ATLAS ITk Strip Detector for High-Luminosity LHC

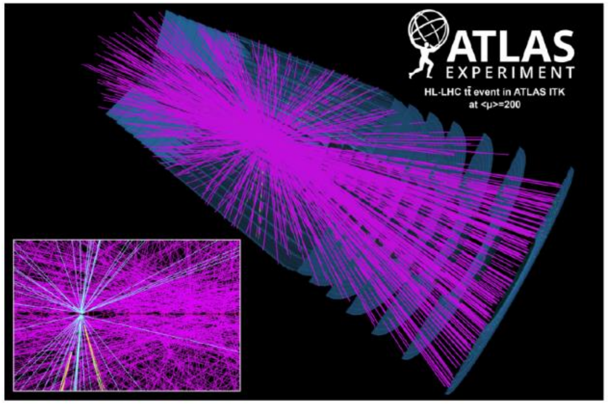
刘佩莲 (IHEP)

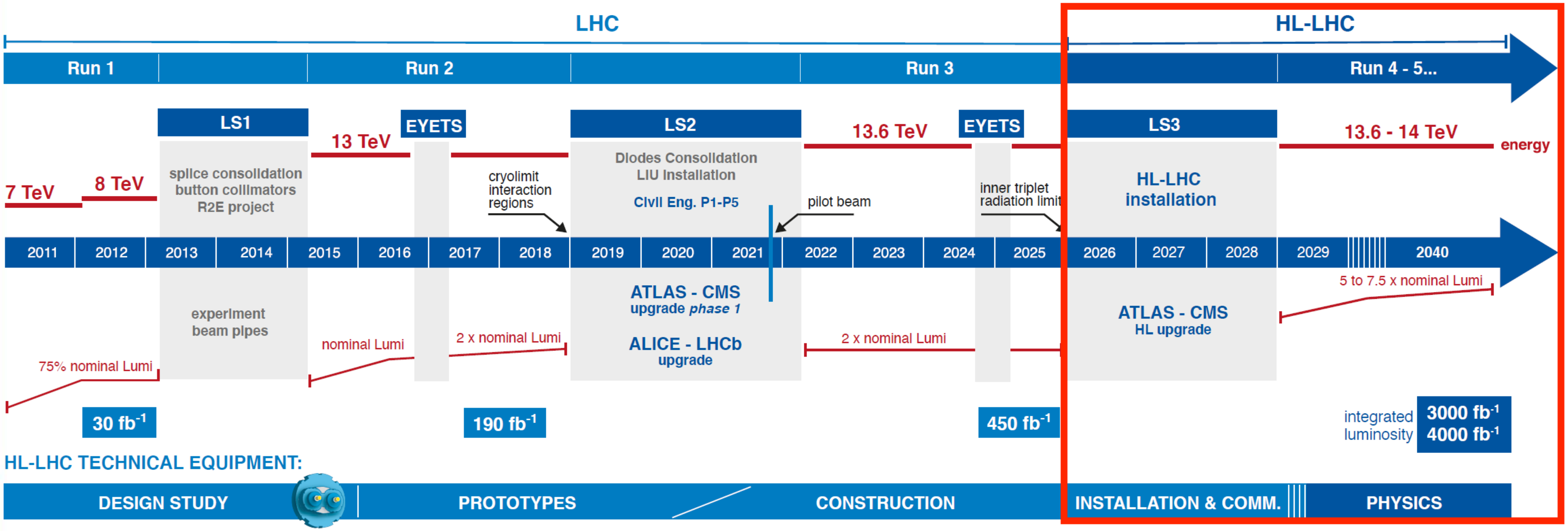
On behalf of the ATLAS ITk Chinese Group

Workshop on Advanced Detectors and Technologies, 2024.6.17-19

Roadmap to High Luminosity LHC

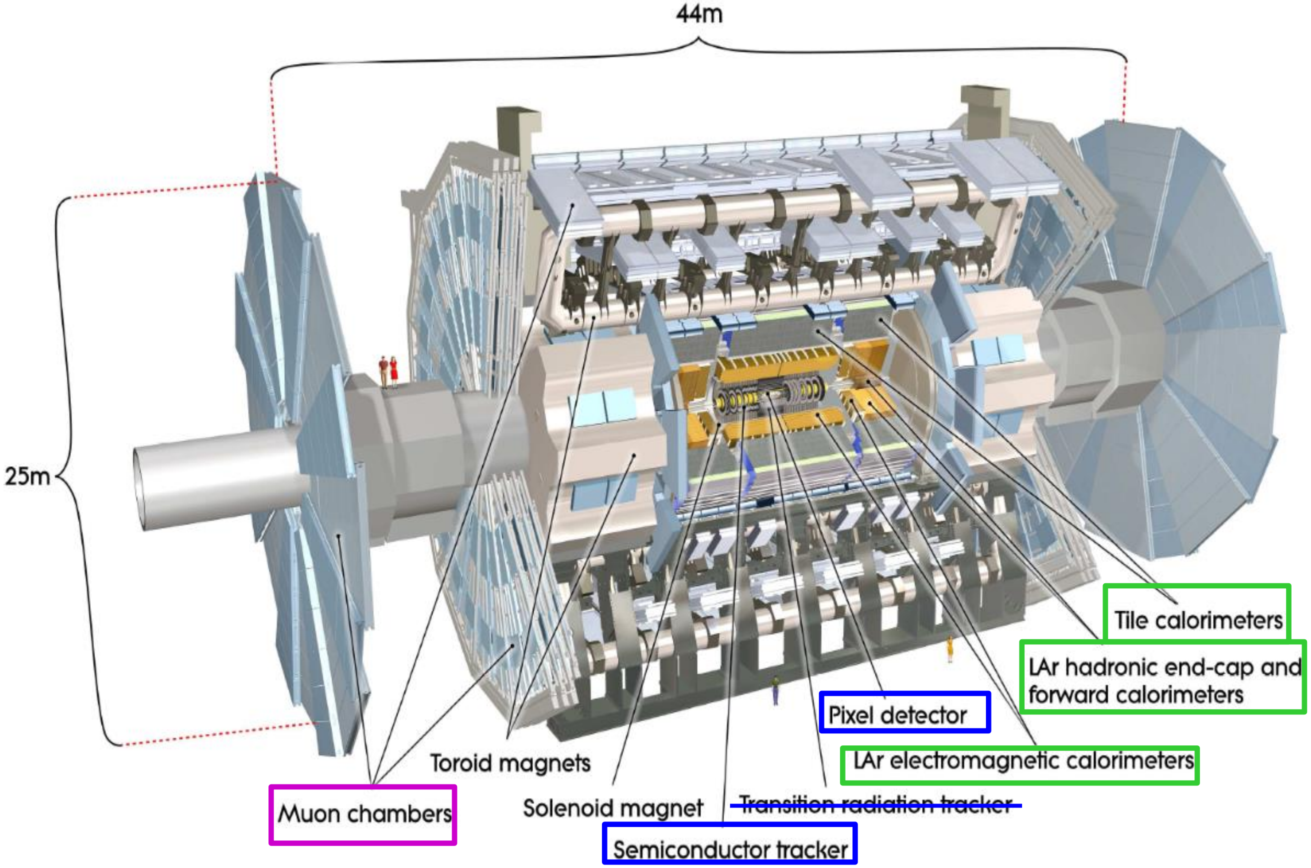
- **HL-LHC (2029):** $\mathcal{L}\sim 7.5\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - To provide 300 fb^{-1}/year during an operating period of ~10 years
  - Up to 200 inelastic pp interactions per beam crossing (pileup)
  - Increased luminosity → ~10 times higher radiation
  - **Harsh environment**



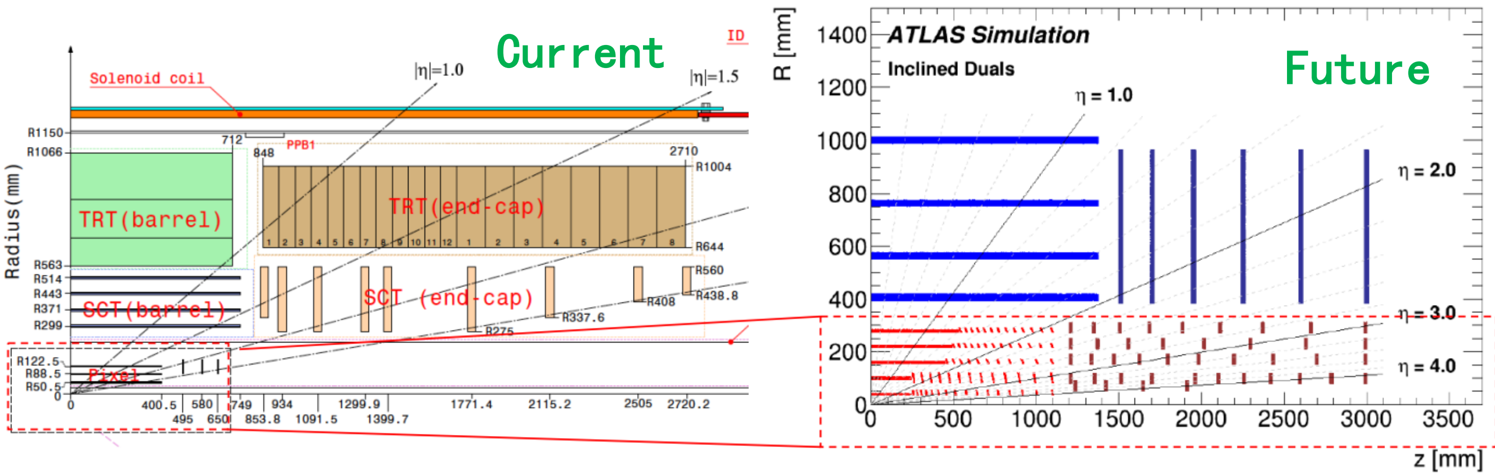


Phase-II Upgrade of ATLAS Detector for HL-LHC

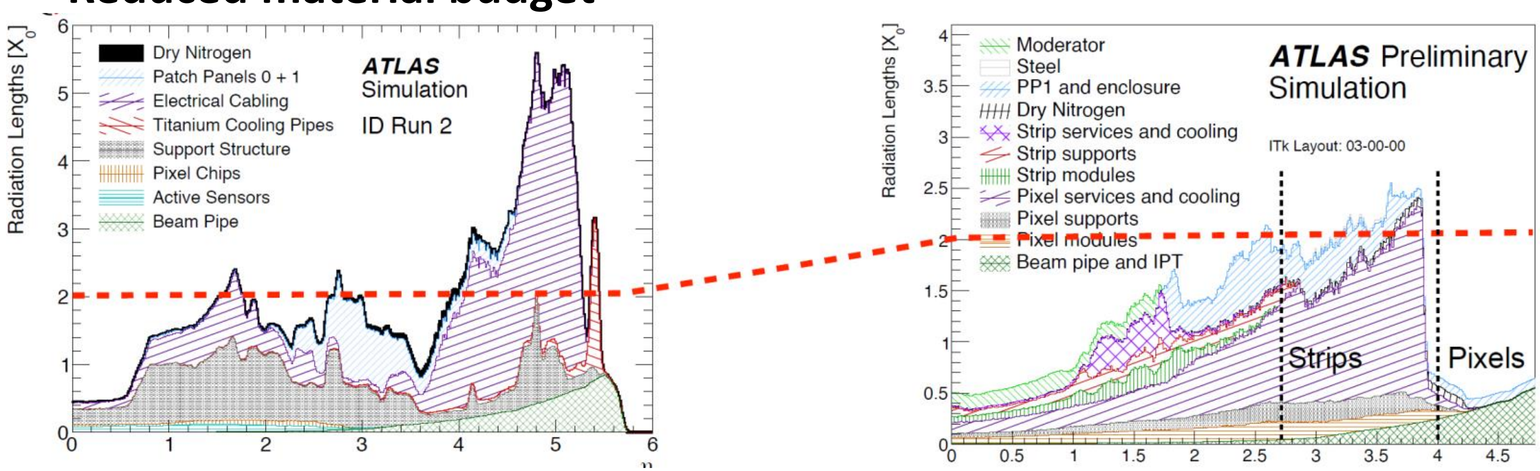
- All-silicon new Inner Tracker (ITk) → Main upgrade
- New inner barrel trigger chambers
- New readout electronics for all systems
- New High-Granularity Timing Detector $(2.4 < |\eta| < 4.0)$
  - Proposed to distinguish between collisions



