Performance of USTC-IME sensors in test beams at DESY and CERN

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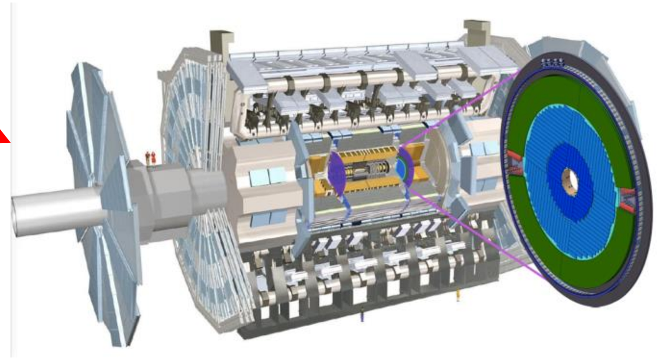
Overview

- Introduction
- Test beam Setup
- Test beam results – USTC-IME-v2.1
  - Time resolution
  - Charge
  - Efficiency
  - Inter-pad gap
- Preliminary result of USTC-IME preproduction
- Summary

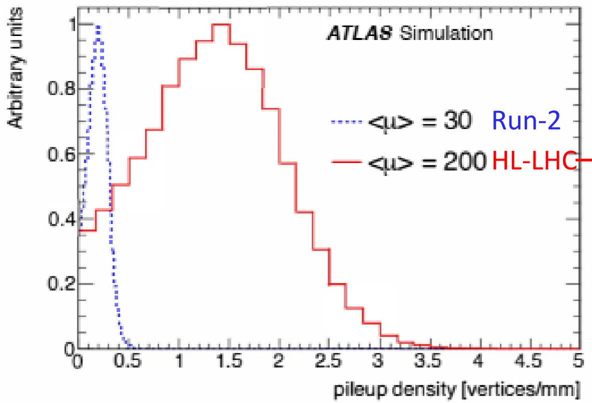
ATLAS HGTD project

- LHC (Large Hadron Collider) → HL-LHC (high-luminosity phase of LHC) in 2028 → pileup vertex densities ↑
- ATLAS (one of the 4 major experiments at the LHC at CERN) → upgrade its detectors
- The HGTD (High-Granularity Timing Detector) is chosen for the ATLAS Phase II upgrade.
- The time information be used as another dimension for identifying the hard-scattering vertex at the HL-LHC.
- HGTD should withstand the non ionizing radiation levels throughout the HL-LHC operations.
  - This determines lifetime
- Because of its good timing performance and radiation hardness, LGAD (Low Gain Avalanche Detector) has been chosen as the sensor.

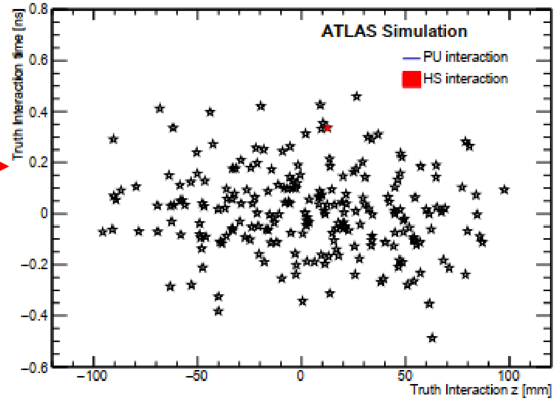
ATLAS Detector in LHC



Position of the HGTD within ATLAS



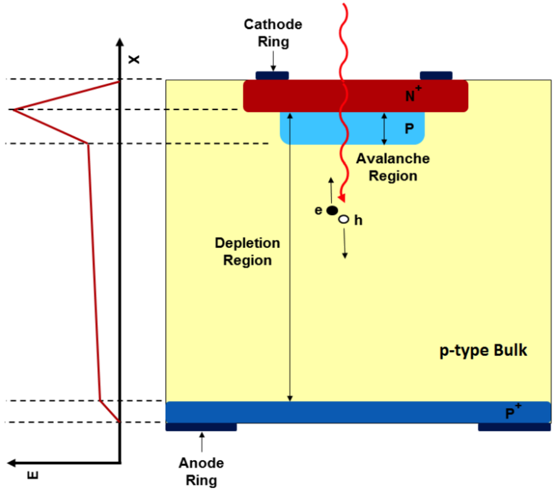
Local pileup vertex densities at generator level



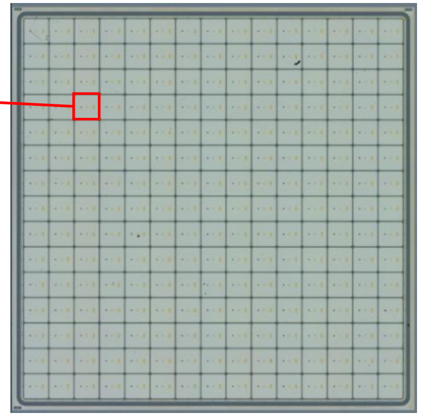
truth interactions in a single bunch crossing in the z–t plane

Low Gain Avalanche Detector

- LGADs are n-in-p silicon detectors containing an extra highly-doped p-layer (gain layer) below the n-p junction.
- The high electric field in gain layer region will accelerate the drifting electrons and generate avalanches.
- With a proper design of gain layer, the LGAD can achieve promising S/N and time resolution.
- Designed parameters:
  - Active thickness: 50 µm
  - Pad size: 1.3 x 1.3 mm^2
  - Collected charge (most probable value): > 4 fC
  - Time resolution: 40 ps (start), 70 ps (end of lifetime)
  - Hit efficiency: > 95%
  - Radiation tolerance: 2.5e15 $\mathrm{n_{eq}}\ \mathrm{cm}^{-2}$, 1.5 MGy

