

Experience and results of the ATLAS ITK pre-production staves at Brookhaven National Laboratory

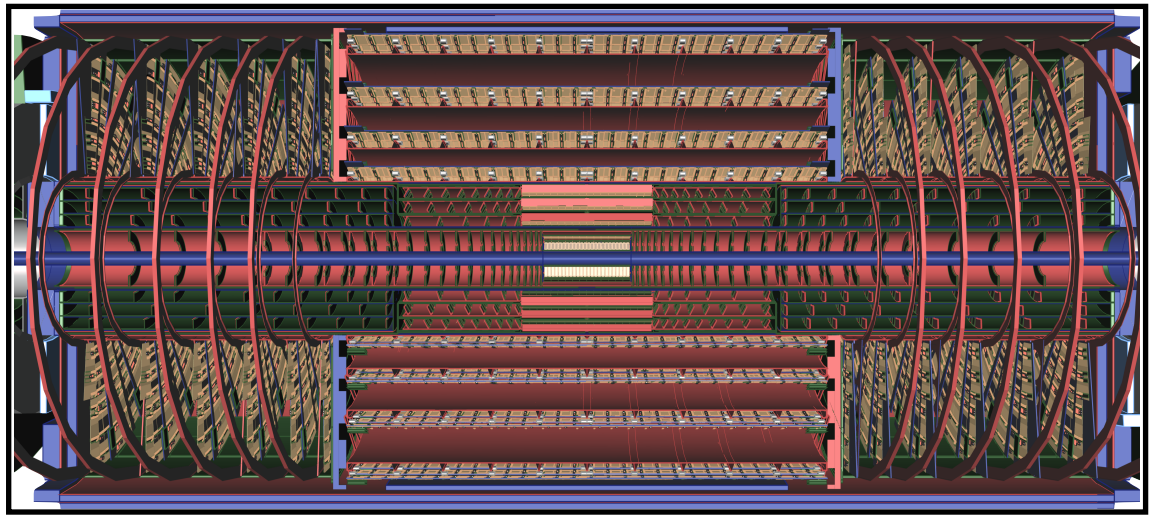
Francesca Capocasa for the ATLAS ITk Strip Collaboration

Brookhaven National Laboratory

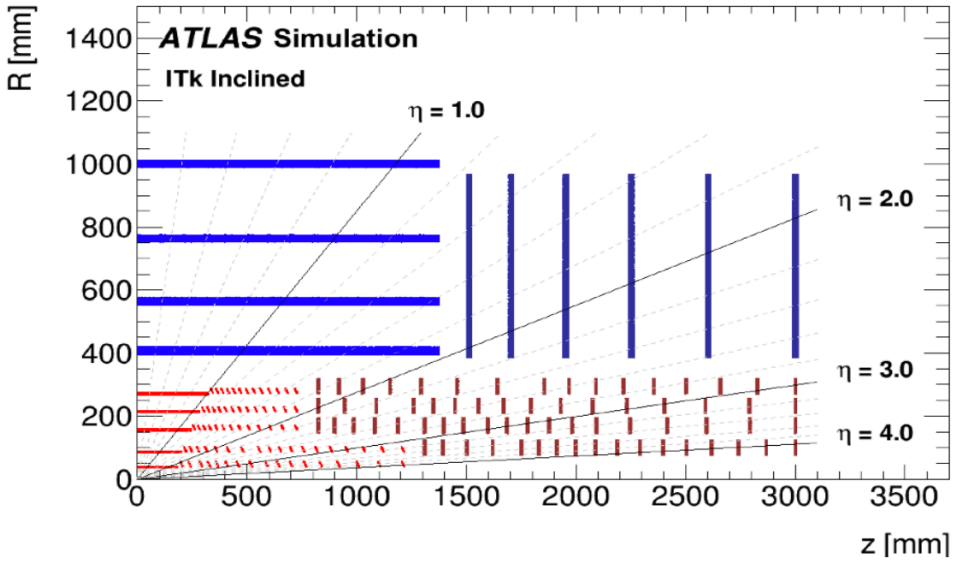
Brandeis

ATLAS ITk

ITk Layout



http://cdsweb.cern.ch/record/2257755/files/ATLAS-TDR-025.pdf



For the HL-LHC, an all-silicon Inner Tracker (ITk) will replace the current ATLAS inner detector

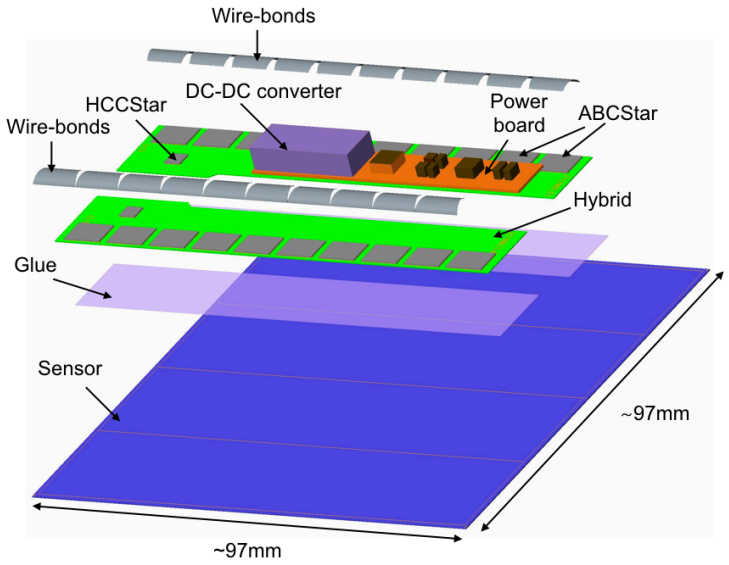
- ITK Pixel Detector
  - 5 barrel layers with inclined sensors in the forward region
  - End-Cap (EC) system containing individually located rings
- ITK Strip Detector
  - 4 barrel layers
  - 6 EC rings on both forward regions

Brookhaven National Laboratory and Rutherford Appleton Laboratory responsible for assembling and testing the ITK's Strip Barrel Detector building blocks, the staves

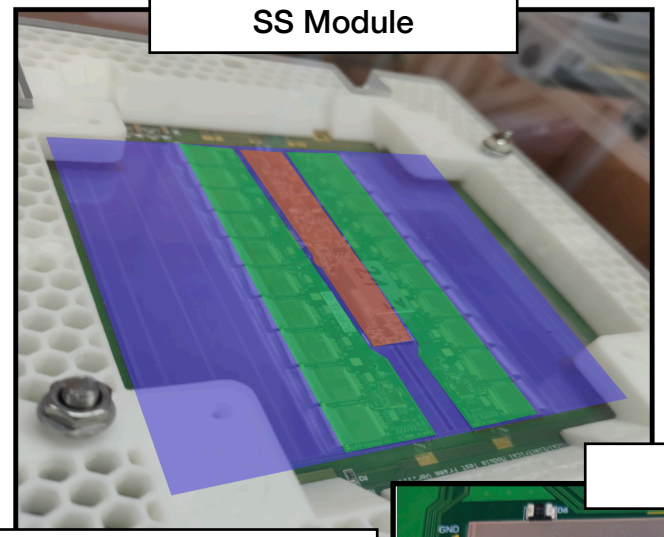
ITk Strip Modules

- The units of the staves are the silicon modules
  - Consists of one sensor and one or two low mass PCBs, called hybrids, and one power board
  - 2 module variant for ITk Barrel Detector having same architecture but different strip length

- Hybrids and power board are glued directly to the silicon sensor

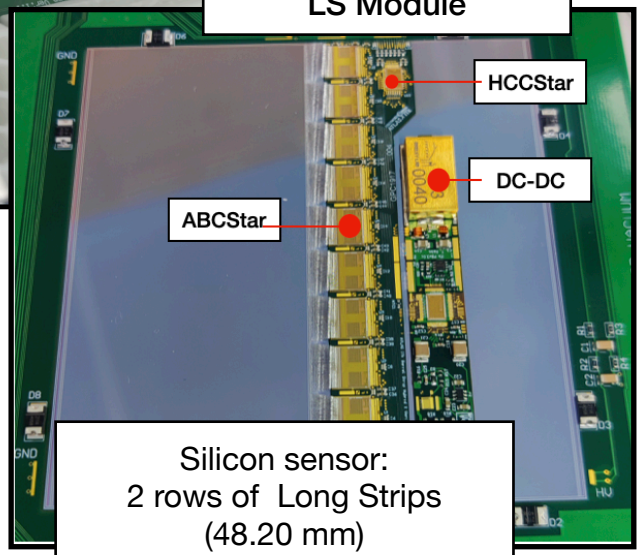


SS Module



Silicon sensor: 4 rows of Short Strips
(24.10 mm) for higher occupancy regions

LS Module



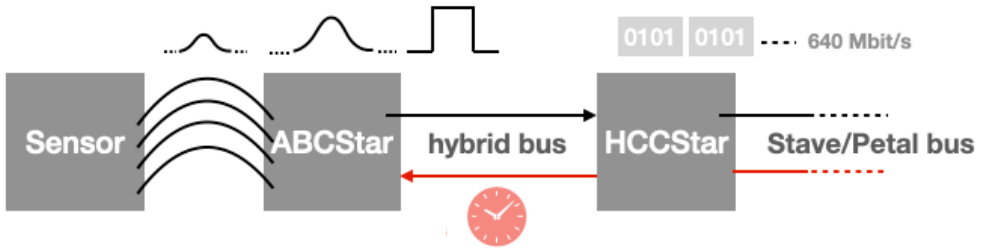
Silicon sensor:
2 rows of Long Strips
(48.20 mm)

ITk Strip Modules

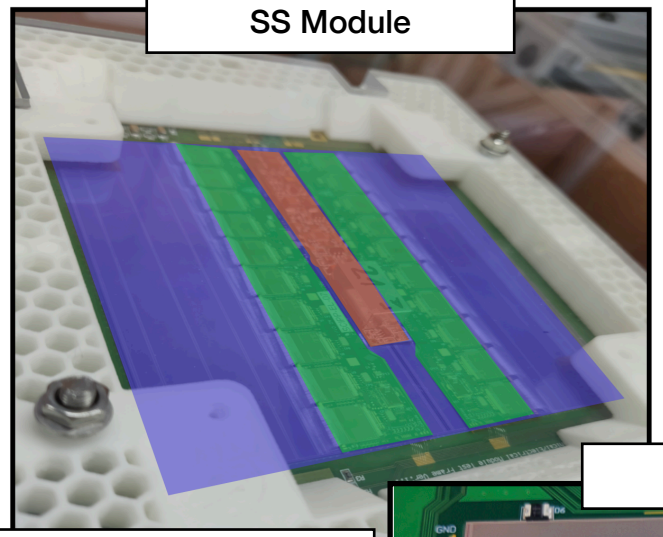
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- The hybrid hosts the readout ASICs:
  - 10 front-end ABCStar chips and a control chip HCCStar
  - Each ABCStar has a binary architecture, 256 channels of trimmable preamplifier, discriminator and control logic
  - Each ABCStar has a point-to-point 160 Mbit/s data path to the HCCStar, enabling fast readout

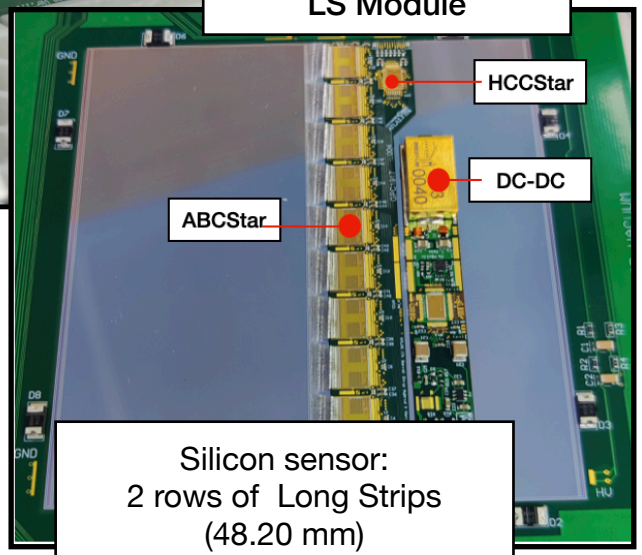


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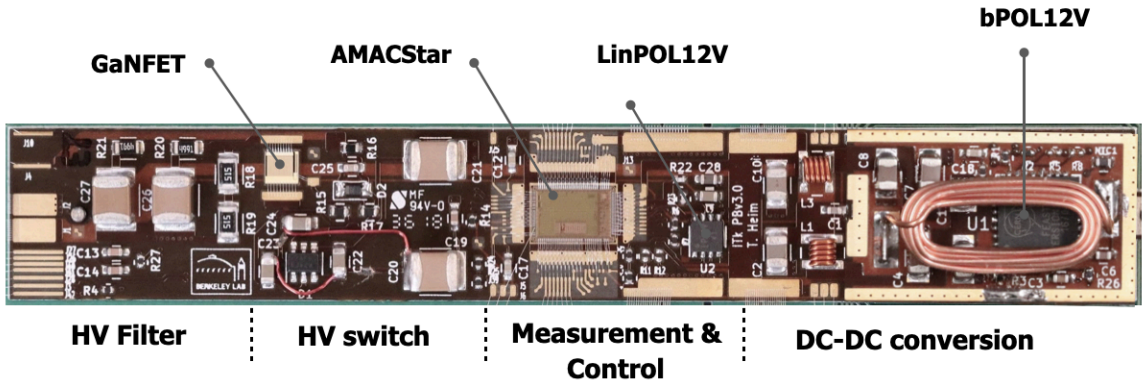
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ITk Strip Modules

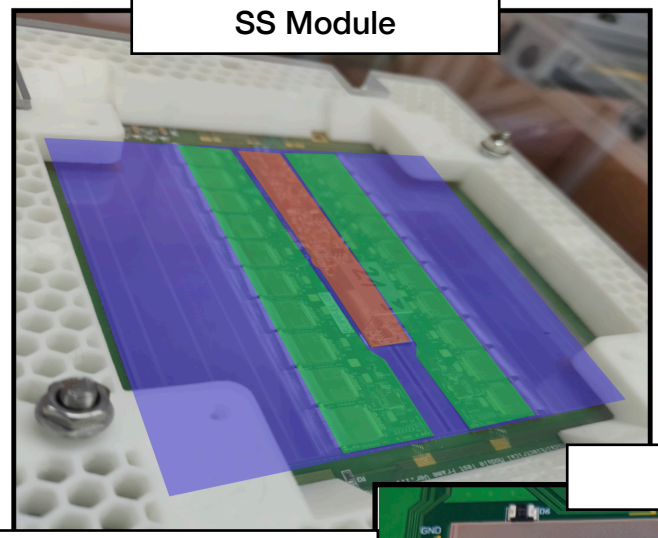
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- Hybrids and power board are glued directly to the silicon sensor

- The Power Board (PB) provides power, control, monitoring and autonomous interlocking
  - Hosts a DC-DC buck converter to step down the LV to 1.5 V used by front-end ASICs
  - Hosts AMAC Chip for Control and Monitor functions (AMACStar):
    - Monitor the sensor HV bias return current
    - Monitor NTCs temperatures on hybrids and powerboard

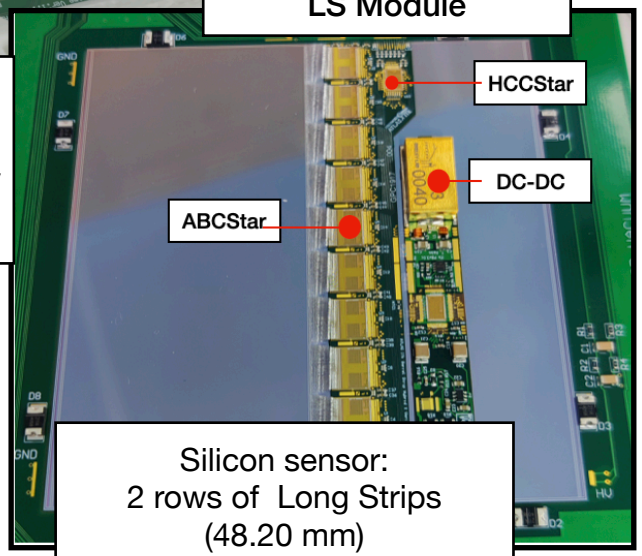


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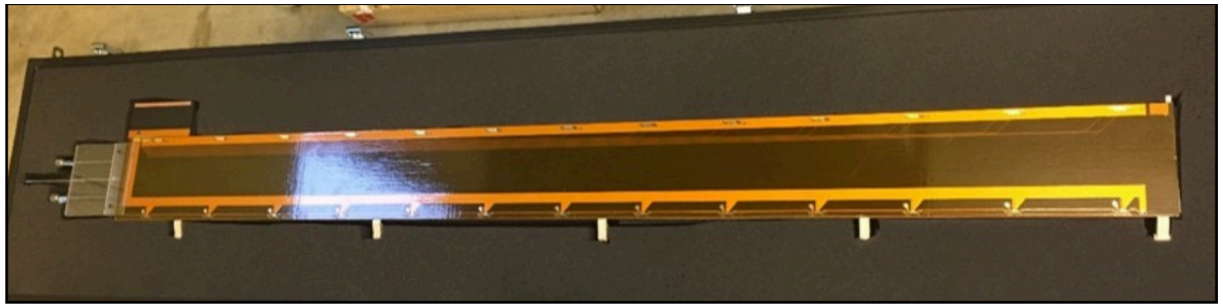
LS Module

