IHEP-IME radiation hard LGAD sensor pre-production for ATLAS High granularity timing detector

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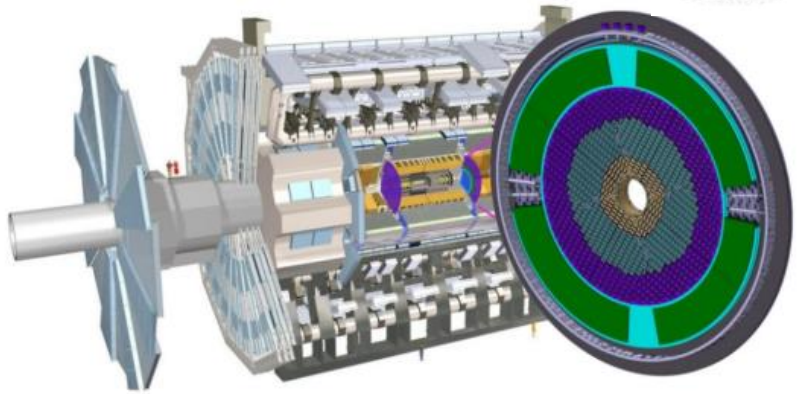
Outline

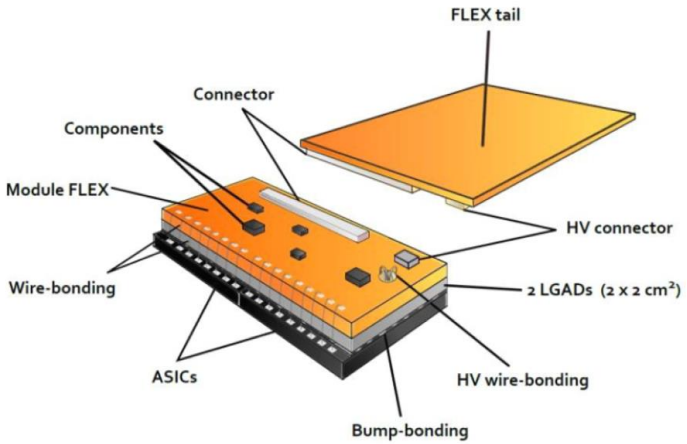
- LGAD sensor for HGTD
  - HGTD project
  - LGAD for HGTD
- IHEP-IME LGAD sensor R&D
- IHEP-IME LGAD sensor pre-production
- Summary

HGTD detector

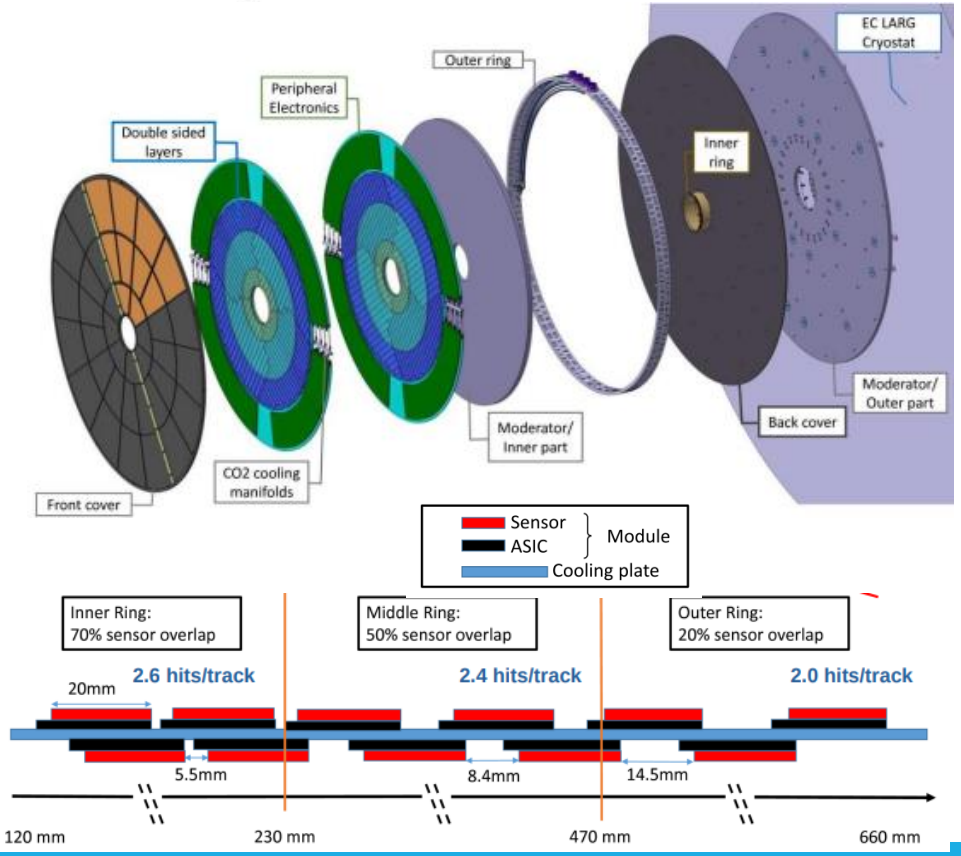
- The High Granularity Timing Detector (HGTD) is designed to provide precise timing information to solve the increased pile-up in HL-LHC.
  - ~3.6 million 1.3×1.3 mm^2 pixels(channels)
    - 6.4 m^2 active area
  - Time resolution target
    - 35-70 ps/hit up to 4000fb^{-1}
  - Luminosity measurement
    - Goal for HL-LHC: 1% luminosity uncertainty



- **8032 modules, each module:**
  - consists of two hybrids (2 sensors+ 2 ASICs)
  - 2x4cm^2, 15x30 channels



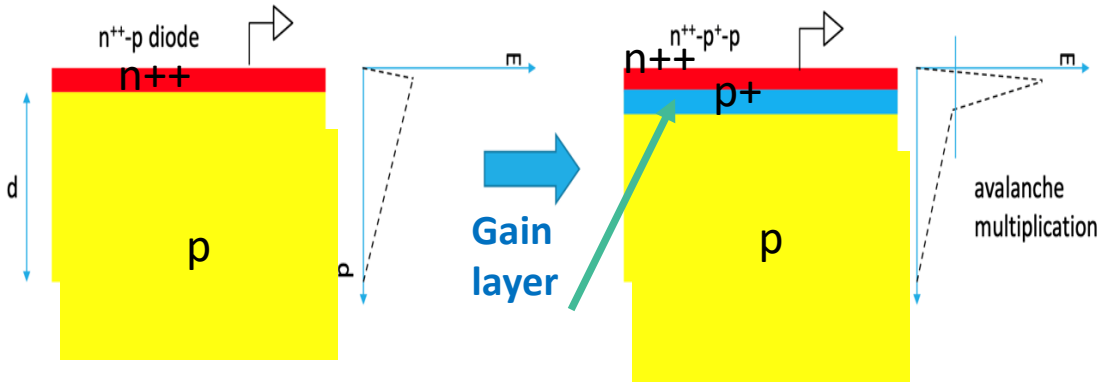
- **~21000 LGAD sensors**
  - 15x15 array
  - Pixel size: 1.3mmx1.3mm



LGAD sensor

➢ **Low Gain Avalanche Detectors (LGAD)： good timing resolution(<35ps)**

- Work in linear mode, Gain:10~50
- Thin depleted region(~50um) to decrease t_{rise} (fast timing)
- Good Signal/Noise ratio, no self triggering



➢ LGAD technology is chosen as detector for HGTD project.

