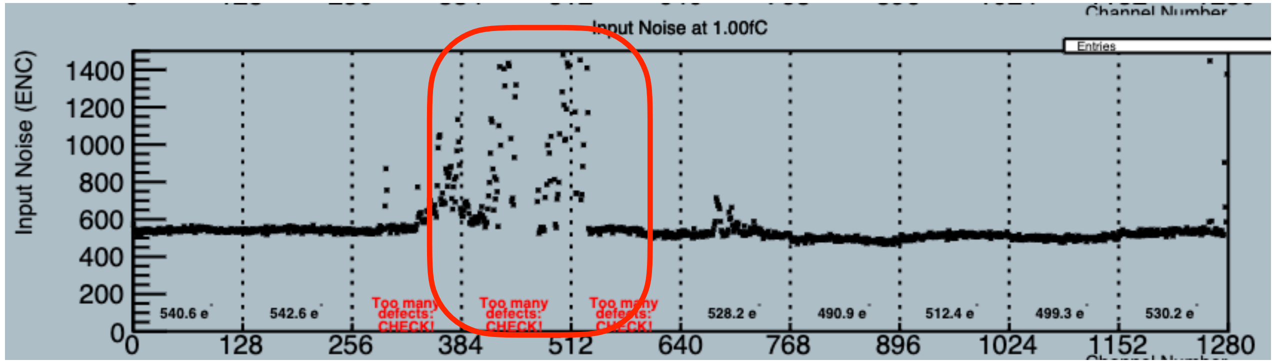

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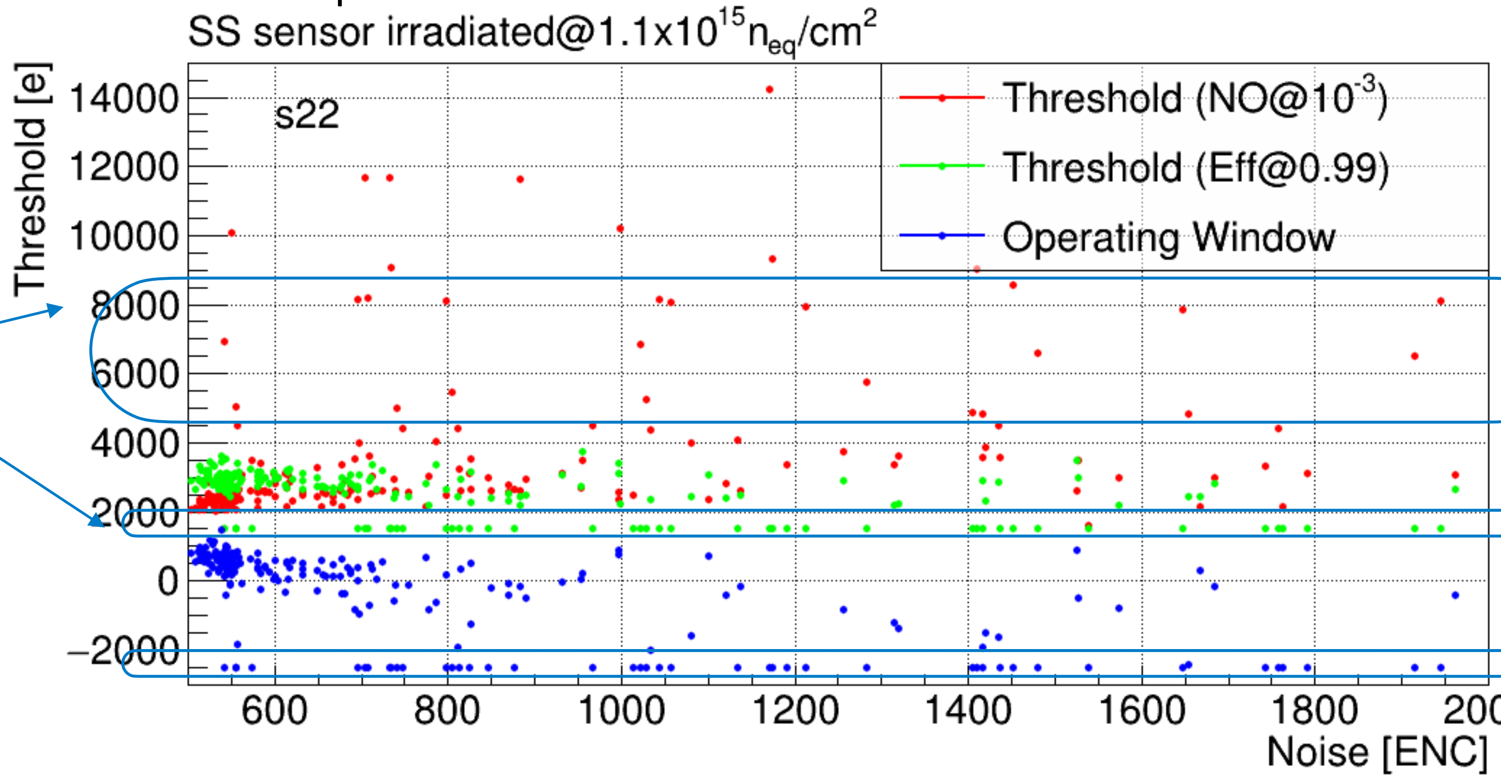


They seem correlated.

Large NO at low noise level?

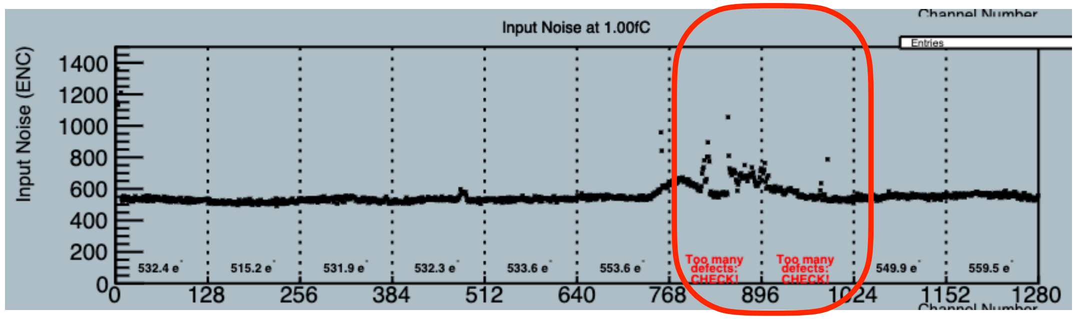
Strips with noise level high than 700e in the coldnoise, 70% strips without operating window.

Max efficiency < 0.99

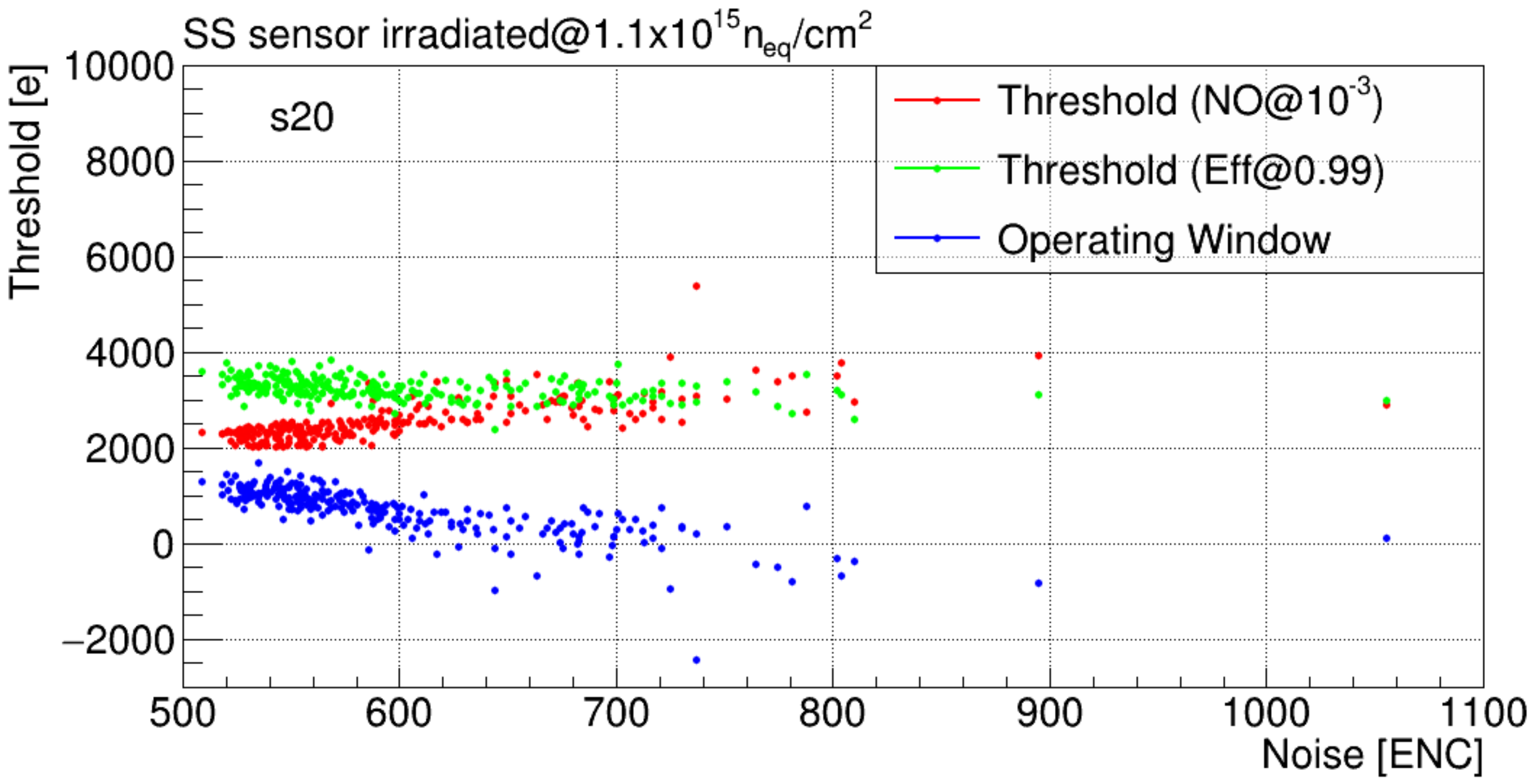
Max efficiency < 0.99

Operating window (s20)

Scatter plot: each point is a strip.
The plots are less scattered.

