Overview of High Granularity Timing Detector Activities in China

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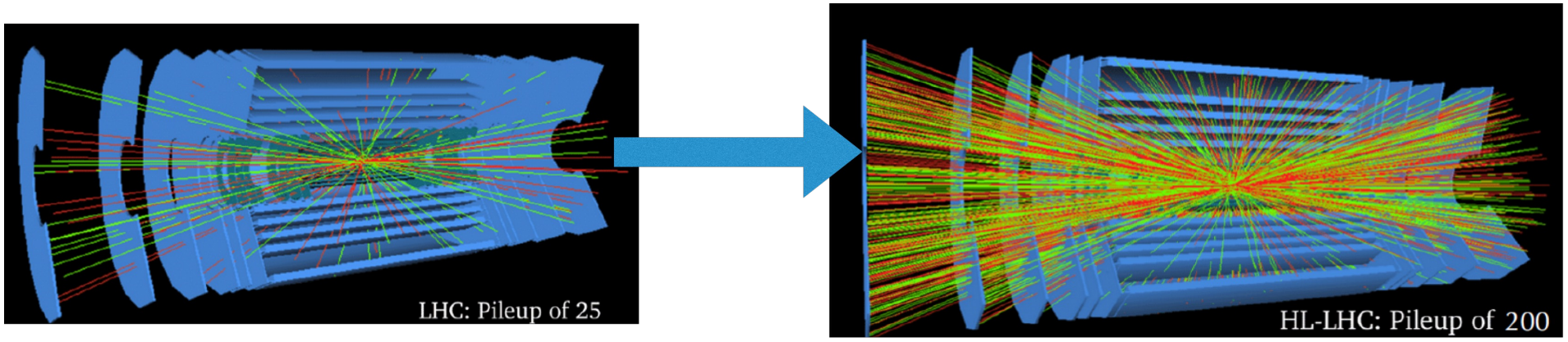
The High-Luminosity-LHC Challenges to Detectors

- High Luminosity LHC upgrade will happen in ~5 years
- One order of magnitude increase in instant luminosity compared to now

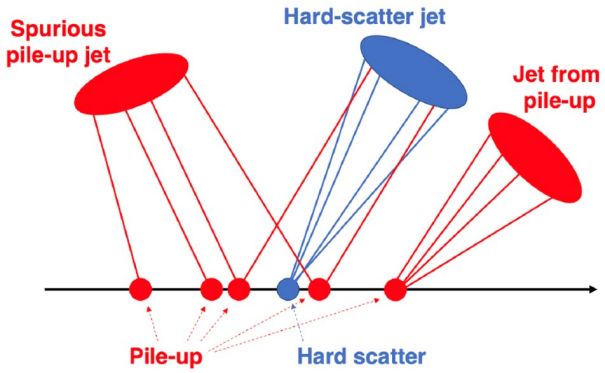


Current detectors cannot cope with such large rates, need:
Larger granularity
Faster trigger rates
New technologies (fast timing)

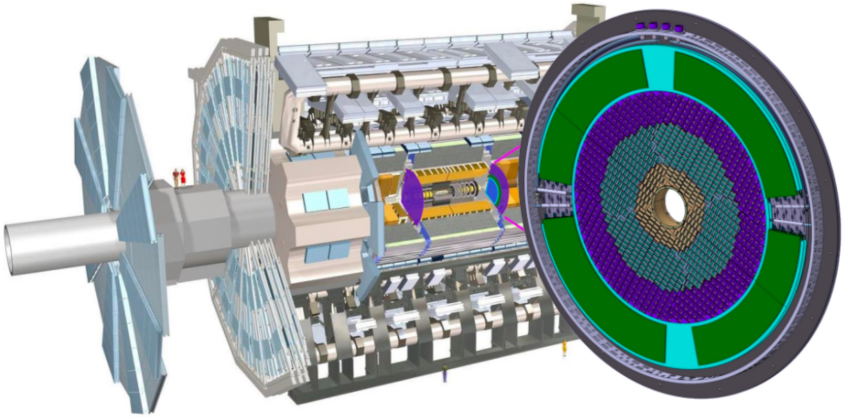
High Granularity Timing Detector (HGTD)

- **HGTD aim to reduce pileup contribution at HL-LHC**
  - **Timing resolution is required to be better than 30 ps (start) - 50 ps (end) ps per track**
- **6.4 m^2 area silicon detector and ~ 3.6 × 10^6 channels**
- **High Granularity: Pixel pad size: 1.3 mm × 1.3 mm**
- **Radiation hardness : 2.5x10^{15} N_{eq} /cm^2 and 2 Mgy**

- **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)**



HGTD @ ATLAS

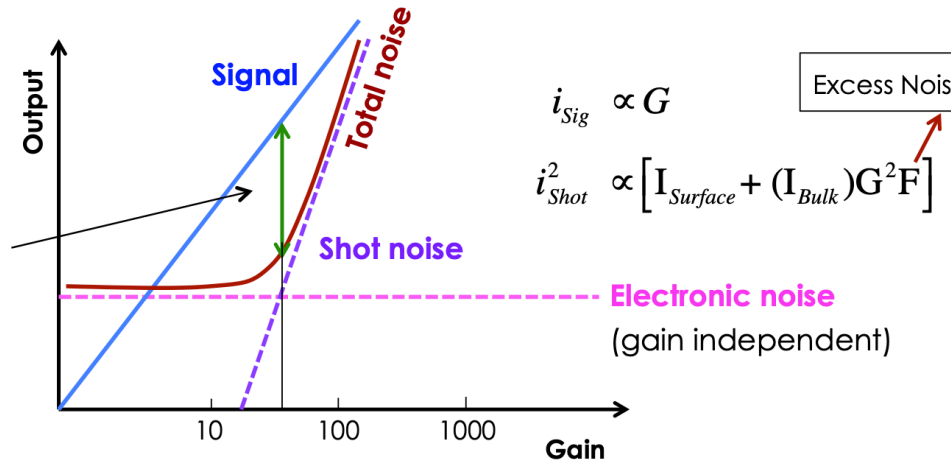


Low Gain Avalanche Detectors (LGAD)

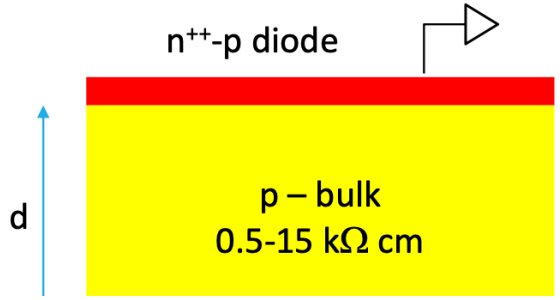
- Compared to APD and SiPM, LGAD has modest gain (10-50)
- High drift velocity, thin active layer (fast timing)
- High S/B, no self-triggering

$$\sigma^2_{jitter} = \left(\frac{t_{rise}}{S/N}\right)^2$$

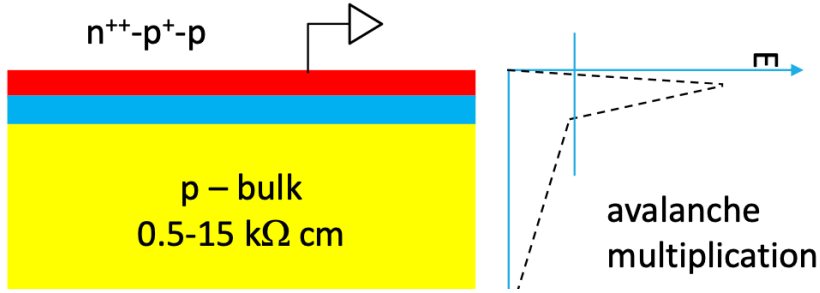
- **Modest gain to increase S/N**
- **Thin detector to reduce t_{rise}**



Conventional PiN diode

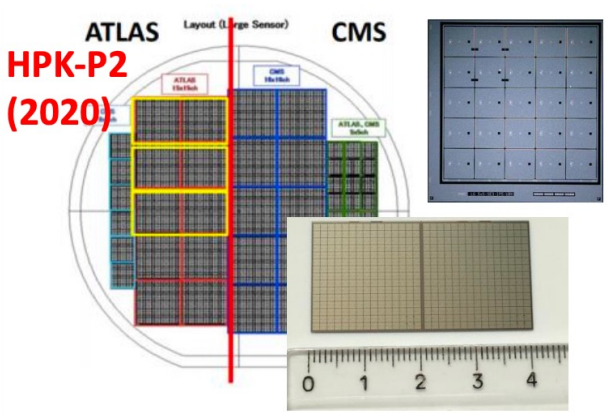


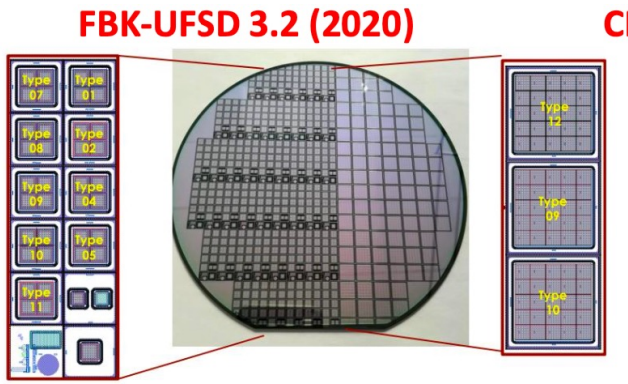
LGAD
P+ gain layer on top of PIN diode

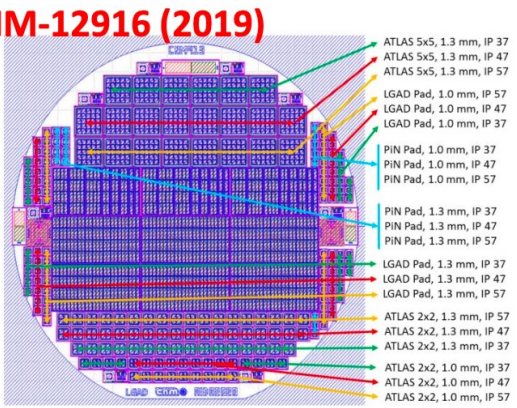


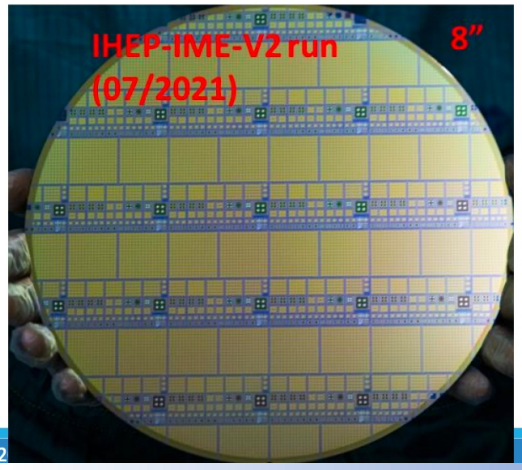
Latest prototypes produced by different vendors