Requirement：

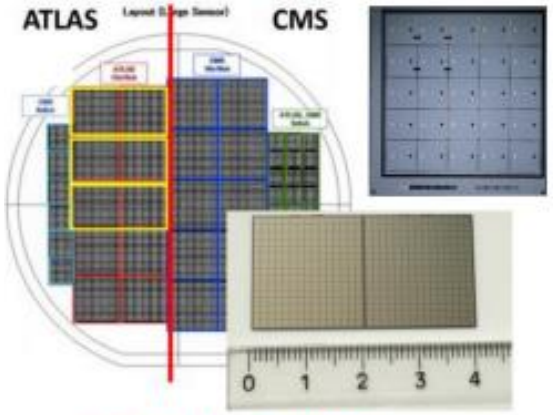
- Size: 15x15 array, 1.3x1.3mm^2 pixel size
- Active thickness: 50um(Thin: faster rise time, lower impact from radiation)
- LGAD sensor can withstand the lifetime of the HL-LHC running: irradiation requirement

  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: 35ps (start), 70ps (end) per hit, while 30ps (start), 50ps (end) per track
- Collected charge per hit >4fC (minimum charge needed by the ASIC to hold good time resolution)
- Hit efficiencies of 97% (95%) at the start (end) of their lifetime

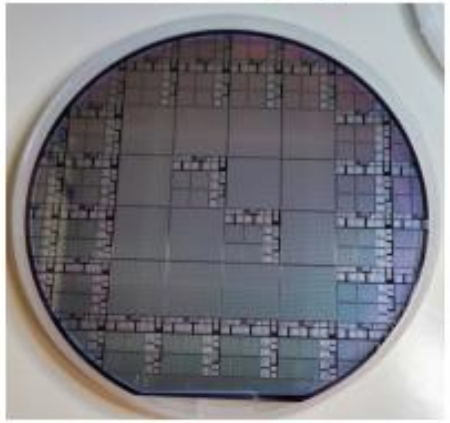
LGAD sensor for HGTD

- LGAD sensors from many vendors have been extensively studied during the R&D phase of the HGTD project.
- Active vendors include: HPK (Japan), FBK (Italy), CNM (Spain), IHEP-IME (China), USTC-IME (China), IHEP-NDL (China) …

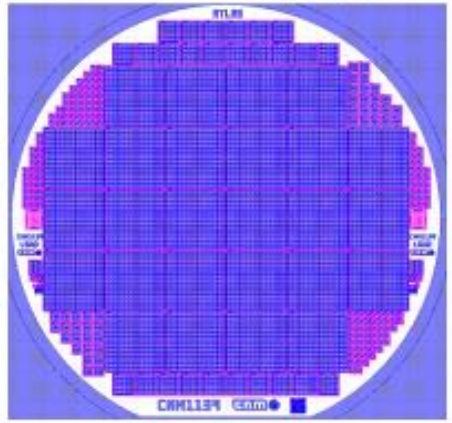
HPK-P2 (2022)



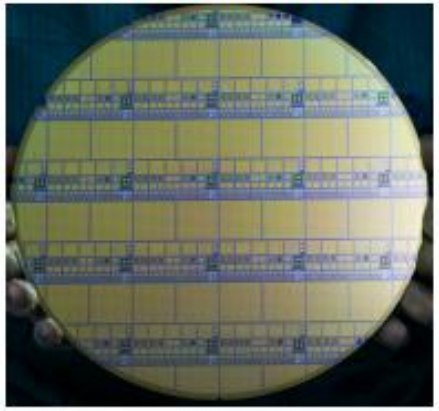
FBK-UFSD 4.0 (2022)



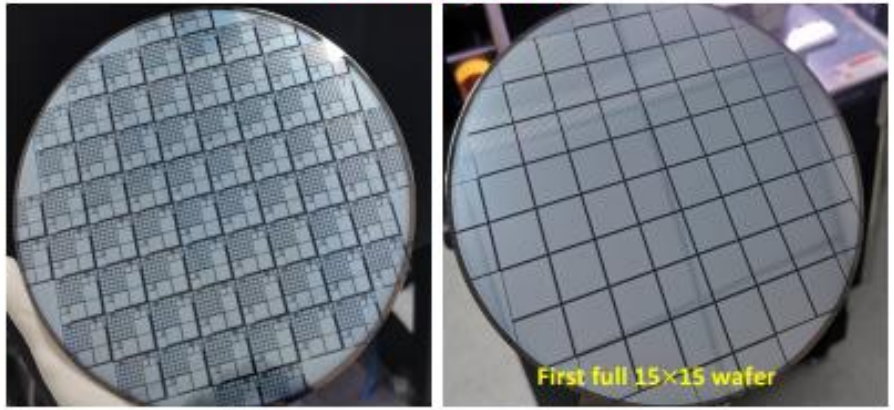
CNM Run 15973 (2022)



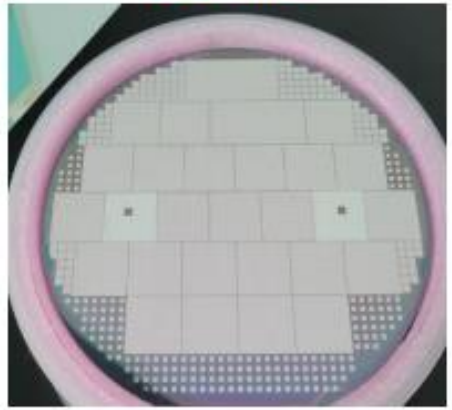
IHEP-IME-v2 run (07/2022)



USTC-IME-v2 (14/2021)



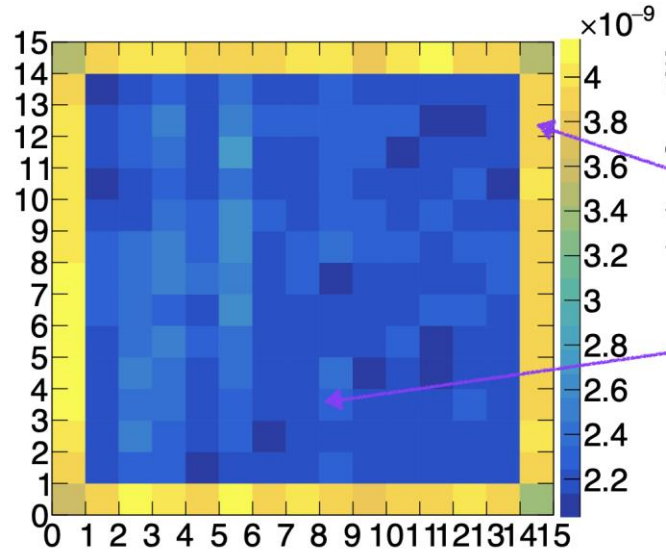
NDL-v4 (2021)

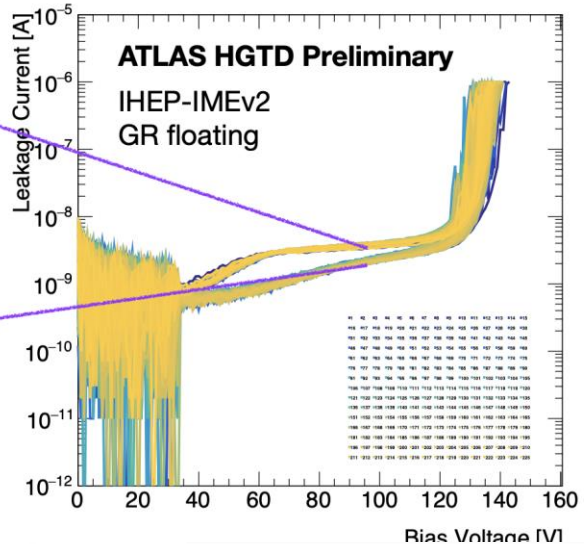


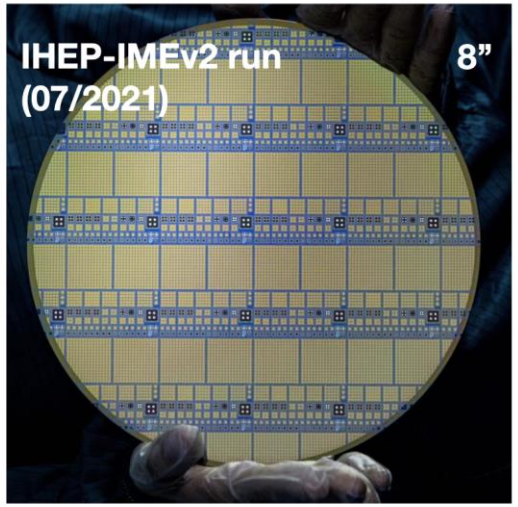
LGAD sensor for HGTD

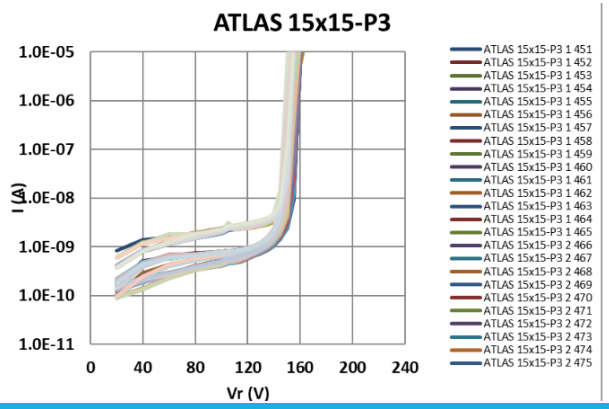
➢ Good uniformity of full size LGAD prototype (15x15 channels)

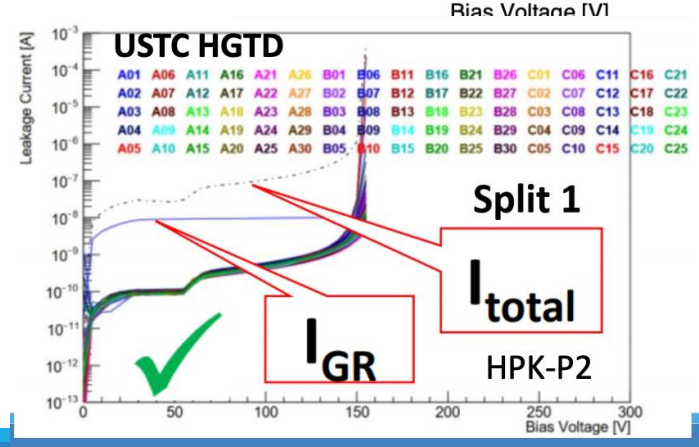
- HPK, FBK, IHEP-IME, USTC-IME, CNM have produced good full-size LGAD prototype.

