Ongoing development on LGAD

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outline

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Development of standard LGAD

Introduction of standard LGAD

Ongoing development of standard LGAD for HL-LHC

Development of IHEP LGAD sensors

Development of AC-LGAD

AC-LGAD vs standard LGAD

Performance of AC-LGAD

Performance of IHEP AC-LGAD Us

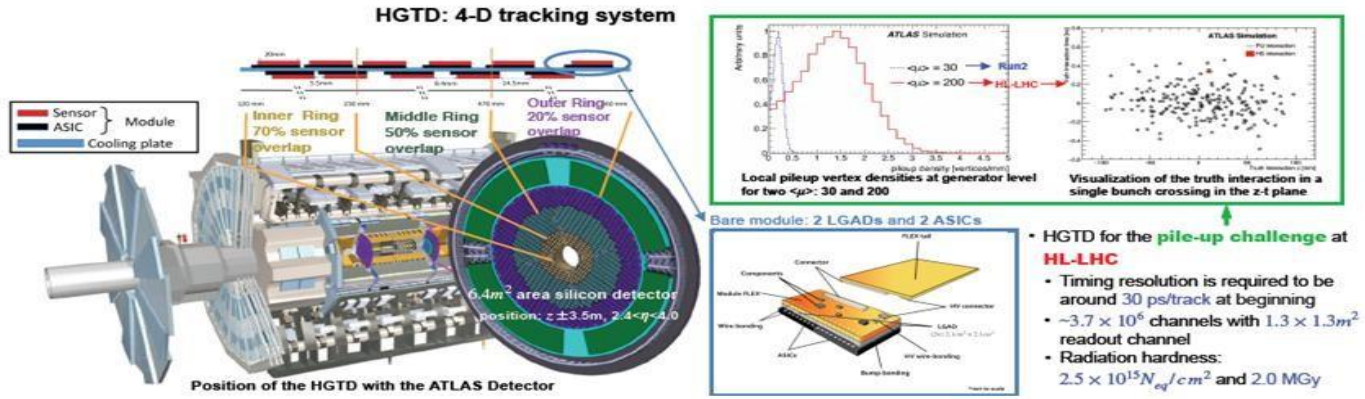
e AC-LGAD for CEPC

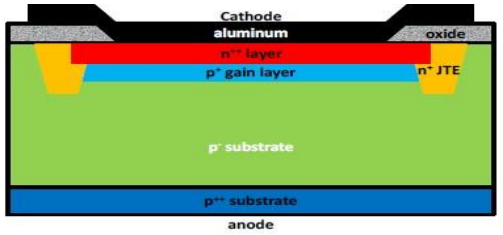
Summary

LGAD-timing detector

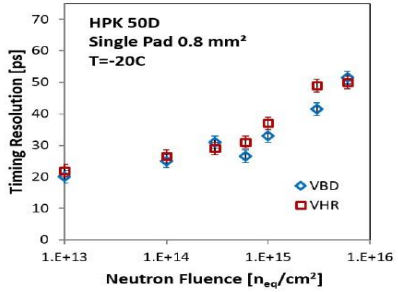
Low Gain Avalanche Detectors(LGAD) is an avalanche PN diode which work below breakdown voltage(liner mode) and with Gain >10 for effectively charge collection. Results show LGAD sensors have timing resolution better than 50ps .

Because of its good timing performance, LGAD has been chosen as sensors for tracking timing detectors, including ATLAS High Granularity Timing Detector (HGTD) project and CMS Endcap Timing Layer (ETL).





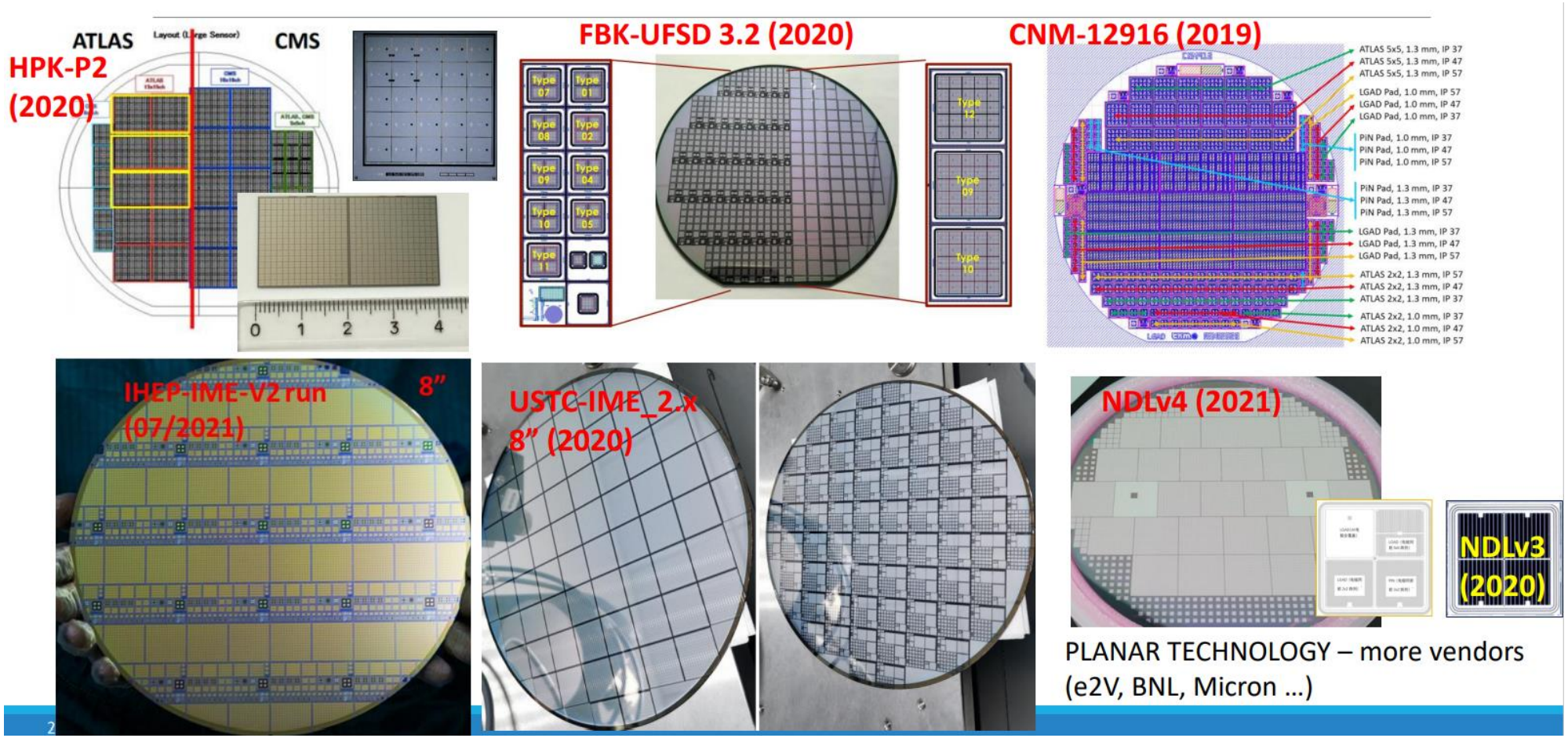
LGAD sensor structure



Timing resolution of LGAD sensors

LGAD-timing detector

Many semiconductor producers and institutes (HPK\FBK\CNM\IHEP\USTC\NDL\BNL) have done researched of LGAD for years