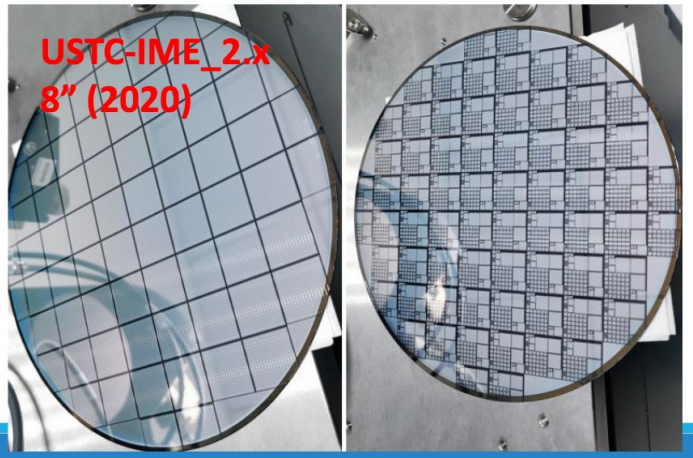
- Lots of prototypes R & D in LGAD in last few years, active vendors includes:
  - IHEP-IME (China), USTC-IME (China), IHEP-NDL(China), FBK (Italy), CNM (Spain), HPK (Japan) …

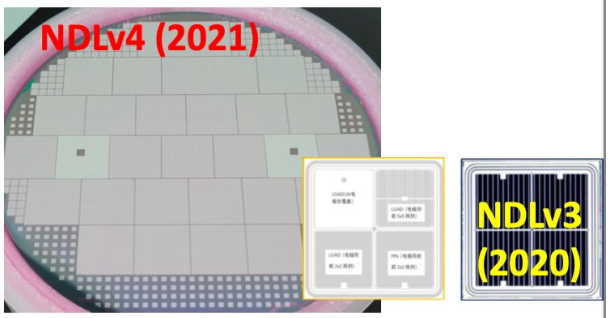












PLANAR TECHNOLOGY – more vendors (e2V, BNL, Micron …)

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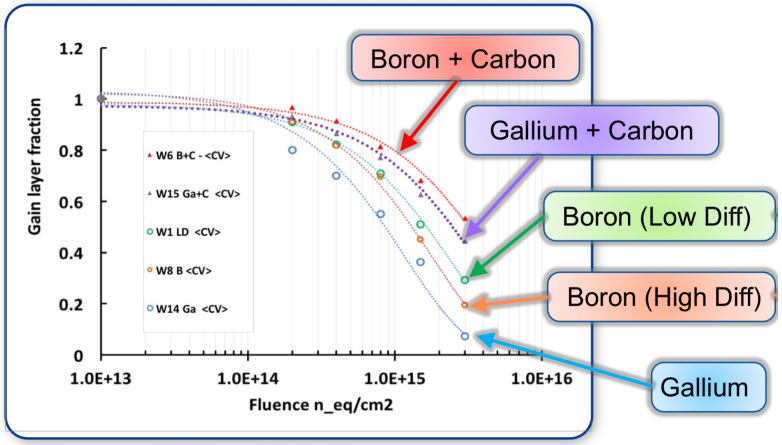
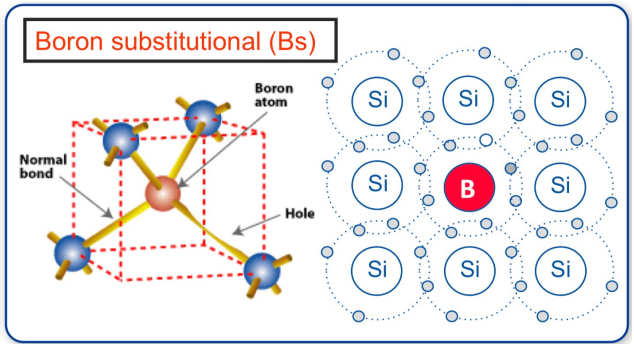
Challenge : LGAD sensor radiation hardness

- 2020, RD50, CMS and ATLAS confirmed Single Event Burnout (SEB) effect in testbeam
  - The key to avoid SEB is reduce the acceptor removal, reduce the operation voltage

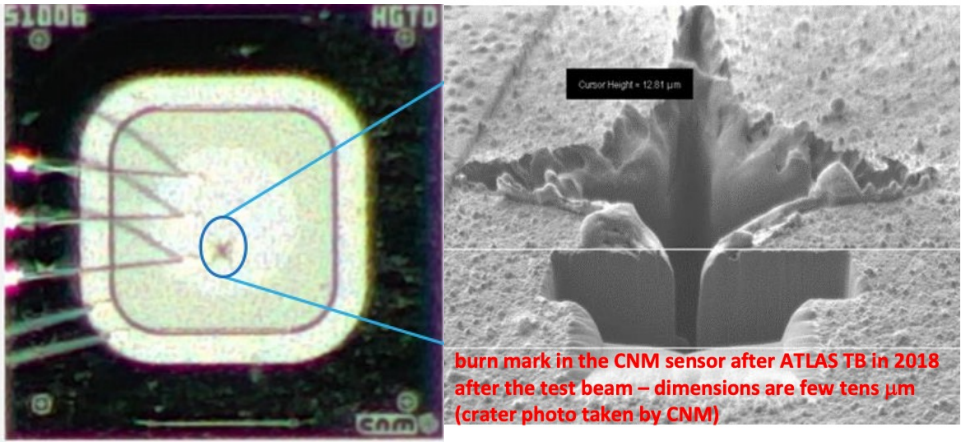


[G.Paternoster, FBK, Trento, Feb.2019]



Single Event Burnout (SEB) effect

2020 CERN SEB test beam: 120 GeV proton



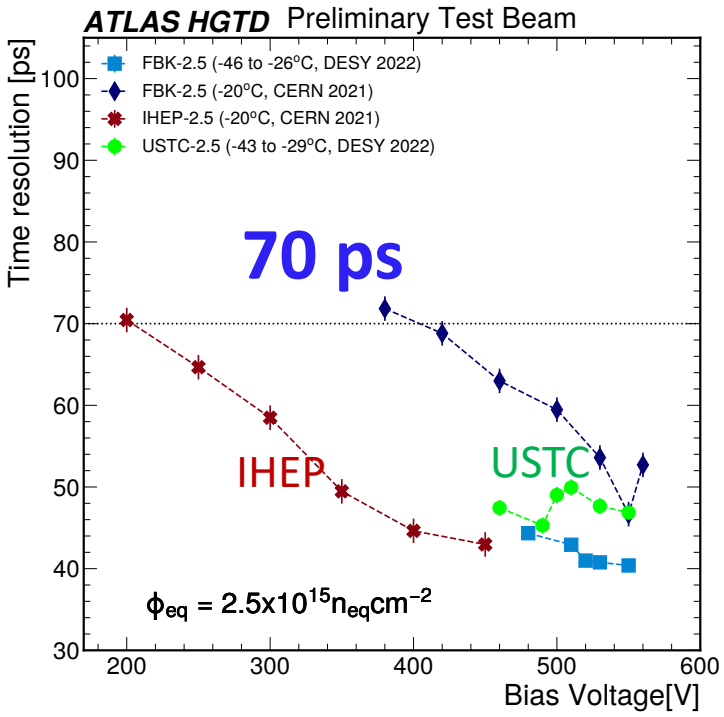
burn mark in the CNM sensor after ATLAS TB in 2018 after the test beam – dimensions are few tens µm (crater photo taken by CNM)

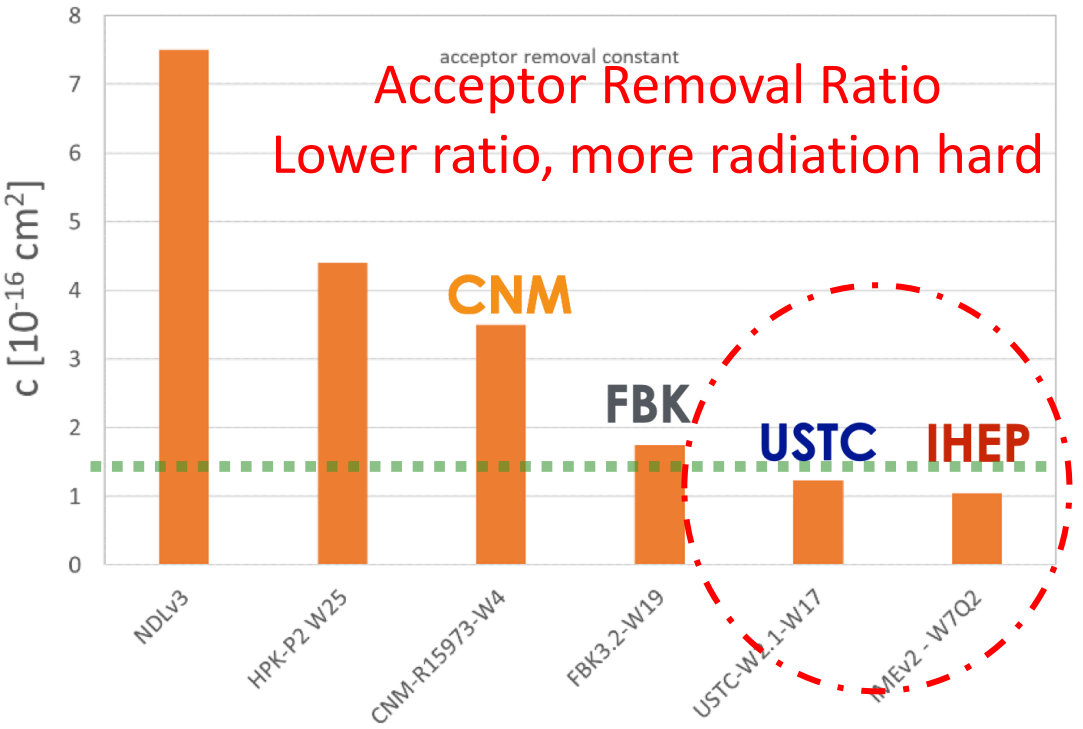
LGAD sensor after Irradiation

- IHEP-IME LGAD with carbon-enriched doping
  - 34 fabrication steps, all masks and processes designed by IHEP, fabricated at IME
  - Significantly lower acceptor removal ratio, the most radiation hard
- After 2.5×10^{15} n_{eq}/cm^2, IHEP LGADs can operated much below 550 V

→ avoid single event breakdown

→ more than 20 sensors in test beam, no single event breakdown by far



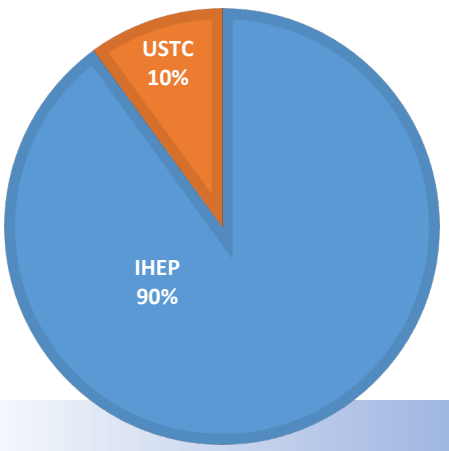


LGAD sensors pre-production

More details in Weiyi's talk

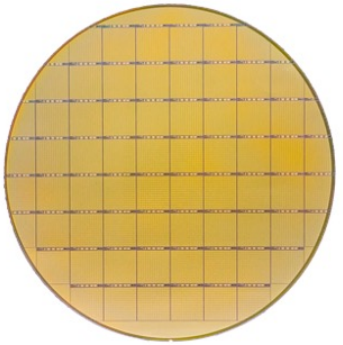
- In May 2013, CERN chosen IHEP-IME in HGTD sensor tendering.
  - First time domestic silicon sensor was chosen by CERN in LHC experiment
  - Won the competition with Hamamatsu (Japan) and FBK (Italy)
- The production plan:
  - IHEP-IME: 90% (66% from CERN tendering+24% in-kind contribution): ~8 m^2
  - USTC-IME: 10% in-kind contribution (~0.8 m^2)

