ATLAS Detector Upgrade

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On behalf of the ATLAS Chinese Clusters

CLHCP 2023

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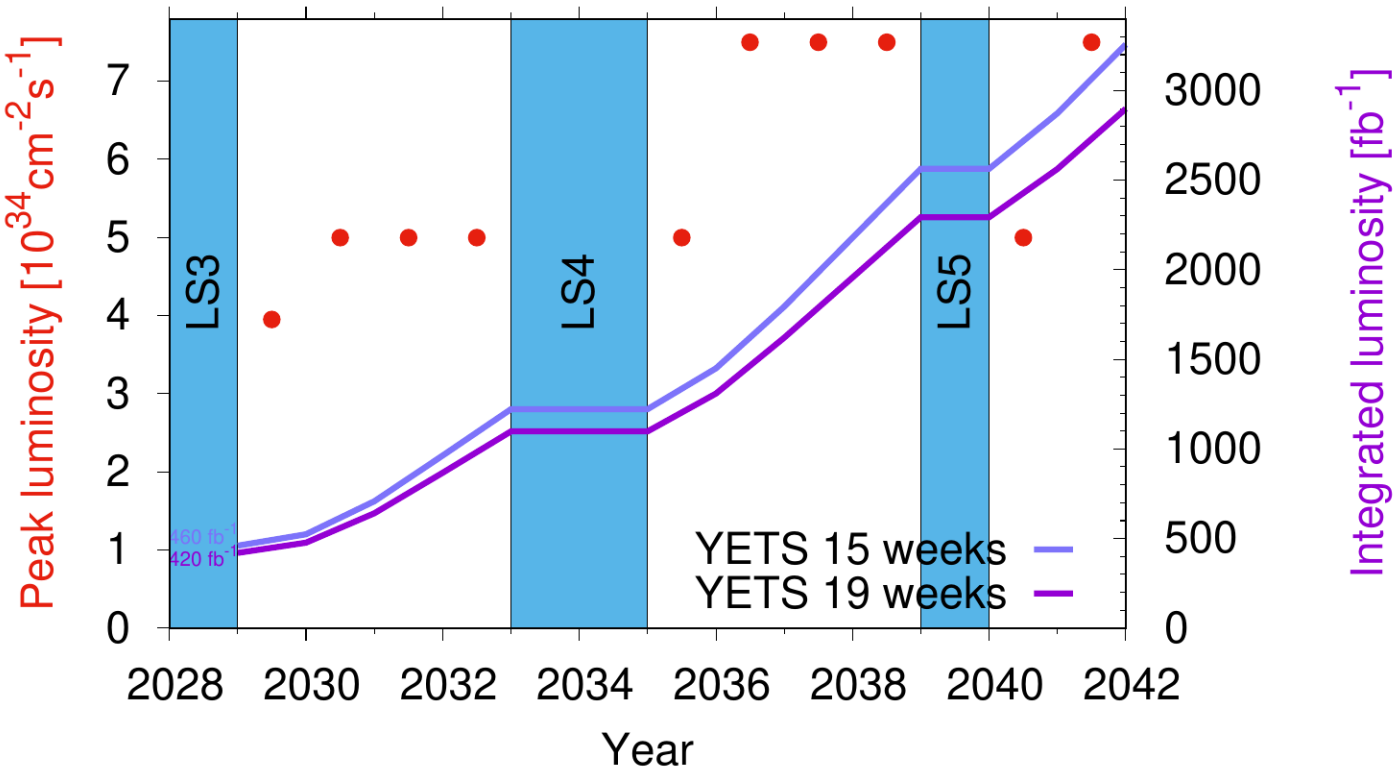
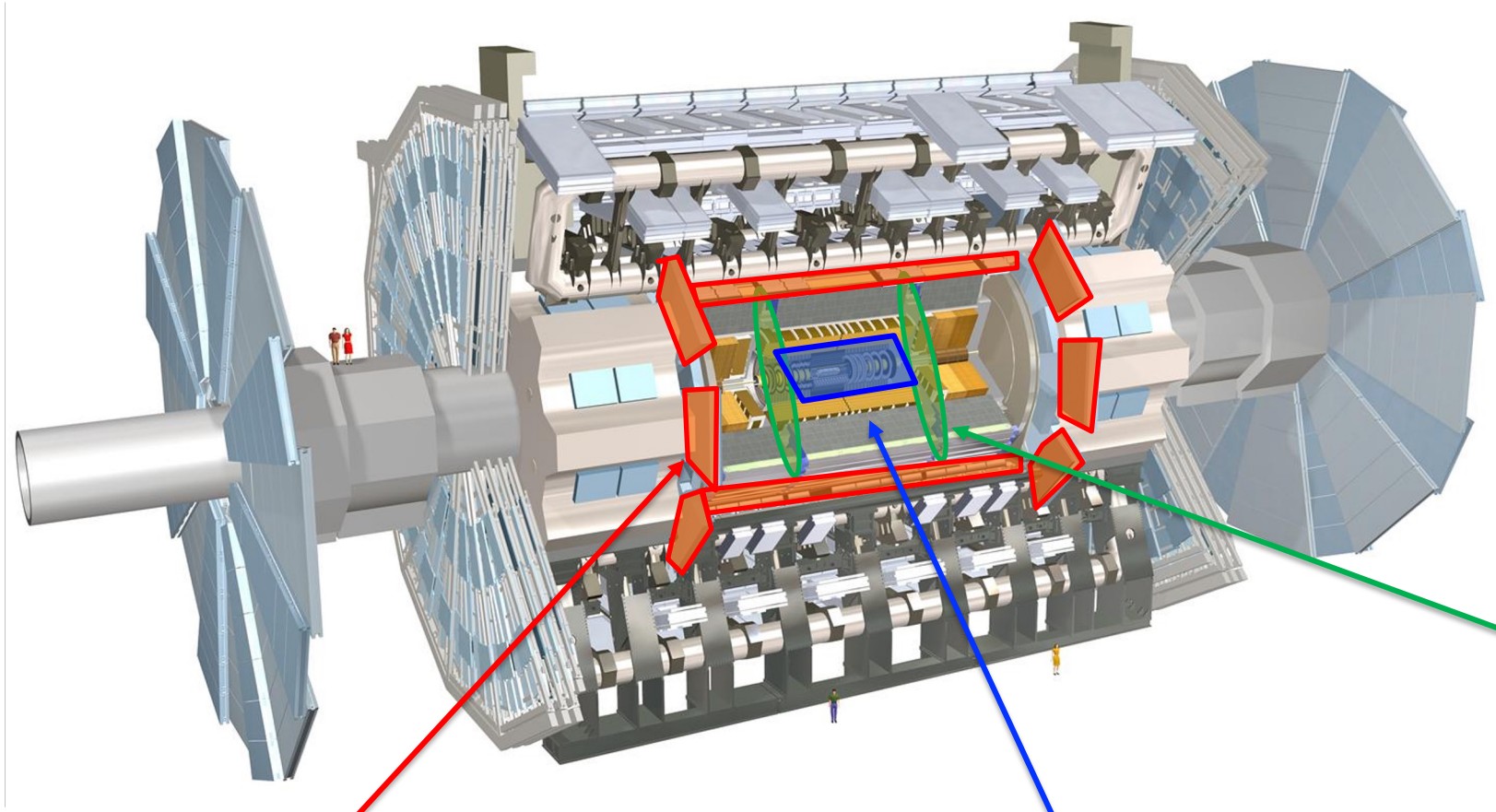
HL-LHC Upgrade



- **Instantaneous luminosity** will increase by a factor of 7
- **Particle density and radiation** levels increase by an order of magnitude
- **Average interactions per bunch crossing** will increase from 50 to 200

- ➢ Increased track density → Improved granularity and response
- ➢ Increased radiation → Higher radiation tolerance
- ➢ Increased event size → Improved readout and triggering

ATLAS Phase-2 Upgrade



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

High Granularity Timing Detector (HGTD)

- Precision time reconstruction (30 ps) with Low-Gain Avalanche Detectors

Additional small upgrades

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

New Muon Chambers

- Inner barrel region with new RPCs, sMDTs, and TGCs

New Inner Tracking Detector (ITk)

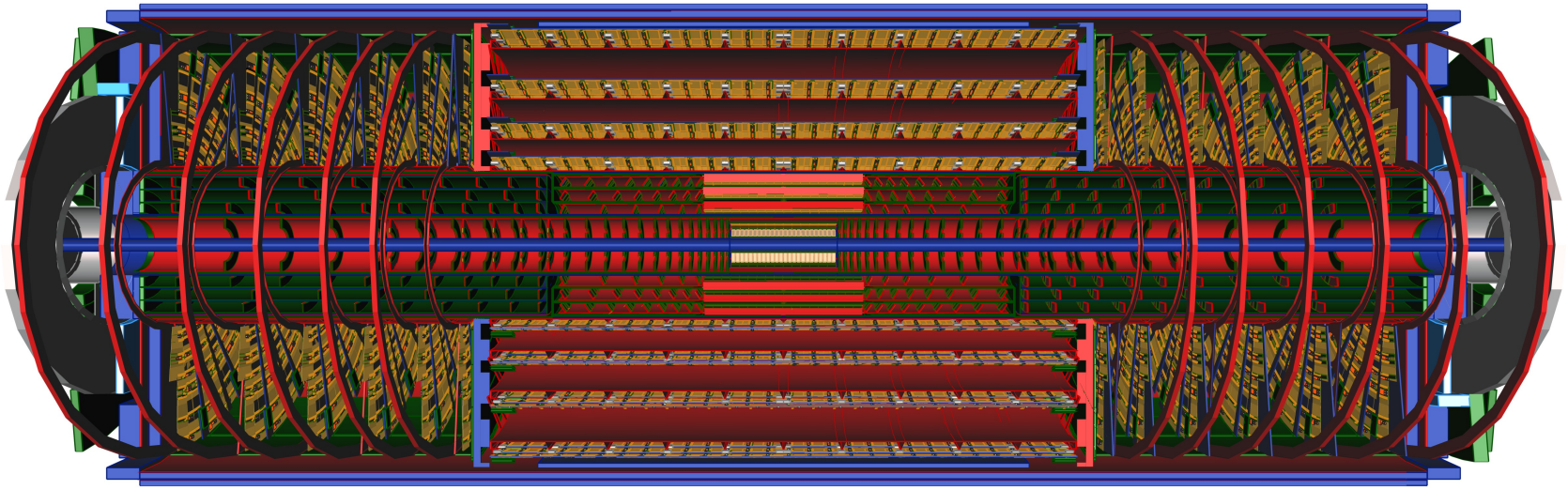
- All silicon with up to $|\eta| = 4$
- Less material, finer segmentation

ATLAS Phase-2 Upgrade: China contributions

- Inner Tracking System (ITK)
  - IHEP and Tsinghua
  - Committed to deliver 1000 strip barrel modules (10m^2 of sensor surface, 10% of total strip barrel modules)
- High granularity timing detector (HGTD)
  - IHEP, NJU, SDU, USTC
  - 100% LGAD sensors, 44% detector modules, …
- Muon System
  - SDU, SJTU, USTC
  - About 900 readout panels, 90 gas gaps and 360 singlets, …

ITK Upgrade

ITK Pixel TDR: https://cds.cern.ch/record/2285585
ITK Strip TDR: https://cds.cern.ch/record/2257755

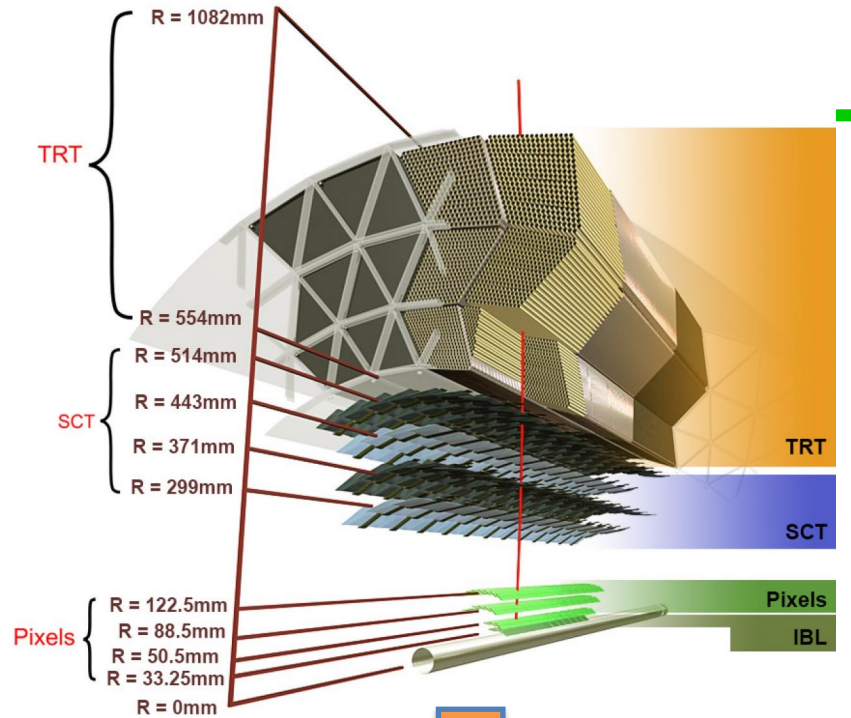


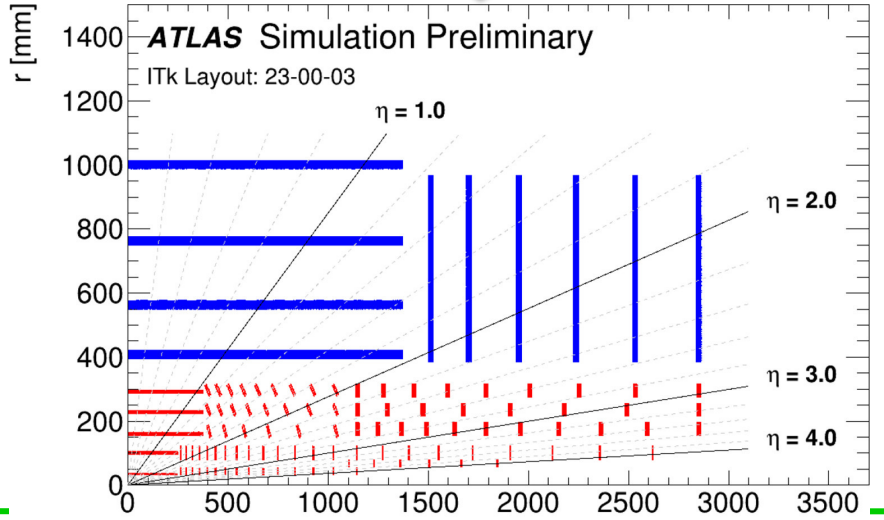
Parallel talks:

- Lei Guo (IHEP)
- Zhan Li (IHEP)
- Shaogang Peng (THU)
- Hui Li (THU)

ITk Upgrade

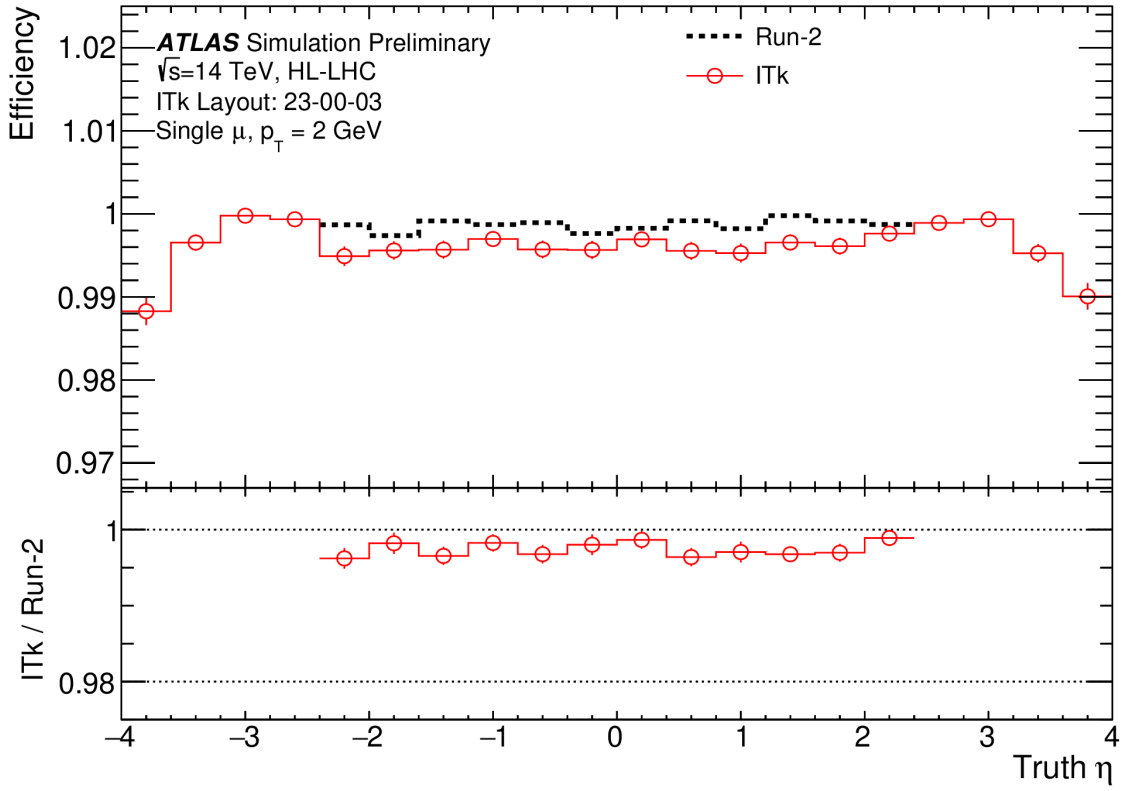
- Current Inner Detector
  - Pixels + Strips + Transition Radiation Tracker
- All silicon ITk for HL-LHC
  - Coverage increased from $|\eta|<2.5$ to $|\eta|<4$
    - 178 m^2 of silicon in the combined system (×2.7 larger)
    - 5 billion individual channels
  - Reduced pixel pitch
    - Current ID: $50\times250\ \mu m^2$ for the innermost layer (IBL) and $50\times400\ \mu m^2$ for the rest
    - ITK: $25\times100\ \mu m^2$ for barrel innermost , and $50\times50\ \mu m^2$ for the rest
  - Lower material budget
    - Maximum of 5% X_0 → 2% X_0
  - Increased trigger rate: 100kHz → 1MHz

