ATLAS Detector Upgrade

Mei Zhao
Institute of high energy physics, CAS

ON BEHALF OF THE ATLAS CHINESE CLUSTERS

2024.11.13-17, QINGDAO

HL-LHC Upgrade

➢HL-LHC upgrade:

- Instantaneous luminosity will be up to **7.5×10^{34} cm^{-2}s^{-1}** which increases by a factor of 7.
- Average interactions per bunch crossing ~1.6 vertex/mm will increase from 50 to **200.**
- Particle density and radiation levels increase by an order of magnitude (radiation $>10^{15} n_{eq}/cm^2$).

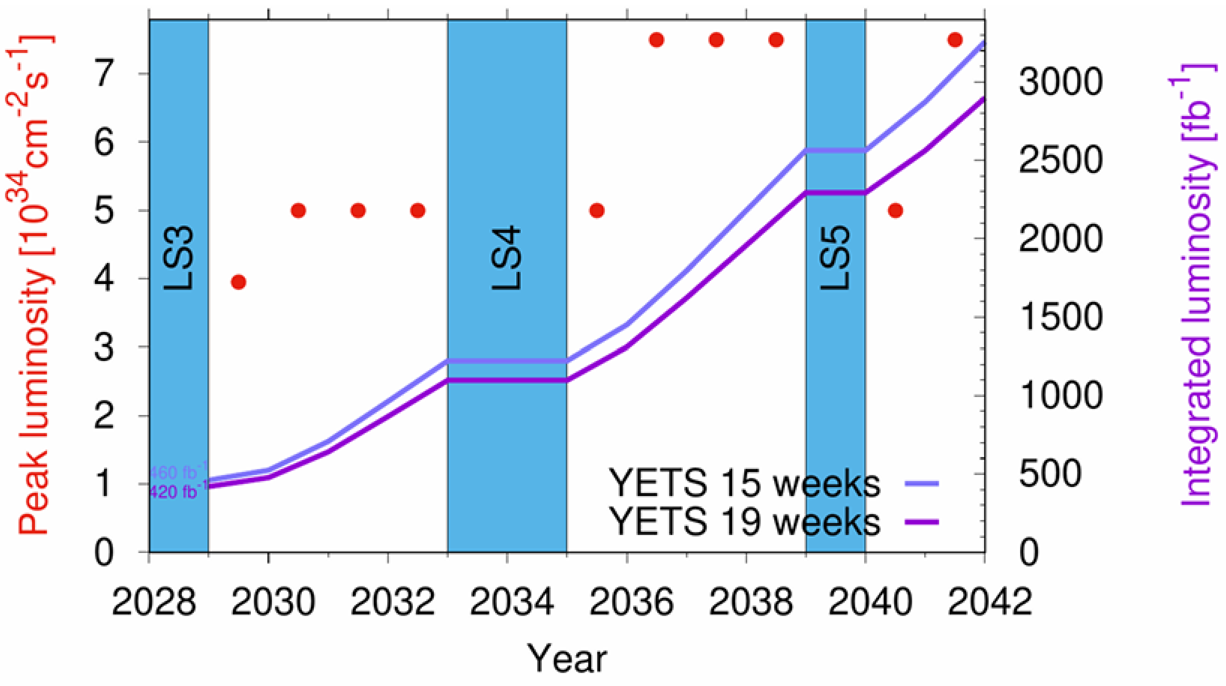
➢Higher Requirement of detectors:

✓Increased hit density : high granularity

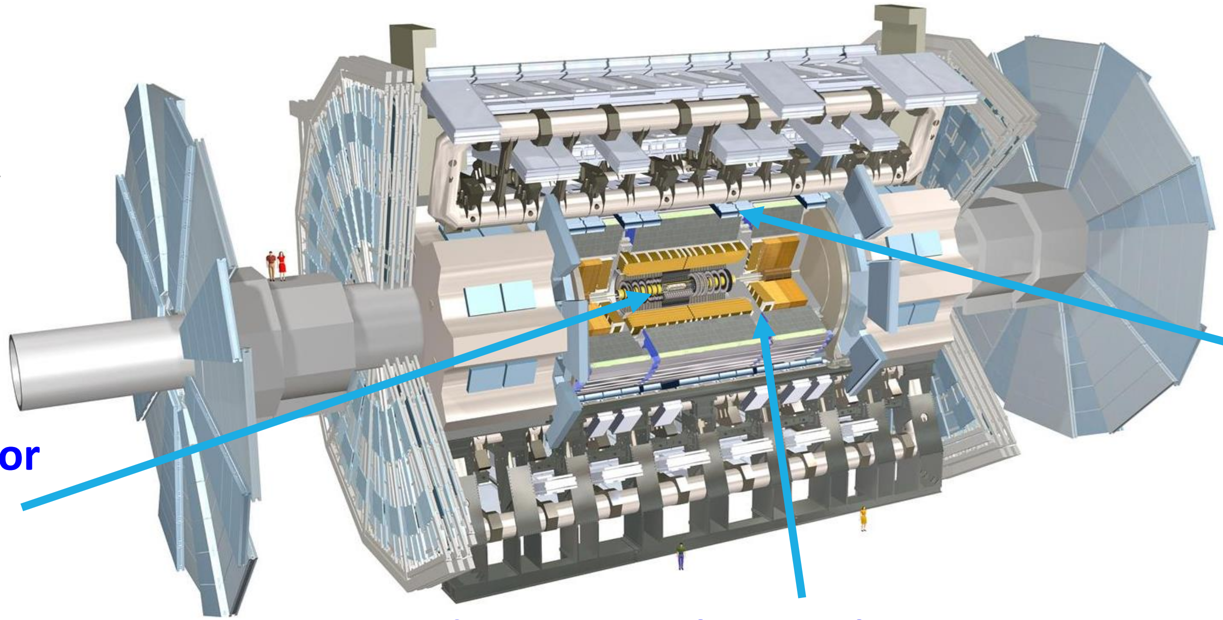
✓Increased data rate: improved readout and triggering

✓Increased radiation levels: higher radiation tolerance

✓Pile-up issues: quick response of hits



ATLAS Phase-2 Upgrade



New Muon system
Inner barrel region with new RPCs, sMDTs, and TGCs

ITK: Inner Tracking Detector
- All silicon with at least 9 layers up to $|\eta| = 4$
- Less material, finer segmentation

HGTD detector: High Granularity Timing Detector
LGAD detector, high granularity and precise timing information

Upgraded Trigger and Data Acquisition System
- Single Level Trigger with 1 MHz output
- Improved 10 kHz Event Farm

Electronics Upgrades
- On-/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors
- 40 MHz continuous readout with finer segmentation to trigger

Other upgrades
- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

ATLAS Phase-2 Upgrade

- **Chinese Clusters: IHEP, USTC, NJU, SDU, Tsinghua, SJTU**

- **Contributions:**

ITK: IHEP, Tsinghua

10% strip barrel modules (> 1000 modules, ~10m^2 of sensor surface)

500@IHEP / 500@RAL (UK)

HGTD: IHEP, USTC, NJU, SDU, SJTU

100% LGAD sensor (90% IHEP + 10% USTC)

LGAD sensor testing(IHEP, USTC, SJTU)

50% ASIC testing (IHEP)

~33% flex tail (SDU)

44% detector assembly (34% IHEP + 10% USTC)

100% front-end electronics board (IHEP +NJU)

>16% high-voltage electronic systems (IHEP+ SDU)

Software and performance (USTC, IHEP)

Muon: USTC, SDU, SJTU

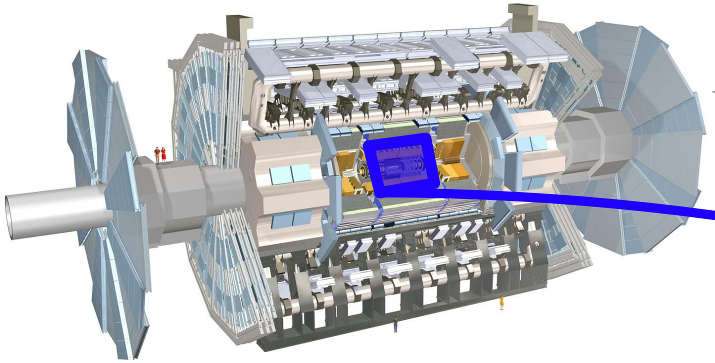
~900 readout panels

72 gas gaps

360 singlets

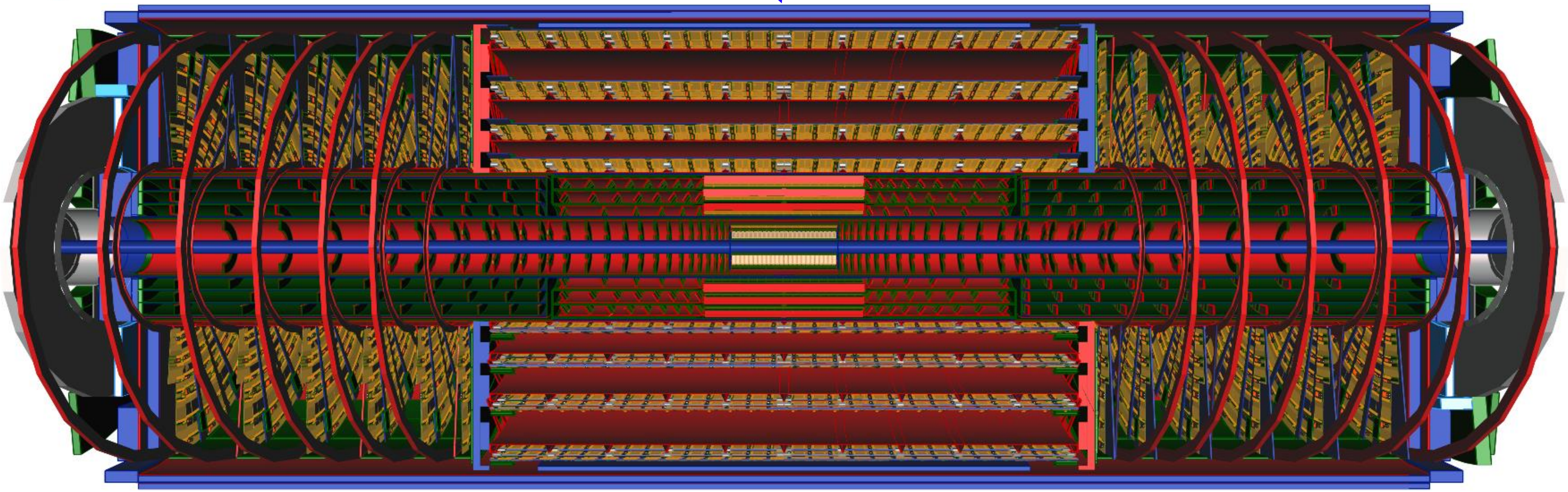
~5000 FEE production and test

ATLAS Inner Tracker (ITk) Upgrade



Inner Tracking Detector (ITk)

- All silicon with at least 9 layers up to |η| = 4
- Less material, finer segmentation



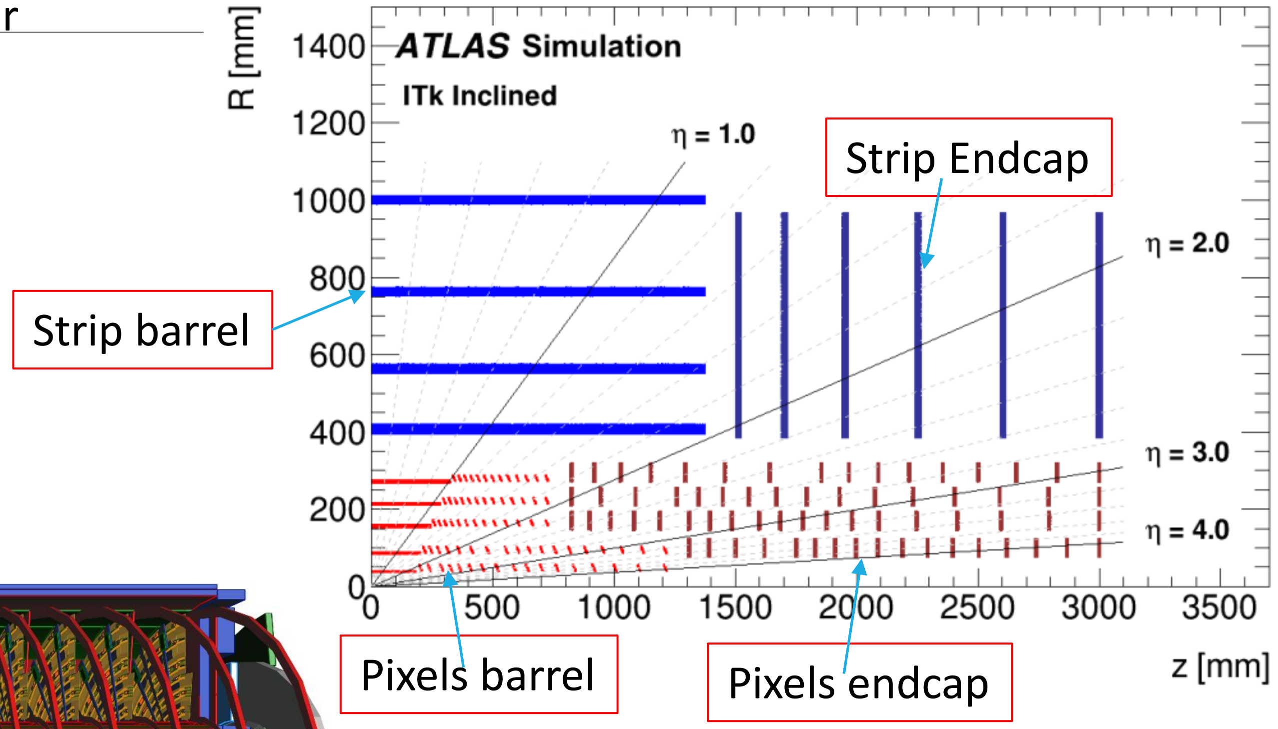
ATLAS Inner Tracker (ITk) Upgrade

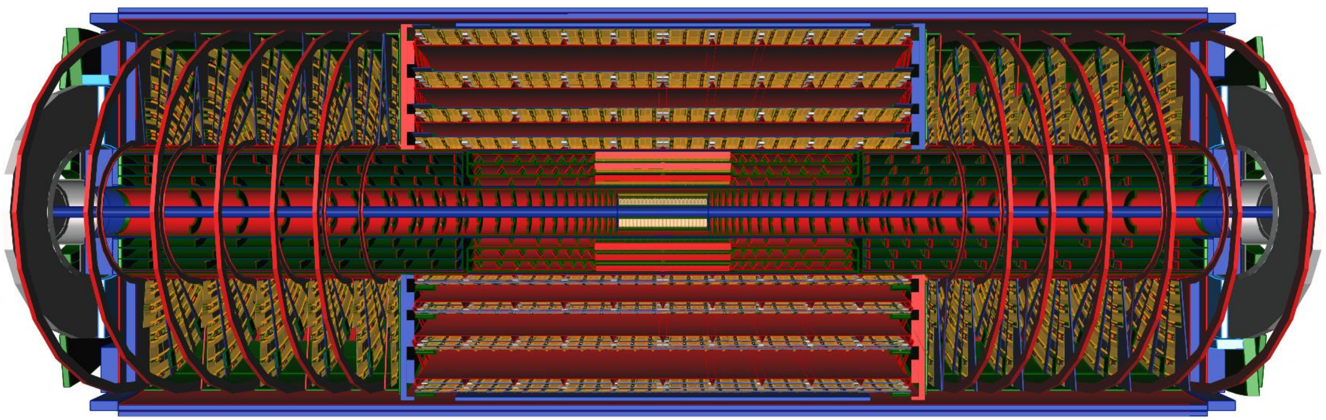
- Current Inner Detector
  ITK Pixels , ITK Strips , Transition Radiation Tracker