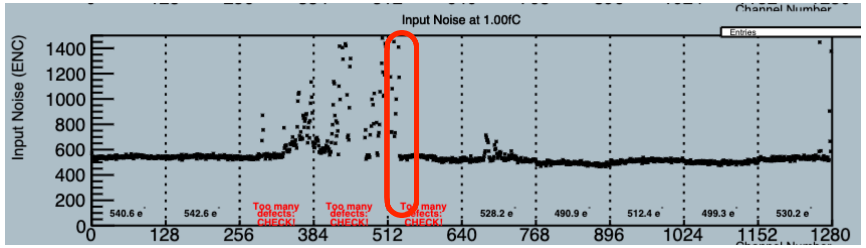


Strip 800-1050
In total: 251 strips

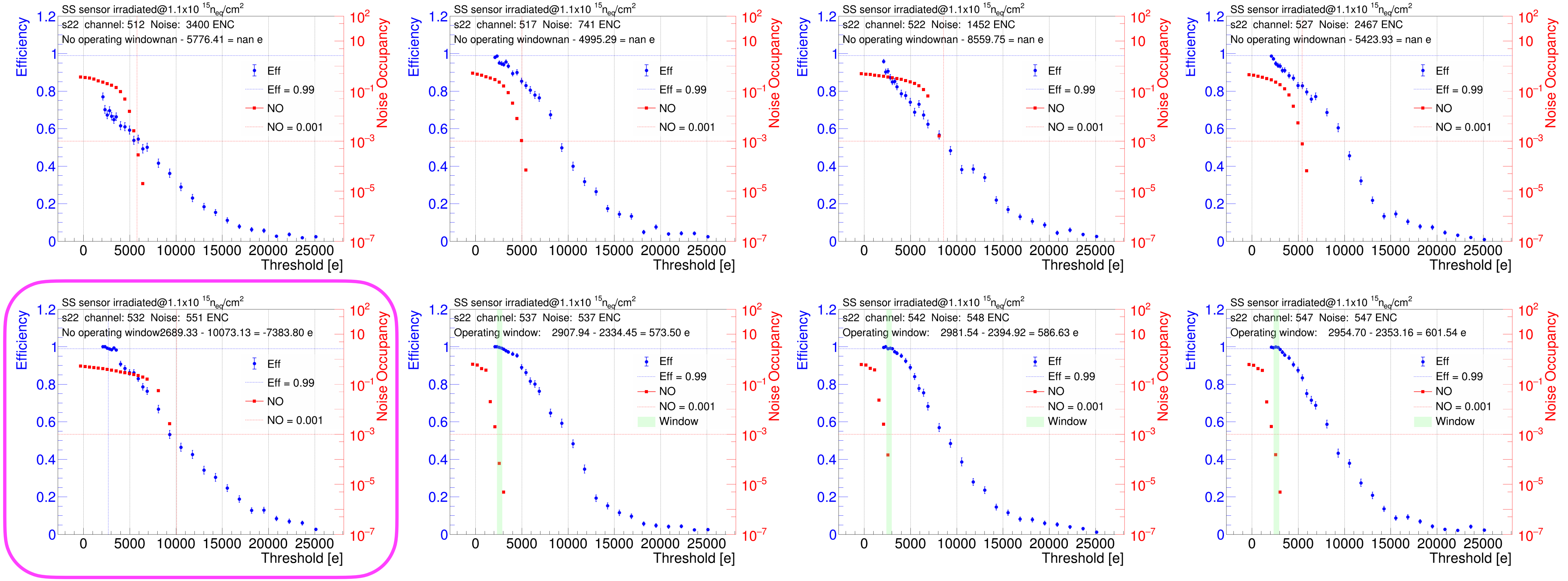


The coldnoise level is low and it has less impact on the strips when compared to s22.

From ‘bad’ to ‘good’ region?



Strip 512-547 per 5 strips



First good strip from ‘bad’ region

Summary

- Mechanical vibrations appear to be producing a voltage → effective discrimination threshold oscillates.
  - Exact mechanism not yet fully understood.
- Different types of noises present, which give different TB results.
- Studies of design modifications to reduce or eliminate cold noise are ongoing.
- These results help us understand how much cold noise must be reduced to have proper tracking at end of lifetime.
- More results will also be coming out to have more understandings about cold noise.

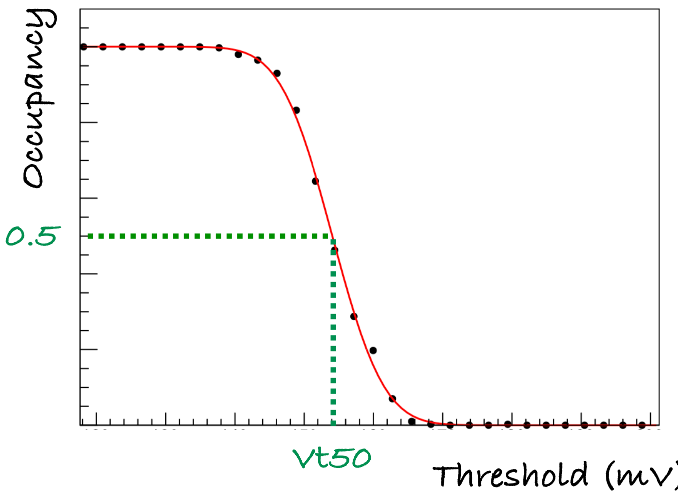
Thank you

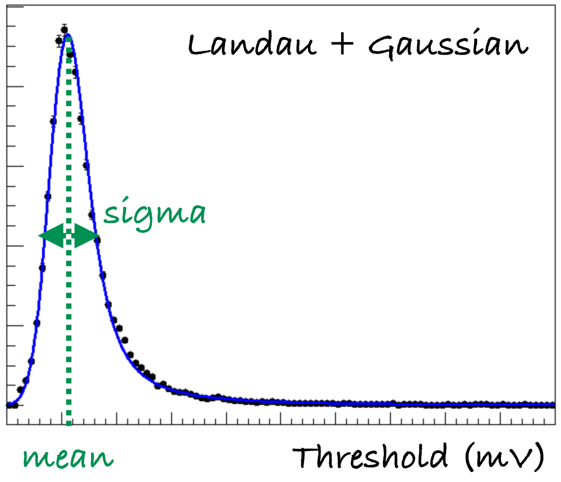
Backup

Noise measurement

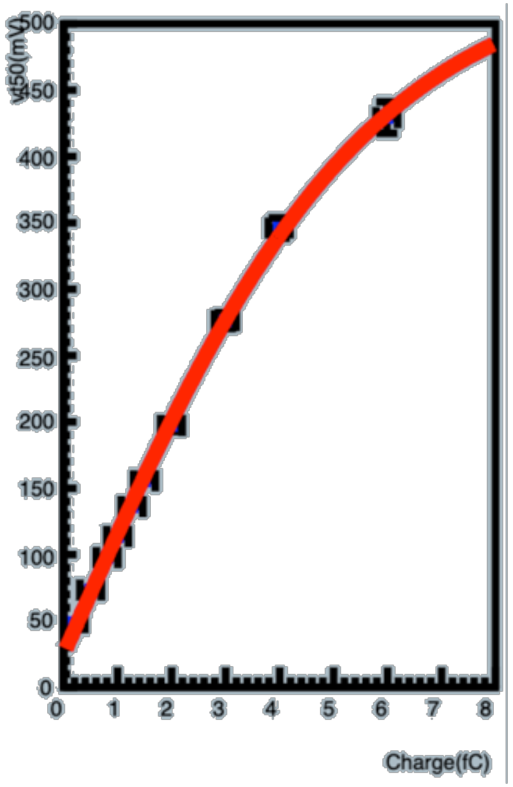
Just illustrations for who might not be familiar with it