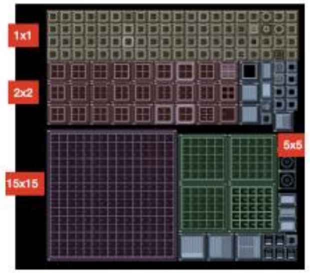


1 LGAD pad



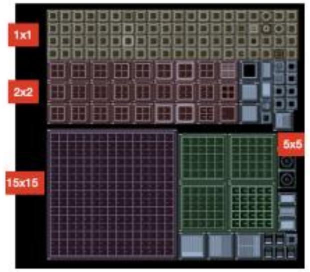
15x15 LGAD sensor

USTC's roadmap on LGAD R&D with IME



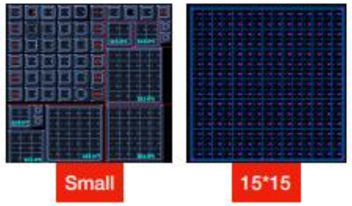
USTC-1.0

Deliver: 2020.7



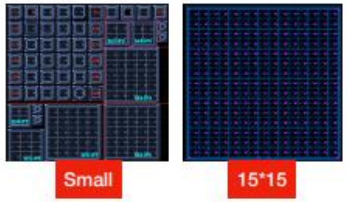
USTC-1.1

Deliver: 2020.10



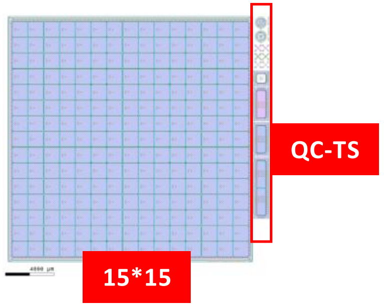
USTC-2.0

Deliver: 2021.4



USTC-2.1

Deliver: 2021.10



USTC-pre

Deliver: 2023.6

	USTC-1.0	USTC-1.1	USTC-2.0	USTC-2.1	USTC-pre
Propose	First attempt	Improved the process technology, same layout as 1.0	New layout, mainly for yield study and issues fix	Same layout as 2.0, fast iteration	New layout, based on USTC-2.1-W17, in-kind/tendering preproduction. (10% of total supply ~2100)
Performance	Few sensors can work (VBD ~250V, VGL 40V)	~30% can work (VBD ~300V)	> 99% small sensors and ~35% 15x15 sensors can work, GR leakage disappeared. VBD lowered (~100-170V).	>99% small sensors and ~35% 15x15 sensors can work. Better uniformity, VBDs in idea range (~150-240V).	Under test
Problem	Almost all sensors have large current (VBD < 10V)	Almost all sensors have large GR current	Too low VBD for some wafers.		

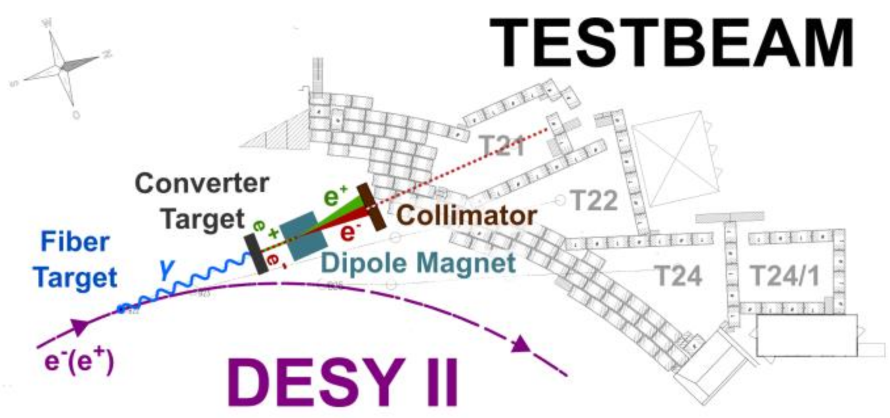
HGTD test beam activities in the past 2 years

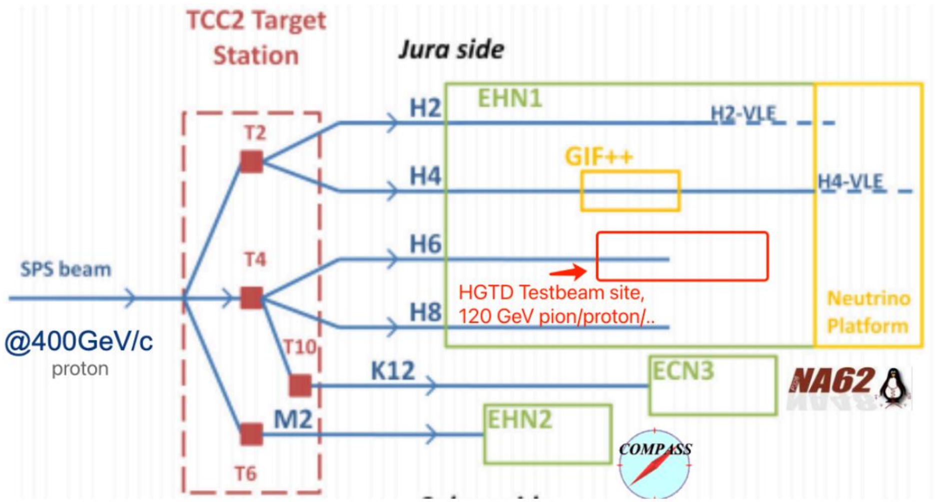
Year	Facility	Type of tests	Period
2023	DESY	ASIC + Sensor	Nov. 2023
	DESY	ASIC + Sensor	Oct. 2023
	CERN SPS	Sensor	Aug. 2023
	CERN SPS	Sensor	July 2023
	CERN SPS	Sensor	May 2023
2022	CERN SPS	ASIC	Oct. – Nov. 2022
	CERN SPS	ASIC	Aug. – Sept. 2022
	CERN SPS	ASIC	July 2022
	CERN SPS	Sensor	May 2022
	CERN PS	Sensor	Mar. 2022
	DESY	Sensor	Feb. 2022

ASIC: Application Specific Integrated Circuit

During the past 2 years, 12 test beam campaigns have been held to test the performance of the sensors, which contains the time resolution, collected charge, efficiency and inter-pad gap.