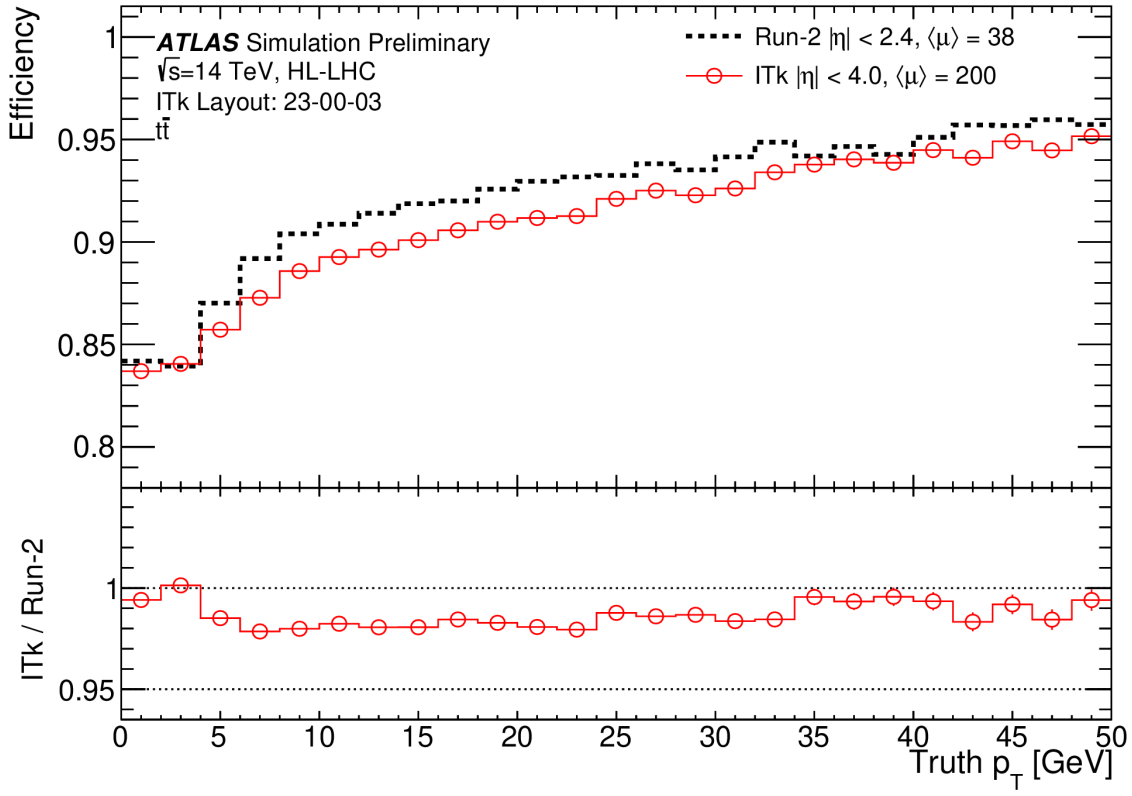




ITK Upgrade

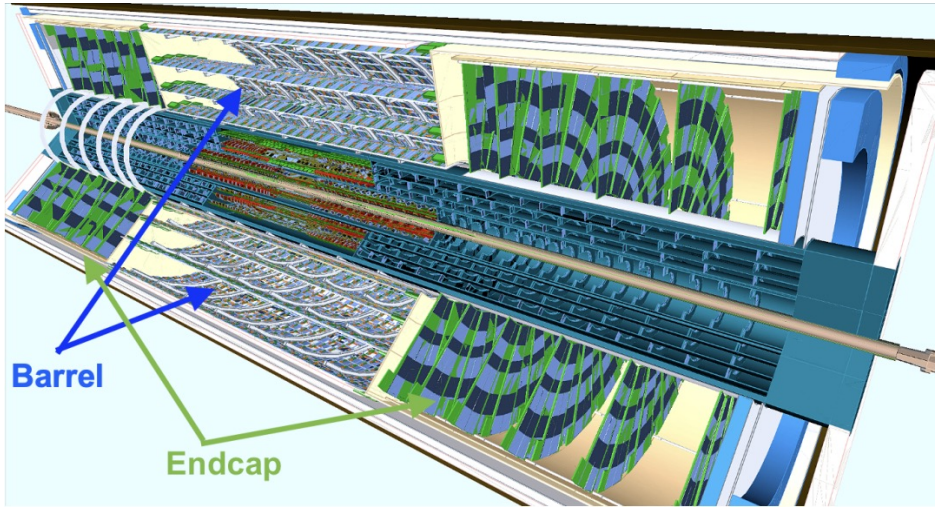
- The ITk will experience 4-5 times the number of pileup interactions as the ID in run 2
- The ITk is expected to have a comparable tracking efficiency for HL-LHC



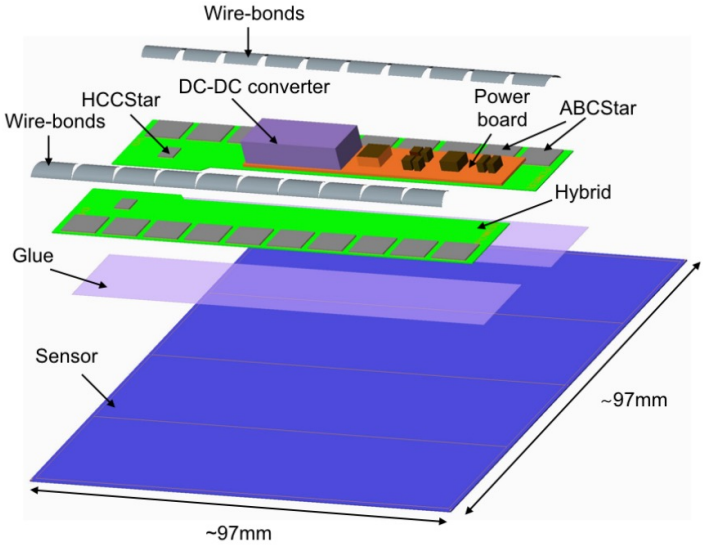


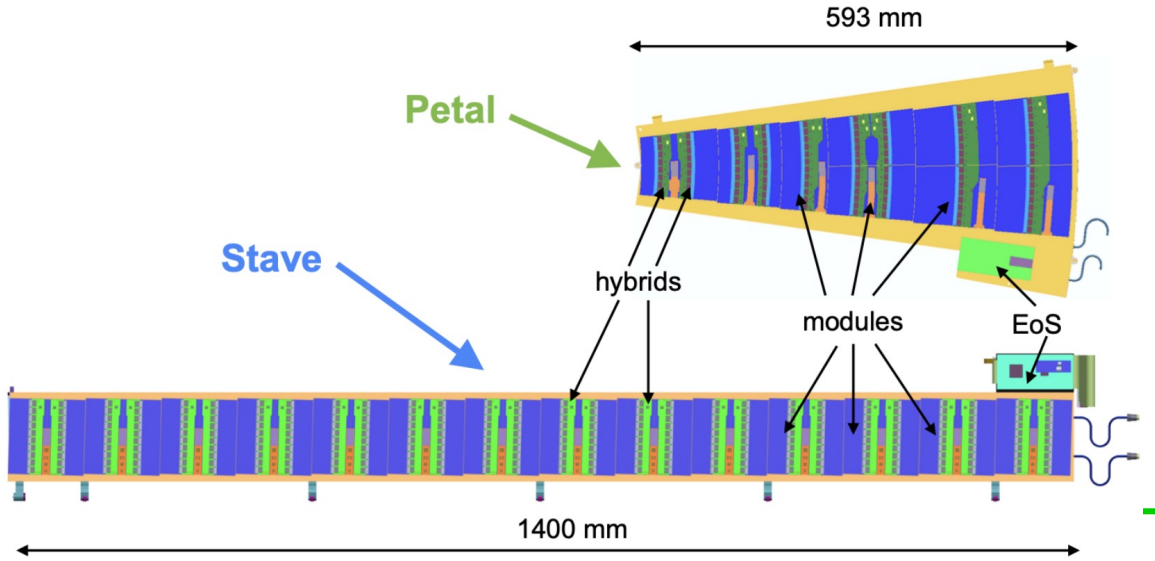
ITk Strip

- Key objectives of the ITk strip upgrade
  - High performance Strip detector module production
  - Radiation hard sensor and readout ASIC study
  - Complex silicon detector system integration
- China contributions: IHEP and THU
  - 1000 strip barrel modules (10m^2 of sensor surface)
    - 10% of total strip barrel modules (US 50% + UK 40%)
  - Additional contributions to strip barrel system integration, installation and commissioning



short-strip barrel module

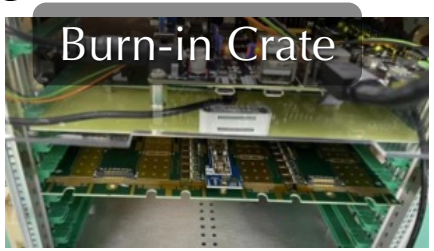


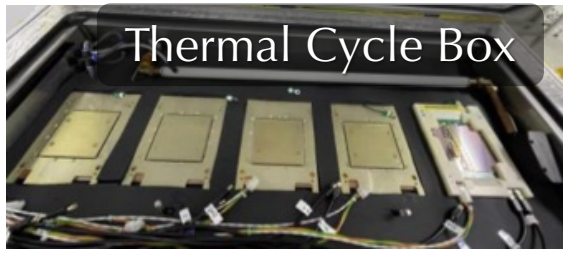


IHEP Site Module Production Status

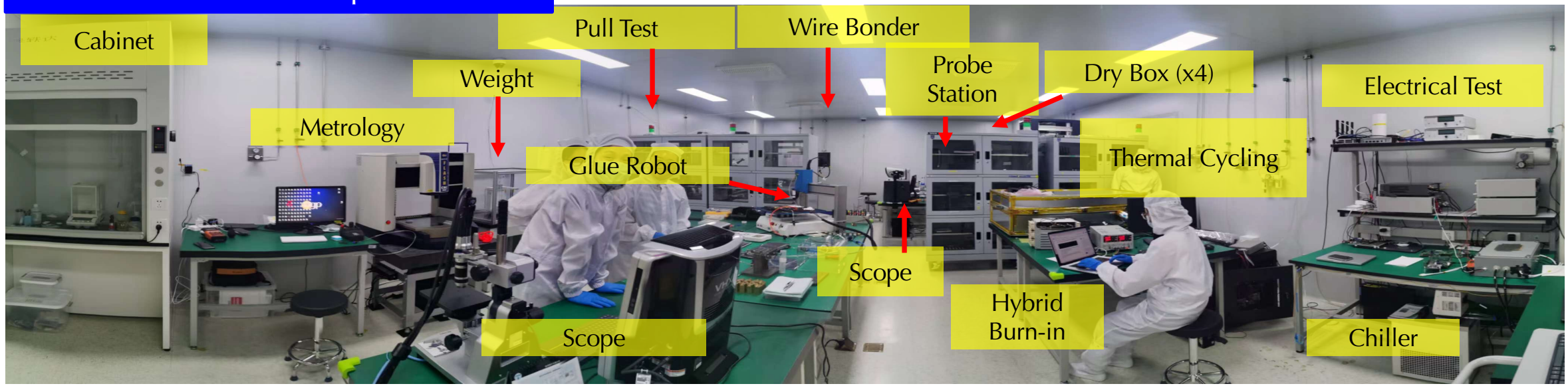
- Passed **all** 29 Qualification Steps for Module production
- X. Shi as UK/China cluster manager for 50% barrel production
- Manufactured production tooling in China

ASIC tools made in China





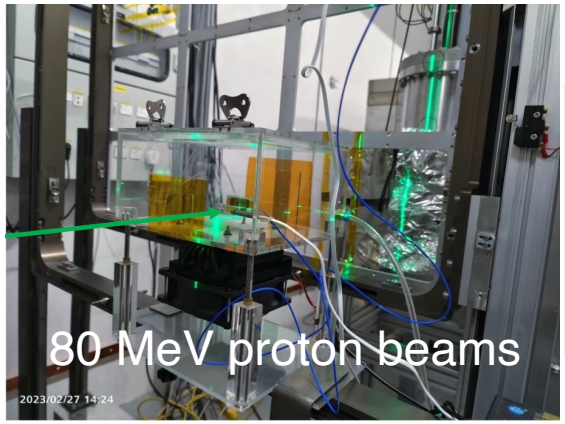
IHEP Site for ITk Strip Module

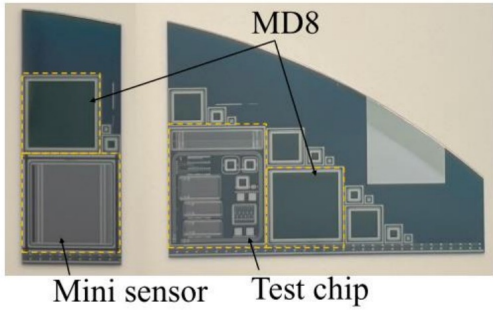


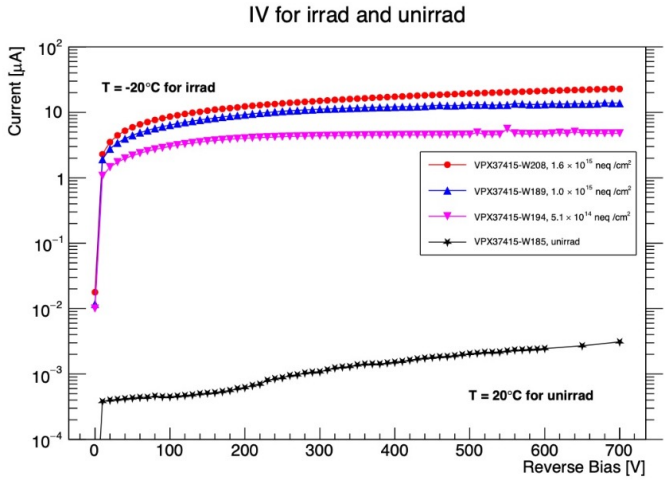
Radiation Study: Strip Sensors

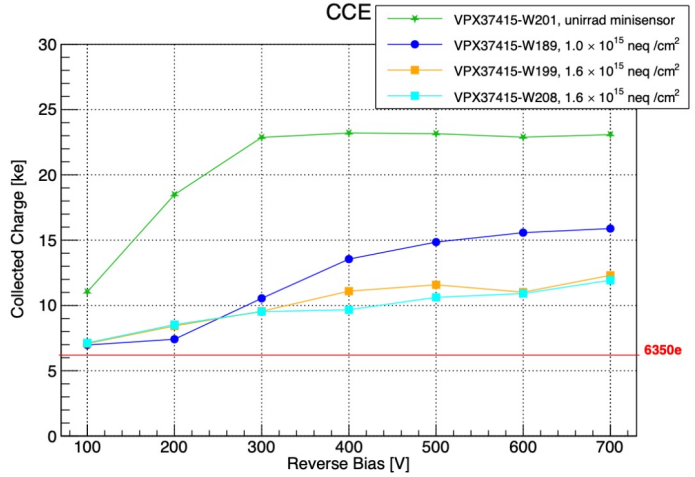
- Associated Proton Experiment Platform (APEP) in CSNS as an irradiation site
  - for ITk strip sensor production quality assurance (QA)
- Strip sensors (Mini, MD8) irradiated with a new code box
  - With controlled temperature and humidity
  - 5.1×10^{14}, 1.0×10^{15}, and 1.6×10^{15} n_{eq}/cm^2
- Post-irradiation measurements are done: IV, CV, and CCE
  - Results consistent with other sites

CSNS could be a proton irradiation site for ATLAS ITk sensor QA, after a formal site qualification