Binary readout chip
For certain injected charges





Response curve



$$\text{gain} = \frac{\text{Vt50}}{\text{Injected charges}}$$

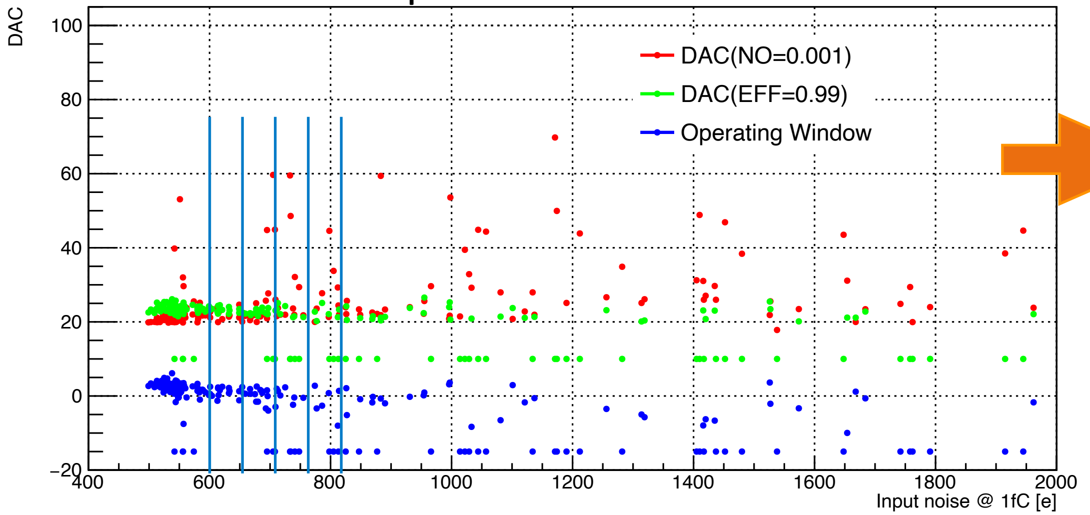
Equivalent Noise Charge (ENC)
Assuming 1fC=6241e

$$\text{ENC} = \frac{\sigma}{\text{gain}}$$

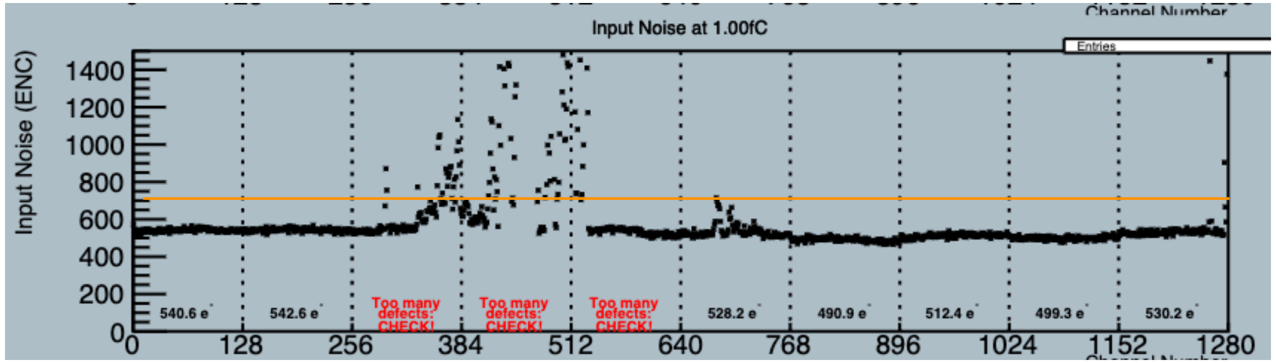
Coldnoise strips (s22)

Strip 360-610

In total: 251 strips



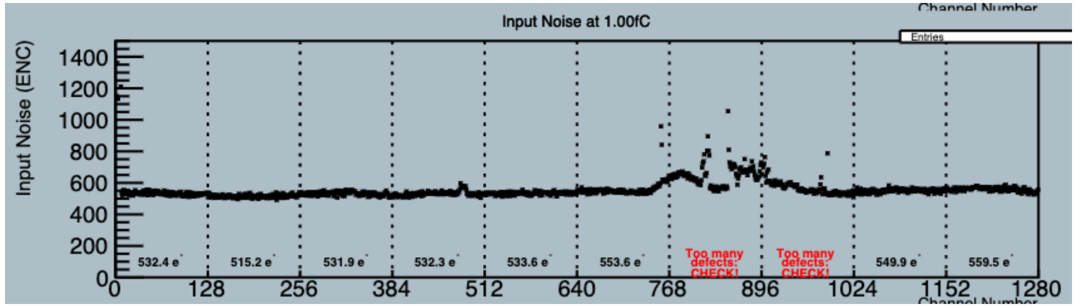
Input noise level @1fC	Total strips	Strips with + OPW	Fraction
<=600e	101	90	89 %
600-650e	14	12	86 %
650-700e	17	11	65 %
700-750e	13	4	31 %
750-800e	6	2	33 %
>800e	100	12	12 %

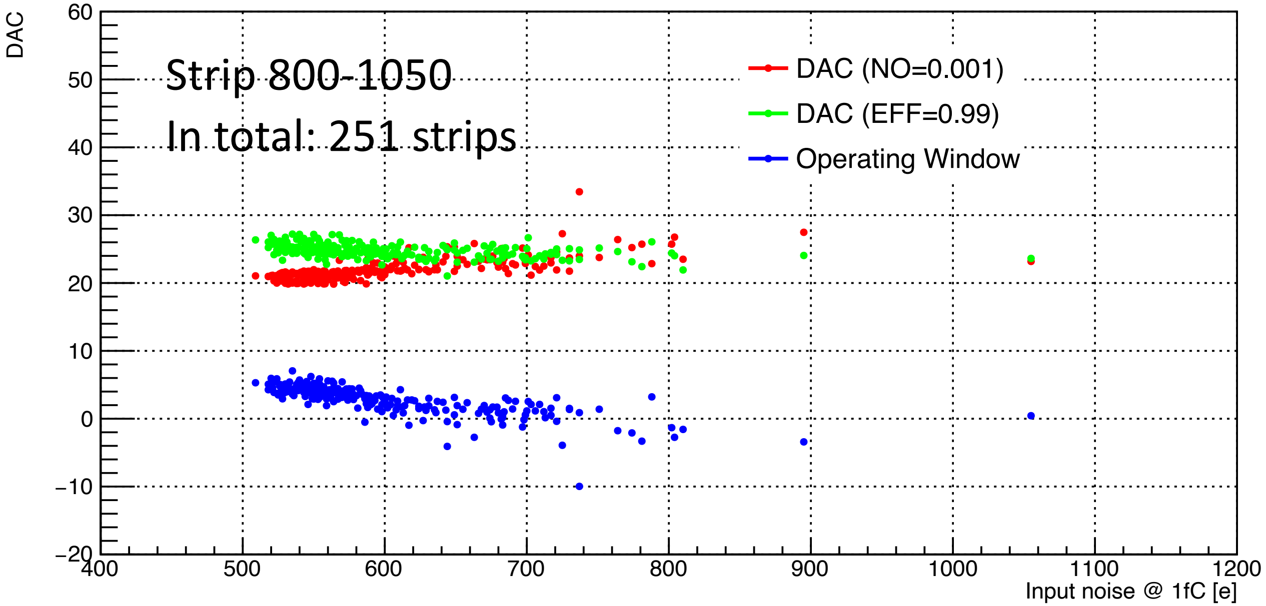


Strips with noise level high than 700e in the coldnoise region are not useful anymore.

Operating window (s20)