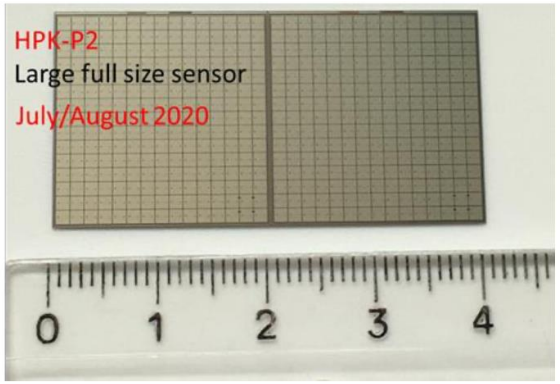










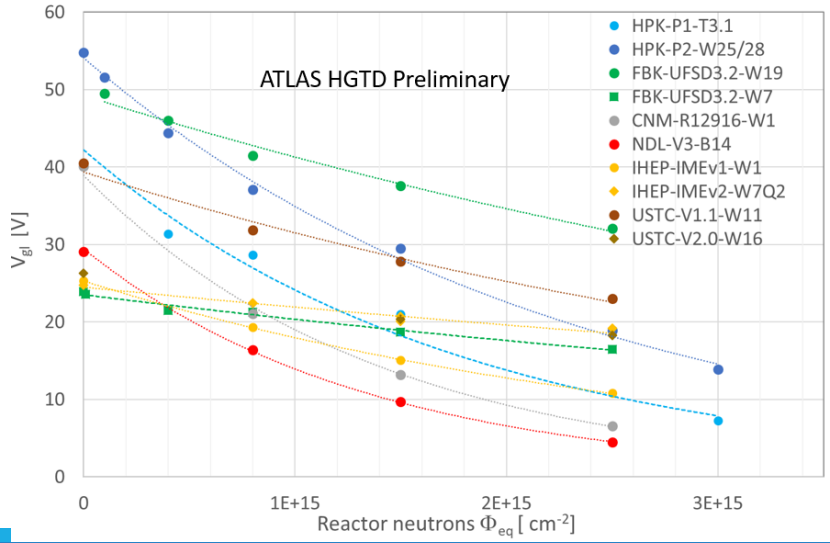


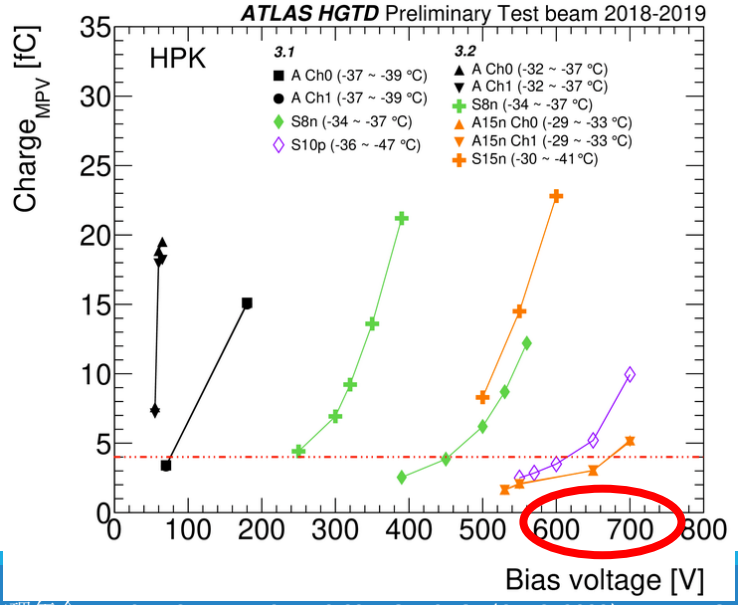
LGAD sensor after Irradiation

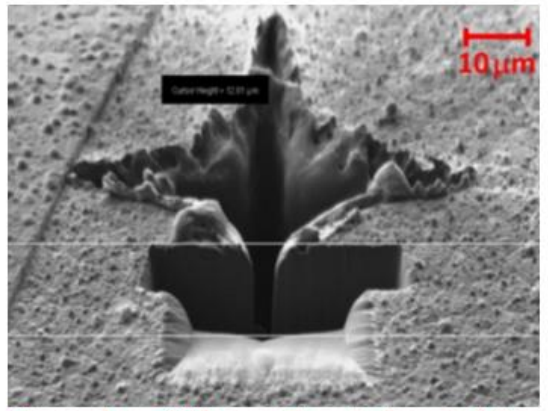
- **Main challenge: Radiation Hardness**
- Boron doping in gain layer became less active after irradiation（**acceptor remove**）
- Key parameter of the gain degradation is the acceptor removal coefficient: *c factor*

$$V_{gl} = V_{gl0} \times \exp(-\boldsymbol{c} \times \Phi_{eq})$$

- Irradiated sensors require higher bias voltage to maintain performances.
- Single Event Burnout (SEB) Occur- when irradiated sensors 2.5 x 10^{15} n_{eq}/cm^2) operated with high bias voltage



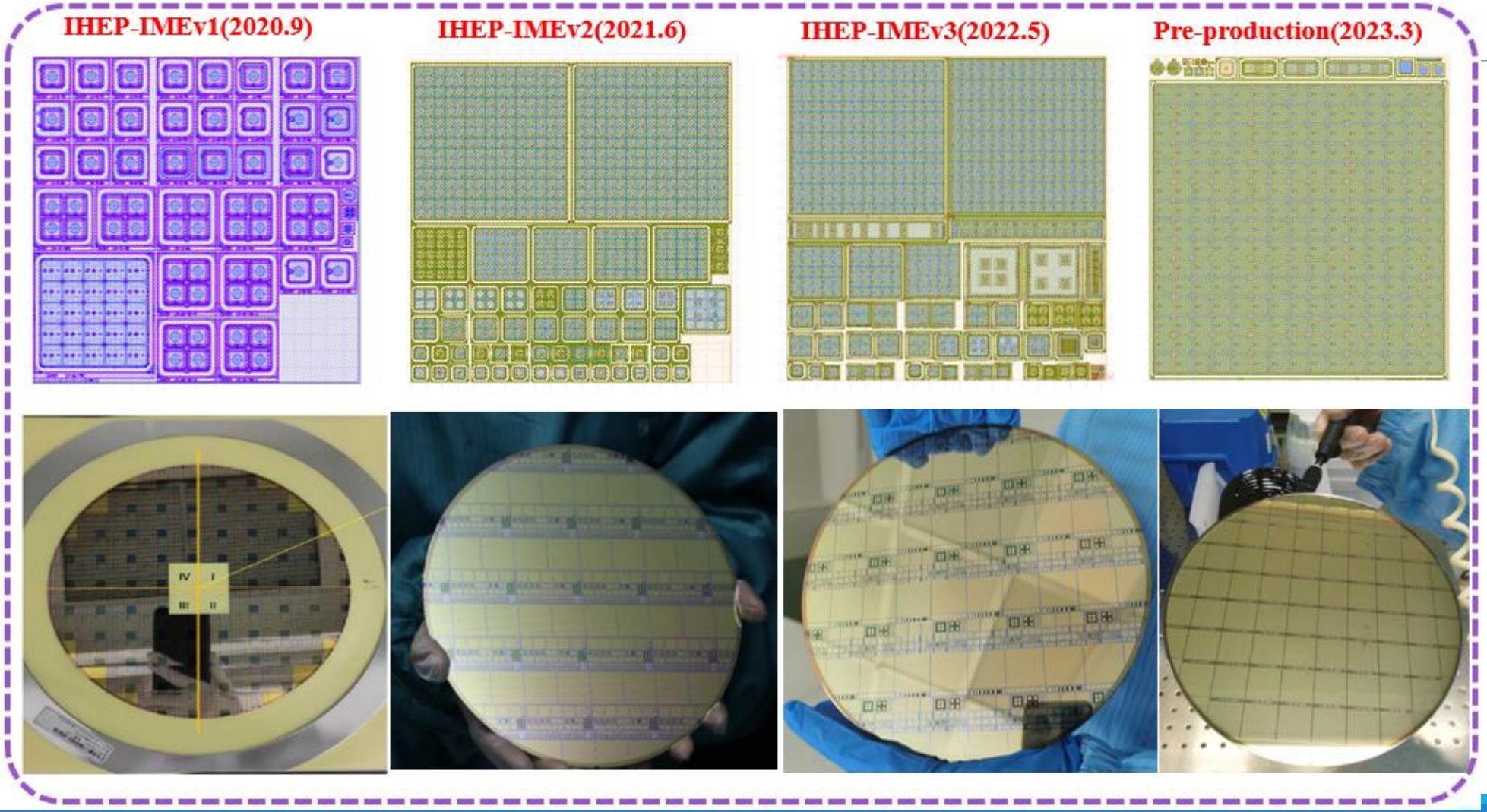




Burn mark on a CNM sensor after proton beam irradiation in Fermilab in 2018 (picture produced by CNM)

- RD50, CMS and ATLAS confirmed Single Event Burnout (SEB) effect in testbeam.