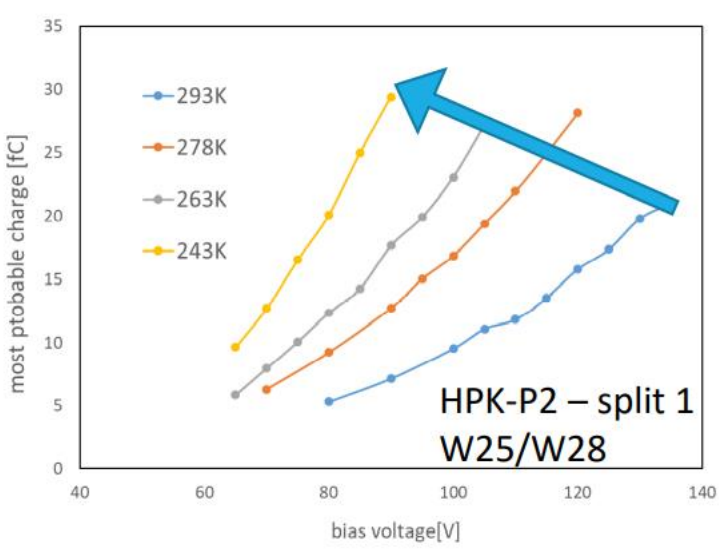
Performance of LGAD

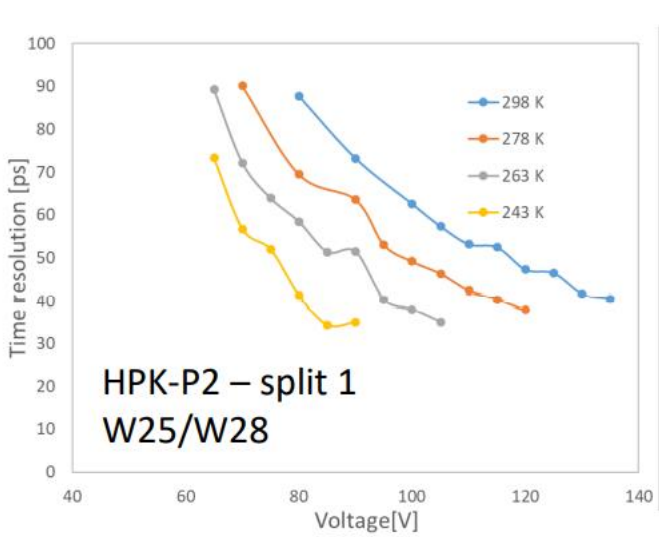
The key property is collection of 4 (ATLAS) /5 (CMS) fC at safe operation voltage over the entire lifetime of the experiments (2.5e15 cm^{-2}).

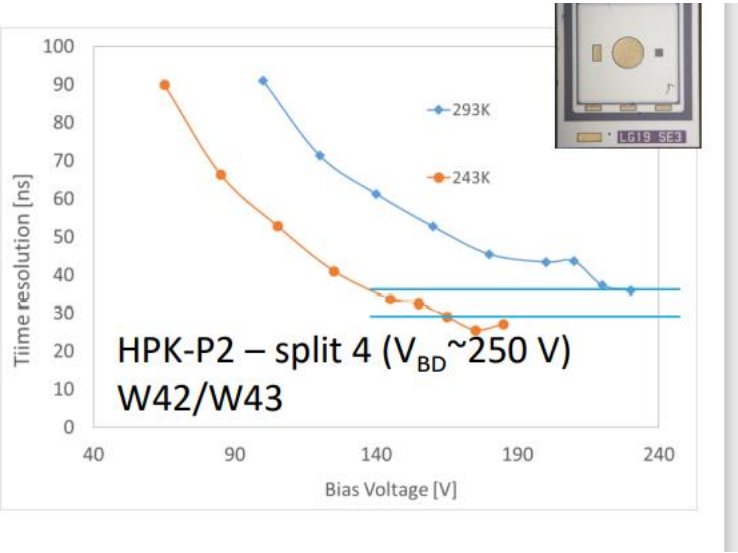
The timing resolution of many sensors all be lower than 50ps and can collect 4fC charge before irradiation.

Breakdown voltages at -30℃ are much lower than at room temperature (50-80 V)

Small difference in doping concentration results in very different performance



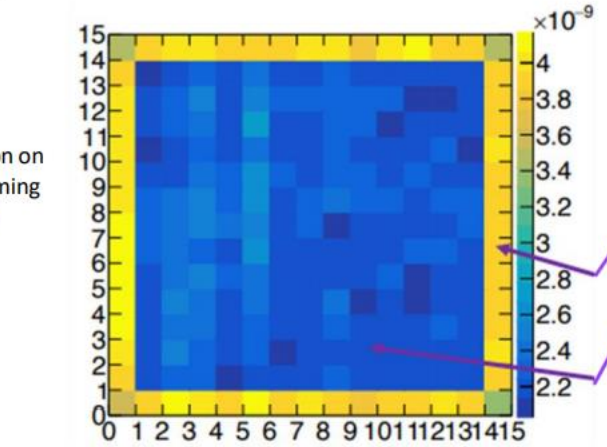


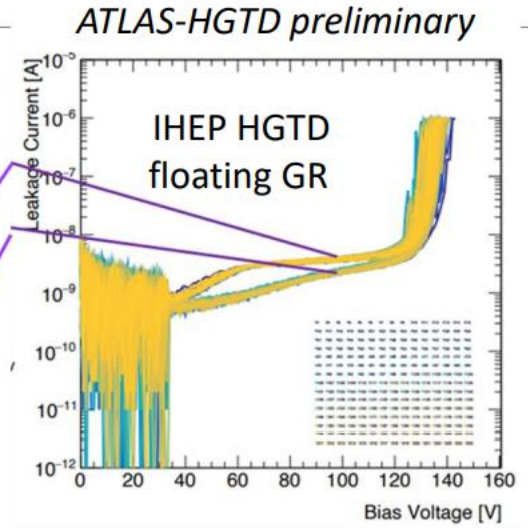


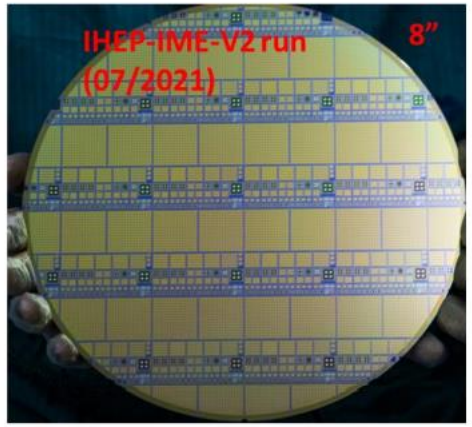
Full size devices

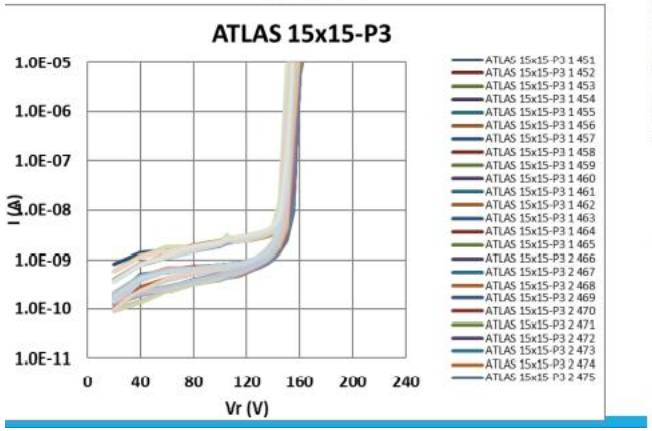
The production of uniform gain layer on large devices has been shown for several vendors.

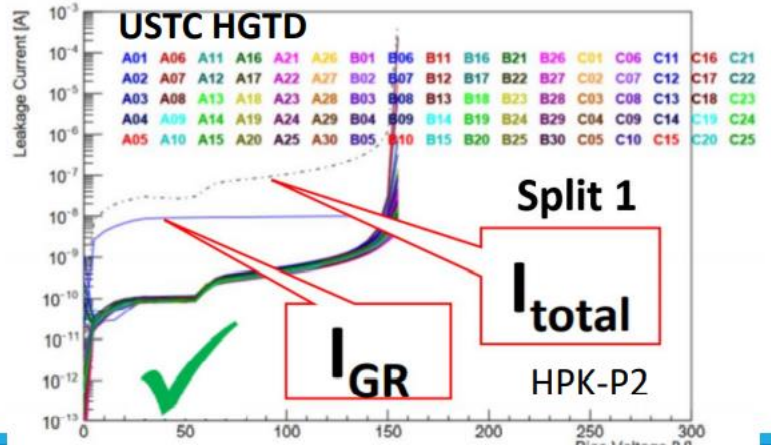
More information on IMEv2 at the coming RD50 workshop.