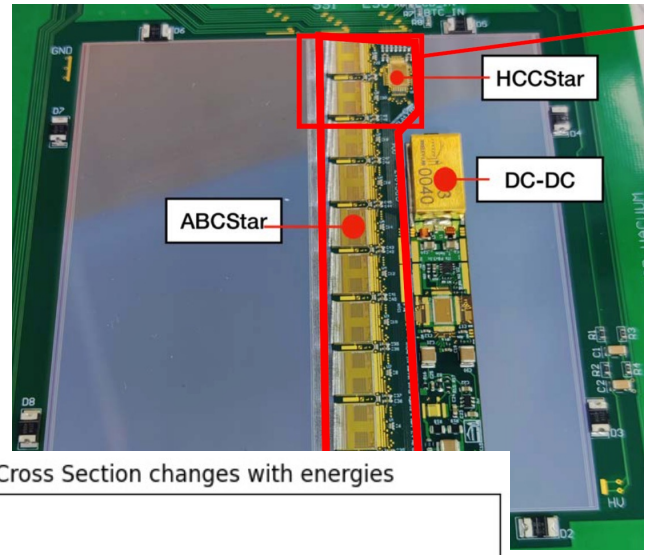


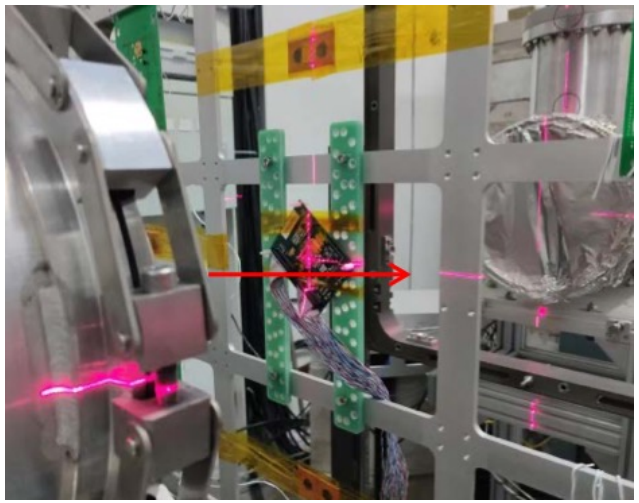


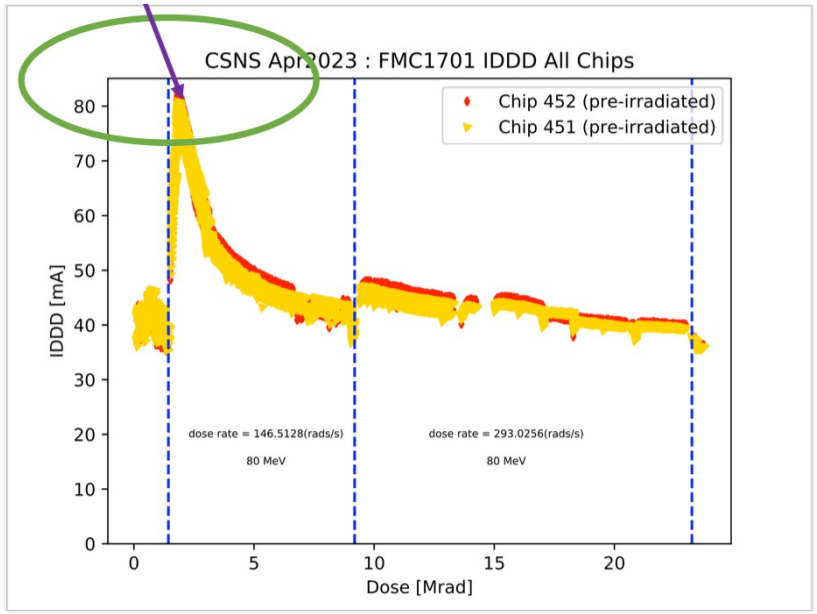


Radiation Study: ASICs

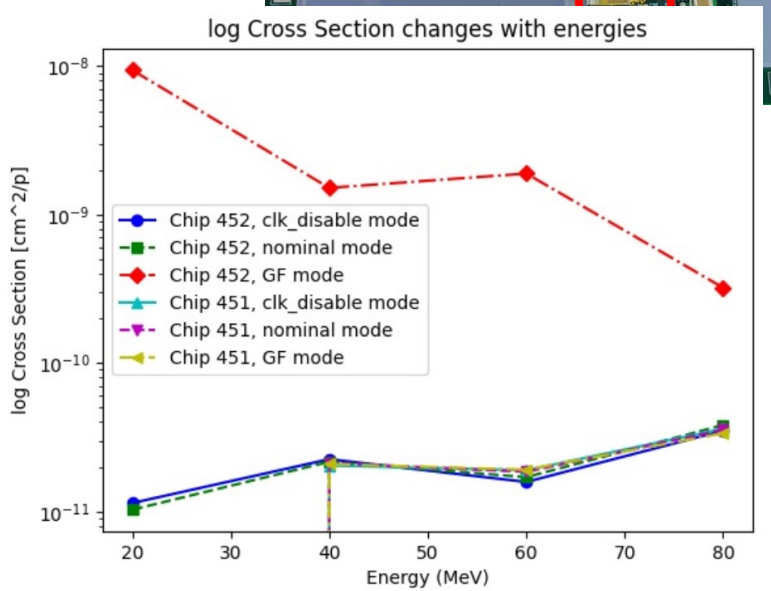
- The ABCStar (ATLAS Binary Chip) front end readout ASIC for strip sensor
  - Key component of ITk strip module, ~300,000 needed for production
  - Target radiation hardness: 1.6×10^{15} n_{eq}/cm^2
- Carried two SEE tests at CSNS in 2023
  - Preliminary results obtained, detailed analysis ongoing







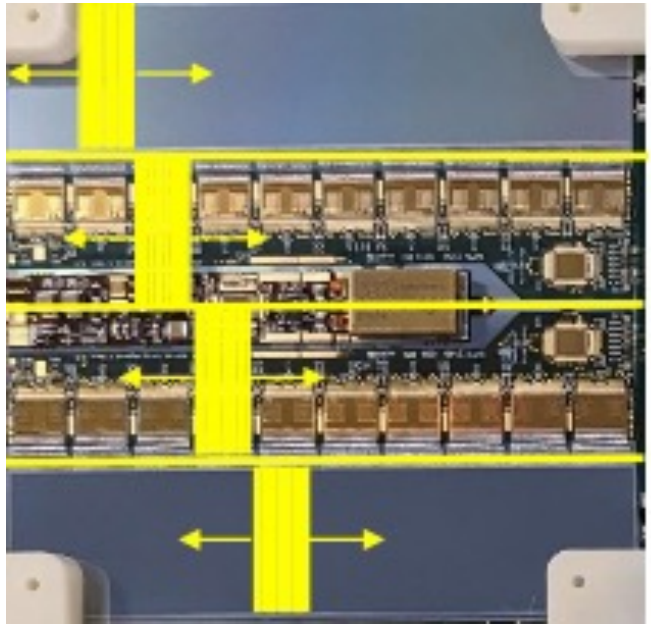
TID bump pertains to the irradiation history

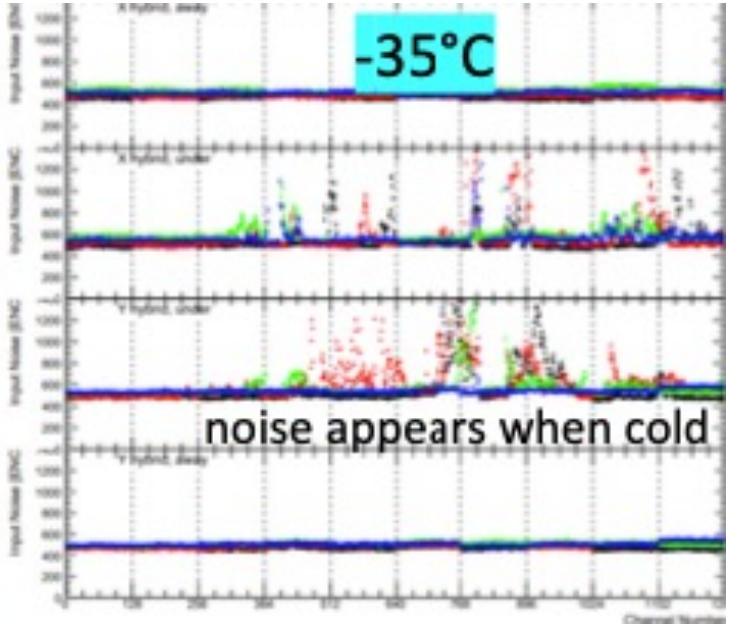


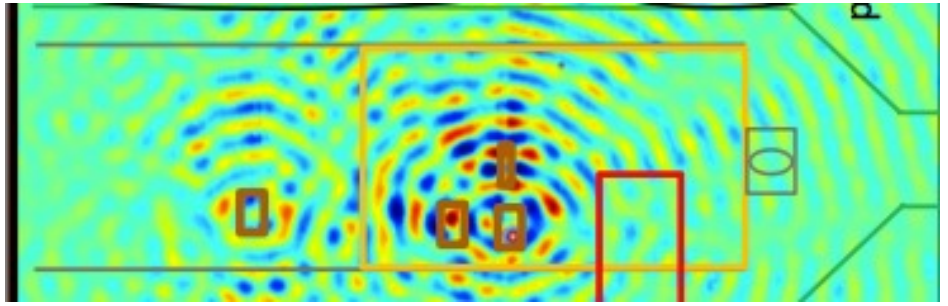
Preliminary SEE cross-section results

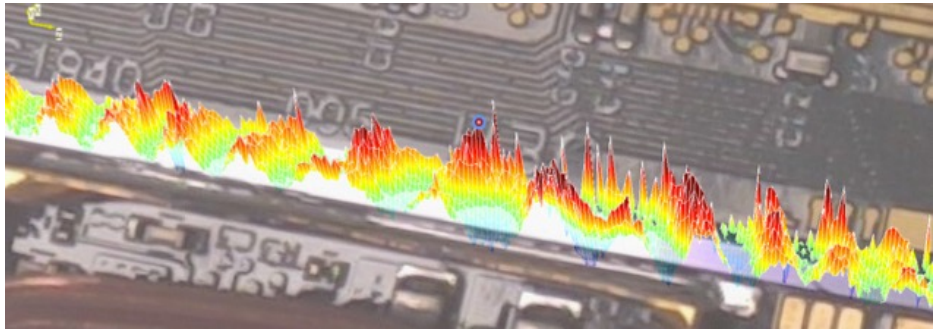
RAL Site Cold Noise Study

- Two FTEs (one postdoc + one student) from IHEP based at RAL contributing to module production and stave loading
- Recently a code noise issue observed in strip modules in thermal cycling
  - 11V capacitors found as source of the issue
- IHEP lead effort for the Cold Noise investigation for the ITk collaboration



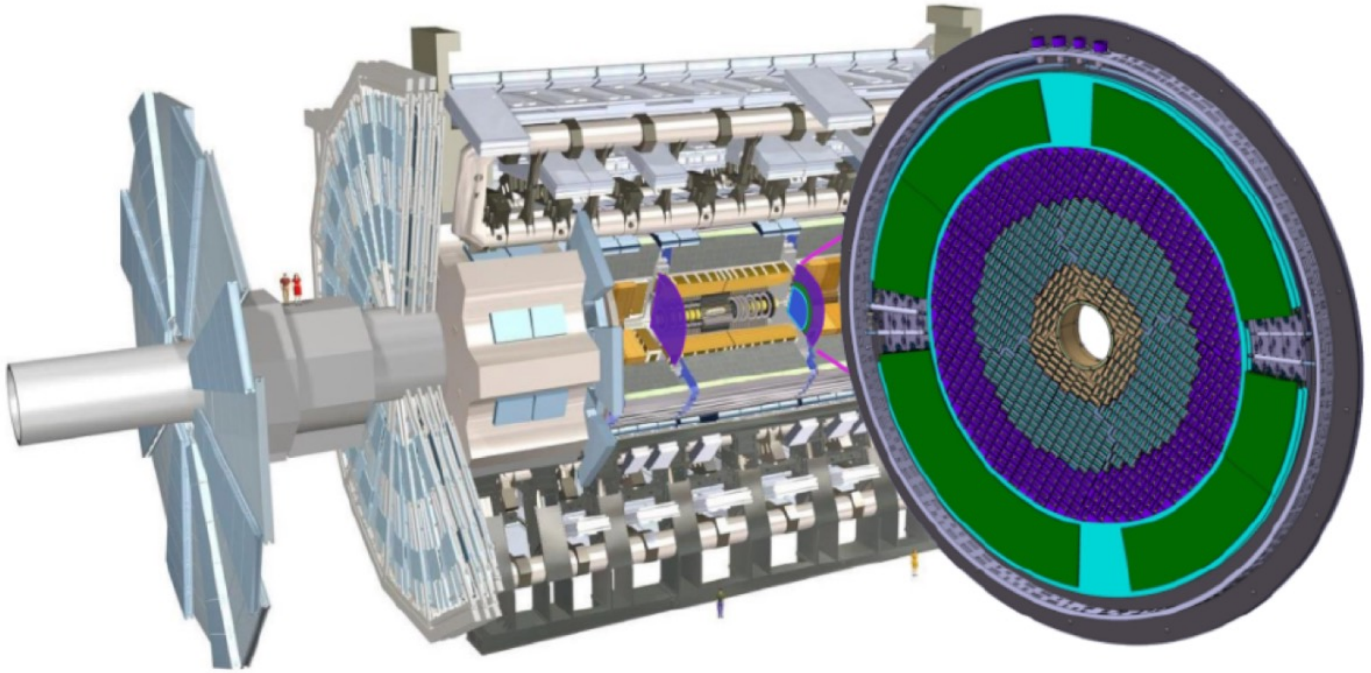






HGTD Upgrade

HGTD TDR: https://cds.cern.ch/record/2719855

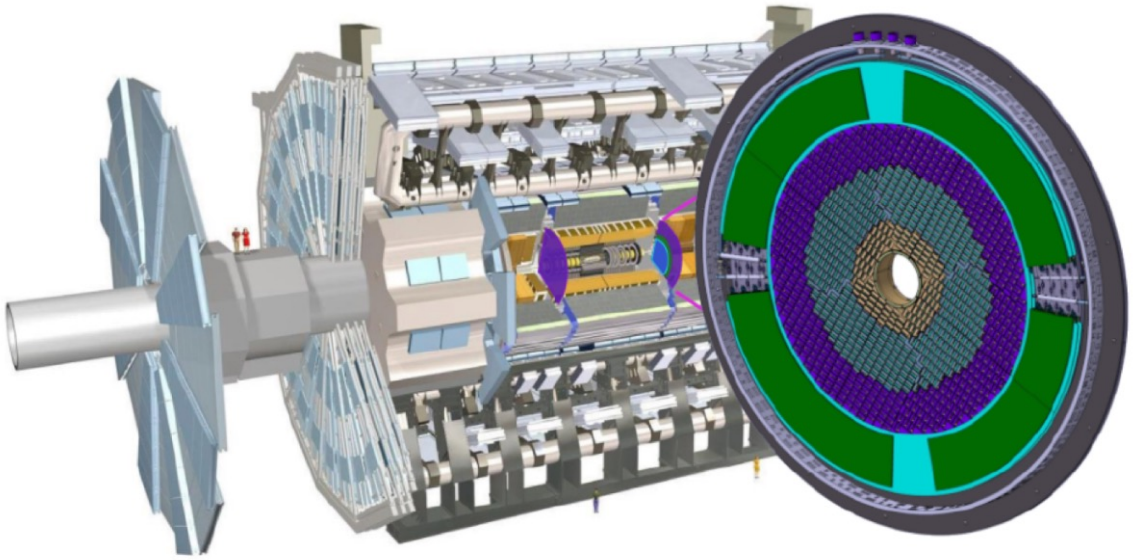


Parallel talks:

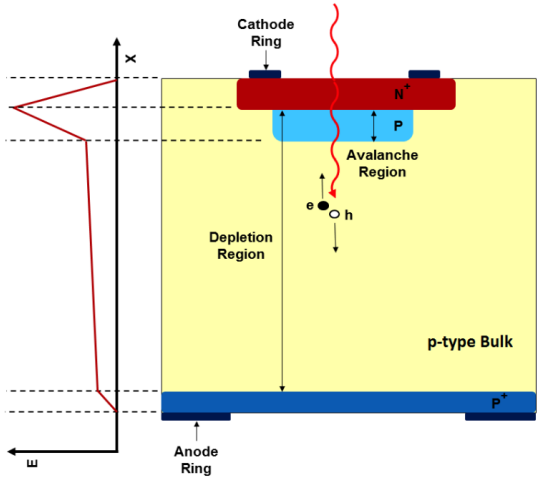
- Kuo Ma (USTC)
- Han Li (USTC)
- Zhuang Li (USTC)
- Aona Wang (USTC)
- Xiangxuan Zheng (USTC)
- Zhijun Liang (IHEP)
- Mei Zhao(IHEP)
- Weiyi Sun (IHEP)
- Xuan Yang (IHEP)
- Xinghui Huang (IHEP)
- Mingjie Zhai (IHEP)
- Zhenwu Ge (NJU)
- Chuanye Wang (NJU)

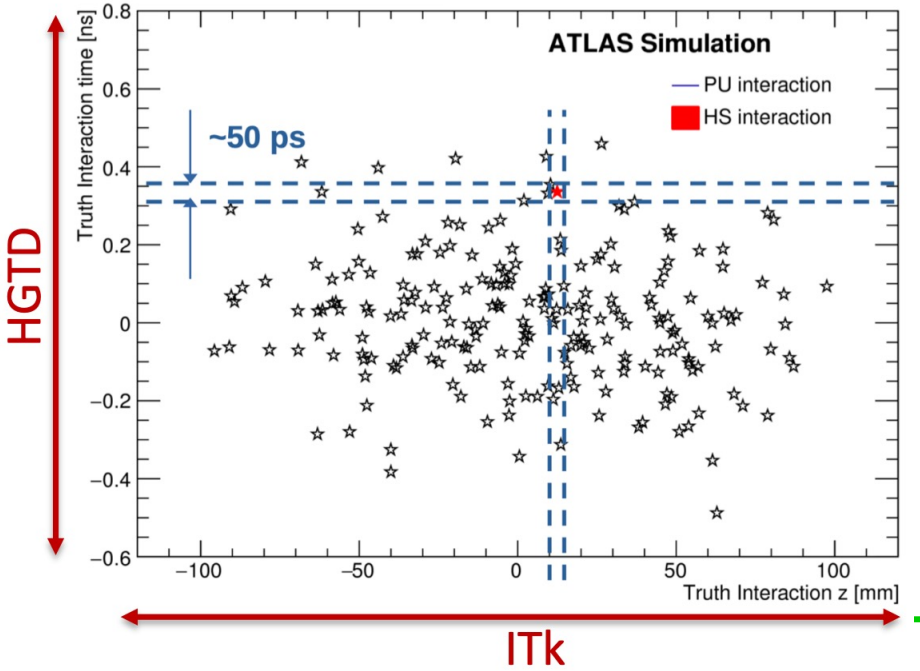
High Granularity Timing Detector (HGTD)

- A new timing detector to be installed for HL-LHC to improve pile-up rejection and objects reconstruction
  - Based on Low Gain Avalanche Detectors (LGAD)
  - Time resolution target: 30 – 50 ps/track (start – End of Life)
  - Will provide a direct measurement on the luminosity



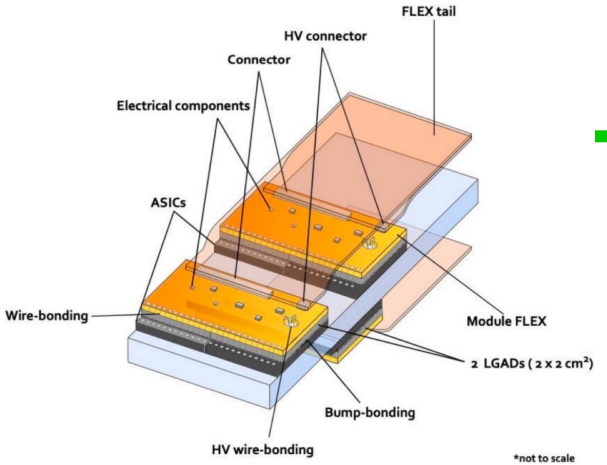
Located between barrel and endcap calorimeters (|z| = 3.5 m)