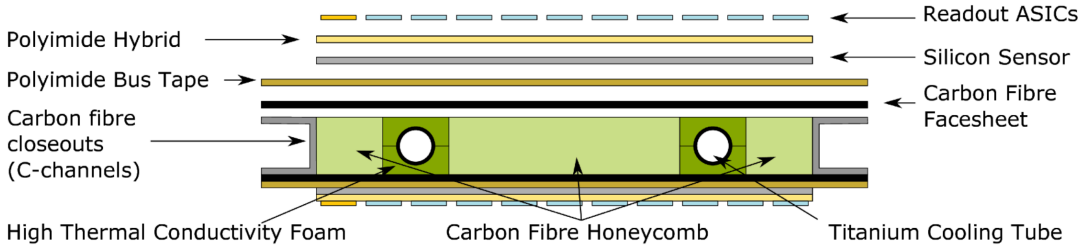


Silicon sensor:
2 rows of Long Strips
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ITk Stave

Staves are the building block of the ITk Strip Barrel detector, which provide mechanical support for the modules and host the common electrical, optical and cooling services



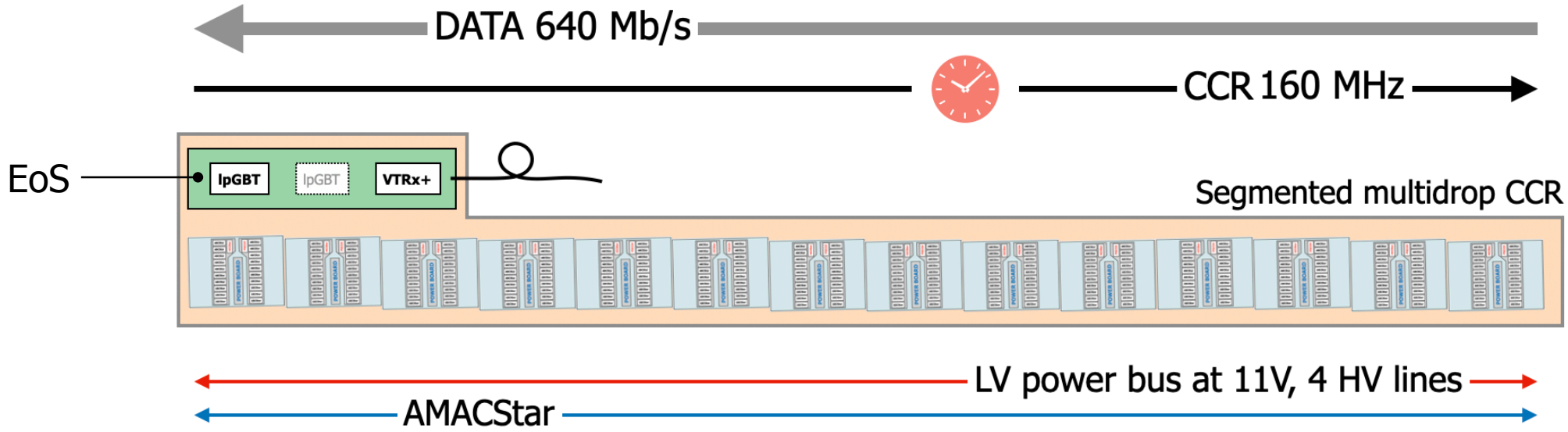


- Stave has a sandwich geometry
  - 1.4 m long support structure (stave core)
    - Provides **mechanical rigidity and support** by using high stiffness and high thermal conductivity carbon fiber
    - Embedded **cooling** with evaporative CO2
    - Large area copper/kapton bus tape mounted on both sides of support structure to route electrical services to and from the stave
  - 14 silicon modules directly glued on both sides of stave core with a stereo angle of 26 Mrad

Stave Schematics

Electrical power (LV, HV), **CCR** (Clock, Control, Reject), **AMACStar signals** and **physics data** are carried by the bus tape to and from the End of Substructure (**EoS**) board

- The **EoS** board hosts a radiation-hard optical link (**VTRx+**) and a data transceiver/serializer (**lpGBT**)

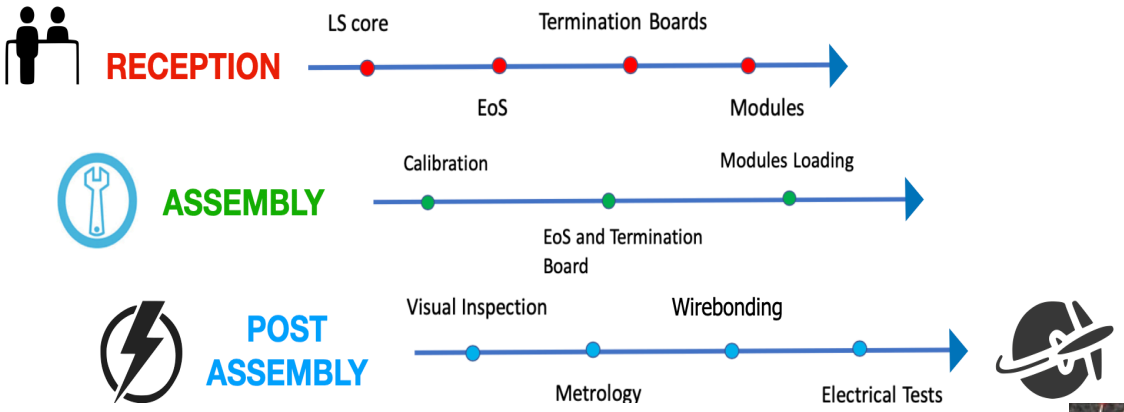


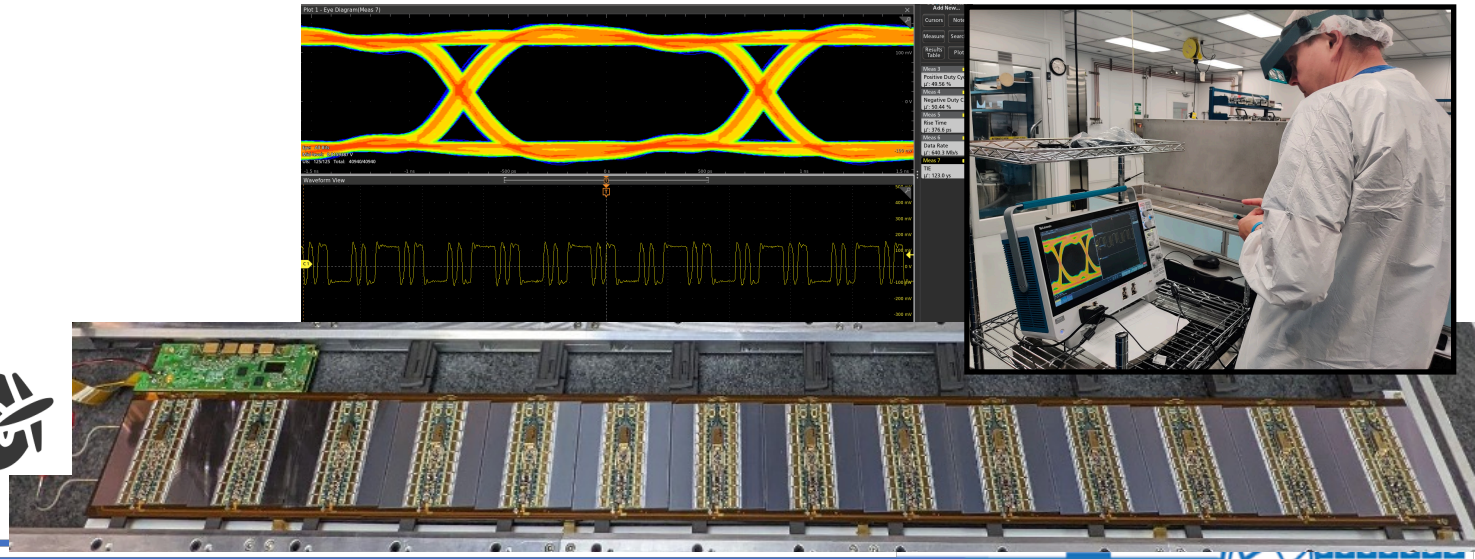
ITk Pre-production

Currently in Pre-Production (PP) phase

- Exercise to prove production readiness
- Aims to demonstrate sites ability to perform assembly procedure, electrical testing including shipment, receipt and storage of components

- Assembled and Tested 2 SS staves at BNL during PP period with final ASICs
  - Extensive campaign to assemble and characterize first PP stave to meet ASICs Production Readiness Review goals



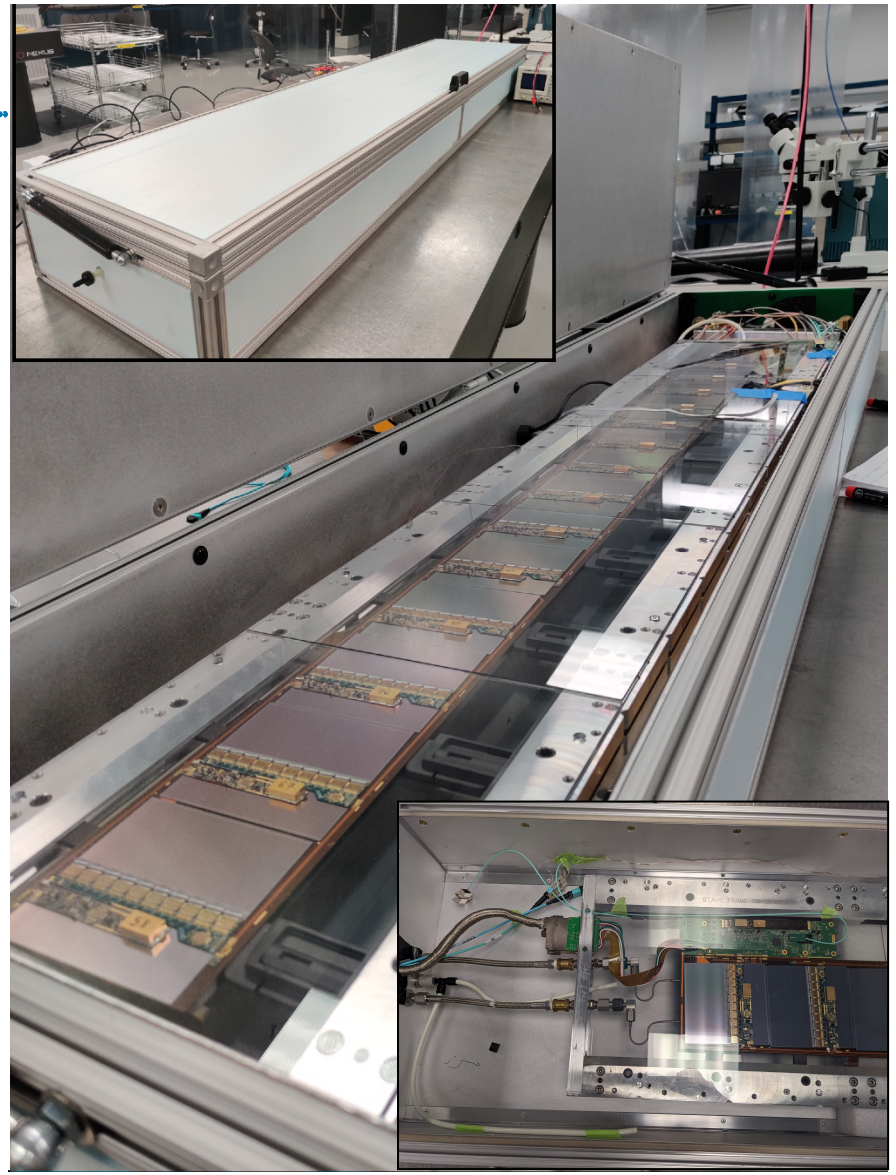


BNL Staves Testing Setup

- Stave has to be proven to work reliably at the expected detector operating temperature (targeting -35°C)
  - Detector will run cold to reduce sensor current due to radiation damage
- To facilitate thermal cycling and electrical test, an instrumented box is necessary
- Chiller (+ high pressure booster pump), dry air, humidity and temperature sensors, etc.
  - ~15°C difference between chiller output and stave input

$T_{chiller}[°C]$	$T_{inlet}[°C]$	$T_{outlet}[°C]$	Pressure[PSI]
35	39.0	40.9	140
30	34.4	36.8	133
20	25.2	28.4	123
10	15.9	20	112
0	7.0	11.0	105
-10	-1.7	4.1	102
-20	-10.5	-4.0	101
-30	-19.4	-12.1	100
-40	-28.5	-20.3	100
-50	-28.7	-20.8	100
-55	-37.7	-28.9	102
-60	-42.4	-33.1	103

- For stave QC we are targeting T stave = average (T_{inlet}, T_{outlet}) = -35 C

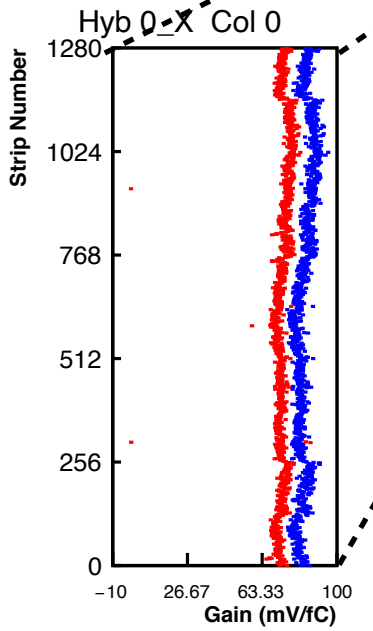


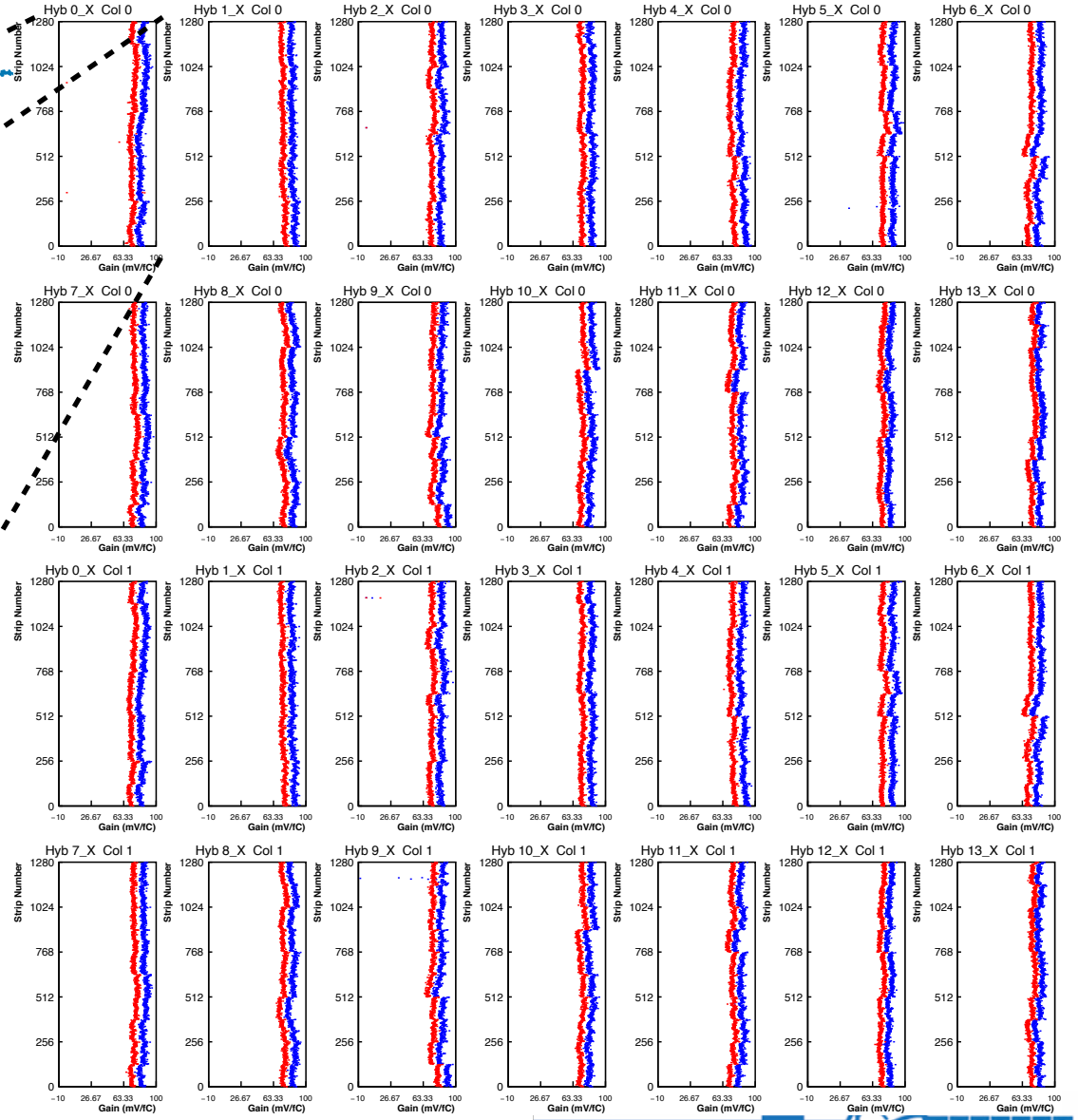
Results Pre-production stave

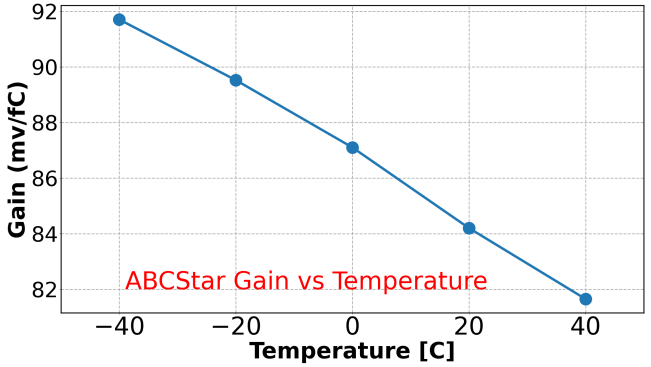
T_{stave} = 24.9 C, -37 C

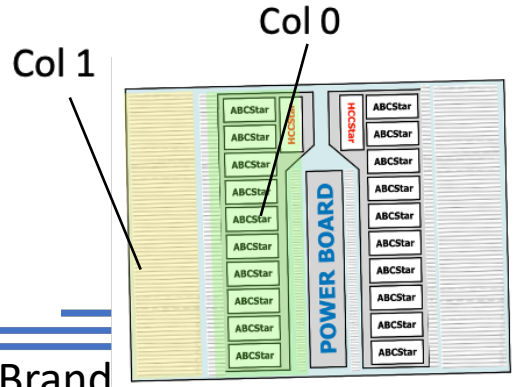
V_{bias} = - 400 V

- First 28 SS modules PP stave assembled in July 2022
- Gain response for the 14 SS modules on the one side of the first pre-production stave
- Gain analyzed independently for the 2 rows of strips of LS modules
- Confirmed ABCStar gain dependencies upon temperature