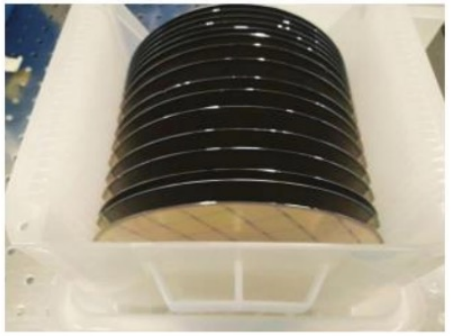
Share of production
Share between vendors



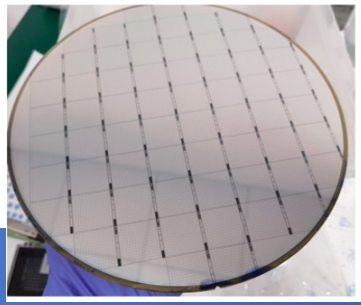
Pre-production LGAD sensors from China

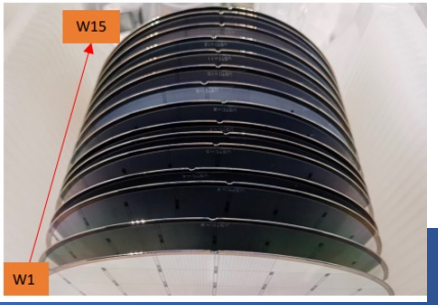
IHEP-IME
Pre-production





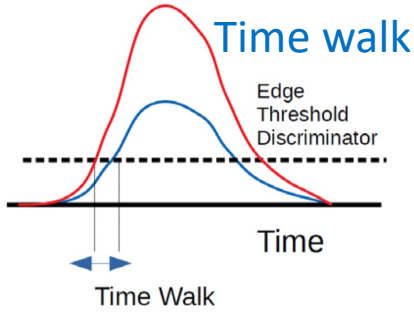
USTC-IME
Pre-production



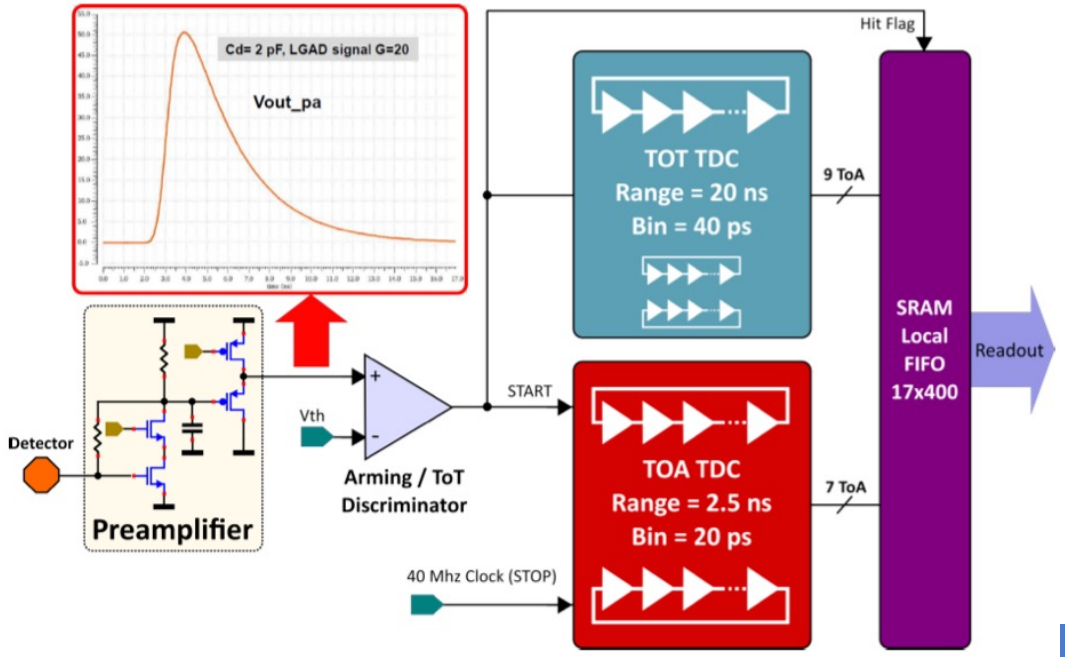


ALTIROC : Fast Timing ASIC

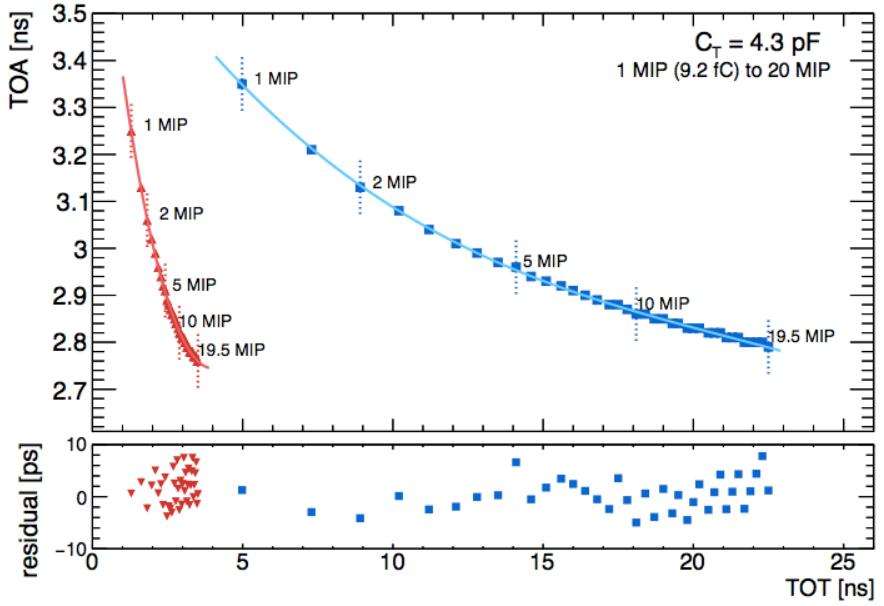
- 225 front-end channels in ALTIROC, each channel has
  - A preamplifier followed by a discriminator:
  - Two TDC (Time to Digital Converter) to provide digital **Hit data**
    - Time of Arrival (TOA) : Range of 2.5 ns and a bin of 20 ps (7 bits)
    - Time Over Threshold (TOT) : range of 20 ns and a bin of 40 ps (9 bits)
  - One Local memory: to store the 17 bits of the time measurement until L0/L1



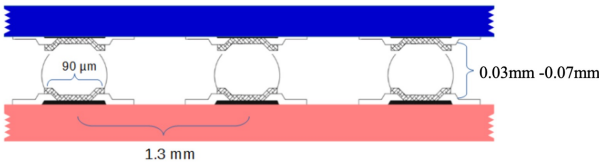
ALTIROC timing ASIC in nutshell



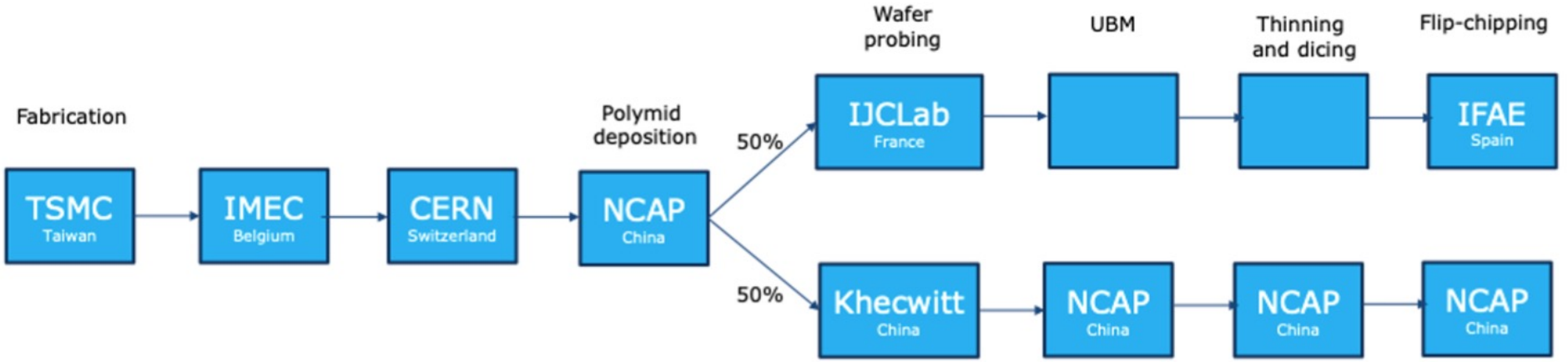
Time walk correction with TOT

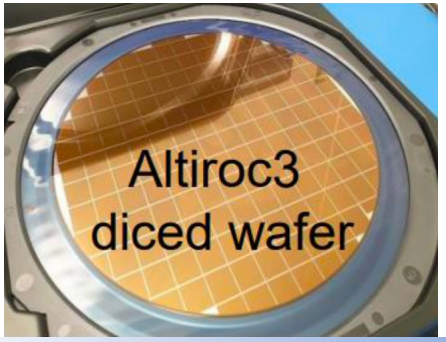


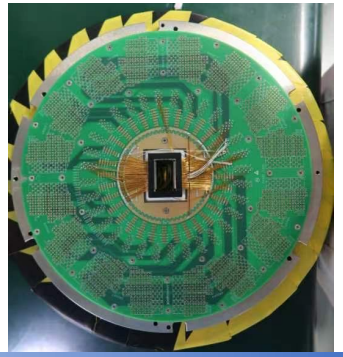
ALTIROC ASIC wafer process and flip-chip

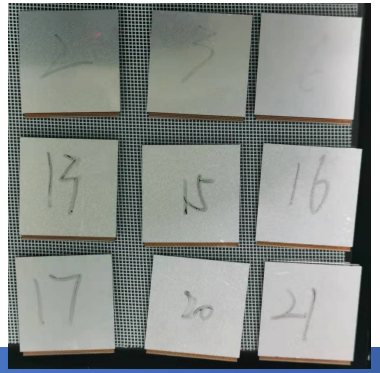


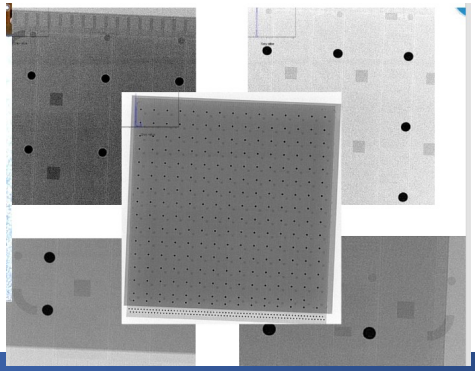
- ALTIROC-A ASIC wafers will be 100% sent to China for polyimide layer deposition
  - 50% to IHEP/Khecwitt for probing, to IHEP/NCAP for UBM/thinning/dicing/flip-chip
  - 50% to IJClab for probing, then to EU vendor for UBM/bump deposition/thinning/dicing/ then to IFAE for flip-chip