Test beam Facility





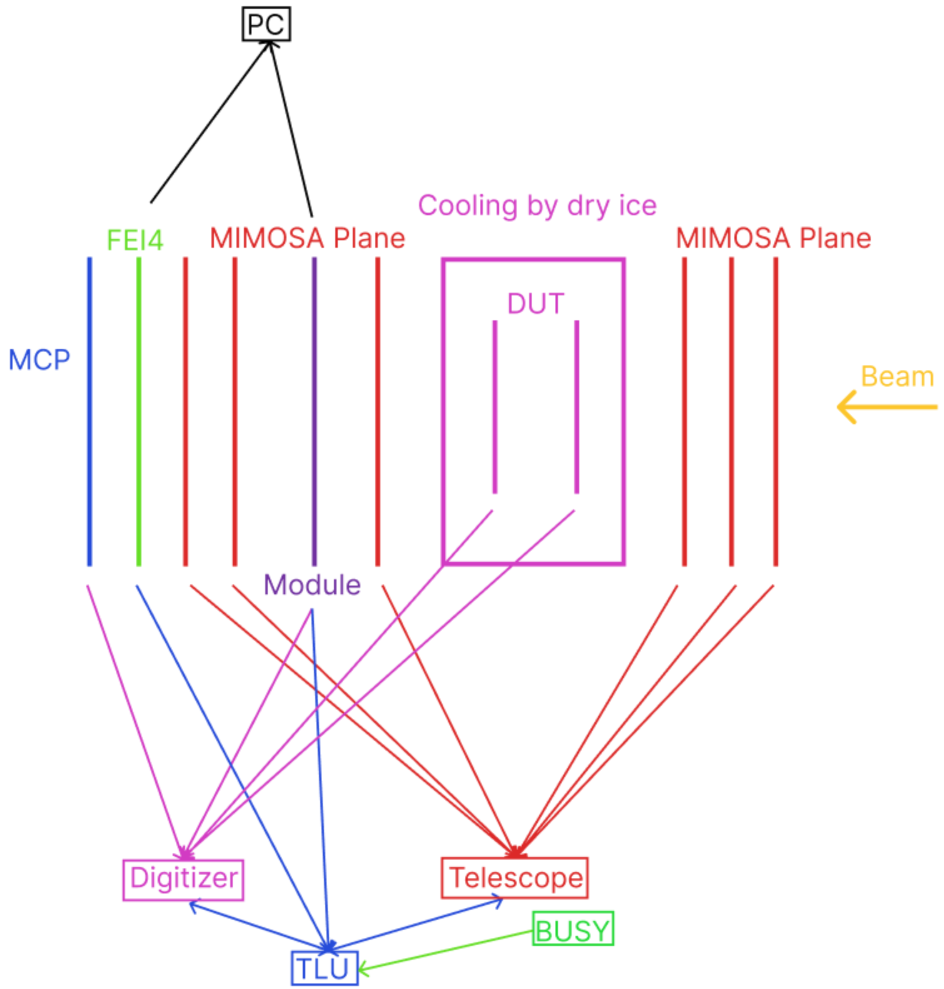
DESY (German Electron Synchrotron):

- Use a continuous 5 GeV electron beam to hit the sensor

CERN SPS (Super Proton Synchrotron):

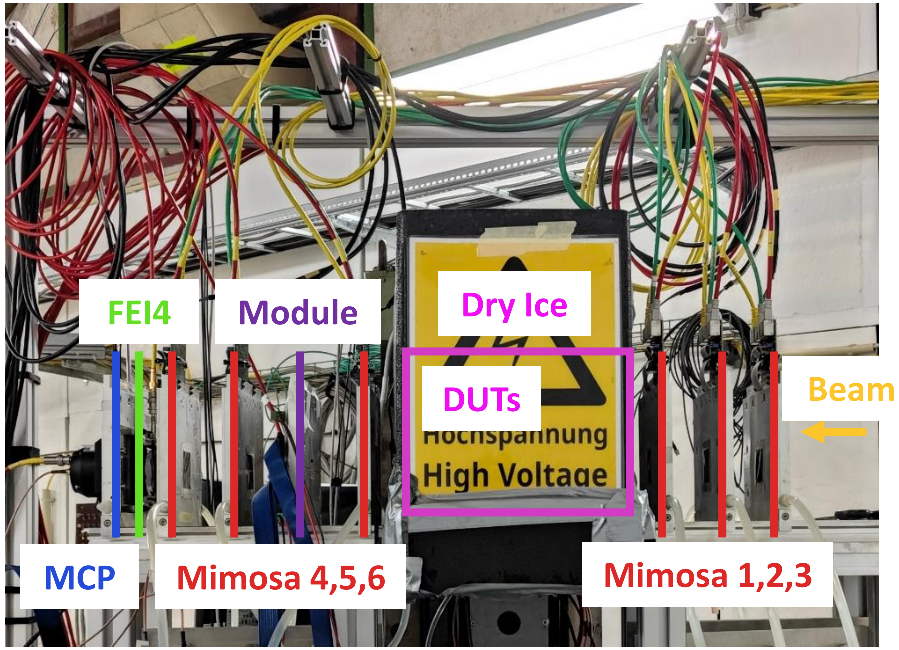
- Use a 120 GeV pion beam to hit the sensor.

Test beam setup (DESY Nov. 2023)