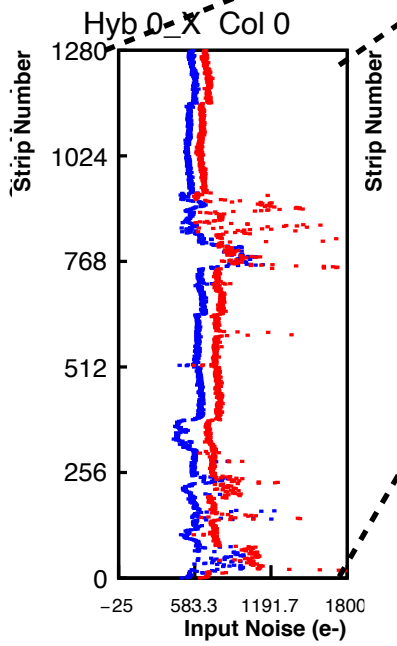


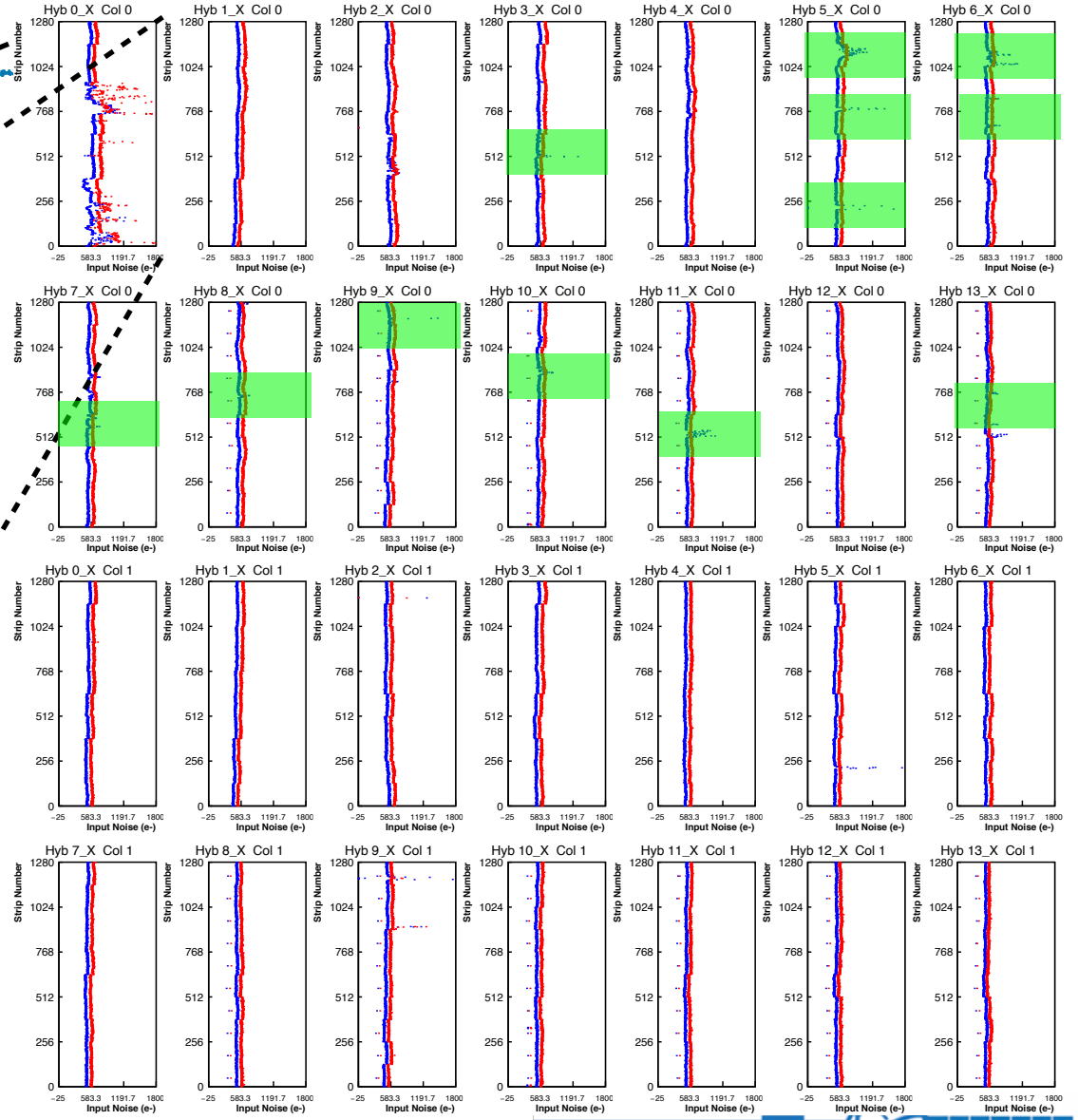
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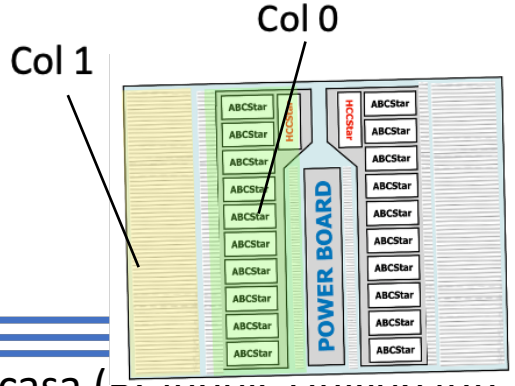
T_{stave} = 24.9 C, -37 C

V_{bias} = - 400 V

- Input Noise response for the 14 SS modules on one side of the first pre-production stave
- Noise profile good except for Cold Noise issue and high current module
- Module #0 has high current and has developed noisy channels over time
- Noise peaks at cold temperature (Cold Noise), already observed at module QC stage





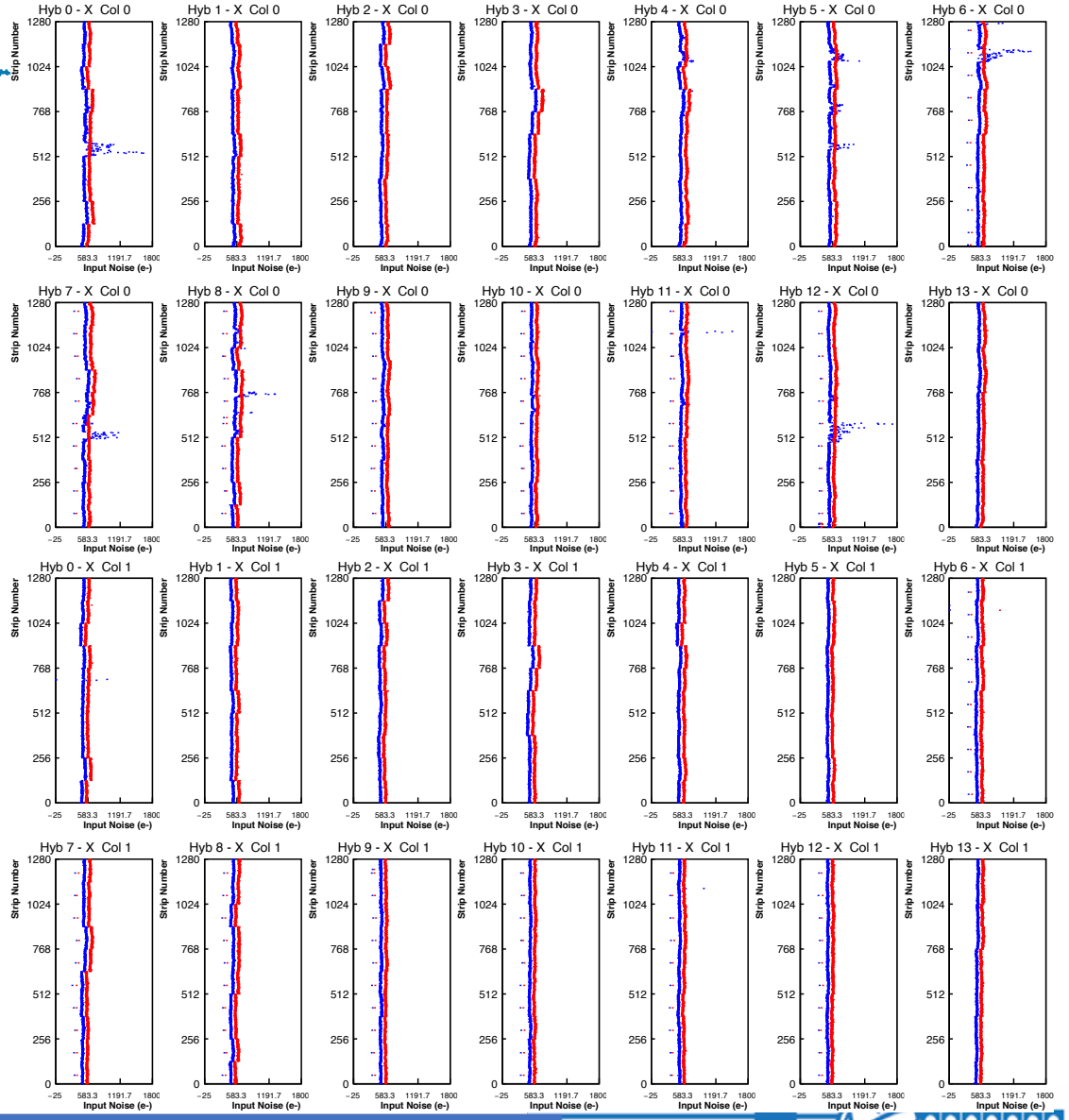


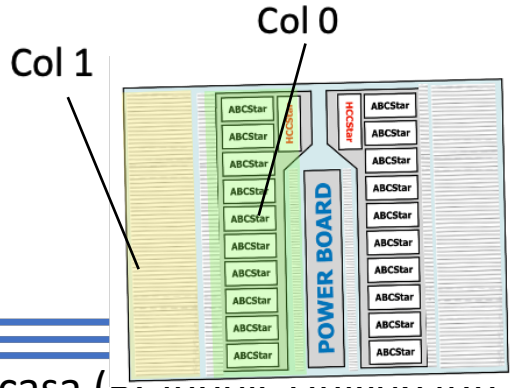
Results Pre-production stave

T_{stave} = 23.9 C, -35 C

V_{bias} = - 400 V

- Second 28 SS modules PP stave assembled in October 2022
- Input Noise response for the 14 SS modules on one side of the second pre-production stave
- Good overall stave performance at room and cold temperatures except for Cold Noise issue

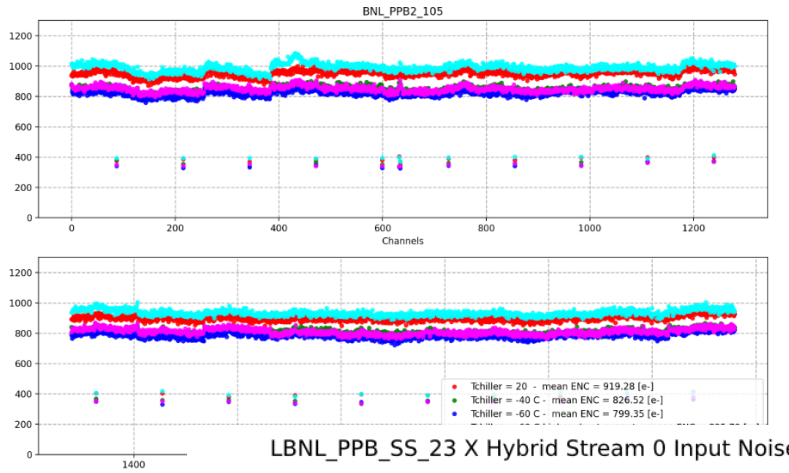




Results Pre-production stave

Cold Noise represents the main challenge of the ITk pre-production

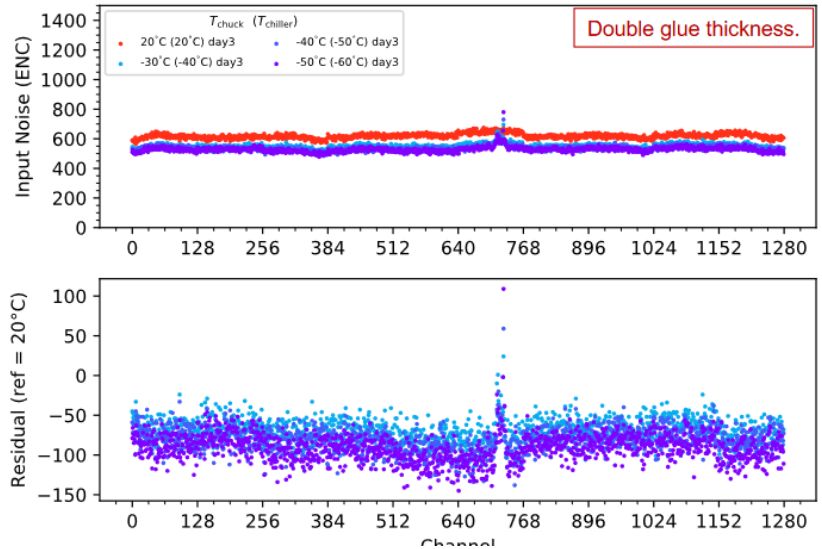
- **Noise peaks** first observed during module QC:
  - Appear below 0 C - Cold Noise
  - Doesn't affect the whole module but only the strip column running "under" PB and hybrid
  - **Reversible**
    - Only present at cold temperatures
  - It's worse for SS modules - appears at higher temperature



LBNL_PPB_SS_23 X Hybrid Stream 0 Input Noise at 1.50 fC

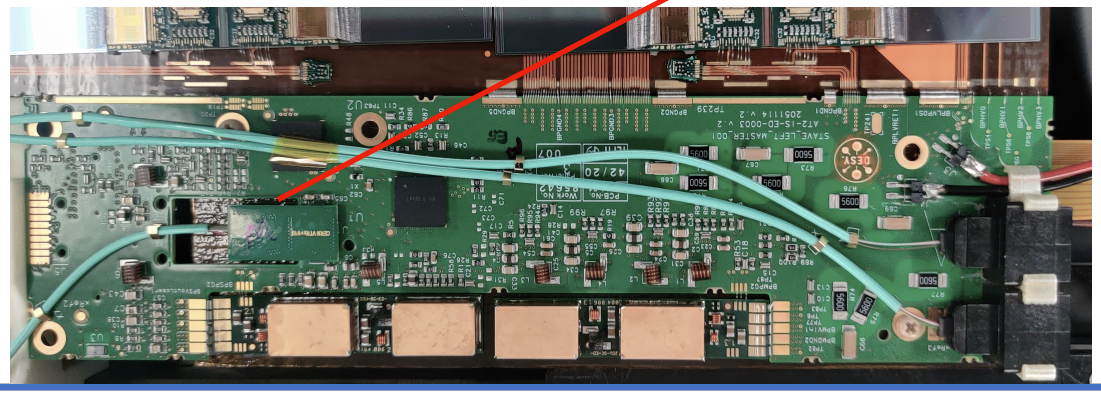
ITk Collaboration has established a Cold Noise Task force to investigate this issue!