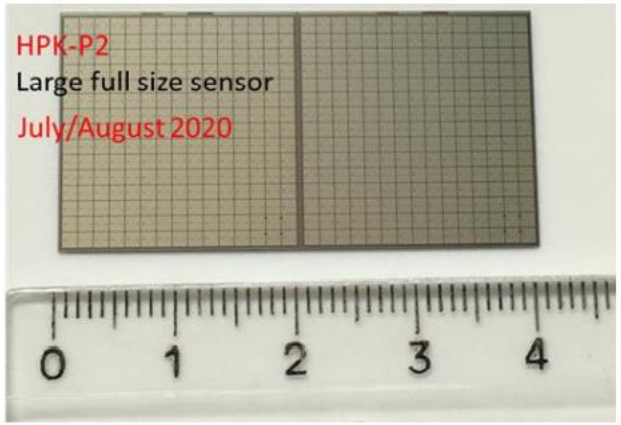








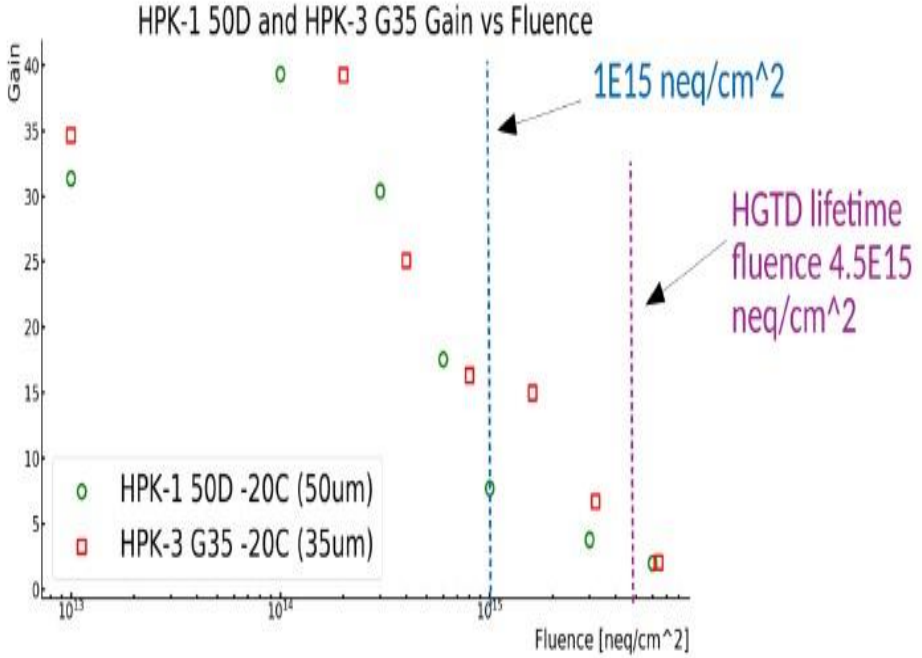


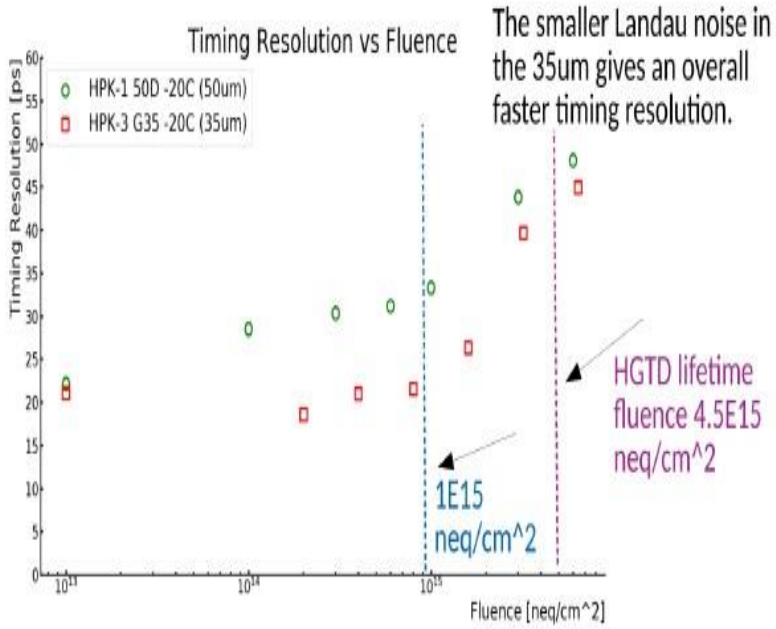


Performance of LGAD

After irradiation Issue:

high voltage needed to get enough charge after 2.5e15 n irradiation was large than 600V；
mortality problem during beam testing.



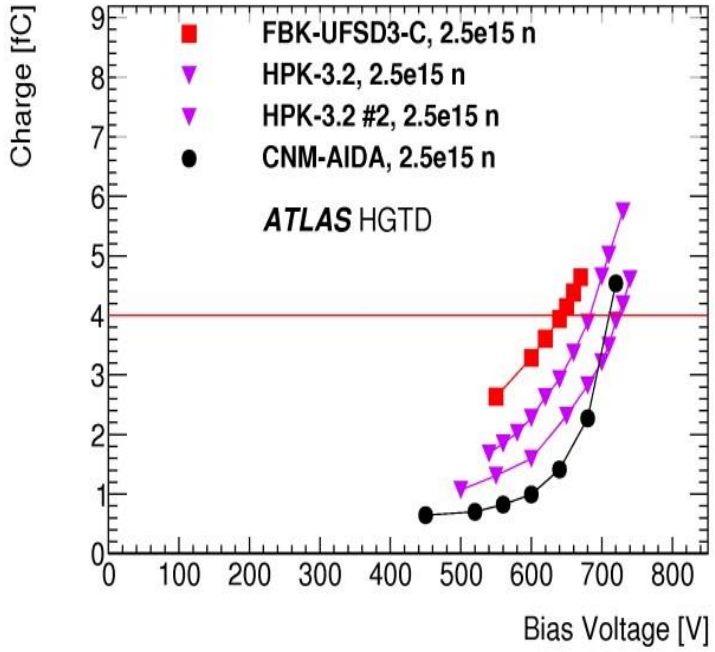


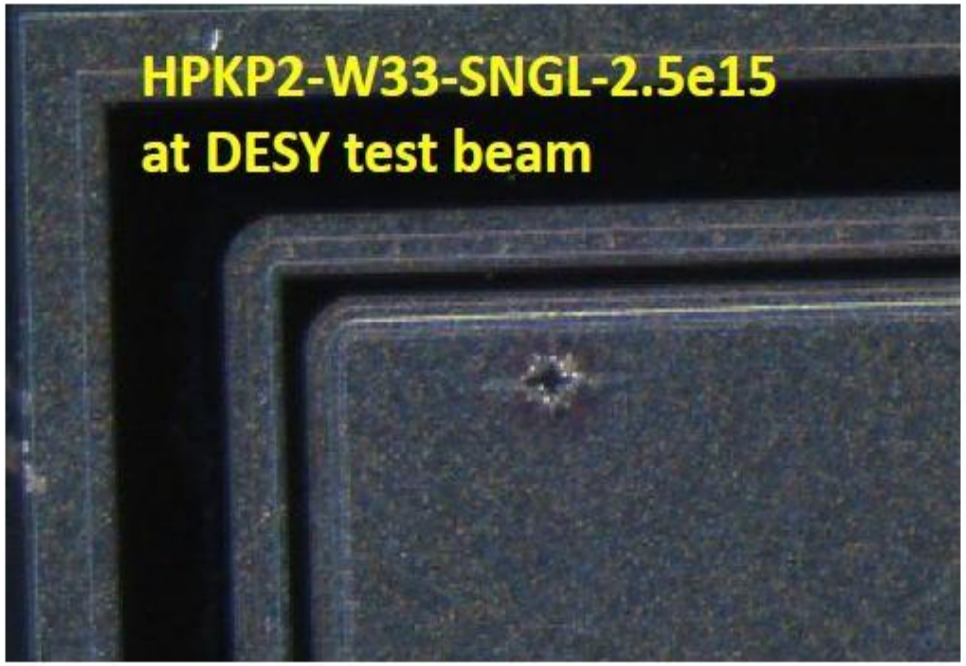
Gain decreases and timing performance change worse as increasing the irradiation fluence

Performance of LGAD

Higher than 600V voltage for 4fC charges (higher electrical field)

It is observed that destructive breakdowns of sensors at very high bias voltage ~600+/-50V for 50um thick detectors in the test beam