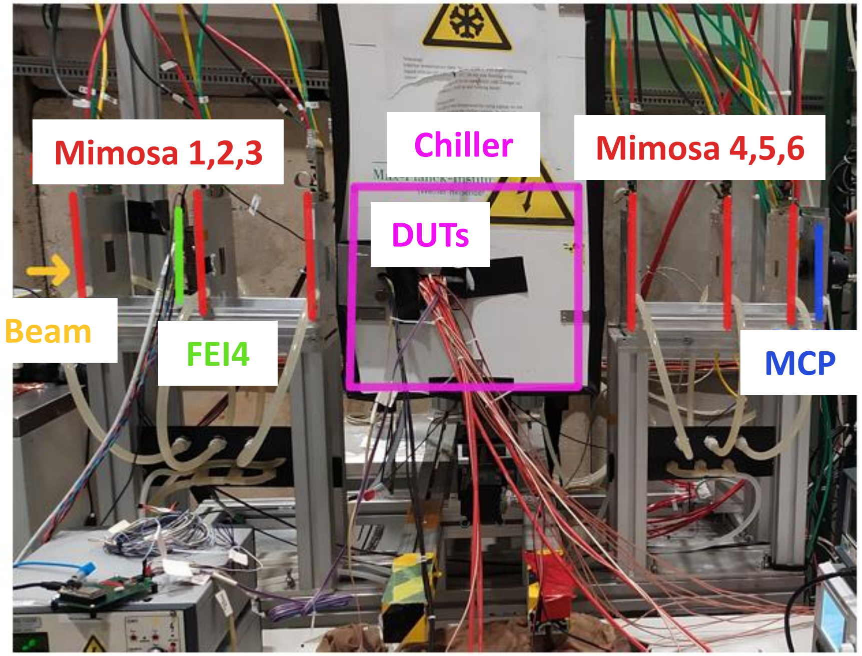


- MCP: Microchannel Plate, as time reference.
- FE-I4: 3D CNM silicon pixel sensor for trigger
- Mimosa planes: connect to a beam telescope
- Module: ASIC+LGAD and ASIC board
- DUT: device under test, LGAD sensors
- Digitizer: for waveform read out.
- Busy: NIM-logic crate to count 250000 events and send busy signal (~20 s) to block new events and store data.
- TLU: Trigger Logic Unit, contains NIM-logic crate, FE-I4.
- Cooling provided by dry ice in cold box

Test beam setup

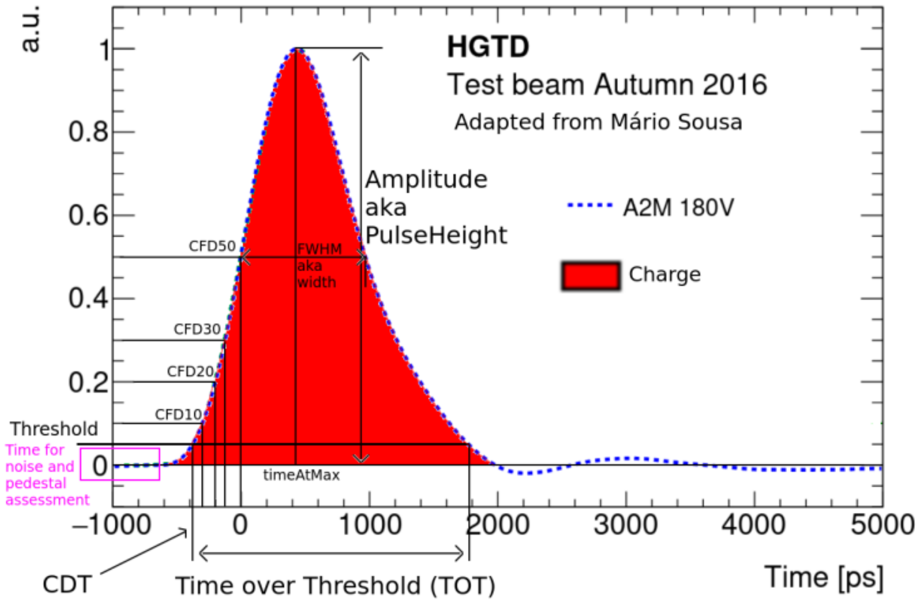


DESY test beam setup (Nov. 2023)



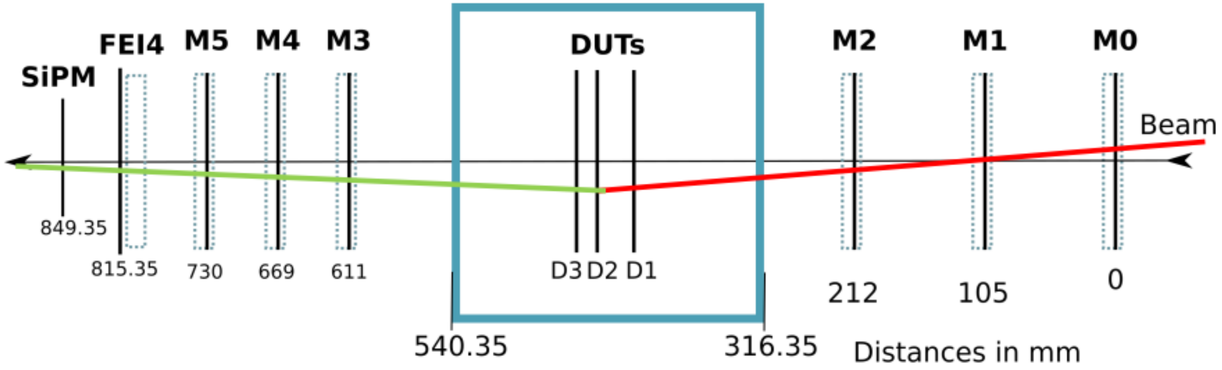
CERN SPS test beam setup (Aug. 2023)

Parameters from waveform



Parameters	Definition
PulseHeight	Maximum of the pulse
timeAtMax	Time at maximum of pulse
TOT	Time over threshold
CTD	Constant threshold discriminator
width	Full width at half maximum
CFDxx	Constant fraction discriminator above xx%
Pedestal	Average of voltage before pulse (~2 ns)
Noise	Standard deviation of voltage before pulse (~2 ns)
PulseHeightNoise	Maximum of voltage before pulse (~2 ns)
Charge	Integral of the pulse in [timeAtMax – 2 ns, timeAtMax + 2 ns]