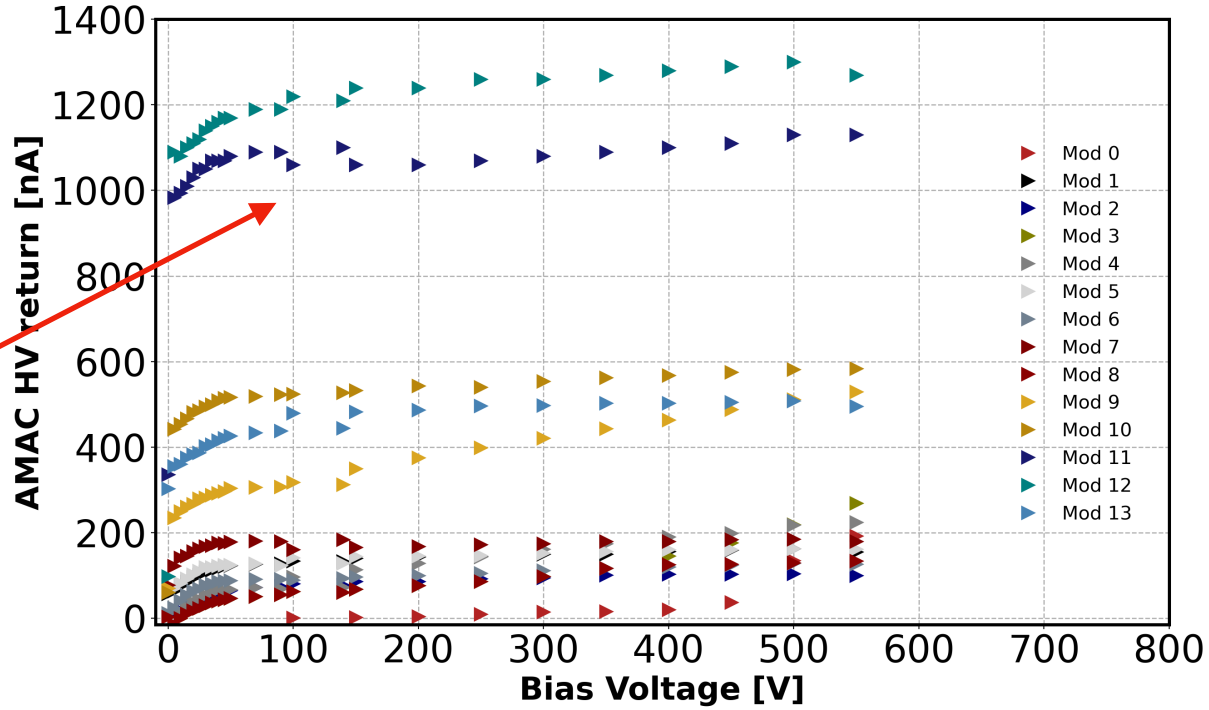
- Switching action of the DC-DC seems to be the source
- New studies with different glues (TrueBlue, Sylgard, SE4445 while baseline is Polaris)
  - No cold noise observed
- Mitigation: thicker glue between hybrids+PB and sensors
  - LS with 300um glue - 120um thicker than nominal - no cold noise
  - SS with 240um glue: less cold noise



AMAC - HV return current measurements

- AMAC provides a mechanism for measuring the HV sensor bias return line
  - Monitoring the leakage current in the silicon sensors become significant during operation, when higher current is expected due to radiation damage
- Current measurement on stave modules are close to expectations
  - Chip-to-chip offset can be corrected by measuring at Vbias =0
  - Modules 11 and 12 are most likely affected by the light from VTRx+

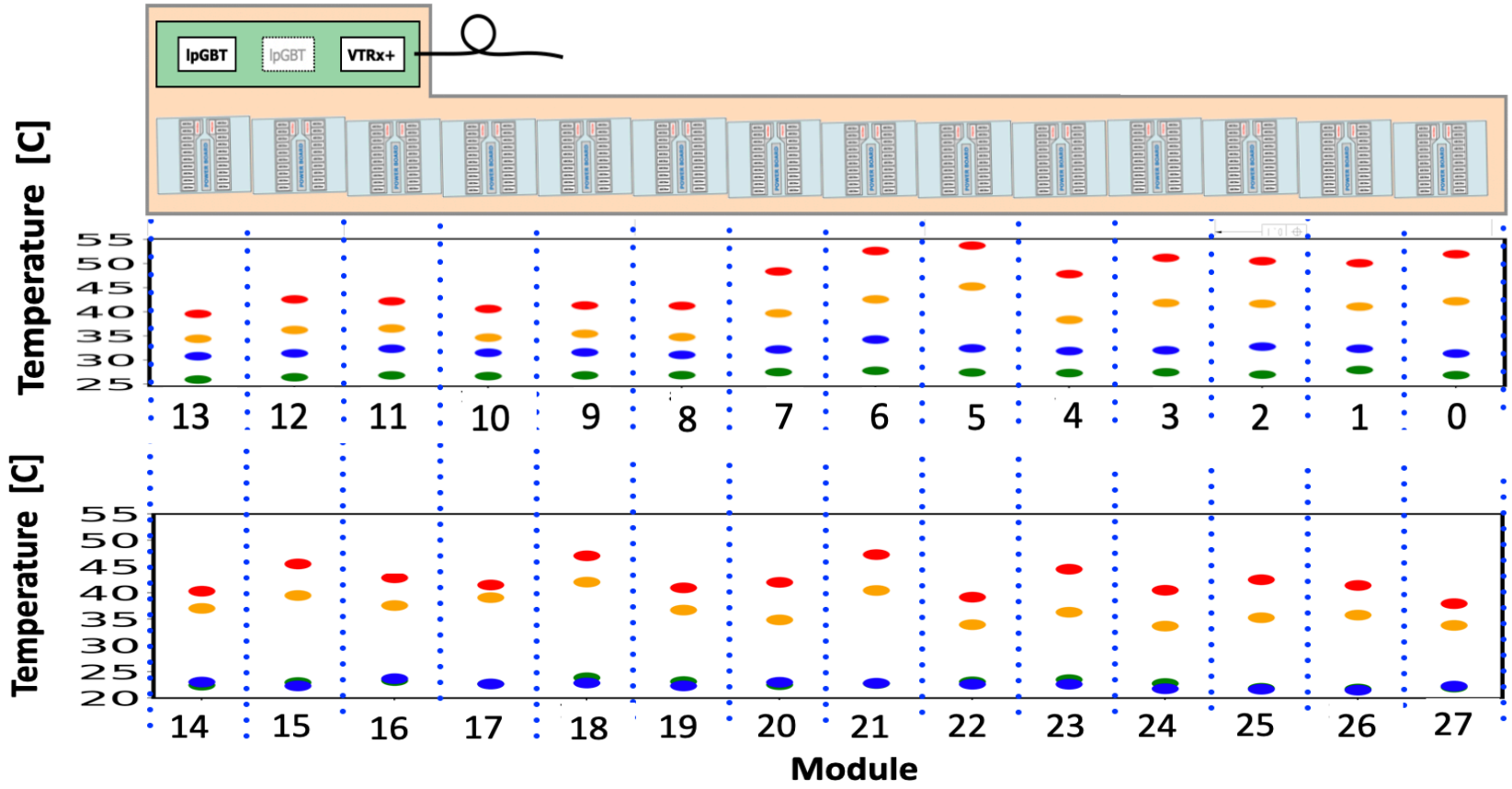


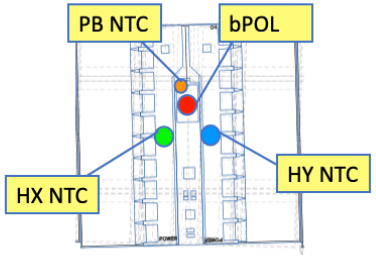


1 ADC Count =~4 nA

AMAC - Temperature monitoring

- AMAC allows on- stave temperature monitoring using :
  - the 10K NTCs on hybrids and power boards - HX, HY and PB NTCs
  - PTAT channel to estimate bPol temperature
- On-stave temperatures show no obvious trend at Room Temperature
  - Affected by module-module variation





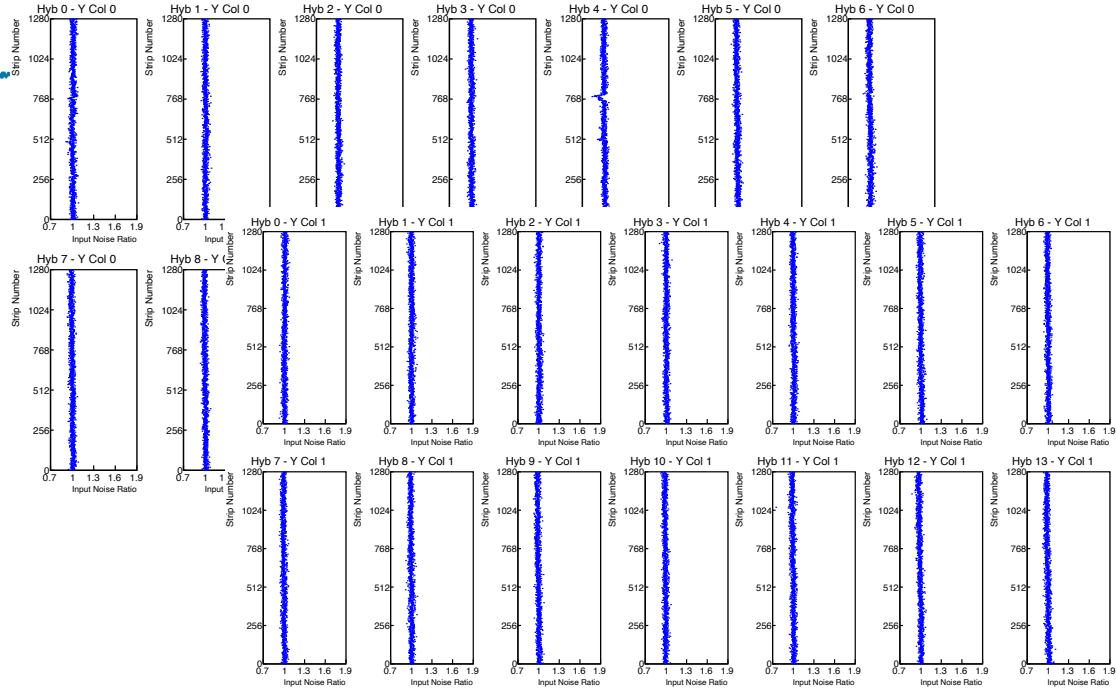
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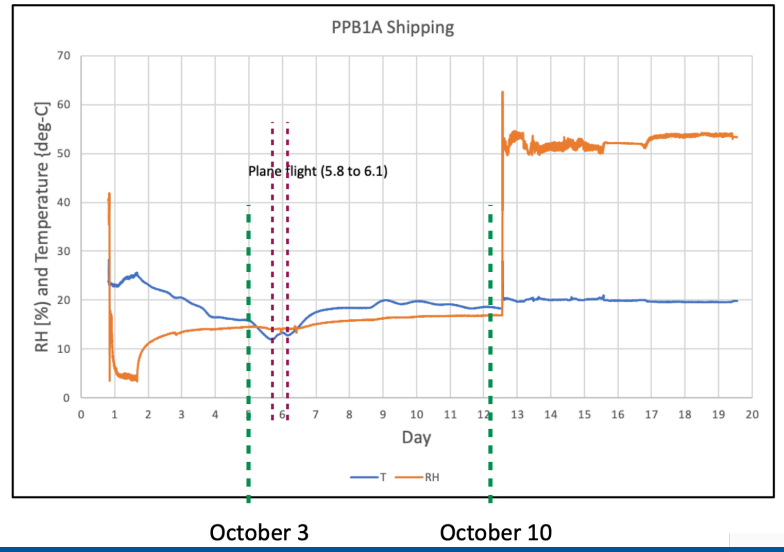
- BNL staves were shipped to CERN where they will be used for System Test (ST)
  - ST validates production chain with final parts and cooling before production starts

BNL staves tested at CERN after shipment :

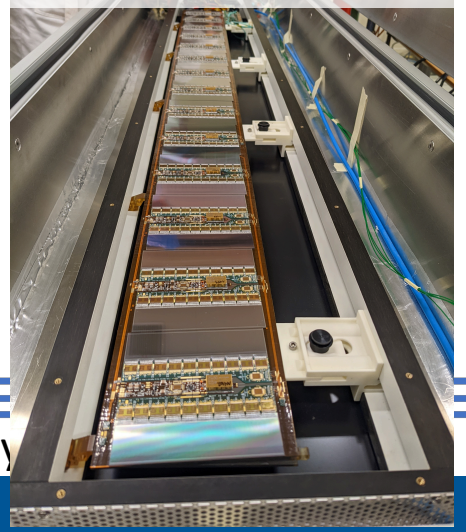
- targeting a relative humidity below 20% seems feasible

- confirmed gain and noise performances

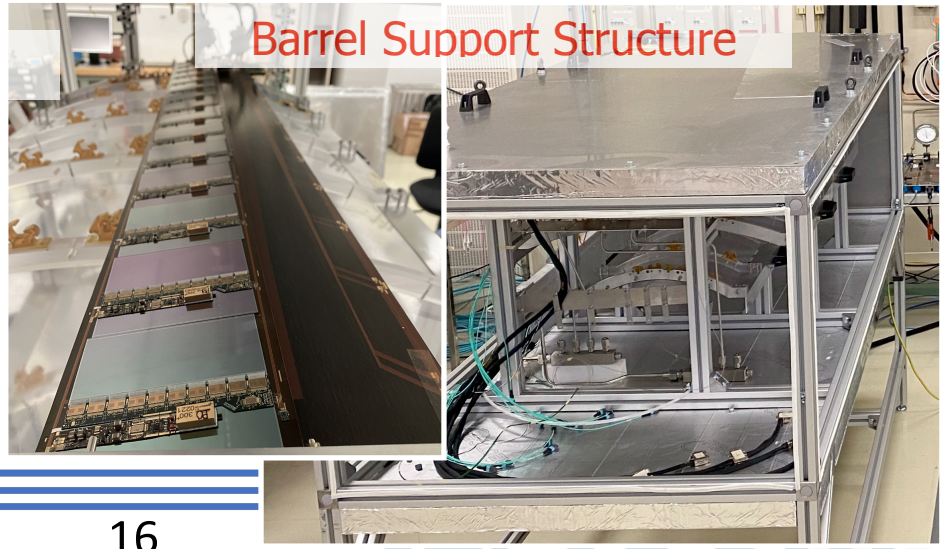




Stave Reception Box

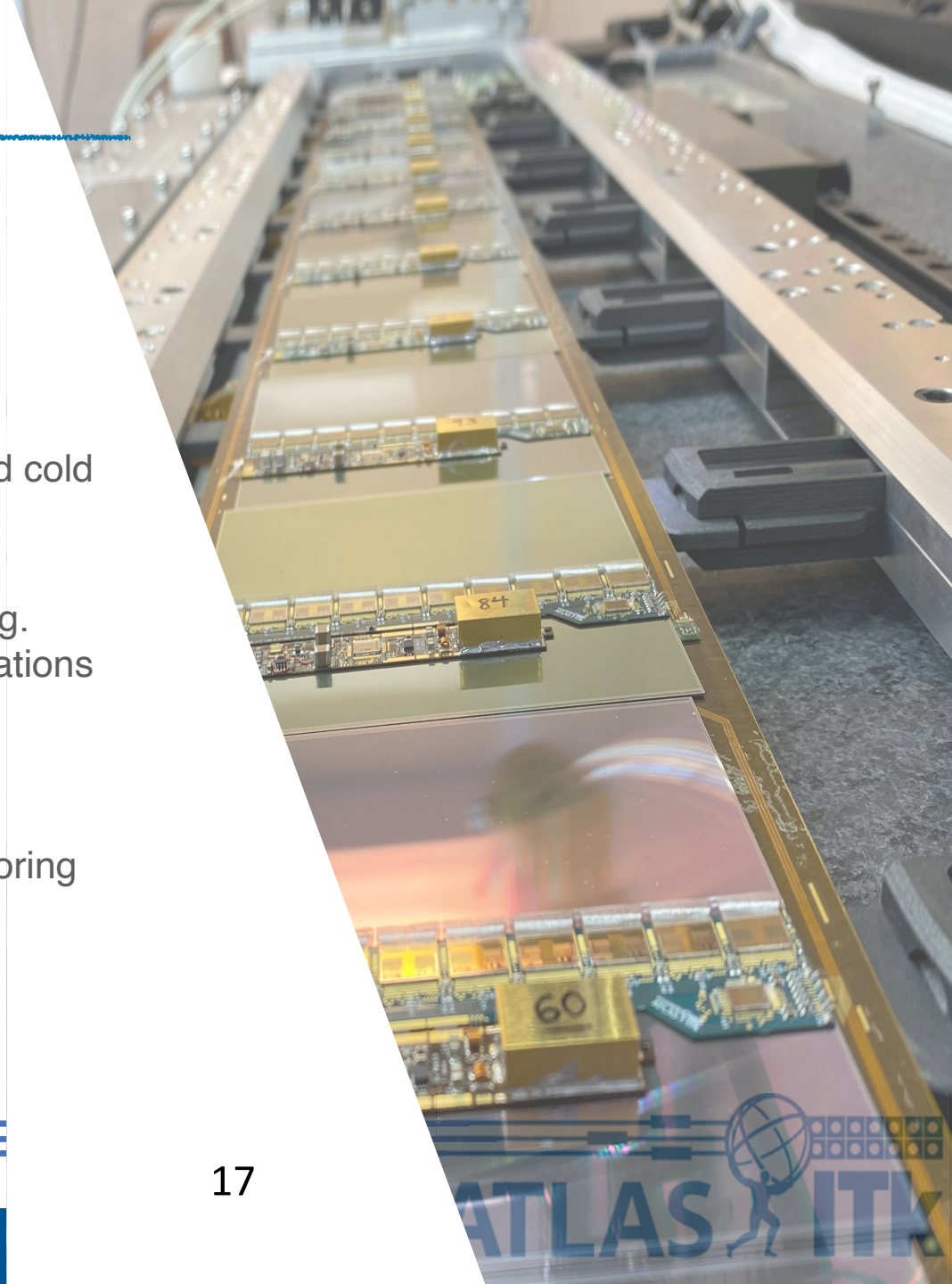


Barrel Support Structure



Summary

- The ITk project deep into pre-production phase with assembly and testing of first pre-production staves at Brookhaven National Laboratory
- Overall good electrical performance of staves at room and cold temperature.
- Unexpected Cold Noise effect found during module testing. Experts are working to understand the source while mitigations are under study
- Good performance of AMACStar Chip for on-stave monitoring of temperature and current measurements