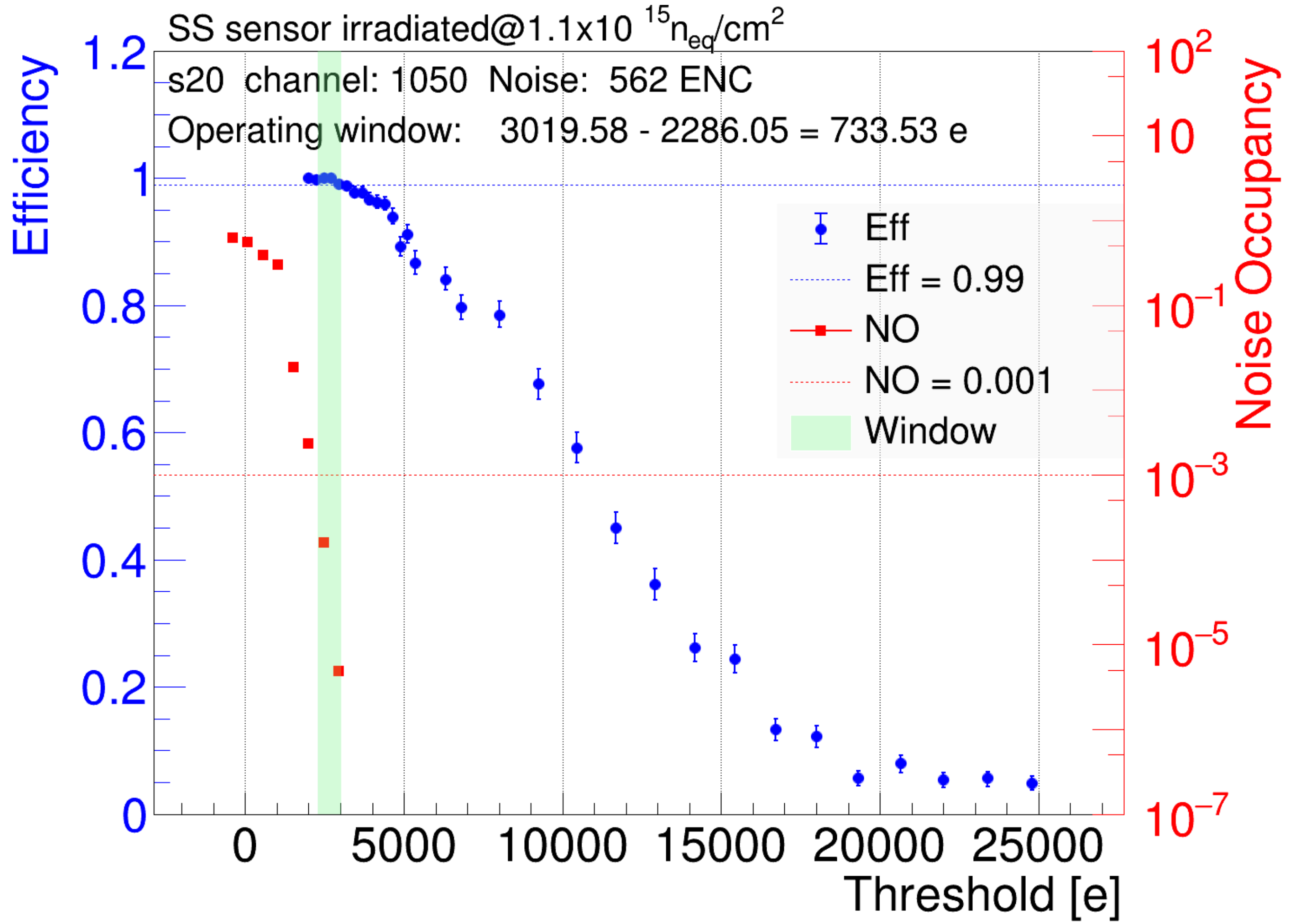
Scatter plot: each point is a strip.
The plots are less scattered.



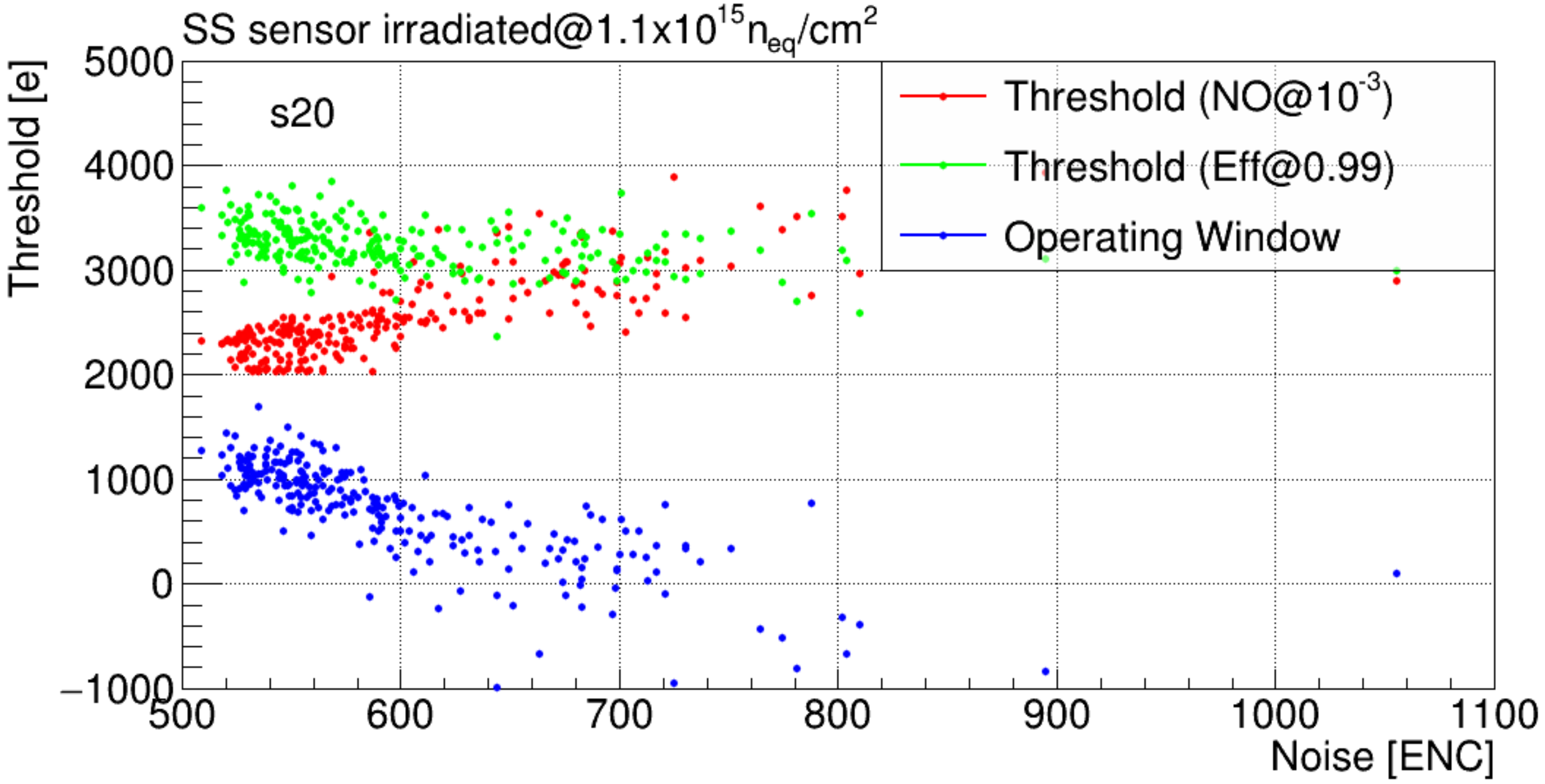


Input noise level @1fC	Total strips	Strips with + OPW	Fraction
<=600e	165	164	99 %
600-650e	32	28	86 %
650-700e	29	22	76 %
700-750e	15	12	80 %
750-800e	5	2	40 %
>800e	5	1	20 %

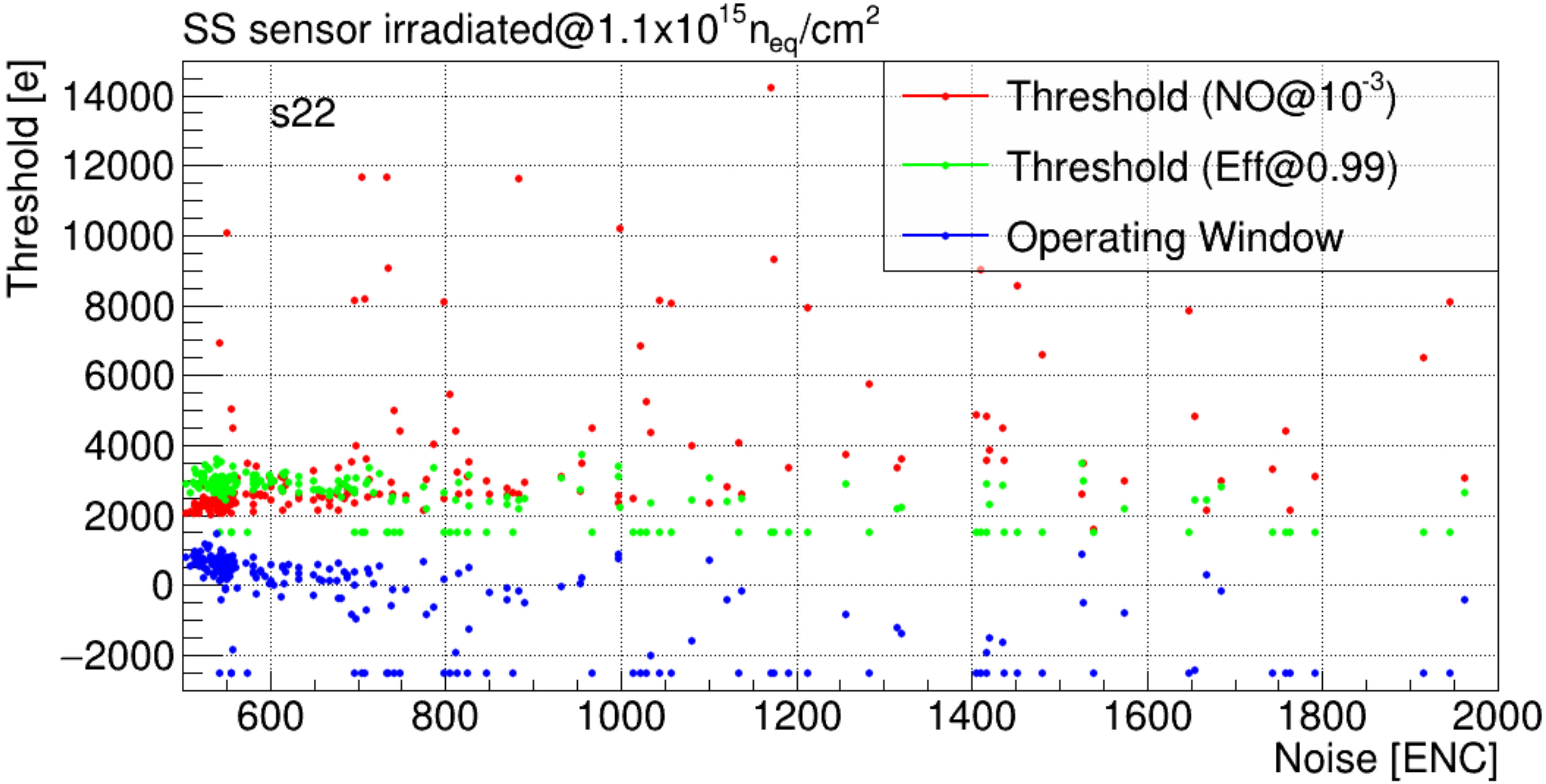
The coldnoise level is low and it has less impact on the strips when compared to s22.