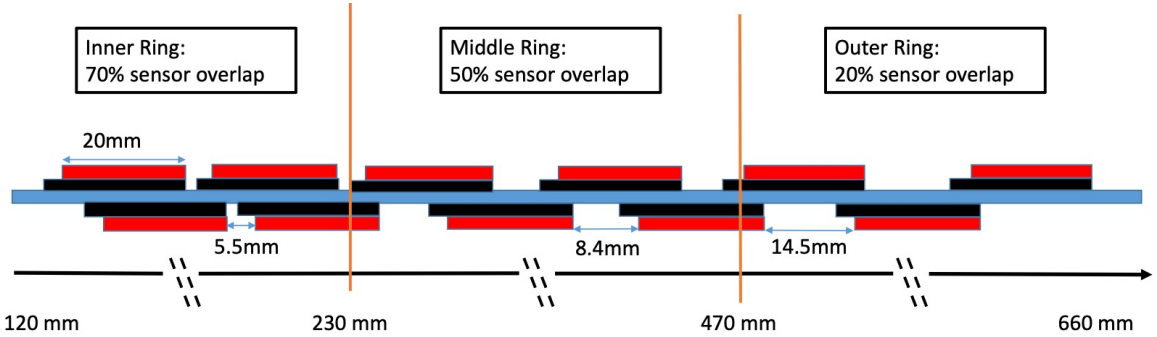


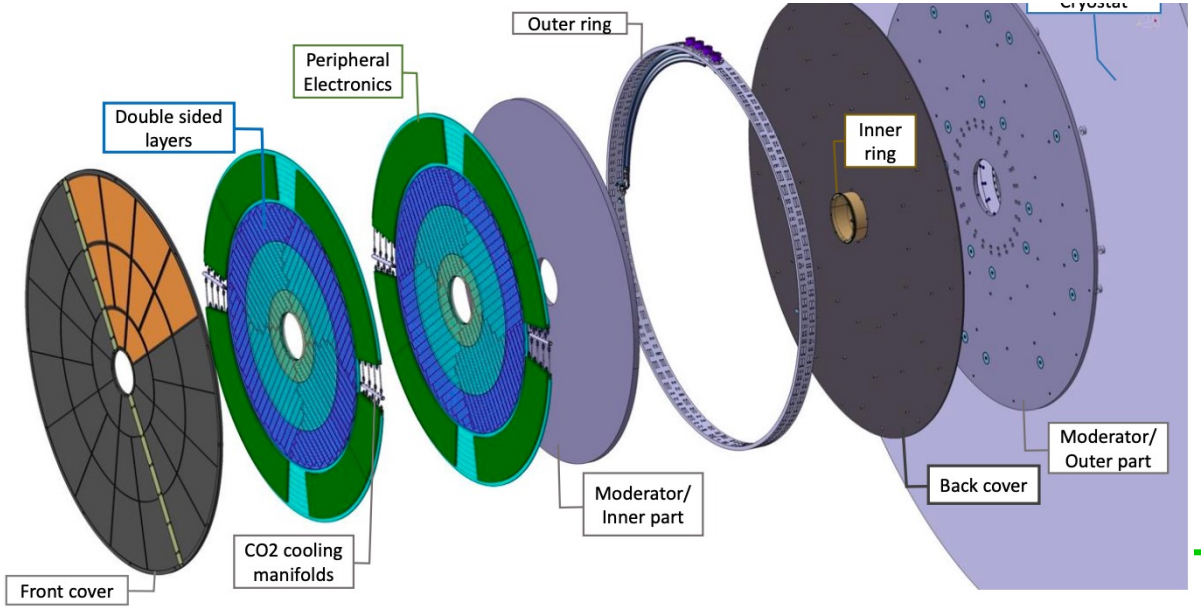
HGTD Layout

- Two disks per endcap with detectors mounted on both sides
- Active area coverage: 2.4 < |η| < 4
- Radius: 120 mm < r < 640 mm
- Target irradiation fluence: $2.5\times10^{15}\mathrm{n}_{eq}/cm^2$
  - detector segmented into three replaceable rings



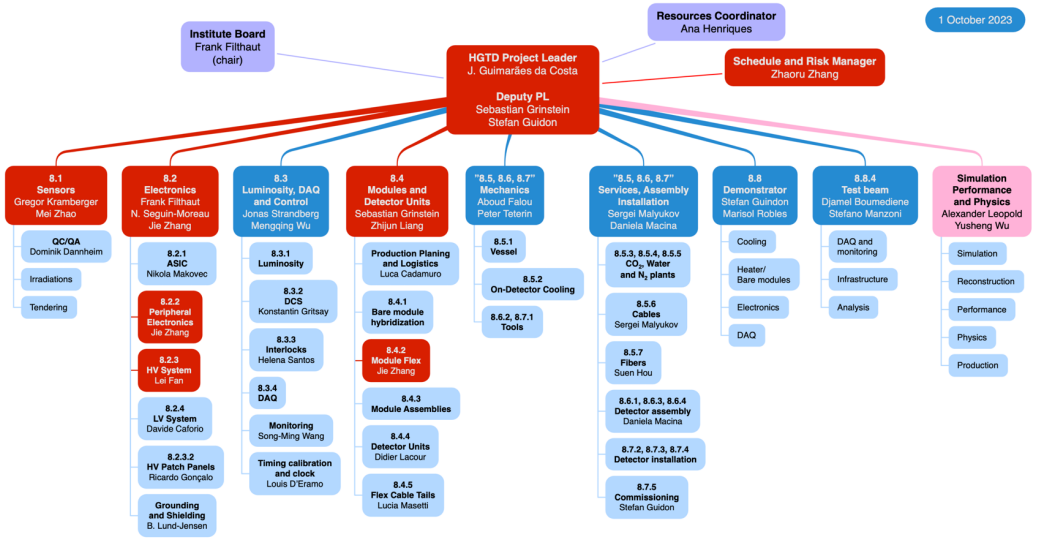
Pad size	1.3 mm × 1.3 mm
Active sensor thickness	50 µm
Number of channels	3.6 M
Active area	6.4 m^2
Module size	30 x 15 pads (4 cm × 2 cm)
Modules	8032

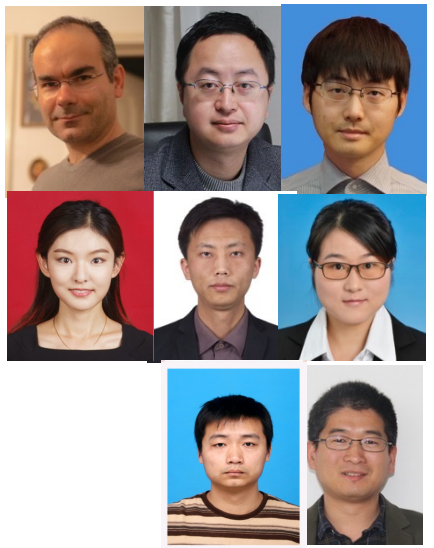




HGTD China

- China team is making key contributions to HGTD
  - 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)
- ATLAS China team played leading roles in HGTD
  - Joao (IHEP) is the project leader
  - 5 Level-2 conveners (Module, Sensor, Electronics, Risk, Simulation)
  - 3 Level-3 conveners (PEB, high-voltage, module flex)
  - 1 Speaker committee

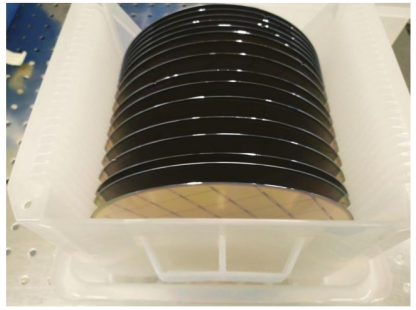


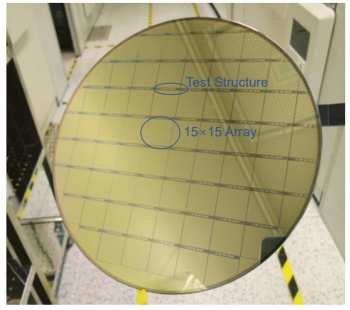


LGAD sensors pre-production

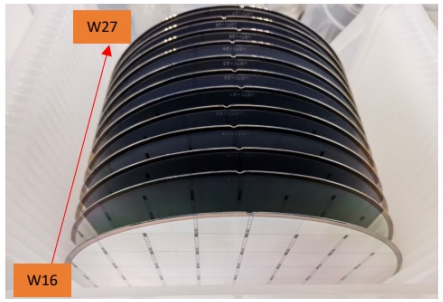
- In May 2013, CERN chosen IHEP-IME in HGTD sensor tendering
  - First time domestic silicon sensor was chosen by CERN in LHC experiment
  - Won the competition with Hamamatsu (Japan) and FBK (Italy)
- The current production plan:
  - IHEP-IME: 90% (66% from CERN tendering + 24% in-kind contribution)
  - USTC-IME: 10% in-kind contribution

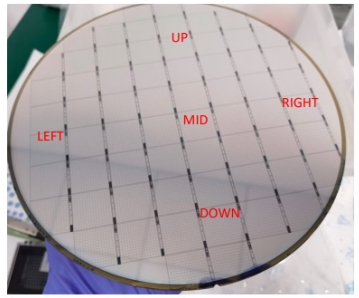
IHEP-IME
Pre-production



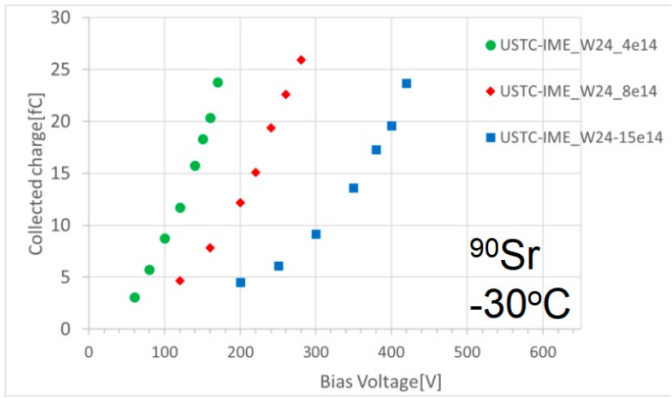


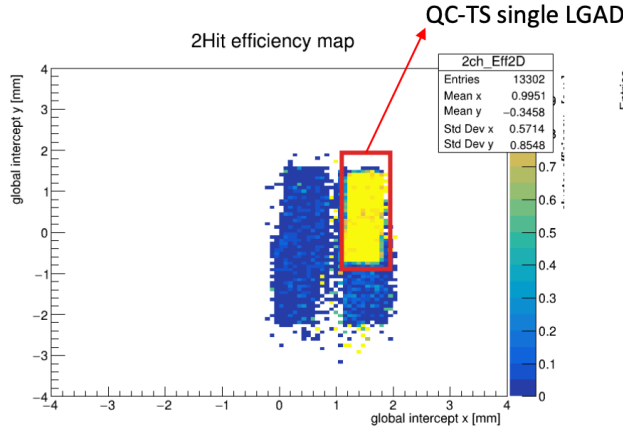
USTC-IME
Pre-production





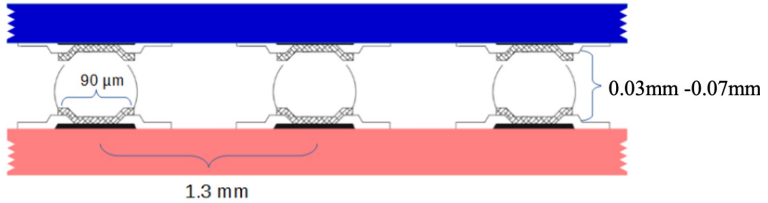
The USTC-IME pre-production sensors have been irradiated and tested in test beam from July to Nov



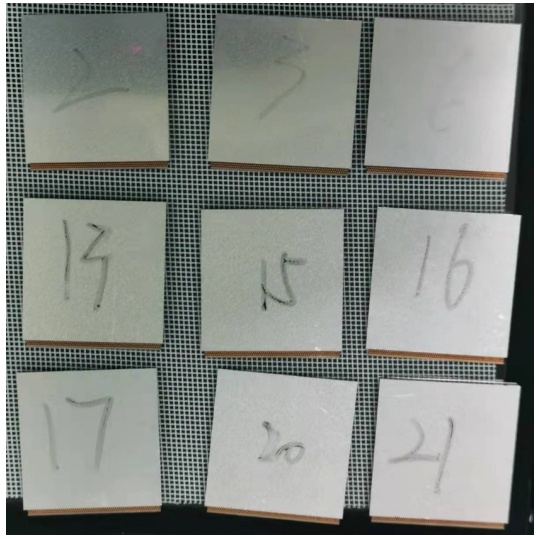


ALTIROC3 full-size hybrid

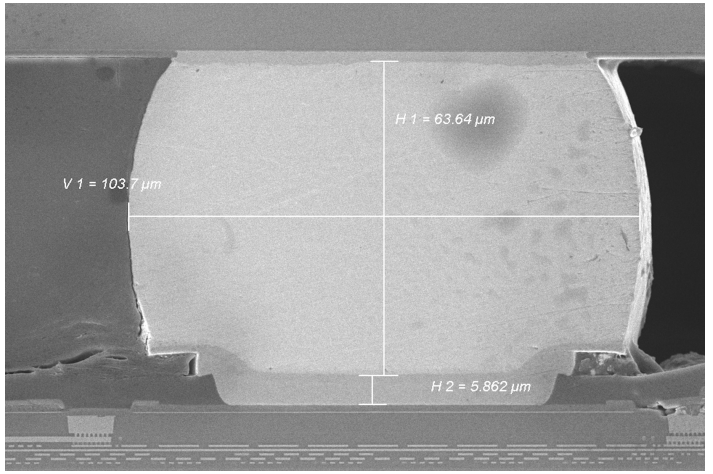
- Hybridization: bump-bonding of LGAD sensors and readout ASICs
- Full size ASIC-ALTIROC3 hybrids
  - IHEP is contributing 50% of hybrids
  - IHEP made prototypes with ALTIROC2 ASIC + IHEP-IME LGAD sensor



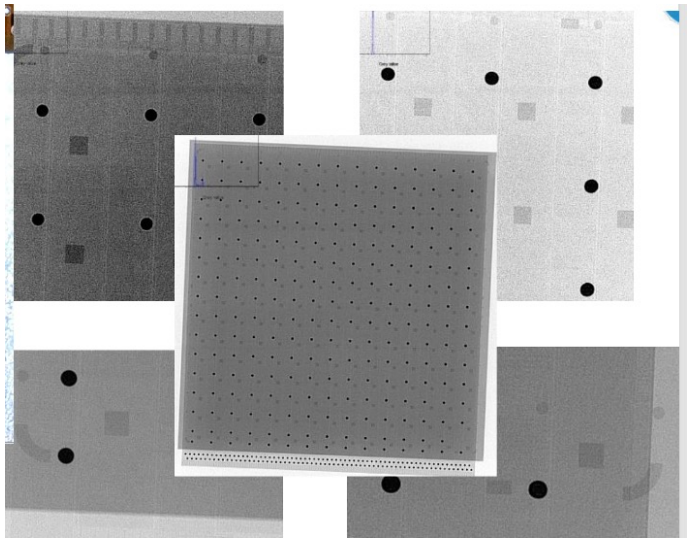
ALTIROC2 + IHEP-IME LGAD



Bump connection in hybrid profile view

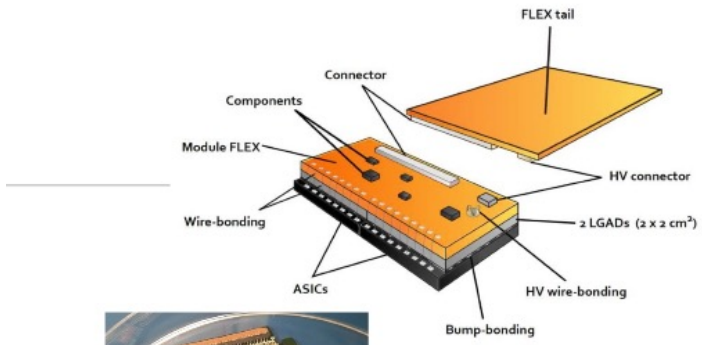


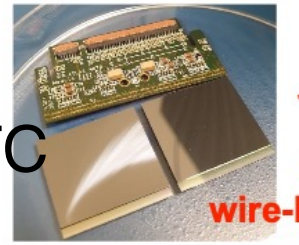
X-ray image of full-size hybrid



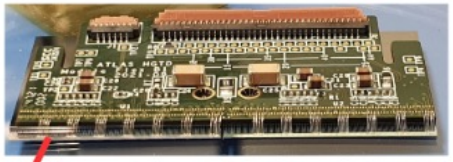
HGTD module assembly

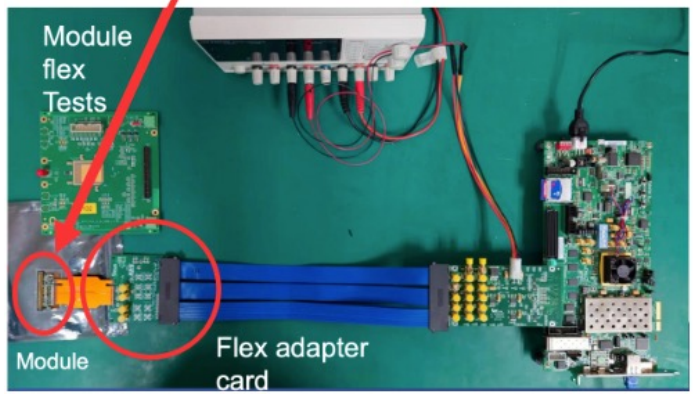
- China is responsible for 44% of module
  - IHEP (34%), USTC(10%) are 2 of the 6 assembly sites at HGTD
- IHEP/USTC developed gantry systems
  - Automatic glue dispending
  - Pattern recognition, automatic assembly
- Several modules have been successfully assembled at IHEP/USTC
- IHEP responsible for 100% of Module Flex design/production
- Module DAQ test system also set up at IHEP/USTC