IHEP-IME LGAD sensor R&D



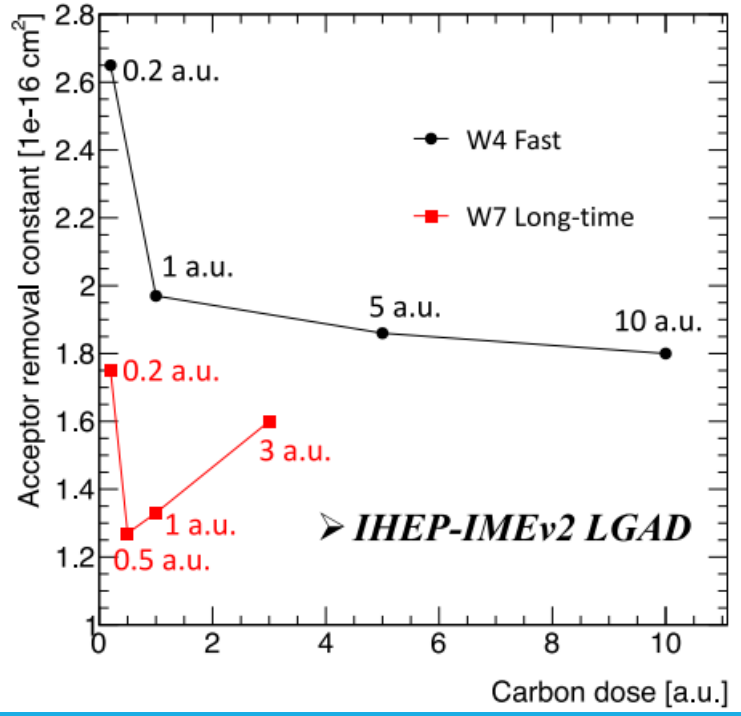
IHEP-IME LGAD sensor R&D

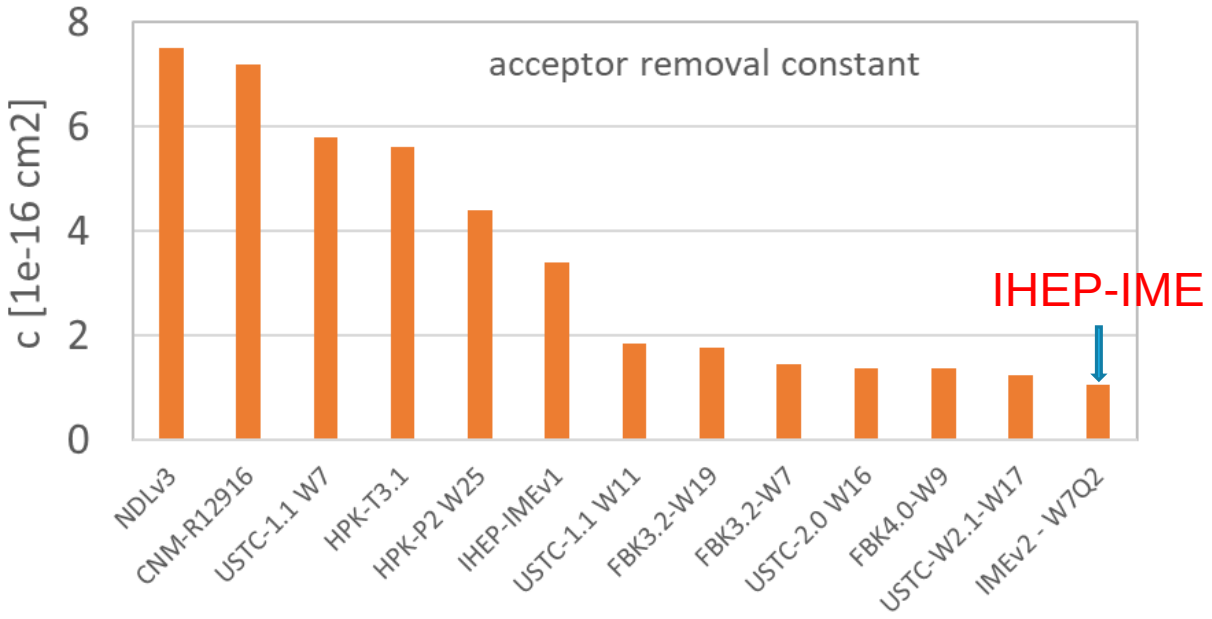
➢ To improve the radiation hardness of LGAD(reduce c factor):

- Design of gain layer： changing the doping concentration

  adding the Carbon to gain layer(doping dose and thermal treatment)

➢ IHEP-IME carbon enriched sensors show very low acceptor removal coefficient(1-2×10^{-16} cm^2), which would reduce the required voltage for enough charge collection and avoid the SEB.