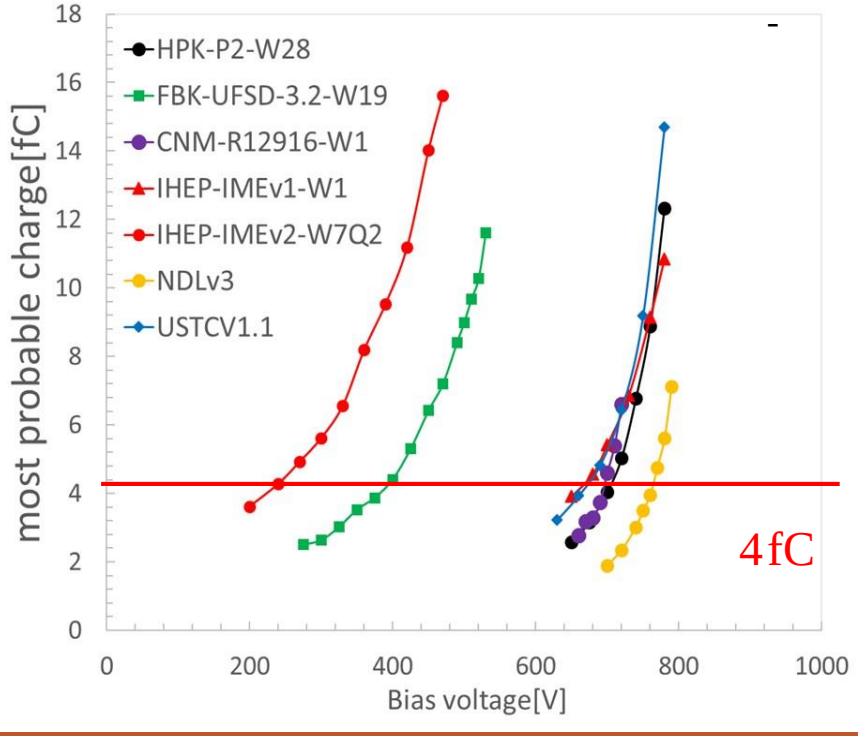


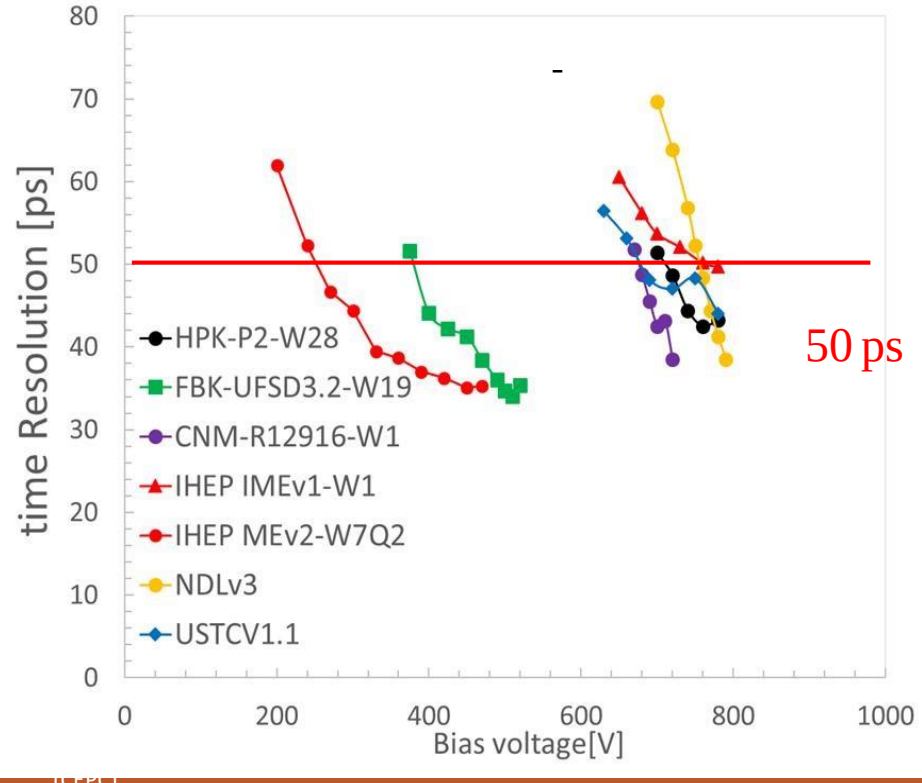
Performance of LGAD

Recent results of LGAD after neutron irradiation of 2.5e15 n_{eq}/cm^2

FBK and IHEP-IMEv2 sensors can collected 4fC at voltage <600V and timing resolution also be lower than 50ps

Beam testing of these sensors recently been done at CERN to check the mortality issues

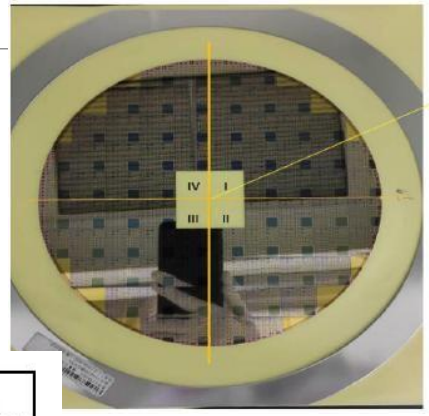


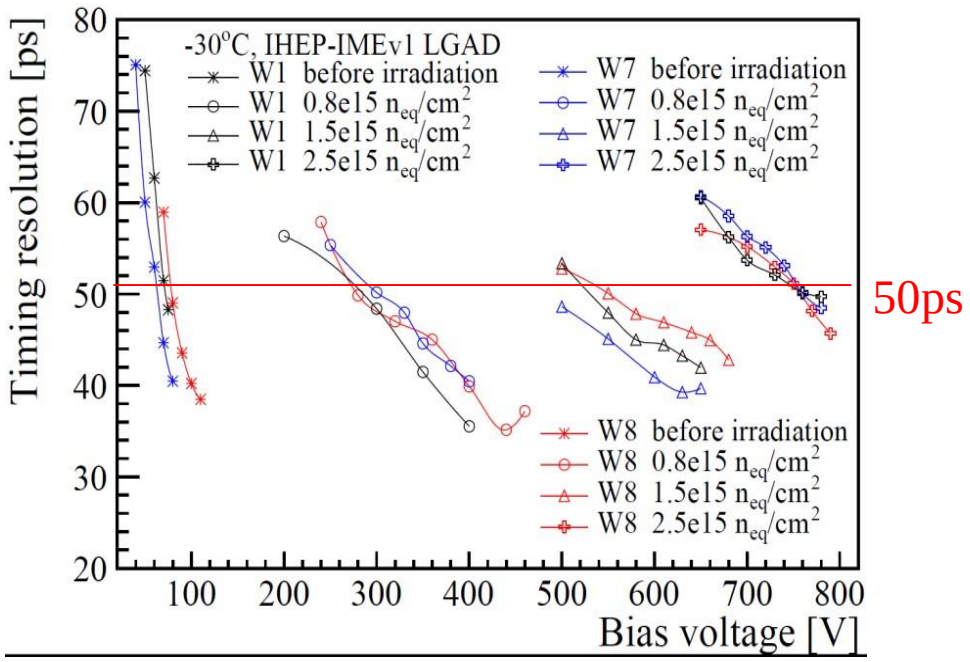


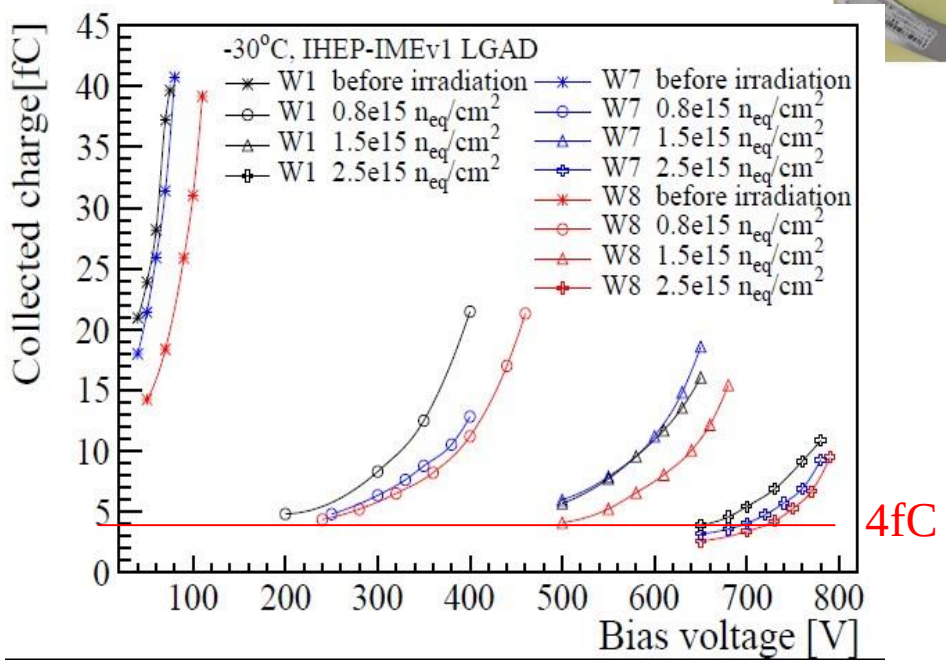
Development of IHEP LGAD sensors

IHEP-IMEv1

8 inch wafers with 50um EPI layer were used
Submit at May 2020, finish at Sept, 2020