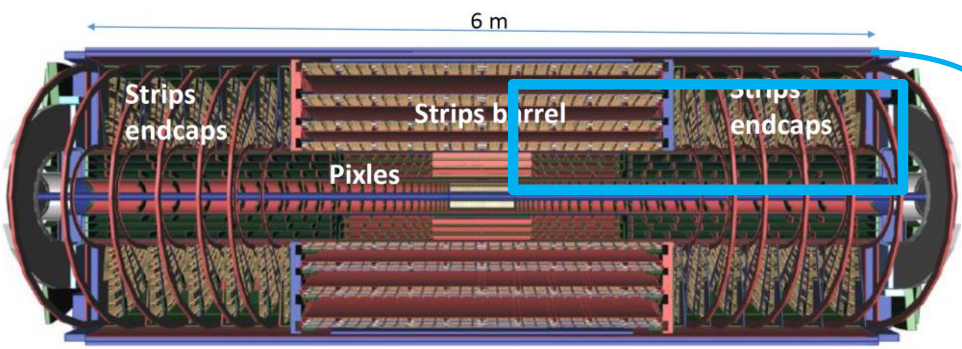
Upgrade of the ATLAS Inner Detector

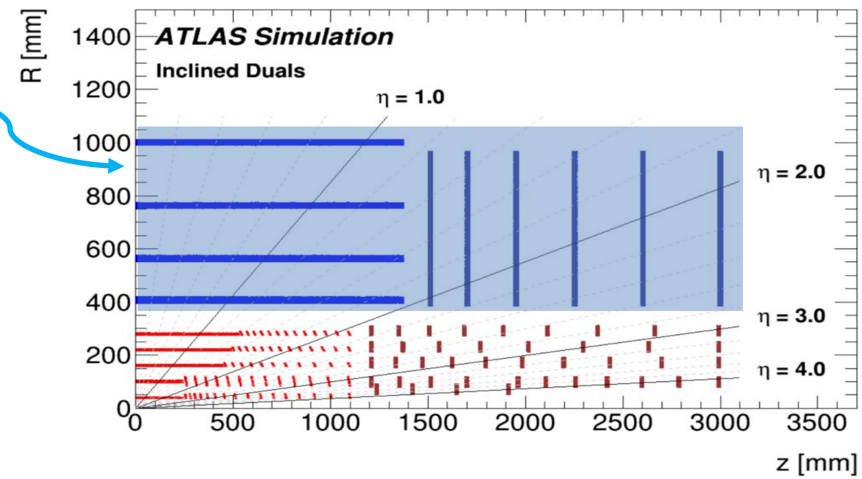


- **New all-silicon Inner Tracker (ITk)**
- **Finer granularity**: 10xstrip channels ; 60xpixel channels
- **Extended coverage to η of 4** ($|\eta| < 2.5$ for present tracker)
- **Reduced material budget**



ATLAS ITk Strip

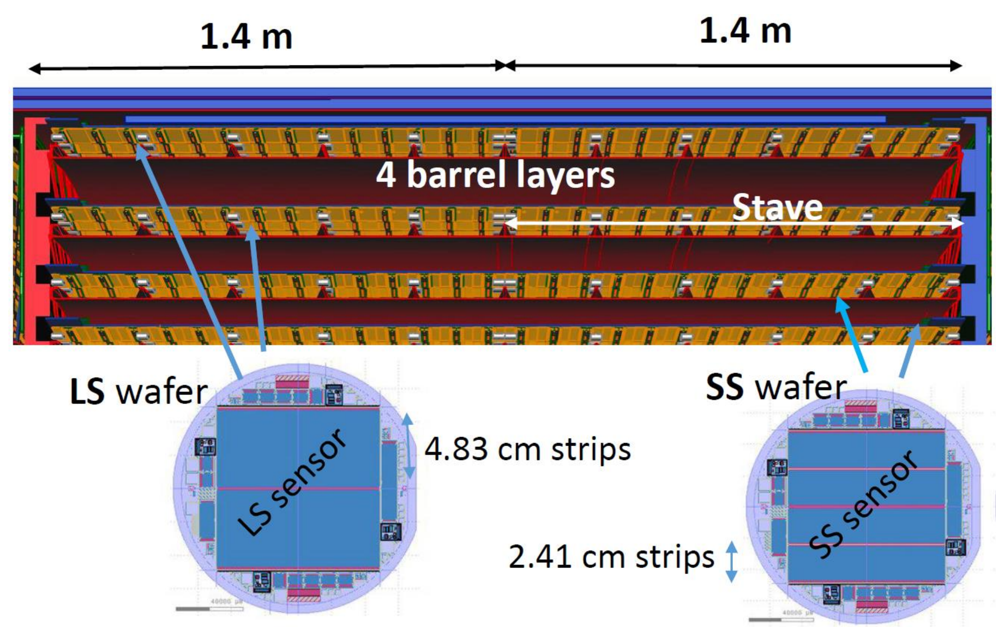




IHEP contributes to the strip barrel detector

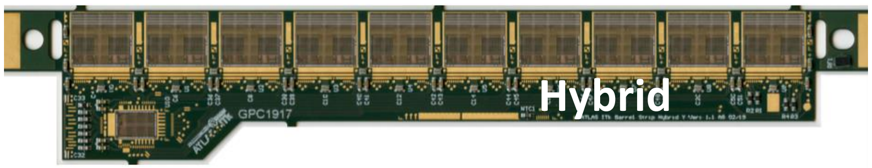
Barrel： 4 layers (double sided)

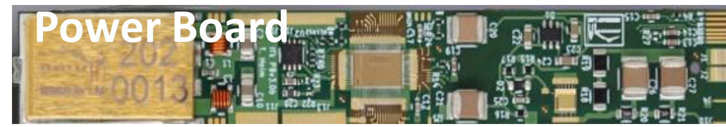
- L3/L2 with **long strip** (LS) modules
- L1/L0 with **short strip** (SS) modules
- Up to ~33MRad dose and $7.2 \times 10^{14} n_{eq}/cm^2$

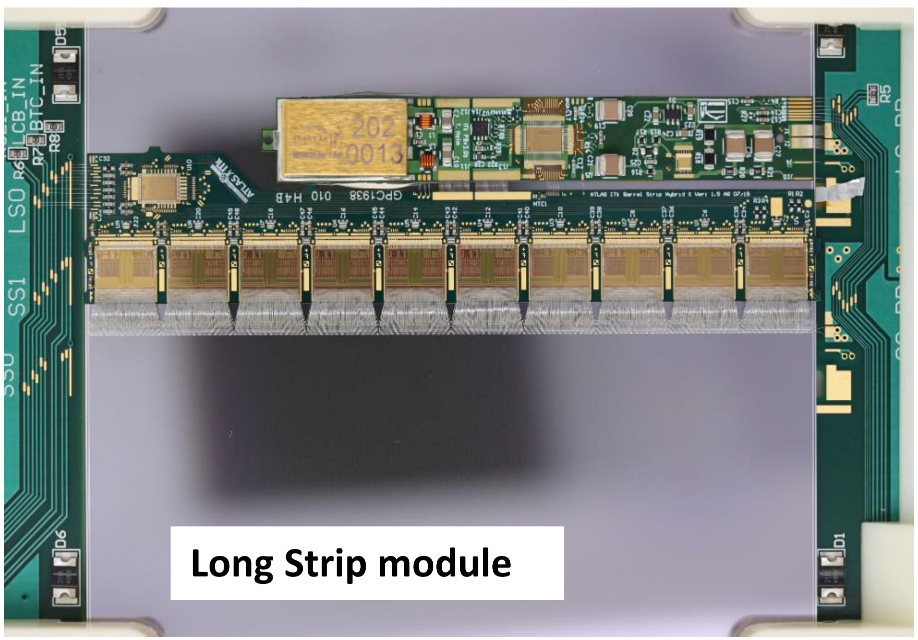


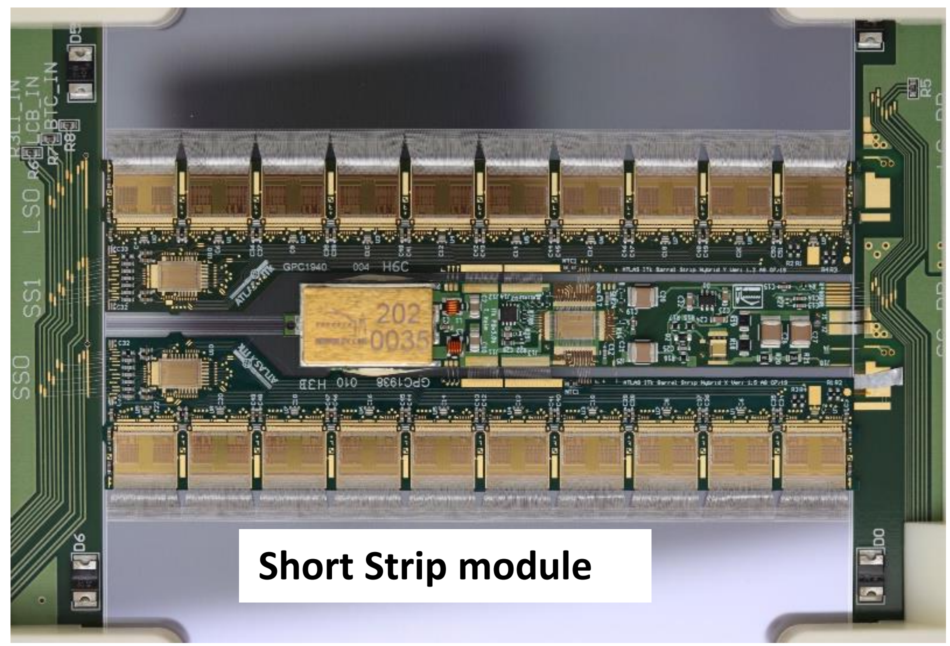
ITk main element: Modules

- **Consists of one sensor, one/two hybrids, and one power board**
  - **Hybrids and power boards are glued directly to silicon sensor**