- Coverage increased up to $|\eta| = 4$

- $178\ m^2$ of silicon in the combined system (x2.7 larger)
- 5 billion individual channels

Schematic layout of the ITK for the HL-LHC phase of ATLAS





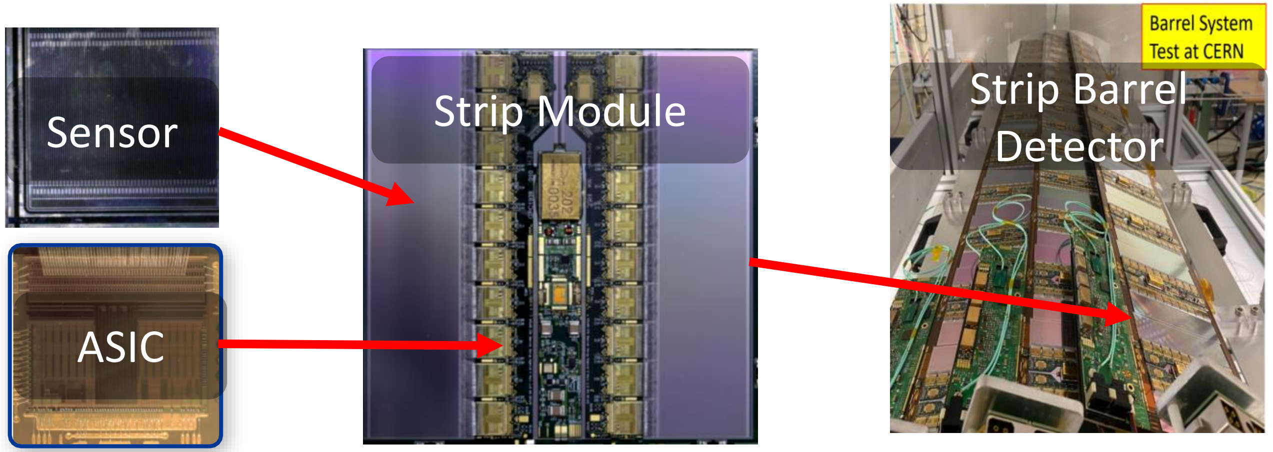
China ITk Strip Detector Contribution

China contribution(IHEP-Tsinghua)

- China (IHEP/Tsinghua) deliver 10% strip barrel modules (> 1000 modules, ~10m^2 of sensor surface)
  - 500@IHEP / 500@RAL (UK)

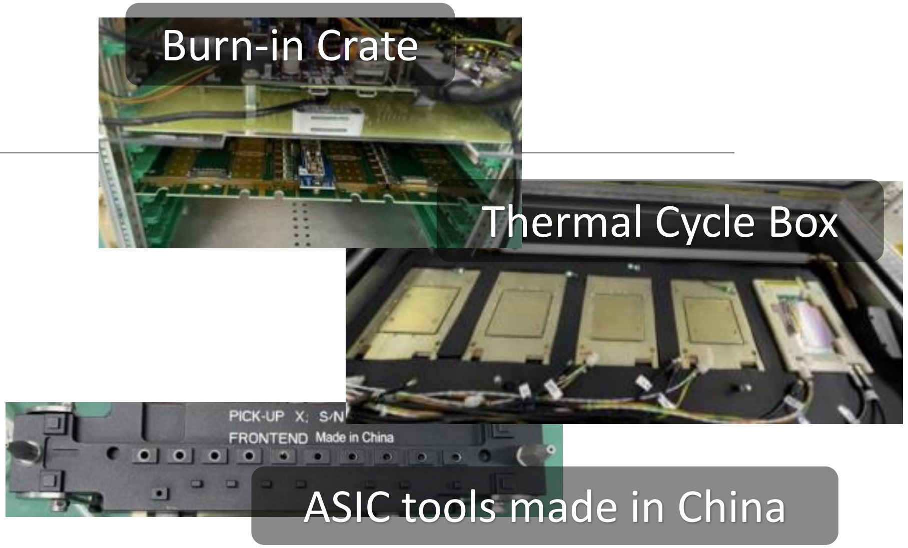
Recent activities

- High performance strip detector module production
- Radiation hard sensor and readout ASIC study
- Complex silicon detector system integration

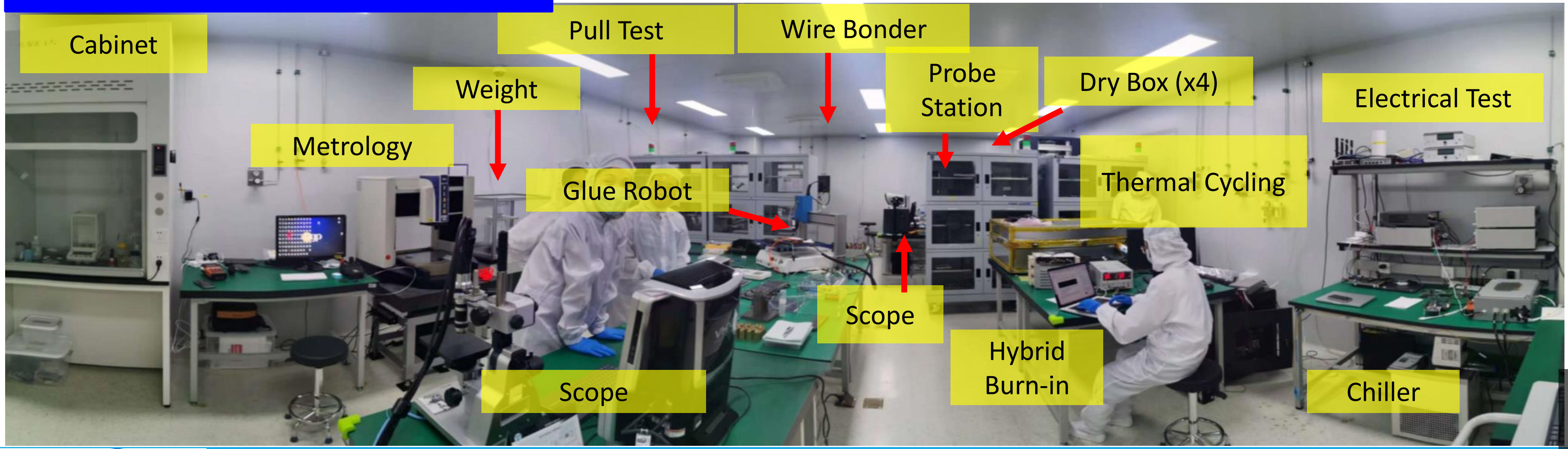


IHEP as Module Production Site

- **Manufactured production tooling in China**
- **Passed all 29 SQ Steps for Module production**
- **Module production starts**

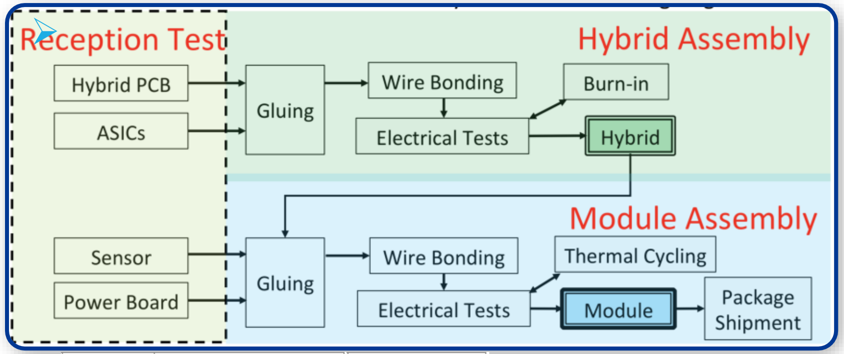


IHEP Site for ITk Strip Module



ITk Strip Module Production Procedure

- **Well defined module production steps to ensure High Quality Modules**
- **Standard Operating Procedure system be developed at IHEP for local production** http://atlasitk.ihep.ac.cn
  - Accessible to PC and Tablets with internal network
  - All SQ 29 steps have been implemented in SOP

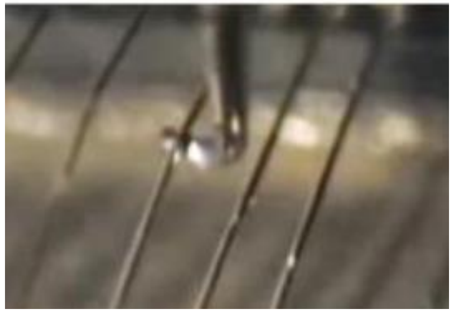


Step Number	Qualification Step	Review End Date
3.2	Sensor Storage	finished: 2021-06-17
6.1	PB Reception	finished: 2022-01-11
6.2	PB E tests	finished: 2022-07-14
6.3	PB Vis Insp	finished: 2021-12-16
6.4	PB Storage	finished: 2021-06-17
8.2	Storage + shipping of glue	finished: 2021-08-26
8.3	Assembling hybrids	finished: 2021-11-20
8.4	Glue weight measurements	finished: 2021-11-21
8.5	Bonding procedures: hybrids	finished: 2022-05-31
8.6	Metrology: hybrids	finished: 2023-03-07
8.7	Visual ins[illegible]: h[illegible]	finished: 2021-08-06
8.8	Hybrid Burn-In	finished: 2023-05-25
8.10	Hybrid Storage	finished: 2021-06-17
8.11	hybrid QC: single panel testing	finished: 2022-08-25
11.1	Storage of modules	finished: 2021-06-17
11.2	Cleaning module jigs	finished: 2021-06-16
11.4	Storage + shipping of glue	finished: 2021-11-29
11.5	[illegible]	finished: 2021-12-09?
11.6	Module assembly	finished: 2022-02-25
11.7	Metrology: modules	finished: 2023-07-10
11.8	Bonding procedures: modules	finished: 2022-05-25
11.9	Visual inspection: modules	finished: 2021-07-19
11.10	Module Thermal Cycling	finished: 2023-10-29
11.11	Single Module Electrical Test	finished: 2022-10-23
12.1	Shipping modules	finished: 2022-04-25
13.1	Cleanroom standards	finished: 2021-11-25
13.2	ASIC Compliance & Handling	finished: 2021-06-03
13.3	Bond Pulling Procedures	finished: 2021-12-03
14.1	Module Reception	Finished: 2022-01-25

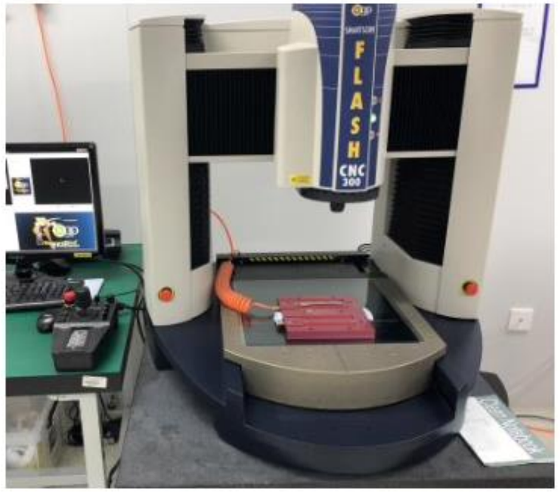
29 Steps

Calibration of glue amount

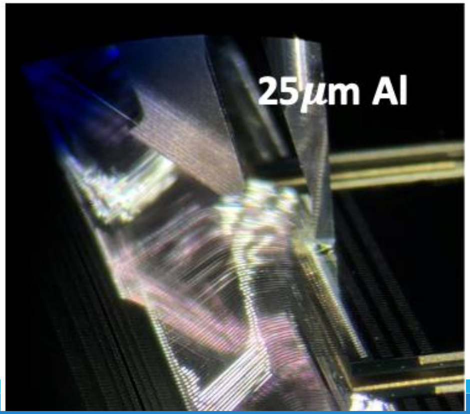
Pull force test



Metrology of glue thickness



Wire bonding



ITK Module production

- **10 prototype modules, be assembled and shipped to CERN**

PPA x3 (1LS + 2SS)

PPB x5 (LS)

Prototype

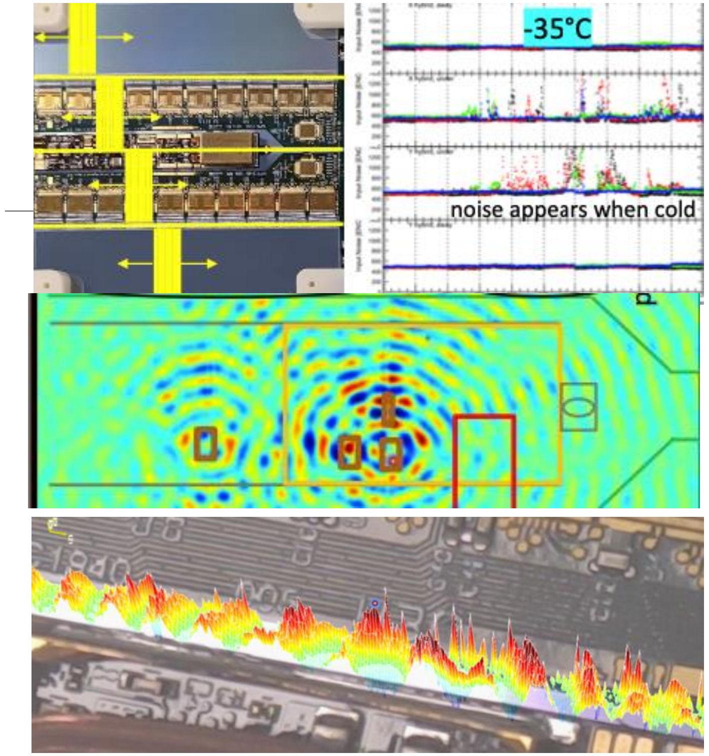
PPA

PPB

ITK Module production

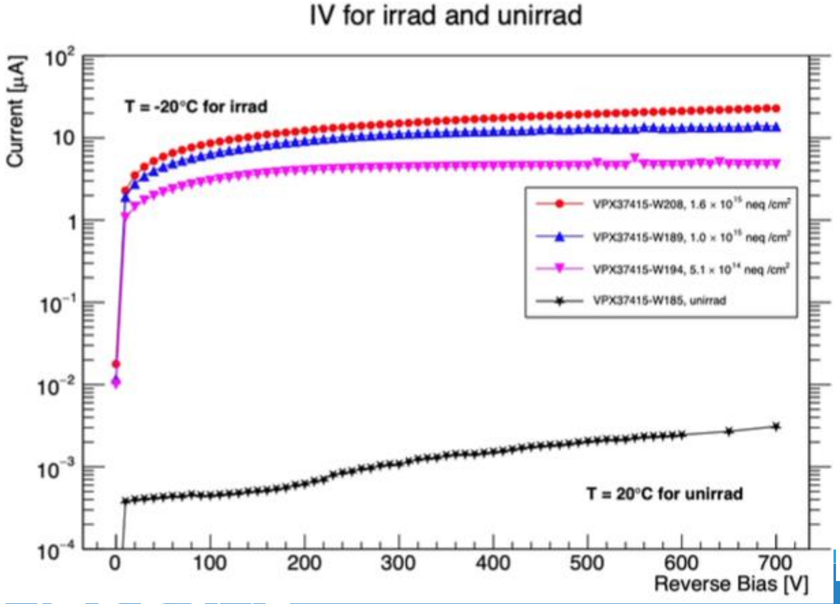
- **China-UK cluster, Shi Xin coordinated the development of 50% of the barrel track detectors**
- **Two FTEs from IHEP/Tsinghua based at RAL(UK)**

