Status of LGAD sensor developed by IHEP-IME

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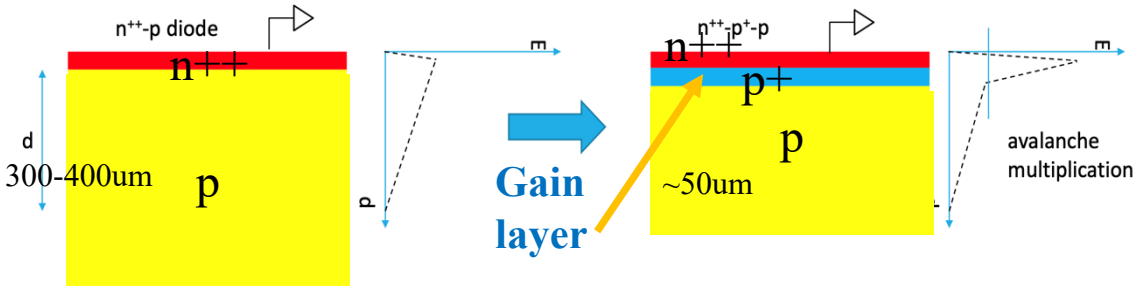
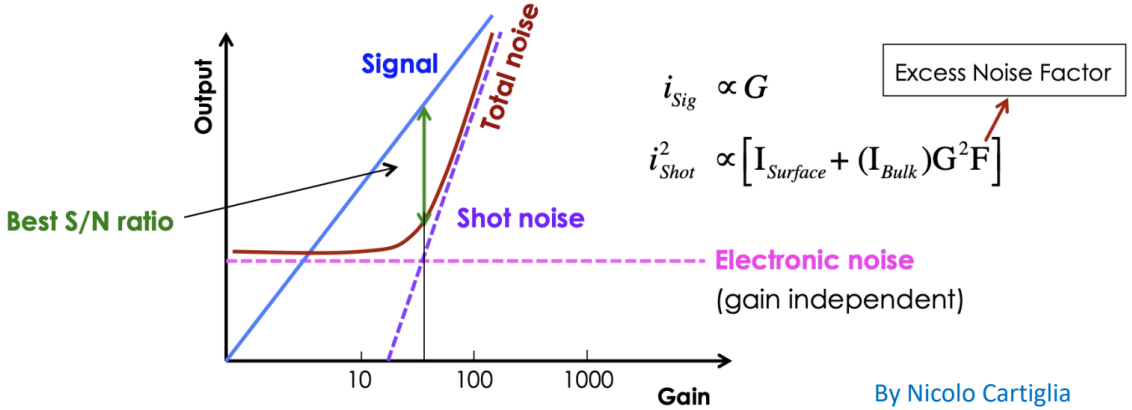
LGAD detector

➢**Low Gain Avalanche Detectors (LGAD)** is a silicon detector technology developed recently, that could measure the particle time at ps precision (~30ps).

➢Compared with PIN, a gain layer between P and N++ is added:

- Work in a linear mode, Gain:10~50
- Good Signal/Noise ratio without self triggering
- Thin depleted region to decrease t_{rise} (fast timing)





Noise increases faster than then signal

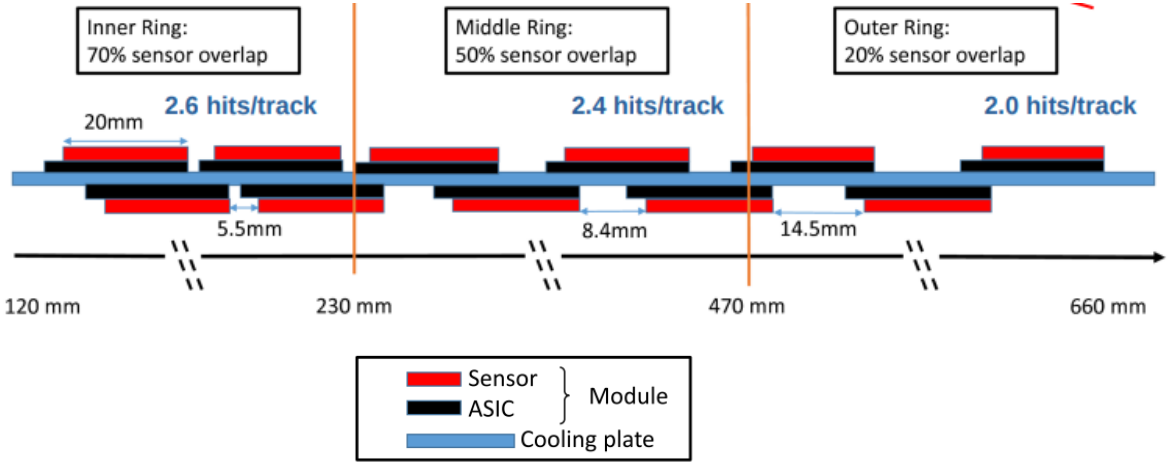
→ the ratio S/N becomes worse at higher gain

https://doi.org/10.1201/9781003131946

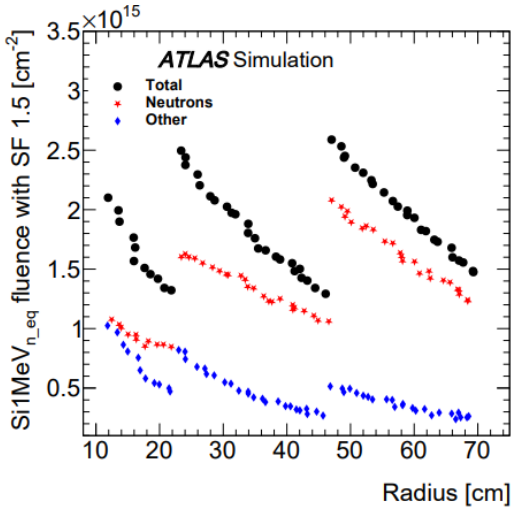
➢**Owning to its good performance, LGAD technology is chosen as detector for ATLAS HGTD project.**

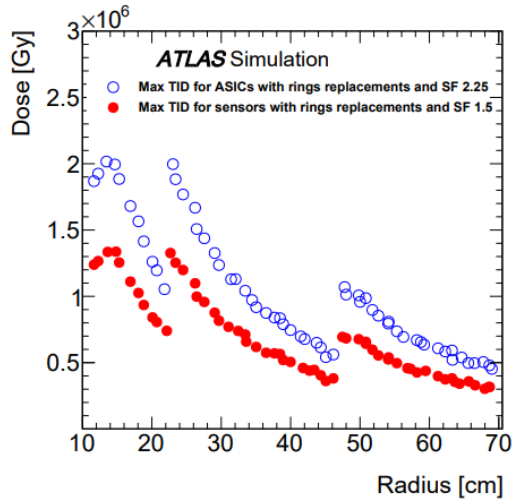
LGAD sensor for HGTD

- ~21,000 LGAD sensors for HGTD project
- Requirements:
  - •Size: 15x15 array, 1.3x1.3 mm^2 pixel size
  - •Active thickness: 50 um(Thin: faster rise time, lower impact from radiation)
  - •LGAD sensor can withstand the lifetime of the HL-LHC running: irradiation requirement
    - Maximum n_{eq} fluences: 2.5×10^{15} n_{eq}/cm^2
    - Total Ionizing Dose (TID): 2 MGy at the end of HL-LHC (4000 fb^{-1})
  - •Time resolution: 35 ps (start), 70 ps (end) per hit, while 30 ps (start), 50 ps (end) per track
  - •Collected charge per hit >4 fC (minimum charge needed by the ASIC to hold good time resolution)
  - •Hit efficiencies of 97% (95%) at the start (end) of their lifetime