Development of IHEP LGAD sensors

- **IHEP-IMEv2**

  8 inch wafers with 50um EPI layer

  Submit at Jan 2021, finish at April, 2021

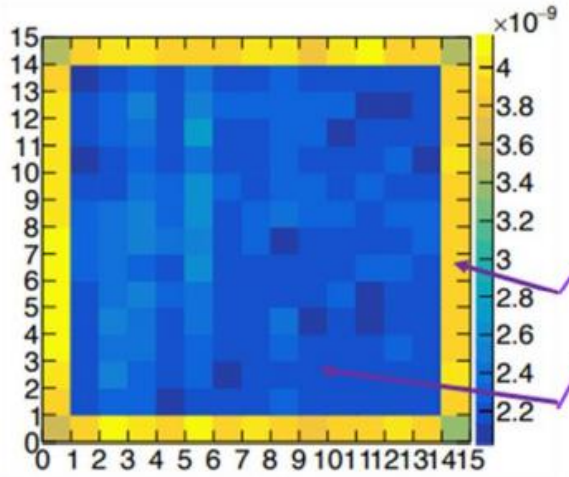
- Add 15x15 sensor array
- Carbon injection to improve irradiation hardness

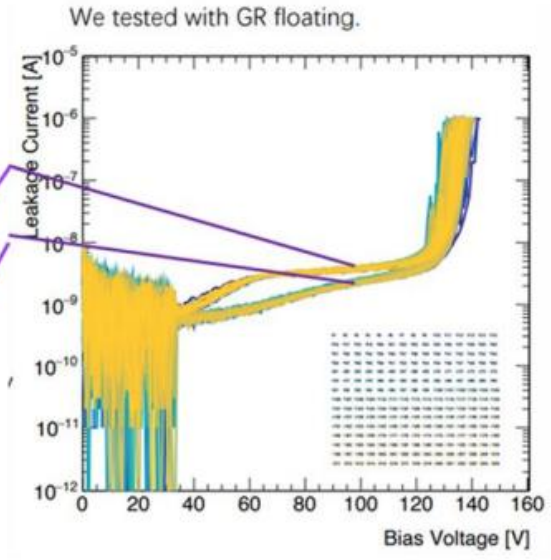
Wafer 4: fast annealing

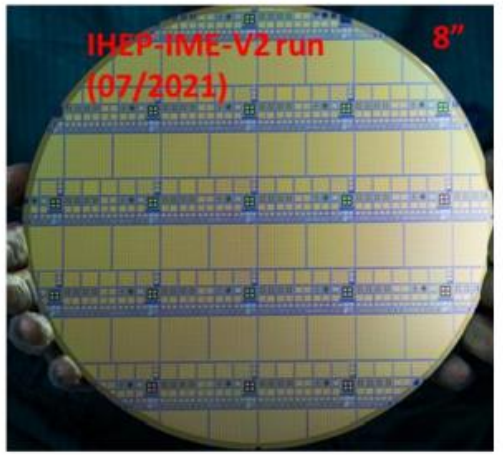
- carbon dose: 0.2 units, 1 unit, 5 units, 10 units

Wafer 7 and 8: long time annealing

- carbon dose: 0.2 units, 0.5 units, 1 unit, 2 units (W7
- carbon dose: 3 units, 6 units, 8 units, 10 units (W8)



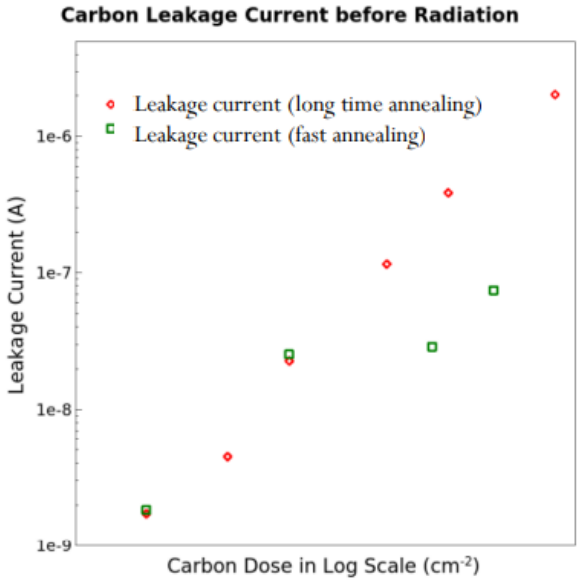


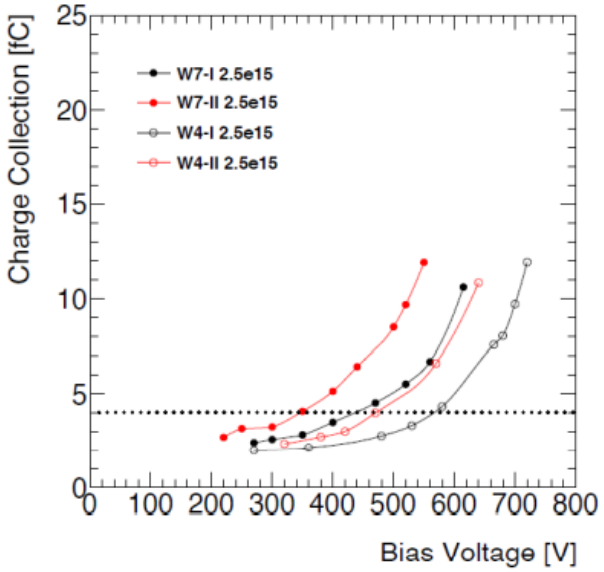


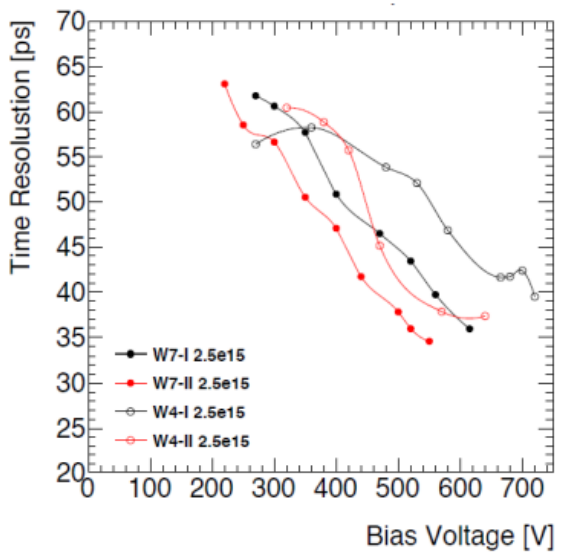
Good uniformity for large size sensors

Development of IHEP LGAD sensors

- Leakage current increases as increasing carbon dose
- After irradiation, the sensor can collected 4fC charge at voltage <400V(around 700V for IHEP-IMEv1), the timing resolution is better than 50ps







More researches should be done to find out the reason for this improvement

4 fC at:

W7-II: 350 V 50.5 ps

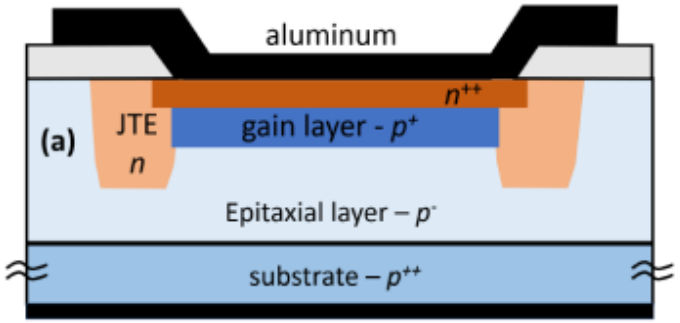
W7-I: 440 V 48 ps

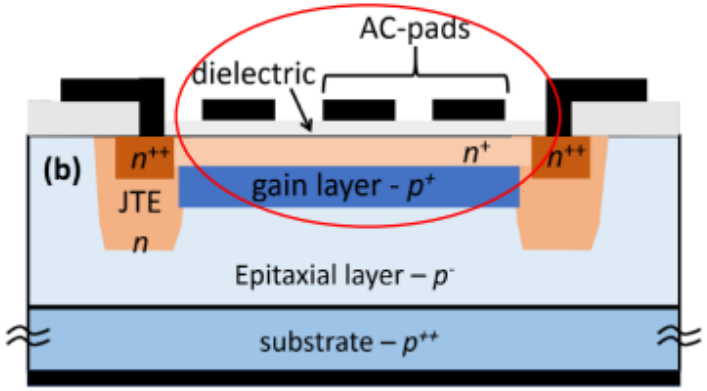
W4-II: 470 V 45.1 ps

W4-I: 560 V 49 ps

Standard LGAD vs AC-LGAD

- Set AC coupling capacitor inside the sensor active region,
- Collected charge from each electrode of coupling capacitor is related with particle injection position.





Standard-LGAD

- The DC readout electrode
- Time resolution ~ 35ps
- Position resolution: sensor size
- Dead zone: JTE, Pstop, 50~100um

AC-LGAD

- AC coupled readout electrode
  Signal AC-coupled through dielectric to metal pads
- Time resolution ~ 35ps
- Position resolution: 5-50 um
- Dead zone : 0 mm (no dead zone)

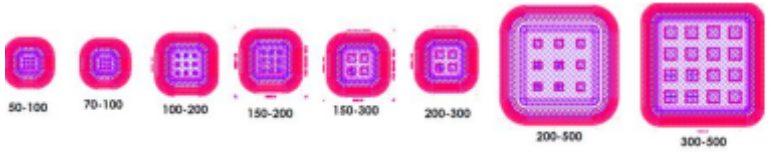
[#] Gabriele D'Amen et al., Electrical and timing performance of AC-LGADs, 37th RD50 Workshop, Zagred, online, 2020.

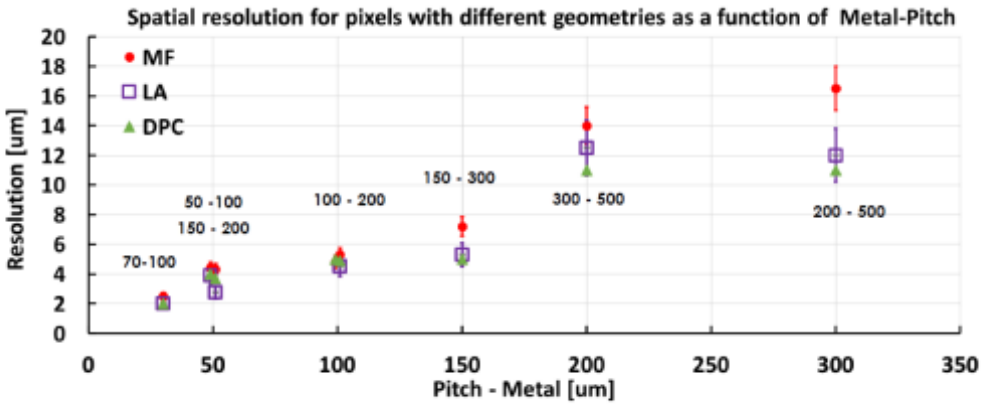
Development of AC-LGAD

BNL、FBK、IHEP etc. have done research on AC-LGAD(RSD), the spatial resolution of this sensor can be lower than 10um.

FBK

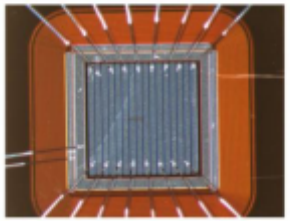
INFN



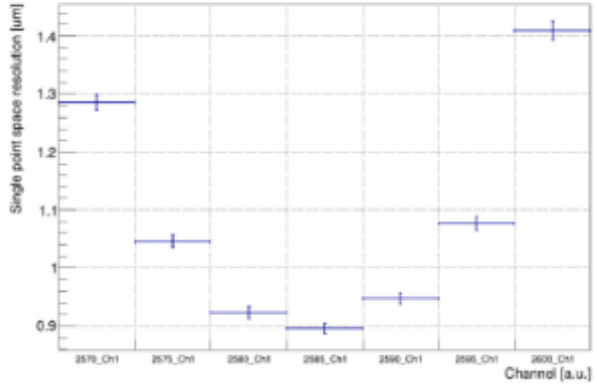


N. Cartiglia, INFN, 19/11/20, RD50 captivity II

BNL



strip pitch 100um,
gap 44um



AC-LGAD's time resolution~26ps
Spatial resolution of ~1um achievable using two strips near the laser focus point

Results obtained in collaboration with FNAL using 120 GeV proton beam show **excellent 4D performances for AC-LGADs** (σ_t = 30 - 35 ps, σ < 15 μm) and ~100% detection efficiency

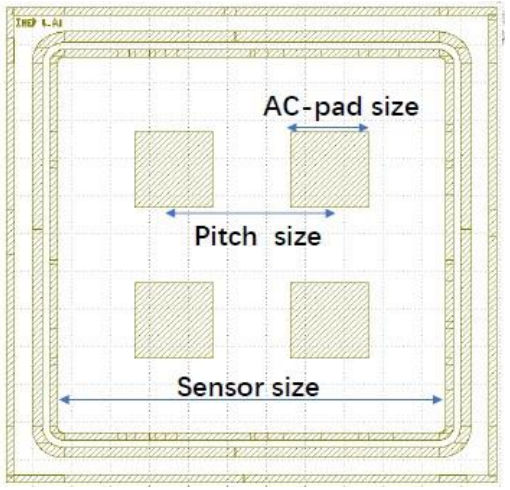
Gabriele D'Amen1, PSD12 2021

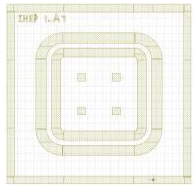
AC-LGAD sensors developed by IHEP

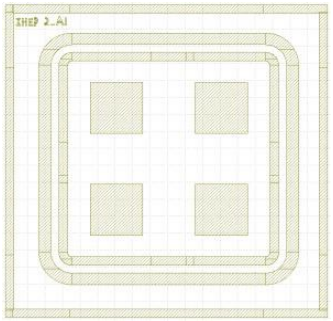
IHEP AC-LGAD first batch :

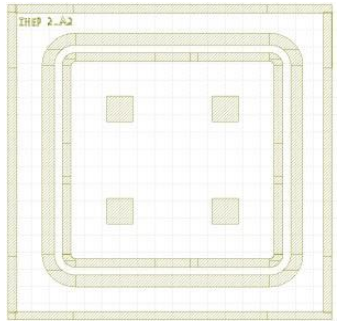
Sensors with different pad-pitch size

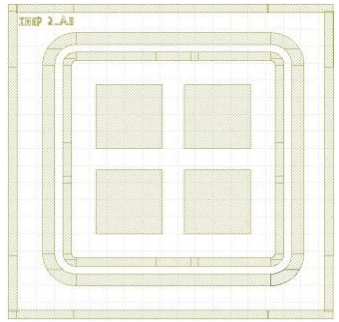
Sensors	Sensor size [μm]	AC-pad size [μm]	Picth size [μm]
1-A7	1000	100	450
2-A2	2000	300	1200
2-A1	2000	600	1200
2-A3	2000	750	1000
4-A1	4000	1000	2000