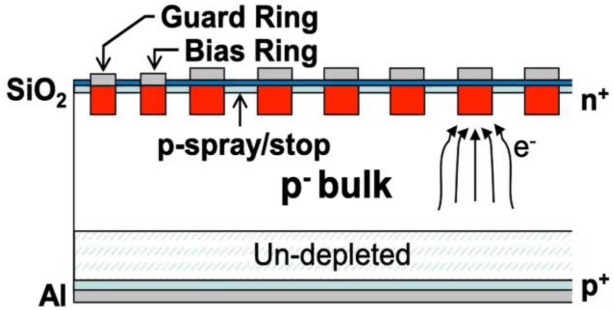


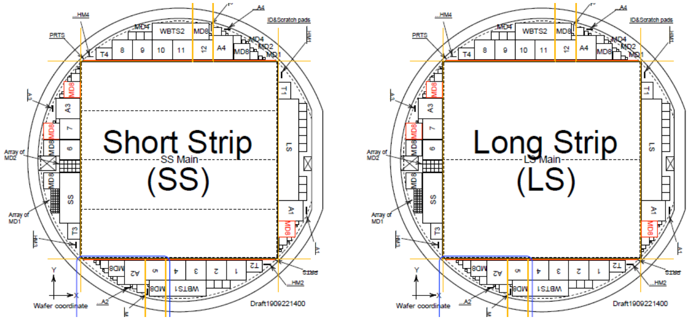




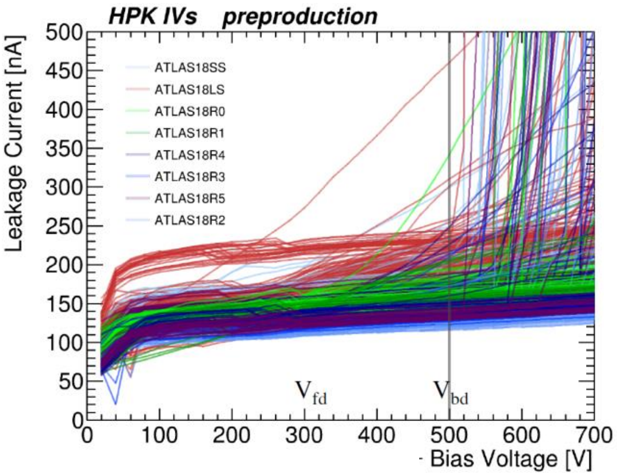
ITk Strip Sensors

- n^+**-in-p with p-stop isolation**
  - Collects electrons -> faster signal, reduced charge trapping
  - Always depletes from the segmented side -> good signal even not fully depleted
  - Active area 9.7×9.7 cm^2, strip pitch 75.5 µm
  - Produced by Hamamatsu Photonics K.K. (HPK) in 6-inch, 320μm thick wafers



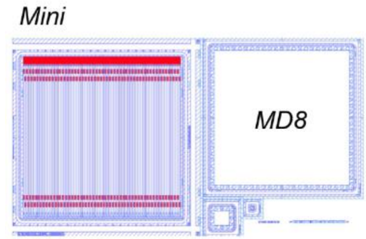


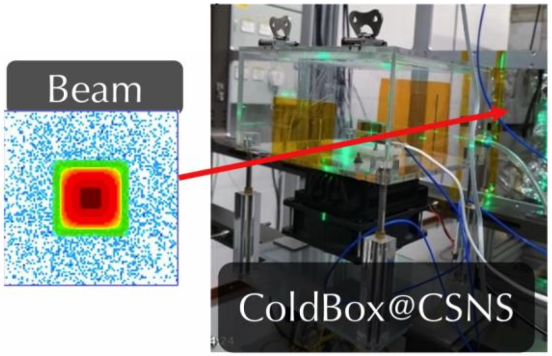
- Halfmoons to validate the characteristics and performance of the sensors
  - Mini sensors, Monitor diodes, test structure …
- Operation bias voltage is set to backplane at -500V at $-30°\text{C}$

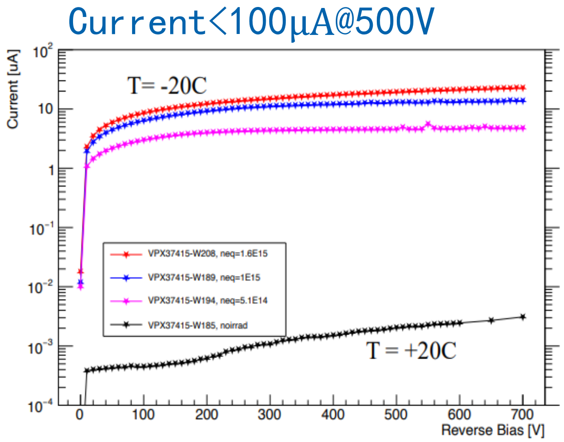


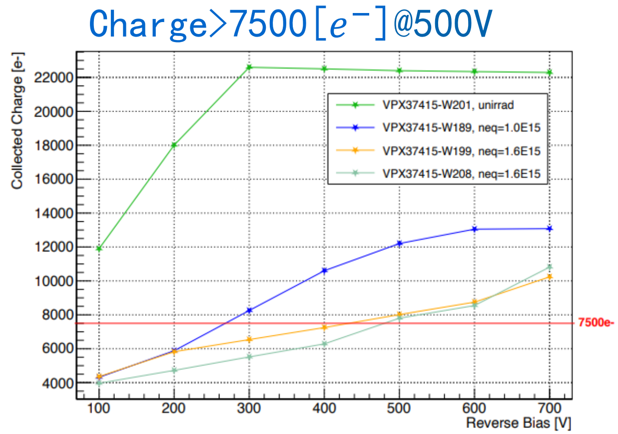
ITk Strip Sensors – Study of radiation effects

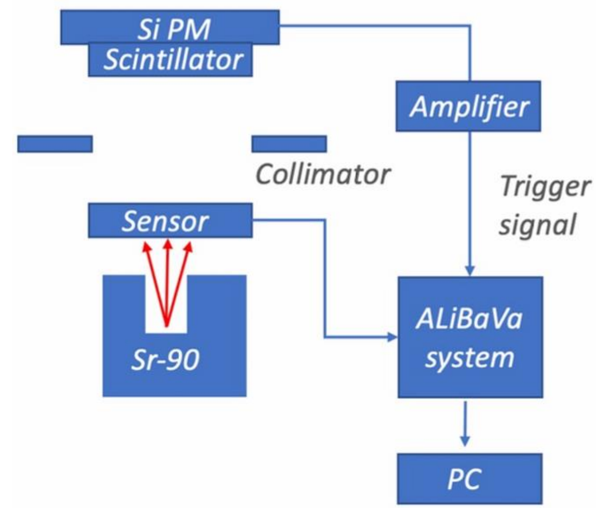
- **Radiation tolerant ($1.6\text{x}10^{15} n_{eq}/cm^2$)**
- **Mini sensors** with same layout as main barrel sensors but with 8mm of strip length.
- Proton irradiation at China Spallation Neutron Source (CSNS)
  - $3\text{x}10^9$ protons/cm^2/s @80MeV
- Sensor characterization
  - **I-V, C-V**
  - **Charge collection efficiency** measurement











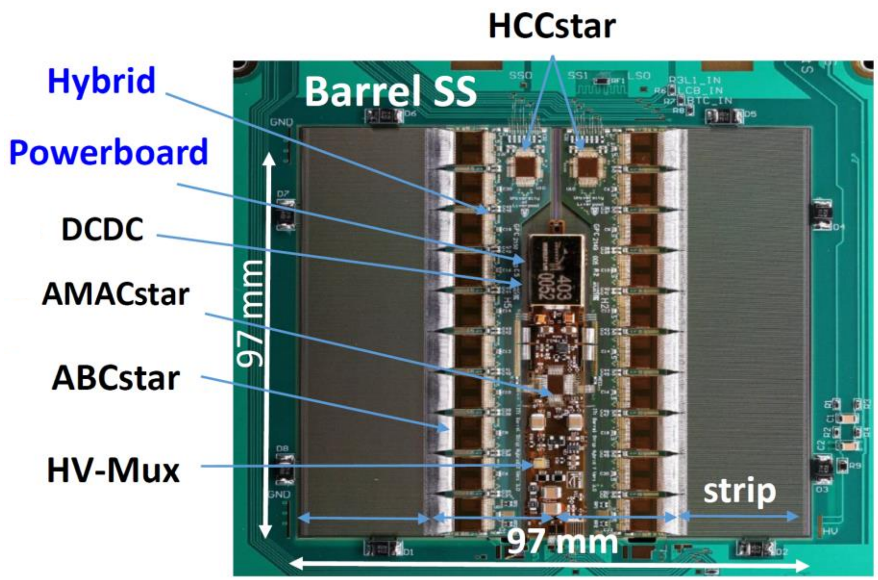
Hybrid and Powerboard

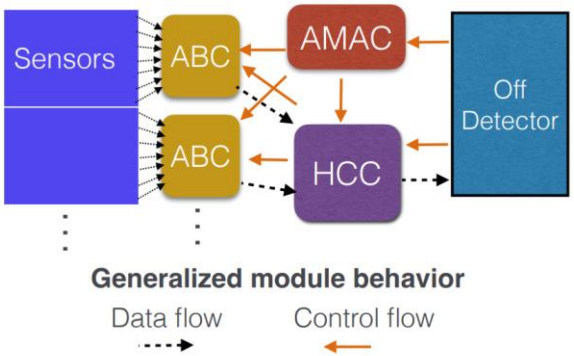
Hybrid

- 10 x **ATLAS Binary Chip (ABCstar)** : custom FE ASICs read 256 channels
- 1x **Hybrid Controller Chip (HCCstar)** : an aggregation readout chip as interface between ABCstars and stave

Powerboard

- **AMACstar**(Autonomous Monitoring And Control): monitors voltage/current/temp
- **DC-DC converter** transforms 11V supply to 1.5V for ASICs

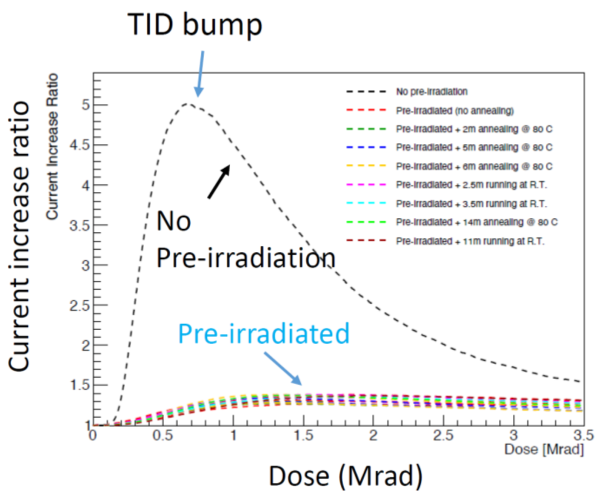




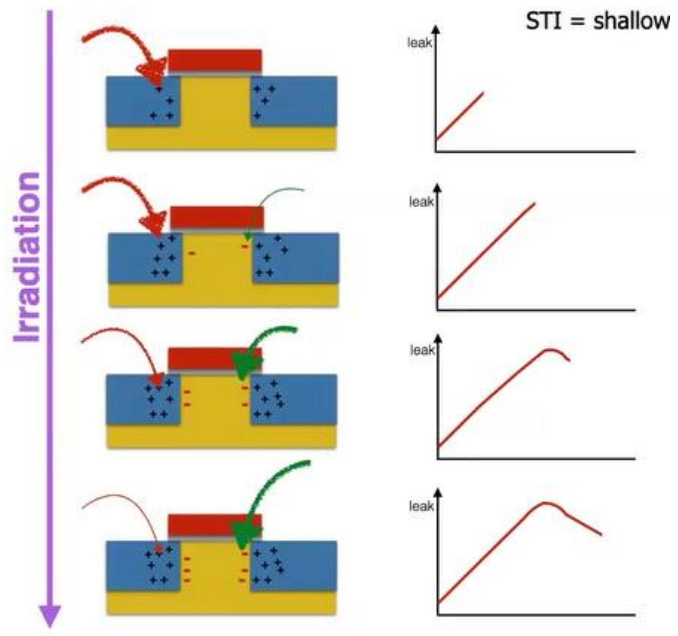
All connections are made by Al wire-bonds

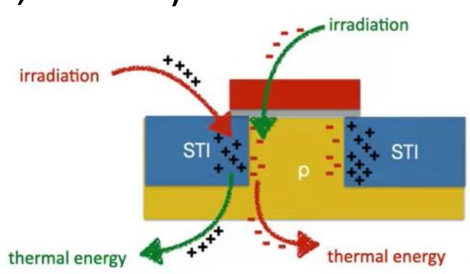
ASICs and TID Bump

- All 3 ASICs made in **130nm CMOS** technology at **Global Foundries (GF)**
- **TID bump**: a well known feature of 130nm GF chips
- Surface effects: generation of charge traps due to ionizing energy loss (Total Ionising Dose, TID)



- Leakage current was induced by positive charge trapped in the bulk of the shallow trench isolation (STI)
  - The creation/trapping of charge (by radiation, faster)
  - Its passivation/de-trapping (by thermal excitation, slower)