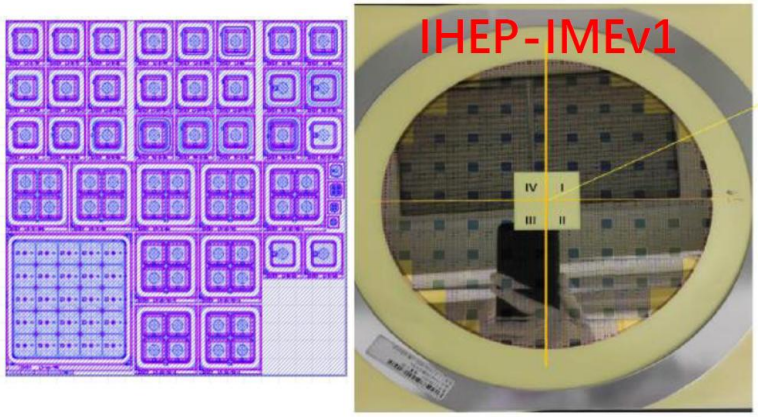
Maximum fluence with replacements



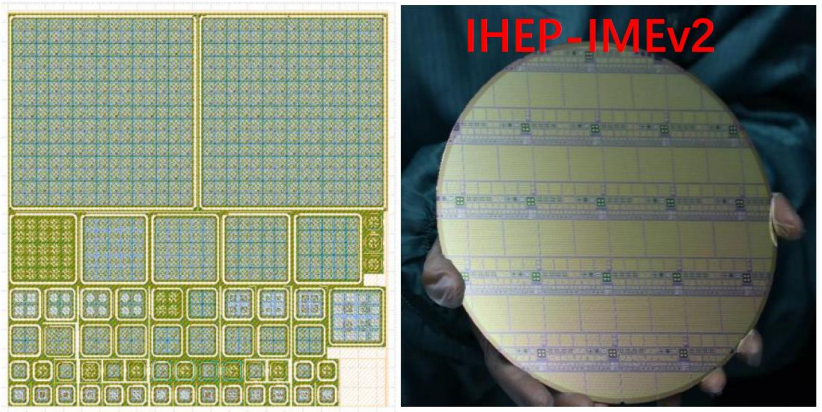


LGAD Development at IHEP

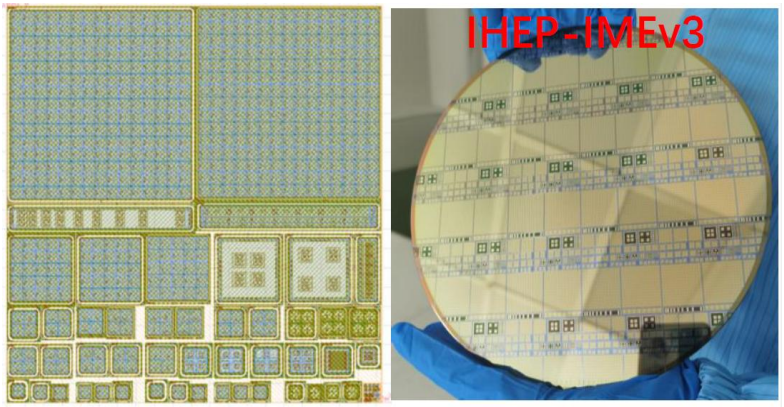
IHEP-IMEv1(2020.9)



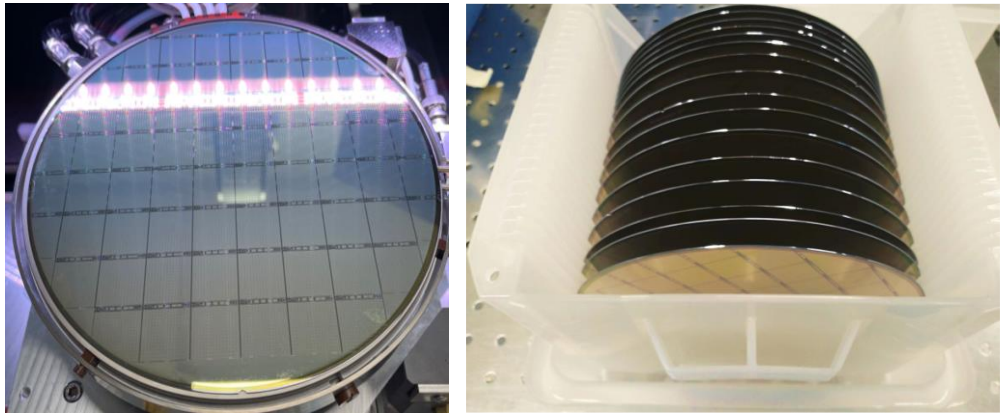
IHEP-IMEv2(2021.6)



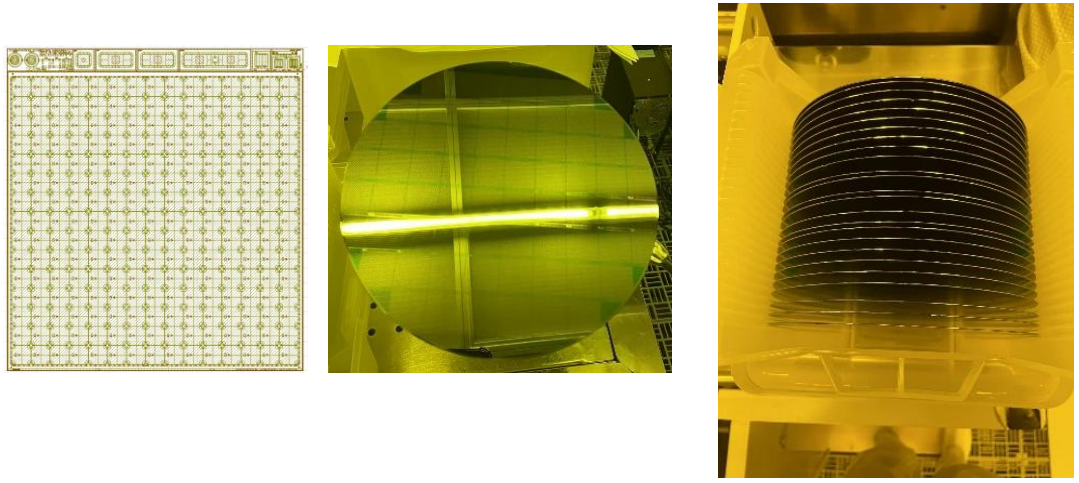
IHEP-IMEv3(2022.5)



Pre-production for ATLAS (2023.7)



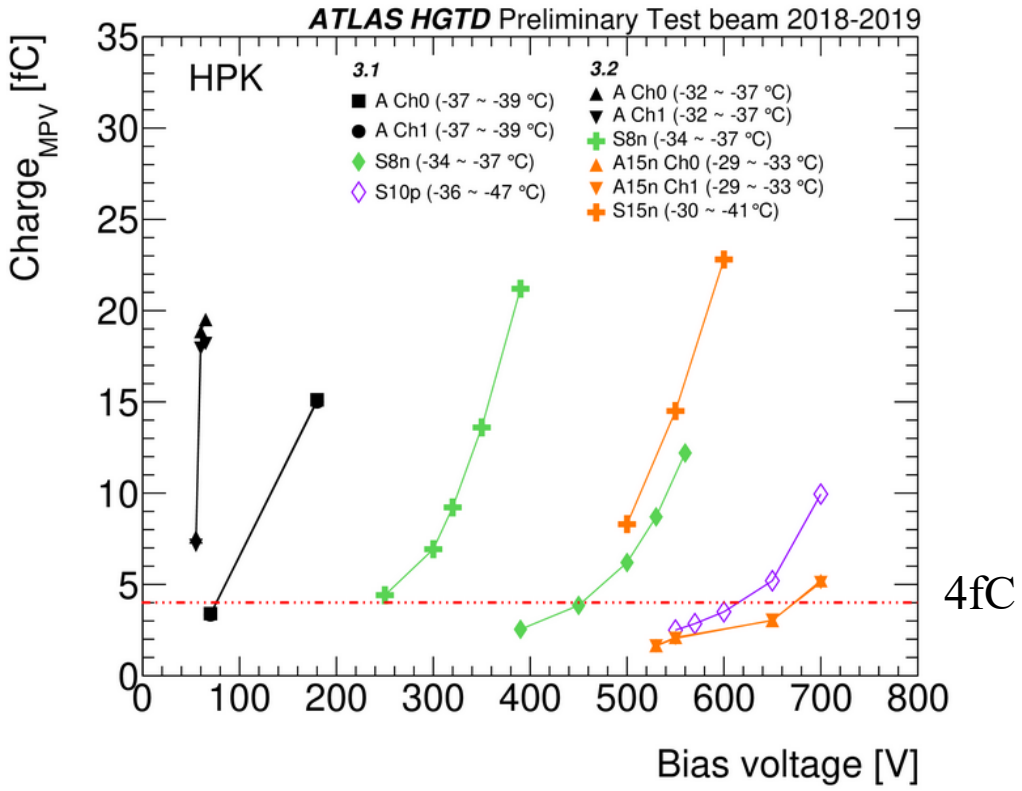
Mass production for ATLAS(2024.6) ongoing



Radiation performance of LGAD

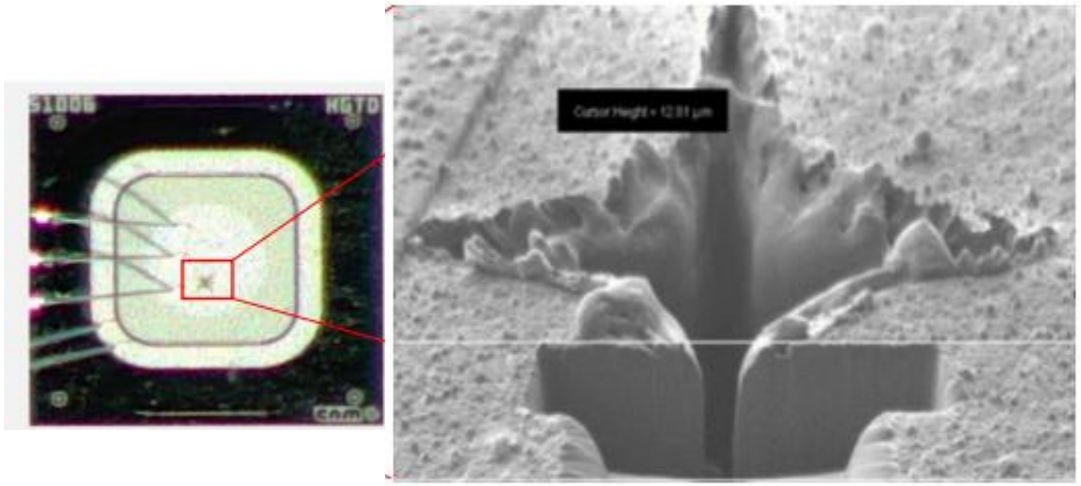
Radiation performance

- The acceptor removal effect occurs (reduction in the effective concentration of the gain region).
- Gain decreases, collected charge reduces, and timing resolution deteriorates.