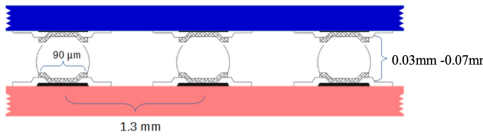








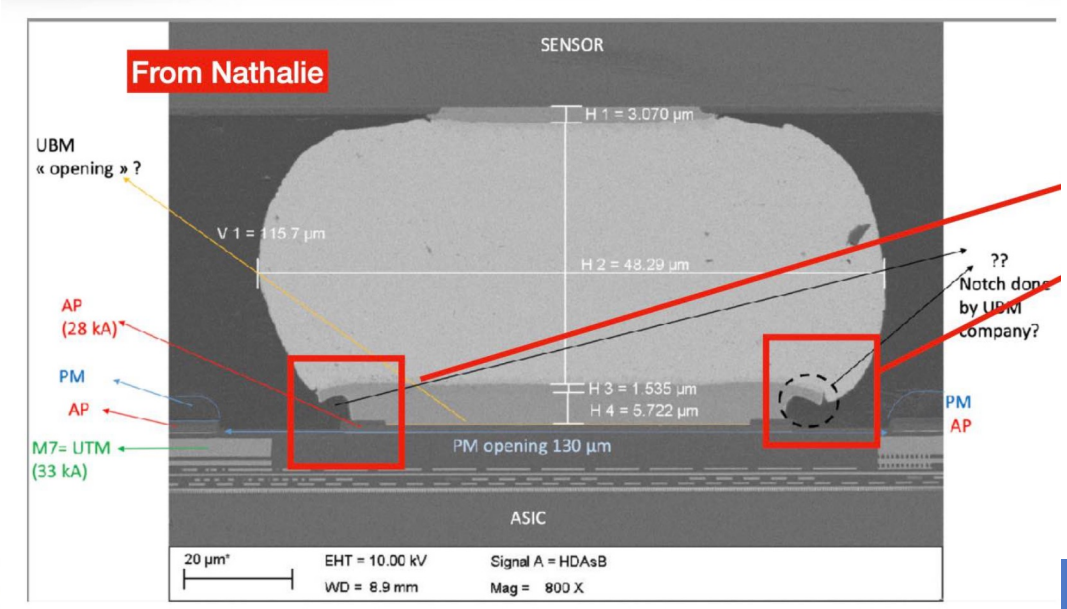
Major improvement in hybrid: new Polyimide layer + thick sensor



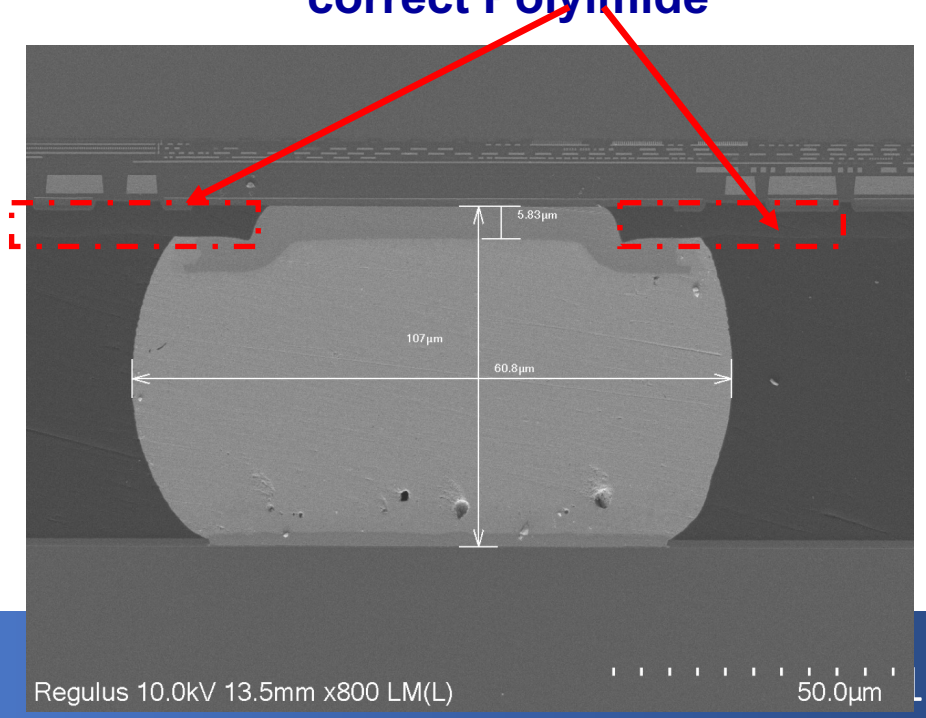
- Polyimide in ALTIROC3 deposited at NCAP/IHEP
  - Optimize to use Soft Polyimide material, and use thick sensor (775um)
  - More robust in thermal cycle, higher yield than ALTIROC2 hybrids.
- In ALTIROC3 hybrids prototyping phase, all ALTIROC3 UBM/thinning/dicing by IHEP/NCAP
- Next step to make the bump bonding thermal stability
  - Increase sensor thickness, increase the number of bumps

More details in Yulong's talk

ALTIROC2 hybrid by TSMC with incorrect Polyimide

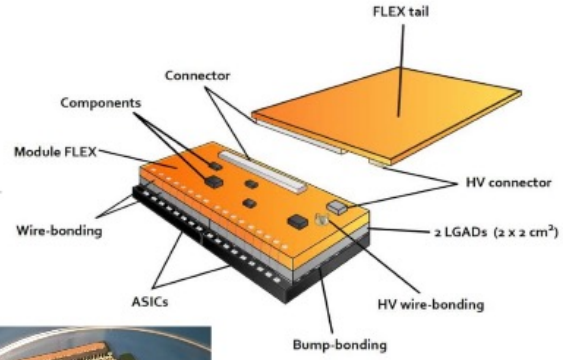


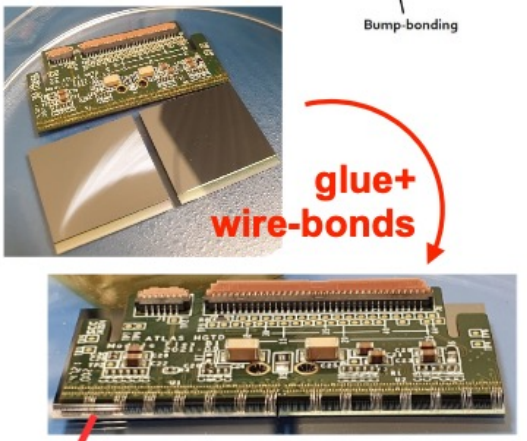
ALTIROC3 hybrid by NCAP/IHEP with correct Polyimide

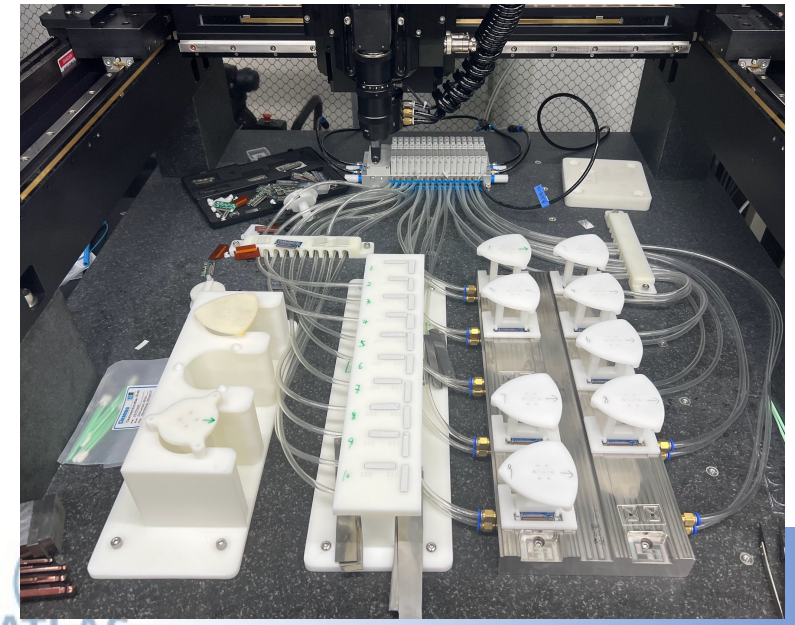


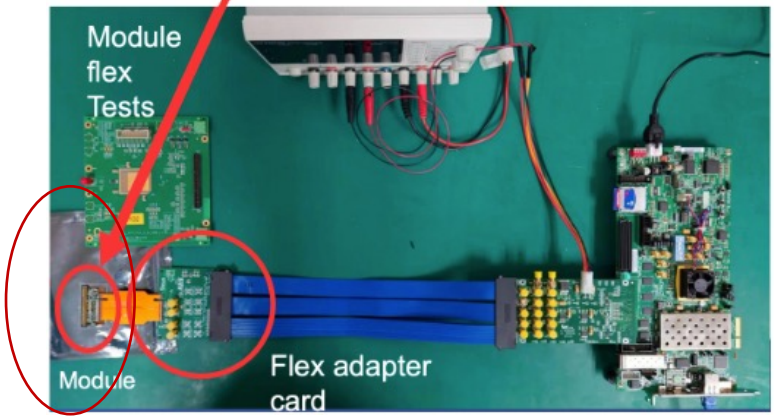
HGTD module assembly

- 6 module assembly site at HGTD
  - IHEP, USTC, Mainz, France, IFAE, Morocco
  - IHEP is largest site, 34% module assembly (~3000)
  - USTC will be 10% of module
- IHEP developed module flex and gantry robot
  - Pattern recognition, glue dispending and assembly
  - Plan to assemble 10 modules each time









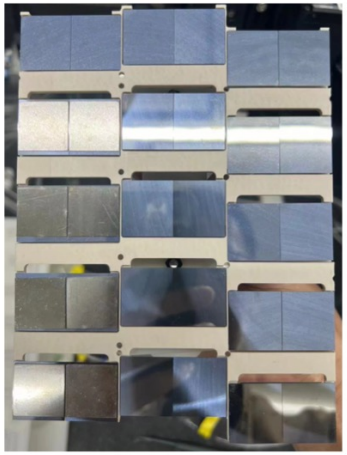
HGTD module loading

More details in Xuan's talk

- IHEP loaded the first two ALTIROC3 detector units for demonstrator
  - Use Gantry system to position all 15 modules and glue dispending
  - Delivered to CERN, and integrated in 52-modules demonstrator