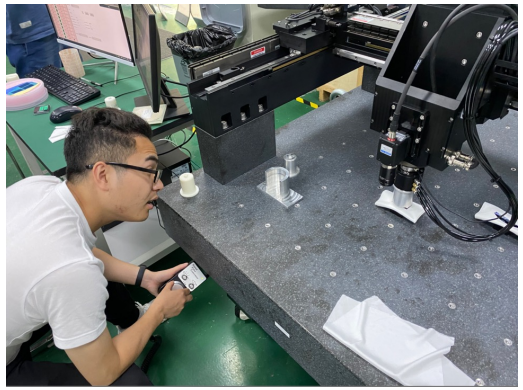


glue+
wire-bonds

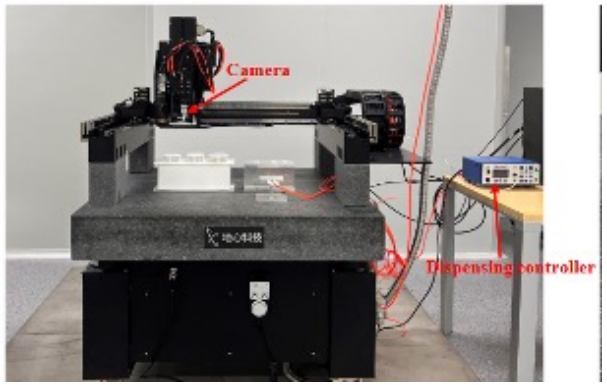




Gantry @ IHEP

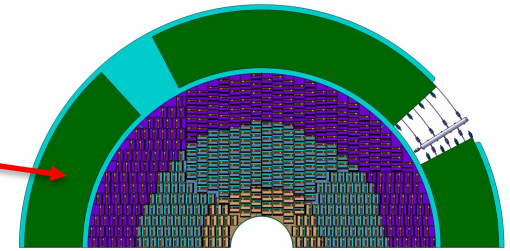


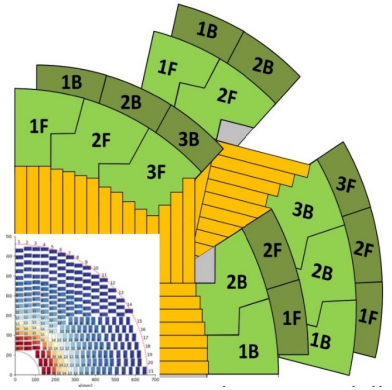
Gantry @ USTC

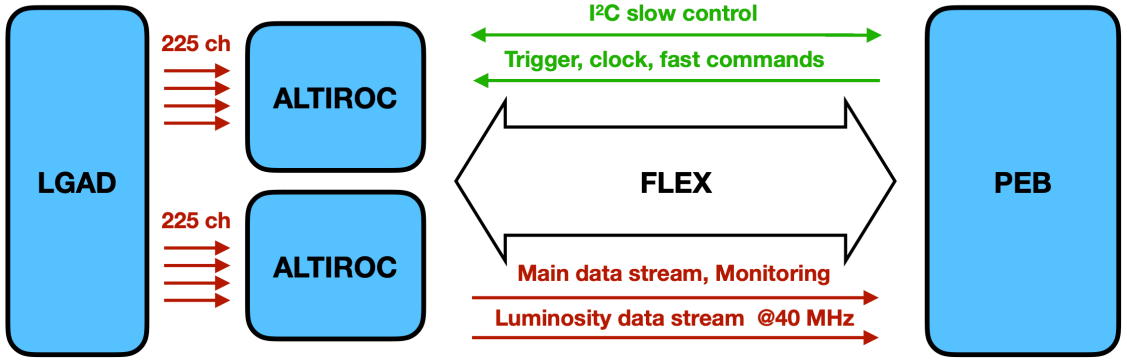


HGTD electronics

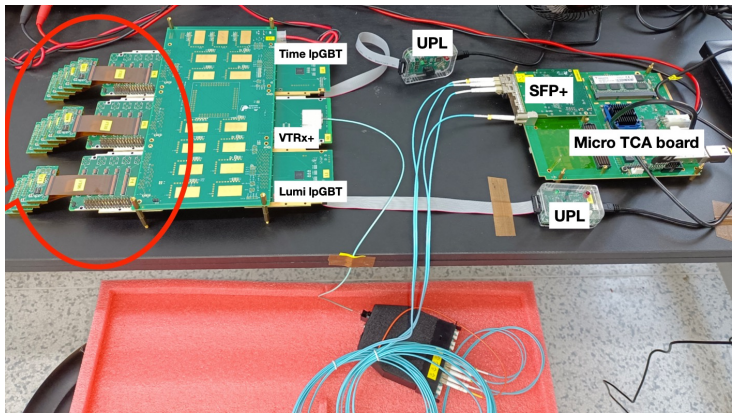
- HGTD on-detector electronics: Peripheral Electronics Boards (PEB)
  - Control, monitoring & data aggregation and transmission
  - Power-supply distribution: LV & HV
  - Thermistor connection between the front-end modules and the interlock system
  - Six types of PEB (front and back side)
- IHEP and NJU developed PEB prototypes
- Moving towards the FDR phase

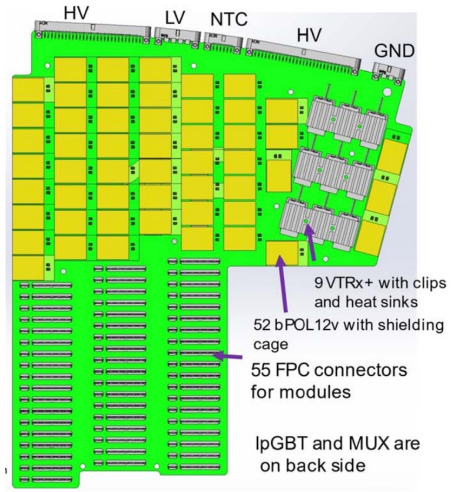






Modular PEB prototype





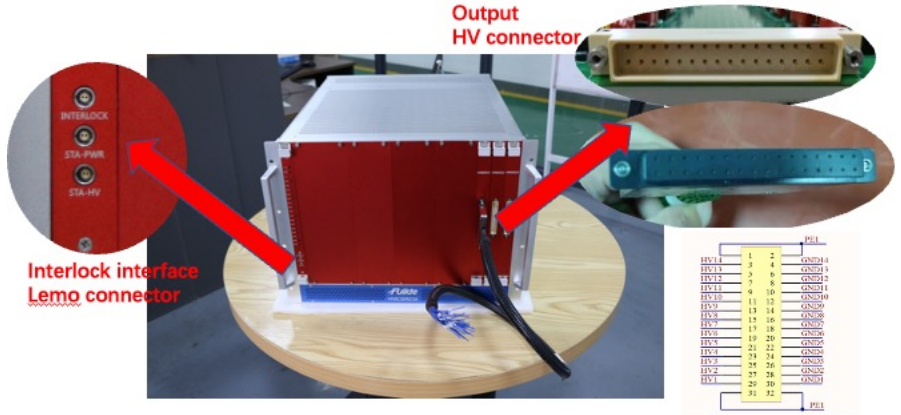
PEB 1F prototype is under production

HGTD electronics

- SDU developed long flex tail prototypes (75cm)
- IHEP developed high voltage power supply prototype

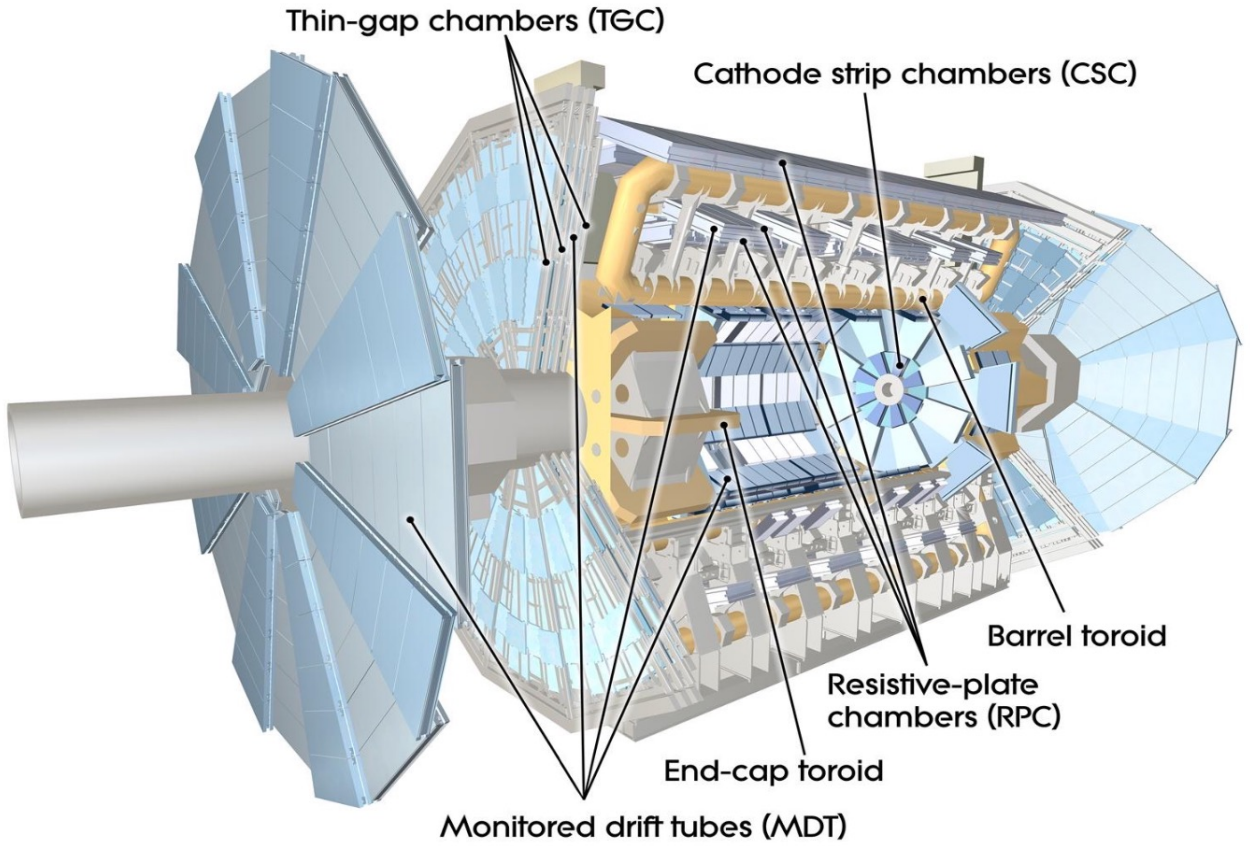
Long Flex tail prototype (75cm)

High voltage power supply prototype



Muon System Upgrade

Muon TDR: https://cds.cern.ch/record/2285580

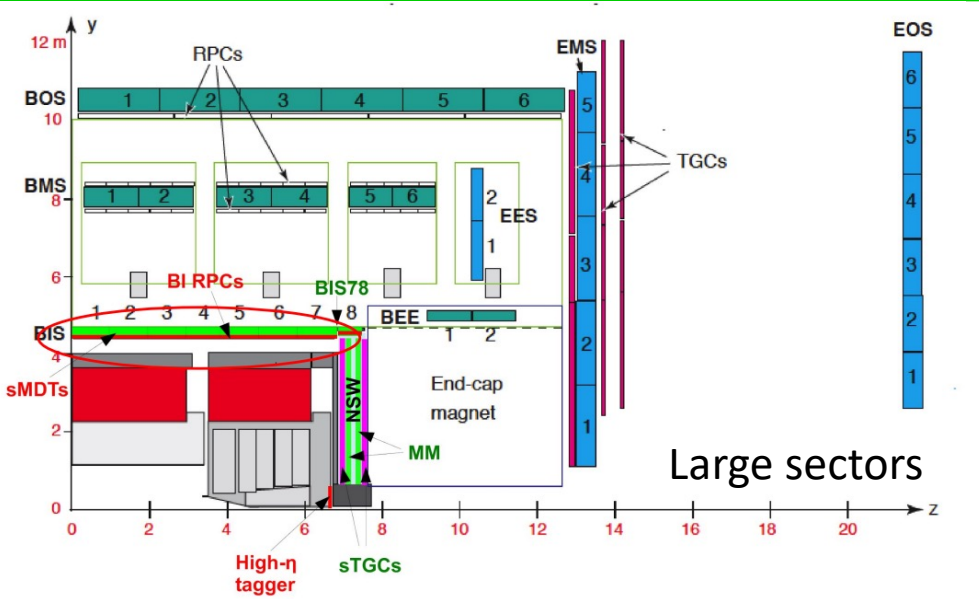


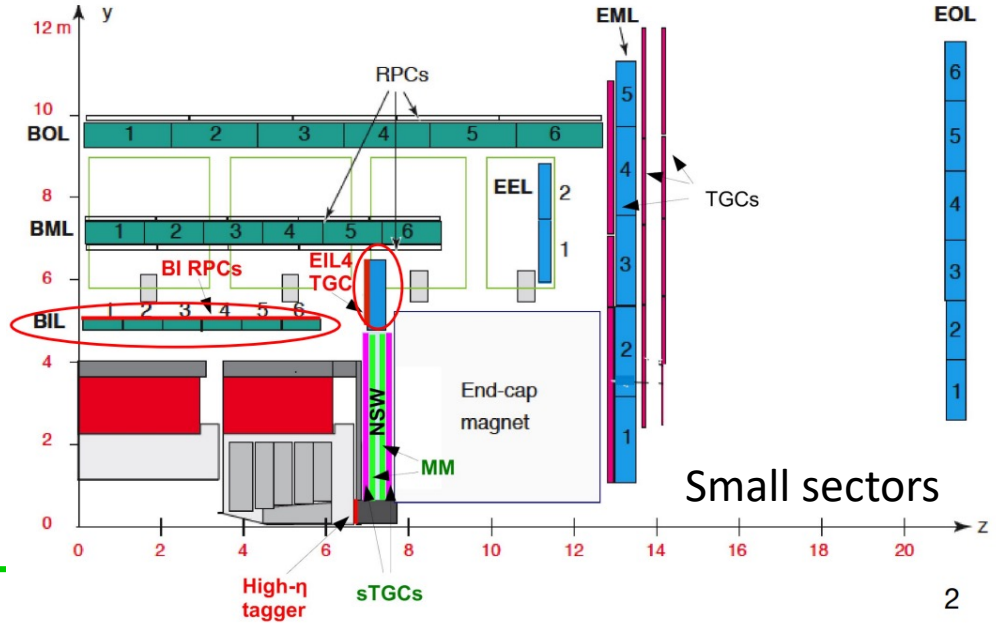
Parallel talks:

- Dongshuo Du (USTC)

Muon Upgrade

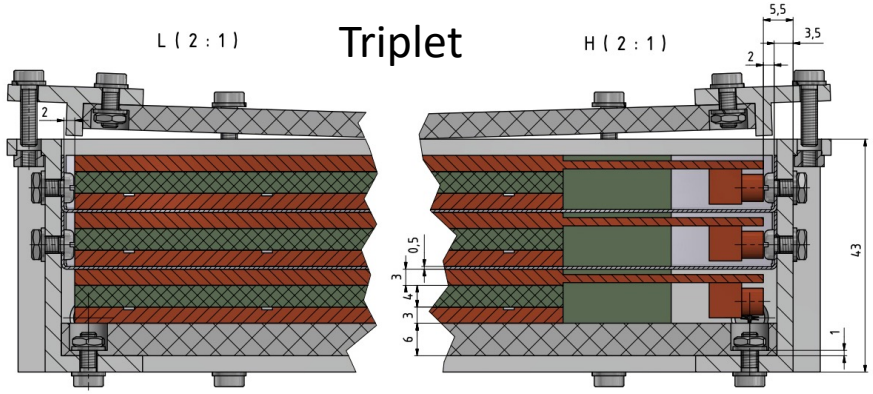
- Current ATLAS Muon Spectrometer
  - Trigger chambers:
    - Three stations of Resistive Plate Chambers (RPCs) in the barrel
    - Three stations of Thin Gap Chambers (TGCs) in the end-cap
    - New Small Wheel (Micromegas + sTGC) before magnet
  - Precision measurement chambers:
    - Three stations of Monitored Drift Tubes (MDTs) in barrel/end-cap
- Phase-II Upgrades
  - New RPCs with increased rate capability in BI
  - sMDT in BIS
  - New TGC triplets in EIL4