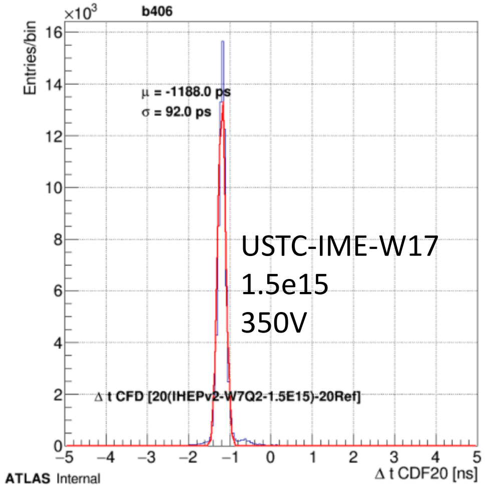
Track reconstruction



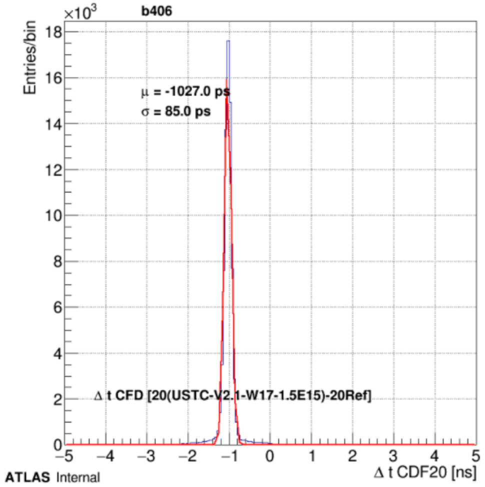
- Upstream triplets:
  - Seed a triplet using M0 and M2 and check if there is a matched hit in M1 with $\Delta R < 100\ \mu m$
- Downstream triplets:
  - Seed a triplet using M3 and M5 and check if there is a matched hit in M4 with $\Delta R < 100\ \mu m$
  - Matched to the FEI4
- Construct all possible triplets, keep the upstream and downstream triplets that minimize ΔR computed between M0 and M5.
- Reject events when $\Delta R_{min} > 150\ \mu m$.
- Keep events with only one reconstructed track matched to the FEI4.
- By now, only 1 group of reconstructed (Xtr, Ytr) is stored for each DUT per event.

Time resolution

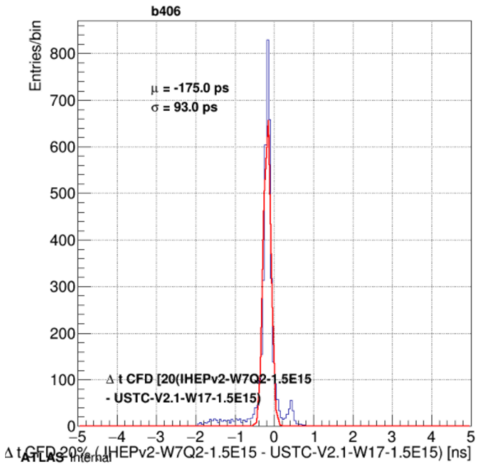
Cuts:
- pulseheight > 3 * Max(noise)
- ΔtimeAtMax(DUT, Ref) in 2 ns range in which the integral is max
- Charge > 2.0



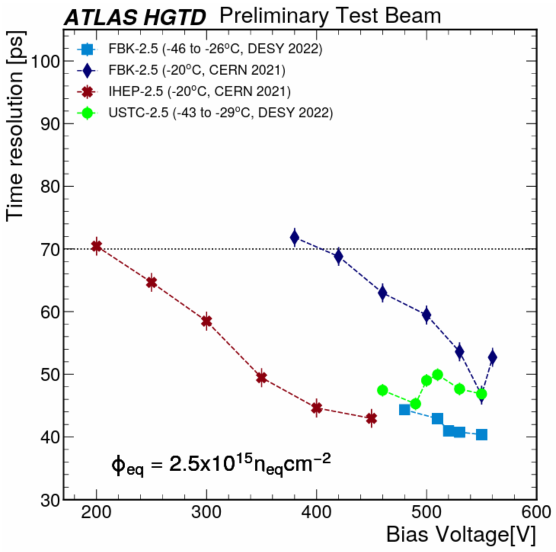
Δt CFD20(DUT1-Ref)



Δt CFD20(DUT2-Ref)



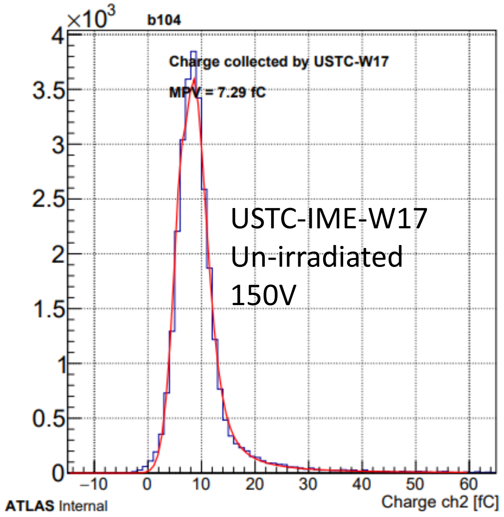
Δt CFD20(DUT1-DUT2)

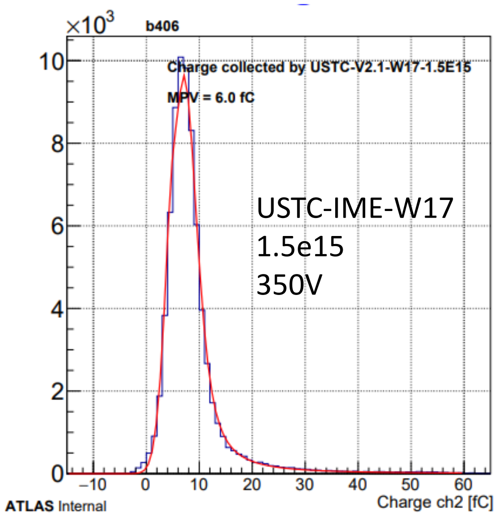


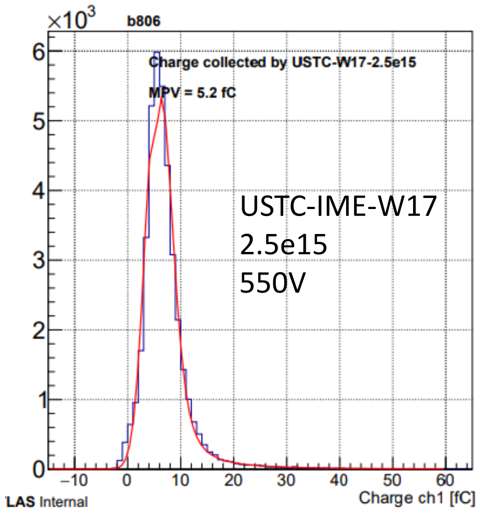
- Calculate the resolution (σ_{ij}) of the time difference between 2 devices by gauss fitting.
- The time resolution (σ_i) of 3 devices can be calculated by $\sigma_i = \sqrt{\frac{\sigma_{ij}^2+\sigma_{ik}^2-\sigma_{jk}^2}{2}}$.
- The USTC-IME-2.1 W17 shows time resolution < 70 ps with bias voltage below 550 V [link] after 2.5E15 fluences.