Dispensing with GluingTool

Backside view after removal

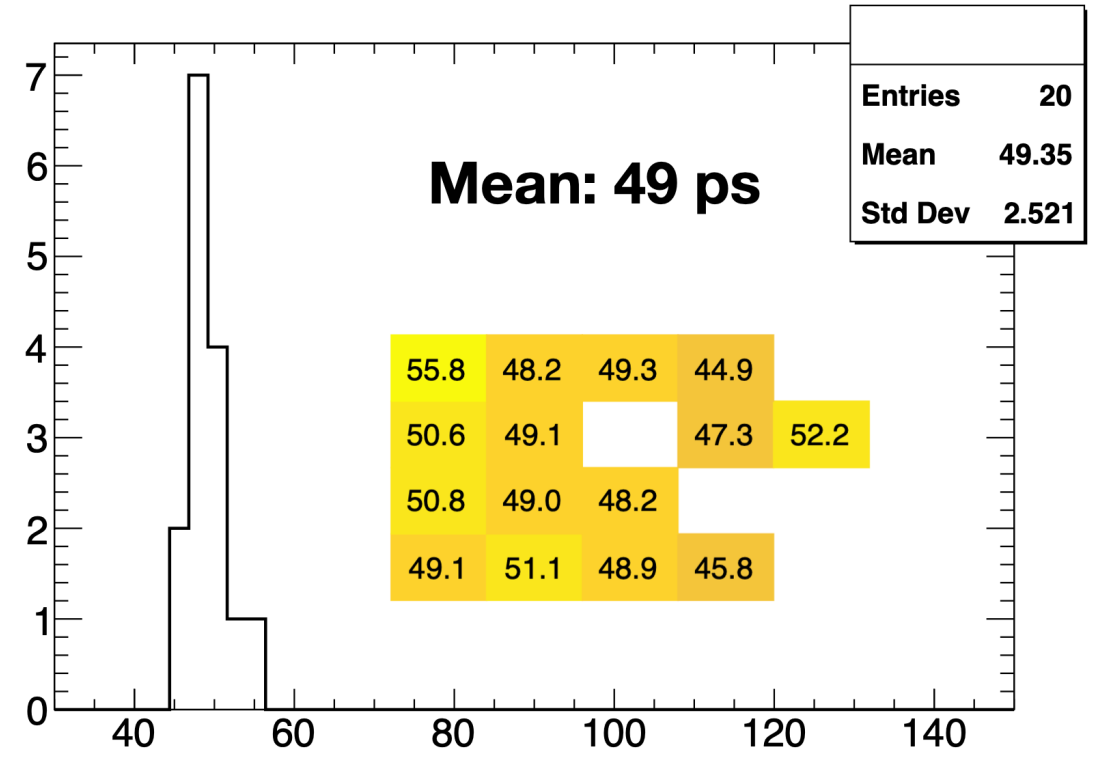


Detector unit shipped to CERN

HGTD Module testing

More details in Weiyi's talk

- Module level Test beam showed that
  - Individual channels can reach ~50ps level timing resolution
  - In next few years, HGTD will have 3M channels @ ~50ps resolution



Peripheral Electronics Boards (PEB)

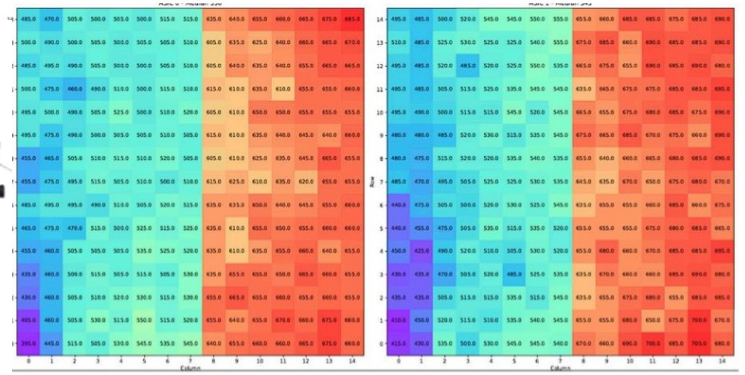
- Comments from P2UG review 2023 about PEB :
- It is comparable with the most difficult boards manufactured for HEP projects
- IHEP and NJU developed 1st Peripheral Electronics Boards at early 2024
  - 4 companies joined full size PEB prototyping
  - All 4 prototypes from different companies are functional
  - Selected the best company for production

More details in Jie's talk

PEB at demonstrator

More details in Jie's talk

- IHEP and NJU played important role testing demonstrator system at CERN
  - Noise levels is measured with 40+ modules
  - 1st time to demonstrate that in system level

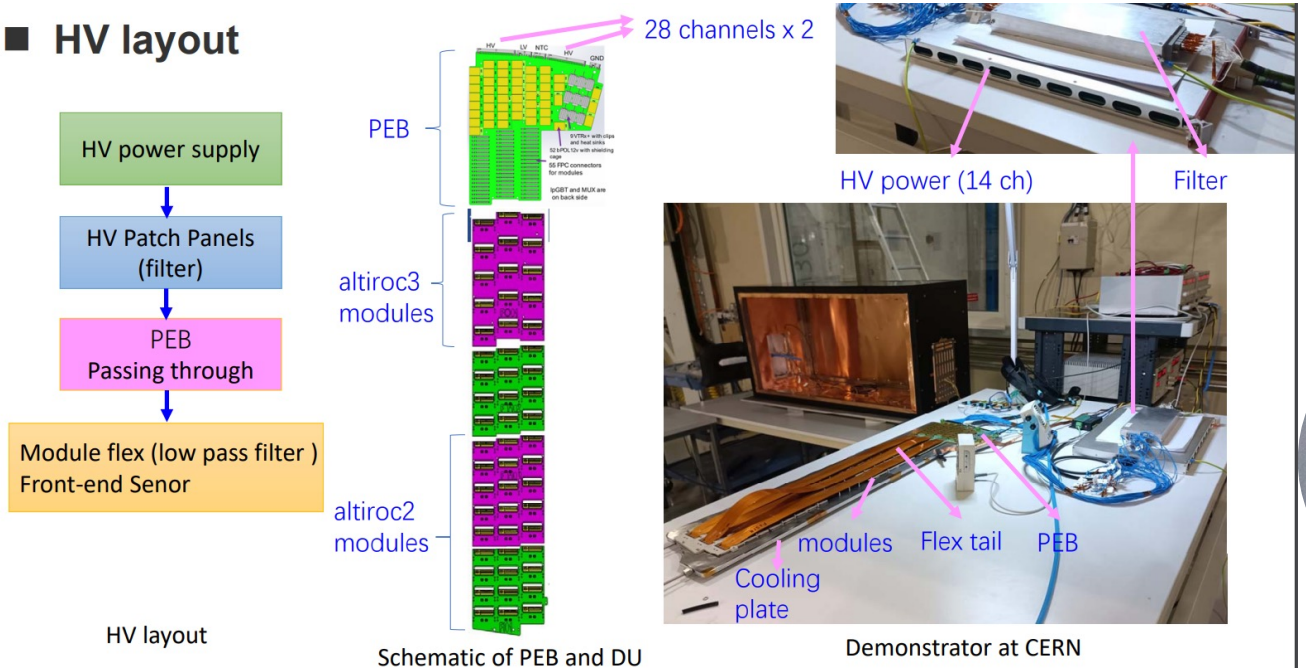


dule threshold scan obtained in demonstrator test

High voltage power supply

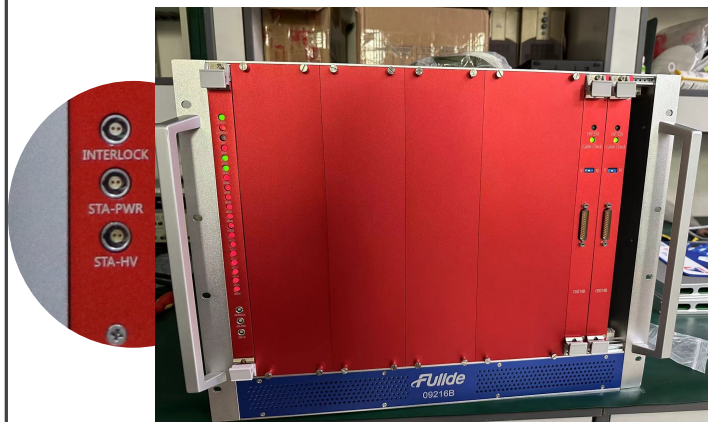
- IHEP team is developing HV power supply prototype for HGTD
  - high resolution current measurement, Dedicated Interlock for ATLAS
  - Two type of HV prototypes with different grounding scheme
  - Passed HV supply FDR review

HV supply testing setup at HGTD demonstrator



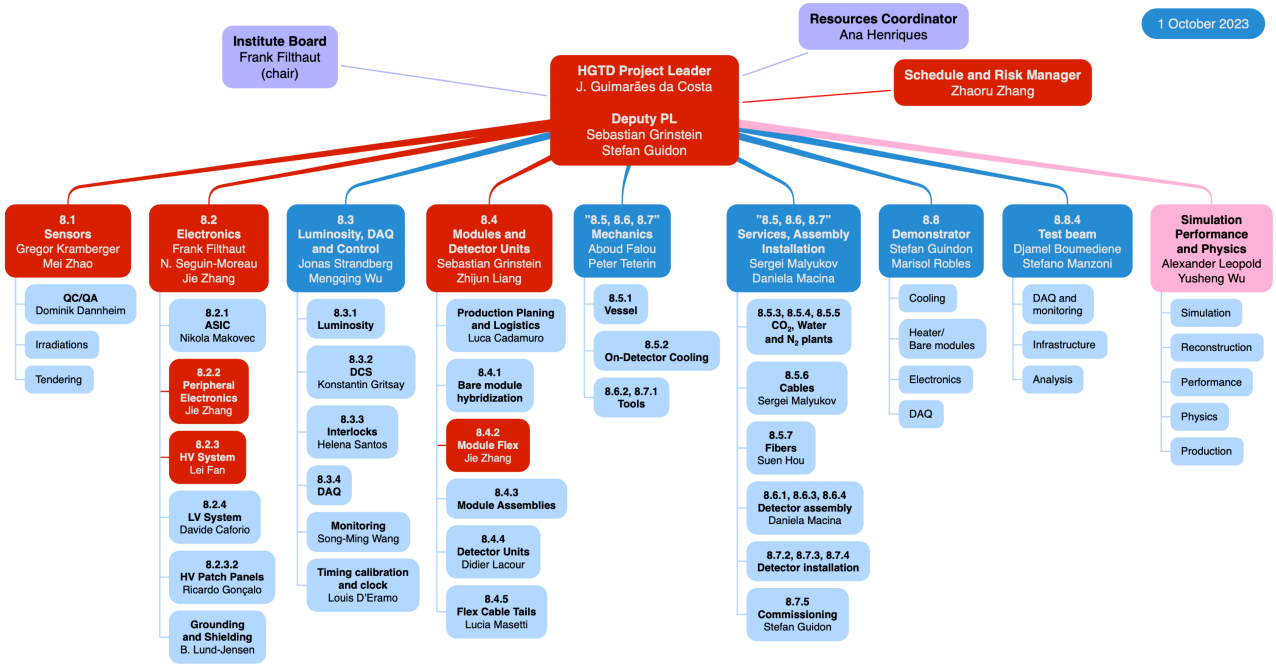
Interlock interface
Lemo connector

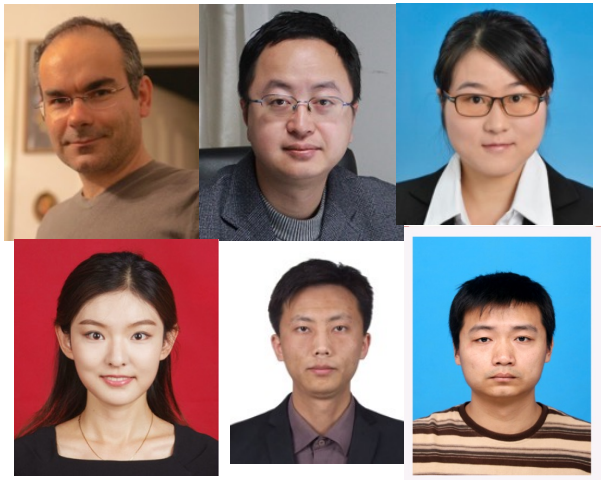
HV connector



ATLAS China team in HGTD management

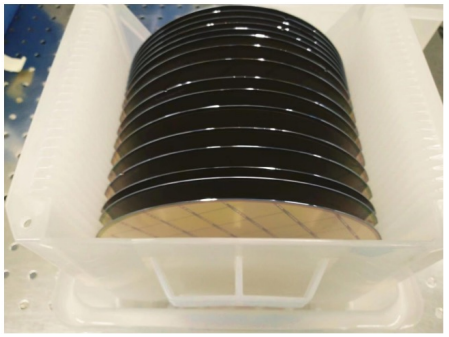
- ATLAS China team played a leading role in HGTD
  - Joao (IHEP) is re-elected as Project leader (2021-2025)
  - 4 Level-2 conveners (Zhijun Liang, Mei Zhao, Jie Zhang, Zhaoru)
  - 3 Level-3 conveners (PEB, high-voltage, module flex)