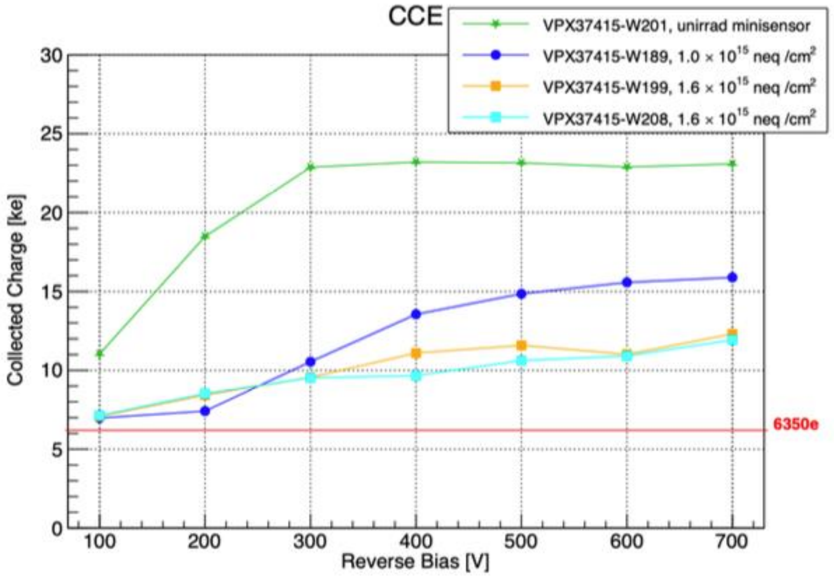
- Contributed to RAL site module production and stave loading
  - Assembled and tested over 20 prototype modules at RAL
- Lead effort for Cold Noise investigation
- Participate in module test beam results analysis
- Module stencil design and distribution
- Coordinate ASIC and power board distribution

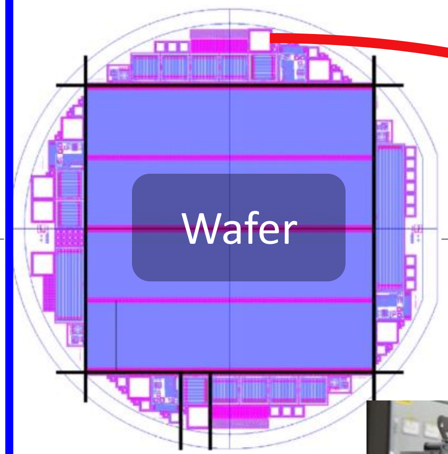


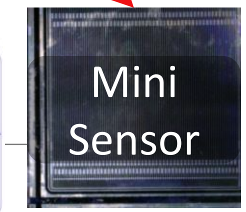
ITK Sensor Irradiation Study

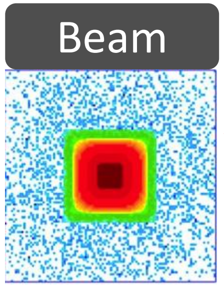
- **Sensor characterization at IHEP**
  - I-V, C-V, to check if any early breakdown
  - CCE (Charge Collection Efficiency)
- **Proton irradiation of strip mini-sensor be carried out at CSNS for quality assurance (QA) site**
  - 80 MeV proton fluence up to 1.6×10^{15} n_{eq}/cm^2
  - Developed temperature and humidity control chamber
- **Promote CSNS as a collaborative group certified sensor/ASIC radiation research site**

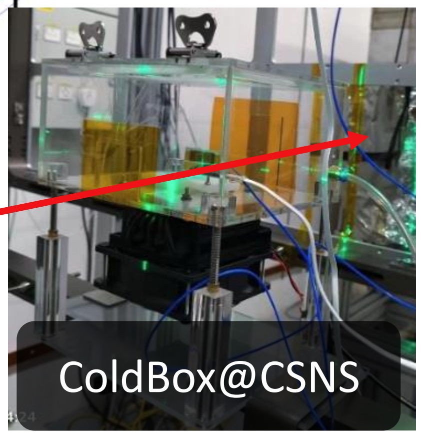


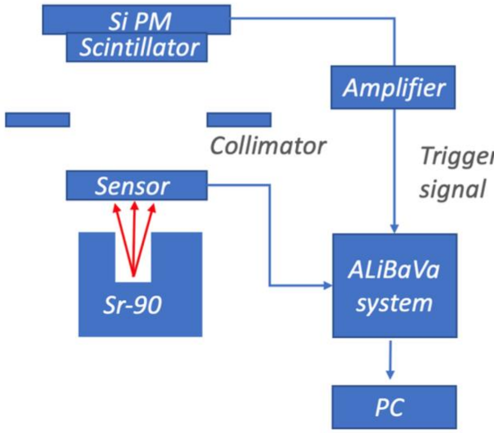












ATLAS ITK

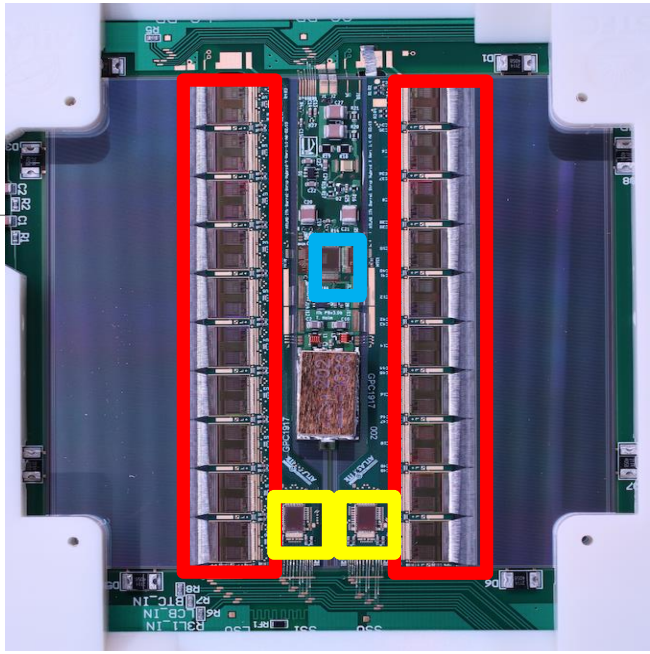
ITK ASICs Design and Study

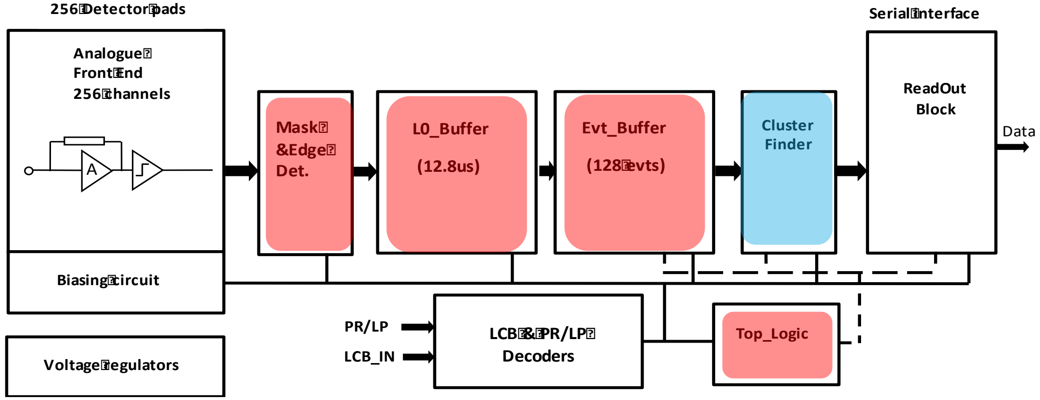
Contributed to design and verification of ABCStar

- Design of several digital blocks
- Build up the UVM setup for chip verification
- Completed ABCStarV0 single chip test
- ASICs TID with X-ray machine at IHEP

Irradiation test of ASICs at CSNS

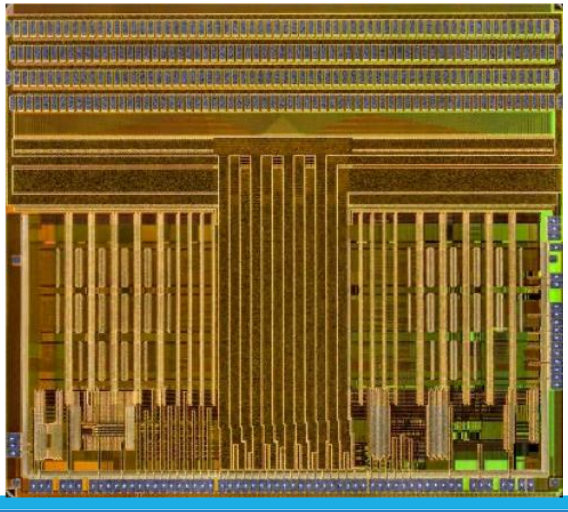
- SEE test of ABCStarV1, HCCStarV1
- SEE test of module level chip set, BETSEE

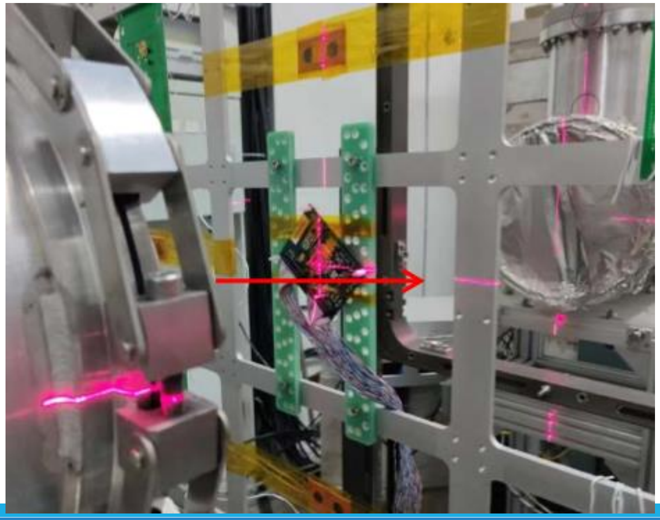




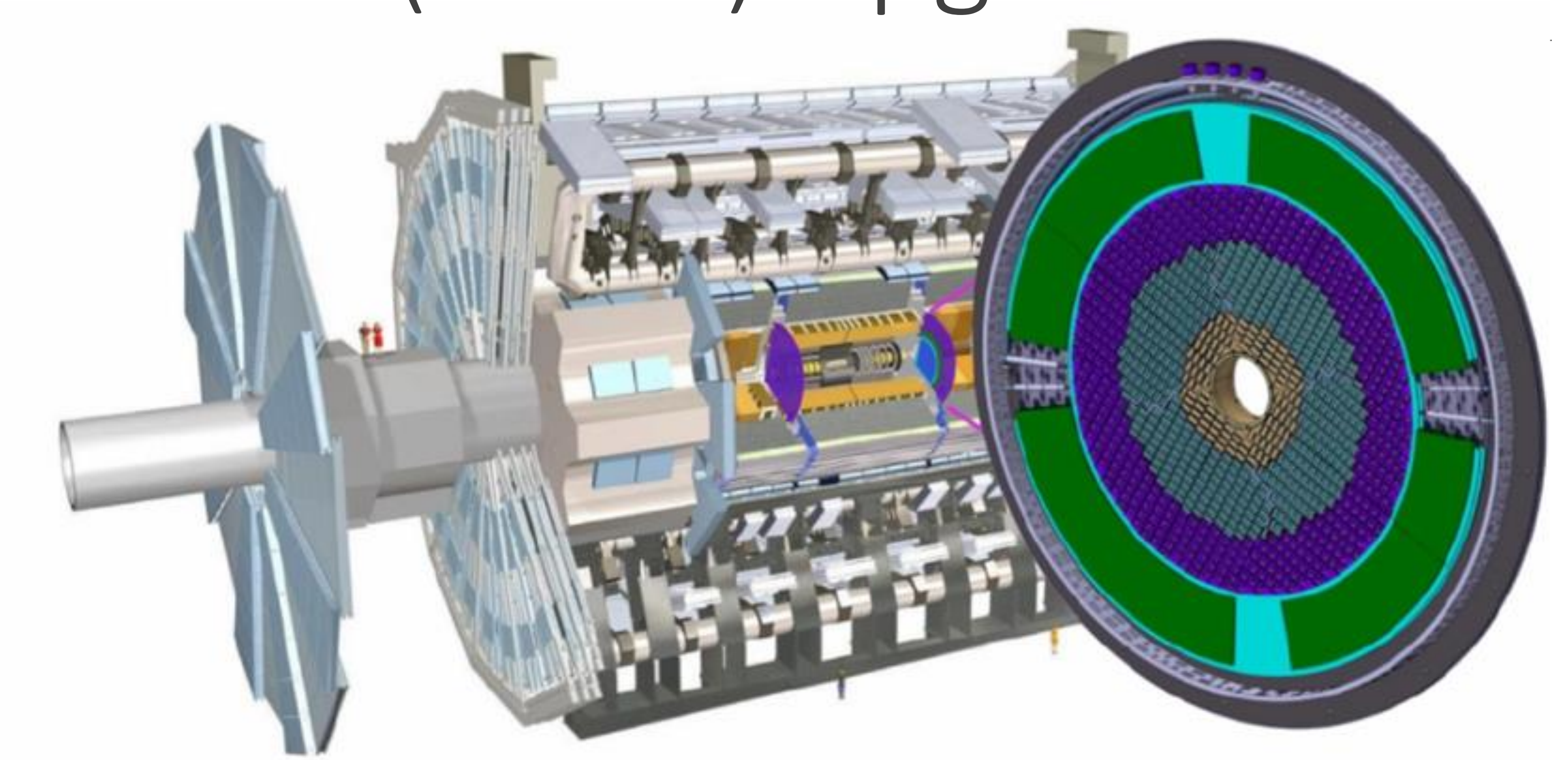
IHEP/THU Contribute to design and verification

IHEP/THU Contribute to verification





ATLAS High Granularity Timing Detector (HGTD) Upgrade

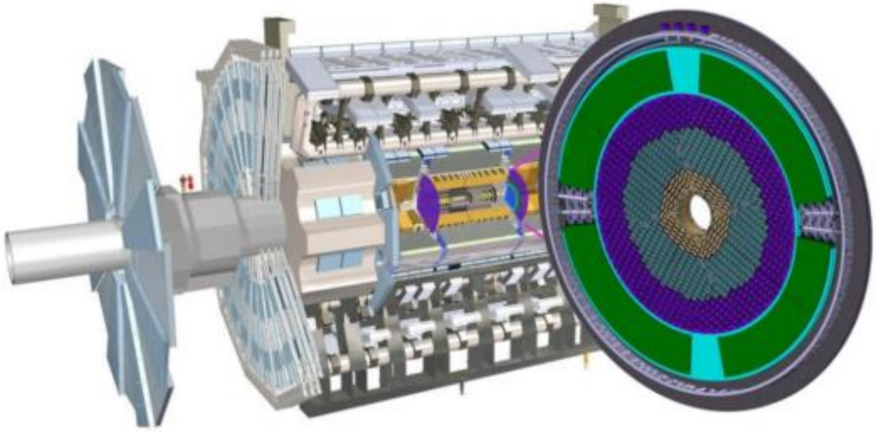


The High Granularity Timing Detector (HGTD) be placed in front of the Liquid Argon end-cap calorimeters , will add precision timing in the very forward region (2.4 < |η| < 4.2) to complement the ITk and to further enhance the pile-up mitigation at the HL-LHC.