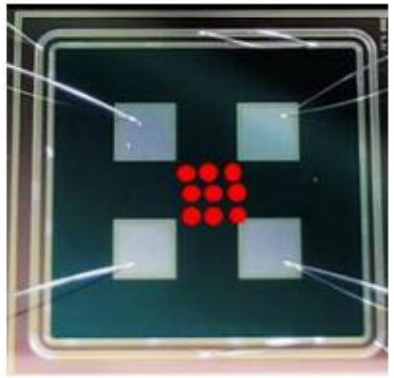


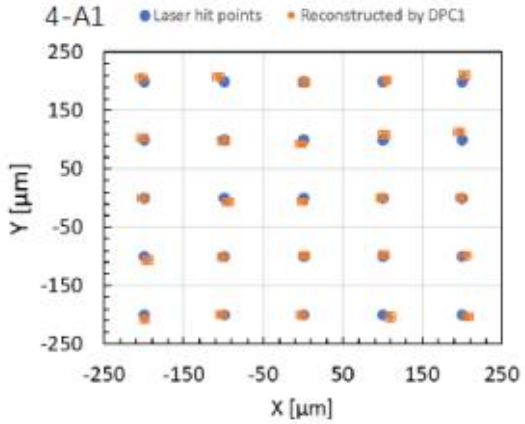




AC-LGAD sensors developed by IHEP

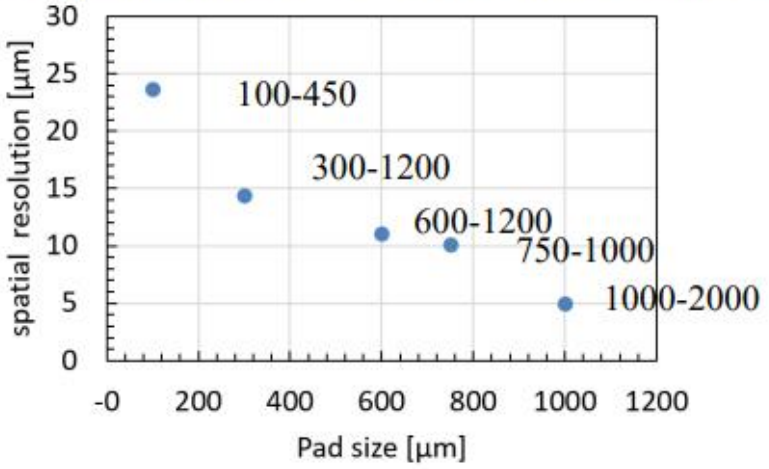
- hit position vs Reconstructed position（DCP method）





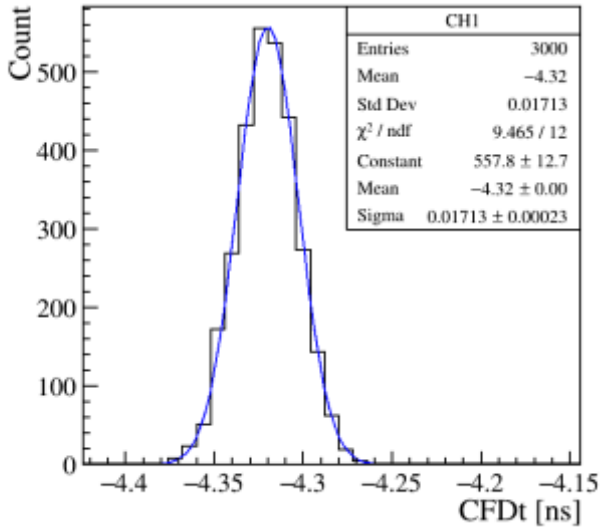
- **Spatial resolution：**

The standard deviation of the displacement difference between the laser and the reconstruction (d_L-d_R)



Timing performance of IHEP AC-LGAD

- The timing resolution is about 15-17 ps (Laser testing)
- Almost no difference for different size of the pads



Sensors	Pad-pitch (μm)	Timing resolution (ps)
1-A7	100-450	15
2-A2	300-1200	16
2-A1	600-1200	17
2-A3	750-1000	17
4-A1	1000-2000	17

From laser test results, the pad size may not affect the time resolution of the AC-LGAD.

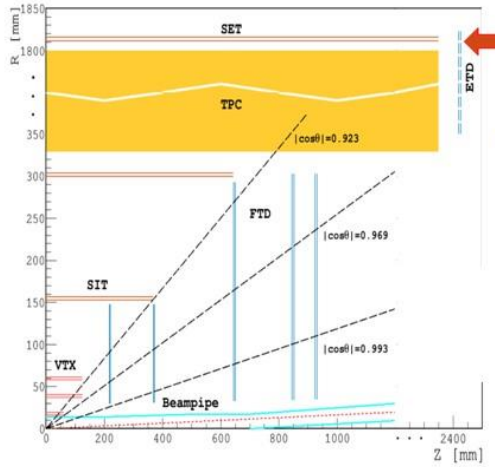
Beam testing should be done to check the real spatial and timing resolution.

Application of LGAD in CEPC

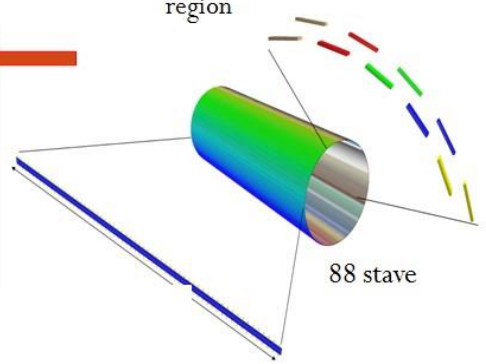
- AC-LGAD(Time resolution<50ps, spatial resolution <10um)

May be used as outer Si tracker for CEPC ?

Baseline detector concept in CDR



Timing detector in Barrel region



Clear the requirement

area, channels, spatial resolution, timing resolution

New design for this application

Strip or pixel， pitch-pad size, process parameters for Gain layer

New readout board (electric circuit)

less charge and high timing requirement

More Beam testing about timing and spatial performance

Summary

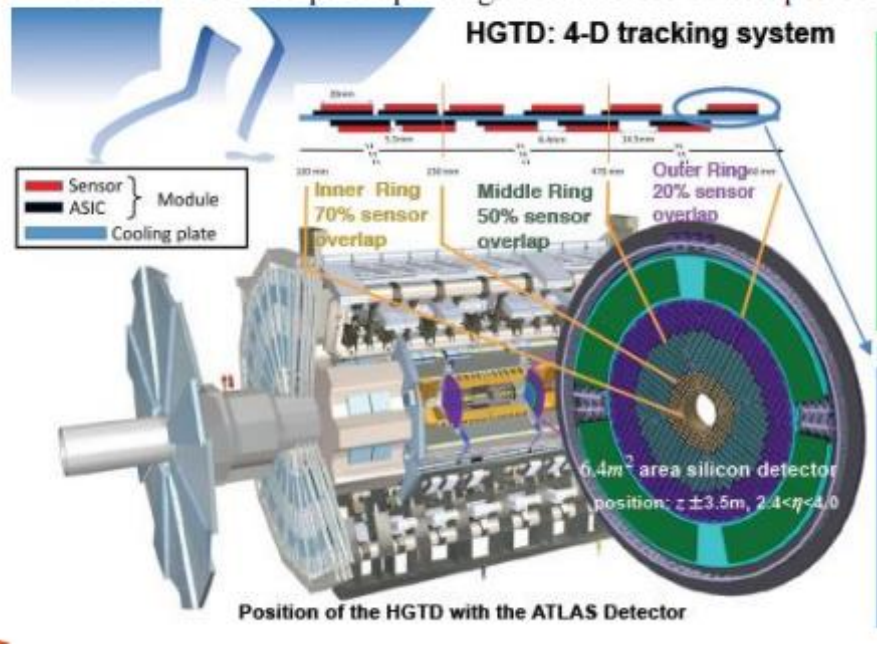
- The recent performance of LGAD sensors, especially the improved post-irradiation performance by changing process for LGAD sensor fabrication including IHEP carbonated LGAD sensors

- The performance of AC-LGAD sensors designed by different institute show spatial resolution of these sensors can be lower than 10um.