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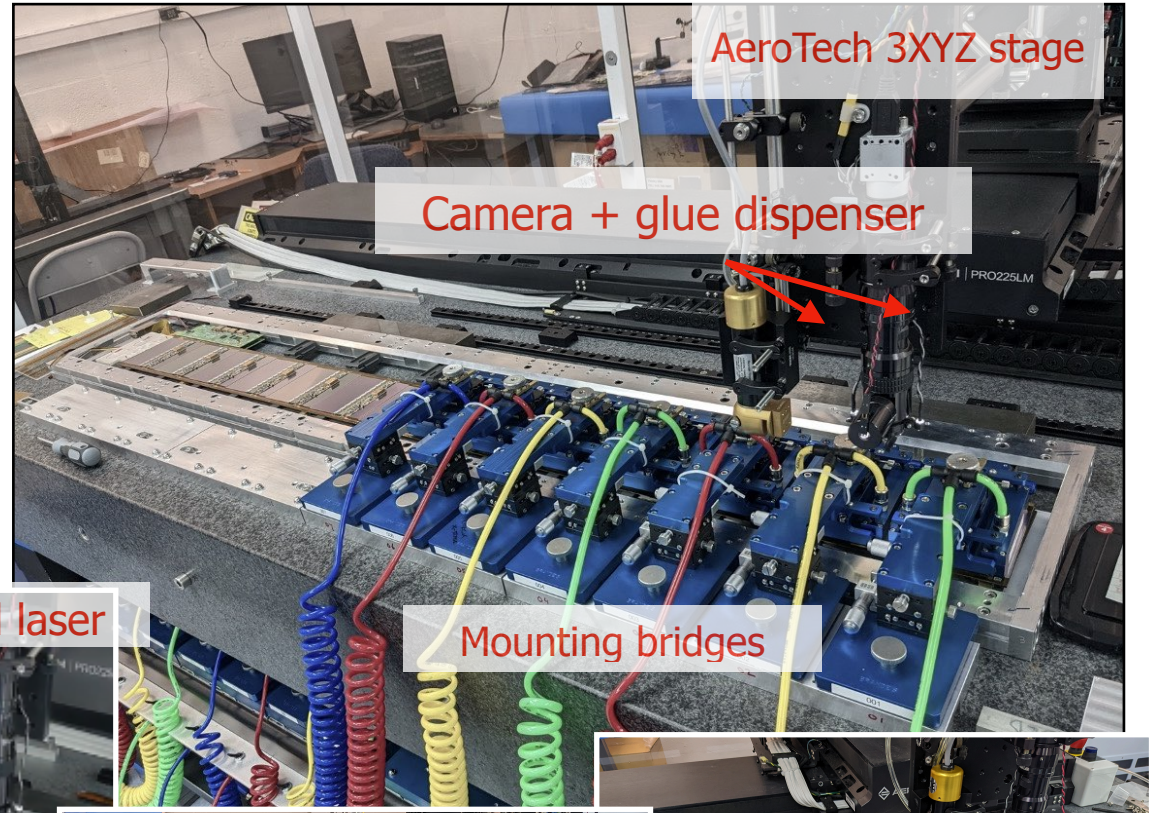
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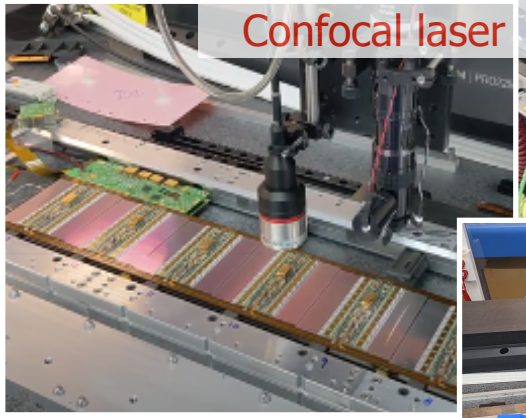
Brookhaven National Laboratory

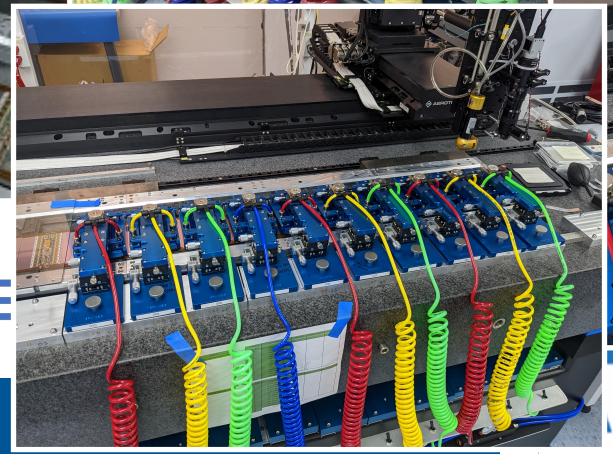
ATLAS ITk

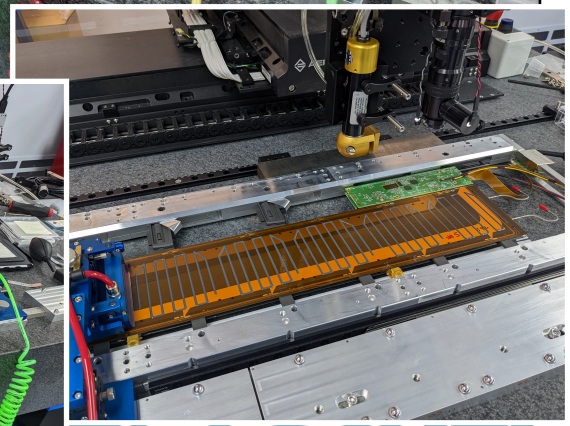
BNL Pre-production staves

- Assembly Station with XYZ stage mounted on Granite Table holds a 10-megapixel camera and a glue dispenser
- Fiducial marks on sensors and reference points on stave core are used to reconstruct modules positions
- Precision mounting bridges allow to locate modules with ~50 um accuracy
- Thermal conductive and radiation-hard glue is used to hold the module in place



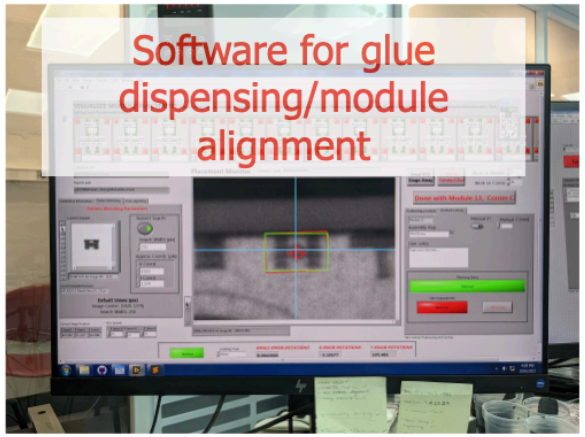


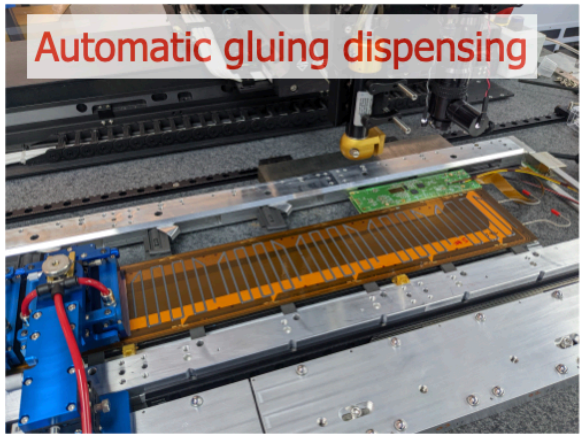


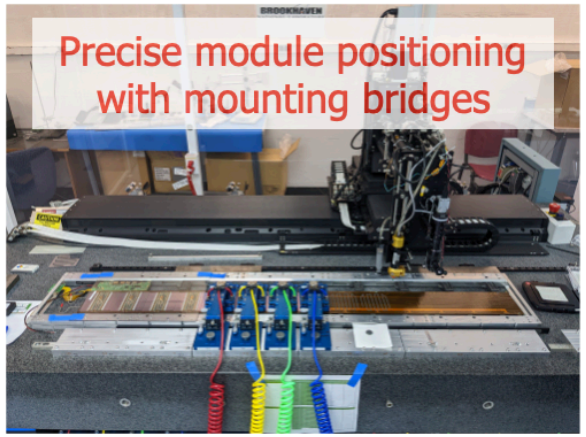


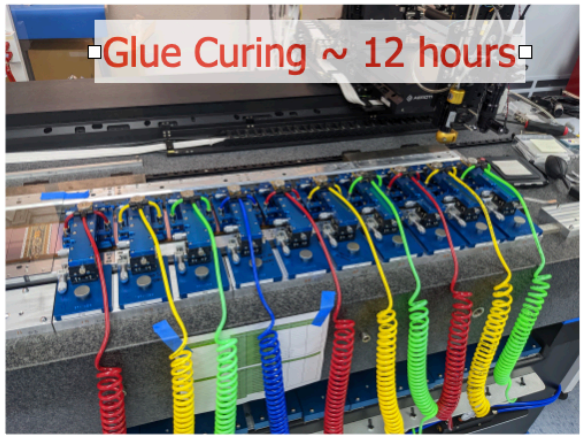
- Ramping up to production rate with assembling 1 side of the stave/ day
- Optimized glue pattern for both LS and SS modules
- Module placement accuracy better than 50 um
- All stave QC (metrology, final survey) in place, not fully finalized

BNL Pre-production staves

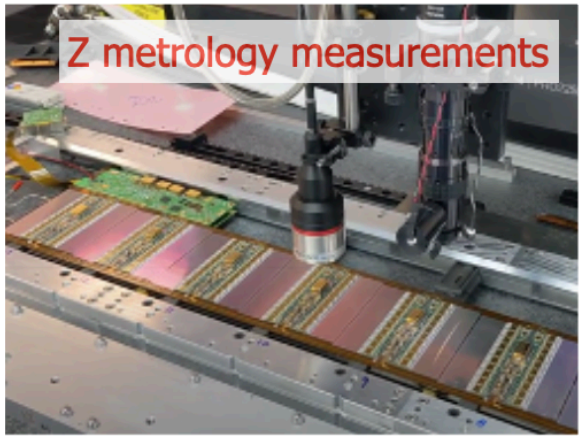












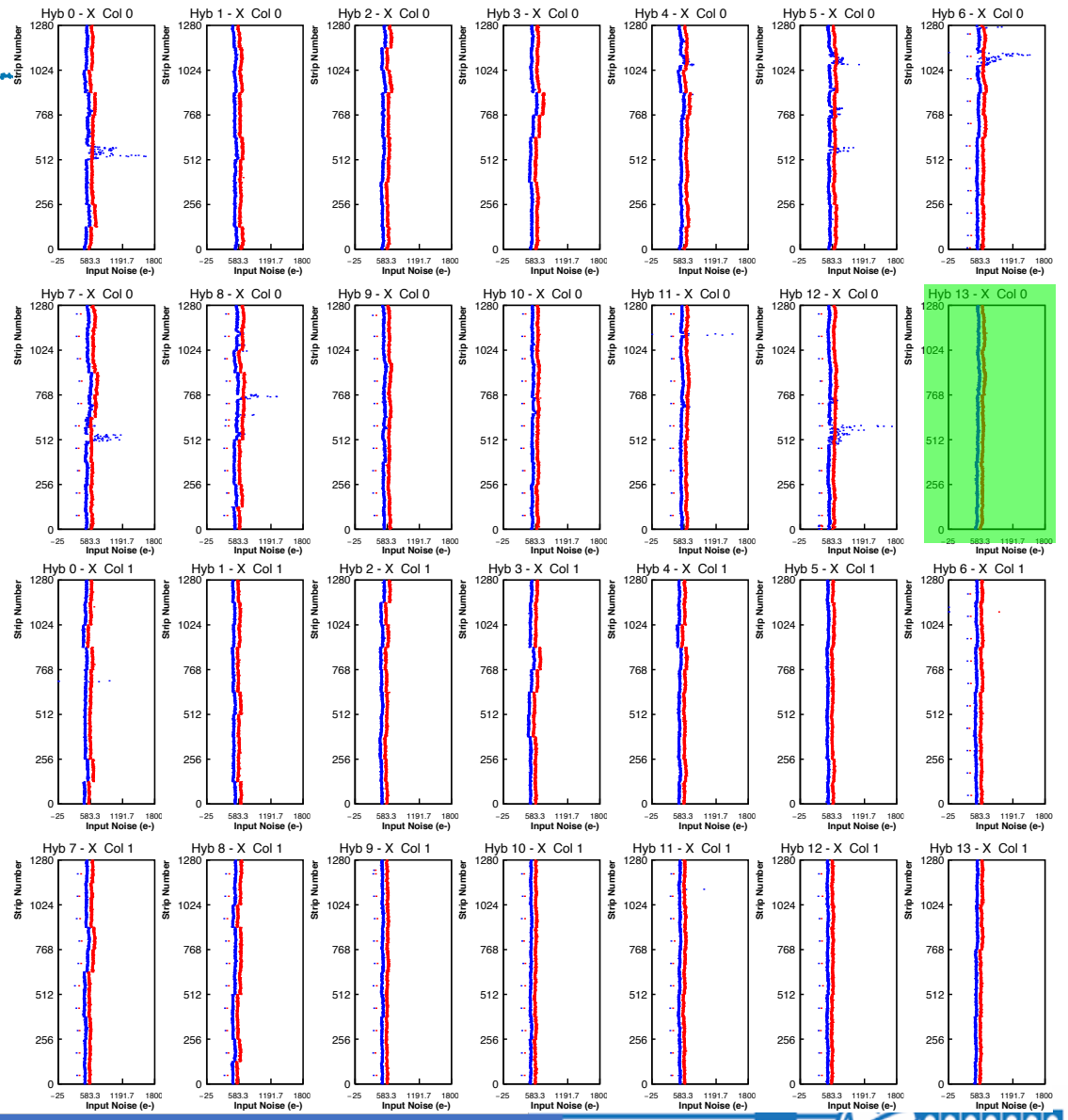
Results Pre-production stave

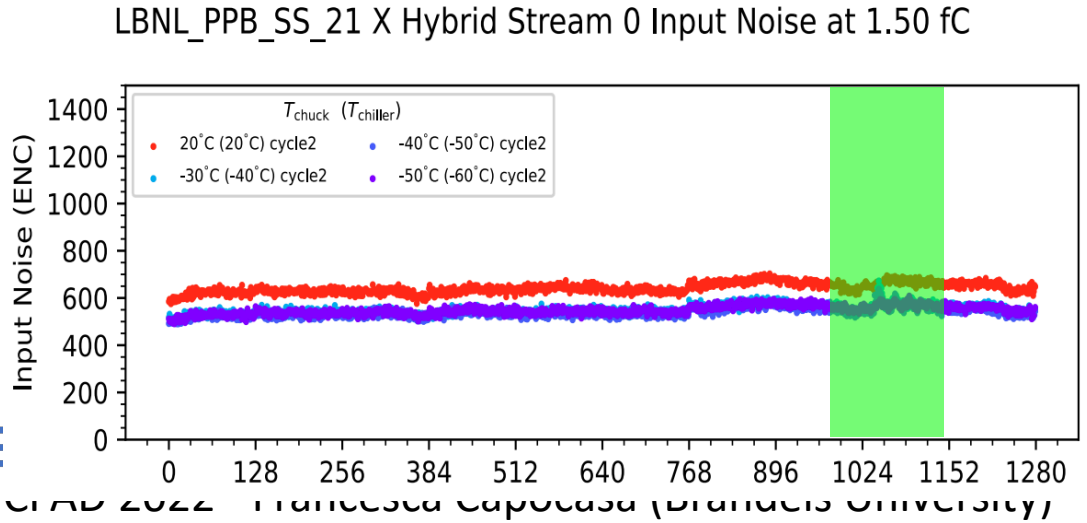
T_{stave} = 23.9 C, -35 C

V_{bias} = - 400 V

- Second PP stave built at BNL
  - Input Noise response for the 14 modules on one side of the first pre-production stave
  - Good overall stave performance at room and cold temperatures except for Cold Noise issue

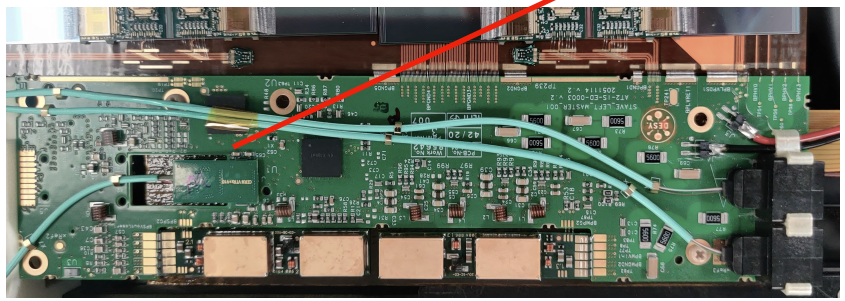
- Promising results: No Cold Noise observed on stave for module with higher glue thickness