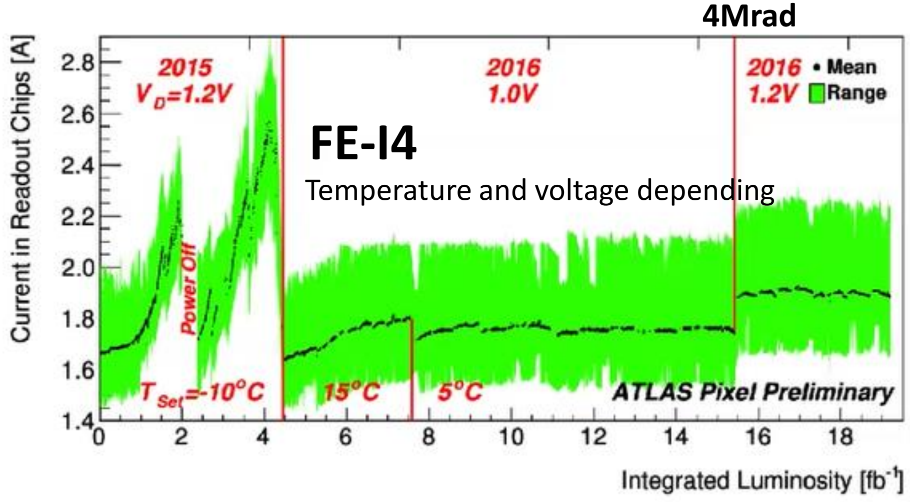


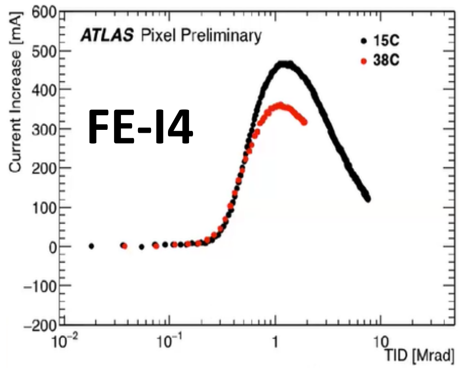
GF 130nm ASICs TID Bump Solution

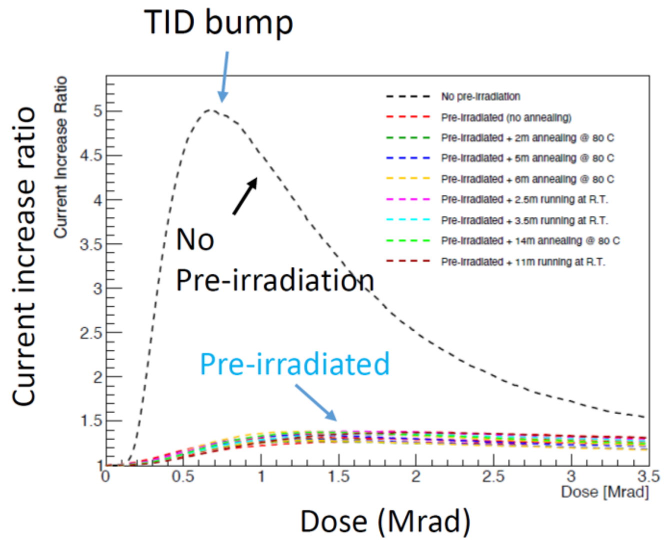
Big challenge on power and cooling. How to Mitigate?

IBL readout chip FE-I4 (130nm)

- Insertable B Layer (innermost pixel layer) installed @2014





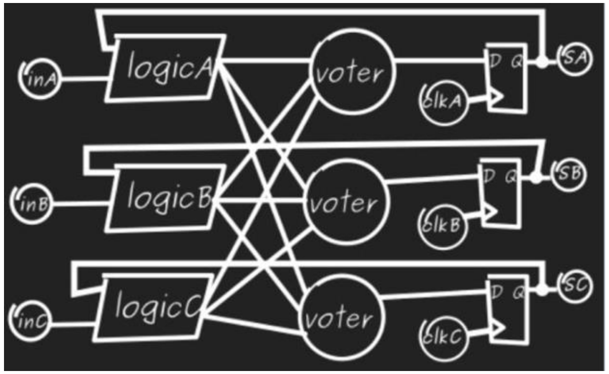


ITk Strip ASICs

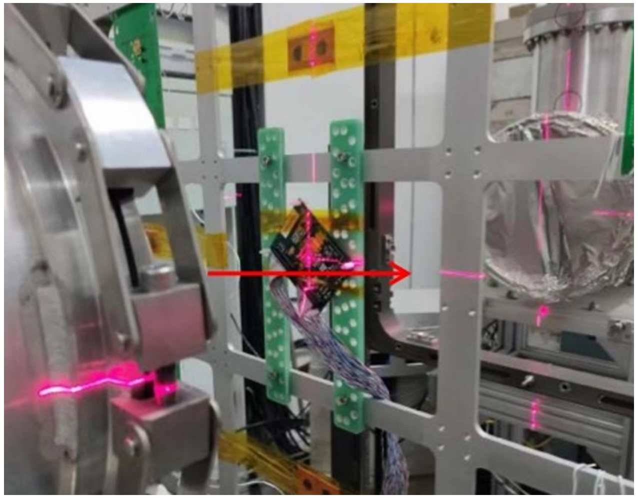
- Pre-irradiating the ASICs to remove the peak
- All 3 ASICs are pre-irradiated using ^{60}Co to 5 Mrad

ASICs and Single Event Effects

- **Single Event Effects (SEE)**:change of state in memory/logic due to an electrical disturbance from radiation, resulting in wrong data and misconfiguration
- **Mitigation** of Single Event Effects
  - Triplication logic and flip-flops as well as reset and clock trees
  - Voting system



- **Irradiation test of ABCstar and HCCstar**
  - $3\text{x}10^9$ protons/cm^2/s @80MeV at CSNS
  - Send 0/1s to chips and read them back (configuration registers and physics package)

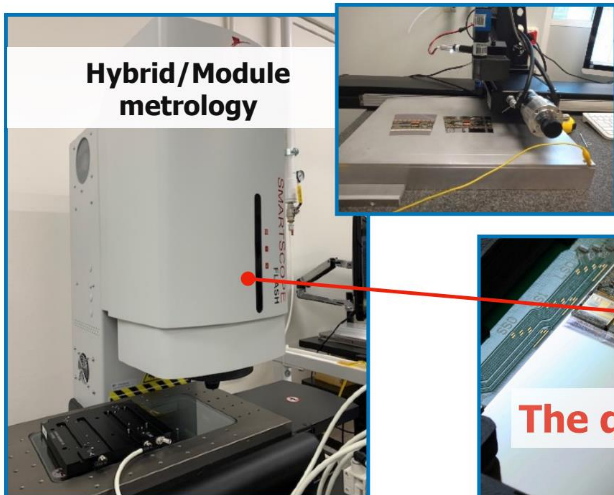


Data flow SEE: $\mathcal{O}(10^{-10})$errors/event/chip

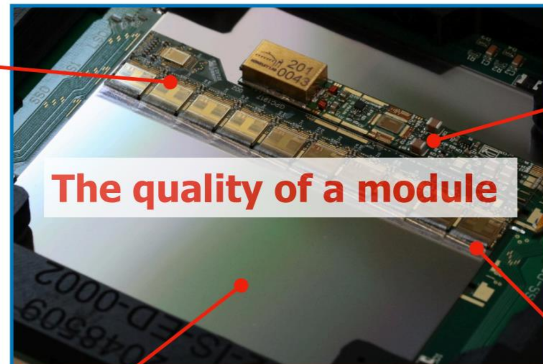
noise occupancy:$\mathcal{O}(10^{-2})$errors/event/chip

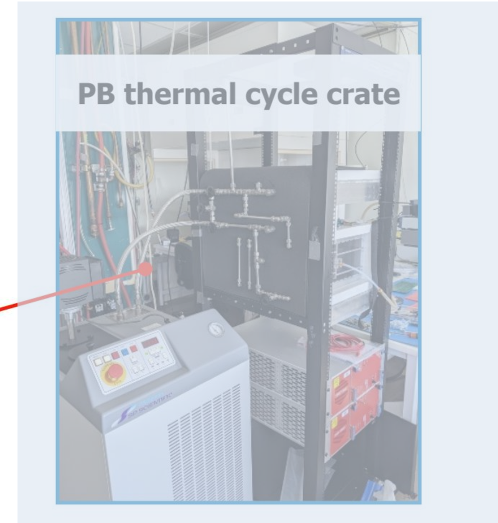
Chip Type	Institute	$\sigma_{\text{SEU}}[cm^2/p]$
V0	IHEP	$(6.3 \pm 0.08) \times 10^{-12}$
	TRIUMF	$(3.7 \pm 0.03) \times 10^{-12}$
V1		$(7.4 \pm 0.08) \times 10^{-12}$

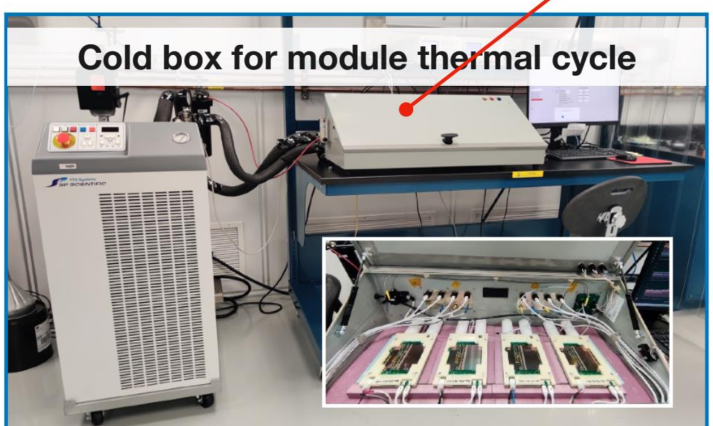
Hybrid and Module Quality Control @IHEP



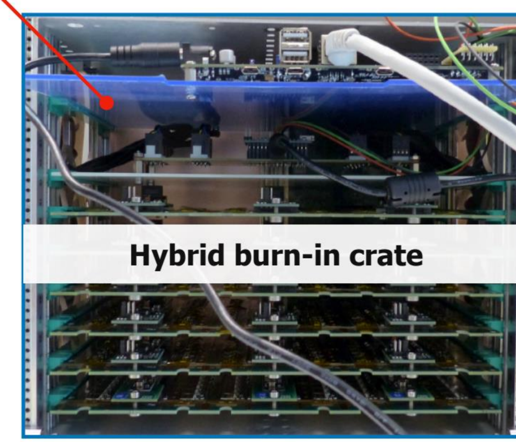
position, tilt, glue height







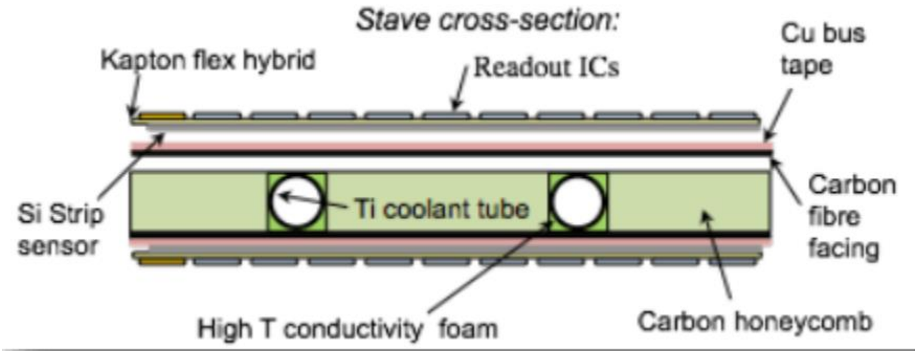
10 cycling between -40℃ and +40℃, 12 hours