ATLAS HGTD

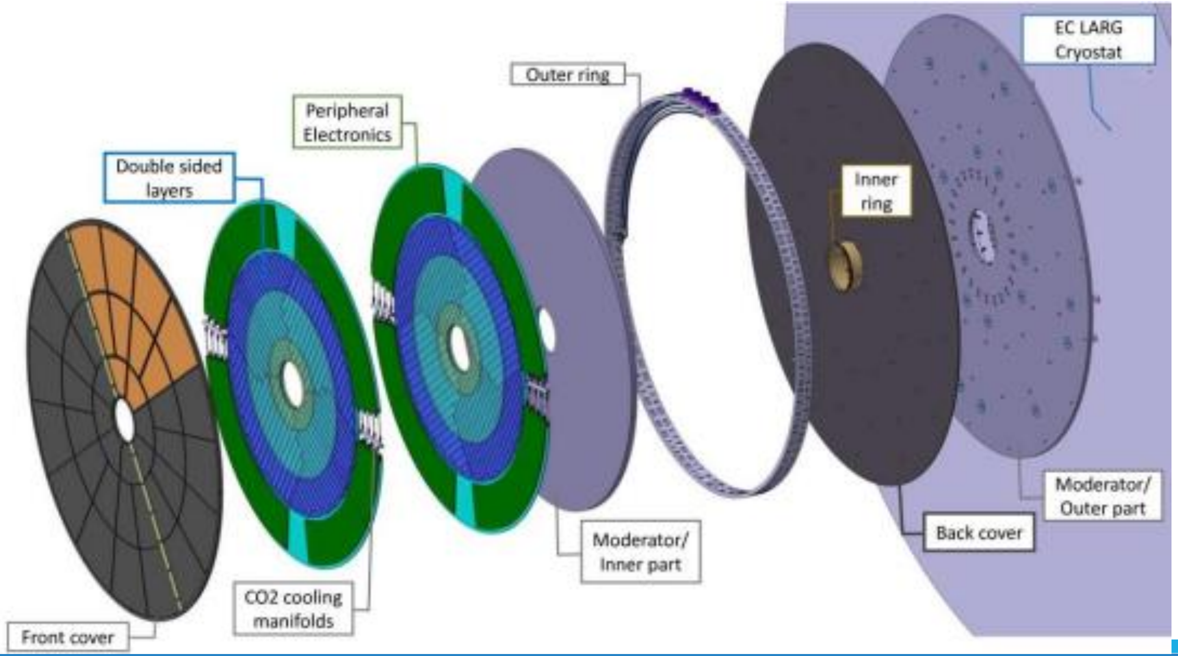
HGTD detector

- **The High Granularity Timing Detector (HGTD)** is designed to provide precise timing information due to increased pile-up in HL-LHC.
  - **~3.6 million 1.3×1.3 mm² pixels(channels)**
    - 6.4 m² active area, 8032 modules
  - **Time resolution target**
    - **30-50 ps /track**
    - **35-70 ps/hit up to 4000fb⁻¹**
  - **Luminosity measurement**
    - Count number of hits at 40 MHz (bunch by bunch)
    - Goal for HL-LHC: 1% luminosity uncertainty



Active region

- z ≈ ±3.5 m from the nominal interaction point
- Total radius: 11cm < r < 100 cm
- Active detector region: 2.4 < |η| < 4.0



High Granularity Timing Detector (HGTD)

China contribution

- 100% LGAD sensor (90% IHEP + 10% USTC)
- 44% detector assembly (34% IHEP + 10% USTC)
- 100% front-end electronics board (IHEP +NJU)
- ~33% flex tail (SDU)
- 50% ASIC testing (IHEP)
- >16% high-voltage electronic systems (IHEP+ SDU)
- Software and performance (USTC, IHEP)

Recent activities

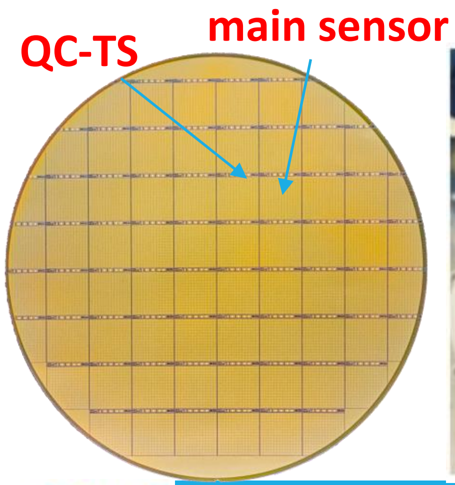
- LGAD sensor pre-production and performance testing
- ASIC testing system build and testing
- Sensor/ASIC hybridization and thermal cycle testing
- Module flex and flex tail design, fabrication, testing
- Module assembly and loading
- Demonstrator build and testing
- PEB 1F design and testing
- Test beam testing and data analysis

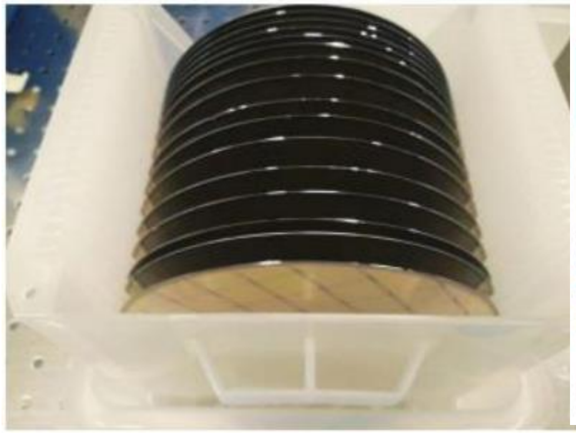
ATLAS HGTD sensor

- LGAD sensors for HGTD project: ~21000
  - •IHEP design:90%
  - •USTC design:10%
- **Sensor pre-productions finished** in 2024 – IHEP and USTC produced comfortably enough sensors for HGTD needs.
- Sensors be delivered to HGTD group and Data be uploaded to DB.
- HGTD group(CERN, JSI, IHEP, USTC, USP) testing results show that the sensors properties fulfill HGTD specification.
- **Production Readiness Review passed on July 25, 2024, and final production start.**

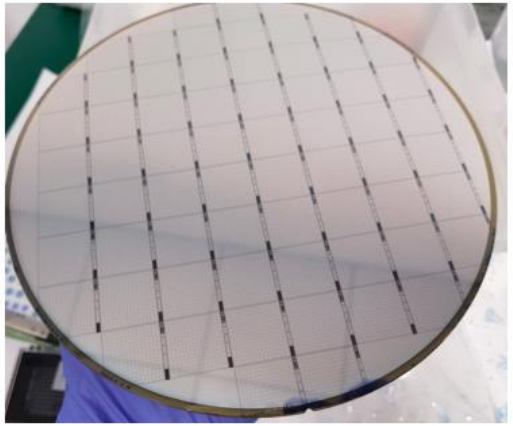
Pre-production	Wafers		Sensors		
	IHEP-IME	USTC-IME	IHEP-IME	USTC-IME	Total
Fabricated	90	27	4680	1404	6084
Passing preproduction requirements	52	13	1702	208	1910
Pre-production with UBM, diced and tested by HGTD	23	5	789	118	907

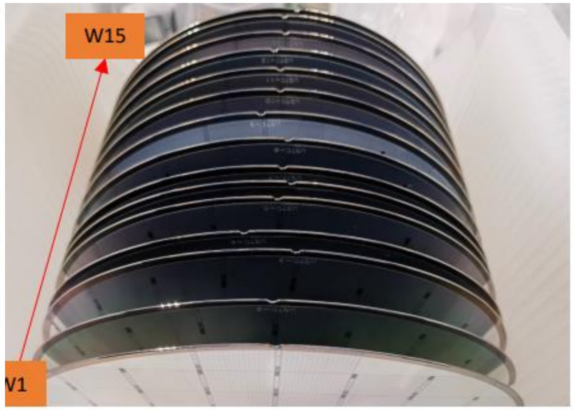
IHEP-IME





USTC-IME

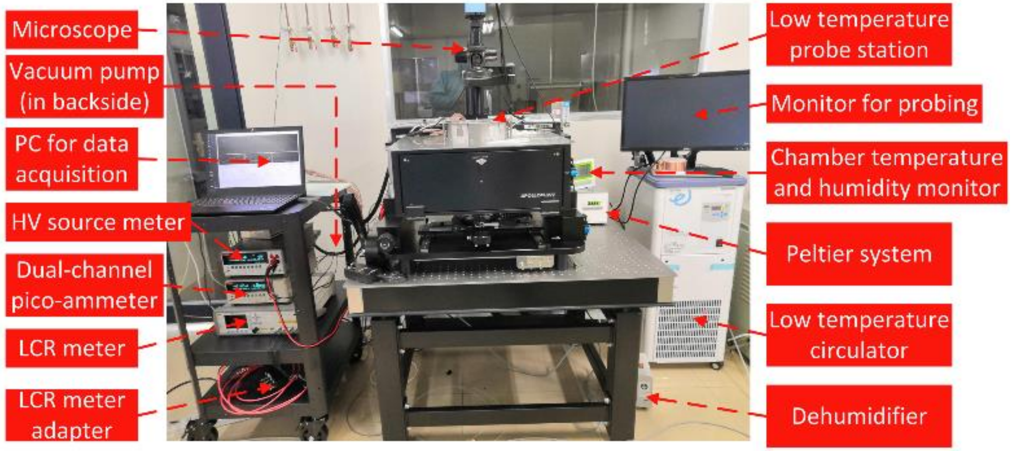




HGTD Sensor testing

➢**Sensor measurements by IHEP and USTC group addressed key questions in preparation of the sensor PRR (pre-/post- irradiation)**

- 15x15 probe card and automatic testing of large array sensors to assess uniformity, sensor quality control
- Charge collection and time resolution with beta source
- Test beam data-taking and analysis
- QC-TS massive test: system development and tests at IHEP and USTC



Manual probe station w/ needle probe card

Semi-auto probe station for production QC

HGTD sensor performance

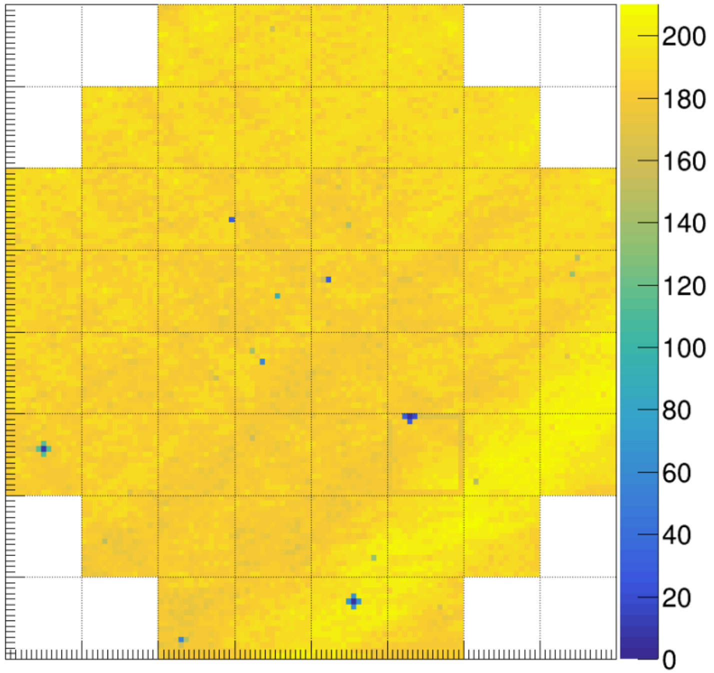
- **The 15x15 array sensors(IHEP+USTC) have good IV performance and uniformity**

Breakdown voltage deviation for 225 pads is less than 5% :
$RMS(V_{bd,pad})/<V_{bd,pad}> < 5\%$

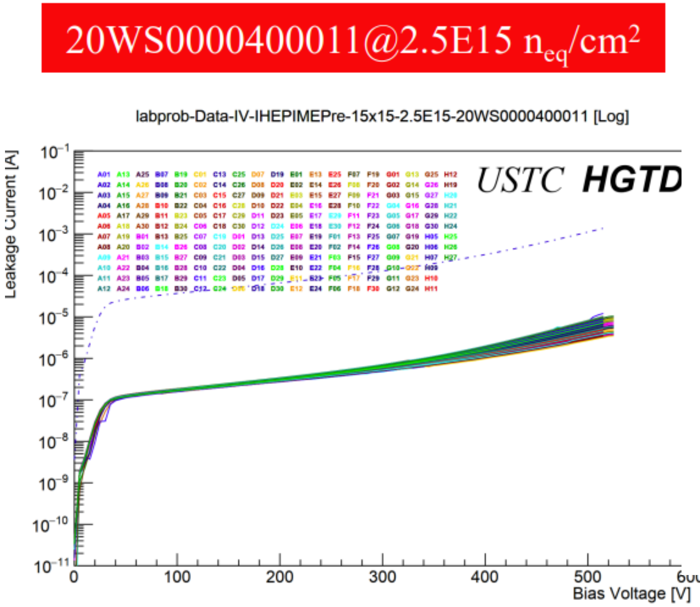
The ratio of the maximum and minimum leakage current is less than 3(Pad leakage current spread at $0.8V_{bd}$) ,peak to peak within a factor of 3X.

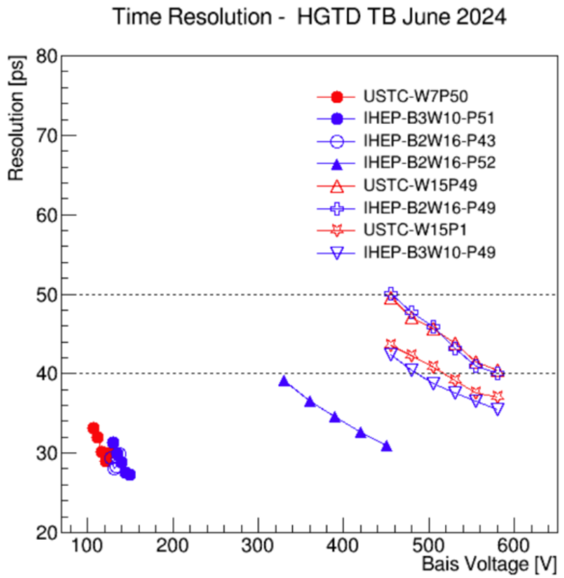
- **Timing resolution:** The timing resolution is better than 35ps(50ps) before(after) irradiation(fluence 2.5e15 n_{eq}/cm^2)
- **Efficiency : 95%~100% for sensors before and after irradiation**
- **fulfill HGTD project requirement**.