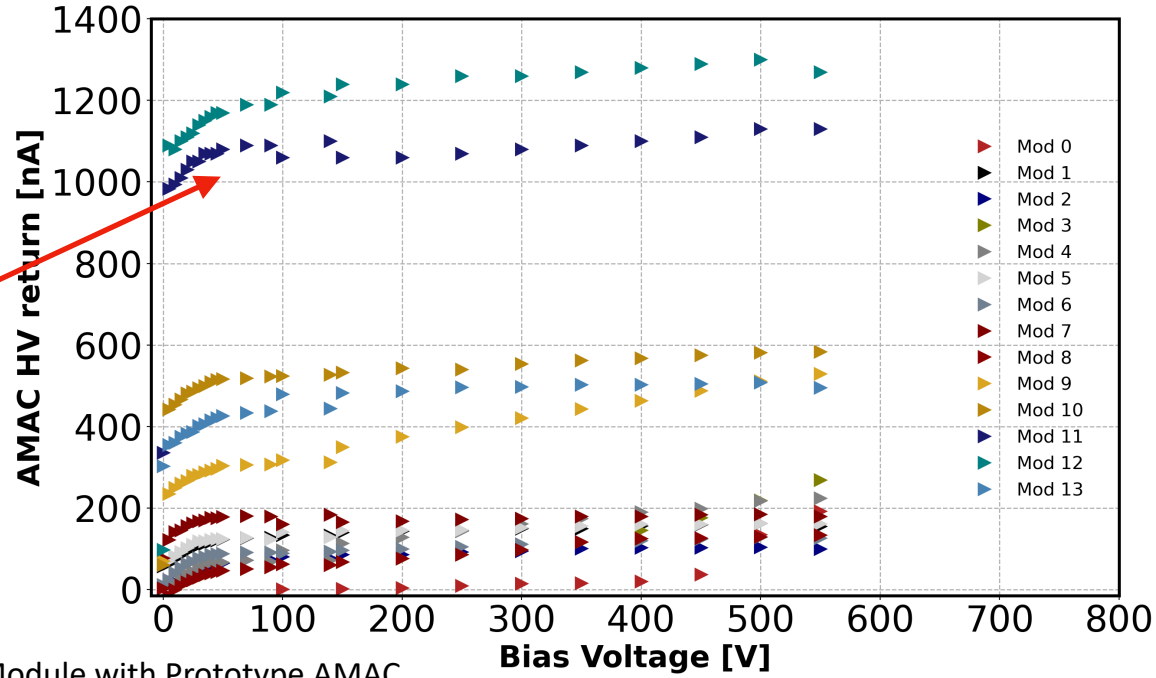


AMAC - HV return current measurements

- AMAC provides a mechanism for measuring the HV sensor bias return line
  - Monitoring the leakage current in the silicon sensors become significant during operation, when higher current is expected due to radiation damage
- Current measurement on stave modules are close to expectations
  - Chip-to-chip offset can be corrected by measuring at Vbias =0
  - Modules 11 and 12 are most likely affected by the light from VTRx+

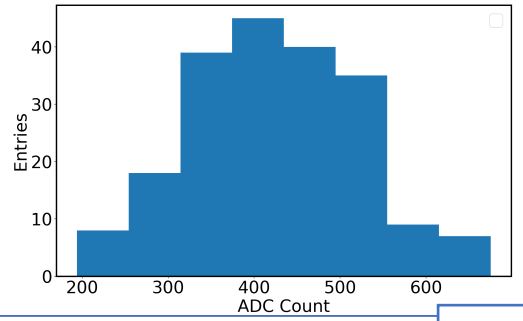


- HV return current measurements with prototype AMAC have shown to be deteriorated by noise induced by AC coupling capacitors between HV ret and hybrid ground

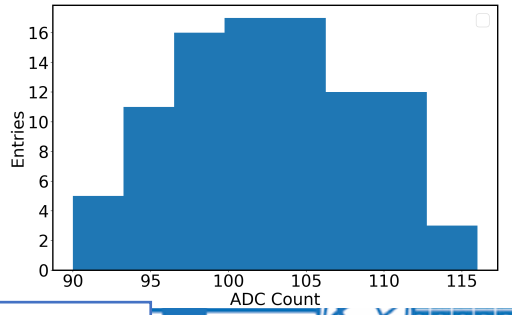


Module with Prototype AMAC

Mu = 424.27 ACD Counts , **std = 97.93 ADC Counts**

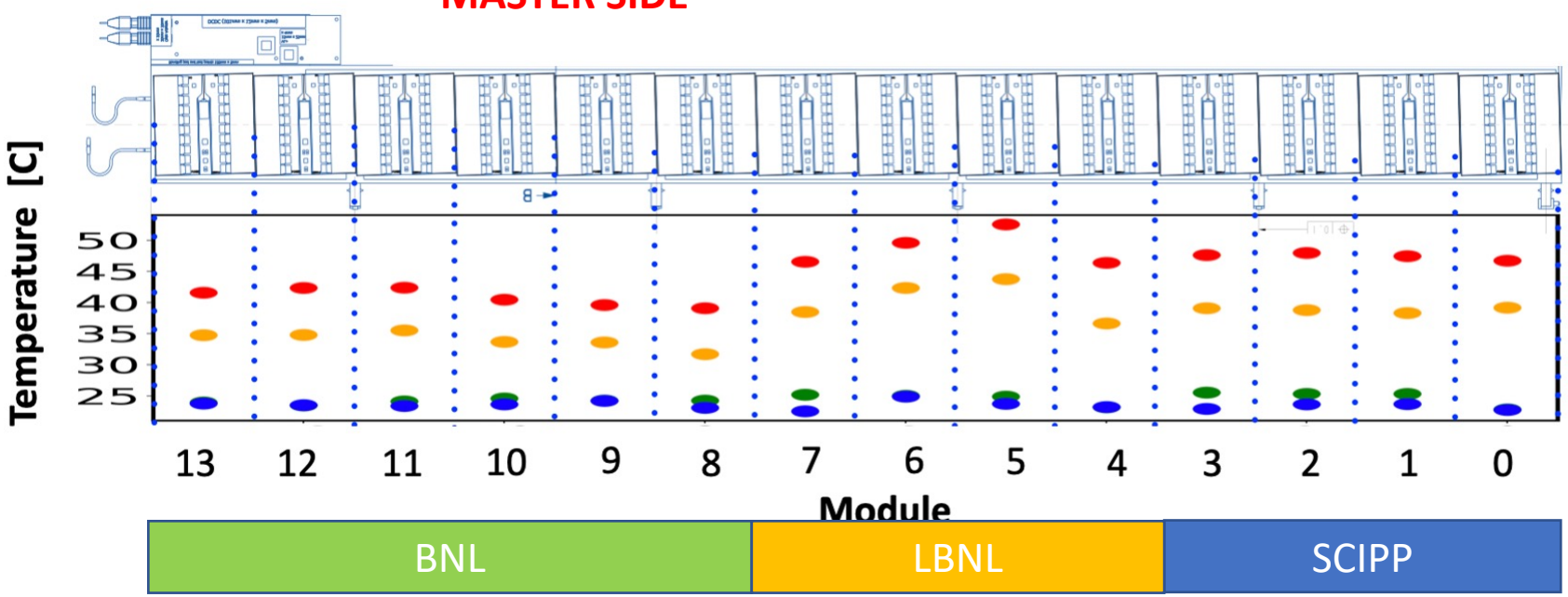


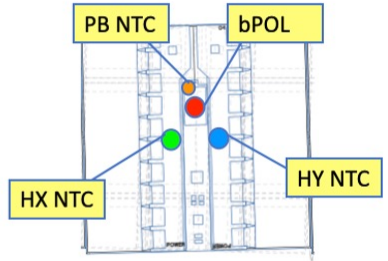
Mu = 102.58 ACD Counts , **std = 5.84 ADC Counts**



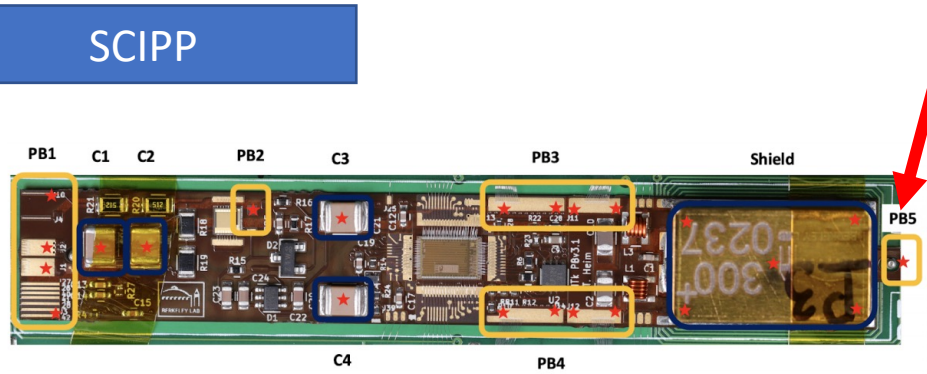
1 ADC Count =~4 nA

MASTER SIDE





If we look at the metrology results of these modules, in particular to the glue thickness in position PB5 (see arrow on PB picture) we can see how this affect the temperature measurements seen above.
Note: Module 6 not pushed all the way down during loading



BNL
MOD 8 PB_5: 144.21 um
MOD 9 PB_5: 58.92 um
MOD 10 PB_5: 67.17 um
MOD 11 PB_5: 43.27um
MOD 12 PB_5: 86.66 um
MOD 13 PB_5: 84 .32um

LBNL
MOD 4 PB_5 :70.0 um
MOD 5 PB_5:227.27 um
MOD 6 PB_5:108.64 um
MOD 7 PB_5:171.97 um

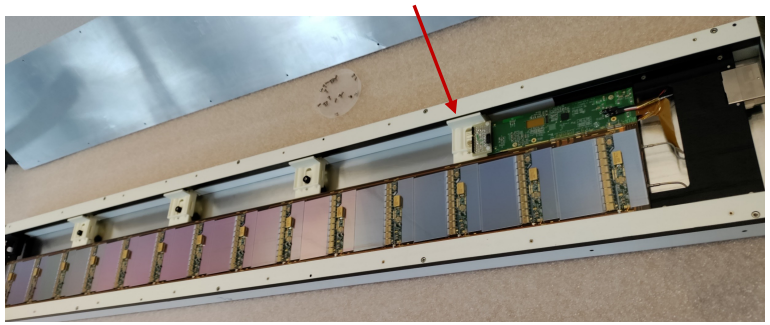
SCIPP
MOD 0 PB_5:75.43 um
MOD 1 PB_5:66.21 um
MOD 2 PB_5:89.70 um
MOD 3 PB_5:64.47 um

Goal is to have relative humidity less than 20% during shipping (and hopefully longer during storage at CERN)

RH for last four staves shipped BNL to CERN

FDR Stave	<20%
PPA1	<30%
PPB1A	<20%
PPB2A	~ 30%

All were shipped in Trespa transport frames



Trespa plate is made by compressing **impregnated paper or wood fibers and epoxy, phenolic or polypropylene resin** at high pressure and high temperature.

Assumes absorbs (and then outgasses) moisture.

There is a new design for transport box. With regards to relative humidity…

- Advantage: Made of aluminum. Should not outgas moisture like Trespa (though there can be some surface moisture that evaporates)
- Disadvantage: Was designed primarily for stave insertion, not shipping. Therefore does not permit the amount of desiccant BNL requested, roughly 1/3 of what we wanted.
- Moisture during shipping is a balance between moisture outgassing (likely mostly from stave itself in new frame) vs absorption by desiccant. Time will tell how well we do.

GaNFET

Allows the isolation of a failed sensor in breakdown connected to the same HV line using commercial GaNFET switch

AMACStar

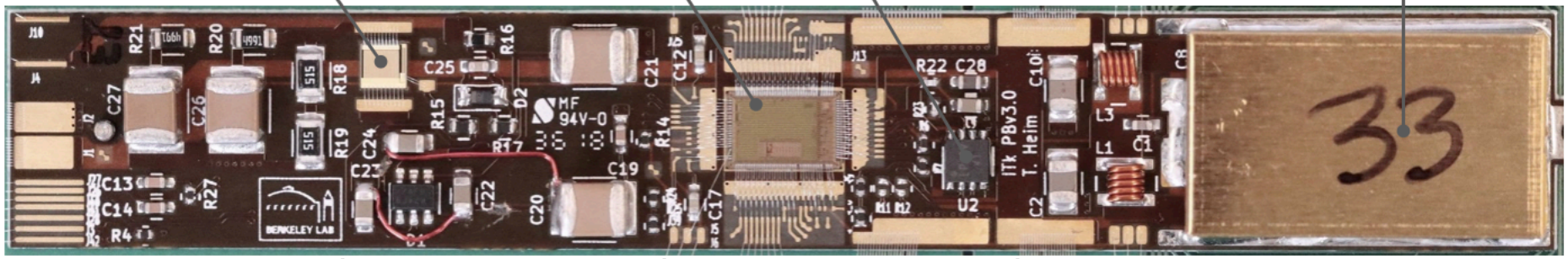
- Enables/Disable DCDC
- Measure Voltage, Currents and Temperatures

LinPOL12V

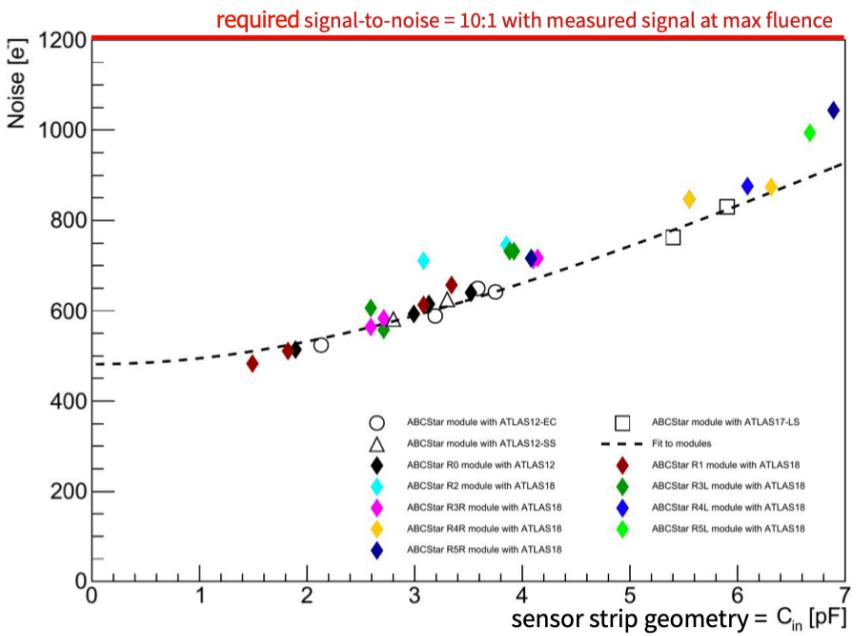
- Radiation hard linear regulator
- 11V input
- 1.4V output for AMACStar
- 3.3V output for HV switch enable

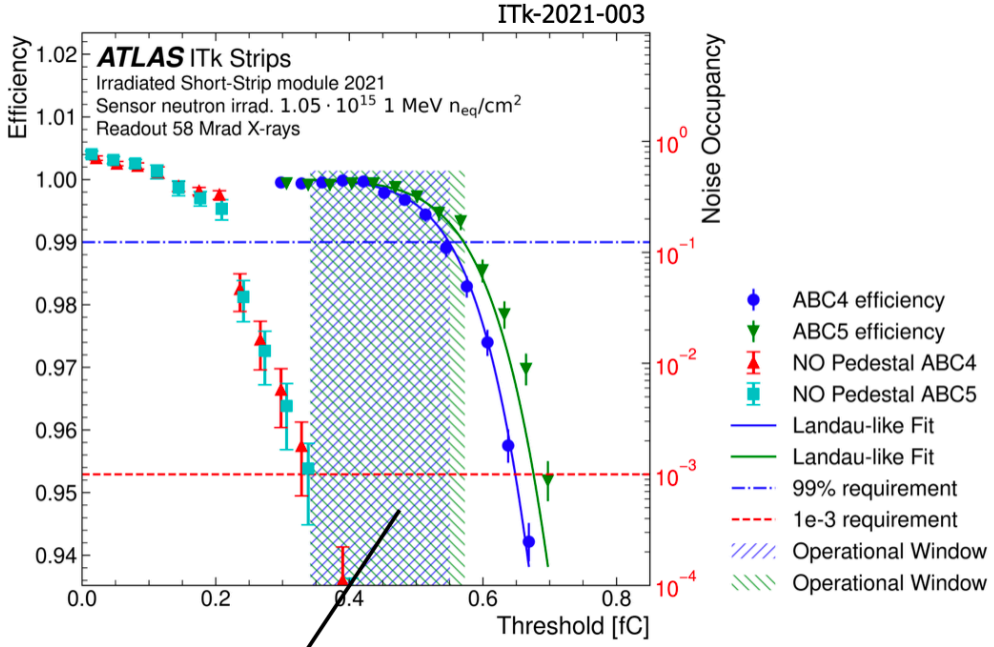
bPOL12V

- Radiation hard buck converter
- 11V input, 1.5V output
- Air-core coil
- 100 µm Al shield to prevent EM noise leakage



HV Filter | **HV switch** | **Measurement & Control** | **DC-DC conversion**





- Strips modules are expected to satisfy through their entire lifetime:
  - Signal-to-noise ratio (SNR) at least 10:1
    - Measure SNR after radiation within requirement
  - Hit Efficiency > 99% and Noise Occupancy < 0.1%
    - Plot on the right shows clear operational window [0.33-0.55 fC] for module irradiated to end-of-life dose

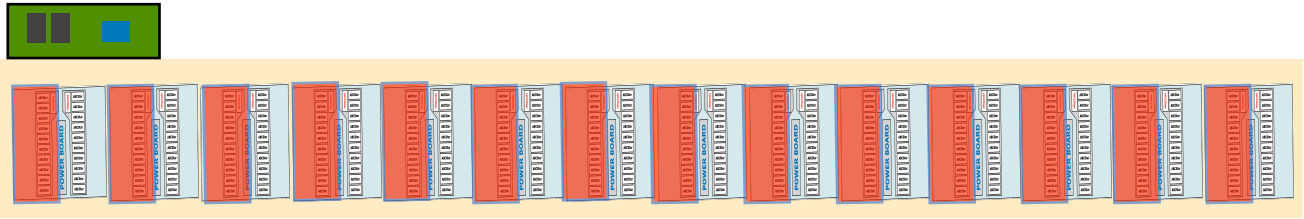
Module built from a neutron irradiated sensor and X-ray irradiated electronics