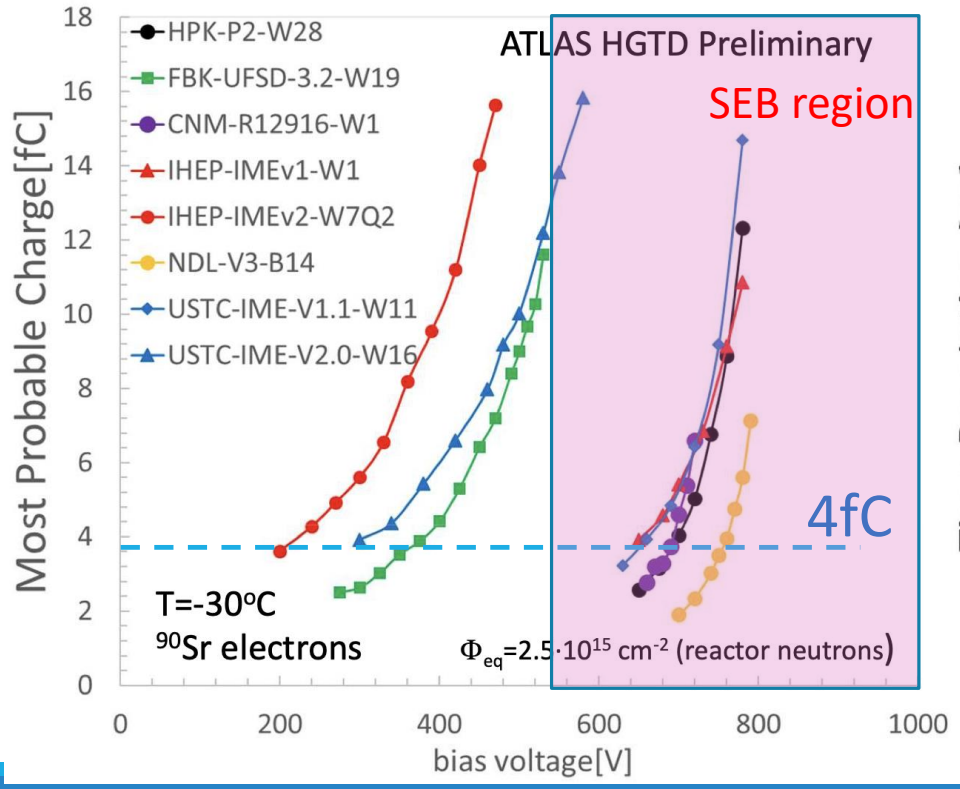


IHEP-IME LGAD R&D: laboratory test

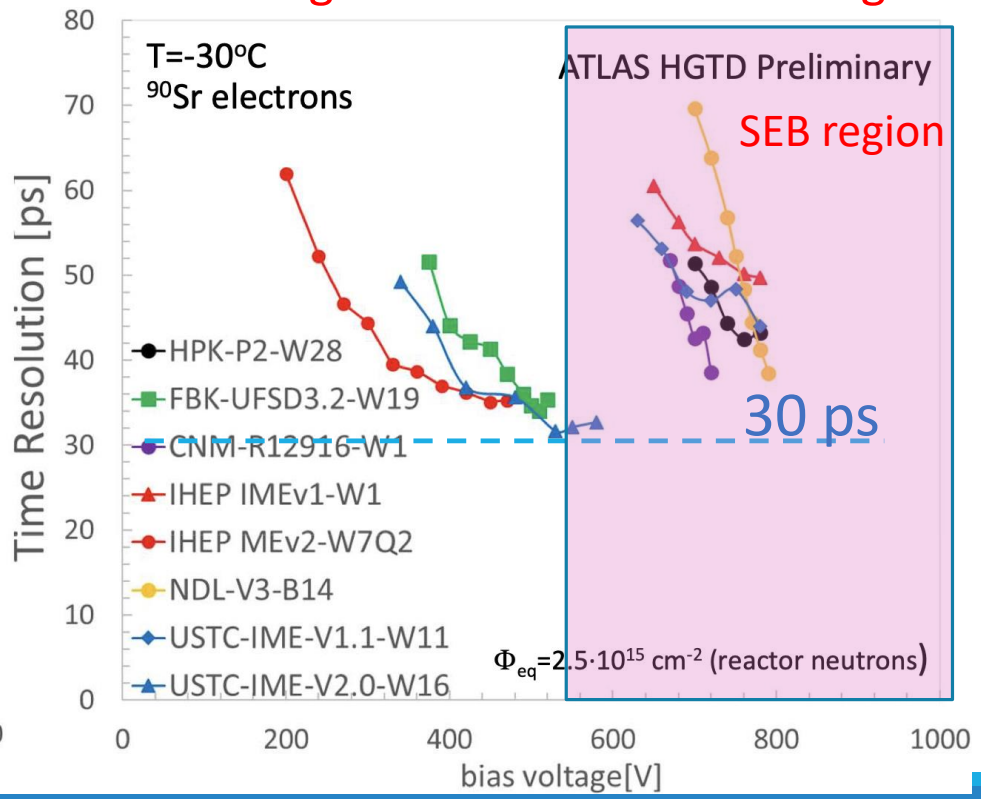
- IHEP-IME sensors with carbon enrichment show good enough **CC/timing after 2.5×10^{15} n_{eq}/cm^2** at voltage less than SEB requirement.

- These sensors performs good enough over the entire lifetime of the experiment.

Time resolution of LGADs Vs Bias Voltage

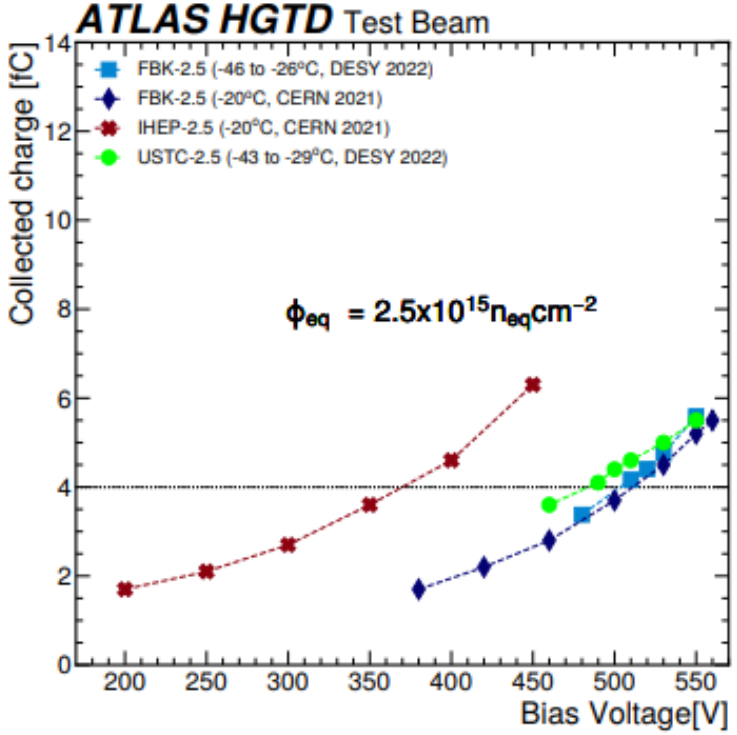


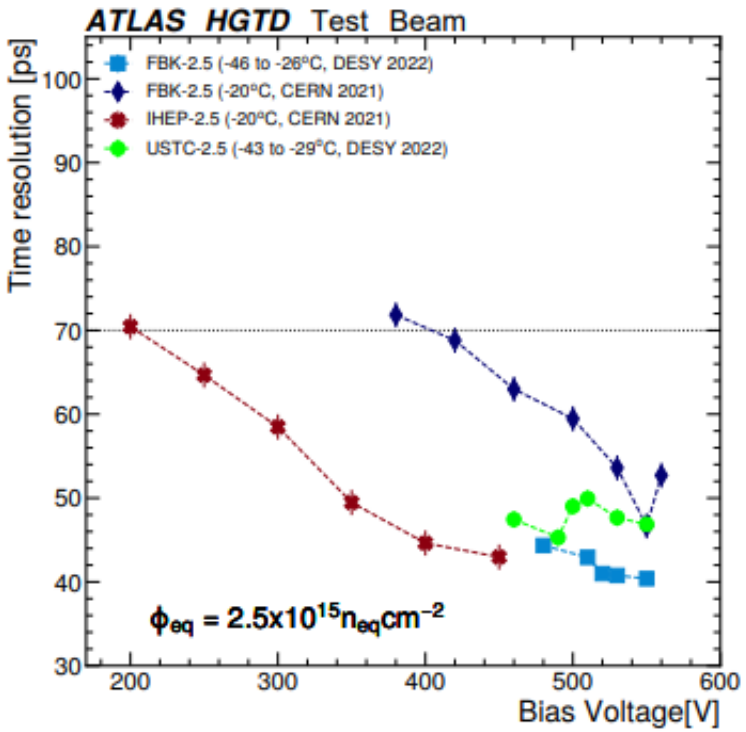
Charge collection Vs bias voltage

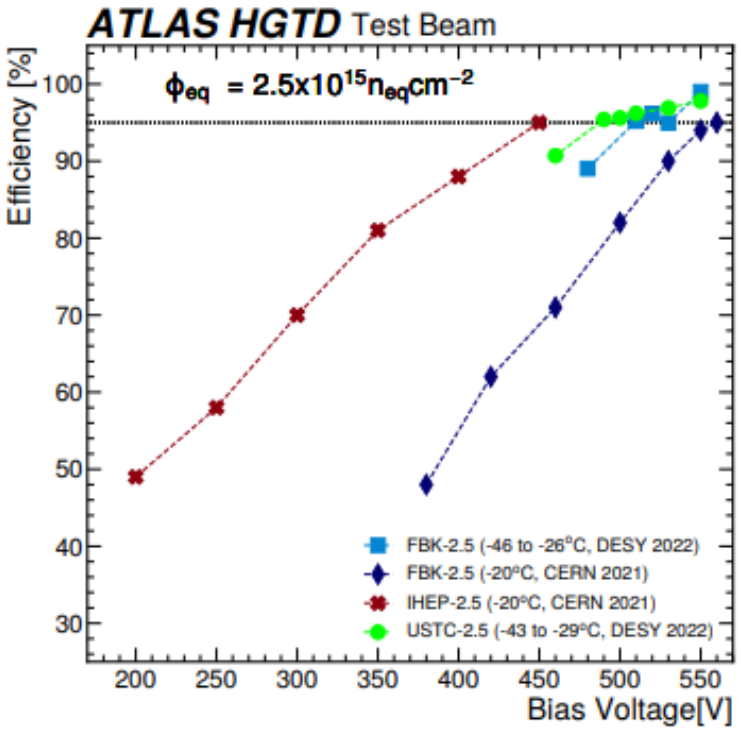


IHEP-IME LGAD R&D: beam test

- IHEP-IME LGAD sensors can collect 4fC charge (minimum charge needed by the ASIC to hold good time resolution) at voltage lower than 550V(SEB safe zone).
- IHEP-IME Carbon enriched sensors have <50 ps timing resolution after 2.5x10^{15} n_{eq}/cm^2.
- IHEP-IME LGAD sensors can achieved the efficiency of 95%, which is required for good operation of the future HGTD after irradiation.