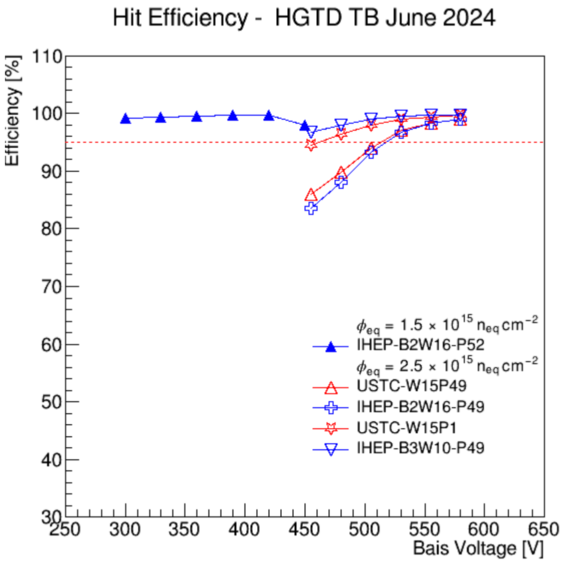
Mapping of V_{bd} of sensors on one wafer



V_{BD} Map



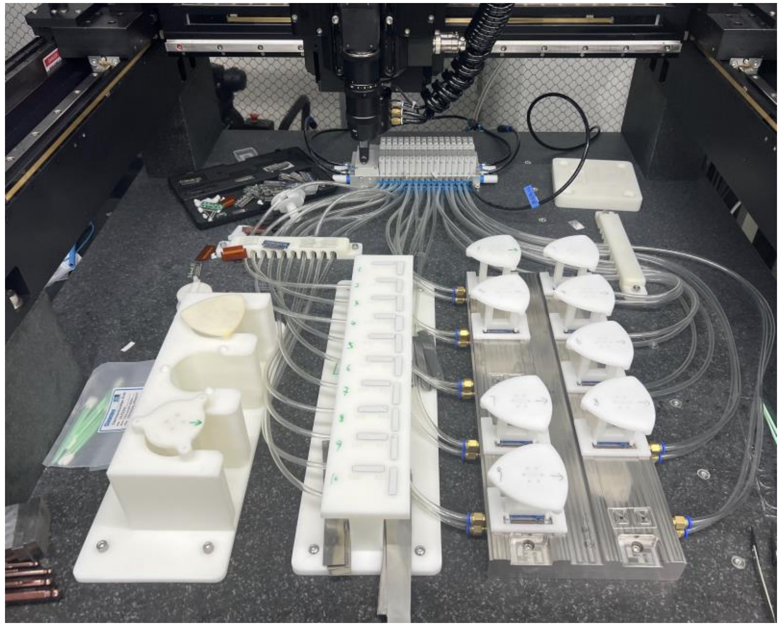


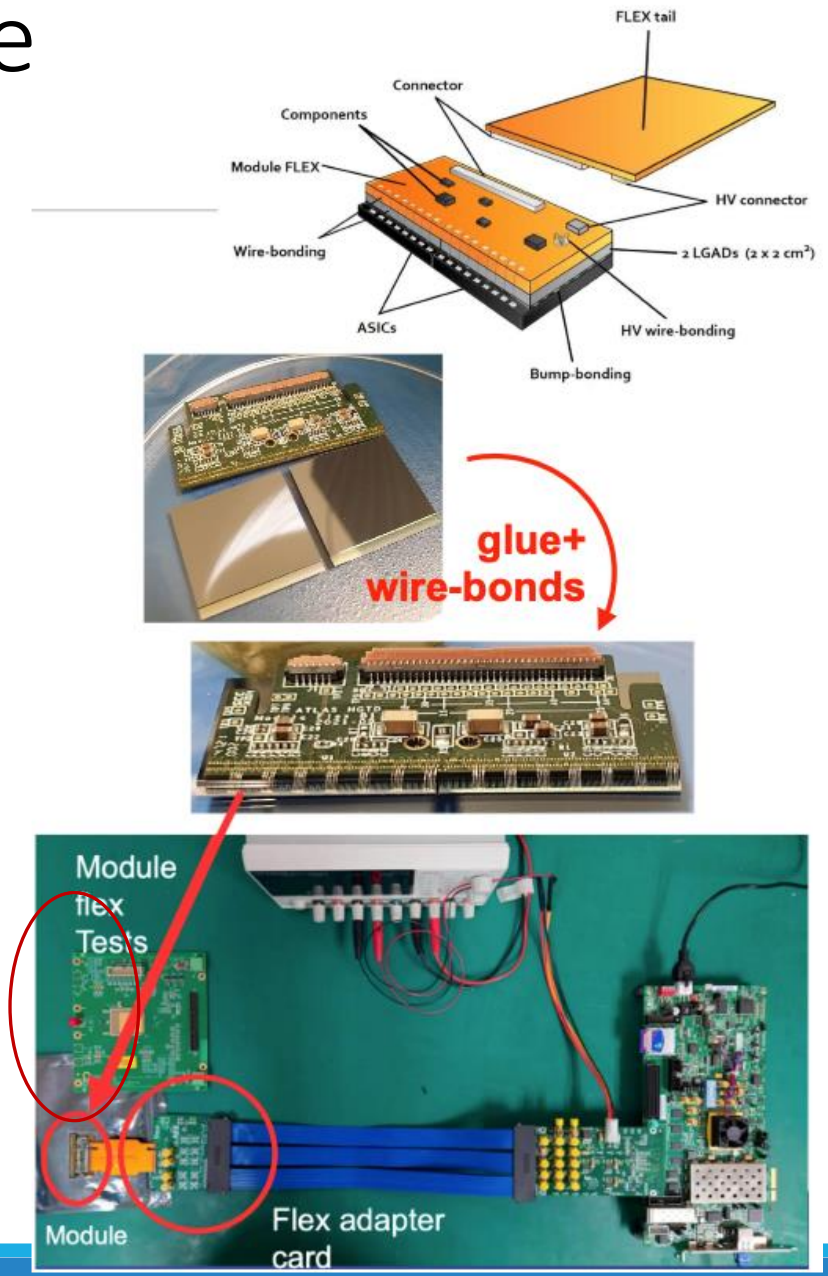


ATLAS HGTD

HGTD module

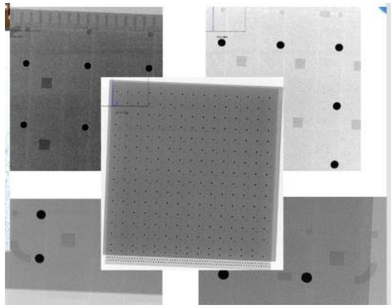
- **Sensor/ASIC hybridization and thermal cycle testing**
- **Module flex and flex tail design, fabrication, testing**
- **Module assembly , testing and loading to Support unit**
- Module FDR passed, green light to pre-production





HGTD Module

- **Hybridization** be done with pre-production sensors and ASIC(Altiroc3 and AltirocA).
- **Module assembly**(hybrids with module flex)
  - IHEP: >50 modules, USTC: 5 modules
  - Thermal cycling testing be done on many modules(IHEP, USTC).
  - Simulation about thermal cycling issues be done to check the module assembly process.
- The work make it clear that thick sensors(775um,un-thinned) is good for thermal cycle issues. The problem is overcome.



USTC

	Type	Sensor	Flip chip bonding	Metrology	WB	Charge scan validation	Radioactive source test	Thermal cycling
DM001	Digital	-	-	Assembled Manually	USTC	Done	-	Done
DM002	Digital	-	-	-	USTC	Done	-	Not yet
FM001	Full	IHEP-IME pre-production	NCAP	Done	USTC	Done	Done	60->75 cycles
FM002	Full	USTC-IME Pre-production	IFAE	Done	USTC	Done	Not yet	Not yet
FM003	Full	USTC-IME Pre-production	IFAE	Not yet	USTC	Done	Not yet	Not yet

IHEP

Thermal Cycle Performance of Unthinned Hybrids with no initial problems

Assembly Lab	Module	Hybrid	Disconnected bumps up to 30 TC	Number of cycles for first disconnect	Bumps first disconnected	Total # cycles survived
IHEP	FM028	0	0	75	1	60
		1	0	120	1	105
IHEP	FM029	0	0			180
		1	0	75	4	60
IHEP	FM031	0	0			180
		1	0	120	1	105
IHEP	FM033	0	0	75	1	60
		1	0			180
IHEP	FM034	0	0	60	1	30
		1	0			180
IHEP	FM035	0	0			150
		1	0			150
IHEP	FM036	0	0			150
		1	x	x	x	x

ATLAS HGTD

HGTD Module Flex and Flex tail

➢ Module Flex：(IHEP, NJU)

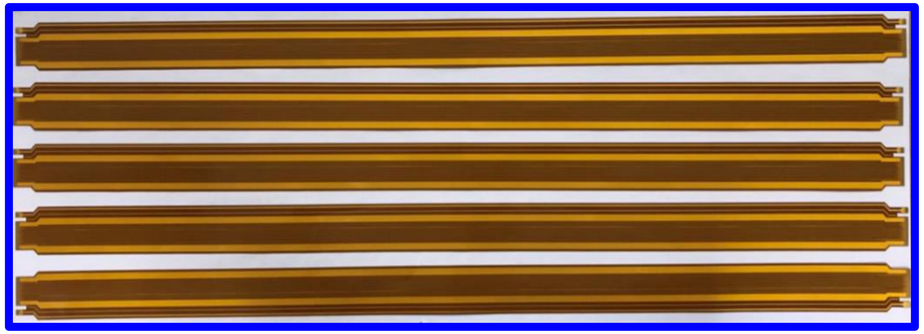
- Module flex be designed, fabricated and distributed to HGTD groups for module assembly

➢ Flex tail：(SDU)

- Flex tail prototypes production & tests: width\length\impedance\voltage drop; Solve the thickness issue.
- First 16 Flex tails with longer lengths are produced, tested and had been sent to CERN. Be used in Demonstrator to validate the detector performance

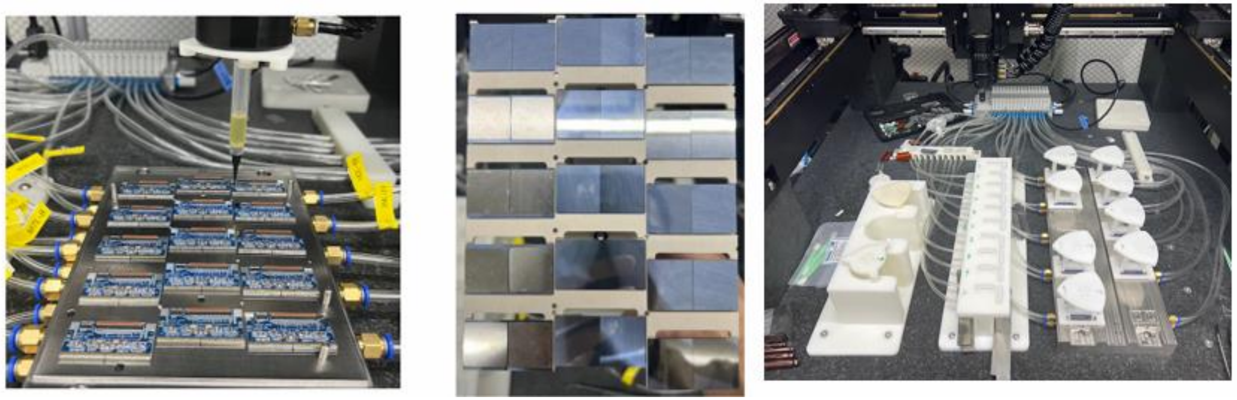
Module Flex

Flex tail

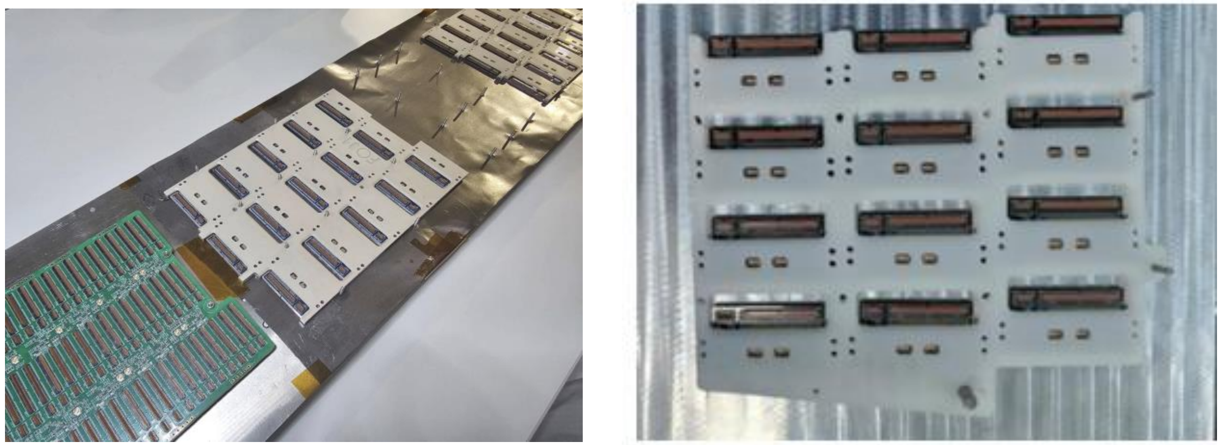


HGTD module assembly and loading

- **Module loading to support unit**
  - IHEP:2 detector unit with 15/12 modules, USTC: 1 detector unit with dummy modules
  - **2 ALTIROC3 detector unit be loaded by IHEP for HGTD demonstrator**
  - Delivered to CERN, and passed reception tests
- Module assembly and loading system in IHEP and USTC are ready for module pre-production.