4fC

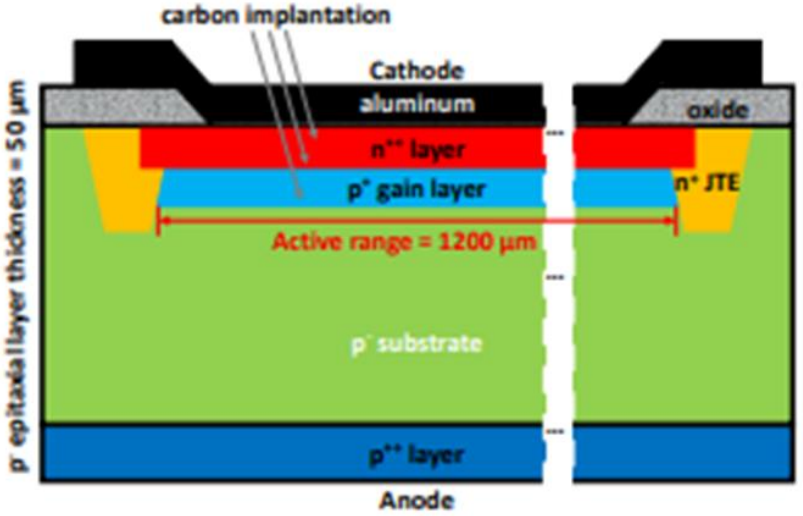
➢ **After increasing the operating voltage, single-event burnout(SEB) occurred during beam testing.**

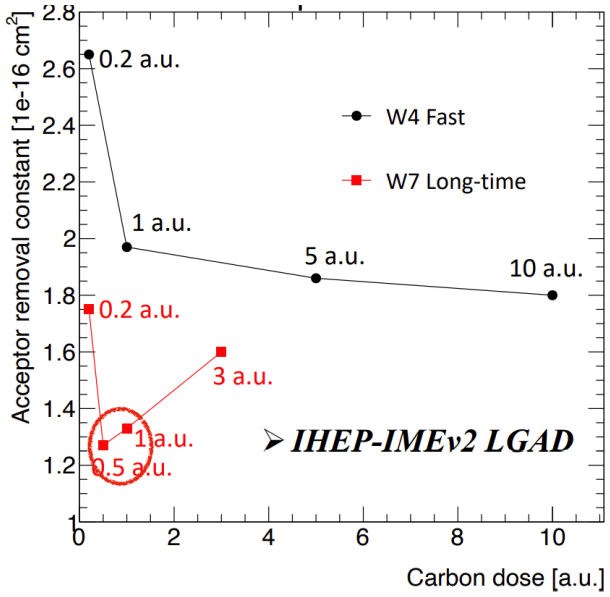


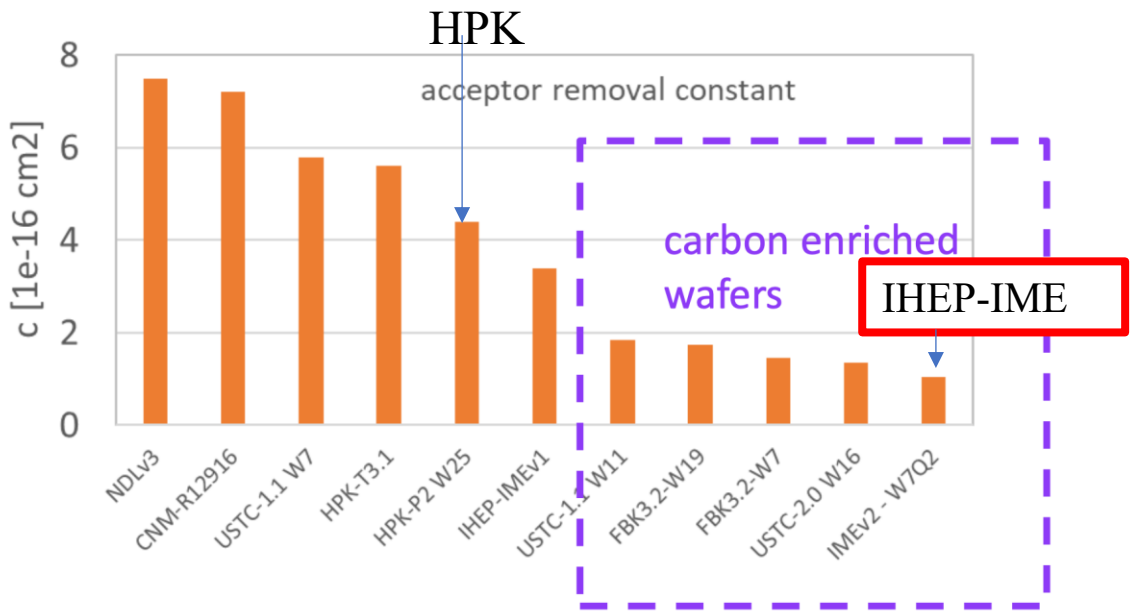
➢ **Research findings:**

- High voltage and high electric fields lead to burnout.
- The operating voltage should be controlled to <550 V (for 50μ sensors), and the electric field should be <12 V/μm to collect sufficient charge.