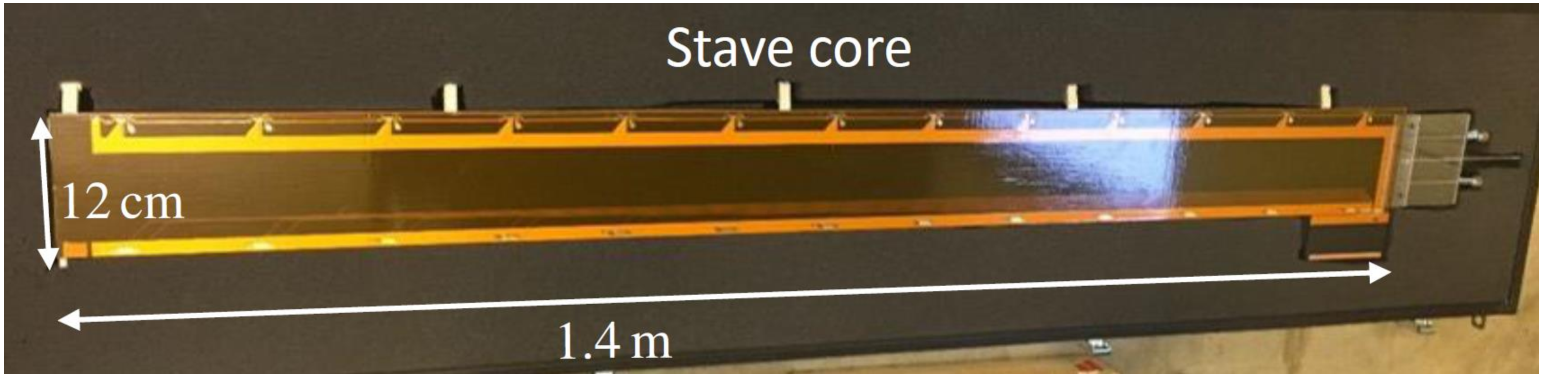


100 hours at 40℃

Local Support Structure: Stave Core

- Mechanical support using high stiffness and high thermal conductively carbon fiber
- Embedded Ti cooling pipes with evaporative CO2 $(-40°C)$
- Copper on Polyimide (Kapton) bus tapes routing electrical connections from and to modules

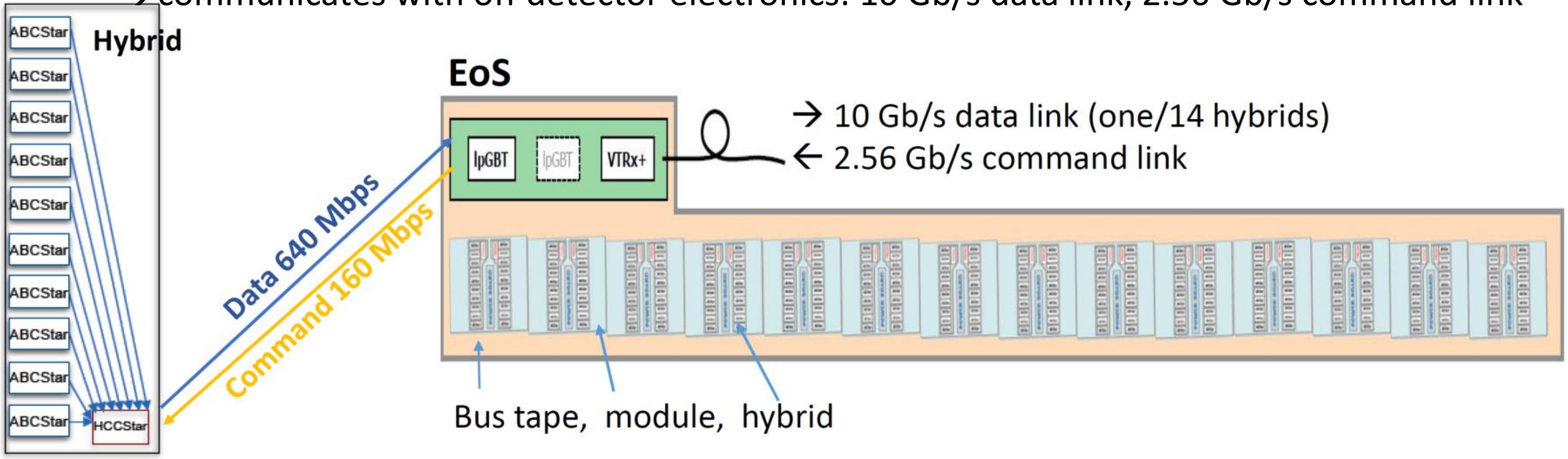




Staves

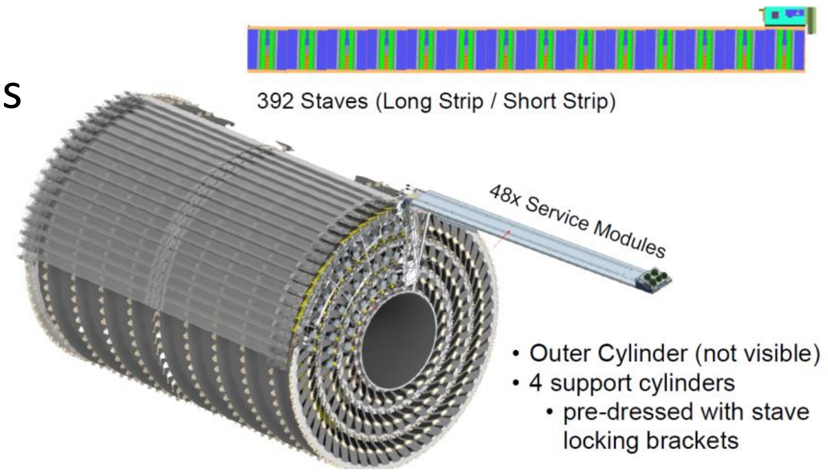
- **28 Barrel modules on each stave (14 modules per side)**
  - Modules are rotated wrt the beam line by $\pm$26 mrad to provide stereo information
- **Readout and control electronics**
  - **ABCstar**: FE chips communicate with HCCstar on each hybrid
  - **HCCstar**: send data at 640Mbps and receive clock and commands at 160Mbps from the End of Substructure (EoS) board over bus tapes
  - **EoS board**: fibre optic driver/receiver (**VTRx+**) and low power GigaBit Transceiver (**lpGBT**, 65nm CMOS CERN developed ASIC)

    → communicates with off detector electronics: 10 Gb/s data link, 2.56 Gb/s command link

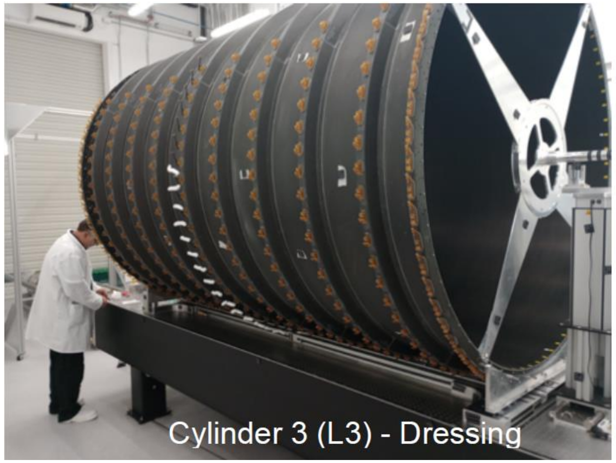


Strip Barrel Integration

- **Staves will be inserted in four concentric Carbon cylinders**
  - 392 barrel staves in total
  - Pre-dressed with stave locking brackets
- The global structure, Outer Cylinder (**OC**), hosts the ITk
- **The barrel integration will be performed at CERN**

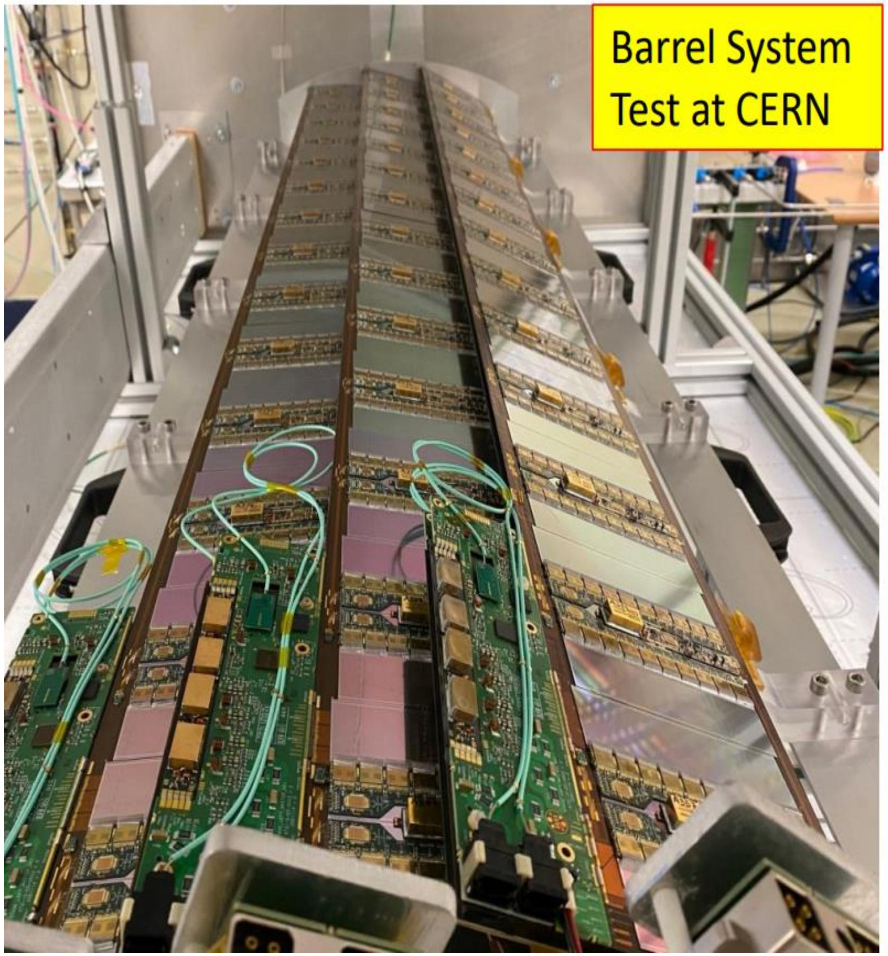


Global Structure :Outer Cylinder (OC)
Hosts the ITk



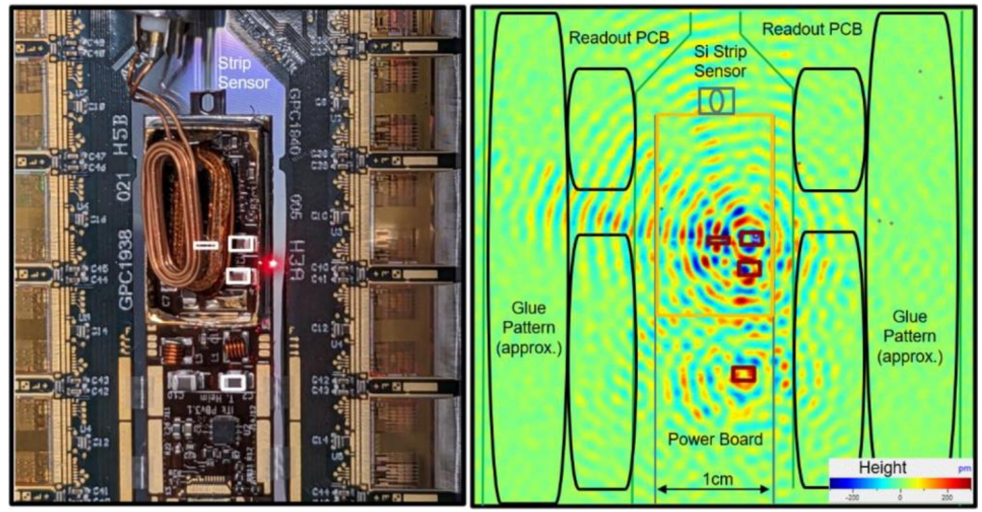
Strip System Test

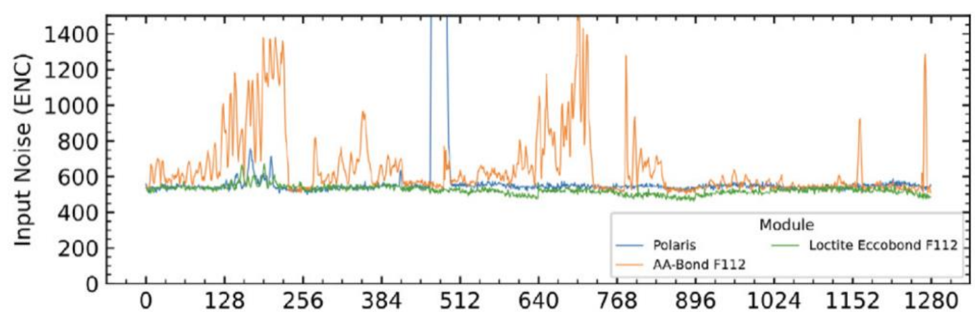
- **System Test validates production chain with final parts and cooling before production starts**
  - Powering chain, cooling, readout…
  - Parallel readout of multiple staves at 1MHz
  - Tests with CO2 cooling system
- **Barrel system test is populated with 8 staves (5 LS + 3 SS)**