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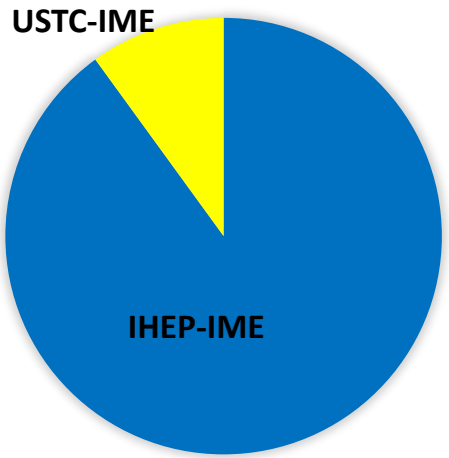
LGAD sensor production for HGTD

- HGTD project of ATLAS needs ~21,000 LGAD sensors
- LGAD developed by IHEP got all the share of the order from CERN tendering

  (totally 90% sensors will be produced by IME according to IHEP design)
- Two Chinese vendors (IHEP/USTC) have 100%
- IHEP-IME LGAD sensors pre-production for HGTD project is ongoing, 5 batches of LGAD sensors be fabricated.



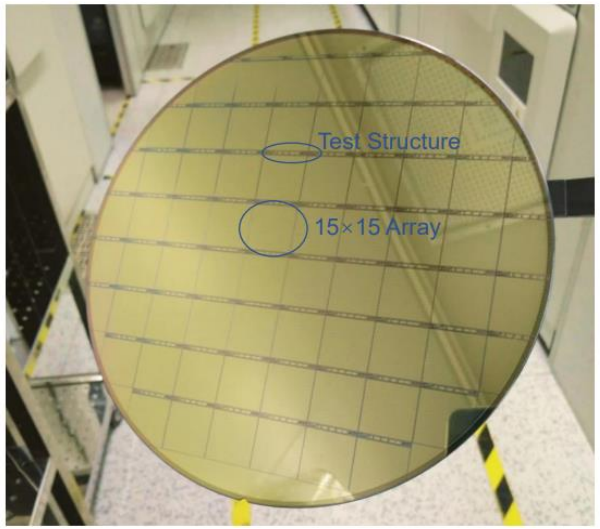
Production：

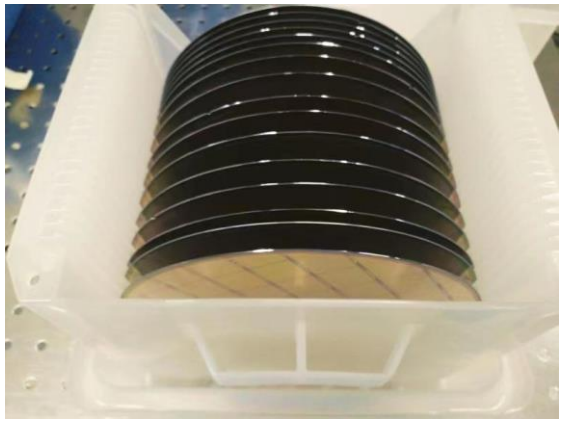
IHEP-IME：

24%(in-kind)

66%(CERN procurement)

USTC-IME: 10%(in-kind)





- 15x15 array sensors and test structure
- 52 sensors on one 8inch wafer

IHEP-IME LGAD sensor pre-production

- IHEP-IME pre-production: ~110 8inch wafers be processed, now 90 wafers be fabricated.
- Wafer testing: 22 wafers be tested
- Good yield，~600 good sensors be fabricated from these wafers(~32 good sensors/wafer)
- 4 wafers be diced for irradiation testing

  2 wafers be sent for UBM and bonding with ASIC

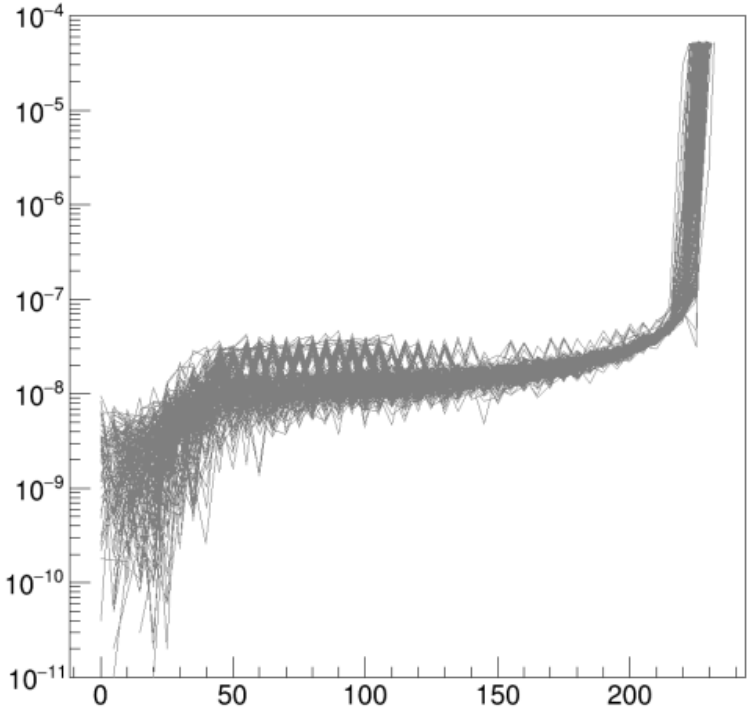
Number	IME Number	V_{BD}	RMS	Sensor Yield	Pad Yield	Threshold (V)
1	GNS4-R-2	212.7	21.21	19/52	99.07%	150
2	GNS4-R-3	222.5	19.79	25/52	99.20%	150
3	GNS4-A-16	196	16.57	18/52	98.76%	150
4	V4-02-12	180.8	10.50	39/52	99.53%	150
5	GNS4-A-15	218.4	21.16	25/52	99.60%	150

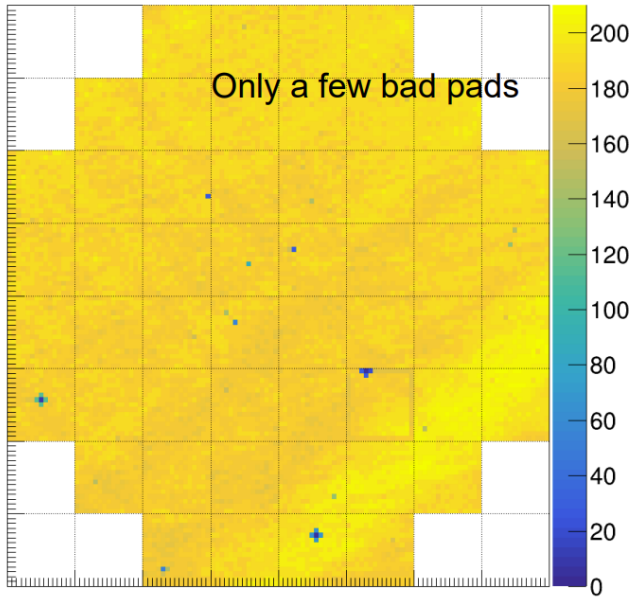
Number	V_{BD}	RMS	Sensor Yield	Pad Yield	Threshold (V)
1	**229.7** $_{MAX}$	23.84	28 (53.8%)	>97%	175
2	188.0	**8.20** $_{MIN}$	**46 (88.5%)** $_{MAX}$	>99%	150
3	**132.6** $_{MIN}$	10.51	44 (84.6%)		100
4	191.5	12.65	32 (61.5%)		150
5	190.2	18.77	41 (78.8%)		150
6	186.2	11.91	40 (76.9%)		150
7	188.3	13.92	37 (71.2%)		150
8	193.2	14.89	25 (48.1%)		150
9	189.4	31.1	27 (51.9%)		150
10	198.8	13.48	22 (42.3%)	>95%	150
11	174.3	15.05	30 (57.7%)		135
12	177.2	**46.56** $_{MAX}$	**17 (32.7%)** $_{MIN}$	91.6%	135
13	192.2	23.58	33 (63.5%)	>99%	150
14	195.6	12.57	35 (67.3%)		150
15	195.7	11.75	34 (65.4%)		150
16	192.7	18.65	35 (67.3%)		150
17	189.0	33.37	35 (67.3%)		150