Radiation performance of IHEP-IME sensor



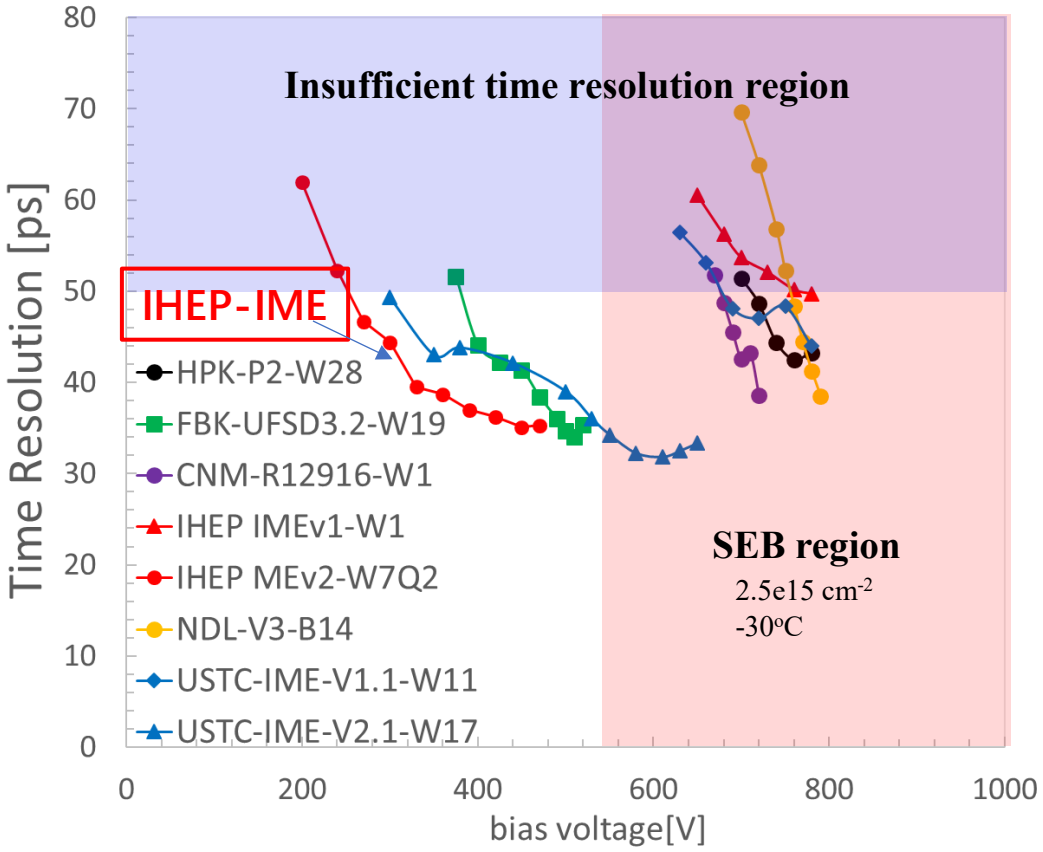


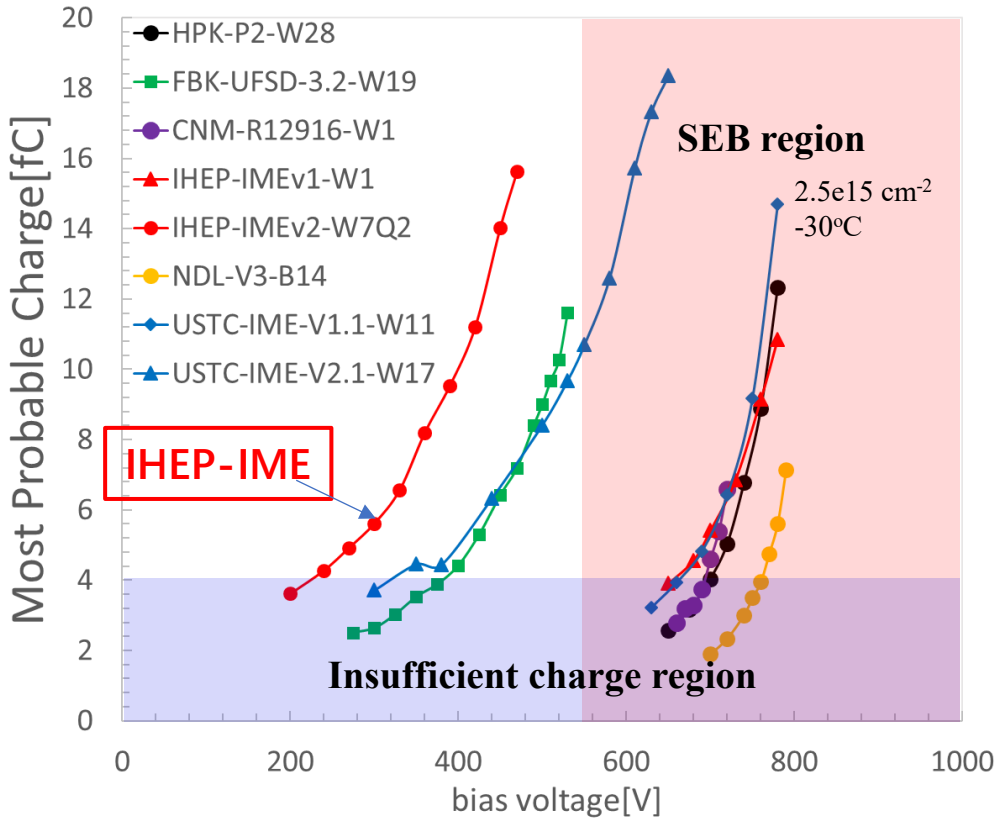


- **Study of Carbon-Doped LGAD**
  Different Carbon Implantation Doses and Heat Treatment Conditions
- Find out the optimal carbon implantation dose and annealing conditions
- The irradiated devices exhibit the minimum acceptor removal constant (reflecting the radiation resistance of the devices).

Radiation performance of IHEP-IME sensor

- **Timing resolution**: The timing resolution is better than 50 ps after irradiation(fluence 2.5×10^{15} n_{eq}/cm^2)
- **Collected charge:** The sensors can collect more than >4 fC charge after irradiation at bias voltage ~400V (SEB limit)
- **Beam tests** conducted by the ATLAS collaboration at CERN
  After irradiation, the carbon-doped IHEP-IME LGAD devices were operated stably under the beam for extended periods without any burnouts.





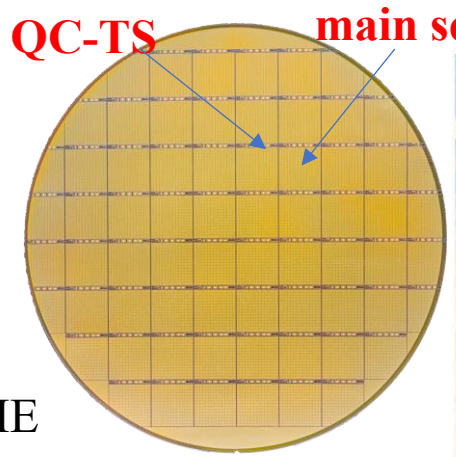
ATLAS HGTD sensor status

- LGAD sensors for HGTD project: ~21,000
  IHEP design:90% USTC design:10%

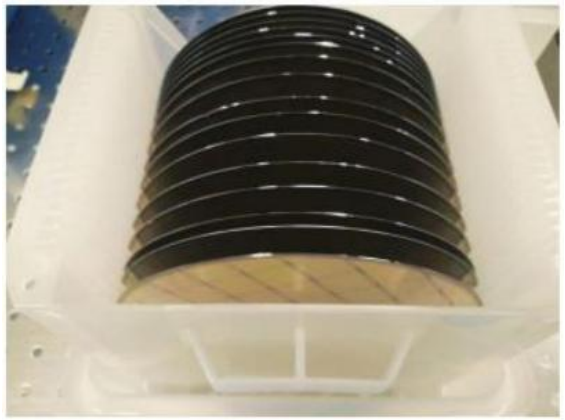
- In 2023, IHEP design LGAD sensors be selected in the HGTD sensor tendering process.
- Pre-production started at June 2023.
- Sensor pre-productions finished in 2023 – produced comfortably enough sensors for HGTD needs.
- HGTD group testing results show that the sensors properties fulfill HGTD specification.
- PRR passed at July 2024, and final production started after it.

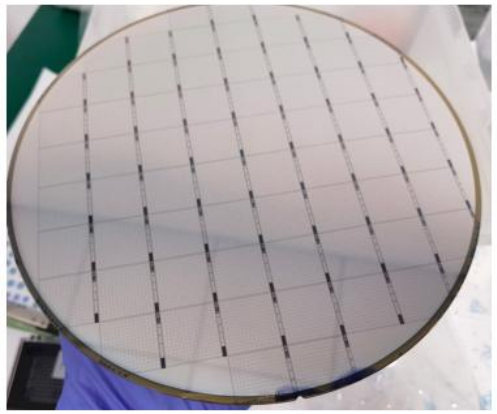
Vendor		Percent
IHEP-IME	CERN	54%
	China in-kind	24%
	Spain in-kind	12%
USTC-IME	China in-kind	10%

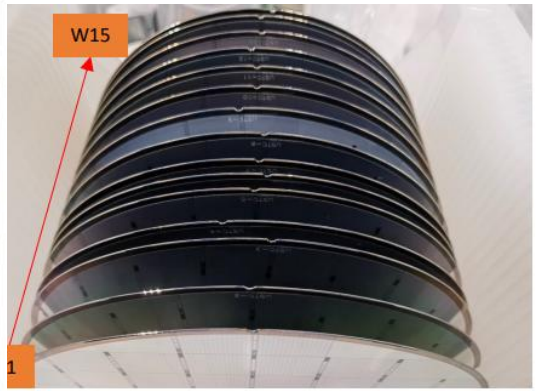
Preproduction	Wafer number	Good sensors
IHEP-IME	58	~1,700
USTC-IME	9	~200