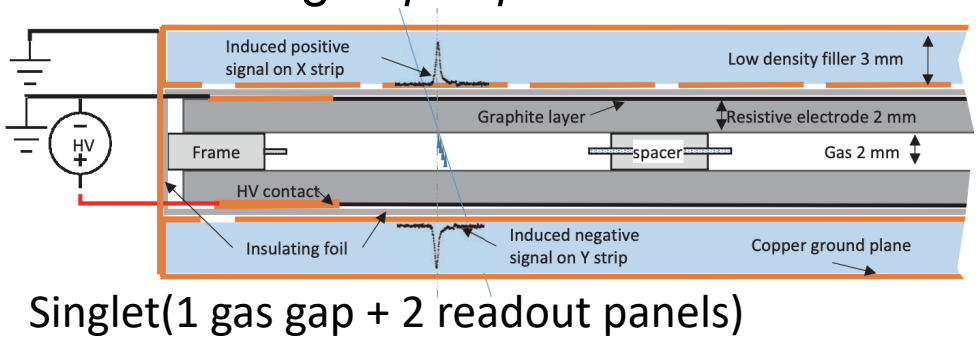




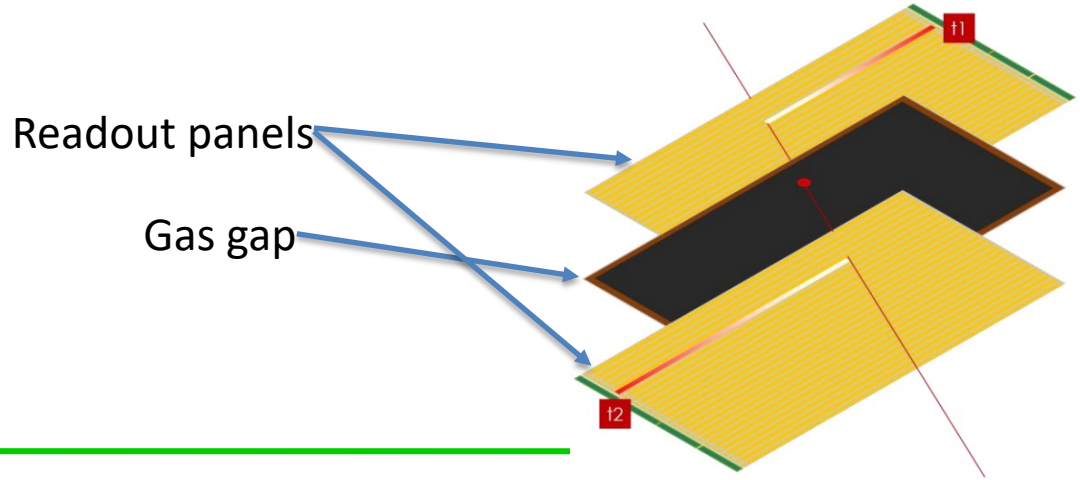
RPC Upgrade

- A new generation RPC system with thin-gap RPCs in the barrel inner(BI) region
  - Current: doublet gas gaps of 2mm → HL-LHC: triplet of 1mm gas gaps
  - Expected to increase the muon trigger acceptance from 70% to about 96%
- BI RPC:
  - 272 triplet RPC chambers, ~1400 m^2 gas gaps
  - Max area of singlets: 1820mm*1096mm
  - 13,500 front-end boards
- Readout
  - New Front-End Electronics
  - New readout design: $\eta - \eta$ readout for 2D



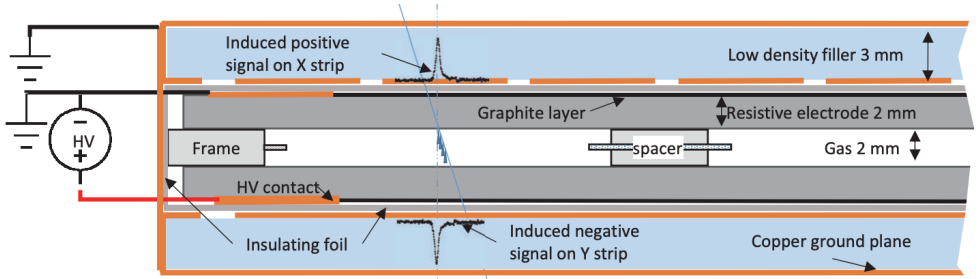


Singlet(1 gas gap + 2 readout panels)

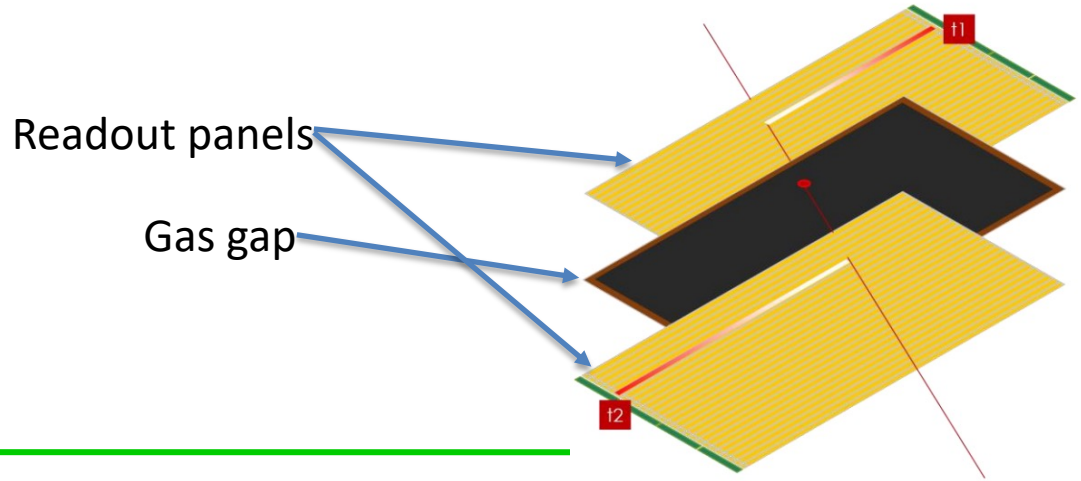


China RPC Upgrade

- China contribution:
  - SDU-SJTU-USTC
  - Mass production of ~900 readout panels, ~90 gas gaps
  - Assembly of ~7000 FEE boards and ~360 singlets
- Recent activities
  - Honeycomb readout panel production
  - RPC gas gap production
  - Singlet assembly training

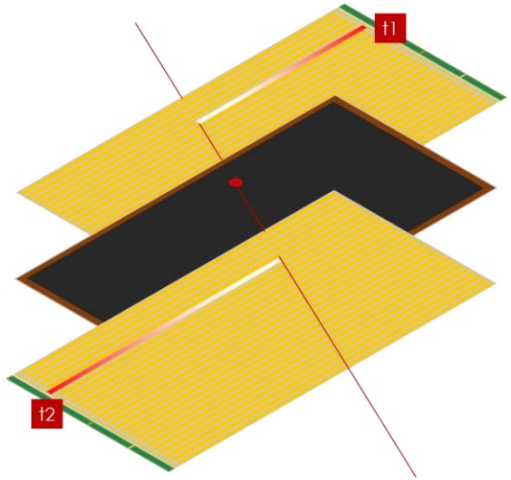


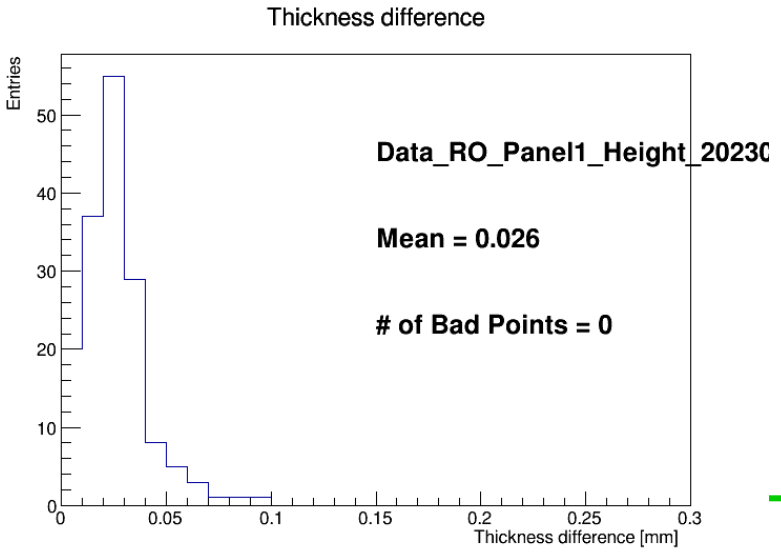
Singlet(1 gas gap + 2 readout panels)



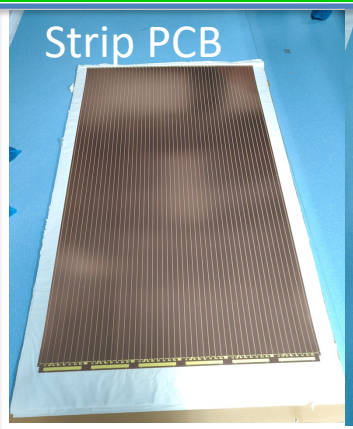
Honeycomb readout panel production

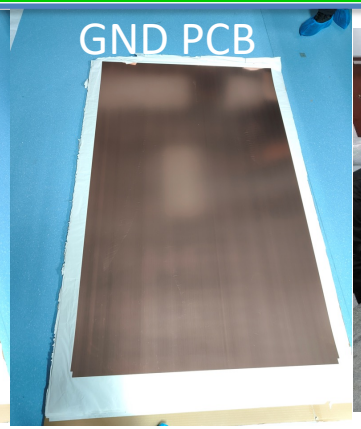
- Components:
  - Two PCBs: strips + GND panel (0.4mm thick, size: 1706×1070 mm)
  - Honeycomb core: 3mm thick
  - Glue: Araldite 2011 (~180g /side)
- Key technologies and challenges:
  - Large-area readout boards
  - High precision and uniformity
    - Flatness: < 0.1 mm
    - Length and width: 1705 +/- 1 mm, 1072 +/- 1 mm
- 8 readout panel prototypes have been assembled
  - All satisfied the specifications
  - Shipped to CERN





Honeycomb readout panel production



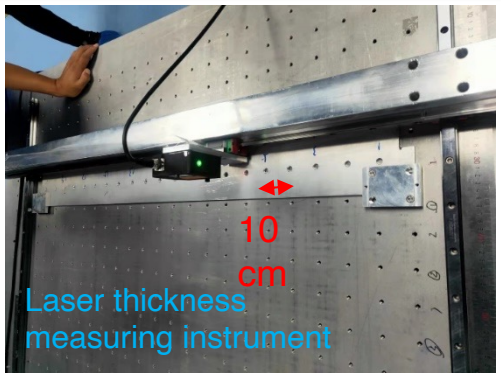


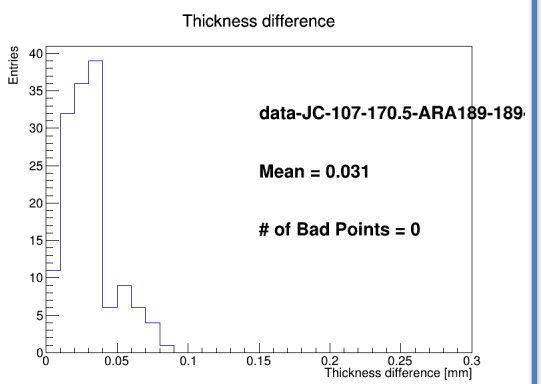
Electrical inspection to make sure no short or broken connections

Honeycomb thickness measurements

Dimensional measurements

Length: 1705 mm
Width: 1072 mm
Diagonal: 2014 mm
Error: +/- 1 mm

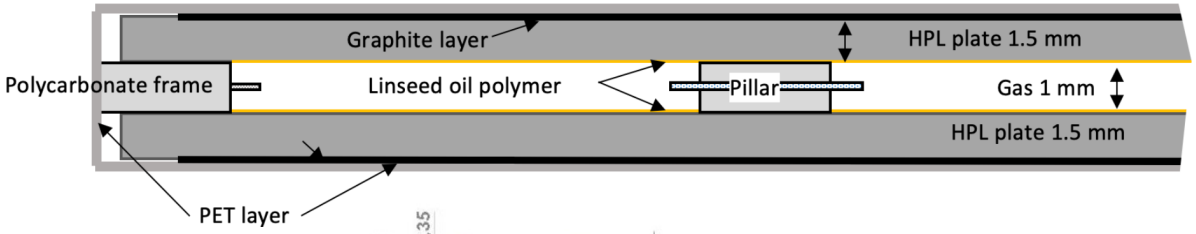


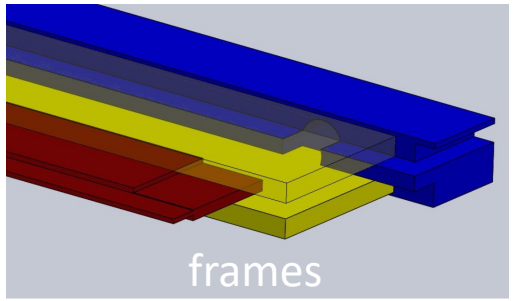


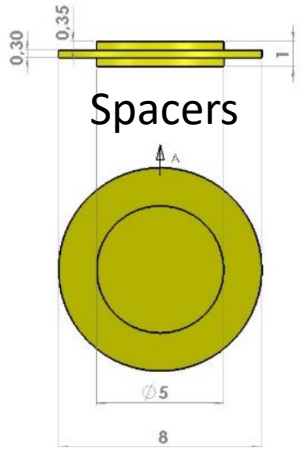
Flatness measurement with a laser system

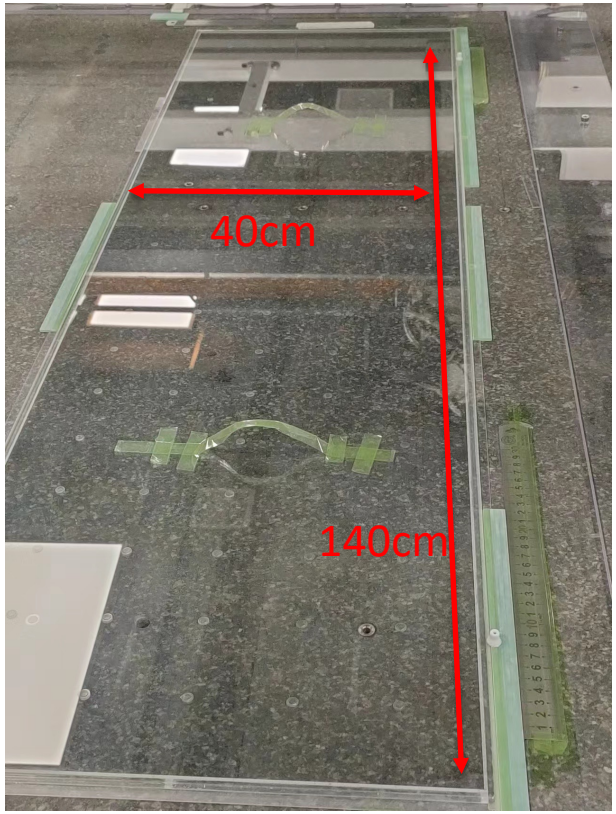
Gas gap production

- Components:
  - Electrode plates:1.5mm thick bakelite
  - Spacer: 1.00 +/- 0.01 mm
  - Polycarbonate frame
  - Graphite layer
  - Graphite connected high voltage link
  - PET layer
  - Gas distributor





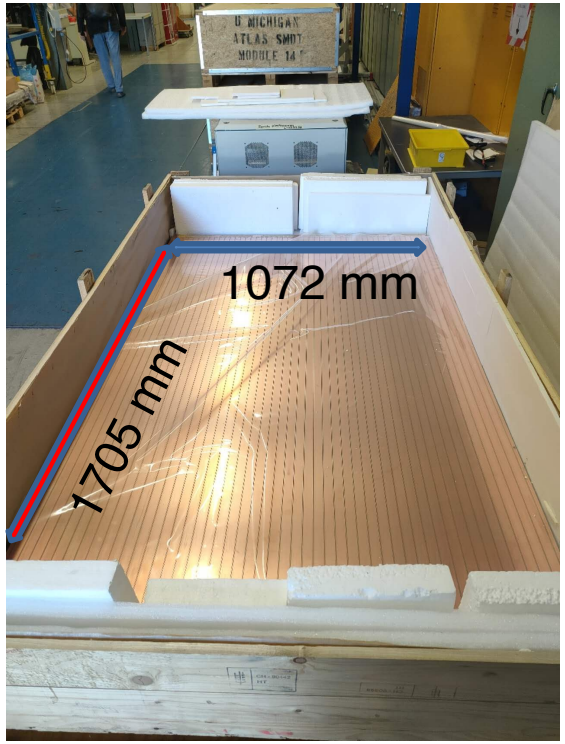


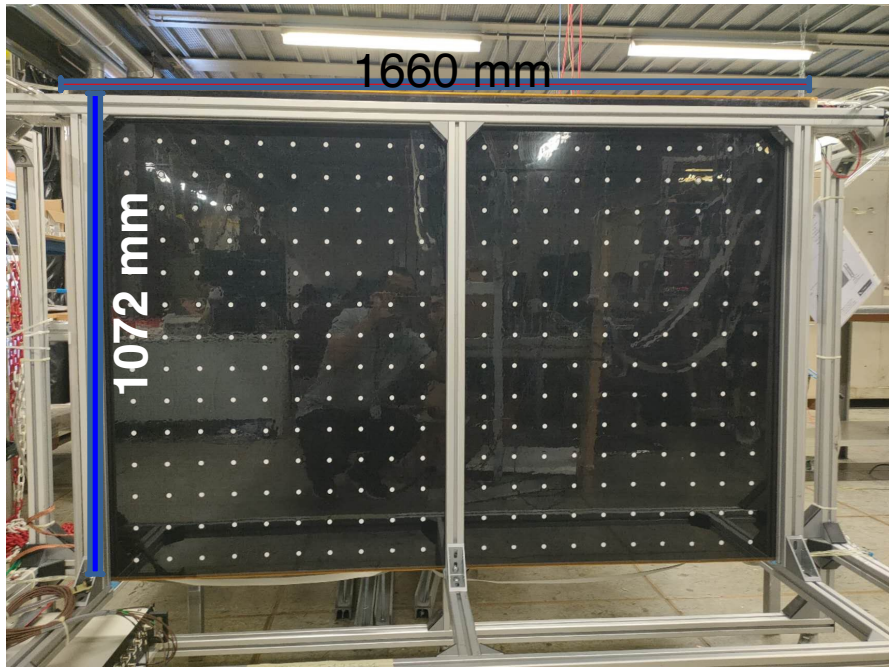


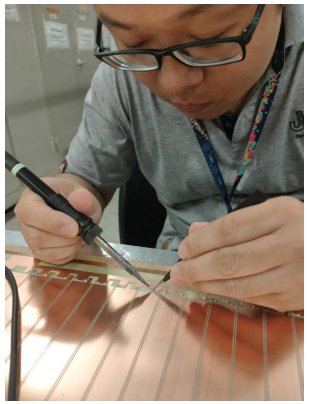
- A glass RPC gas gap is built to R&D the assembly procedure
- The plan is to build 6 bakelite gas-gaps for irradiation test in Feb 2024