Cold Noise delayed Module production by a year

- Unfortunately in May 2022 before modules enter production, a technical issue was discovered
  - **Cold Noise appear below $-20°C$,** only in strip channels under PB and hybrids
  - Dedicated studies tracked down to **capacitors in the DCDC** domain of the powerboard vibrating at 2MHz
  - **Piezoelectric effect** below $-20°C$
  - **Vibrations** travelling across the sensor and coupling back into the sensors
  - By May 2023 a **mitigation** technique was put in place: **changing the glue** which minimizes the noise (different stiffness)

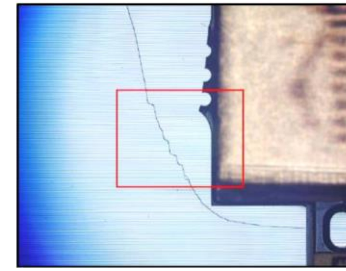


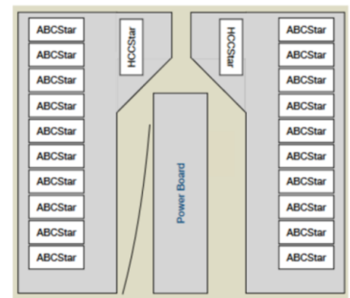


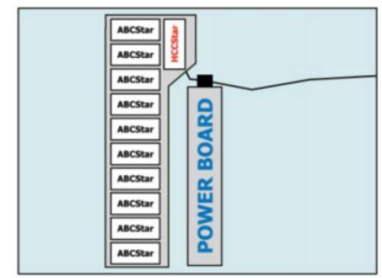
- **Module production was delayed by a year**

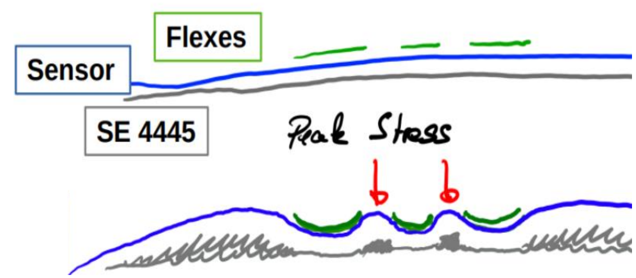
Project status – Sensor Cracks

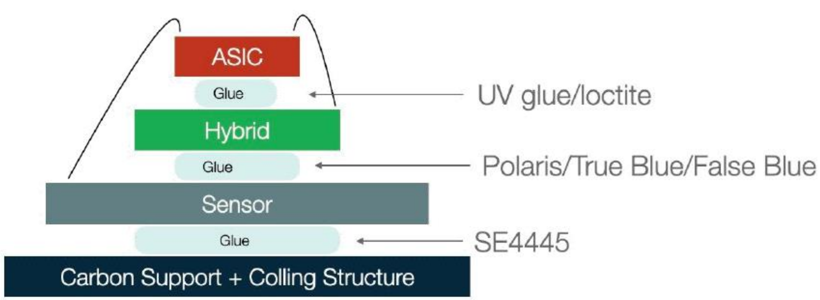
- Another technical challenge discovered in June 2023 during stave tests
- Some sensors failed high voltage testing (early breakdown <100V)
- Cracks appear at some point during **thermal cycling/powering (R.T. to $-40^{\circ}\mathrm{C}$)** only on some modules
- Simulations indicate the issue is the coefficient thermal expansion **(CTE) mismatch** between bybrids/powerboard and sensor
  - Stress peaks between hybrids and powerboard
- **Mitigation**
  - **'Interposer'** added between the flexes and sensor
  - 95% of stress reduced











IHEP Site Module Production

- To deliver 1000 ITk Strip barrel modules and contribute to system integration/testing
- Passed all 29 Site Qualification steps for Module production
- Produced 8 prototype and 6 pre-production modules
  - Protoype 5LS + 3LS
  - PPA x 3 (1LS + 2SS) and PPB x 3 (3LS)

IHEP Site for ITk Strip Module

Summary

- In view of **HL-LHC**, the ATLAS experiment will upgrade its complete Inner Detector with an all silicon **Inner Tracker (ITk)**
- ITk is expected to improve the ATLAS performance operating under a harsh environment
- The **Strip detector** has been through many years of design and R&D with the **pre-production** ‘smoothly’ ongoing in several areas
- Two major technical issues have significantly delayed the production schedule
  - **Cold Noise** issue has been mitigated by changing the glues
  - **Sensor Crack** issue is still under investigation
- The production will start soon.

backup

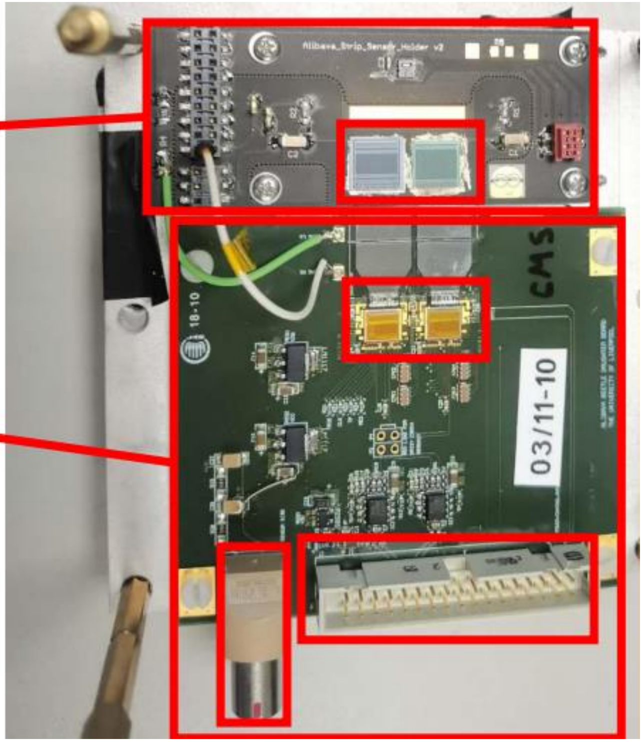
Alibava System

- ALiBaVa (A Liverpool Barcelona Valencia collaboration) system is an analogue readout system used to read out the signal from the sensors

- Two different laboratory setups
  - Radioactive source setup
  - Laser setup

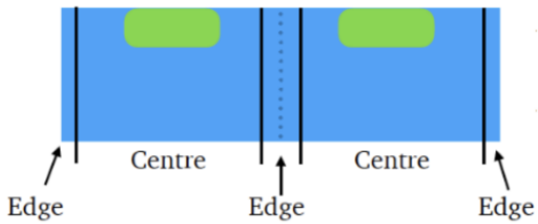
- Detector board
  - 1 or 2 sensors

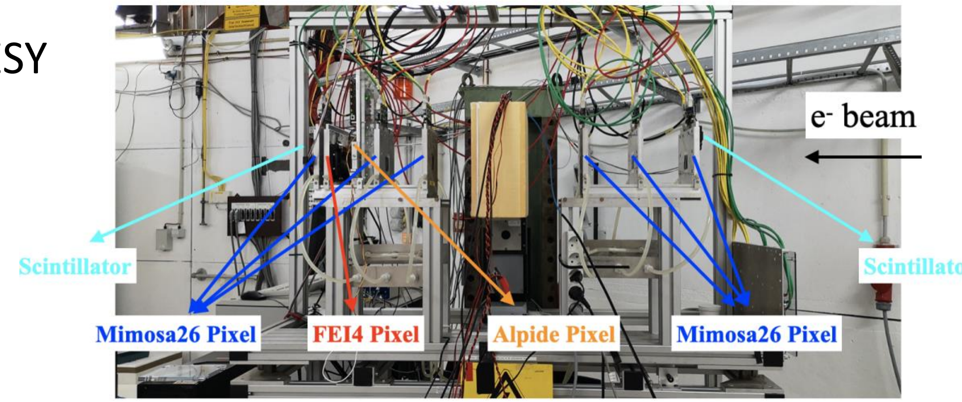
- Daughter board
  - 2 Beetle chips
    - 128 channels each
    - Analogue or binary output mode
  - HV power supply for sensors
  - Sending analogue output signals to the motherboard



Beam Test

- 5 GeV electron beam @DESY



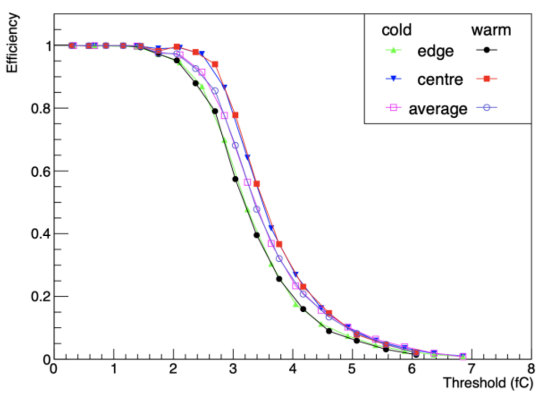


Main goal is to demonstrate pre-production module performance

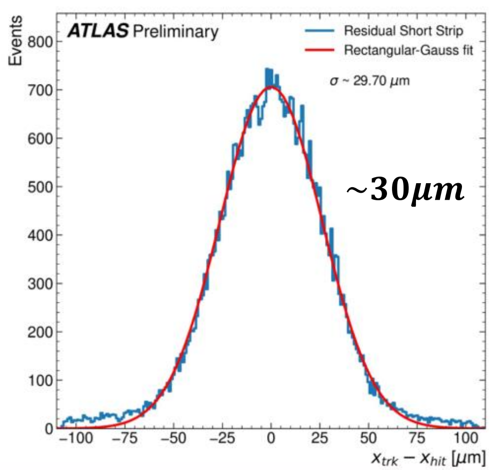
✓ To check uniformity of response across various sensor regions