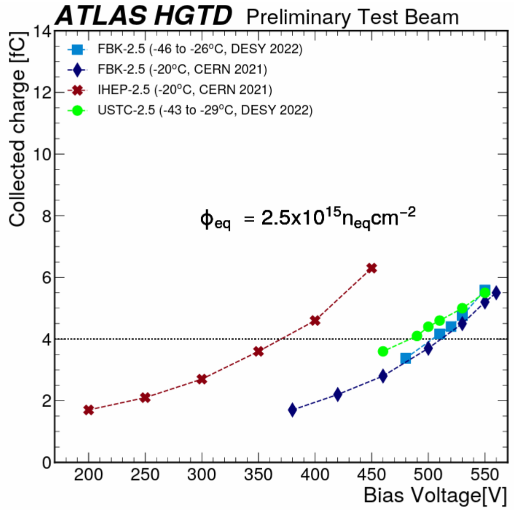
Collected Charge

Cuts:
- pulseheight > 3 * Max(noise)
- ΔtimeAtMax(DUT, Ref) in 2 ns range in which the integral is max
- (Xtr, Ytr) in center range (0.4x0.4 mm^2) of DUT







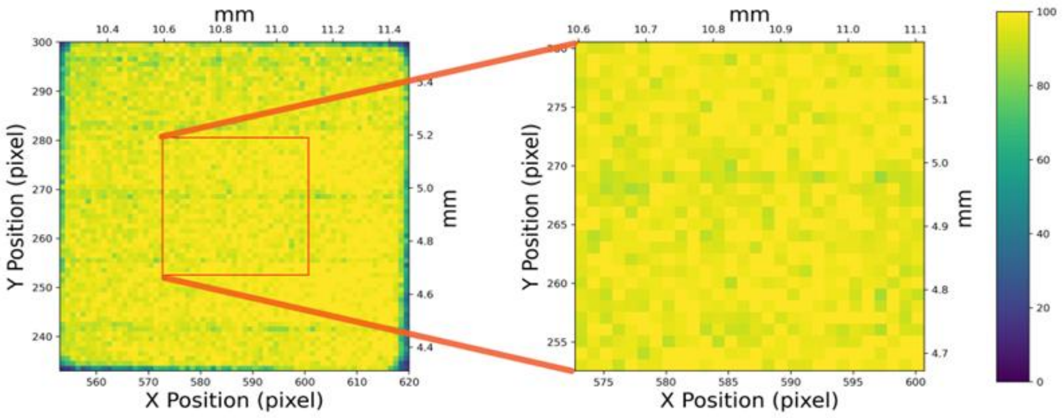


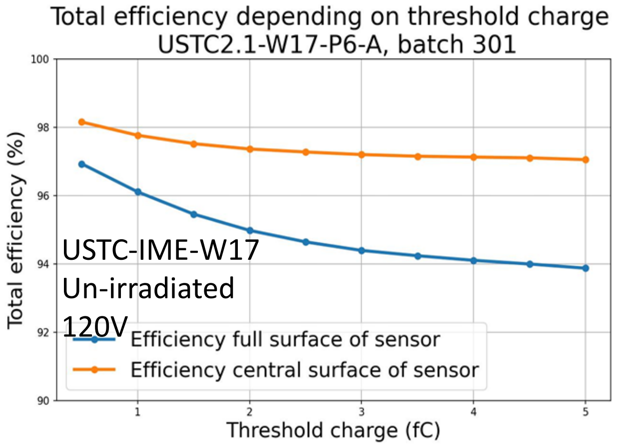
- Use center of the DUT to extract the charge value
- Fit charge distribution with convolution of Landau & Gaussian
- Extract the MPV to get the collected charge.
- The USTC-IME-2.1 W17 shows collected charge > 4 fC with bias voltage below 550 V after 2.5E15 fluences.

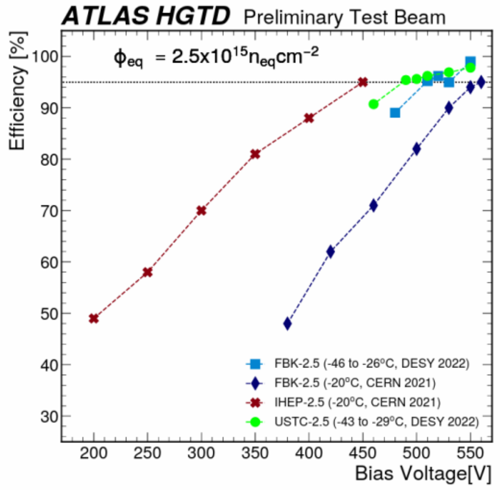
Efficiency

Cuts:
- pulseheight > 3 * Max(noise)
- ΔtimeAtMax(DUT, Ref) in 2 ns range in which the integral is max
- (Xtr, Ytr) in center range (0.5x0.5 mm^2) of DUT

Efficiency map (charge > 2.0 fC)