IHEP-IME



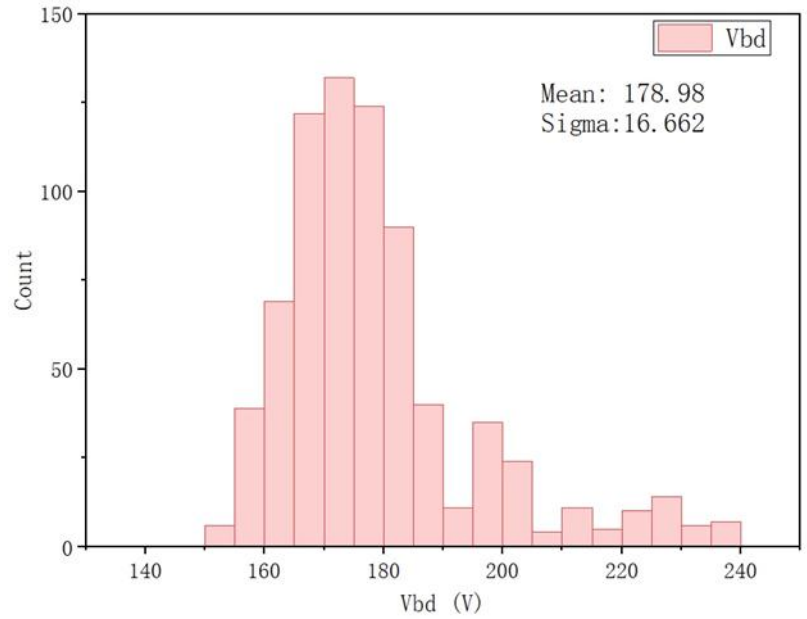




USTC-IME

IHEP-IME pre-production

ATLAS ID	IHEP-IME ID	thickness(um)	Average Vbd (V)	# of good sensors	sensor yield	UBM
20WS0000110002	v1-R2(w1)	775	212.7	19	37%	no
20WS0000110003	v1-R3(w2)	775	222.5	25	48%	no
20WS0000110016	v1-A16(w3)	775	196	18	35%	no
20WS0000200012	v2-12(w4)	775	180.8	39	75%	no
20WS0000110015	v1A15	775	217.7	22	48%	yes
20WS0000110005	v1R5	300	190	42	80.77%	yes
20WS0000200016	v216	300	201.7	40	76.92%	yes
20WS0000300010	V310	300	196.1	31	59.62%	yes
20WS0000400007	V4-7	300	169.9	31	59.62%	yes
20WS0000400009	V4-9	300	168.2	33	63.46%	yes
20WS0000400011	V4-11	300	170.8	39	75.00%	yes
20WS0000400012	V4-12	300	170.7	33	63.46%	yes
20WS0000400014	V4-14	300	162.1	30	57.69%	yes
20WS0000400015	V4-15	300	172	39	75.00%	yes
20WS0000400020	V4-20	300	177.8	28	53.85%	yes
20WS0000400022	V4-22	300	160	26	50.00%	yes
20WS0000400024	V4-24	300	178.1	31	59.62%	yes
20WS0000400001	V4-1	300	178.1	43	82.69%	yes
20WS0000400003	V4-3	300	167.4	6	11.54%	yes
20WS0000400013	V4-13	300	174.9	40	76.92%	yes
20WS0000400023	V4-23	300	164.8	34	65.38%	yes
20WS0000300001	V3-1	300	178.1	43	82.69%	yes
20WS0000300005	V3-5	300	172.3	36	69.23%	yes
20WS0000300015	V3-15	300	177.6	38	73.08%	yes
20WS0000300022	V3-22	300	176.6	44	84.62%	yes
20WS0000300023	V3-23	300	171.1	39	75.00%	yes
20WS0000300024	V3-24	300	174.3	41	78.85%	yes



558 sensors within the +-8%
(V_{bd}: 165V~195V)

core preproduction – all finished in accordance with specs and requirements

IHEP-IME pre-production

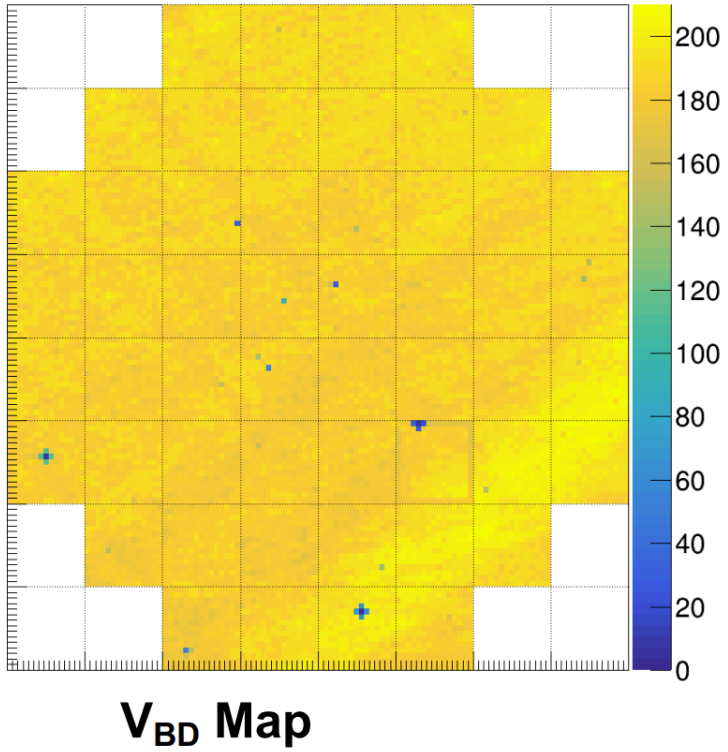
- **The 15x15 array sensors have good IV performance and uniformity**

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

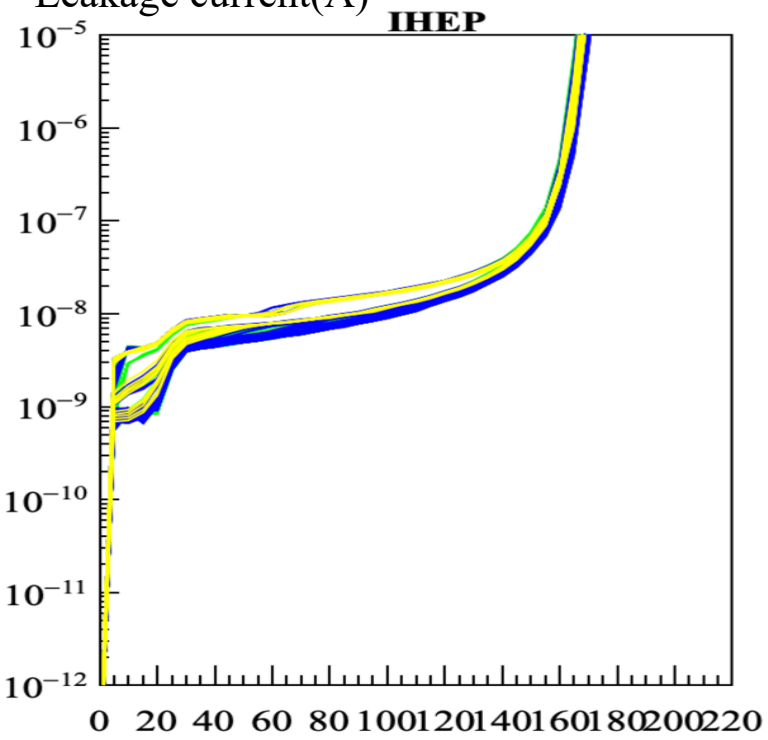
  The ratio of the maximum and minimum leakage current is less than 3 (Pad leakage current spread at $0.8V_{bd}$) ,peak to peak within a factor of 3X.

- **Yield**： pad yield: >99%, sensor yield: ~64%

Mapping of V_{bd} of sensors on one wafer

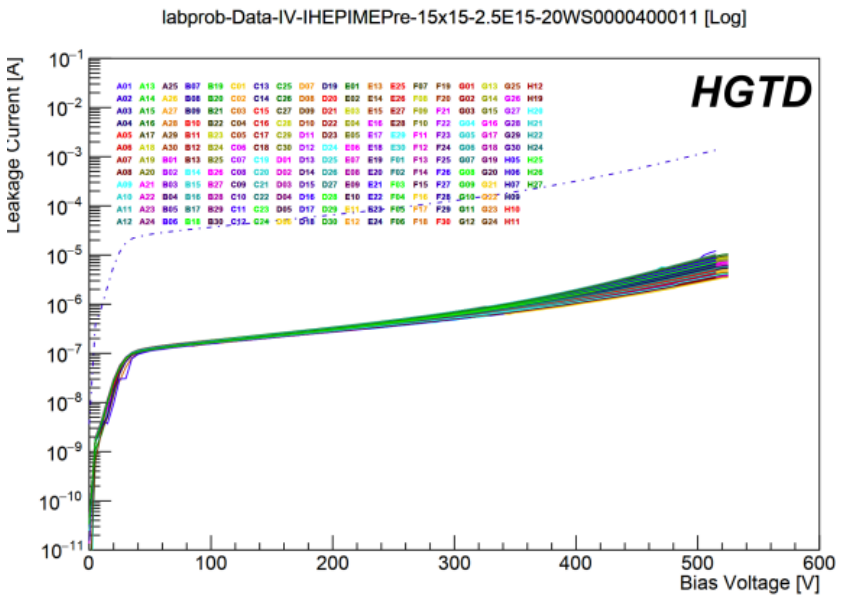


Leakage current(A)



Bias voltage(V)