SS sensor irradiated@1.1x10 $^{15}n_{eq}/cm^2$
s20 channel: 1050 Noise: 562 ENC
Operating window: 3019.58 - 2286.05 = 733.53 e
Efficiency
1.2
1
0.8
0.6
0.4
0.2
0
Noise Occupancy
10^2
10
10^{-1}
10^{-3}
10^{-5}
10^{-7}
0
5000
10000
15000
20000
25000
Threshold [e]
Eff
Eff = 0.99
NO
NO = 0.001
Window

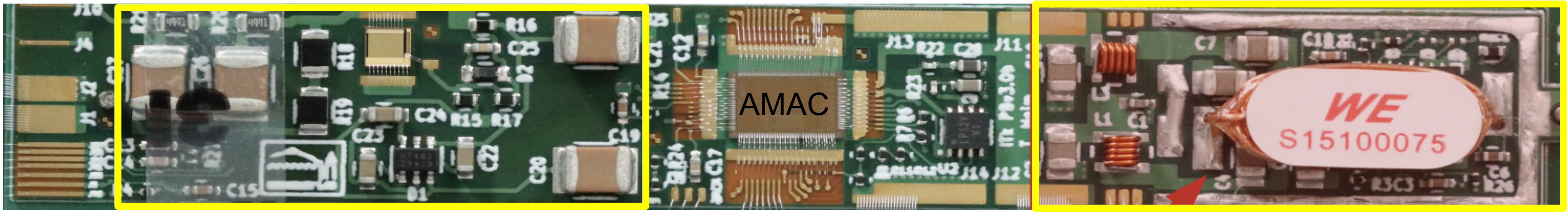


SS sensor irradiated@1.1x10^15 n_eq/cm^2
s20
Threshold [e]
5000
4000
3000
2000
1000
0
−1000
500
600
700
800
900
1000
1100
Noise [ENC]
Threshold (NO@10^-3)
Threshold (Eff@0.99)
Operating Window


SS sensor irradiated@1.1x10^15 n_eq/cm^2
s22
Threshold [e]
Noise [ENC]
Threshold (NO@10^-3)
Threshold (Eff@0.99)
Operating Window
14000
12000
10000
8000
6000
4000
2000
0
−2000
600
800
1000
1200
1400
1600
1800
2000

Cold Noise *Instigator*

Powerboard



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

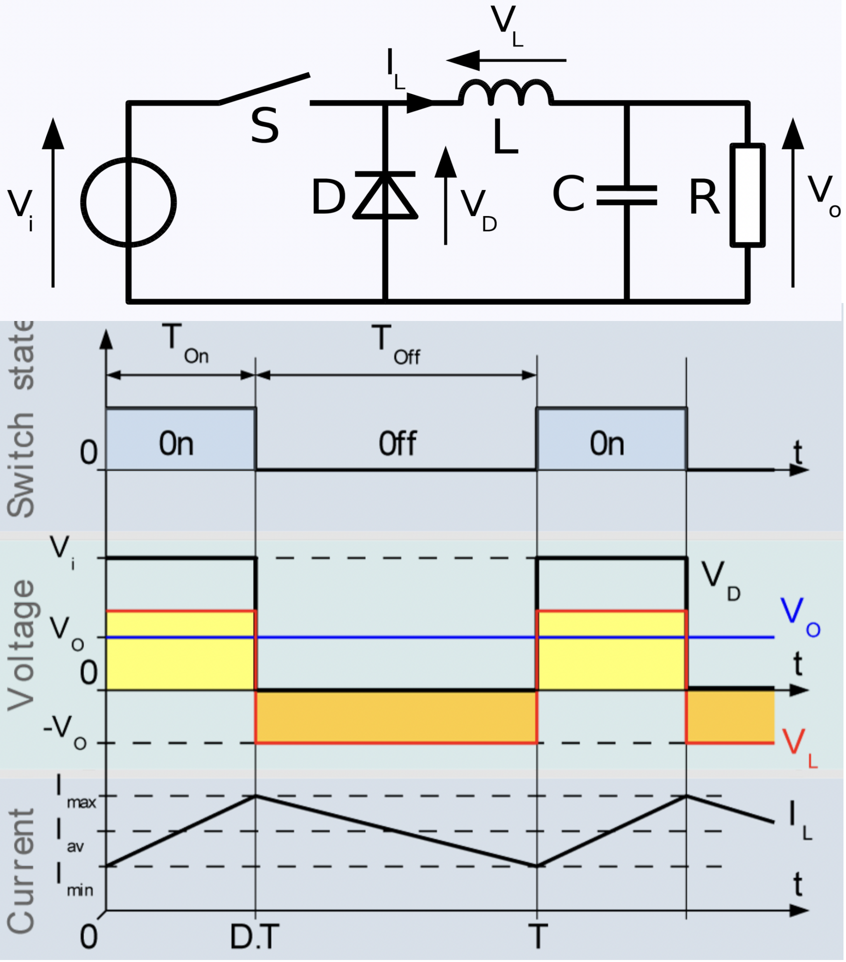
"Singing" capacitors known phenomenon when dielectric used in capacitor has piezoelectric effect
- Occurs with a oscillating voltage on capacitors
- Buck converter a potential candidate for singing capacitors

The Powerboard: A Closer Look

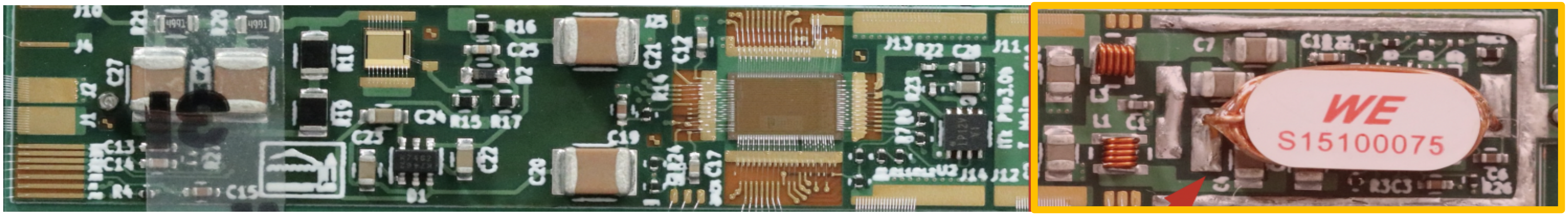
Voltage Stepdown:

- 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



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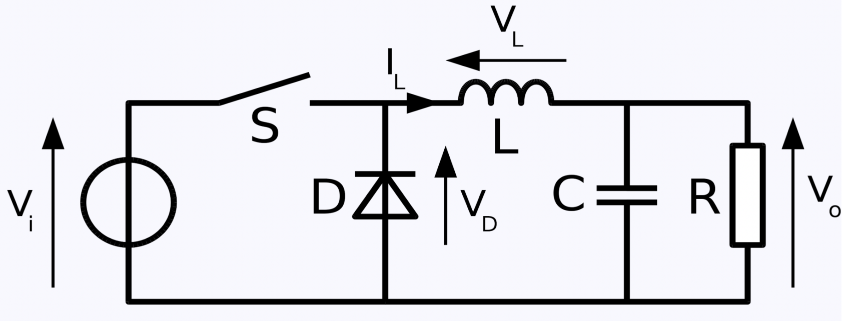