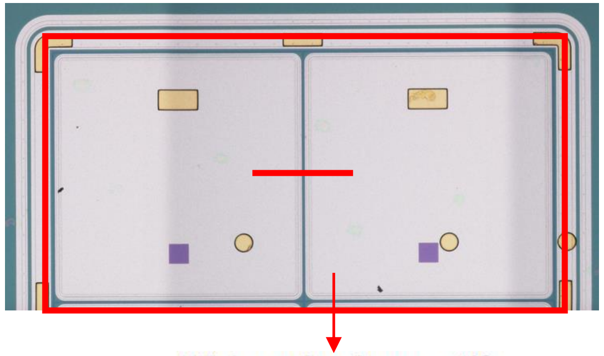


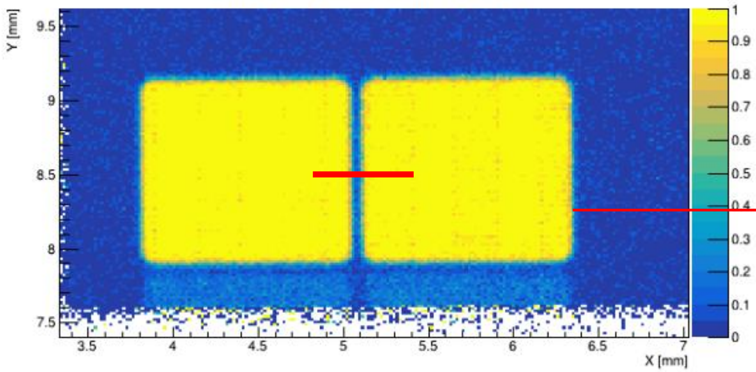
- Efficiency (XX fC) = $\dfrac{Events(Selected, charge > XX\ fC)}{Events(Selected)}$
- The scattering at the edge of the sensor can reduce DUT's efficiency during analysis.
- Use the cut on position (Xtr, Ytr) to reduce multiple scattering's influence.
- The USTC-IME-2.1 W17 shows efficiency> 95% with bias voltage below 550 V after 2.5E15 fluences.

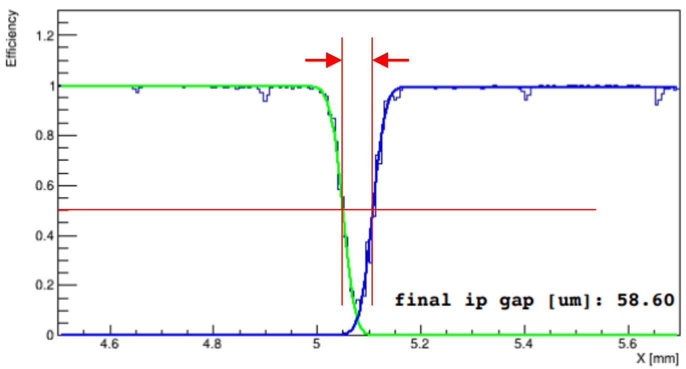
Inter-pad gap

Effective IP gap	70 µm	80 µm	90 µm	100 µm	110 µm	120 µm
Fill factor	90 %	88 %	87 %	85 %	84 %	82 %

Sensor	Bias (V)	IP measured (µm)
W19 2x2 IP3	155	59
	145	63
	135	65
W17 2x2 IP3	170	60
	160	59
	150	62

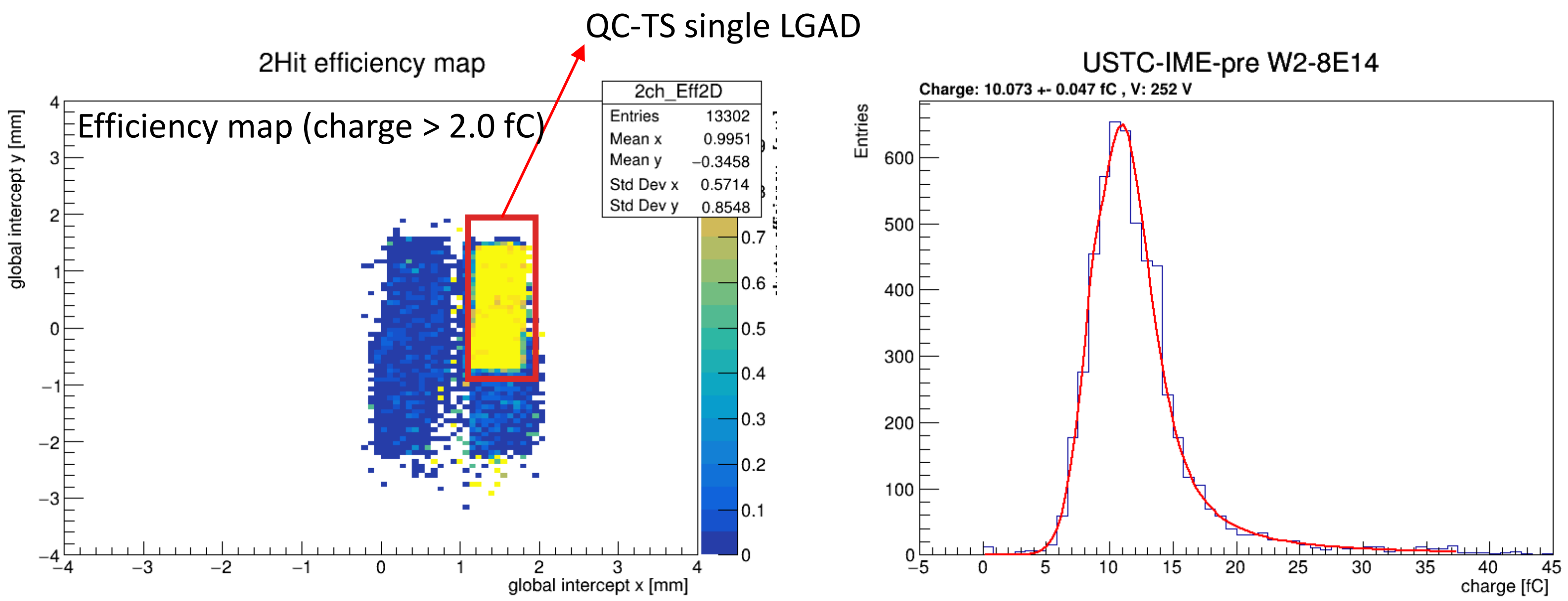






- Use error functions to fit the efficiency of both pads.
- Use the FWHM of the fitting curves to get the inter-pad gap.
- The USTC-IME-v2.1 show ~60 µm inter-pad gap for un-irradiated IP3 sensors. (< 100 µm required)

Preliminary result of USTC-IME preproduction



- The USTC-IME preproduction sensors are already produced and tested in test beam from July to Nov.
- The preliminary result shows the W2 has 10.073 fC collected charge at 252 V after 8E14 fluences
- More data is still being analyzed.