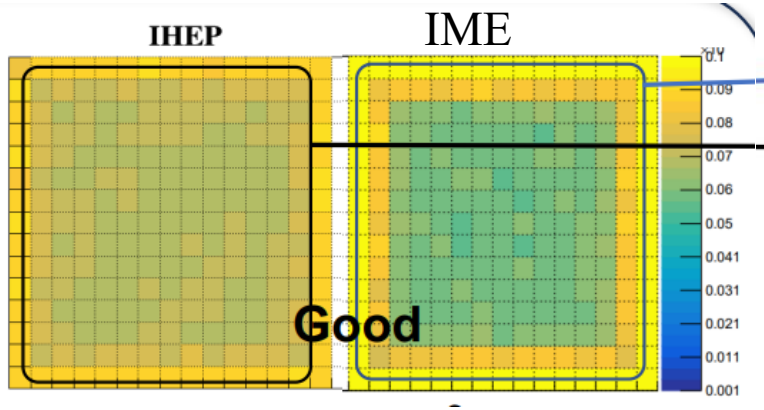
20WS0000400011@2.5E15 n_{eq}/cm^2

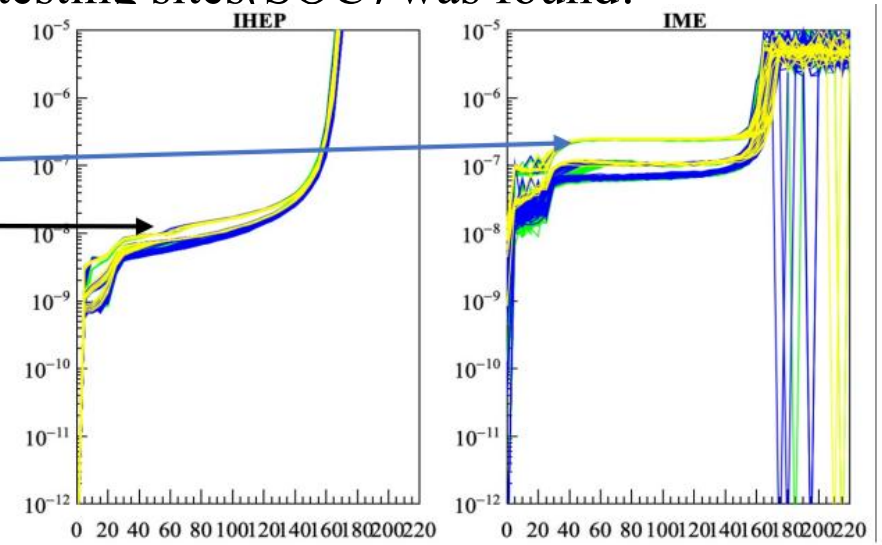


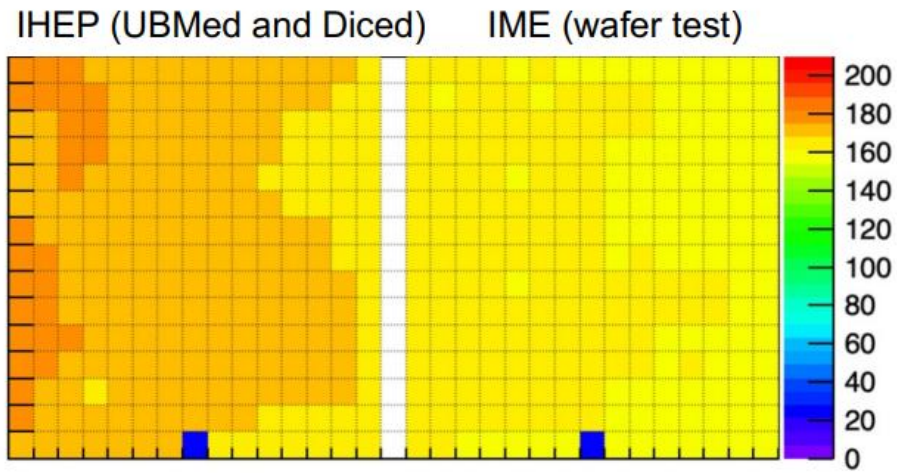
IHEP-IME pre-production

- 62 sensors(~13k pads) from IHEP-IME been tested by IHEP
- No mismatch between results from vendors(CQC) and HGTD testing sites(SOC) was found!

- All pads from good sensors are good, The location of bad pad(s) is the same before and after UBM(CQC and SQC)





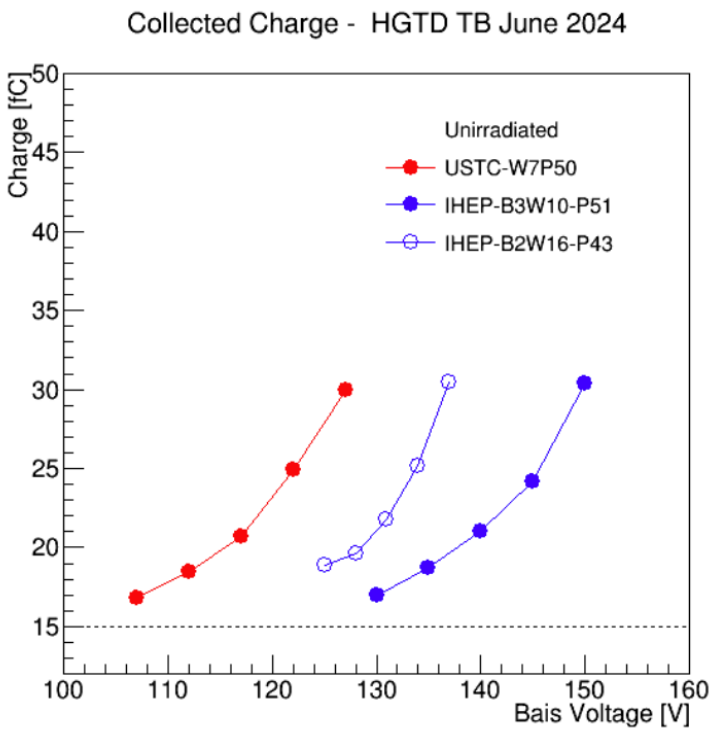


	HGTD testing(after UBM and dicing)	Yield
IHEP-IME	62 sensors (50 good + 12 bad)	sensor yield [good/(IME good)] 100%
	13950 pads	yield per pad [good/(IME good)] 100%

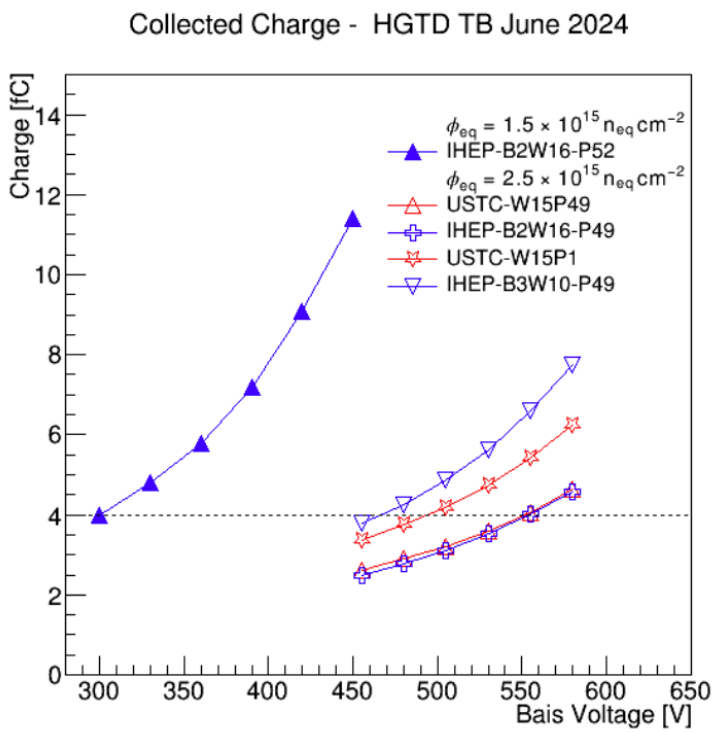
IHEP-IME pre-production

Performance of pre-production sensors: Beam test results

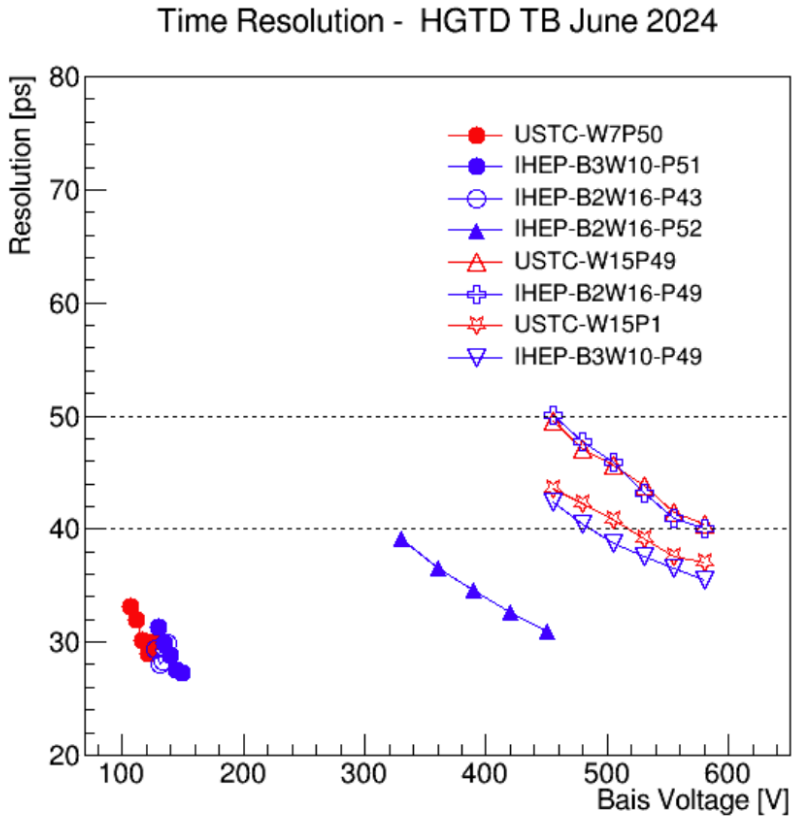
- Collected charge: The sensors can collect more than 15 fC charge before irradiation and >4 fC charge after irradiation at bias voltage <550 V (SEB limit)
- Timing resolution: The timing resolution is better than 35 ps (50 ps) before(after) irradiation(fluence 2.5×10^{15} n_{eq}/cm^2)
- The collected charge and timing performance of sensors from pre-production fulfills HGTD requirement.