PPB-1B - Production Site

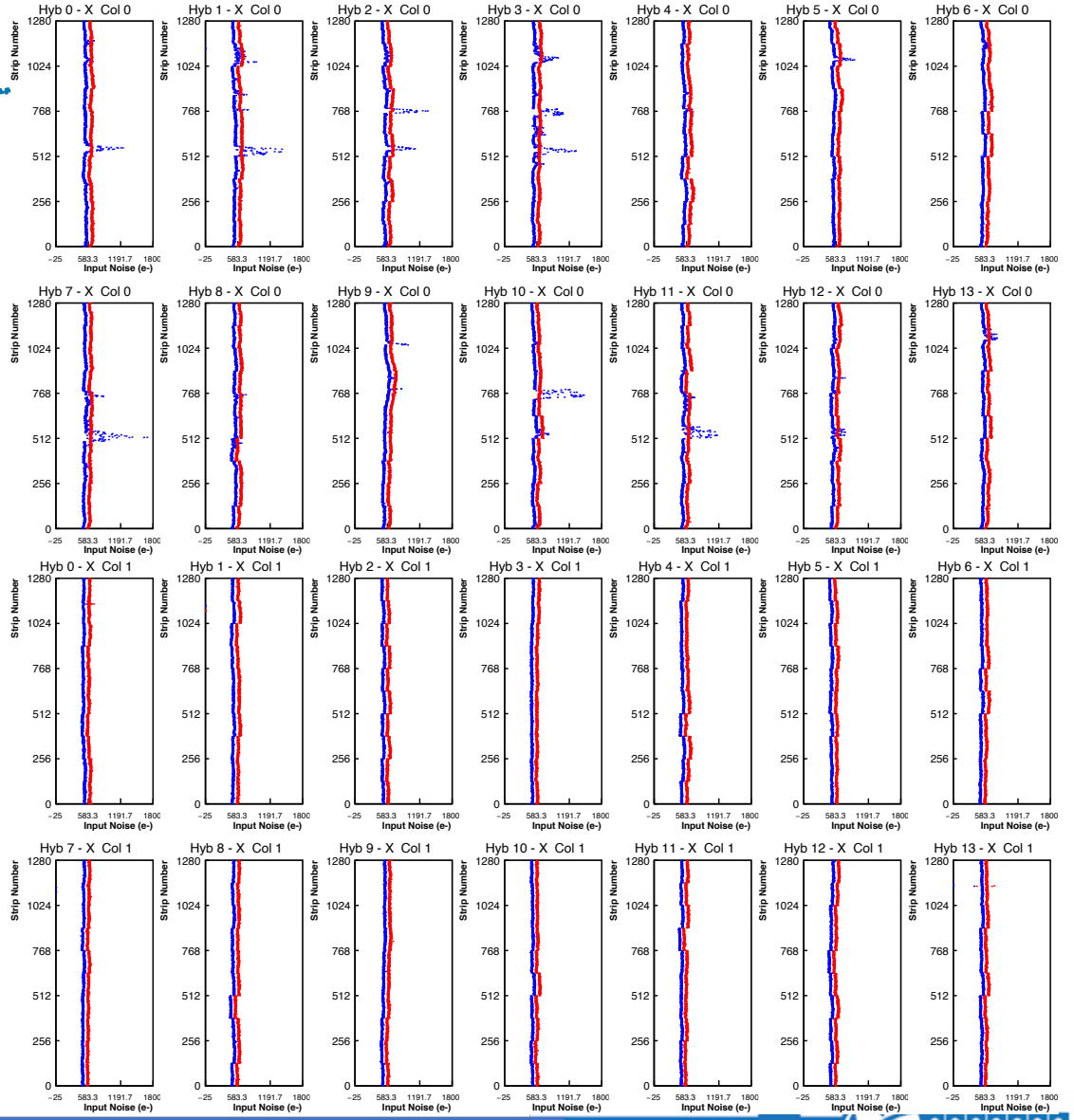
MAIN SIDE

T_{stave} = 24.9 C, -37 C

V_{bias} = - 400 V



- Input Noise response for the 14 modules on the **MAIN** side
- Input Noise analyzed independently for the two row of strips
- Noise profile good except for Cold Noise issue

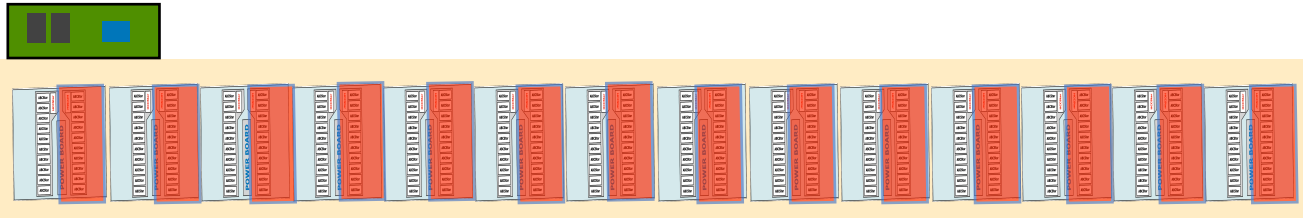


PPB-1B - Production Site

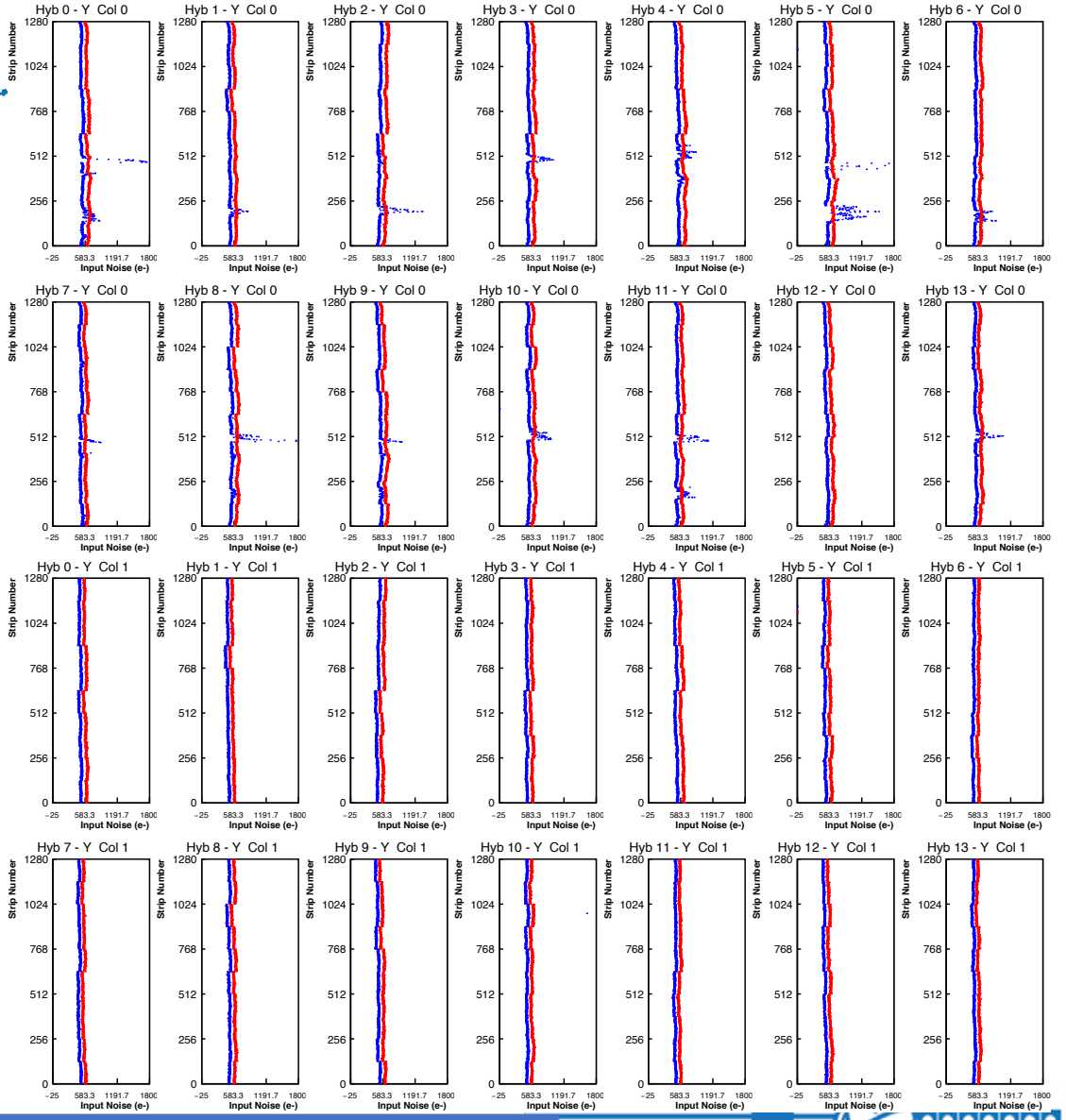
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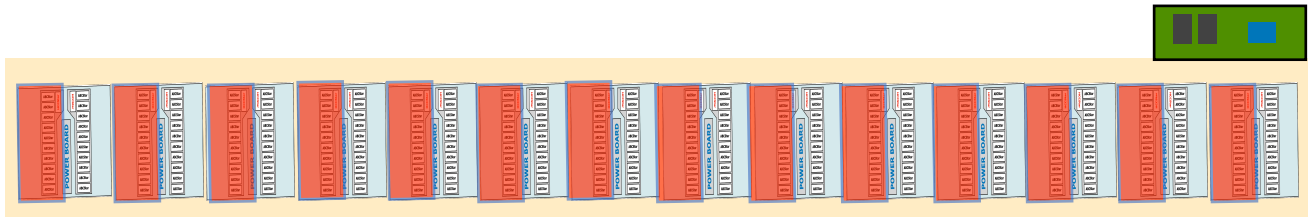


PPB-1B - Production Site

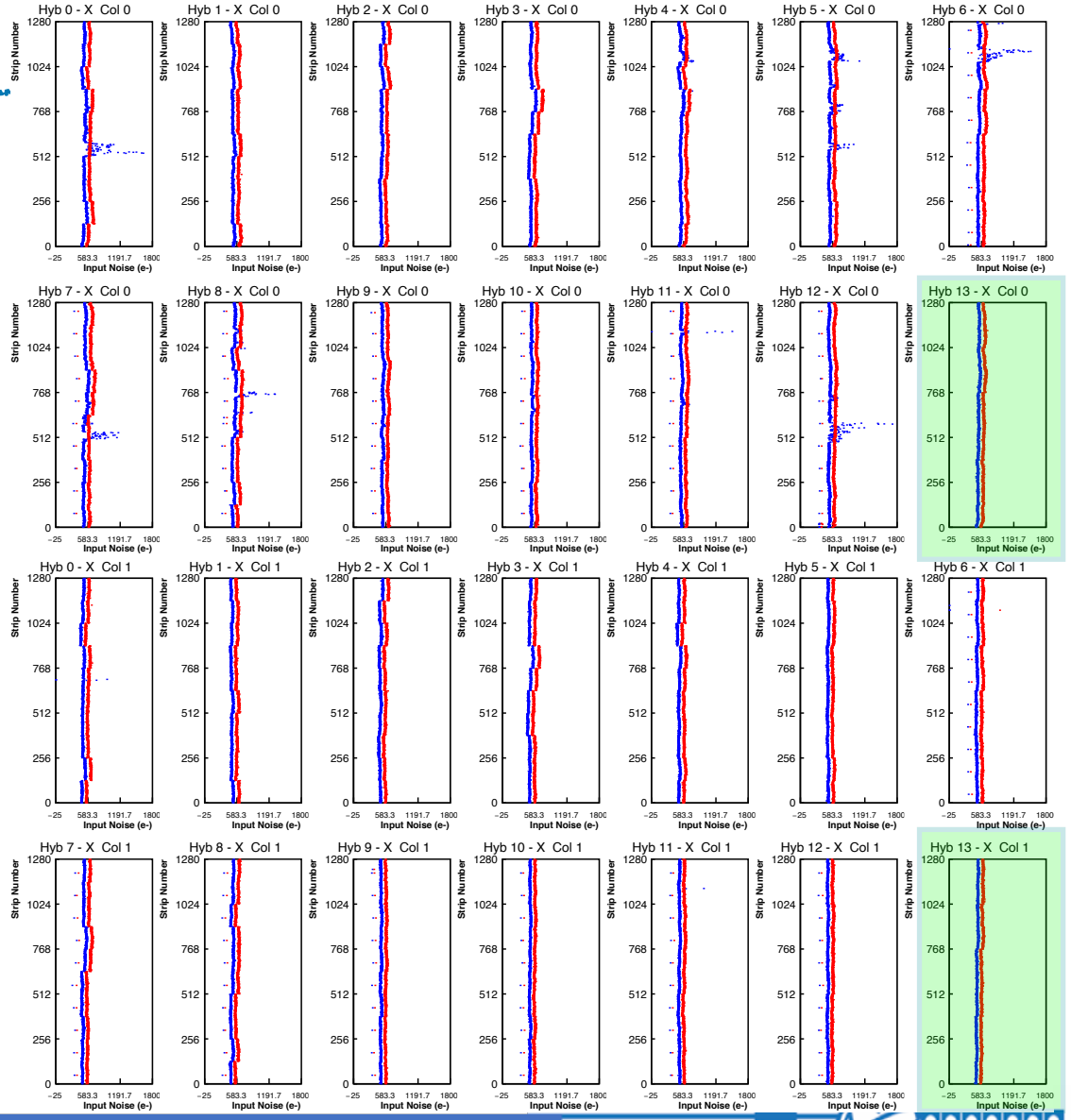
SECOND SIDE

T_{stave} = 24.9 C, -37 C

V_{bias} = - 400 V



- Input Noise response for the 14 modules on the **SECOND** side
- Input Noise analyzed independently for the two row of strips
- Noise profile good except for Cold Noise issue

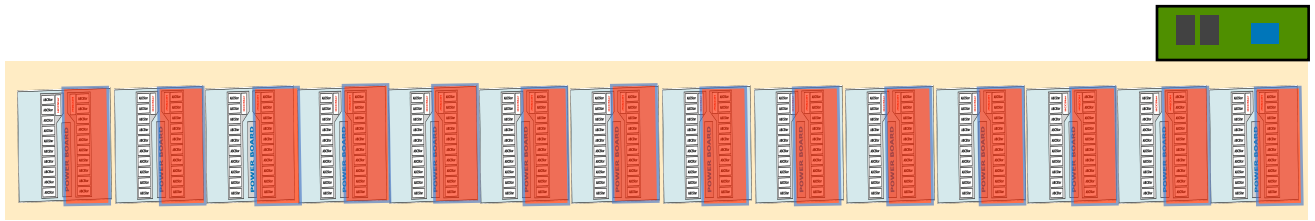


PPB-1B - Production Site

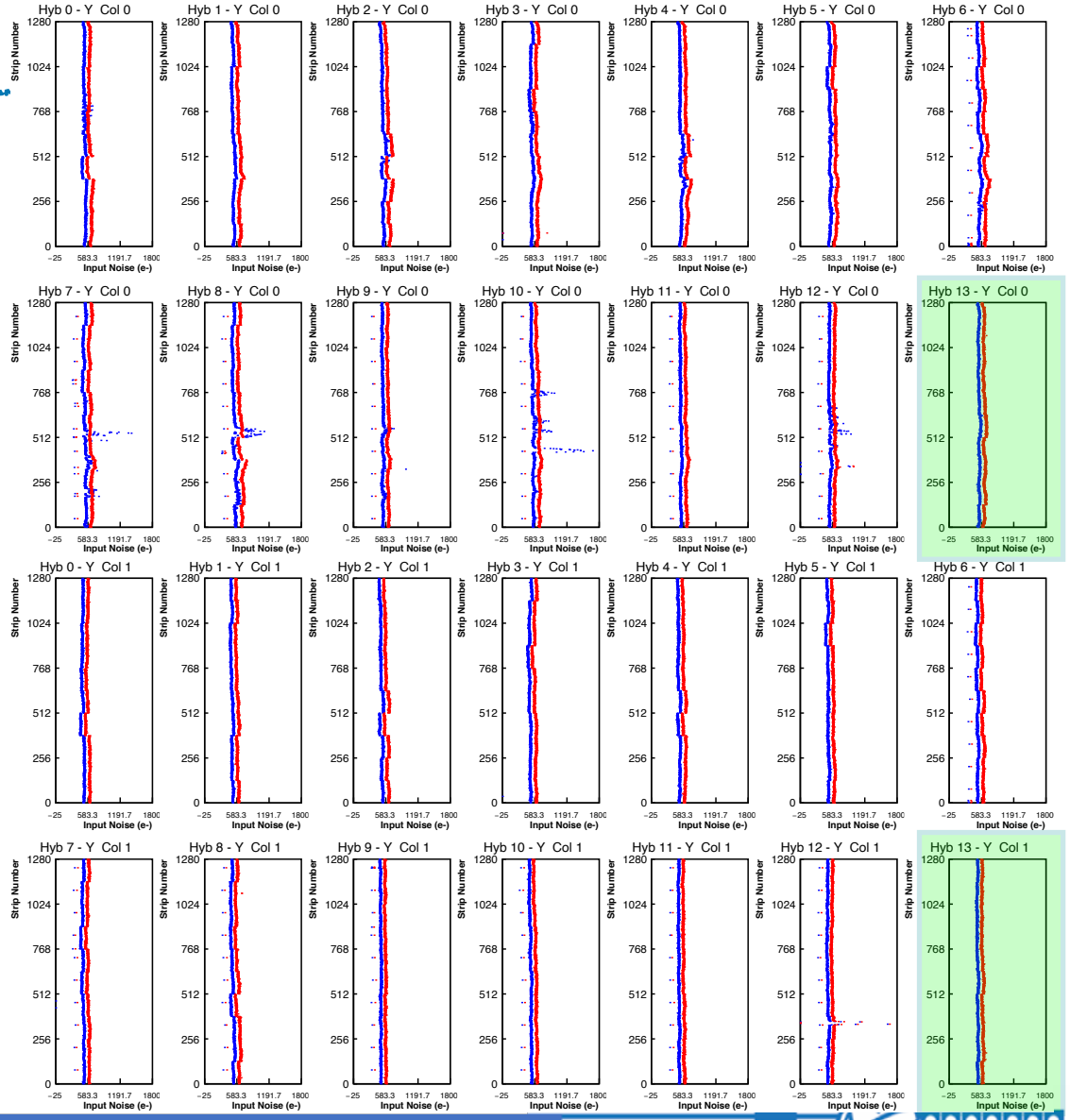
SECOND SIDE

T_{stave} = 24.9 C, -37 C

V_{bias} = - 400 V



- Input Noise response for the 14 modules on the **SECOND** side
- Input Noise analyzed independently for the two row of strips
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PPB-1B - Production Site