Module assembly and loading @IHEP

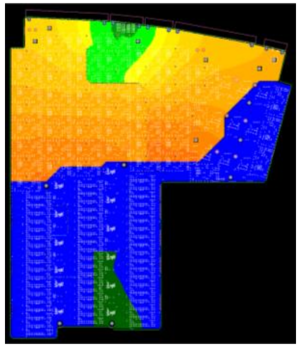


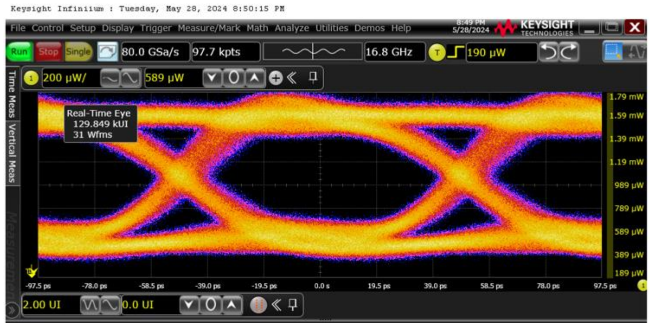
Detector unit

Module assembly and loading @USTC

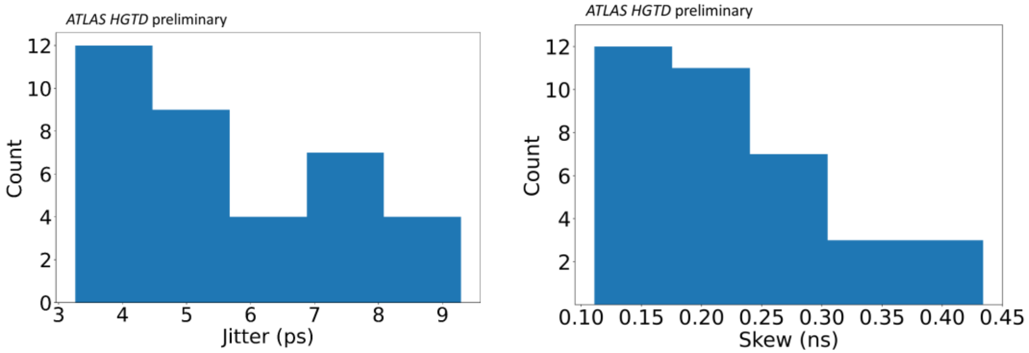
HGTD Electronics

- **IHEP and NJU developed 1st Peripheral Electronics Boards at early 2024**
  - PEB 1F, support to 52 modules power supply, control and signal readout
- **PEB testing be carried out by IHEP, NJU and CERN, no problem shows**
  - IR drop simulation and measurements to make the output of bPol12v satisfy the requirement of ALTIROC,
  - Power integrity analysis, Signal integrity analysis, Reliability testing with full loads, Tests with demonstrator
- **High-precision high-voltage power supply be produced and tested(IHEP and SDU)**
  - Passed the FDR review and is ready for mass production

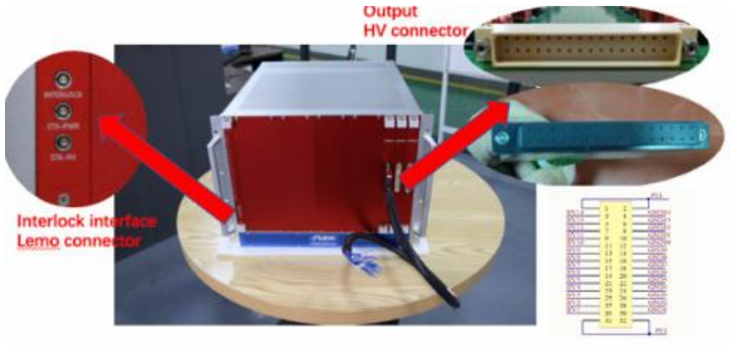




Optical eye diagram scanning



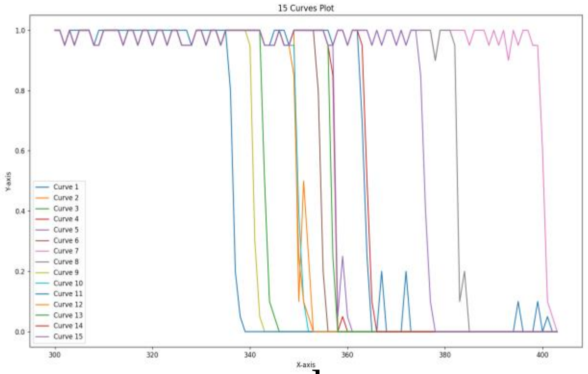
Clock jitter and skew measurement



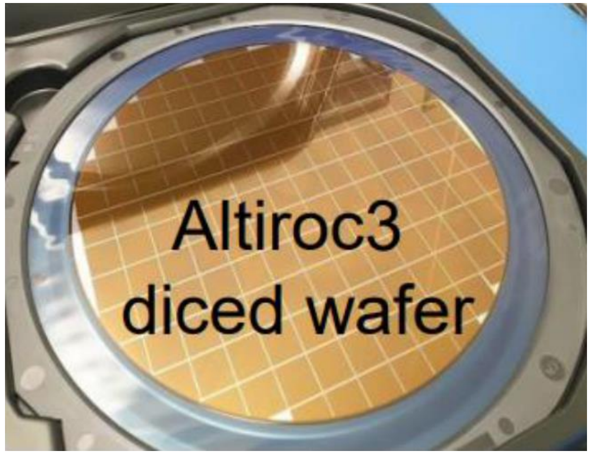
High voltage power supply

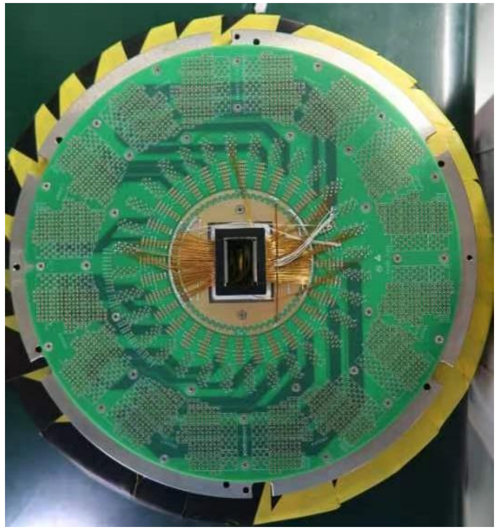
HGTD ASIC

- **ASIC wafers will be 100% sent to China for polyimide layer deposition, 50% UBM/thinning/dicing at China (IHEP/NCAP)**
- **ASIC test and multi-chip testing system setup：**
- ✓ Together with Chinese company, built the **probing testing system for ASIC** wafer testing(IHEP)
  50% ASIC to IHEP/Khecwitt for probing. Now probe card is ready, software ongoing
- ✓ **Build a test system for multi-chip testing**, beam testing etc；(SDU)
  Current status: i2c configuration , tot& toa readout, vth &vthc scanning

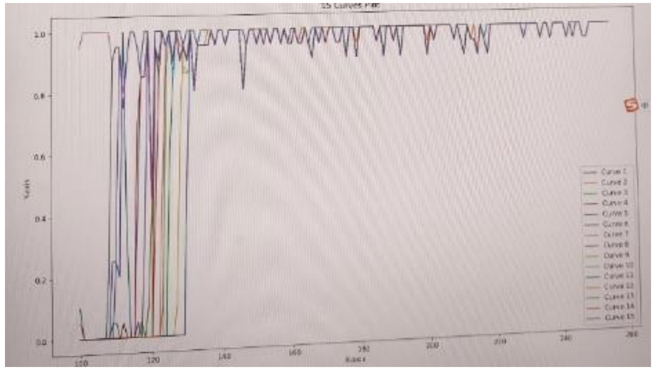


vth





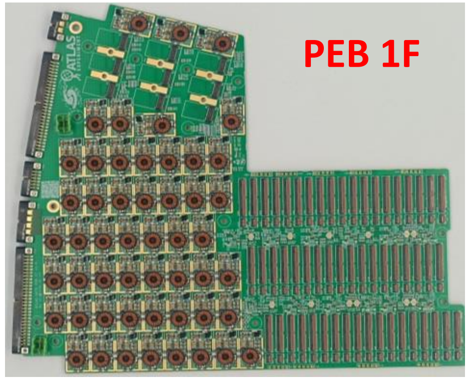
Probe card for ASIC testing

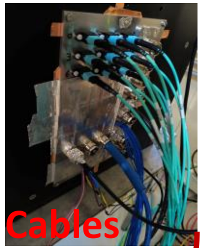


vthc

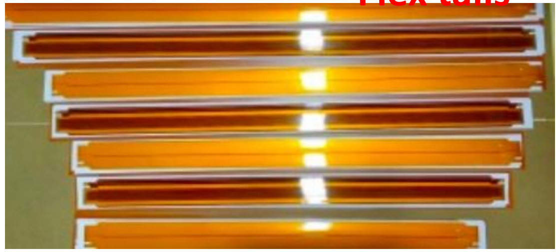
Joint test with demonstrator at CERN

- **Build the demonstrator at CERN (IHEP and NJU)**
  - With full chain from module to DAQ server（PEB 1F + 42 modules in 3 columns + Flex tails + HV + cooling）
- **IHEP and NJU played important role testing demonstrator system at CERN**
  - Demonstrator were measured with 42 modules, no major problem
  - 1st time to demonstrate that in system level



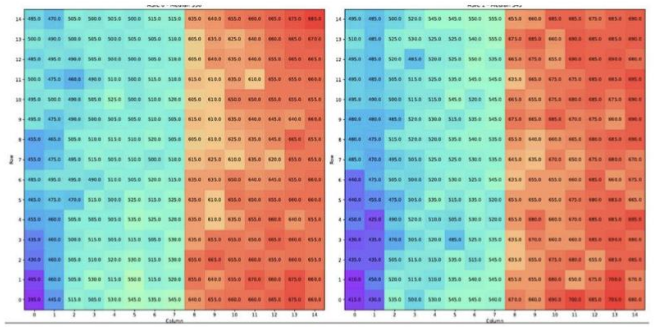


Flex tails



DUs + cooling plate

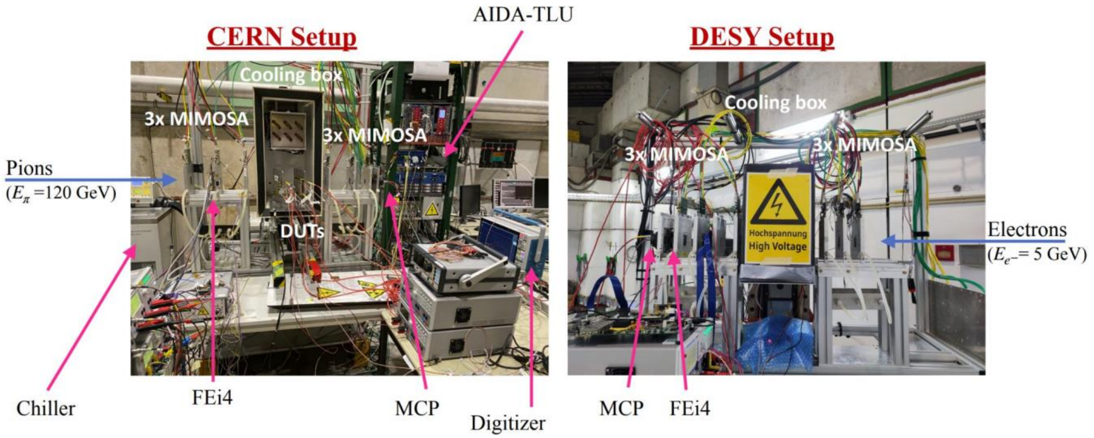
Demonstrator at CERN



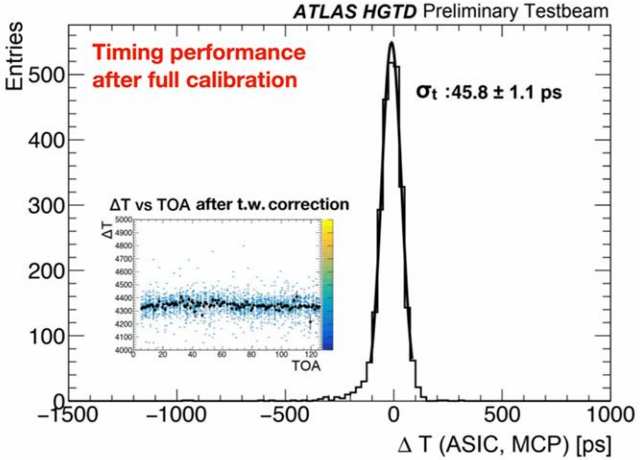
Module threshold scan obtained in demonstrator test

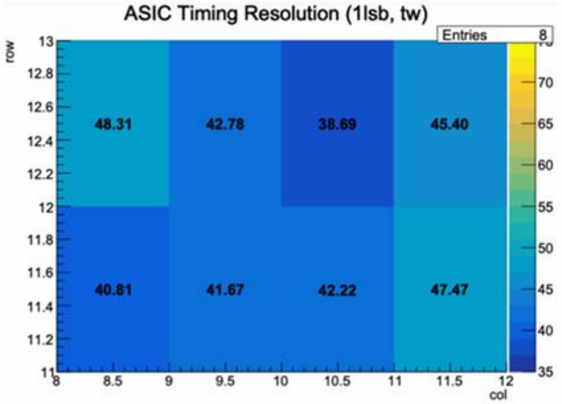
HGTD Beam Test

- **Participate in the sensor and Module level Test beam(DESY, SPS)** and data analysis(IHEP, USTC, NJU)
- Results showed that Individual channels can reach ~47ps level timing resolution. The efficiency is larger than 98%.
- After irradiation, the timing resolution ~43ps.