unirradiated sensor

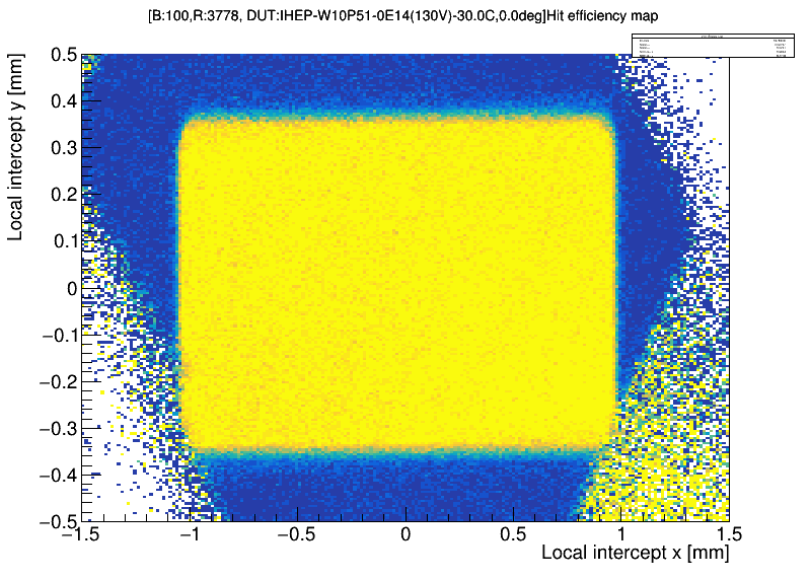


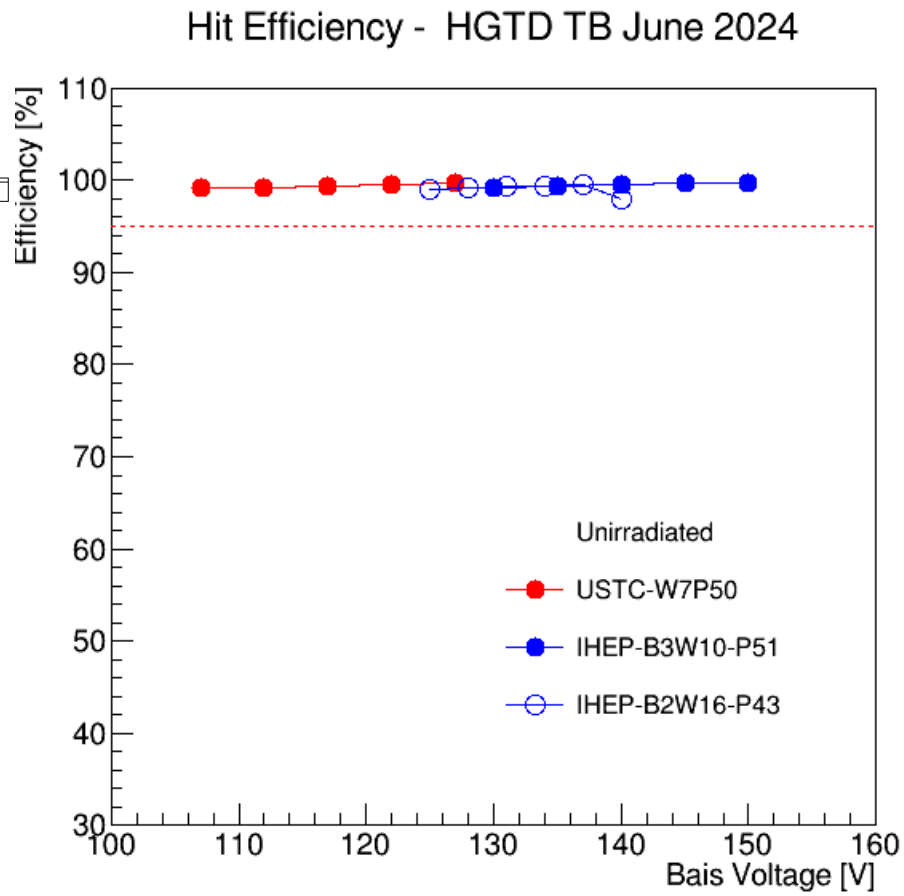
irradiated sensor

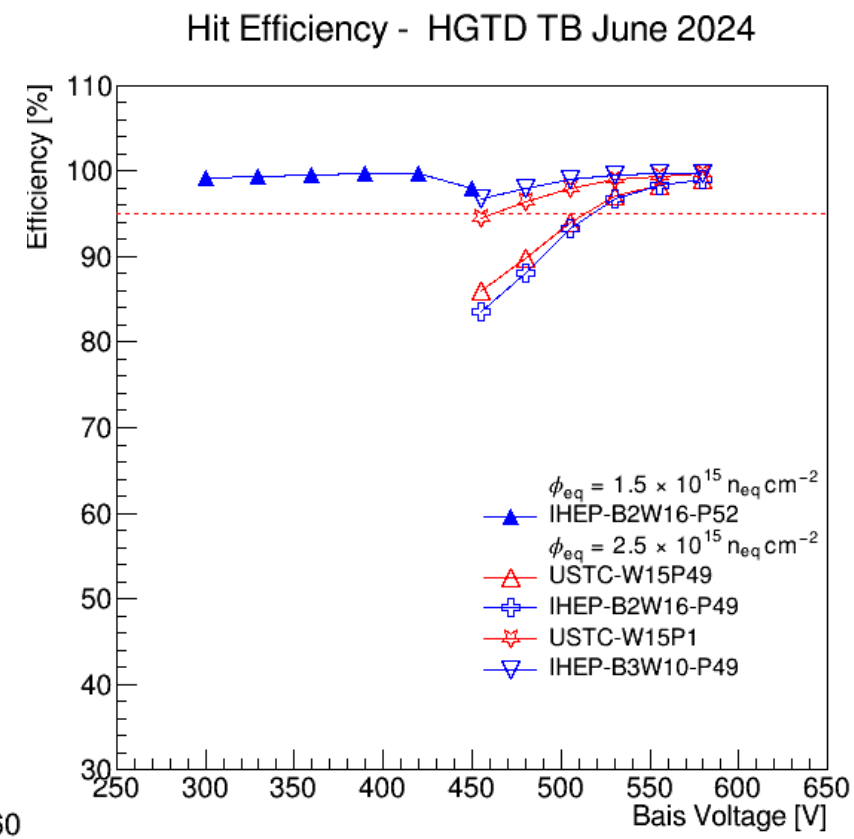


IHEP-IME pre-production

- **Performance of pre-production sensors: Beam test results**
- **Efficiency : 95%~100% for sensors before and after irradiation, fulfills HGTD project requirement**