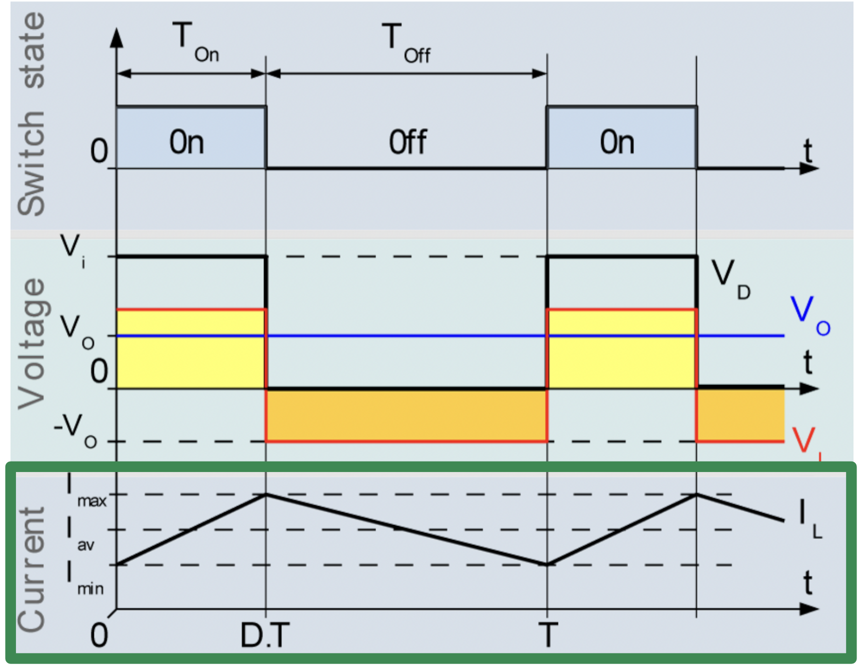

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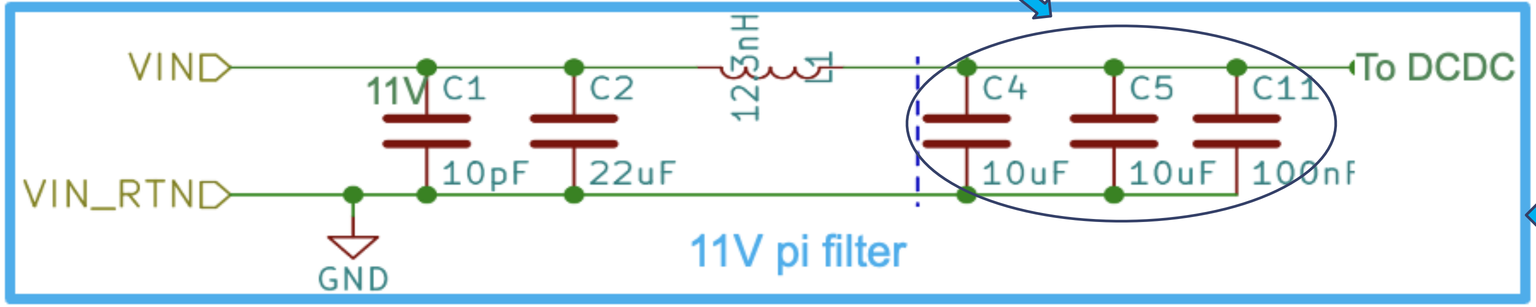
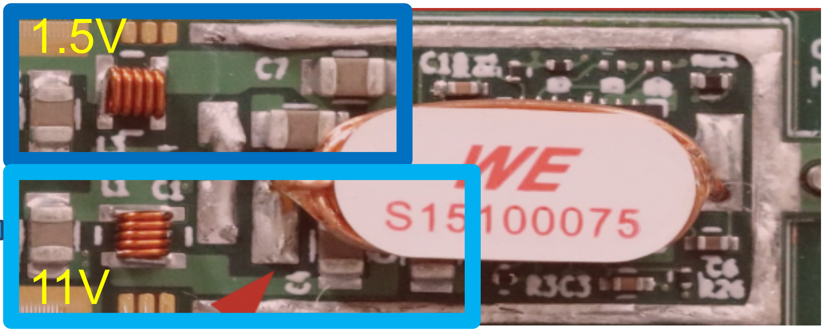
Filtering:

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



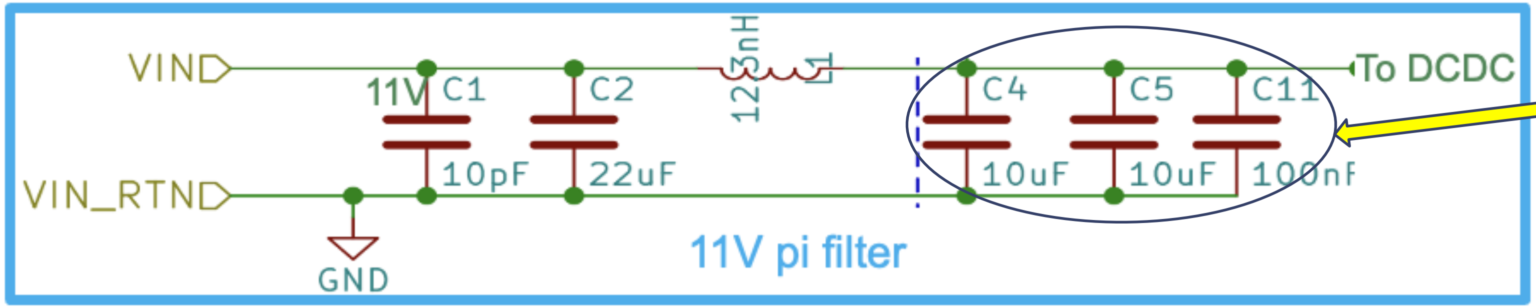


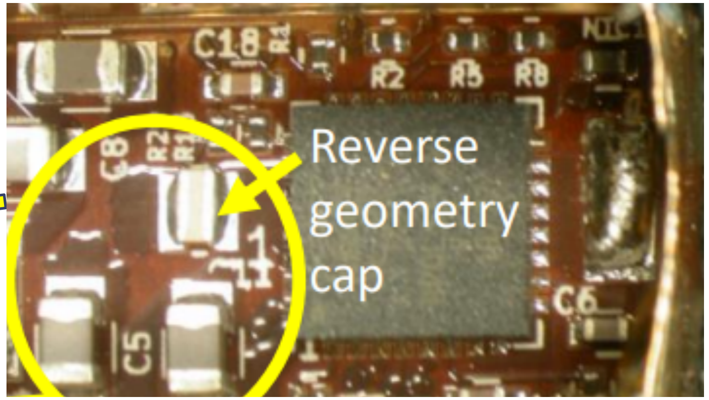
Replace Suspected Capacitors

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

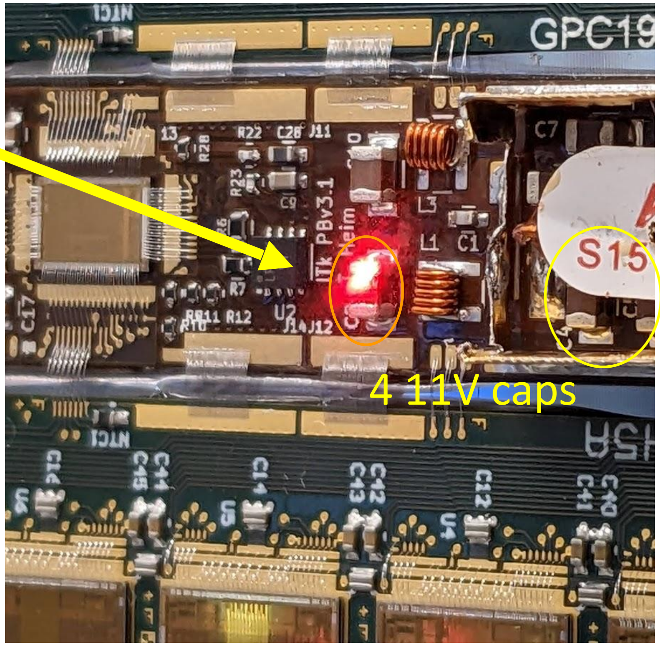
- Cold Noise slightly decreased but persistent
  - unexpected

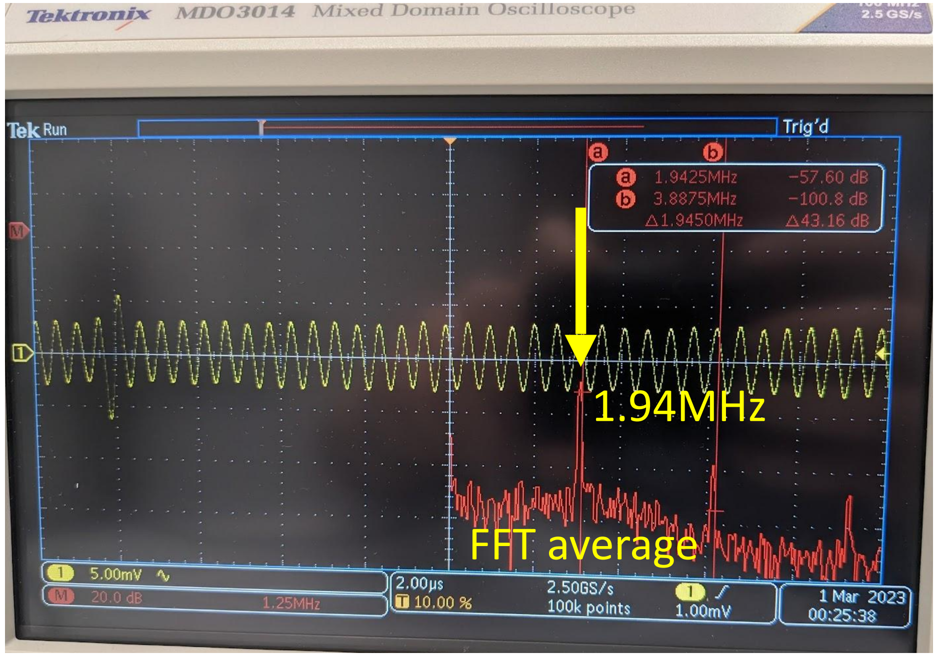
- Motivation to start looking for the “right tool” to identify individual vibrating components
  - Attaching transducers to small components not ideal