IHEP-IME LGAD sensor pre-production

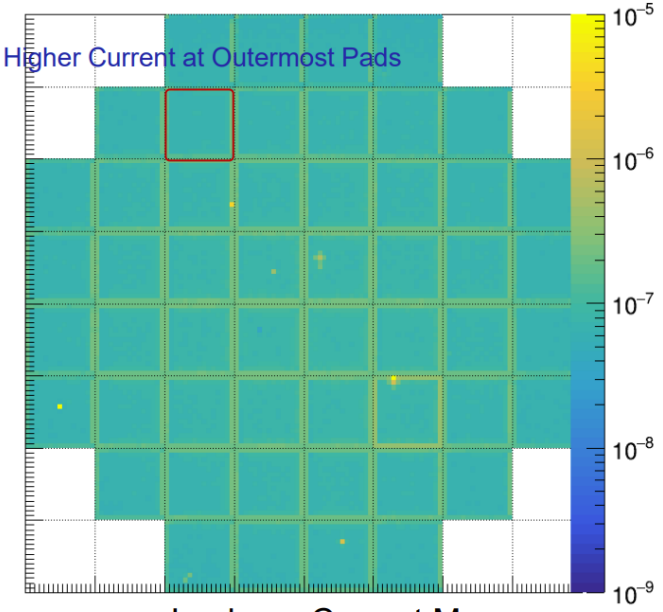
Good uniformity of full size LGAD sensor from pre-production:

IV performance, Breakdown voltage, and leakage current





Break-down Map

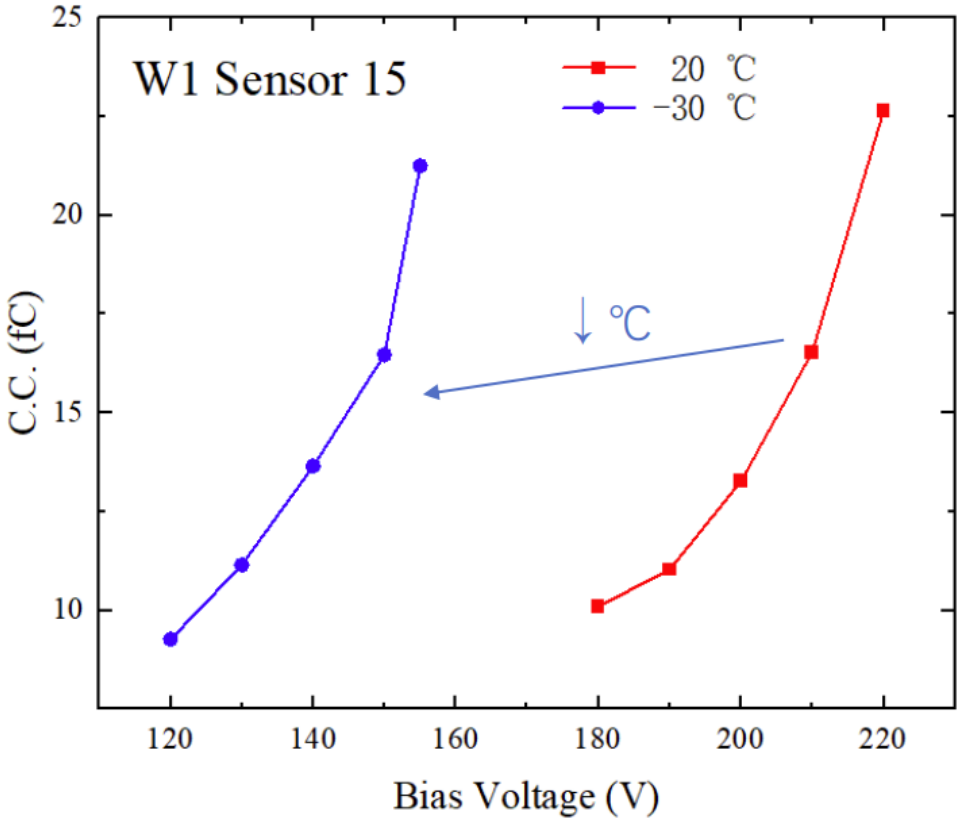


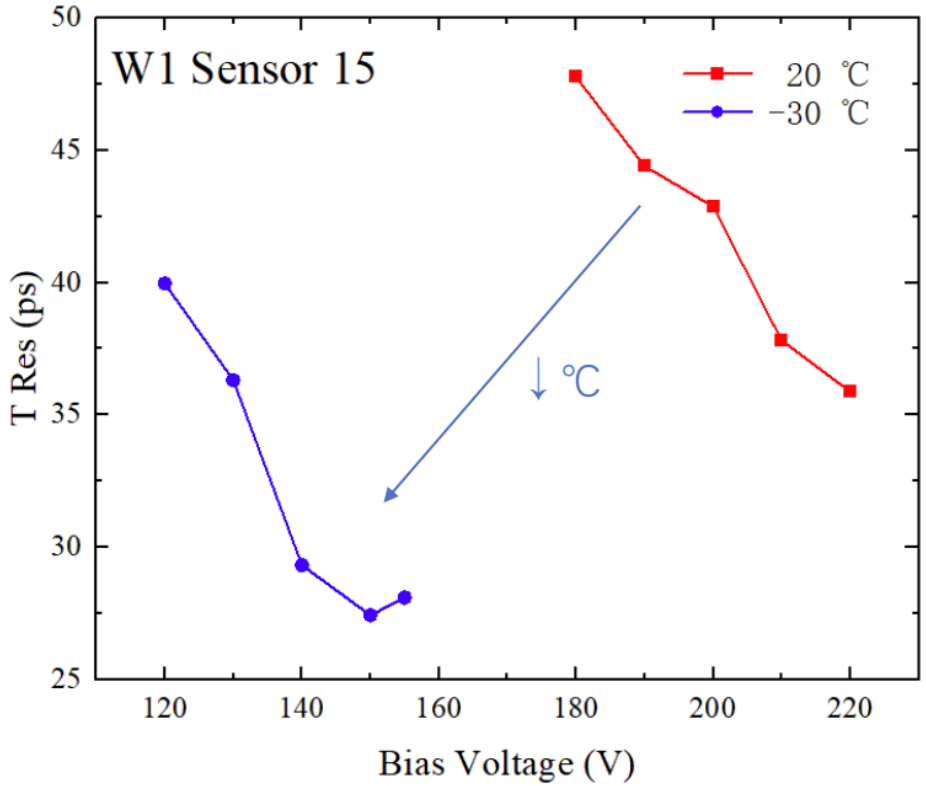
Leakage Current Map

Break-down Voltage: 188.0±8.53 V
Leakage Current: 9.3E-8 A
Yield:
Sensor: 46(88.5%) Pad: 11675 (99.8%)

IHEP-IME LGAD sensor pre-production

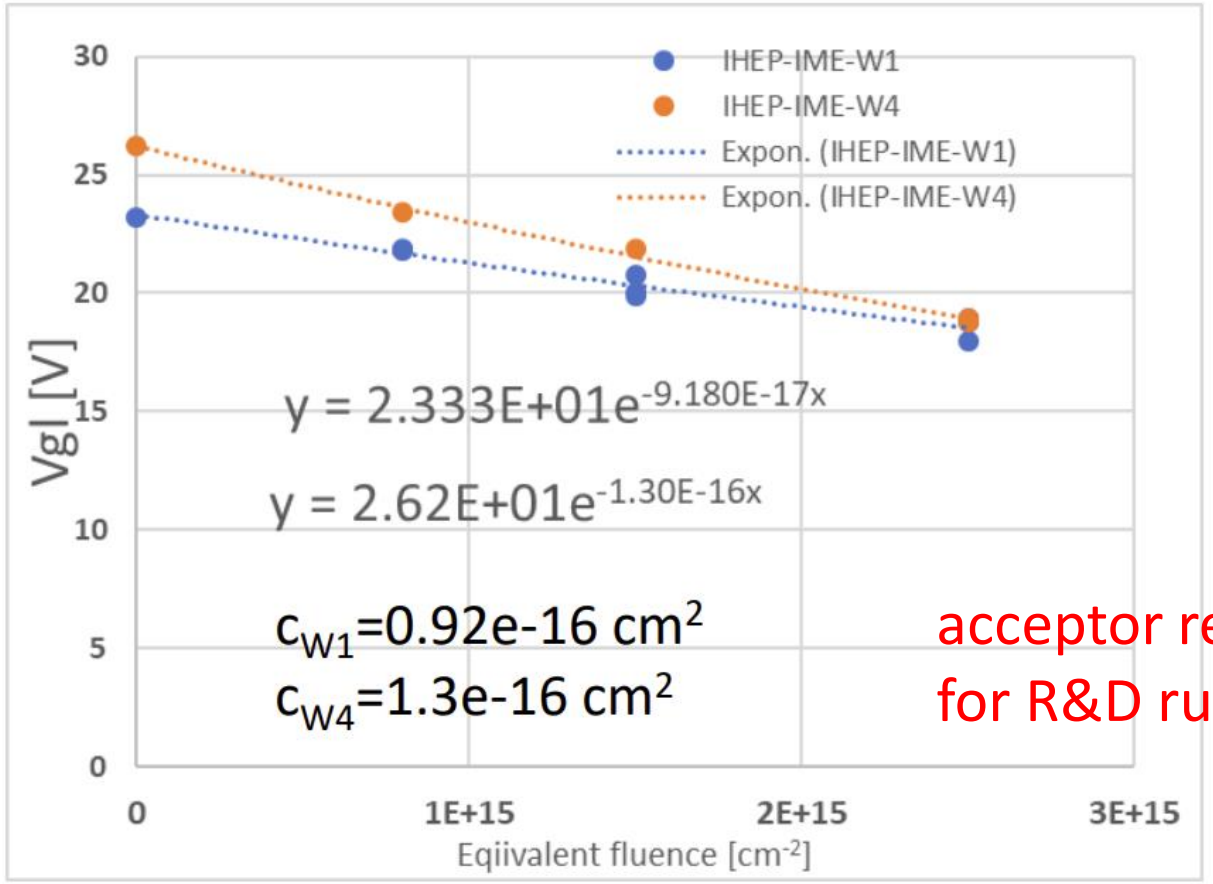
- Before irradiation, sensors from W1 can collect >15fC charge and reach <35ps timing resolution.