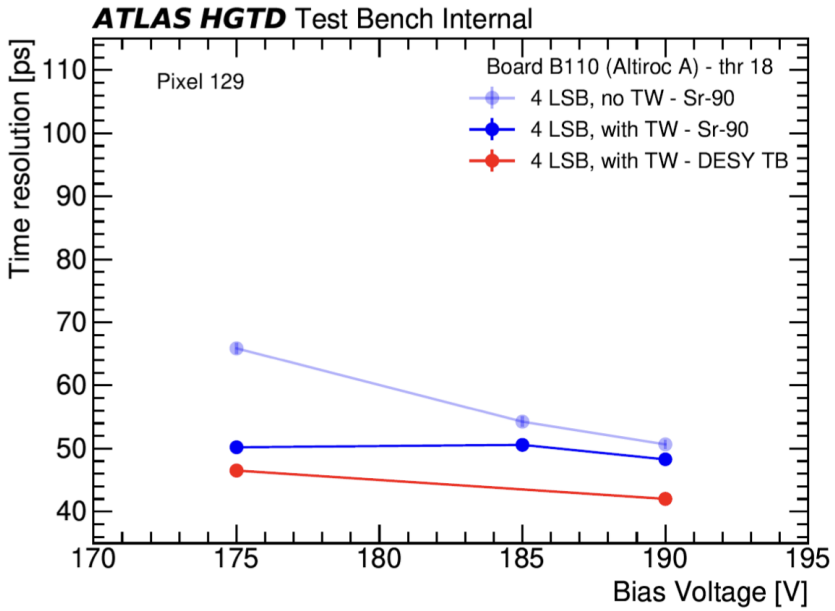




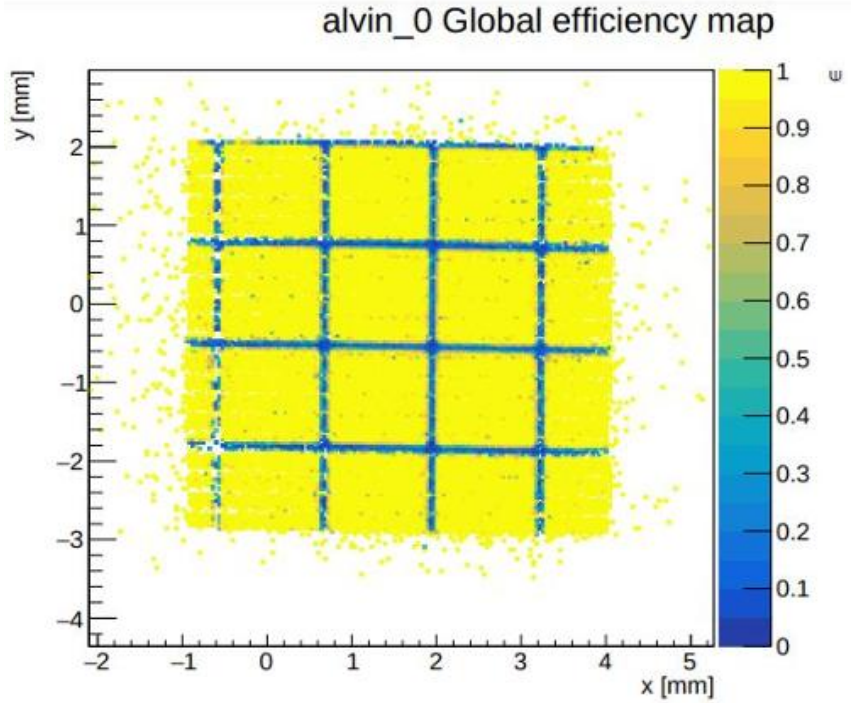


IHEP-IME pre-production:Hybrid performance

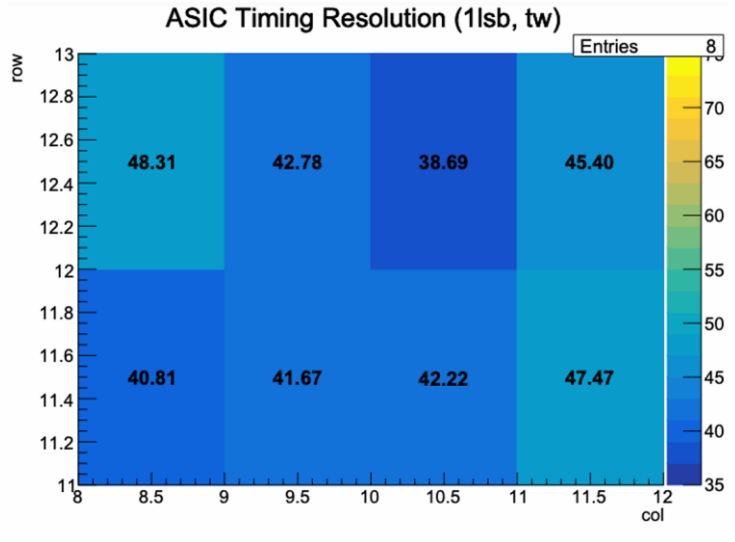
- Pre-production sensor+ ASIC(Altiroc3 and AltirocA) hybridization be tested at CERN and DESY test beam.
- The timing resolution can reach <50ps. The efficiency >98% and inter-pad gap less than 100um.
- Testing results of irradiated sensor with ASIC are very good in terms of timing resolution.



best time resolution reached O(42 ps)



efficiency >98% over the global map
effective inter-pad gap $\lesssim$ 100 μm



Irradiated sensors(2.5e15 n_{eq}/cm^2) with AltirocA
Best time resolution:~42ps

Production status: IHEP-IME

- **IHEP-IME Pilot batch** been delivered to IHEP on 15th May, including main sensors and QC-TS.
- **17 wafers: 403 good sensors** and 17x25 QC-TS.
- All the sensors been tested by IME, with UBM.
- Sensor quality check will be done next by IHEP. 17x25 QC-TS will be distributed to CERN, USP and JSI for process quality check and irradiation test.
- 50% of main sensors will be sent to CERN(IFAE) for hybridization, others will be hybridized at NCAP in China.
- Other IHEP-IME production sensors will be delivered in 5 batches in this and next year, total sensor number is ~20000.

Table 1: Number of good sensors for wafers [from B4-W2 to B4-W19]

Wafer serial number	W2	W3	W4	W5	W6	W8
Number of good sensors	20	12	25	22	26	35
Wafer serial number	W9	W10	W11	W12	W13	W14
Number of good sensors	27	26	27	29	22	29
Wafer serial number	W15	W16	W17	W18	W19	Total
Number of good sensors	26	15	16	24	22	403

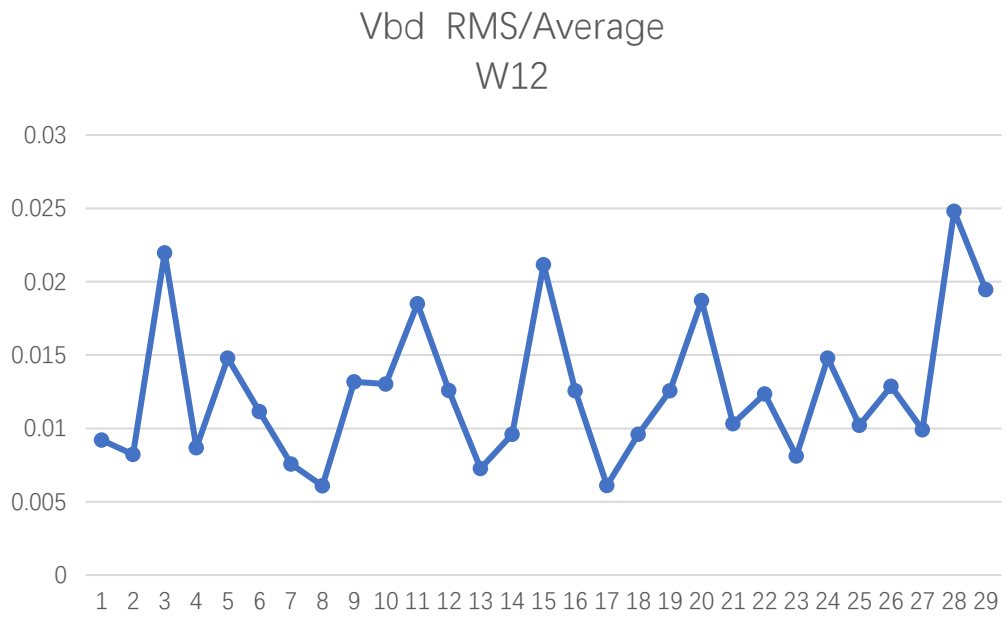
Yield: 403/884 = ~45%

Production status: IHEP-IME

Wafer	Average V_{bd}	V_{bd} RMS/Average	Leakage current ratio	Yield
W2	168V	0.010=1%	1.49	20/52=38.5%
W3	168V	0.011=1.1%	1.66	12/52=23%
W4	171	0.0094=0.94%	1.62	25/52=48%
W5	169V	0.0099=0.99%	1.49	22/52=42.3%
W6	170V	0.0095=0.95%	1.31	26/52=50%
W8	174V	0.011=1.1%	1.76	35/52=67.3%
W9	177V	0.0097=0.97%	2.02	27/52=52%
W10	181V	0.010=1%	1.95	26/52=50%
W11	175V	0.012=1.2%	1.82	27/52=52%
W12	179V	0.013=1.3%	1.89	**29/52=55.8%**
W13	176V	0.012=1.2%	1.84	22/52=42.3%
W14	174V	0.014=1.4%	1.83	29/52=55.8%
W15	179V	0.015=1.5%	2.01	26/52=50%
W16	179V	0.012=1.2%	1.80	15/52=28.8%
W17	179V	0.014=1.4%	1.97	16/52=30.7%
W18	178V	0.015=1.5%	1.90	24/52=46%
W19	177V	0.014=1.4%	2.06	22/52=42.3%

The 403 sensors from 17 wafers fulfill the HGTD requirement:

- Breakdown voltage in the range: 165V< V_{bd} <195V
- 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.



Good uniformity

Average Yield: 45.6%

Summary and Plan

- For ATLAS HGTD project, LGAD sensors' pre-production is finished, and IHEP-IME sensors fulfills the project requirement.
- Review passed and final production started.
- IHEP-IME production:

  Pilot batch be delivered to IHEP, including main sensors and QC-TS.
- IHEP will continue to do the sensor quality check for all the IHEP-IME sensors(~20000).
- Sensor production delivered in five batches(every 3 months), is scheduled to be completed next year.