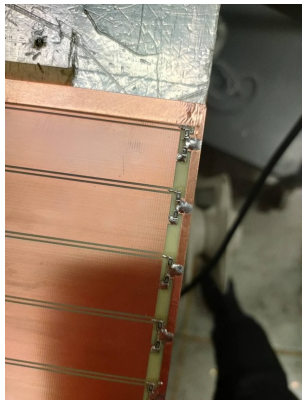
Singlet assembly

- A BIS RPC chamber (triplet) was assembled at CERN in Oct to exercise the assembly procedure
  - Readout panels produced by USTC
  - Gas gaps produced by Italy



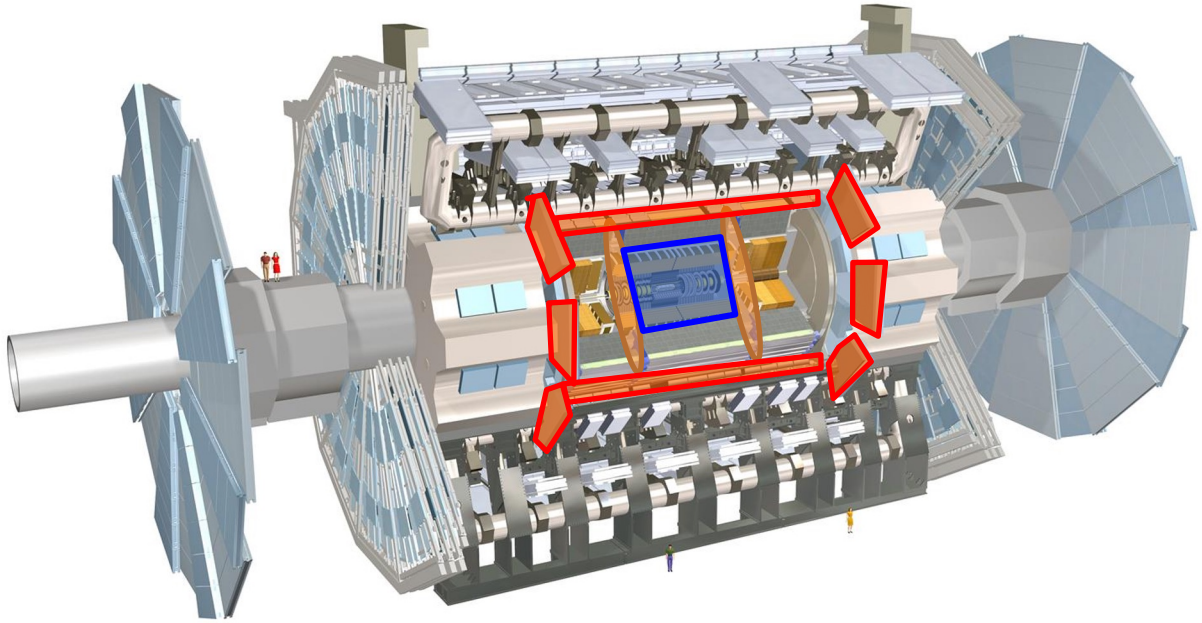






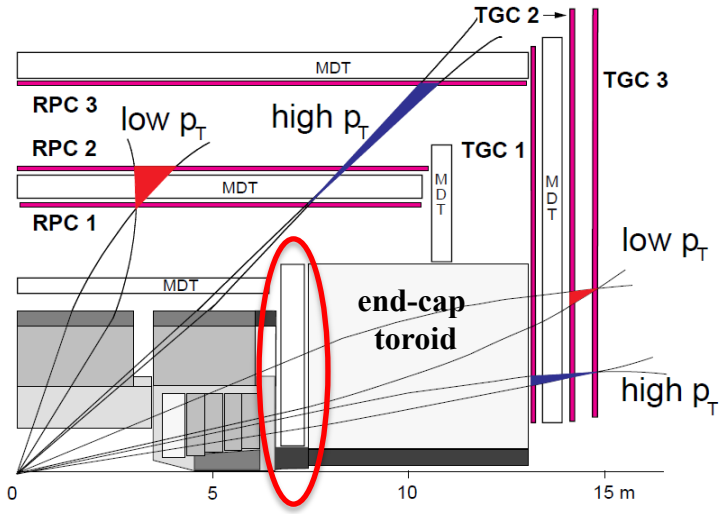
Summary

- ATLAS is making a significant upgrade to its detector to cope and thrive in the HL-LHC environment
- China clusters actively participating in several sub-detectors
  - Inner Tracker (ITk)
  - High Granularity Timing Detector (HGTD)
  - Muon Resistive-plate Chambers (RPC)
- Achieved significant progress and taking some leading roles
  - HGTD PL, ITk UK/China CM, etc ...



Backup

ATLAS Phase I: Muon New Small Wheel



- Precise trigger and tracker extended to $1.3 < |\eta| < 2.7$
- super Thin Gap Chamber (sTGC) as trigger detector
- Micromegas (MM) as tracking detector

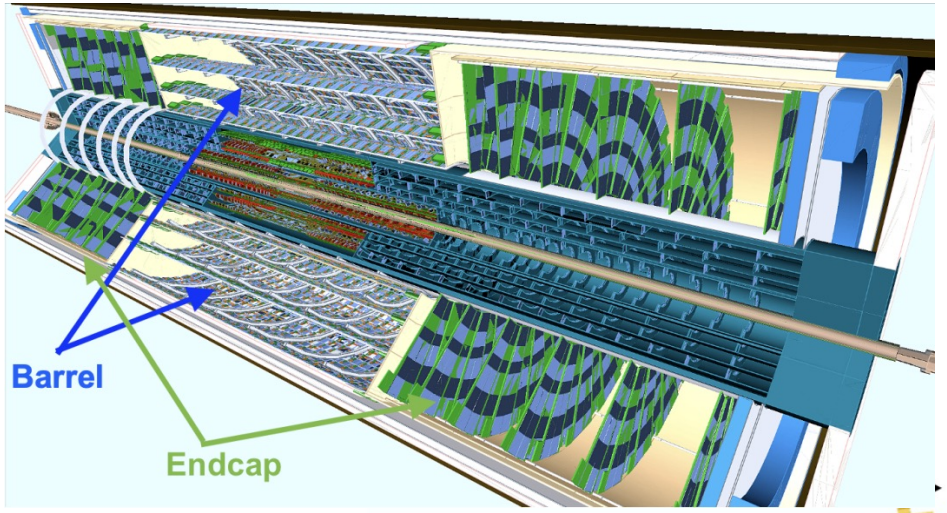
- SDU: 128 QS2-sTGC detector construction, 1/6 of the total sTGCs
- USTC: Front-end Electronics Board R&D + mass production, 800 + 800 FEB boards, ~ 360 kCHF core contribution (as estimated in 2014)

ITk Strips

- ITk strips for HL-LHC

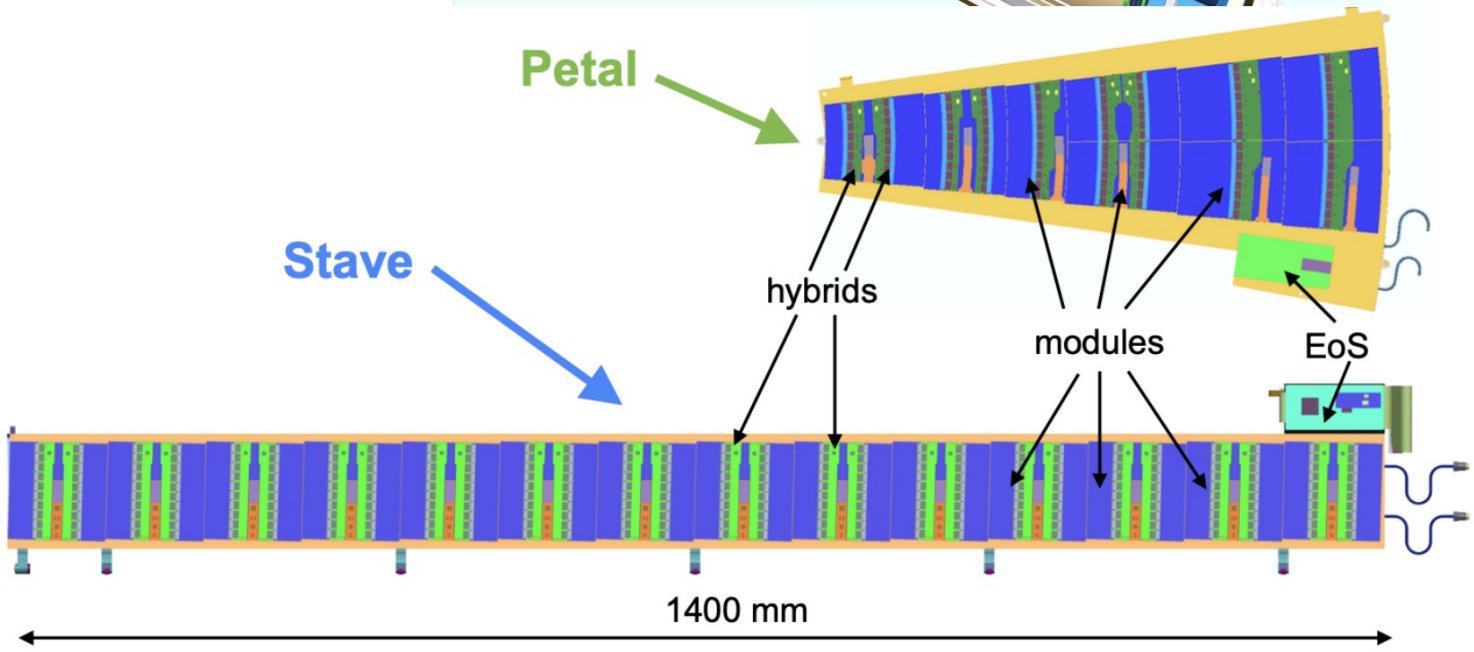
Current SCT (Strips)
- 4088 sensors
- 61 m^2 of silicon
- Strip length: 12.8 cm
- 6 million strips
- Dose: up to 3.8 Mrad

HL-LHC ITk Strips
- 17,888 sensors
- 165 m^2 of silicon
- Strip length: 1.4 – 6 cm
- 60 million strips
- Dose: up to 50 Mrad



ITk Strips – Barrel
- 4 barrel layers
- 392 staves (14 modules/stave/side)
- 10,976 modules

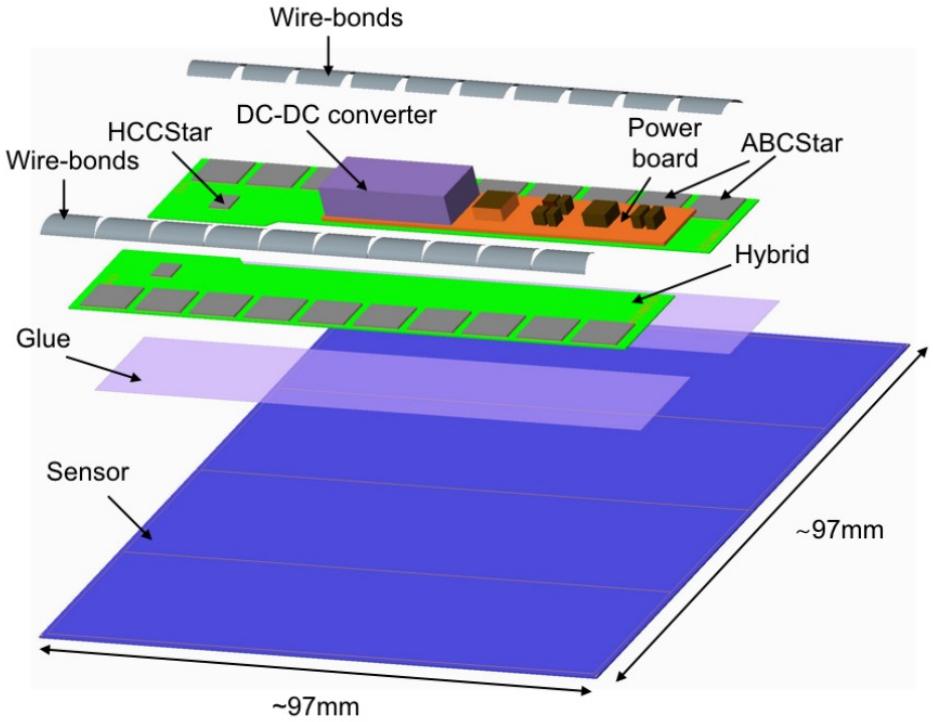
ITk Strips – 2 Endcaps
- 6 disks/endcap
- 384 petals (6 modules/petal/side)
- 4,608 modules



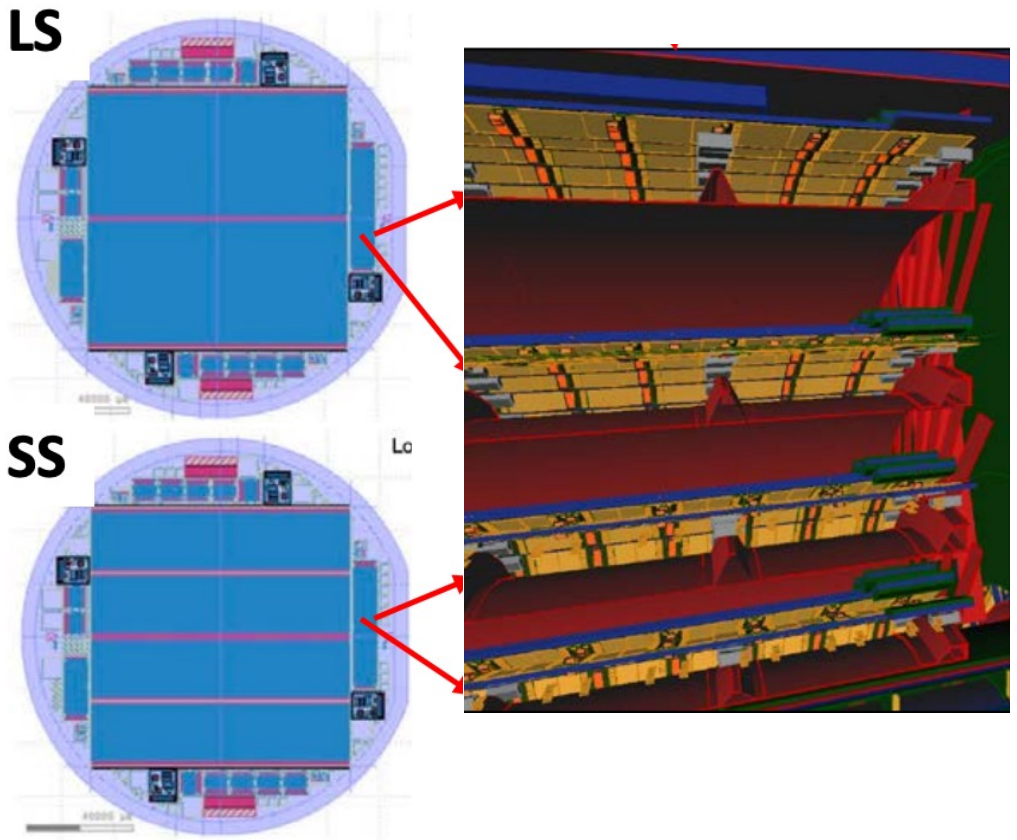
ITk Strips Barrel

- Strip modules for the Barrel

Single-sided micro-strips
- Sensor pitch: 75.5 um
- Shorts Strips (SS): 24.1 mm for inner two layers
- Long Strips (LS): 48.3 mm for outer two layers



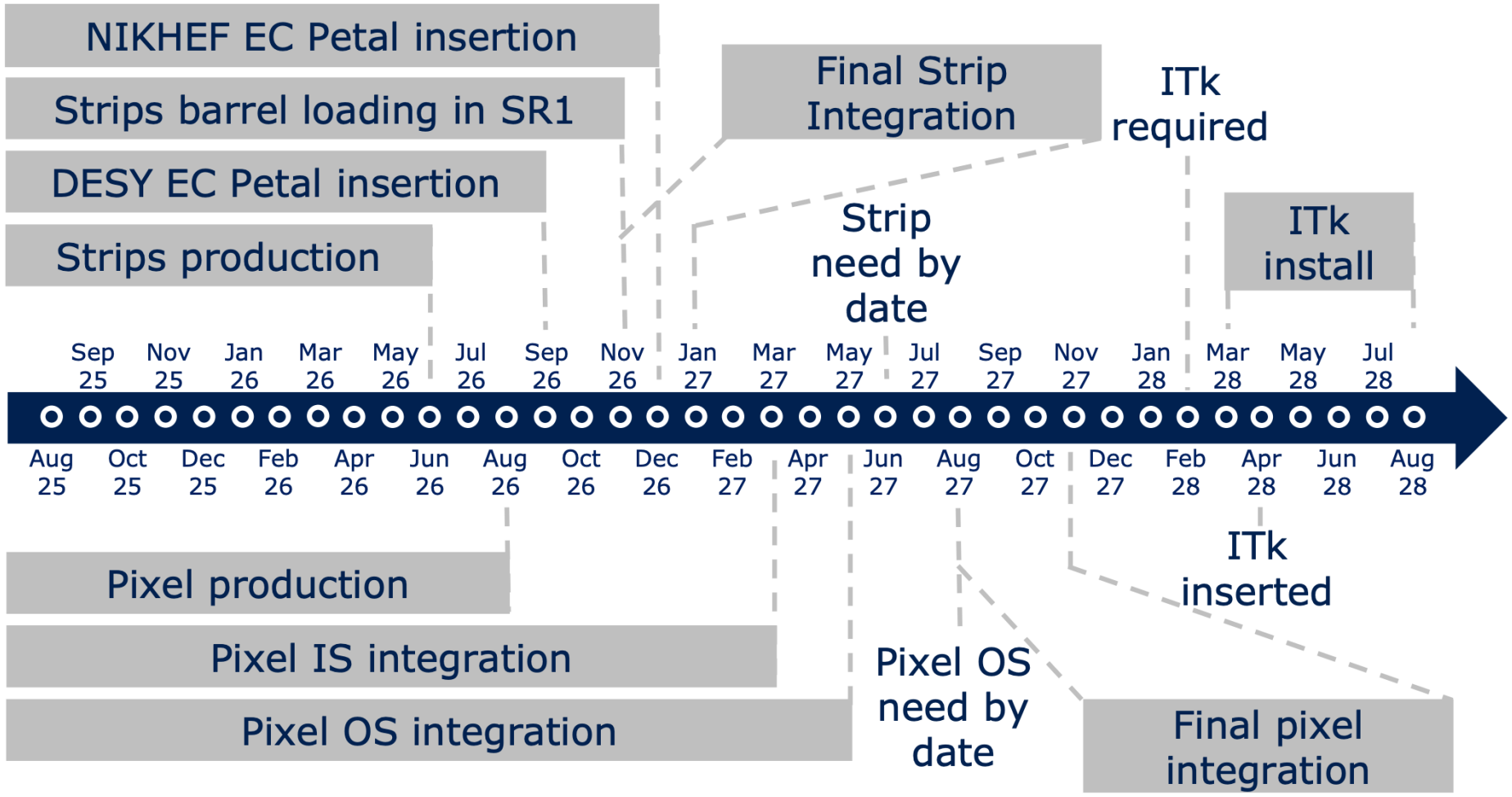
short-strip barrel module



Electronics glued on top on the sensor
- Amplifying, buffering, control, readout circuit with developed ASIC
- Power circuit, also with ASIC and DCDC converter