Right Tool for the Job - Vibrometer





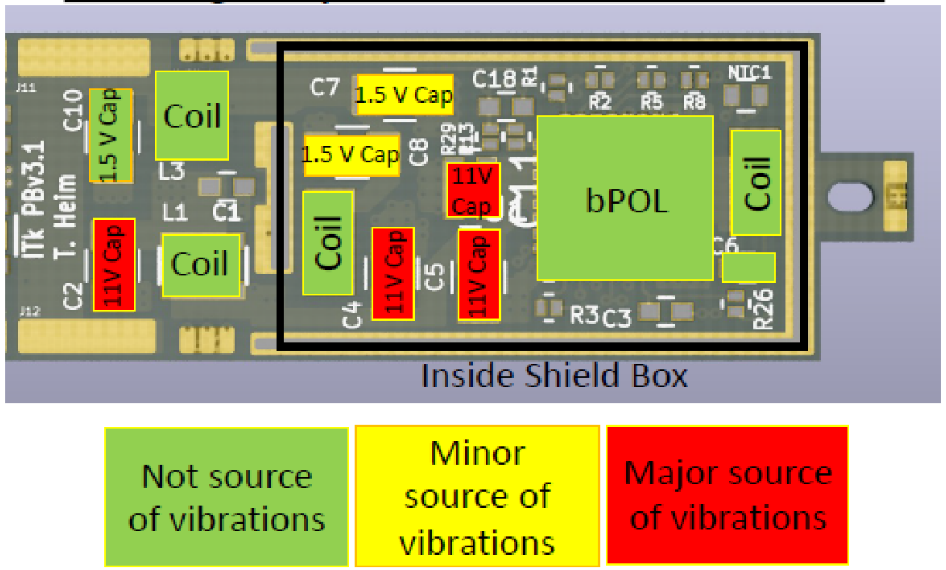
- Laser doppler Vibrometer used to measure frequency and amplitude of vibrations
  - Non-contact measurement
  - No mass loading
  - Laser spot 40 µm
  - Sensitive to MHz range

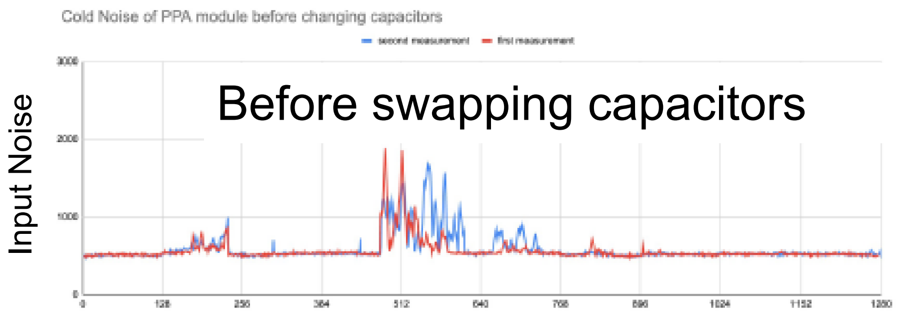
- Spot measurements of different components
- Identified vibrating capacitors at frequency of buck converter
- Unexpected capacitor vibrating

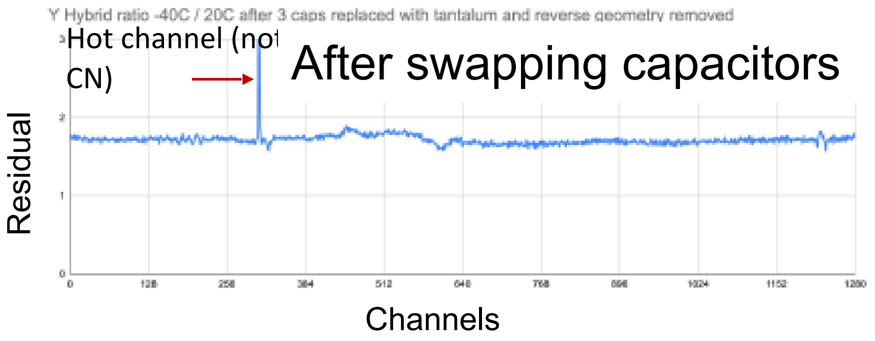
Identified Vibrating components

- 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**
- When all 4 capacitors were replaced or removed then the Cold Noise disappeared
- 4 11V capacitors are the primary **source of Cold Noise**

Vibrating Components on Barrel Power Board

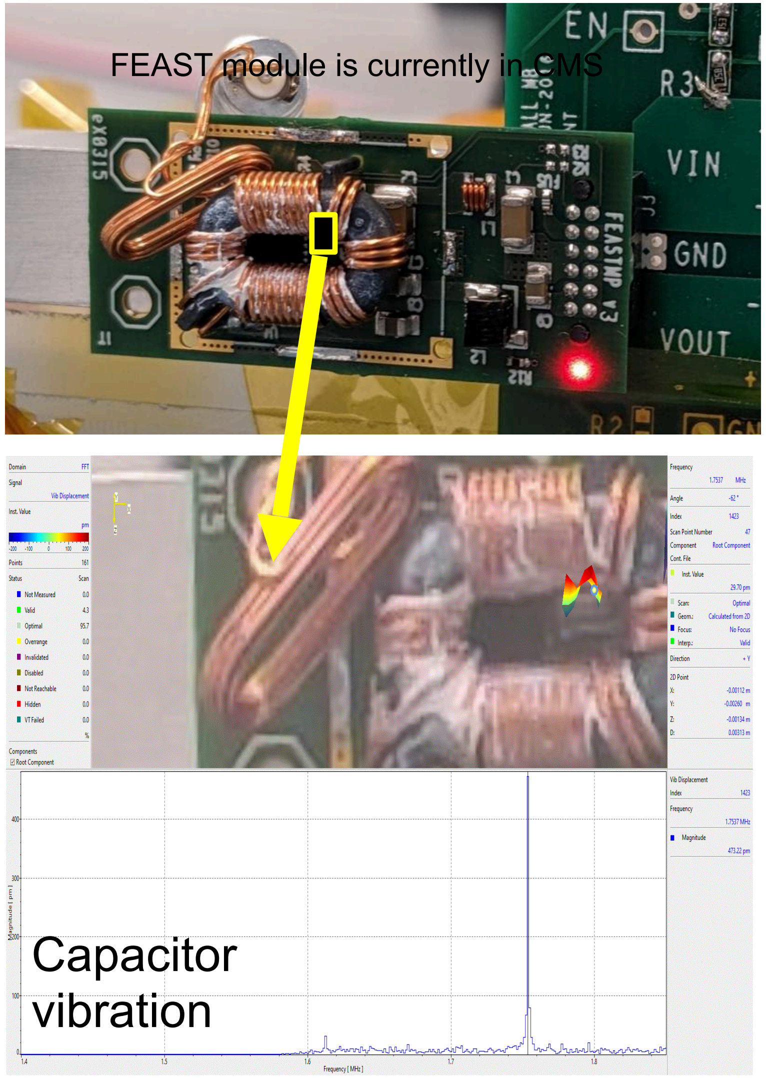






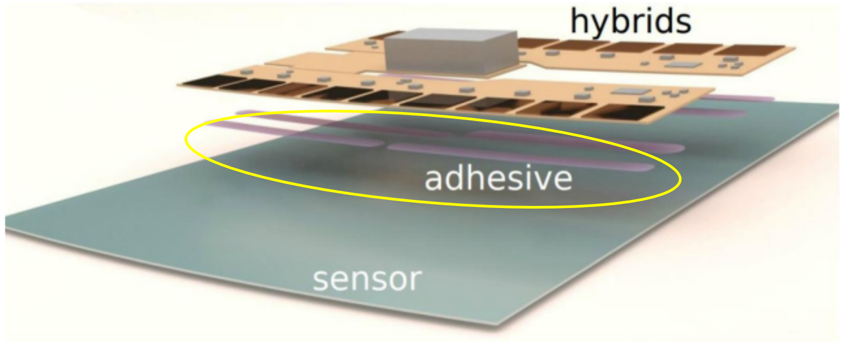
We Are Not Alone

- CERN’s bPOL (on ITk strip module) and FEAST DCDC power converters used in multiple experiments
- 0.5 nm vibrations seen on both versions
- FEAST has been running in CMS operationally for over a year
- These capacitor vibrations are the same as our module
- Source and scale of **vibrations not unique** to ATLAS ITk strip