✓ To evaluate track reconstruction capability

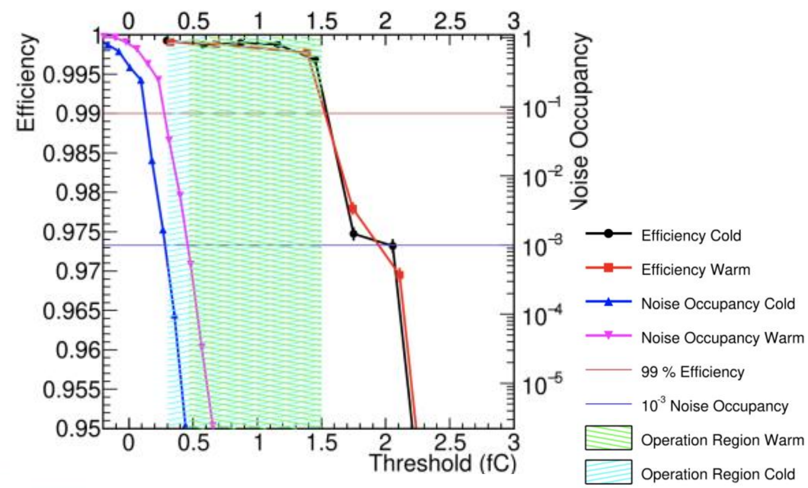
✓ To determine operational window: eff.>99% and noise occu.<0.1%



Sensor uniformity



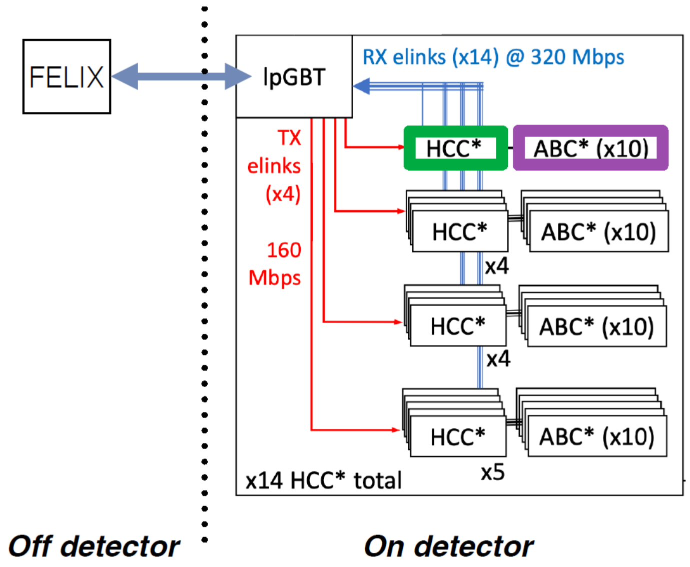
Tracking resolution

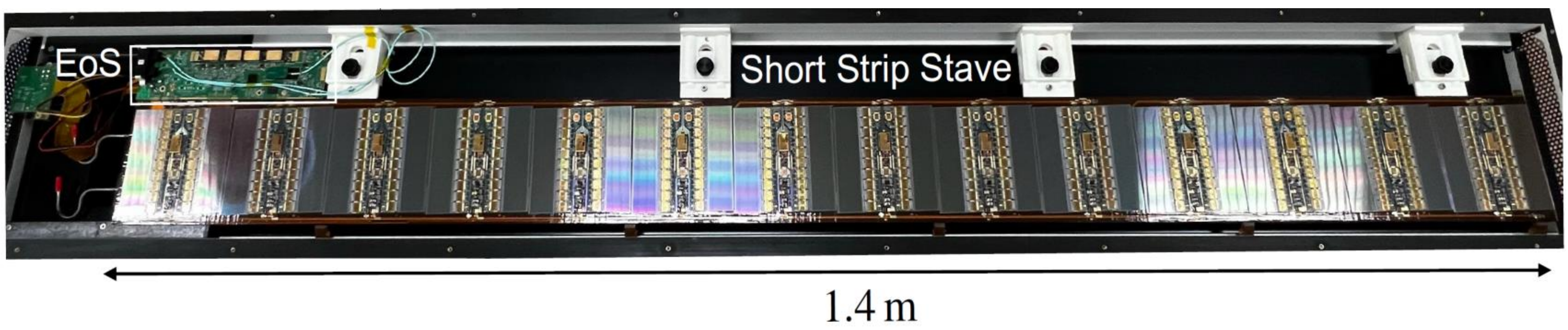


Operational Window

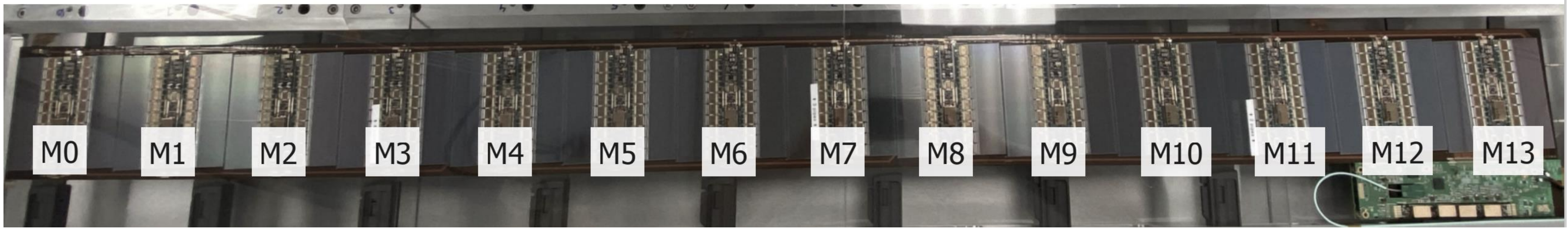
Staves

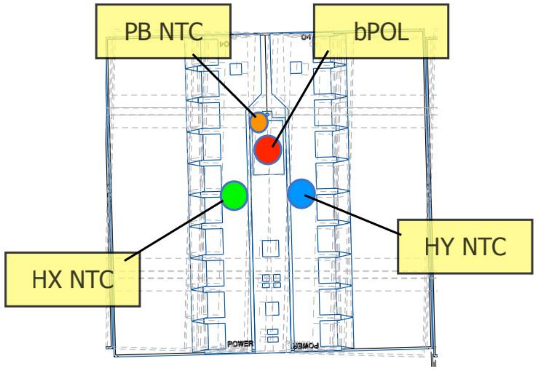
- **28 Barrel modules on each stave (14 modules per side)**
  - Modules are rotated wrt the beam line by ±26 mrad to provide stereo information
- The **End of Substructure (EoS)** electronic board
  - Facilities the communication and power distribution for all modules
  - Hosts radiation-hard fibre transmitter – receiver (**VTRx+**) and associated electrical transceivers (**lpGBT**, low power GigaBit Transceiver

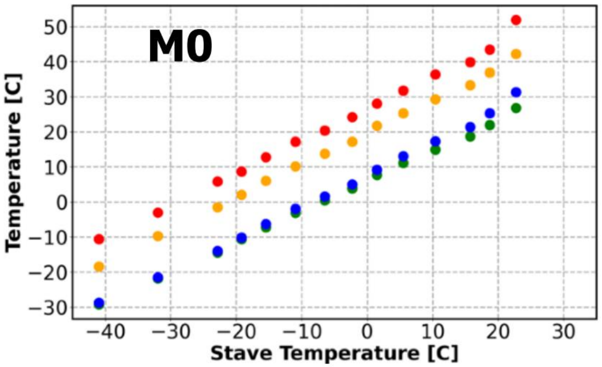


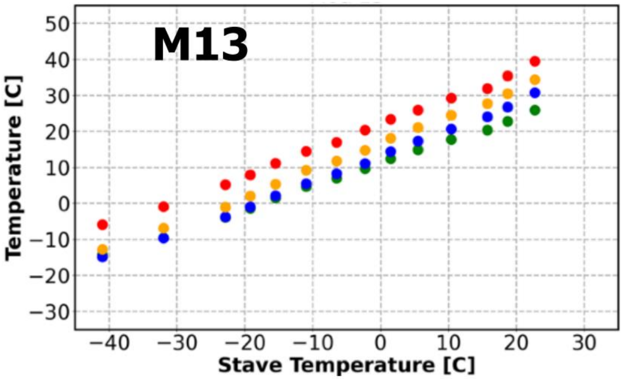


Staves: Temperature Measurement



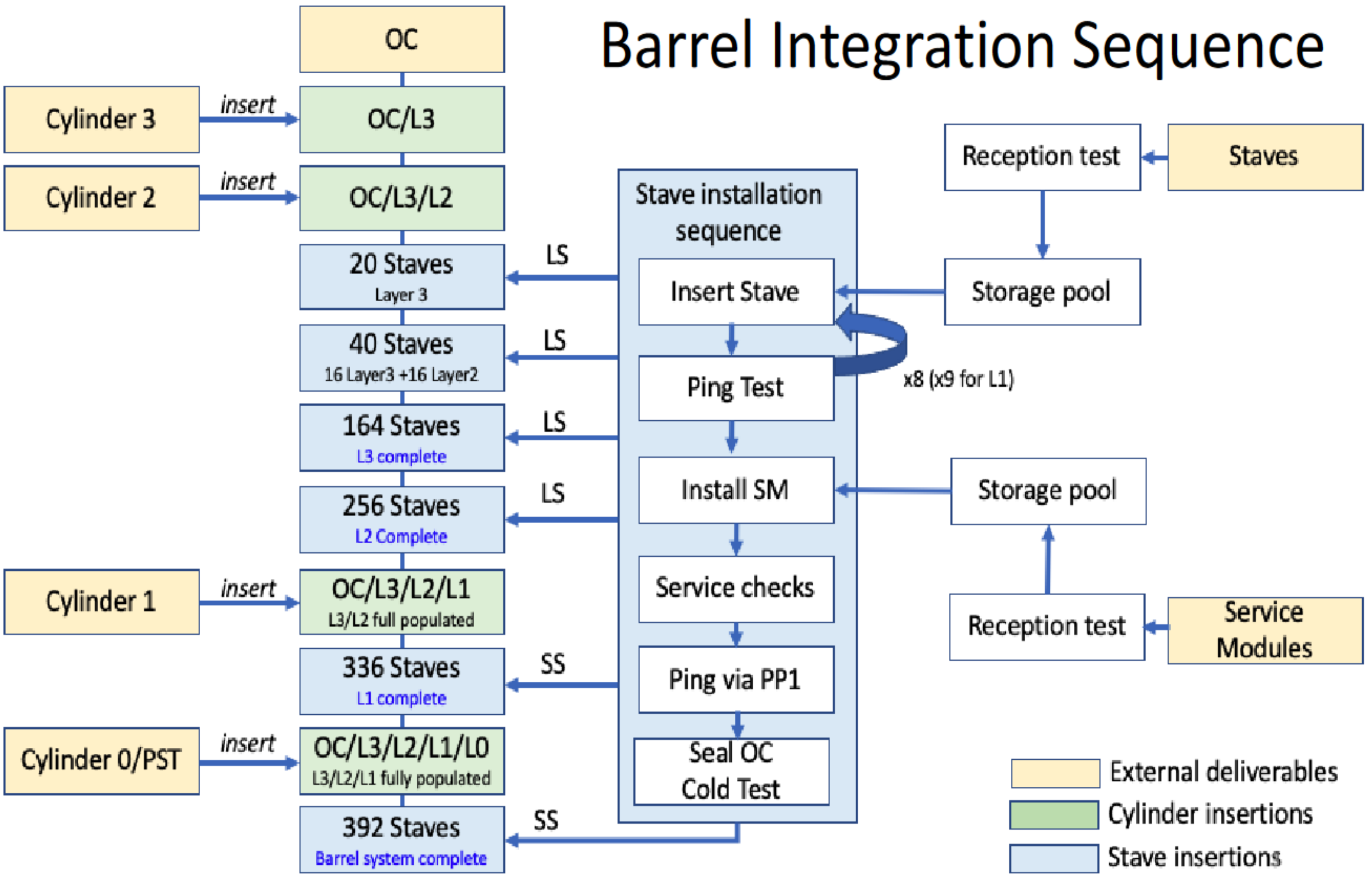






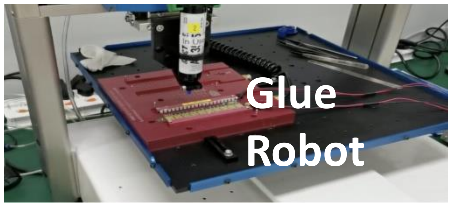
- AMACStar allows on-stave temperature monitoring using the 10K NTCs on hybrids and power boards - HX, HY and PB NTCs
- Affected by module-module variation
- Module temperatures linear with stave temperature