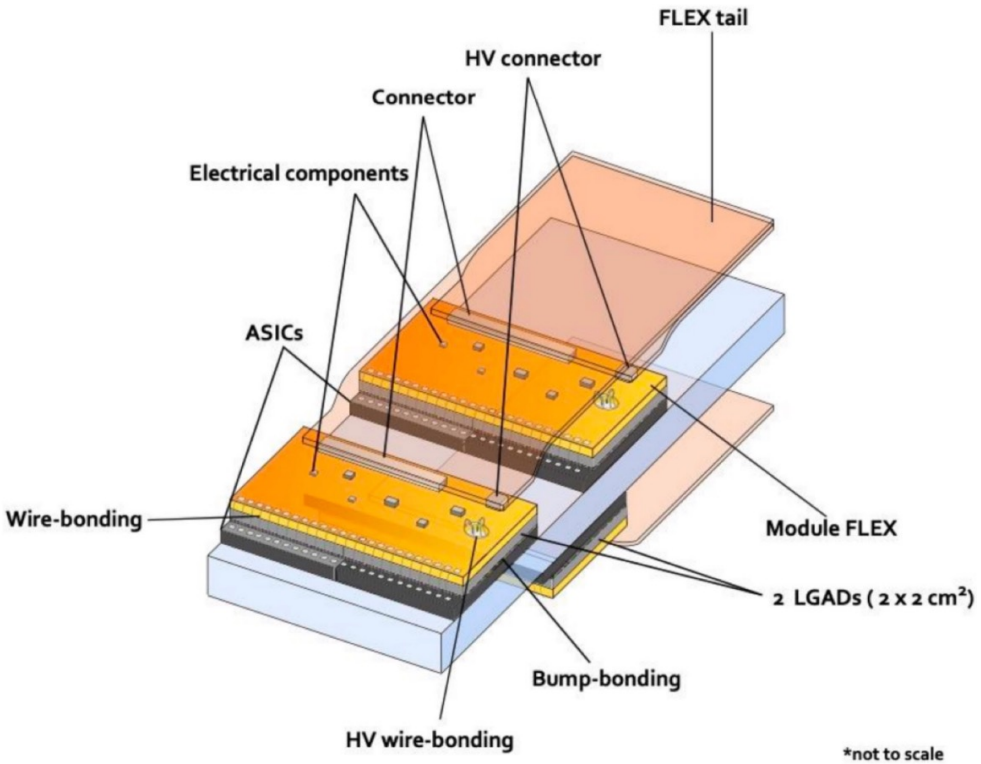
ITK project timeline

- Both pixel and strip detectors are progressing well through preliminary stages of production

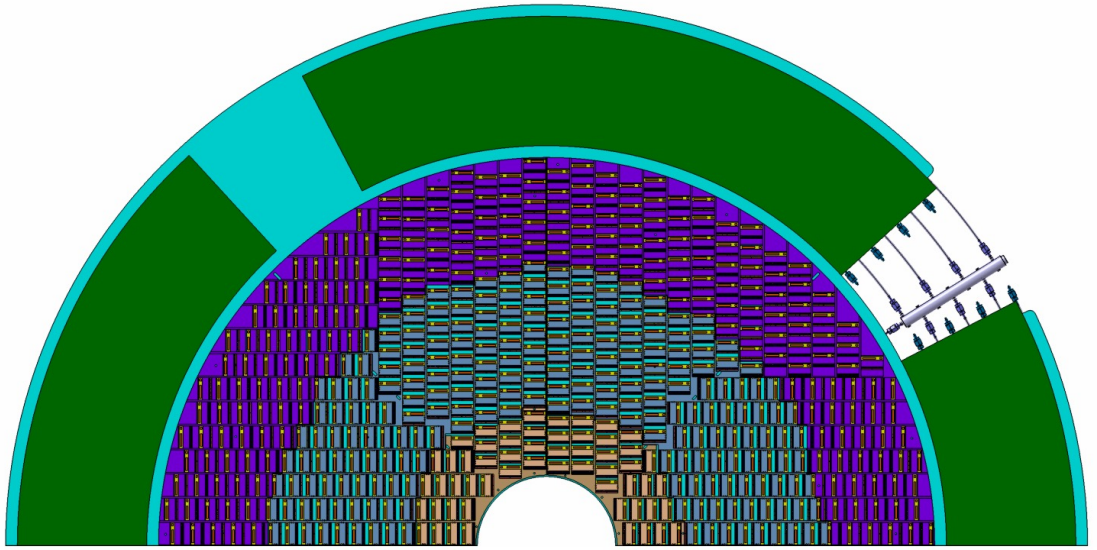


HGTD modules

- Two single -chip hybrids (chip + sensors) connected to the same flex PCB
- The module flex is connected via flex tails, arranged in rows, to the Peripheral Electronics Boards (PEB)

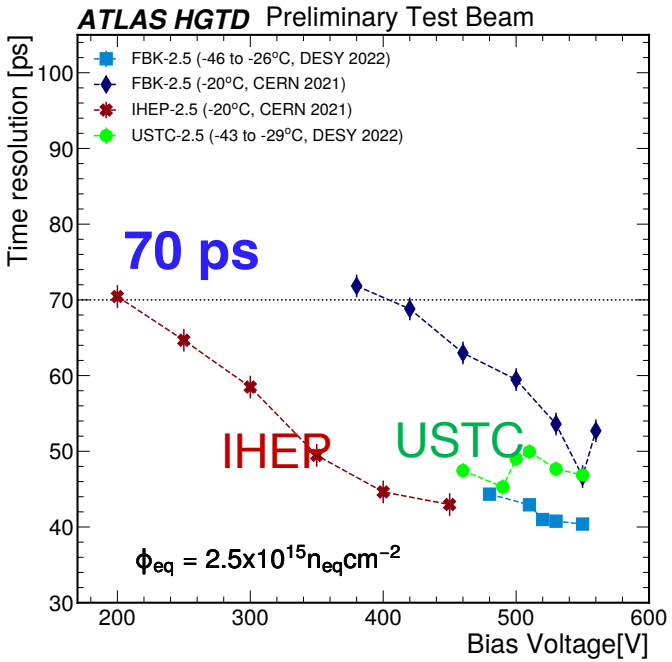


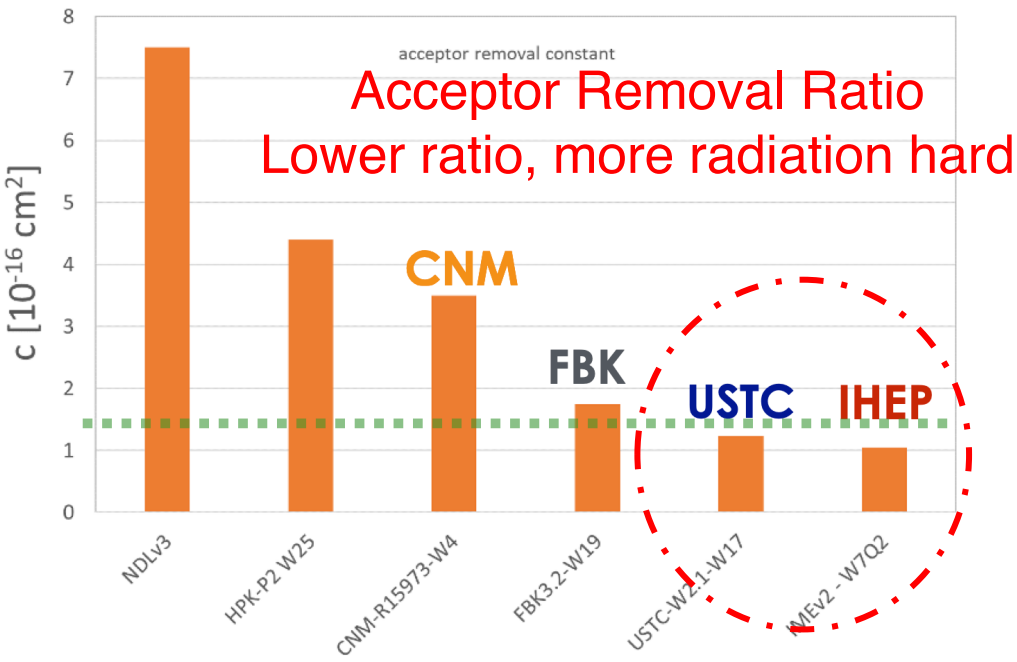
Pad size	1.3 mm × 1.3 mm
Active sensor thickness	50 µm
Number of channels	3.6 M
Active area	6.4 m^2
Module size	30 x 15 pads (4 cm × 2 cm)
Modules	8032



LGAD sensor after irradiation

- Lots of prototypes R&D in LGAD in last few years, active vendors includes:
  - IHEP-IME, USTC-IME, IHEP-NDL, FBK (Italy), CNM (Spain), HPK (Japan) …
- IHEP-IME and USTC-IME LGAD with carbon-enriched doping
  - Significantly lower acceptor removal ratio, the most radiation hard
- After 2.5×10^{15} n_{eq}/cm^2 , LGADs can operated below 550 V
  - To avoid single event breakdown

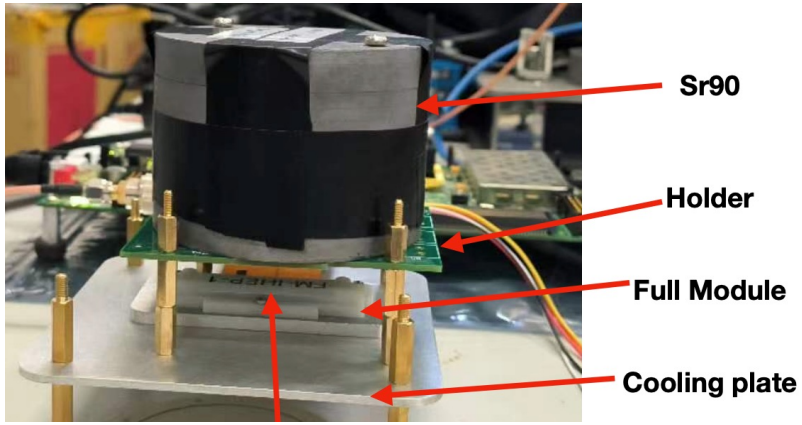




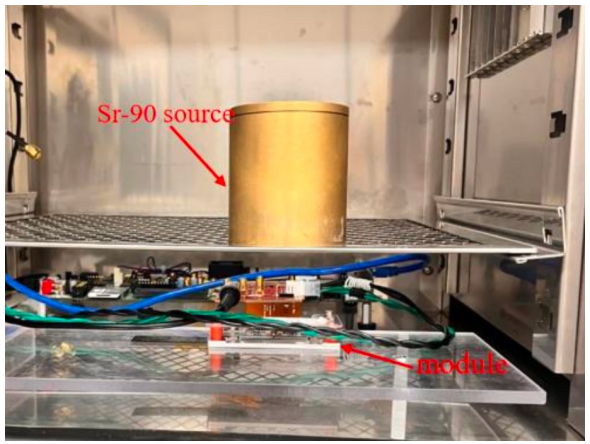
HGTD module assembly

- Module DAQ test system also set up at IHEP/USTC

Beta source test setup(IHEP)

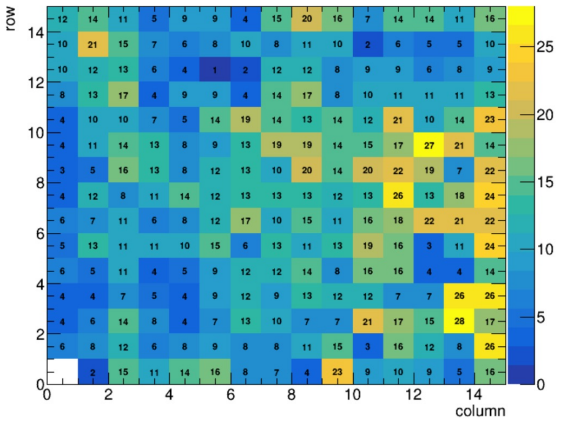


Beta source test setup(USTC)

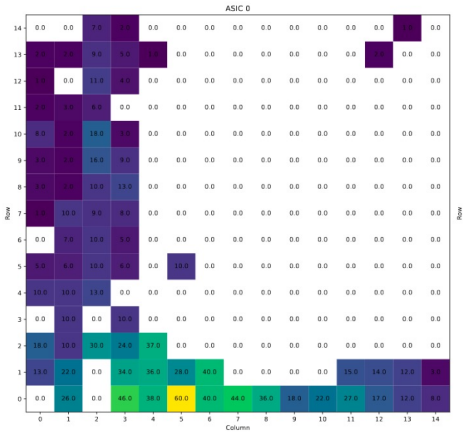


Hit maps in beta source test

IHEP FM02

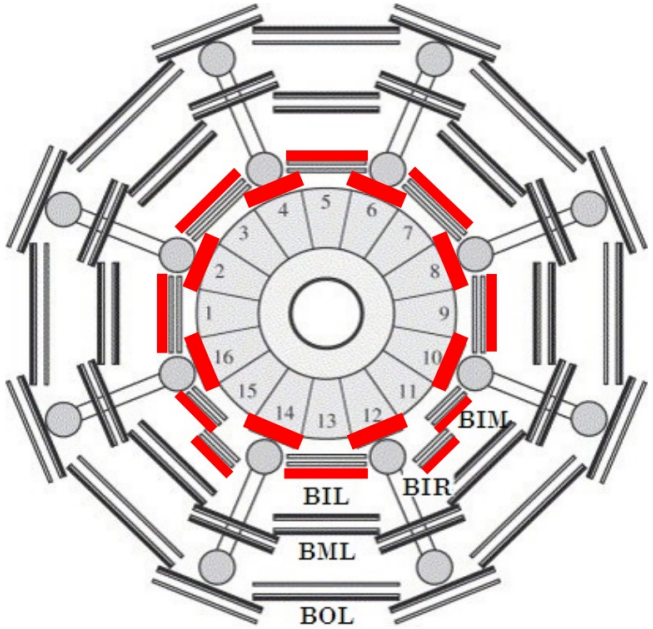


USTC FM03

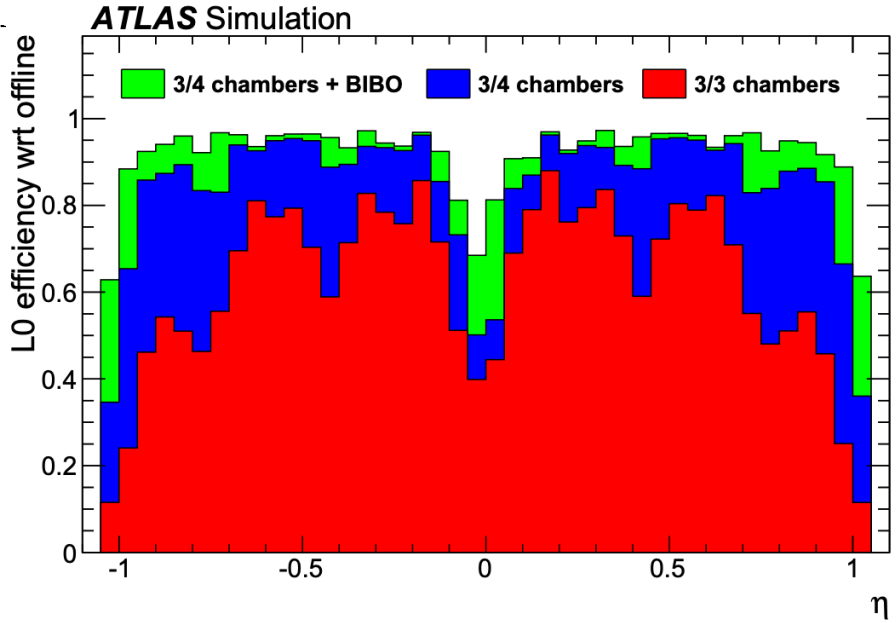


RPC Upgrade

- A new generation RPC system with thin-gap RPCs in the barrel inner region
  - Current: doublet gas gaps of 2mm → HL-LHC: Triplet of 1mm gas gaps
  - Expected to increase the muon trigger acceptance from 70% to about 96%



	Standard RPC	BIS78 RPC
Effective Threshold	1 mV	0.3 mV
Power Consumption	30 mW	6 mW
Technology	GaAs	BJT Si + SiGe
Gap Width	2 mm	1 mm
Operating Voltage	9600 V	5800 V
Charge x Hit	30 pC	5-7 down to 3 pC
Electrode Thickness	1.8 mm	1.2 mm
Time Resolution	1 ns	0.4 ns
Gaps per Chamber	2	3



Honeycomb readout panel production

- Assembly procedure established
  - Sticking X shape tape on the PCB, and mix the epoxy glue
  - Spreading Araldite 2011 glue on the PCB
  - Gluing Aramid paper honeycomb on the PCB with the vacuum bag
  - Aligning 2PCBs + honeycomb layers
  - Gluing 3 layers (2PCBs + honeycomb) with the vacuum bag
- Quality check
  - The flatness of the readout panel in 10 cm * 10cm less than 100 um