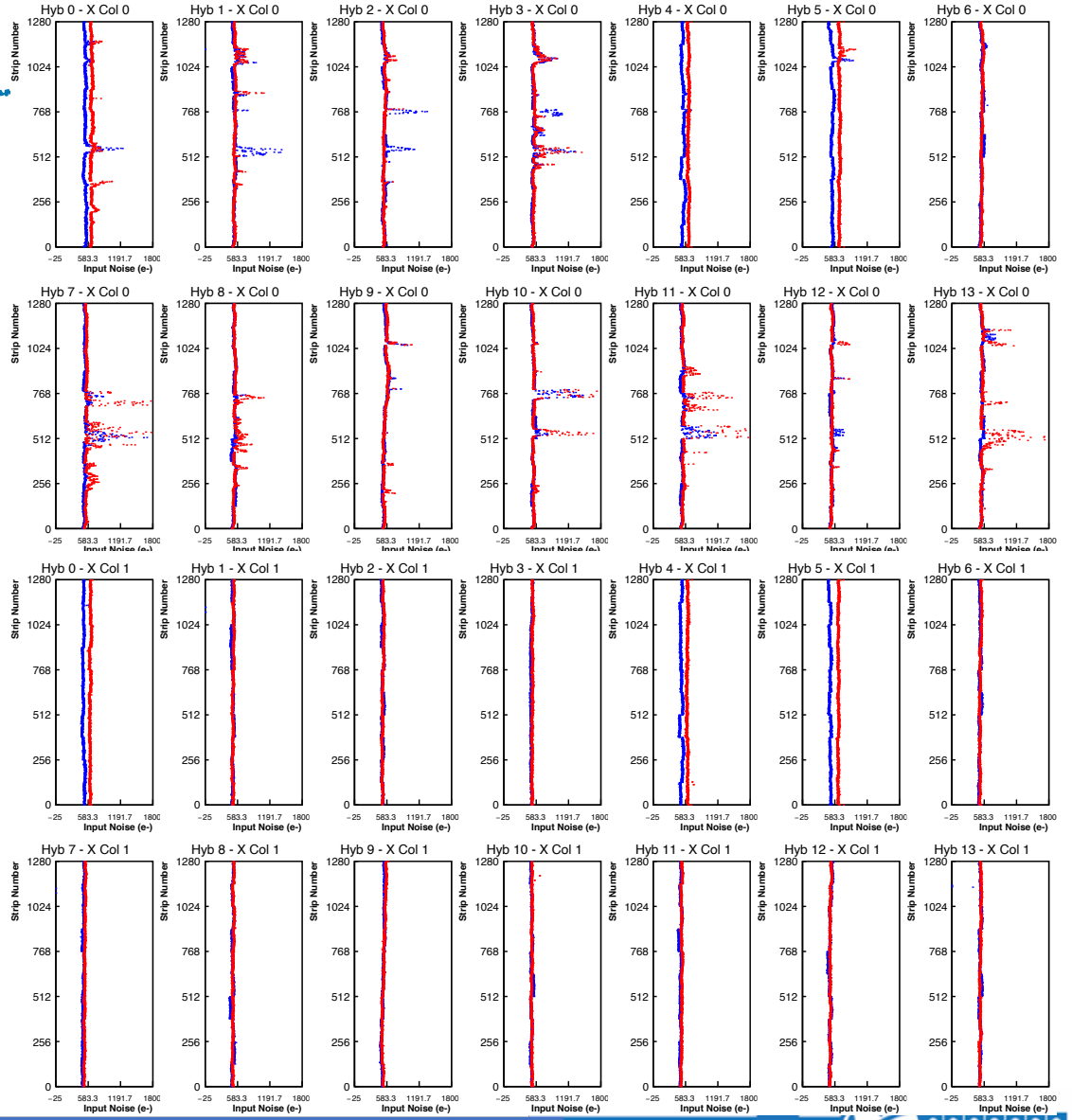
MAIN SIDE
Cold Temp

V_{bias} = - 400 V

Input noise comparison for all the modules on MAIN side when ON and OFF the stave

ON — T_{stave} = -37 C

OFF-Stave — T_{chuck} = -35.5/40 C



- Some modules show higher noise when tested at production sites
- It doesn't appear that cold noise is reduced on stave
- There are regions that didn't show noise in cold box but do show on stave and vice versa

PPB-1B - Production Site

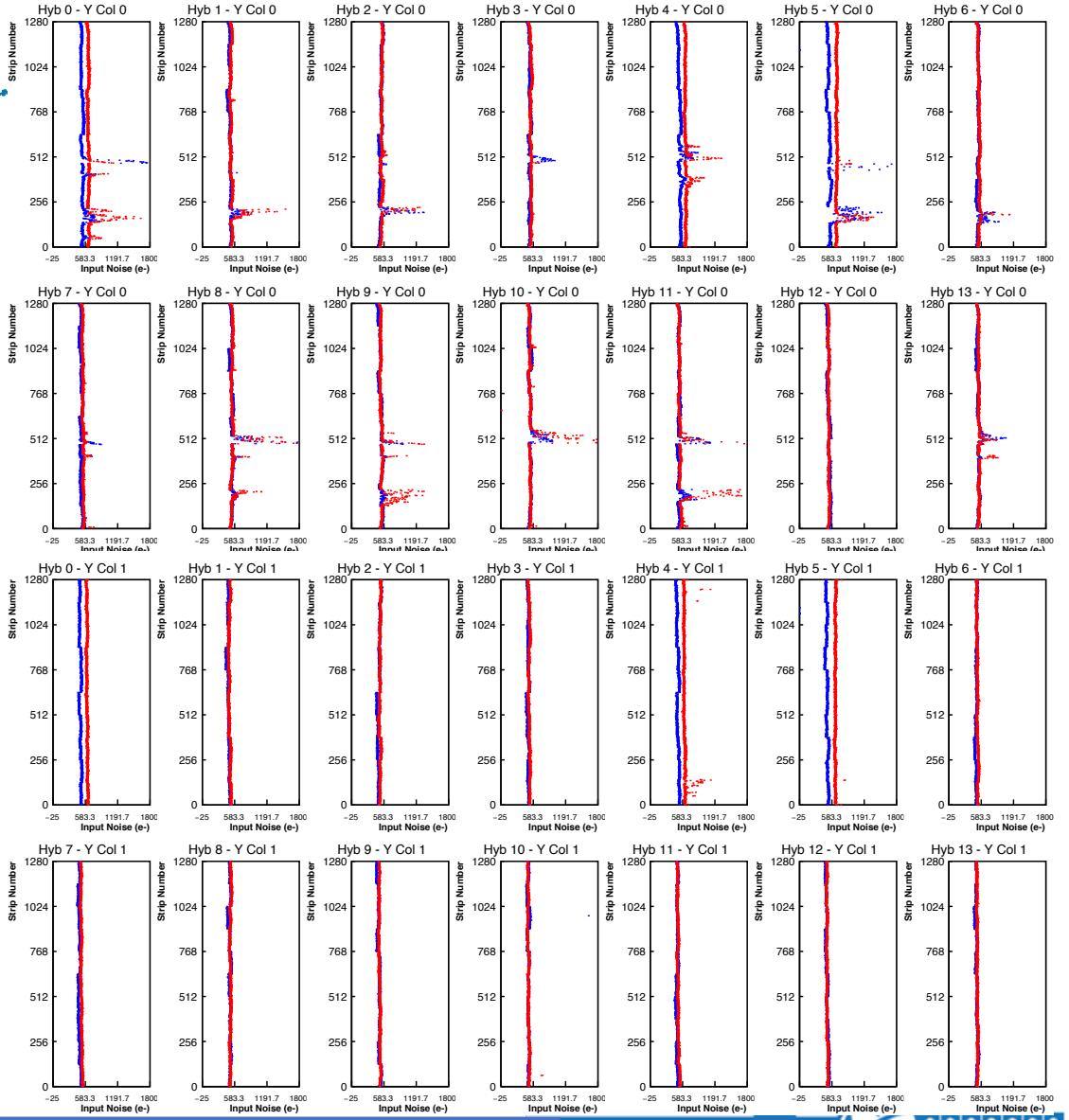
MAIN SIDE
Cold Temp

V_{bias} = - 400 V

Input noise comparison for all the modules on MAIN side when ON and OFF the stave

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PPB-1B - Production Site

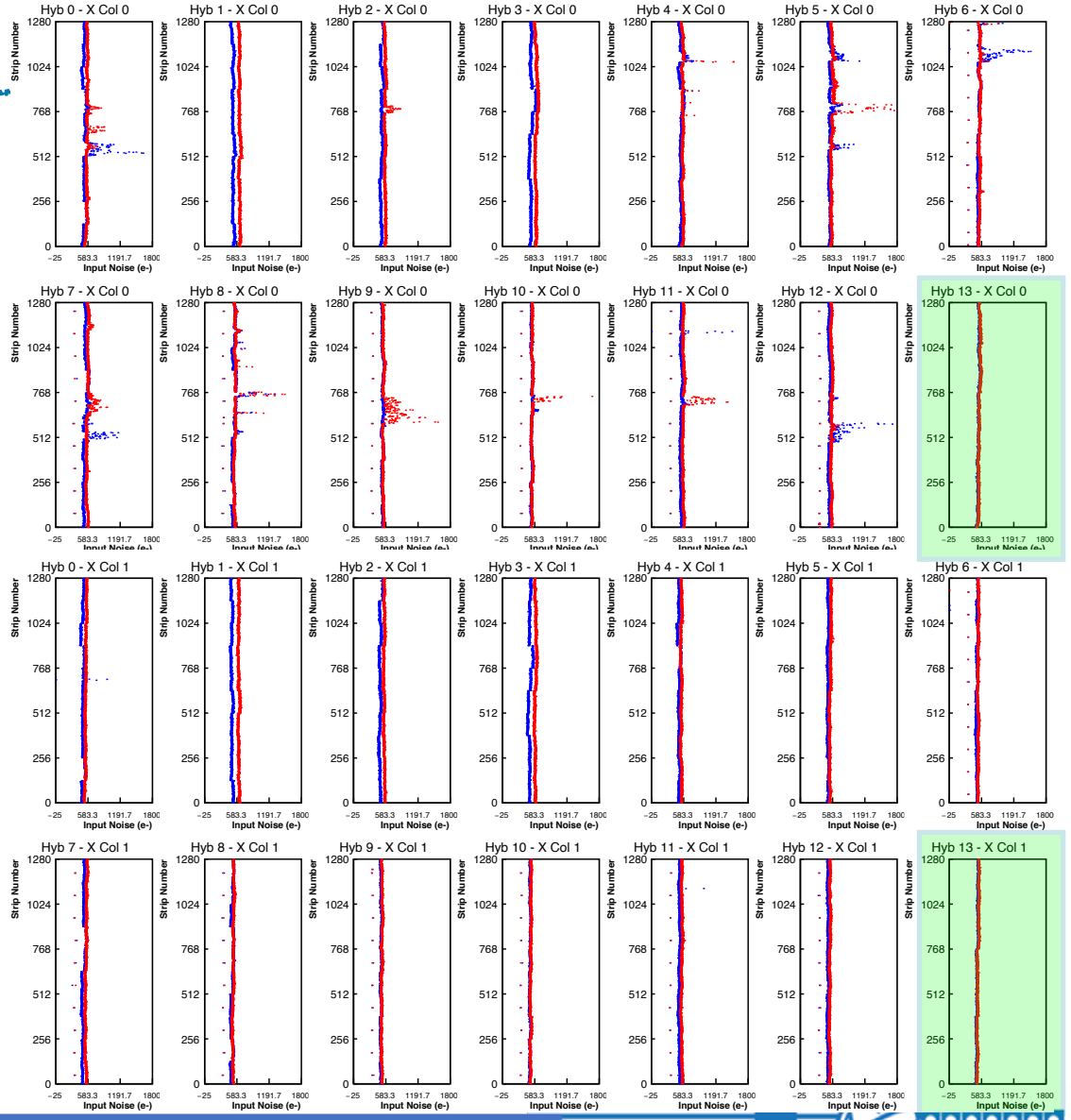
SECOND SIDE
Cold Temp

V_{bias} = - 400 V

Input noise comparison for all the modules on SECOND side when ON and OFF the stave

ON — T_{stave} = -37 C

OFF-Stave — T_{chuck} = -35.5/40 C



- Some modules show higher noise when tested at production sites
- It doesn't appear that cold noise is reduced on stave
- There are regions that didn't show noise in cold box but do show on stave and vice versa
- Mod pos 27 - LBNL module with raised PB and hybrids

PPB-1B - Production Site

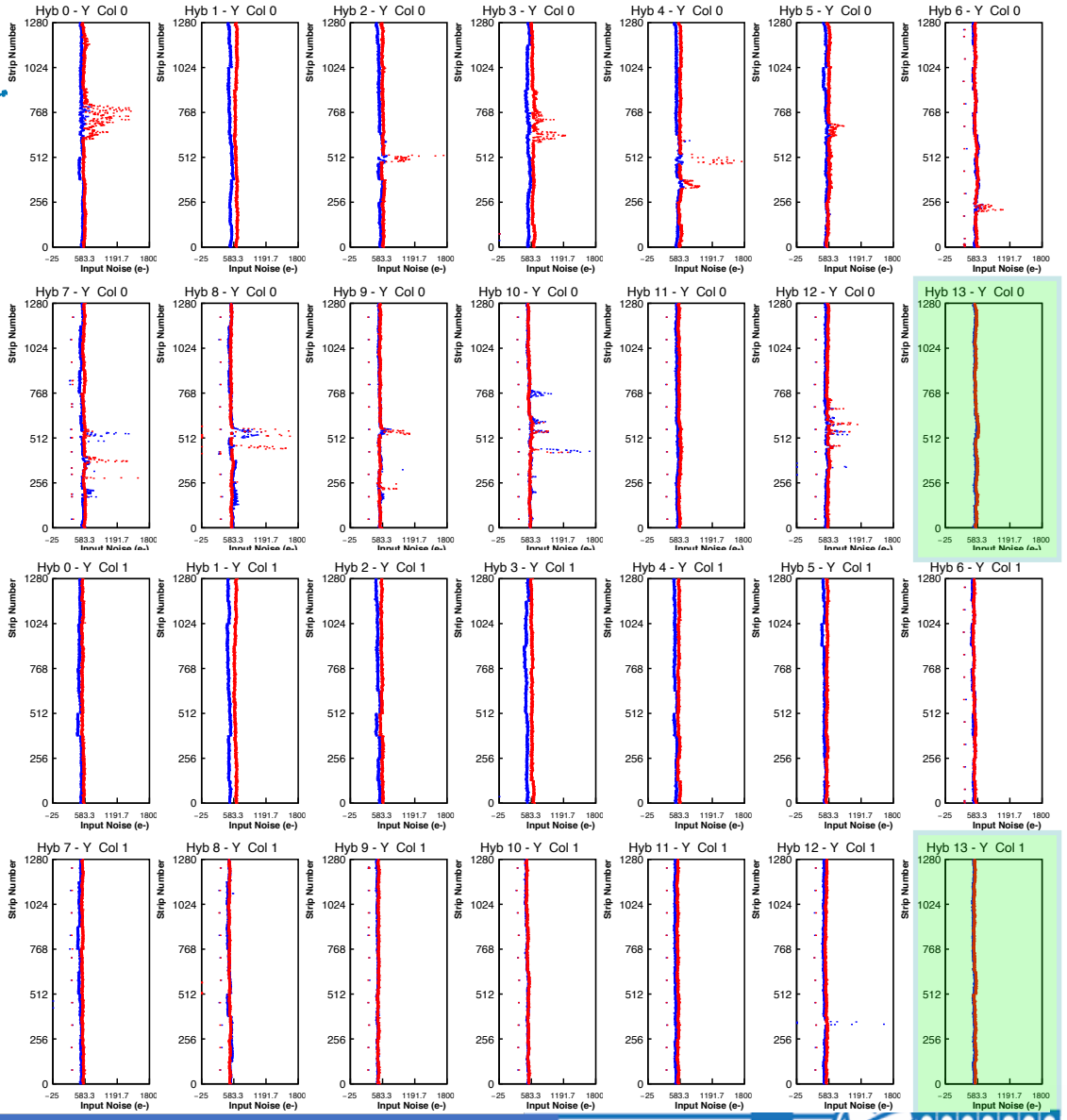
SECOND SIDE
Cold Temp

V_{bias} = - 400 V

Input noise comparison for all the modules on SECOND side when ON and OFF the stave

ON — T_{stave} = -37 C

OFF-Stave — T_{chuck} = -35.5/40 C



- Some modules show higher noise when tested at production sites
- It doesn't appear that cold noise is reduced on stave
- There are regions that didn't show noise in cold box but do show on stave and vice versa
- Mod pos 27 - LBNL module with raised PB and hybrids