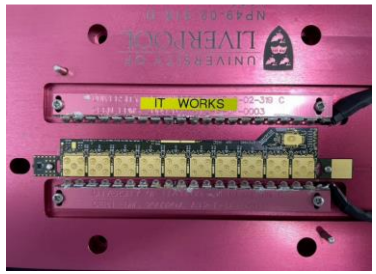
System Integration

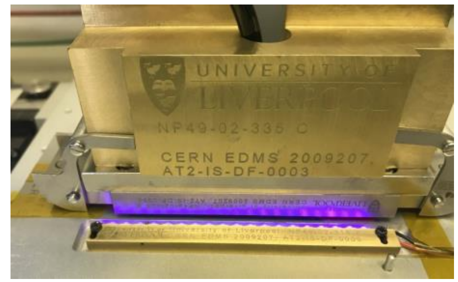


Module Assembly and Metrology @IHEP

- Amount and height of glue matters
  - Heat emission, mechanical support, wire bonding
  - Controlled by glue robot and tooling

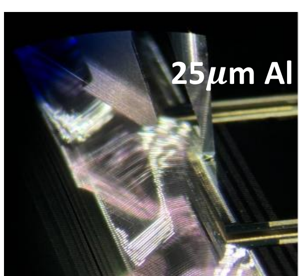


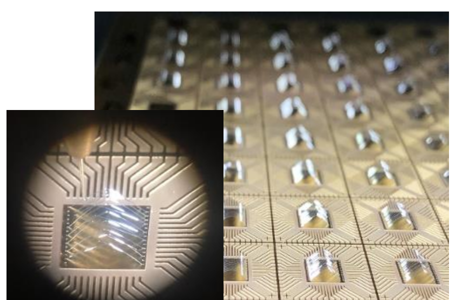




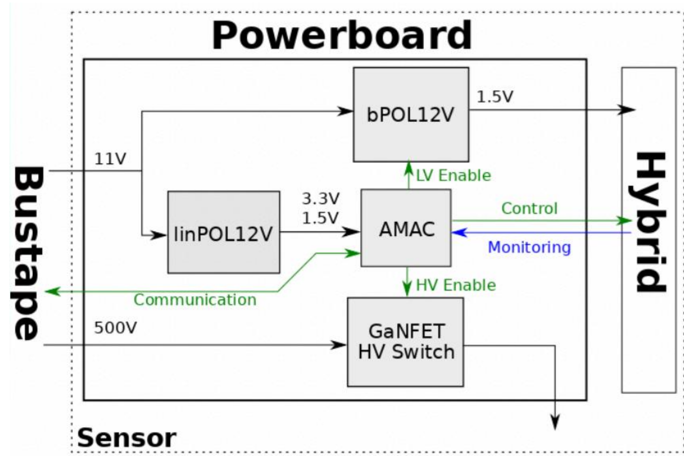
- Metrology for position and tilt, and glue height

- Pull test to measure the strength of bonded wires





powerboard



GaNFET

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

AMACStar

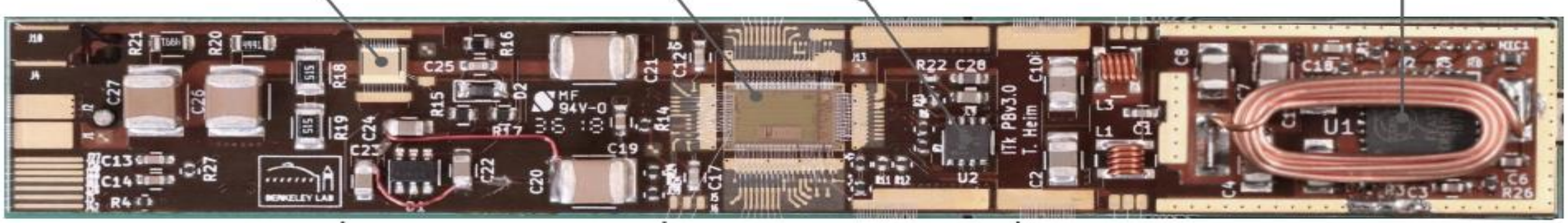
- Enables/Disable DCDC
- Measure Voltage, Currents and Temperatures

bPOL12V

- Radiation hard buck converter
- 11V input, 1.5V output
- Air-core coil

LinPOL12V

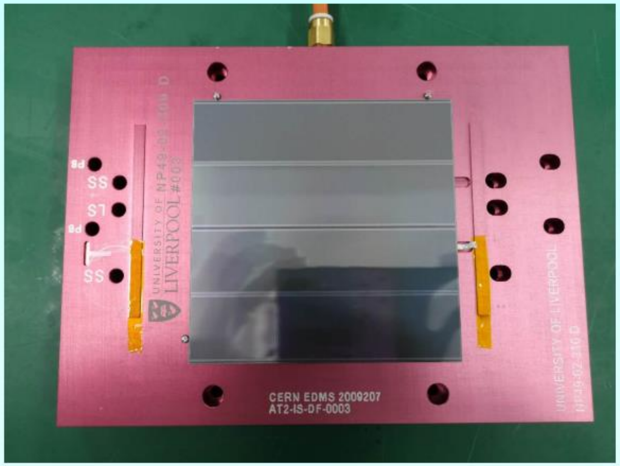
- Radiation hard linear regulator
- 11V input
- 1.4V output for AMACStar
- 3.3V output for HV switch enable



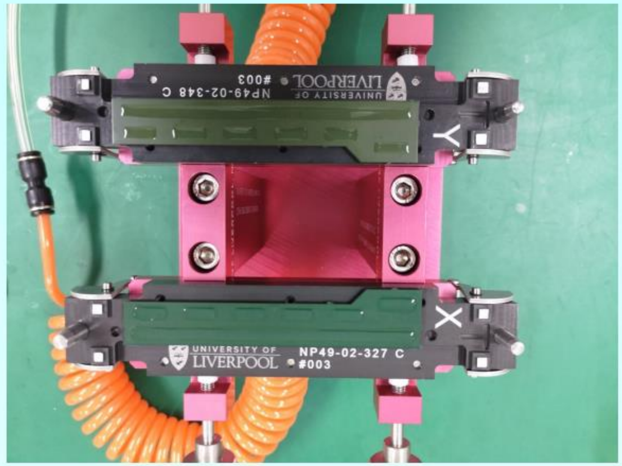
HV Filter | **HV switch** | **Measurement & Control** | **DC-DC conversion**

Module Assembly

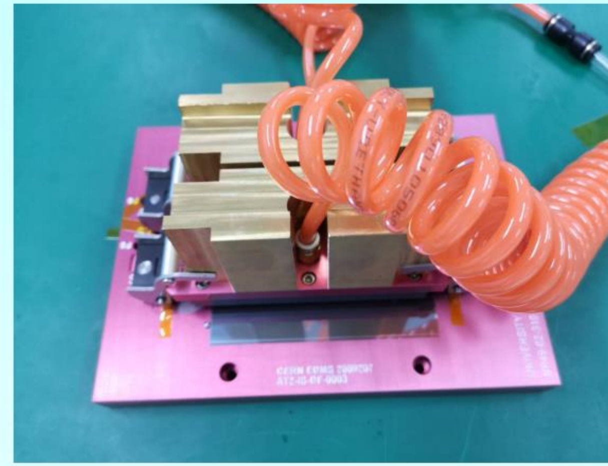
- Align Sensor on sensor plate



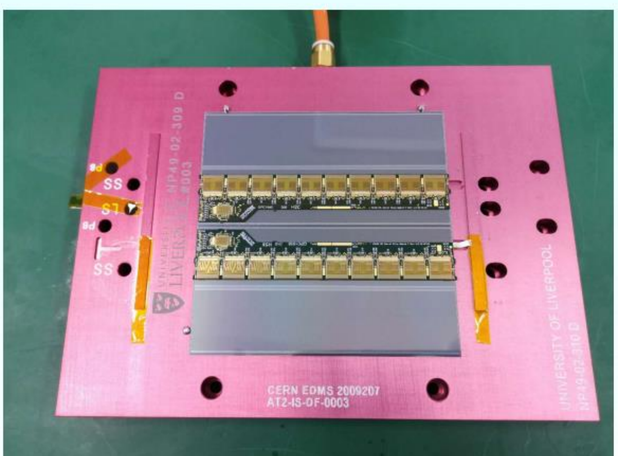
- Dispense glue on Hybrid through Stencil



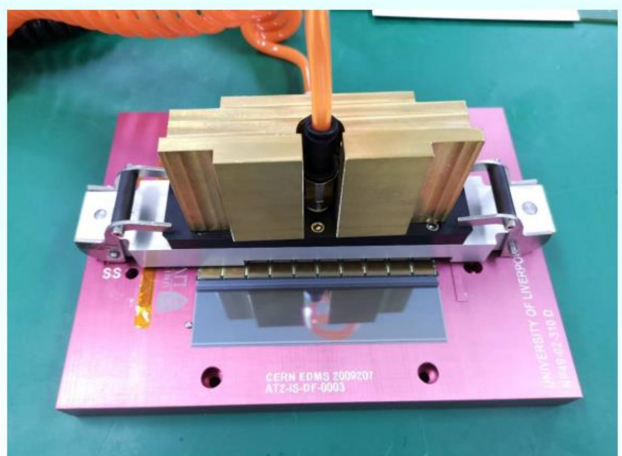
- Glue Hybrids on sensor



- Module without Powerboard



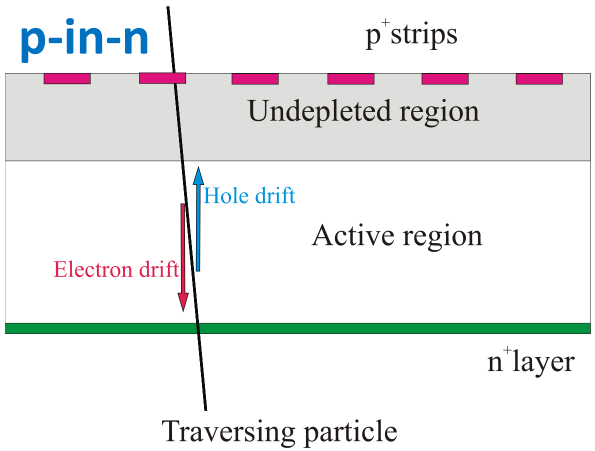
- Glue Powerboard to sensor



- Assembled Module

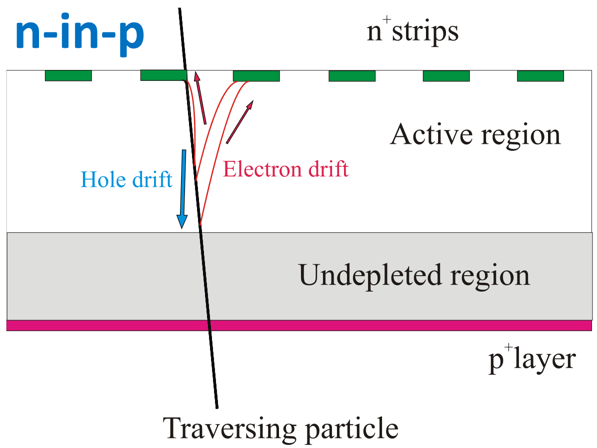
Type Invertion

n-type silicon after high fluences:
(type inverted)



- p-in-n (LHC)
  - Collects holes (slower)
  - Depleted from the back

p-type silicon after high fluences:
(still p-type)



- n-in-p (HL-LHC) ，
  - Collects electrons
  - High CCE even not fully depleted