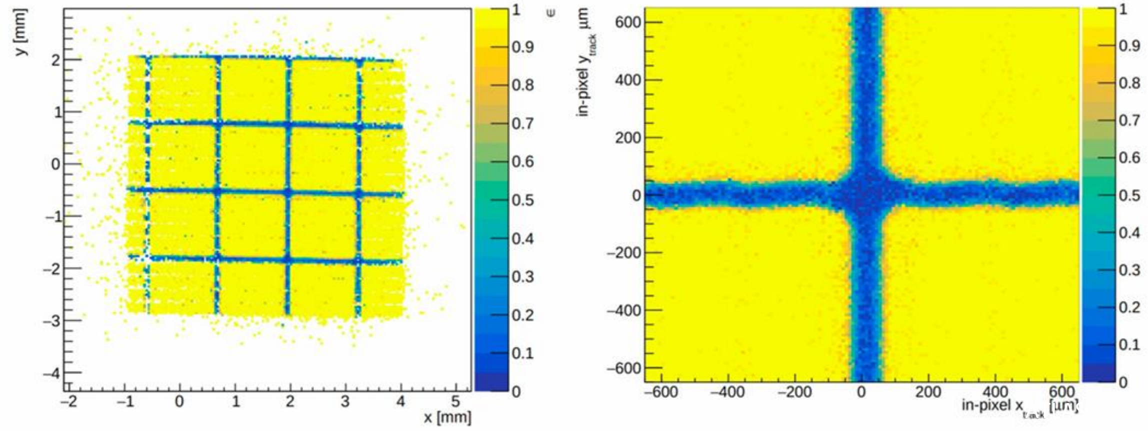


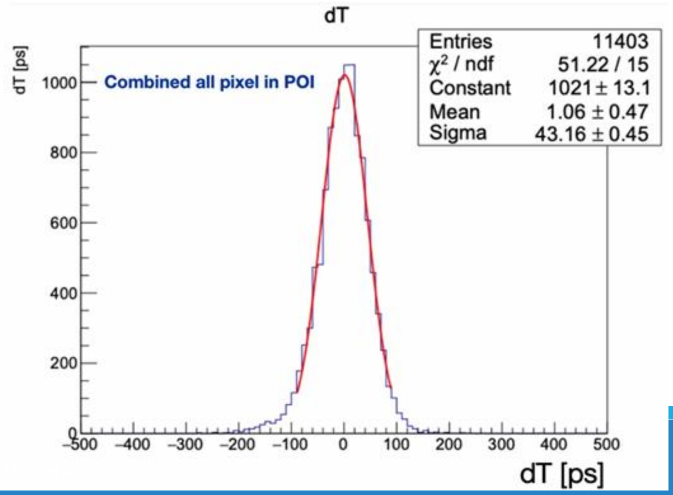
Timing performance before irradiation





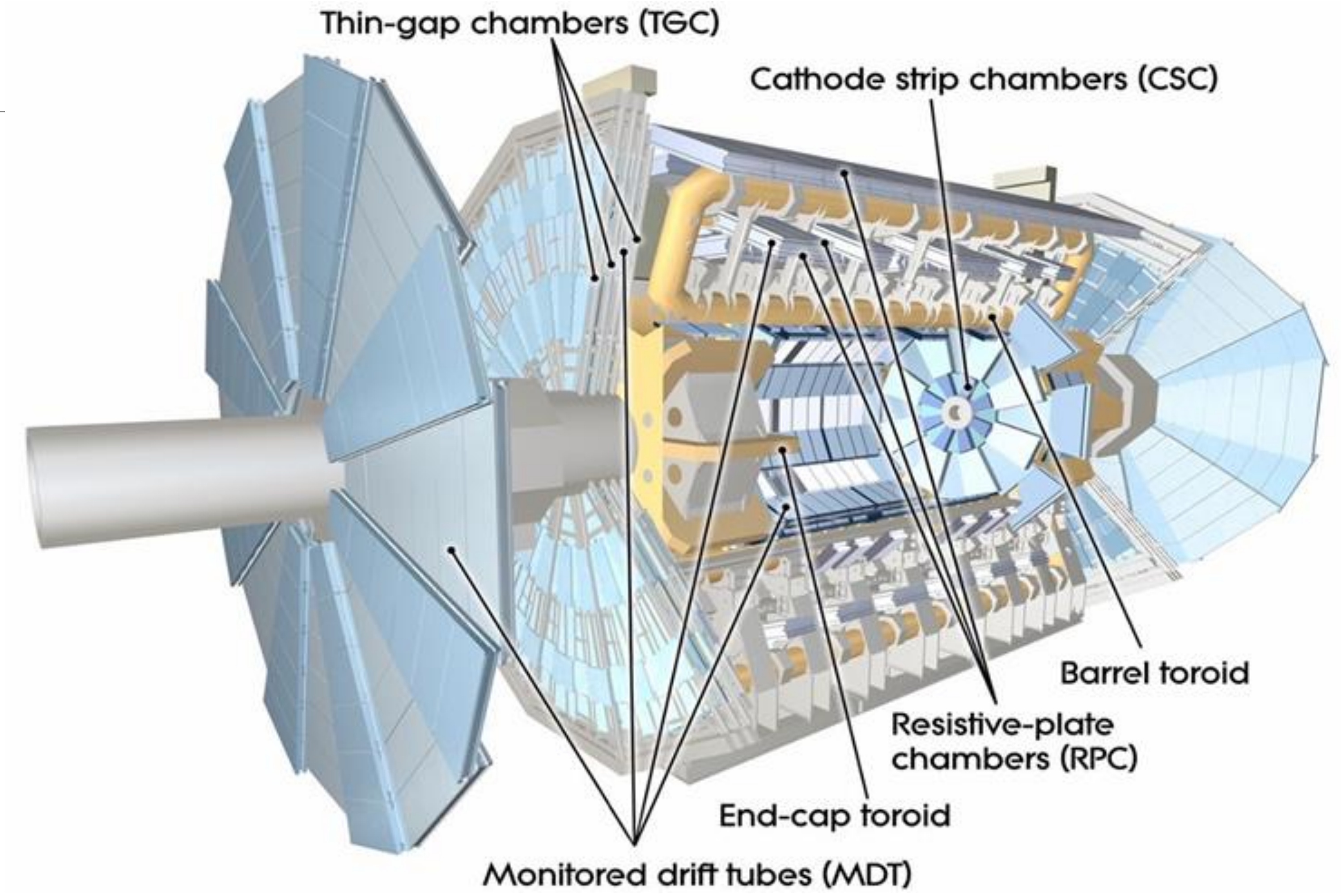
Efficiency of pixels



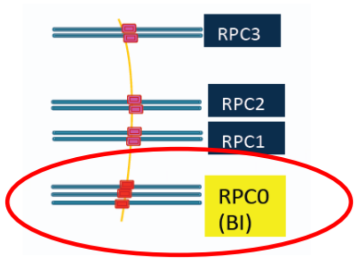


Timing performance after 2.5e15 n_{eq}/cm^2

Muon system

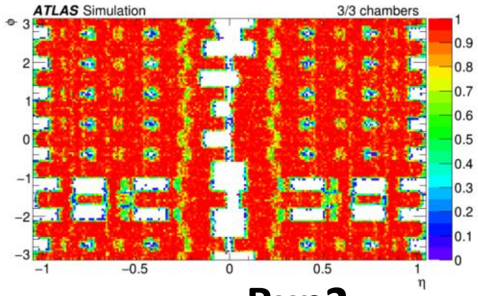

Thin-gap chambers (TGC)
Cathode strip chambers (CSC)
Barrel toroid
Resistive-plate chambers (RPC)
End-cap toroid
Monitored drift tubes (MDT)

Muon system upgrade

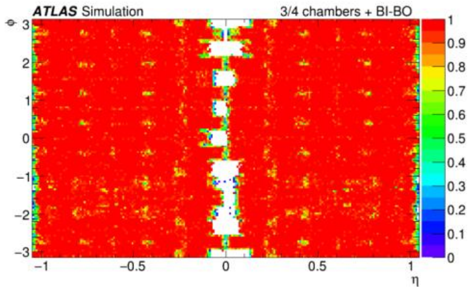


- 9 layers instead of 6

- A new generation RPC system with thin-gap RPCs in the barrel inner(BI) region
  - Current: doublet gas gaps of 2mm → HL-LHC: triplet gas gaps of 1mm
  - Nine layers instead of six and expected to increase muon trigger acceptance from 70% to about 96%



Run2

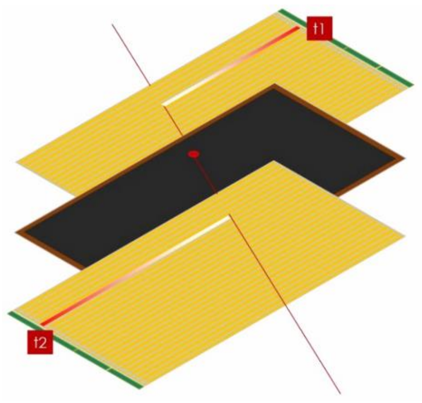


With new BI Layer

- BI-RPC:
  - Max size of singlets: 1820mm*1096mm
  - 9000 front-end boards

- New Front-End Electronics
  - Integrates TDC into an ASIC chip
  - Use Manchester encoding to highly improve data transmit speed

- New readout design:
  - η- η readout for 2D information



Singlet= 1 gas gap + 2 readout panels

Muon system upgrade

China contribution(USTC-SDU-SJTU)

- Mass production of 912 readout panels and 72 gas gaps
- Assembly of 360 singlets
- Manufacture and test of about 5000 front-end electronic boards

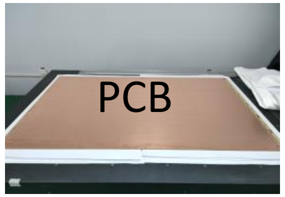
Recent activities:

- Readout panel production
- RPC gas gap production
- Singlet assembly work
- Data acquisition system

Readout panel production

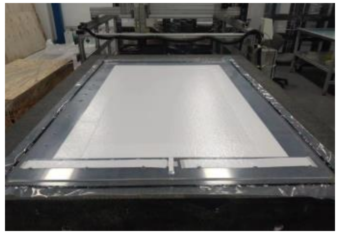
➢ Components:

- Two PCBs: strips + GND panel (0.4mm thick, size: 1705×1072 mm^2 or 1705×890 mm^2)
- Honeycomb core: 3mm thick
- Glue: Araldite 2011 (~180g /side)



➢ Key technologies and challenges

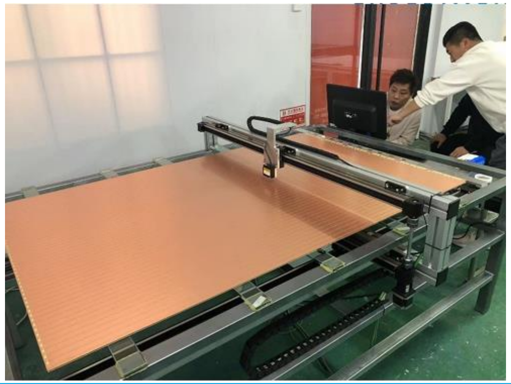
- How to ensure proper alignment among the ground, strip panel, and paper honeycomb?
  - ➡ All layers (2 PCBs + honeycomb) aligned to two reference bars fixed on the marble table
- How to apply sufficient pressure uniformly over such a large area (1705 x 1072 mm^2)?
  - ➡ Vacuum-bag-based readout panel production method



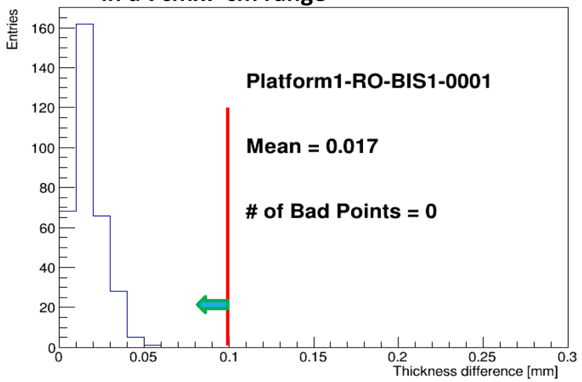
➢ ~300 readout panel prototypes have been assembled

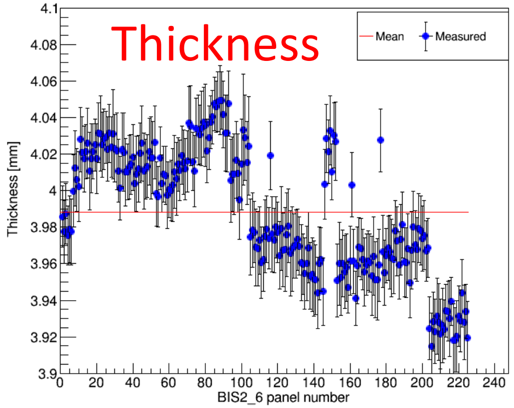
- All satisfied the specifications (Flatness: < 0.1 mm in 7cm x 7cm matrix)

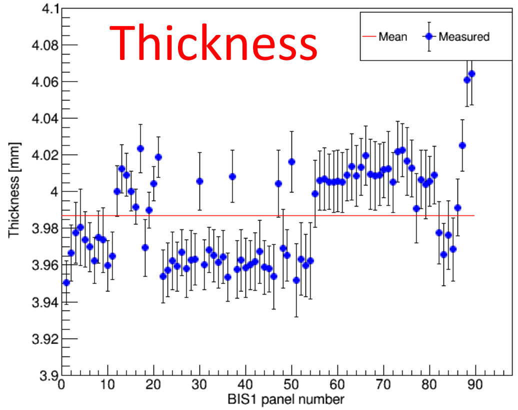
Thickness measurement



Flatness: Maximum variation of 4 points in a 7cmx7 cm range

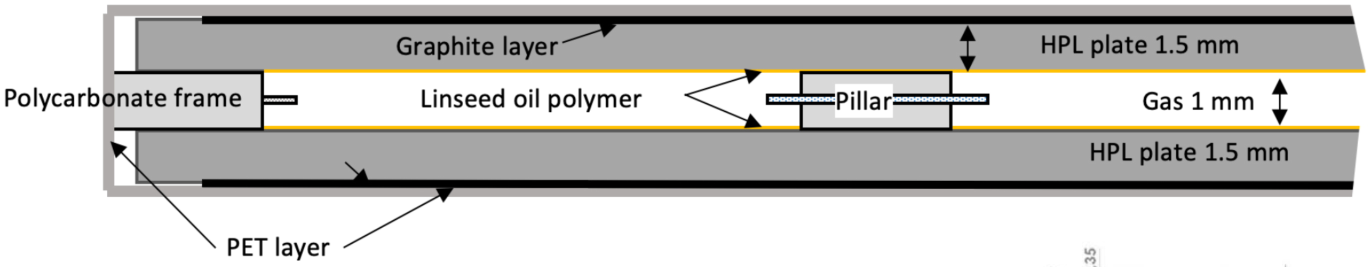


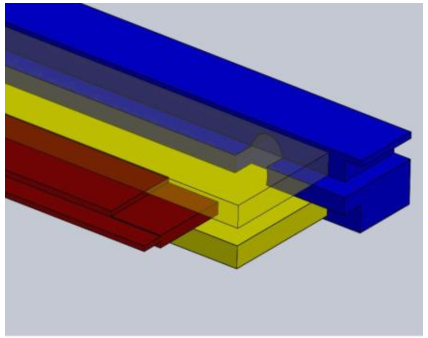


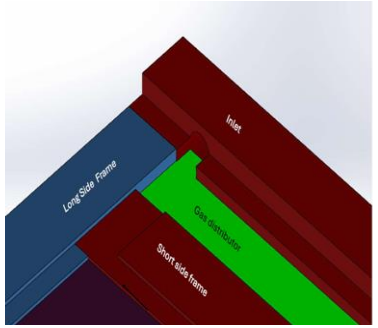


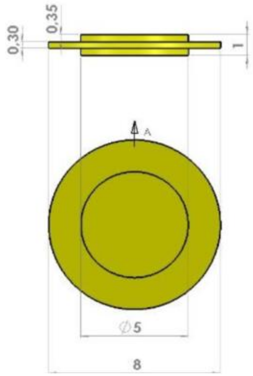
Gas-gap production

- **Gas gap components:**
  - High Pressure Laminates plates (HPL)
  - Graphite electrodes
  - Insulating PET foil
  - Frames and spacers
  - HV/Ground contact

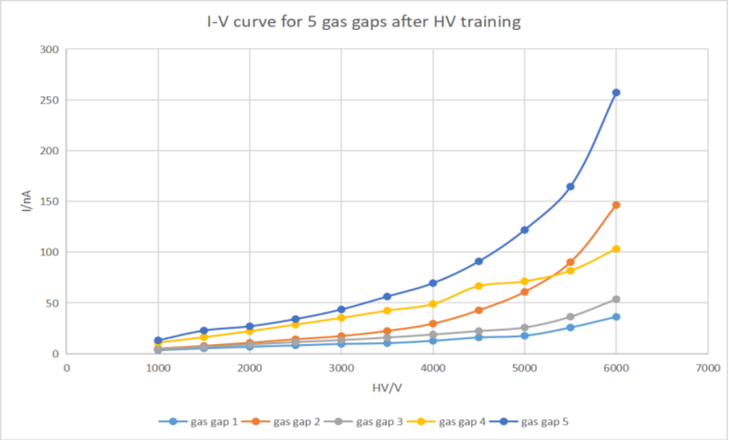






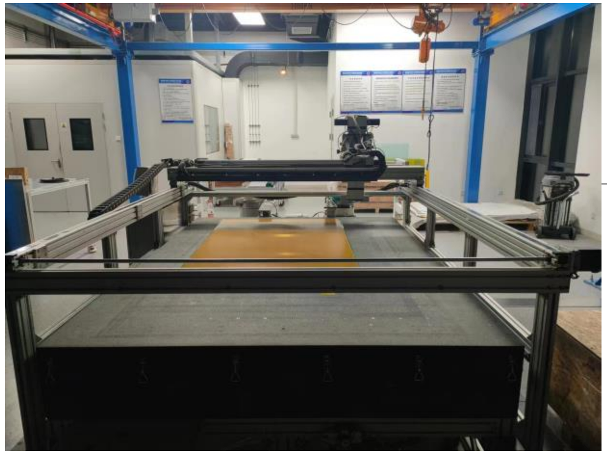


- **Key technologies and challenges**
  - Graphite coating
    - ✓ Surface resistivity shall be 350±100 kΩ/□
  - PET foiling
    - ✓ Absence of bubbles > 2-3 mm² between PET foil and graphite layer
  - Closed gas gap with good tightness and flatness
    - ✓ The flatness of the gas gap is guaranteed by spacers and frames.
  - Linseed oiling
    - ✓ To improve the smoothness of the electrode surface
    - ✓ Ensure that the final linseed oil coating is thin and well polymerized.