IHEP-IME LGAD sensor pre-production

- Preliminary results of IHEP-IME sensors from pre-production show comparable irradiation performance with R&D run.

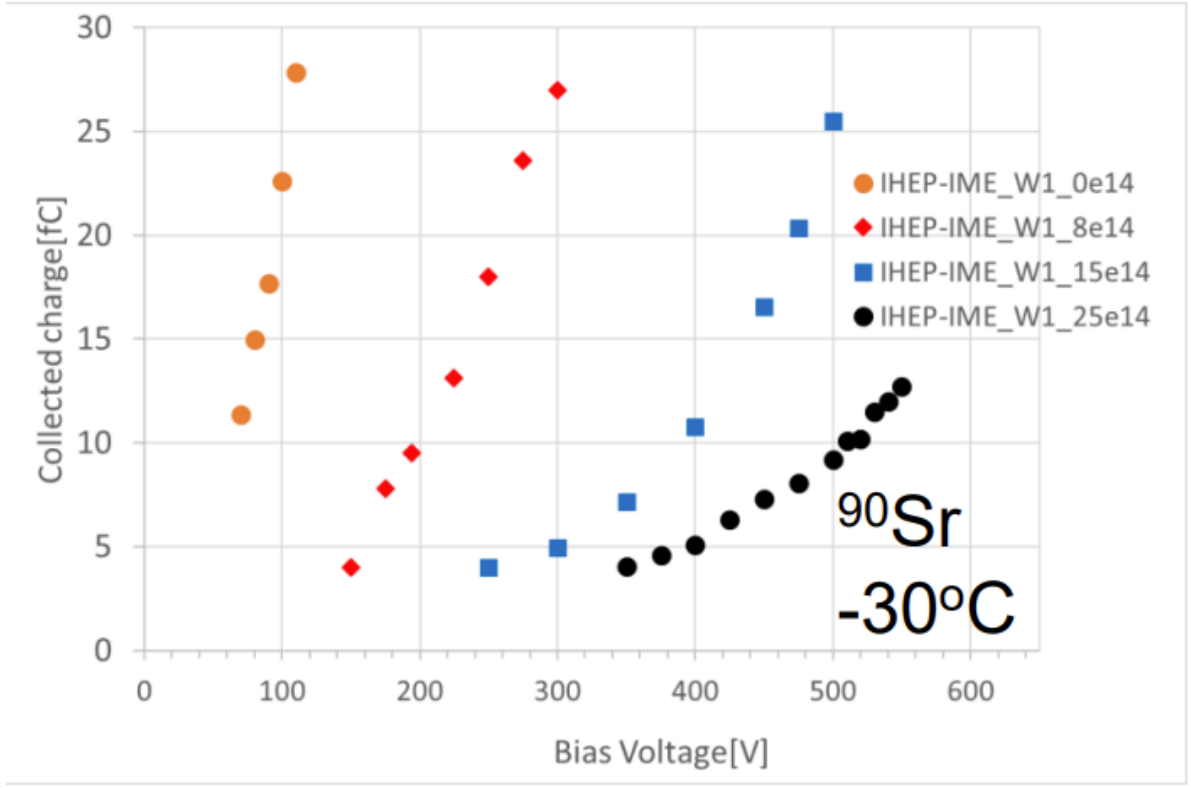


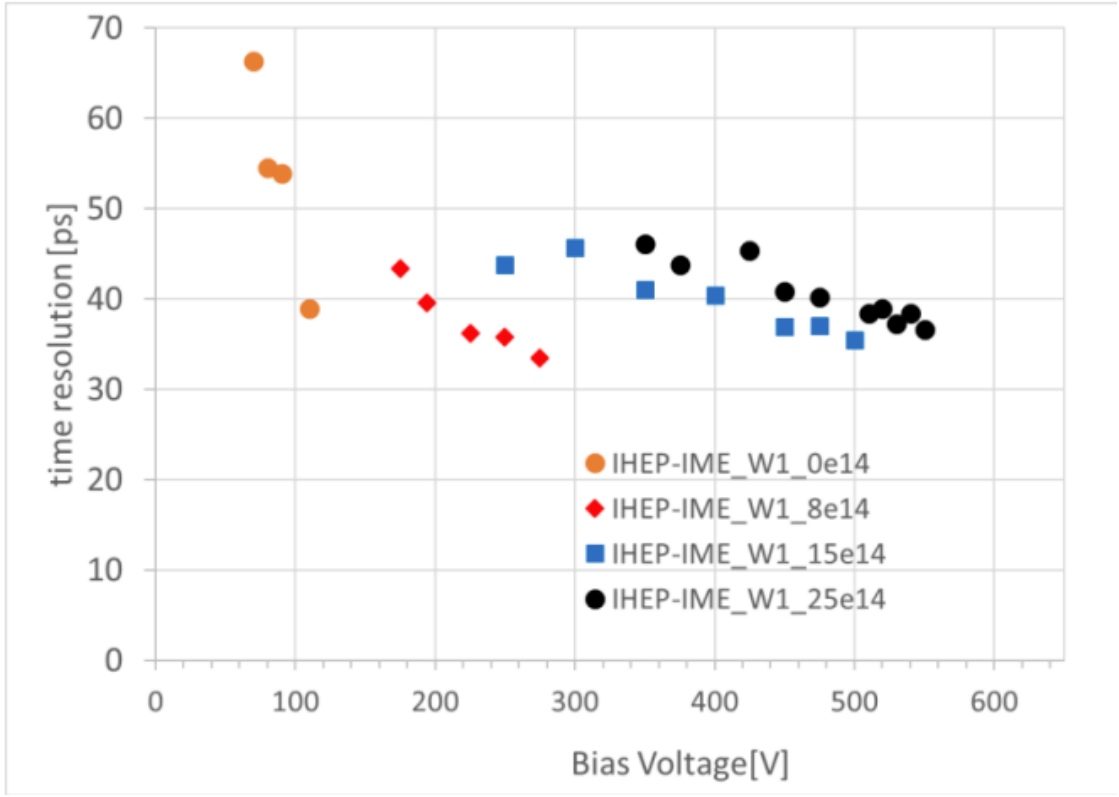
acceptor removal coefficient for R&D run:1.07e-16 cm^2

IHEP-IME LGAD sensor pre-production

After neutron irradiation: 2.5x10^{15} n_{eq}/cm^2

- IHEP-IME pre-production sensors can collect 4fC charge (minimum charge needed by the ASIC to hold good time resolution) at voltage lower than 400V(SEB safe zone).
- IHEP-IME pre-production sensors have <40 ps timing resolution.





Summary

➢LGAD is chosen as sensors for HGTD project as it has good time resolution <30ps to improve pile-up.

➢IHEP-IME LGAD sensor R&D

- Carbon enriched LGAD sensors show good radiation performance. The sensors fill the HGTD requirement, including charge collection, time resolution and hit efficiency.

Irradiated sensors work at lower than 550V, Collected charge> 4fC, Time resolution better than 50 ps, An efficiency larger than 95%

➢IHEP-IME LGAD sensor pre-production

- ~110 wafers be processed. Until now, ~600 good sensors be fabricated(24 wafers).
- Good uniformity of full size LGAD sensor from pre-production
- IHEP-IME sensors from pre-production show comparable irradiation performance with R&D run.

After irradiation, IHEP-IME pre-production sensors can collect 4fC charge and have <40 ps timing resolution at voltage lower than 400V(SEB safe zone).

- Sensor bonding with ASIC ongoing, testing will be done next.