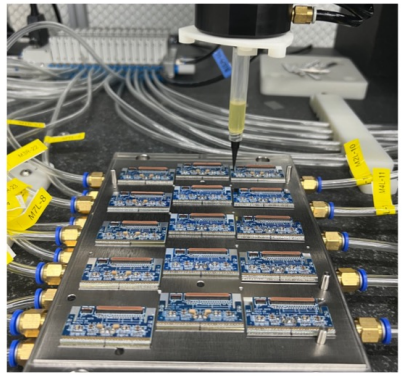




HGTD summary

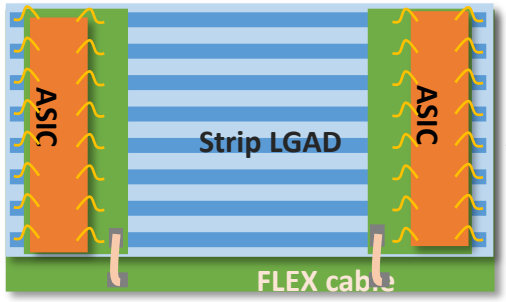
- **China is making key contributions to HGTD**
  - **100% (90% IHEP, 10%USTC) LGAD sensor, produced 1.7k sensor @pre-production**
  - **50% hybrization (IHEP), 100% ALTIROC3/sensor UBM/bumping from IHEP/NCAP**
  - **44% module assembly (IHEP, USTC), loaded two ALTIROC3 detector units**
  - **100% front-end electronics board (IHEP, NJU), prototyped 1st full-size PEB**
  - **>16% high-voltage electronic systems(IHEP,SDU), prototyped 1st HV supply**
  - **33% flexible PCB tails (SDU), 1st prototyped tested**
  - **50% ASIC testing (IHEP)**

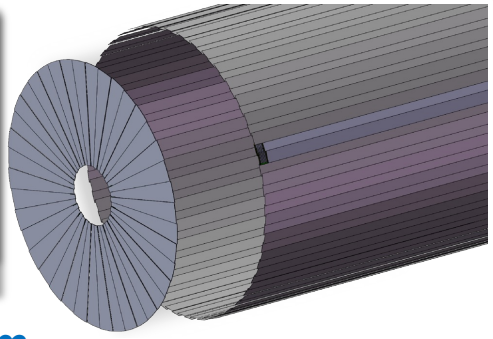




Other future Application of LGAD

CEPC : Outer Tracker+ TOF





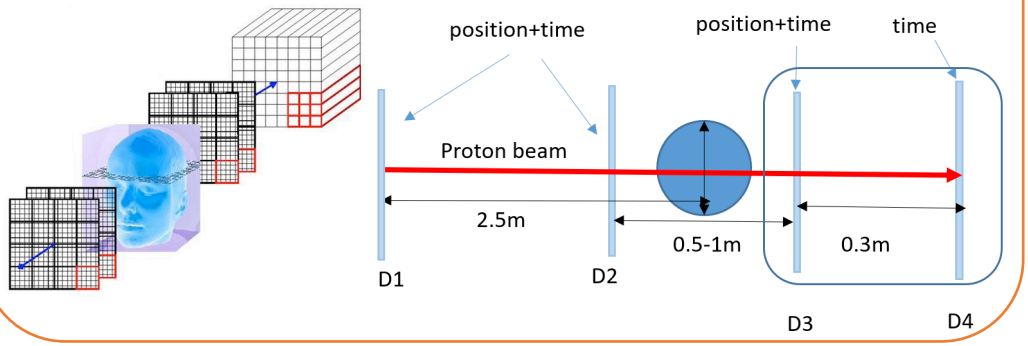
Spatial resolution: 10um

Timing resolution: 30- 50ps

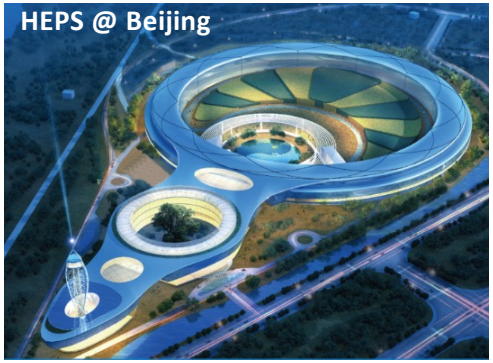
>70m^2 area

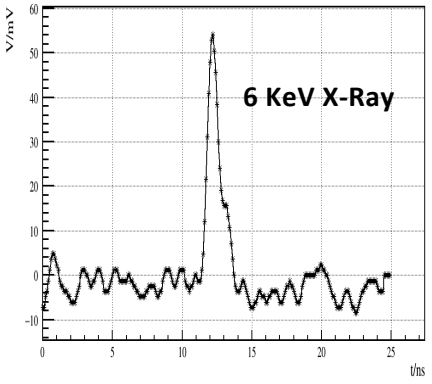
Nuclear Medicine Instruments:

Such as proton therapy and proton CT



X-ray detectors @ advanced light sources





other applications

- Beam Telescope for Beam Test Platform
- LiDAR: Positioning and Navigation
- Track and time detectors in other particle physics and nuclear physics experiments
- …

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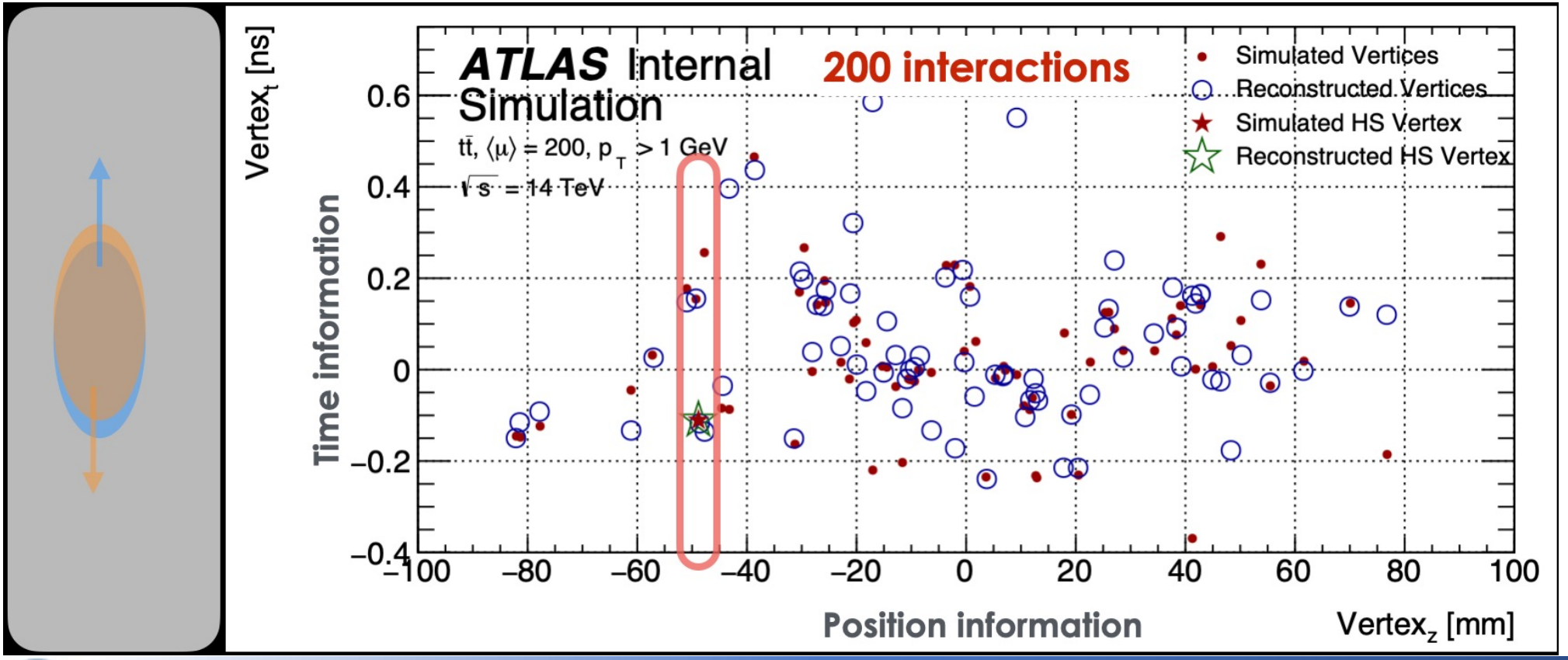
Backup

Motivation

- Pileup background is major challenges at high luminosity LHC
- High precision timing info can reduce the pileup by one order of magnitude