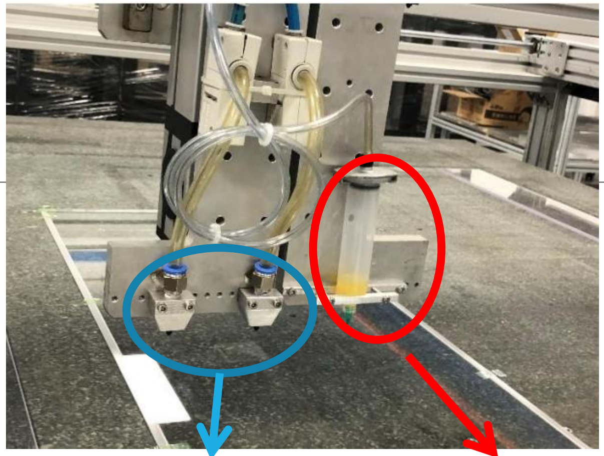


- **5 RPC gas gap (130 cm x 68 cm) are built for R&D of the assembly procedure**
  - The HV test results are very promising

Gas-gap production

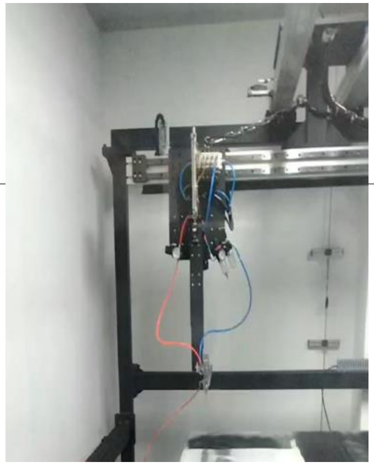


Platform



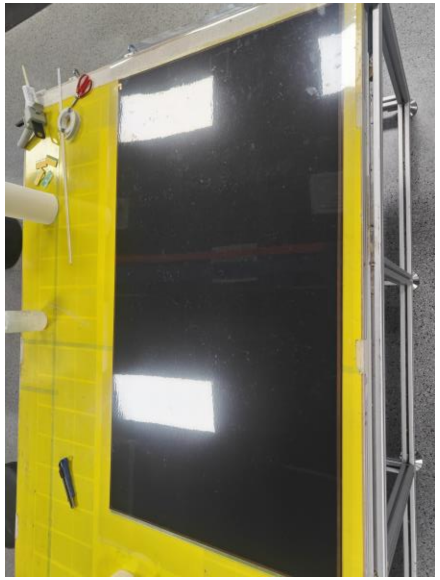
Spacer pickers

Glue syringe

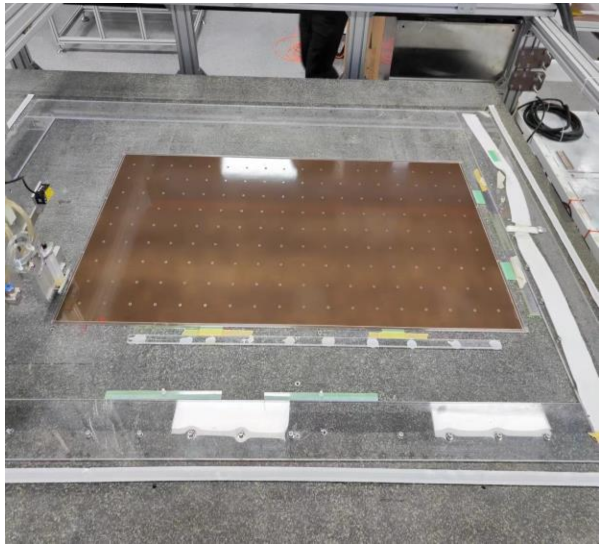


Graphite spraying system

Graphite coating

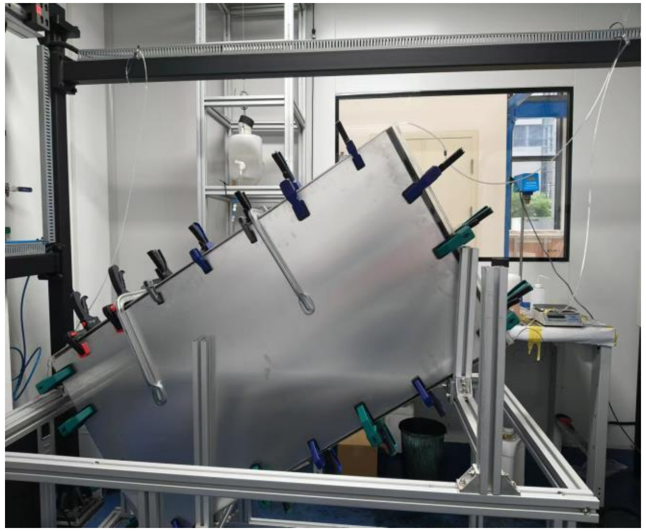


PET foiling：
Mirror-like surfacing



Attach the spacers on
the bakelite

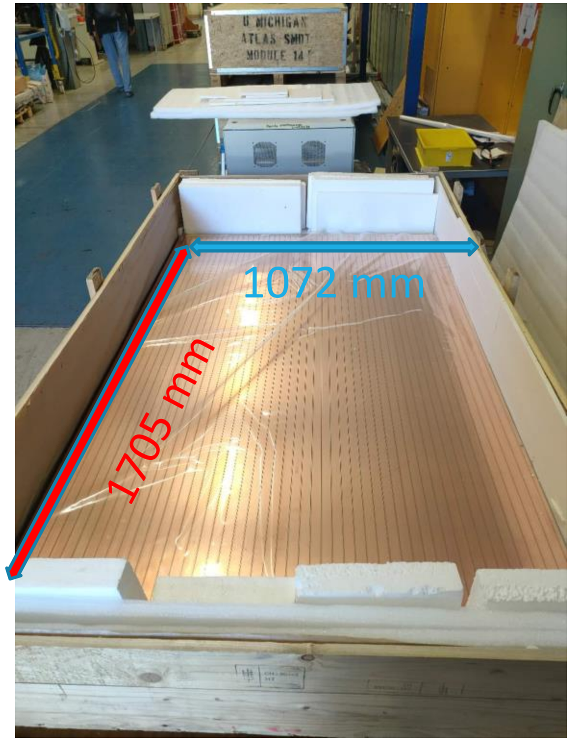
Gas gap tightness test

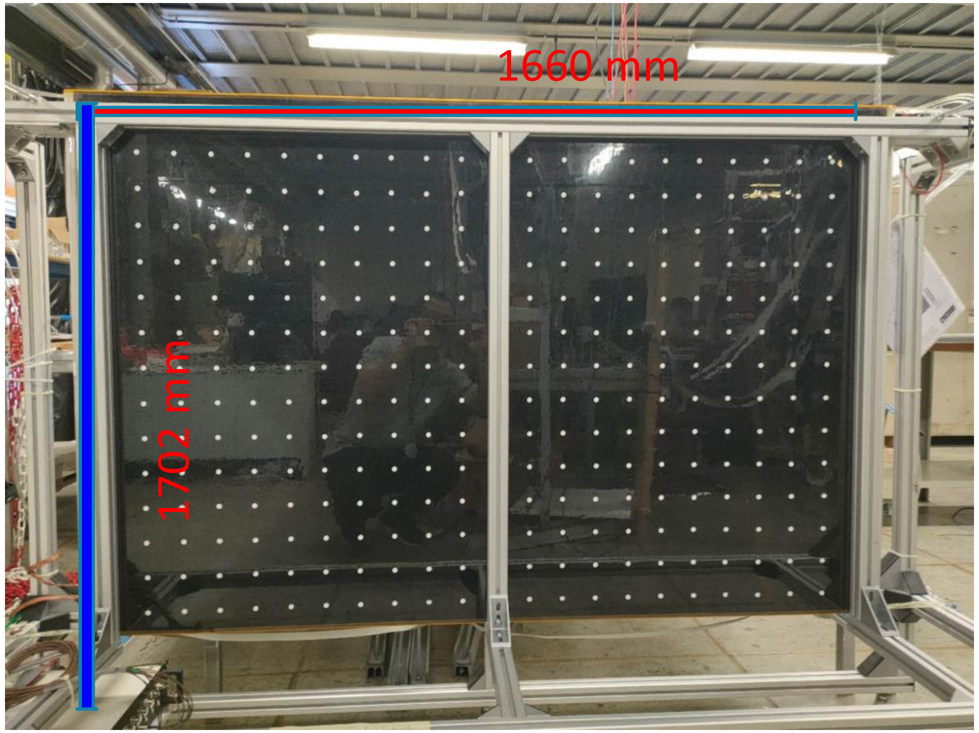


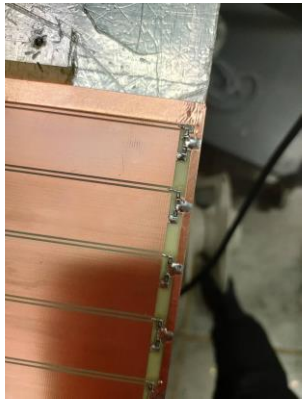
Linseed oiling

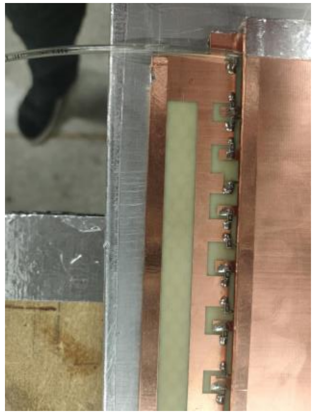
Singlet assembly work

- **3 BIS RPC chambers were assembled at CERN to exercise the assembly procedure**
  - Readout panels produced by USTC
  - Gas gaps produced by Italy









Data acquisition system

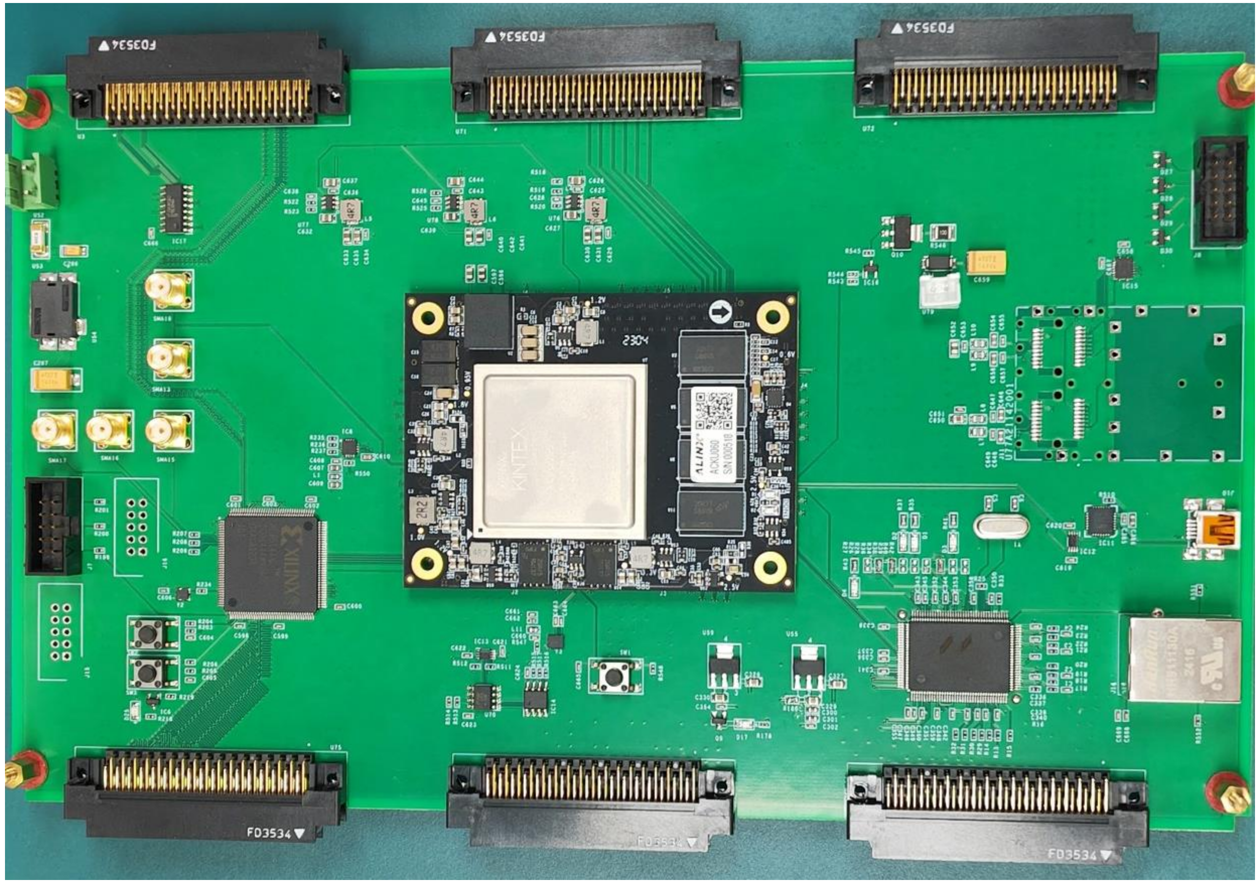
➢ **New front-end electronics (FEE)** with a specialized Manchester encoding for data transmission

➢ DAQ functions：

- Provide 40MHz clock for FEE
- 144 channels decode
- Self-trigger & data selection
- Data package & upload

➢ Decoder design goals

- Decode rate: 560Mbps – 640Mbps
- Decode latency:< 100ns
- BER < 0.1%



Summary

- ATLAS upgrade require its detector to cope with the Phase-II operational conditions with an average of up to 200 pile-up events, the corresponding data rates and an unprecedented radiation environment.
- China clusters contribute to several sub-detectors of ATLAS

  Inner Tracker (ITk) : strip barrel modules assembly

  High Granularity Timing Detector (HGTD): sensor, module assembly, PEB, etc.

  Muon Resistive-plate Chambers (RPC) : readout panel prototypes, Gas-gap production, Singlet assembly, etc
- People from China clusters take leading roles and participated in many works.
- Significant progress be made by us during this year in the ATLAS detectors.