Summary

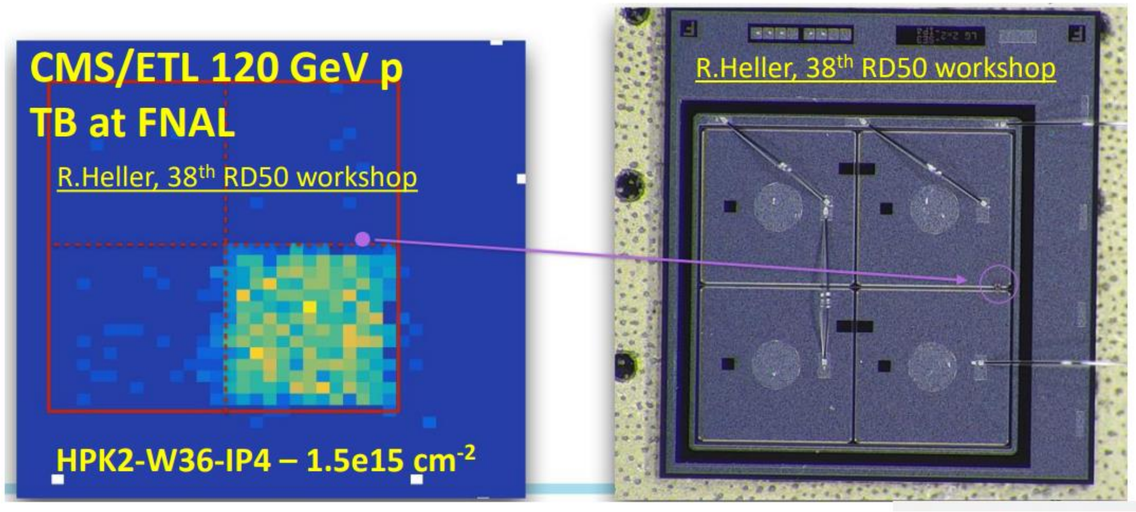
- During the past 2 years, 12 test beam campaigns have been held to test the performance of the sensors.
- The USTC-IME-v2.1 W17 show a good performance with bias voltage below 550 V after 2.5E15 fluences
  - For un-irradiated IP3 sensors, The USTC-IME-v2.1 W17 have inter-pad gap ~60 µm
- The USTC-IME-pre has been produced based on USTC-IME-v2.1 W17.
  - The test of the USTC-IME-pre is ongoing. The data is still being analyzed.

V	Efficiency [%]	Charge [fC]	Resolution [ps]
550	98.0853	5.47876	46.8651
530	97.3266	4.98833	47.6568
510	96.4113	4.69176	49.9384
500	95.2276	4.38139	49.0192
490	95.5674	4.19849	45.2849
460	91.1402	3.72371	47.4517

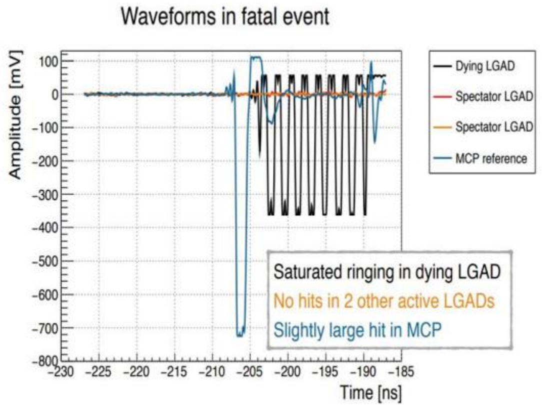
Performance of USTC-IME-v2.1 W17 after 2.5E15 fluences [Paper link]

Backup

Safe zone of bias voltage - Single Event Burnout (SEB)

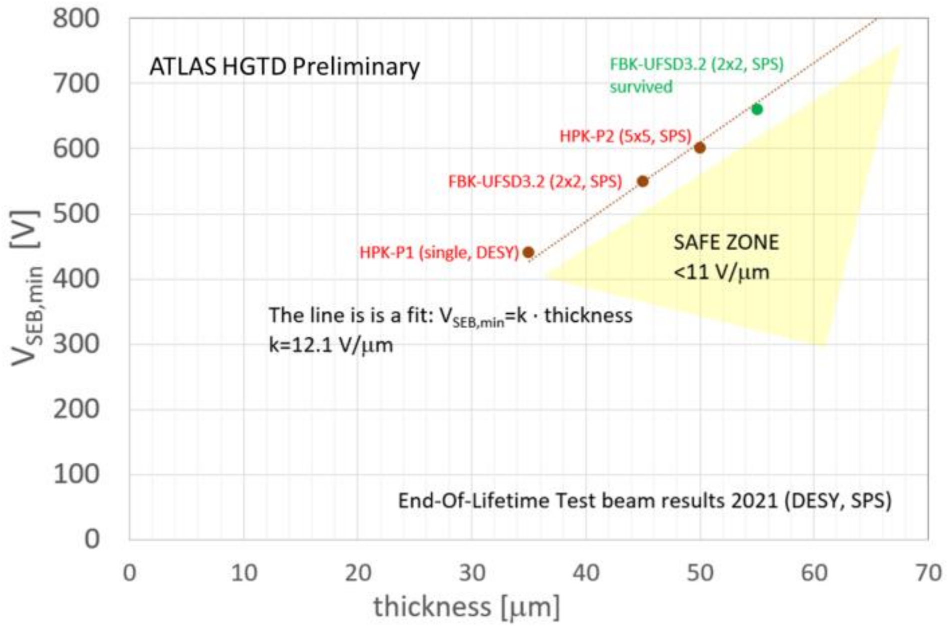


- During the test beam, some sensor died at high bias voltage with the “star shaped crater”.
- The fatality was caused by the high energy deposition of one single beam particle.
- Some signals from the event in which sensor died were recorded and the tracking information point to the place of the crater.
- This means bias voltage should not be too high, to ensure sensor won’t be damaged.



Death within 1 ns of proton arrival.

Safe zone of bias voltage



- The minimum of V_{SEB} is thickness dependent.
- The test result shows the electric field should be limited to < 11 V/μm.
- For 50 μm sensors with adequate performance, the bias voltage should < 550 V.