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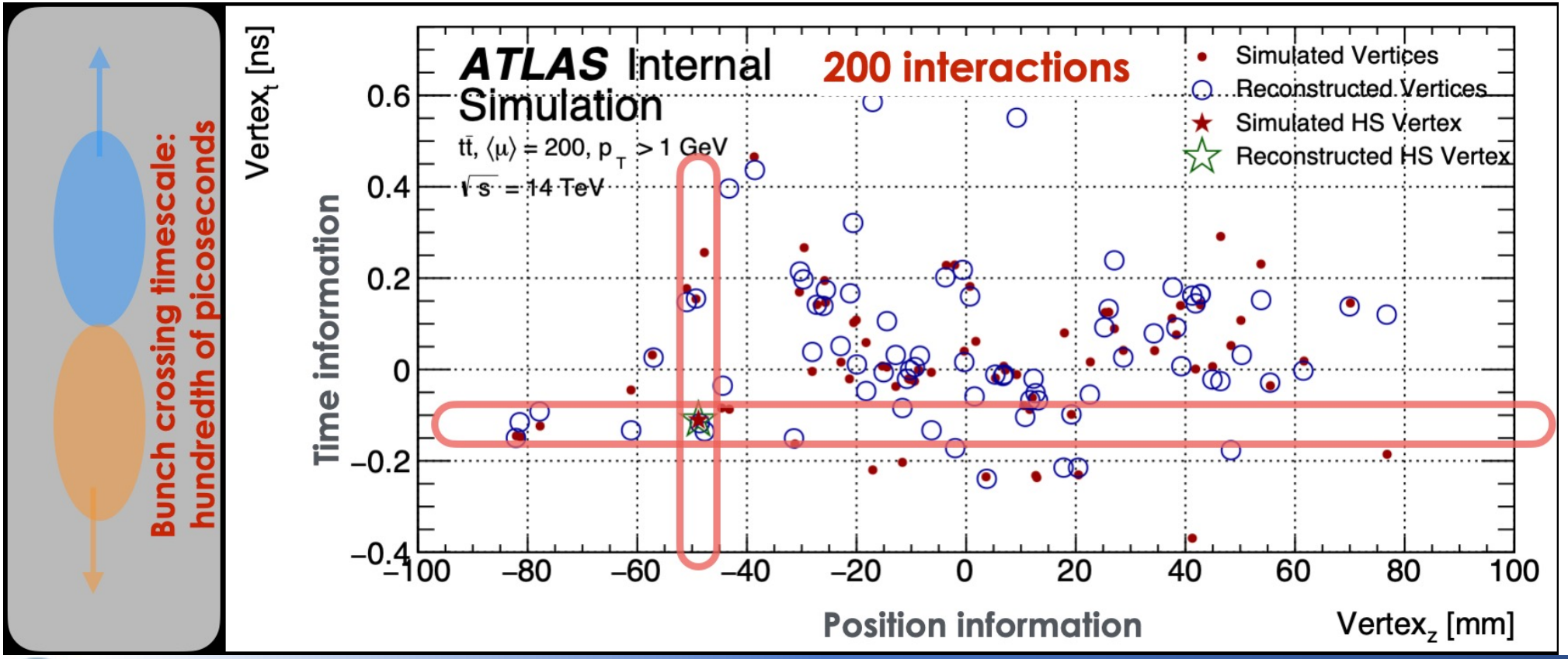
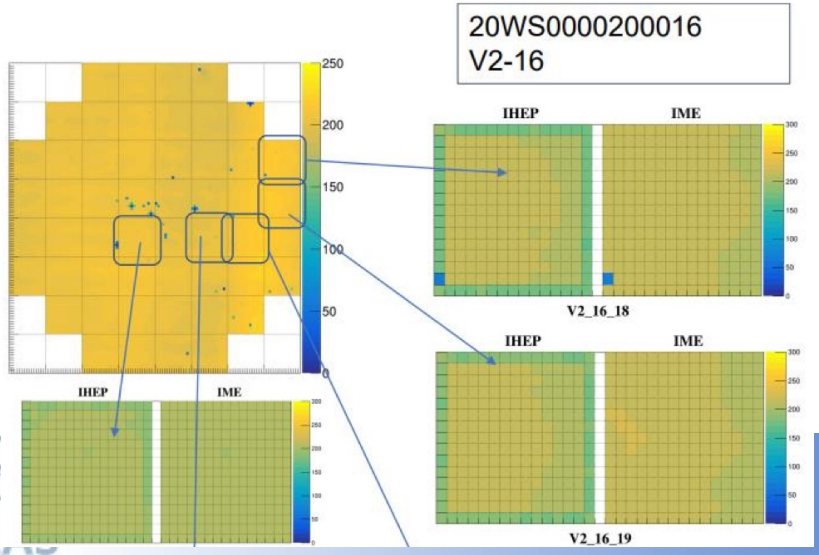


LGAD sensors pre-production

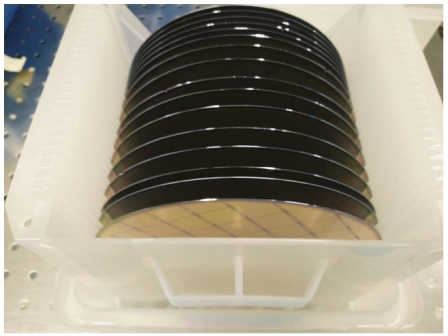
- In May 2013, IHEP-IME LGAD was selected by CERN in HGTD sensor tendering.
  - First domestic silicon sensor chosen by CERN in LHC experiment
- IHEP-IME will produce 90% of LGAD sensor for HGTD (~20k good sensor)
  - 1.7k good sensor fabricated in pre-production by far

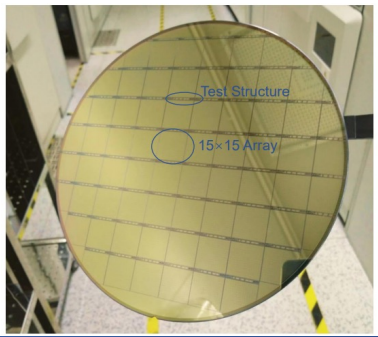
Vendor		Percent
IHEP-IME	CERN	54%
	China in-kind	24%
	Spain in-kind	12%
USTC-IME	China in-kind	10%

	IHEP-IME
Wafer fabricated	90 wafers
Considered as pre-production	52 wafers (1702 good sensors)



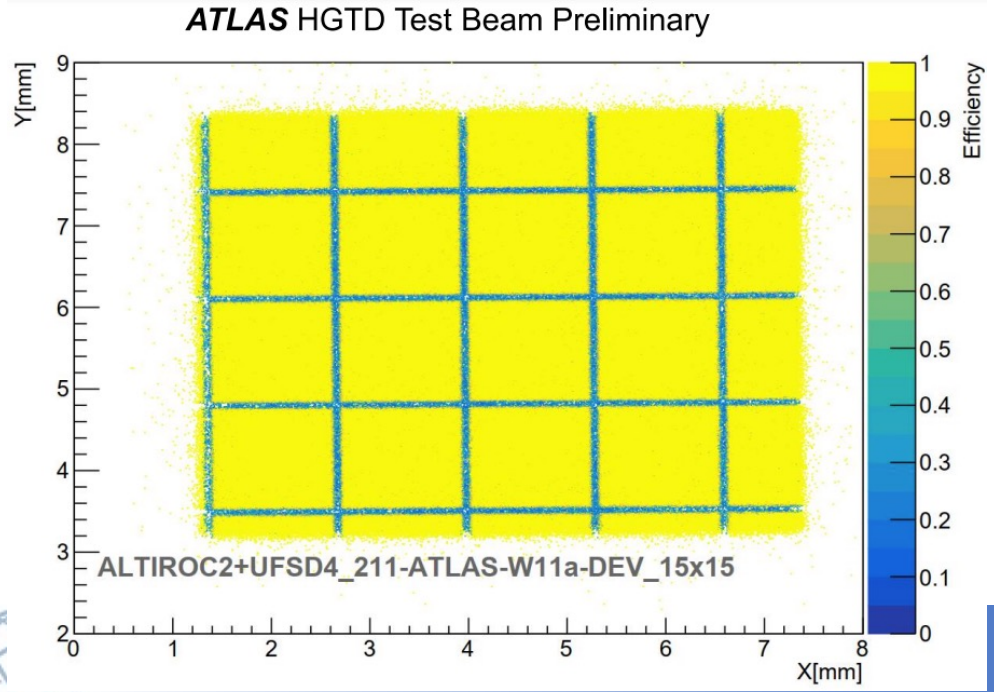
Pre-production LGAD sensors from China

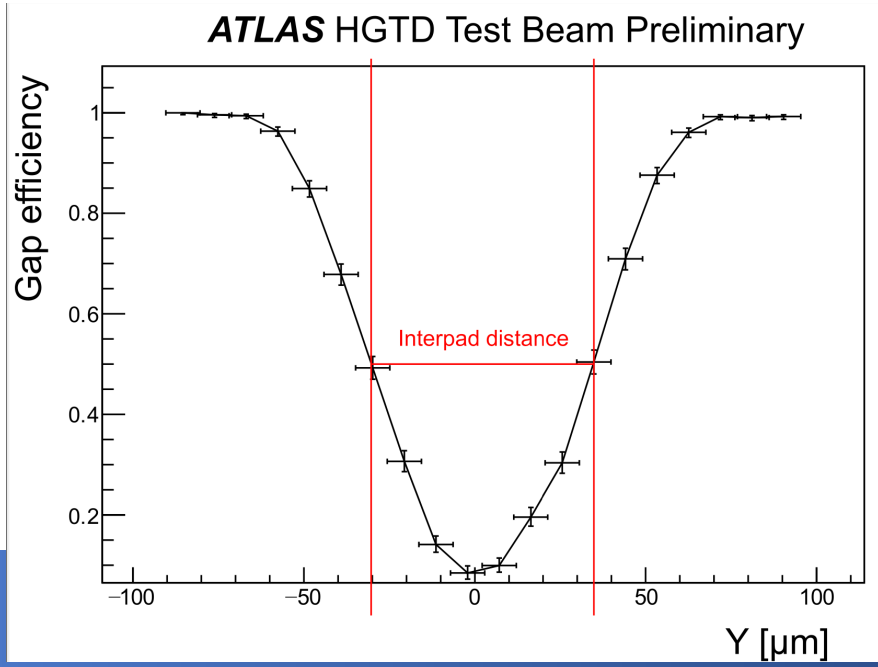




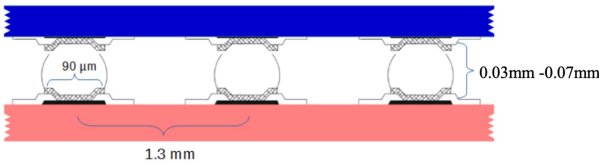
Hybrid test beam result

- Hybrid functionality was validated by test beam
  - The EUDET telescope is used for track reconstruction
  - Sensor bias voltage is -180 V, corresponding to a charge of ~20 fC
  - ASIC threshold 4.8 fC
- Close to 100% efficiency in the center of the pixel (pad)
  - The gap between pixels (pads) is about 50μm

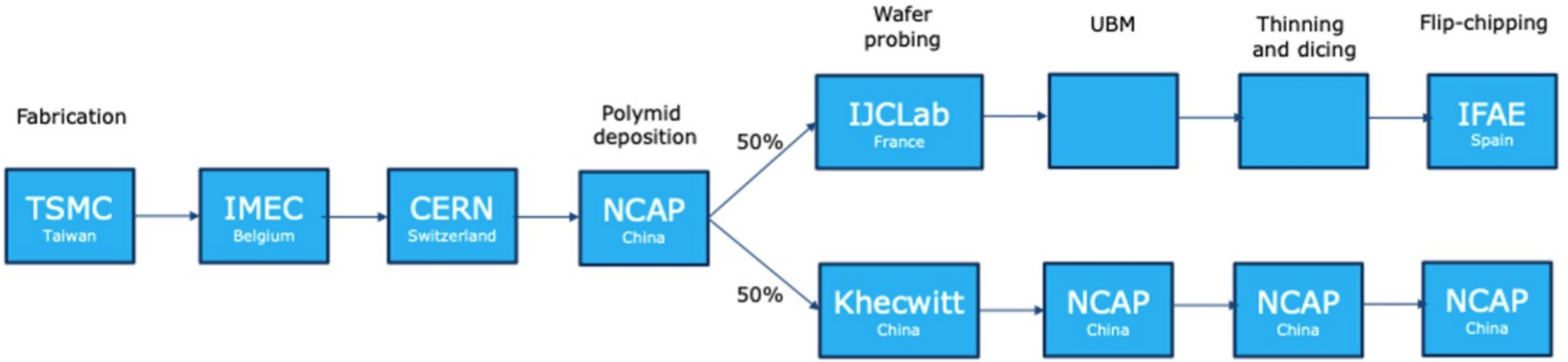


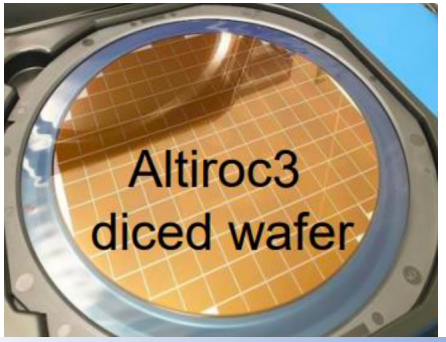


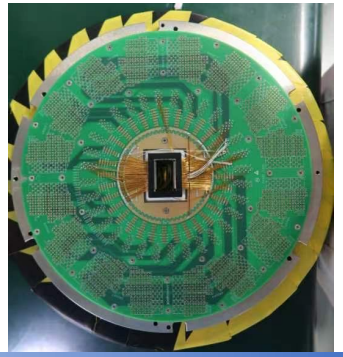
ALTIROC ASIC wafer process and flip-chip