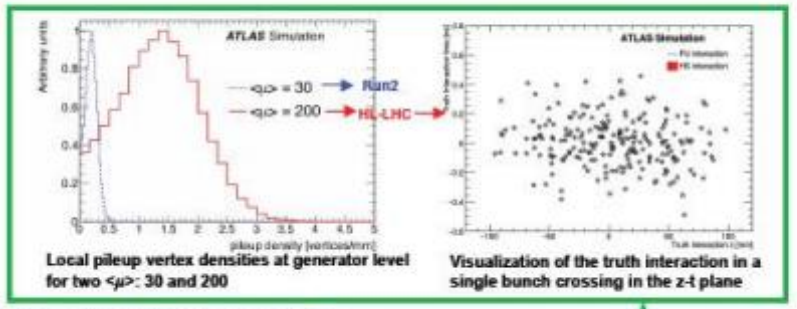
- Application of AC-LGAD in CEPC also be discussed and we still need do more research for this

Backup

The expected increase of the particle flux at the high luminosity phase of the LHC (HL-LHC) with instantaneous luminosities up to L= $7.5 \times 10^{34}\text{cm}^{-1}\text{s}^{-1}$ will have a severe impact on the ATLAS detector performance. The pile-up is expected to increase on average to 200 interactions per bunch crossing. The reconstruction and trigger performance for electrons, photons as well as jets and transverse missing energy will be severely degraded in the end-cap and forward region, where the liquid Argon based electromagnetic calorimeter has coarser granularity and the inner tracker has poorer momentum resolution compared to the central region. A High Granularity Timing Detector (HGTD) is proposed in front of the liquid Argon end-cap calorimeters for pile-up mitigation and for bunch per bunch luminosity measurements.



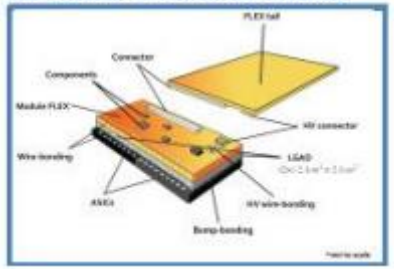
Position of the HGTD with the ATLAS Detector



Local pileup vertex densities at generator level for two <μ>: 30 and 200

Visualization of the truth interaction in a single bunch crossing in the z-t plane

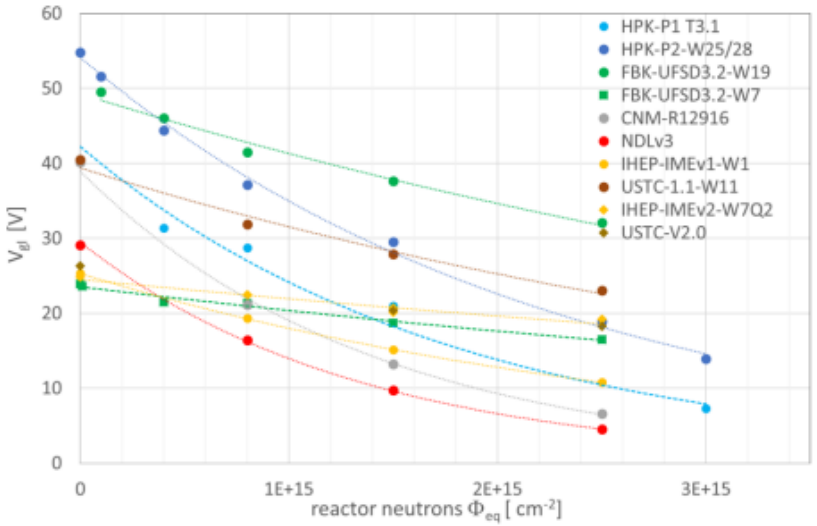
Bare module: 2 LGADs and 2 ASICs

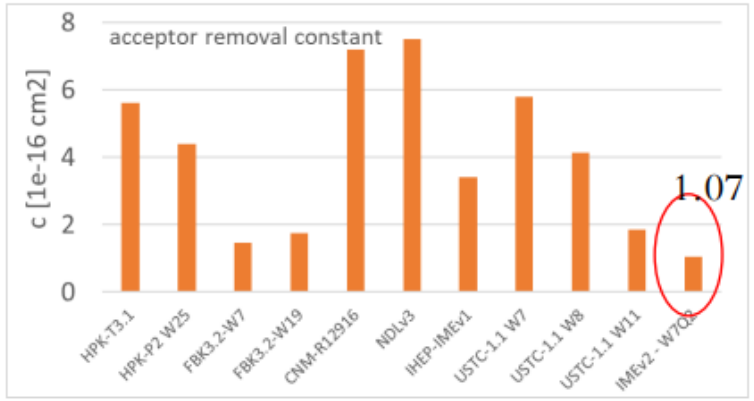


- HGTD for the **pile-up challenge** at **HL-LHC**
  - Timing resolution is required to be around 30 ps/track at beginning
  - ~3.7×10^6 channels with $1.3 \times 1.3 m^2$ readout channel
  - Radiation hardness: $2.5 \times 10^{15} N_{eq}/cm^2$ and 2.0 MGy

Backup

- V_{gl} change and acceptor removal

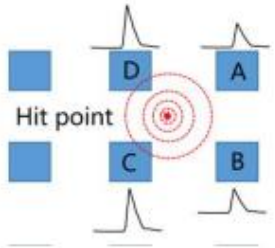




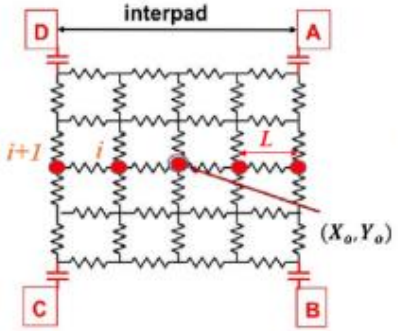
- DPC method

Position reconstruction by Discretized Positioning Circuit model (DPC) [#]

[#] M. Tornago, et al. Nuclear Inst. and Methods in Physics Research, A 1003 (2021) 165319



Discretized Positioning Circuit model (DPC)

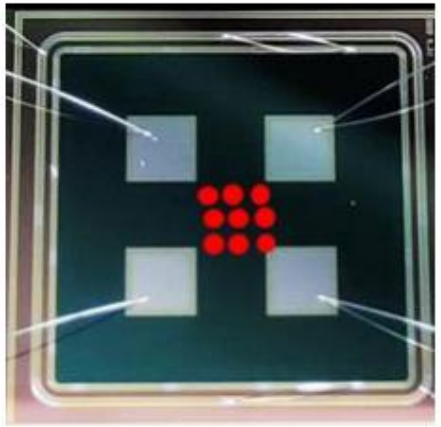


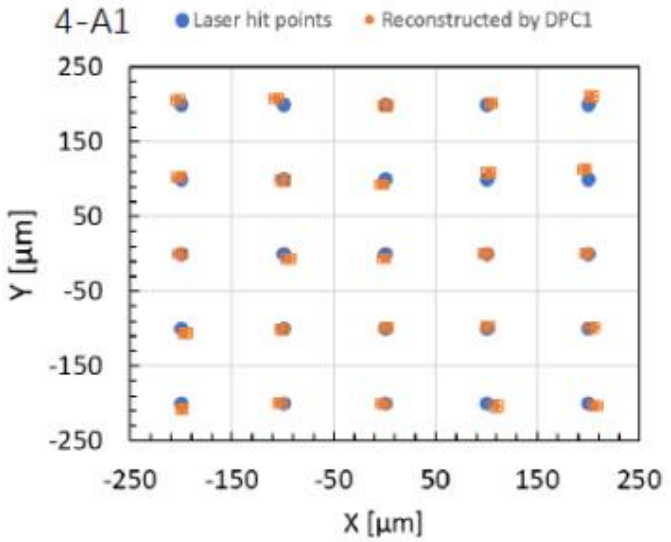
$$X = X_0 + k_x\left(\frac{q_A + q_B - q_C - q_D}{q_A + q_B + q_C + q_D}\right) = X_0 + k_x m$$

$$Y = Y_0 + k_y\left(\frac{q_A + q_D - q_B - q_C}{q_A + q_B + q_C + q_D}\right) = Y_0 + k_y n$$

$$k_x = L\frac{\sum(m_{i+1} - m_i)}{\sum(m_{i+1} - m_i)^2} \qquad k_y = L\frac{\sum(n_{i+1} - n_i)}{\sum(n_{i+1} - n_i)^2}$$

- hit position vs Reconstructed position





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