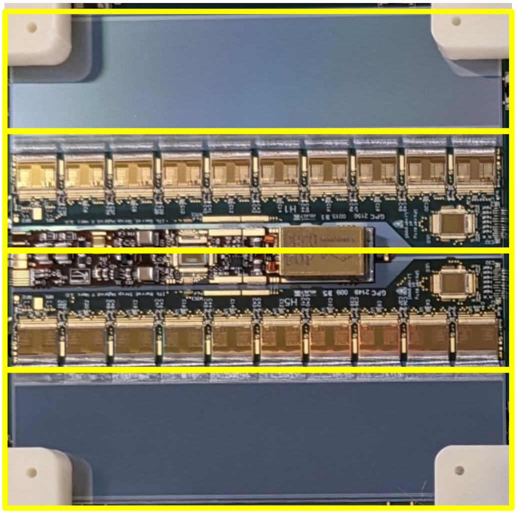


Glue Choice

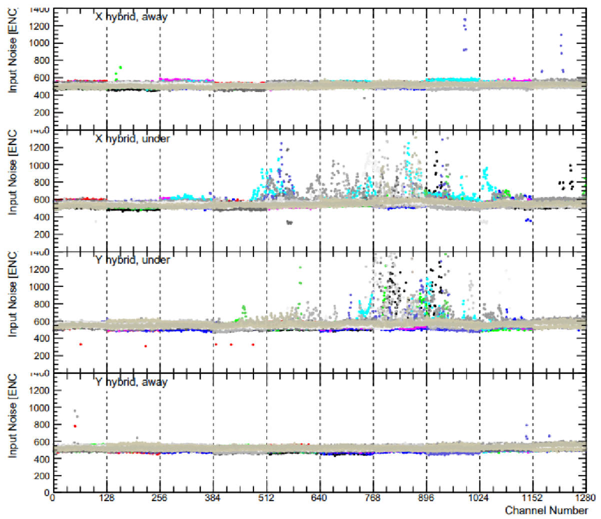
- Several years of testing dozens of glues to qualify for the senor surface
- 3 glues were acceptable for use before considering Cold Noise levels
- Loctite turned out to be the best with respect to Cold Noise
- Only 1/8 module types have limited CN with Loctite (short strip)
- First 2 years of production are non-short strip module types
- Production has begun using Loctite Eccobond F112



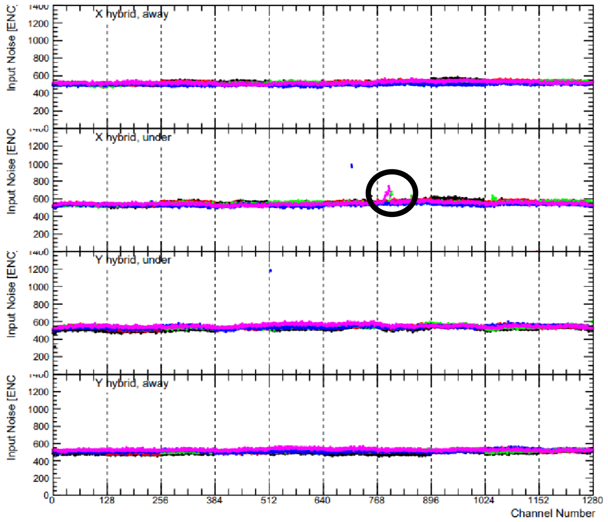
Glues used:



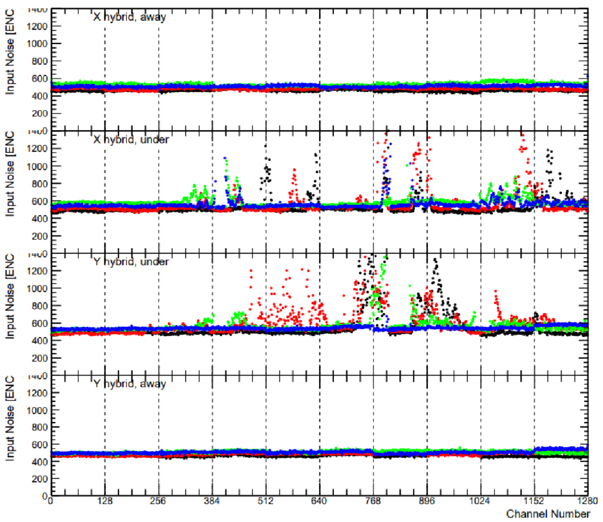
Polaris PF-7006



Loctite Eccobond F112



AA-BOND F112



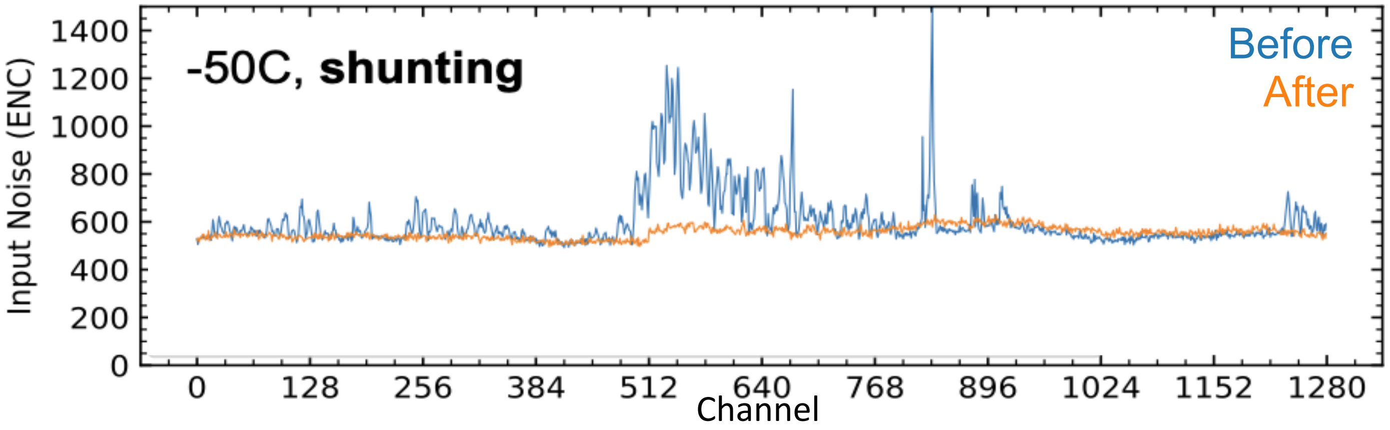
Mitigation Stategy

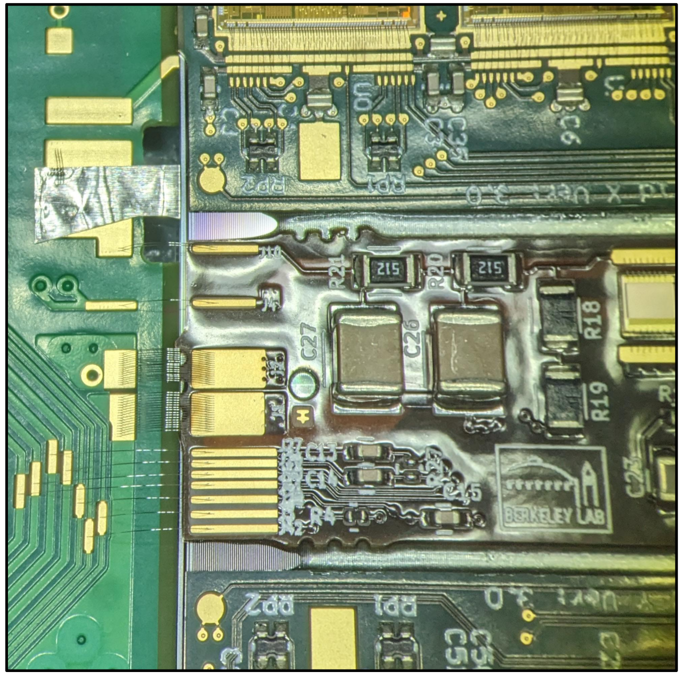
Procedure:
- Filled in gaps between hybrids and PB on existing module.
  - Originally built with worst glue (False Blue) → severe cold noise.
  - Filled gaps with more False Blue.

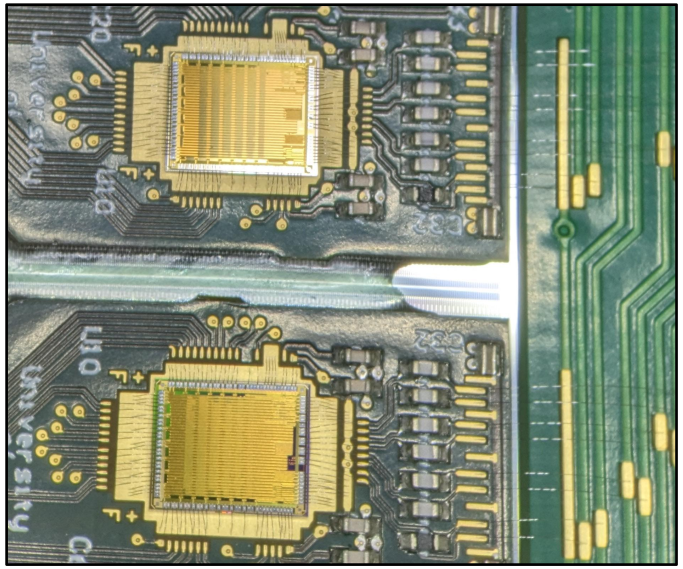
Results:
- Almost completely removed the cold noise!

- 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.







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