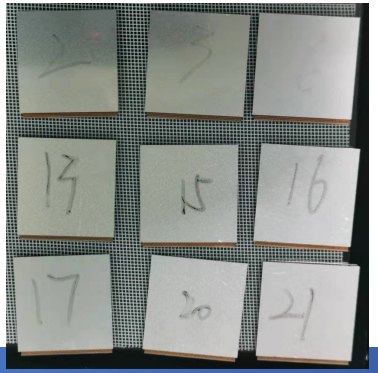


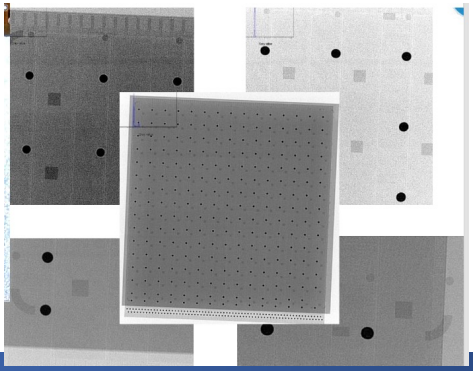
- ALTIROC-A ASIC wafers will be 100% sent to China for polyimide layer deposition
  - 50% to IHEP/Khecwitt for probing, to IHEP/NCAP for UBM/thinning/dicing/flip-chip
  - 50% to IJClab for probing, then to EU vendor for UBM/bump deposition/thinning/dicing/ then to IFAE for flip-chip



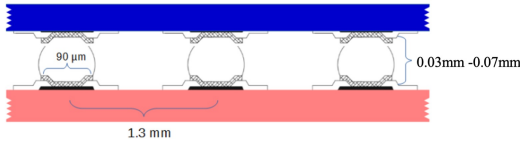






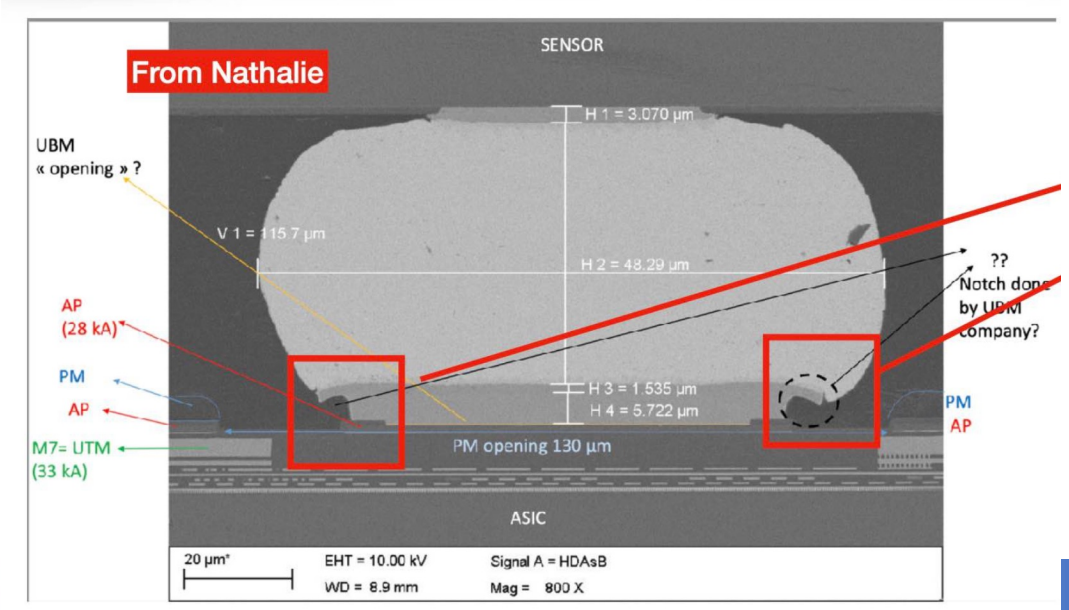


Major improvement in hybrid: new Polyimide layer ALTIROC2 VS ALTIROC3 hybrid

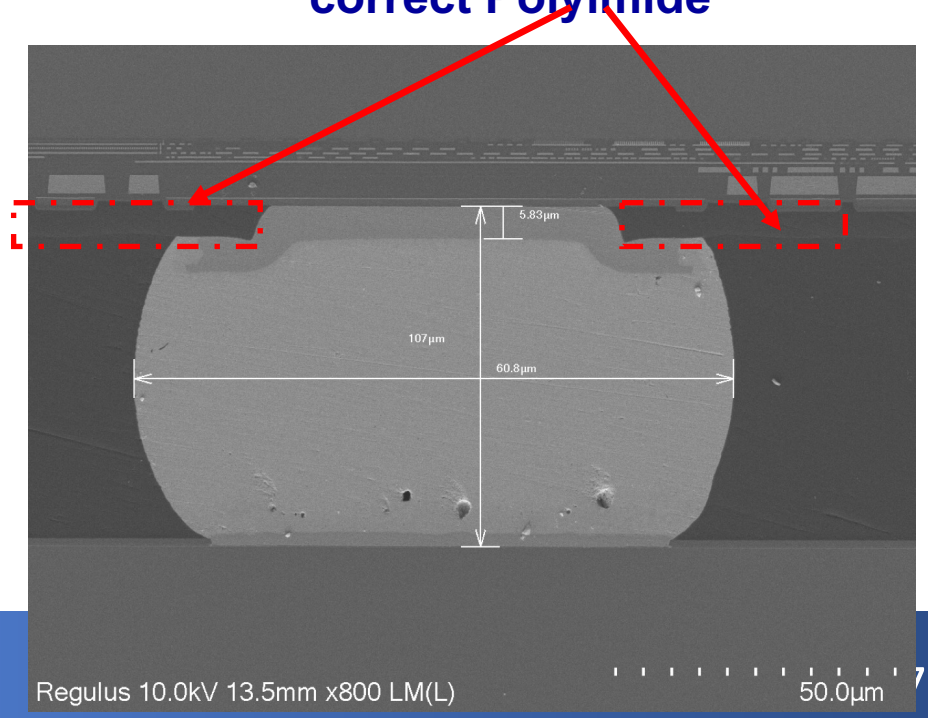


- Polyimide in ALTIROC3 deposited at NCAP/IHEP
  - Optimize to use Soft Polyimide material
  - More robust in thermal cycle, higher yield than ALTIROC2 hybrids.
- In ALTIROC3 hybrids prototyping phase, all ALTIROC3 UBM/thinning/dicing by IHEP/NCAP
- Next step to make the bump bonding thermal stability
  - Increase sensor thickness, increase the number of bumps

ALTIROC2 hybrid by TSMC with incorrect Polyimide



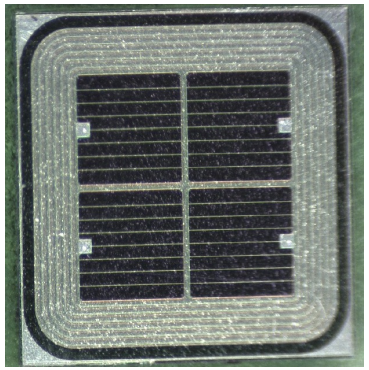
ALTIROC3 hybrid by NCAP/IHEP with correct Polyimide



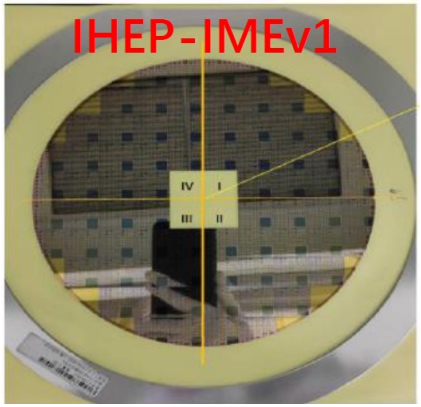
LGAD sensor development @ IHEP

- Since 2019, IHEP started LGAD designed, collaborated with 3 foundries on LGAD fabrications
  - Beijing Normal University (NDL), Tsinghua University, Institute of Micro-electronics (IME)

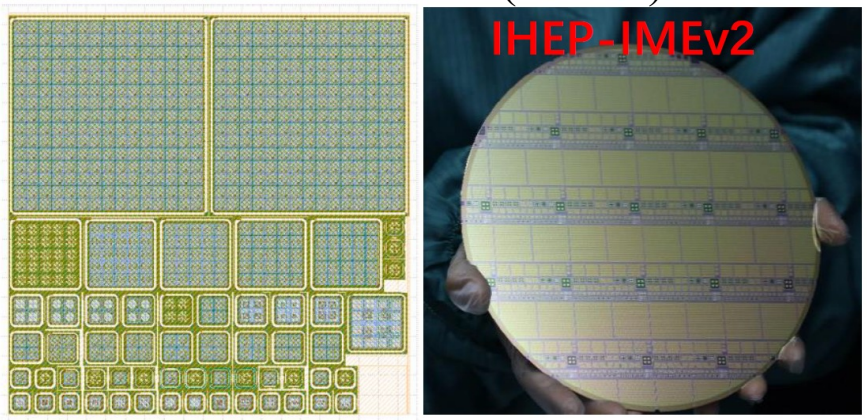
IHEP-NDL(2019)



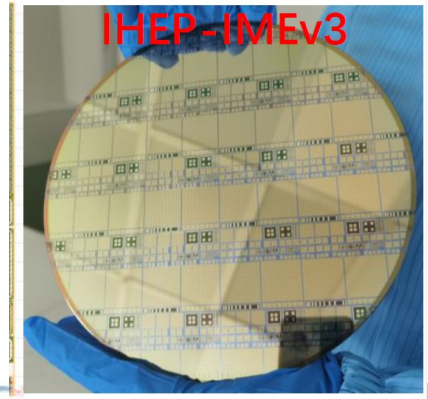
IHEP-IMEv1(2020.9)



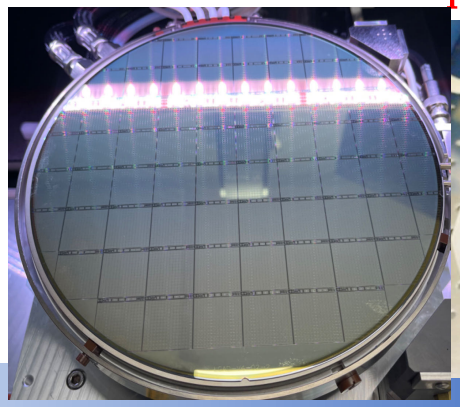
IHEP-IMEv2(2021.6)



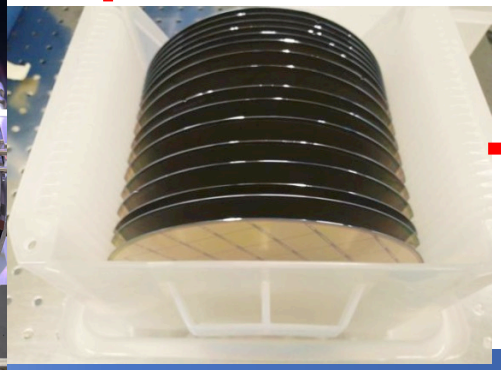
IHEP-IMEv3(2022.5)



Pre-production for ATLAS (2023.7)



Pre-production



Mass production for ATLAS (2024.6)

28