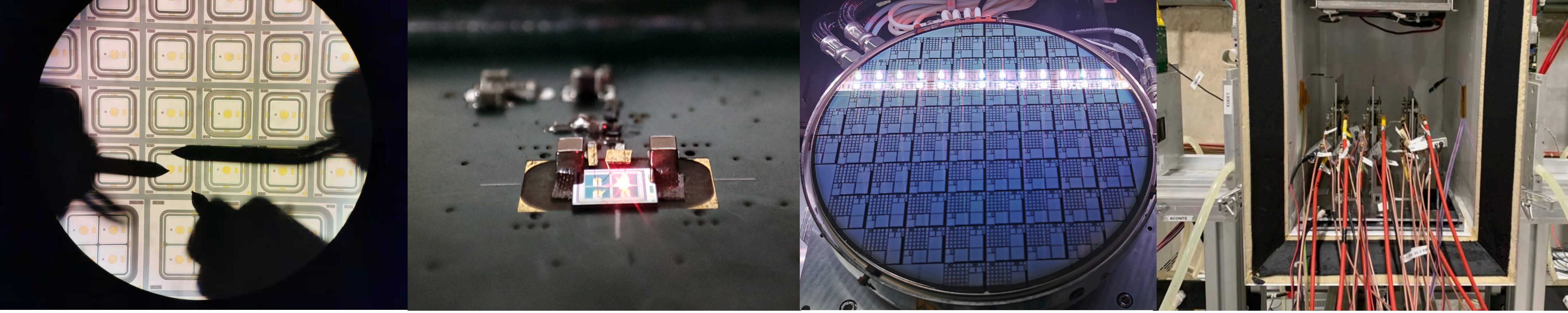


Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector:

laboratory and test beam campaigns

Xiao Yang (CERN)

On behalf of the ATLAS HGTD Group

September 26th, 2023
16th Topical Seminar on Innovative Particle and Radiation Detectors, Siena

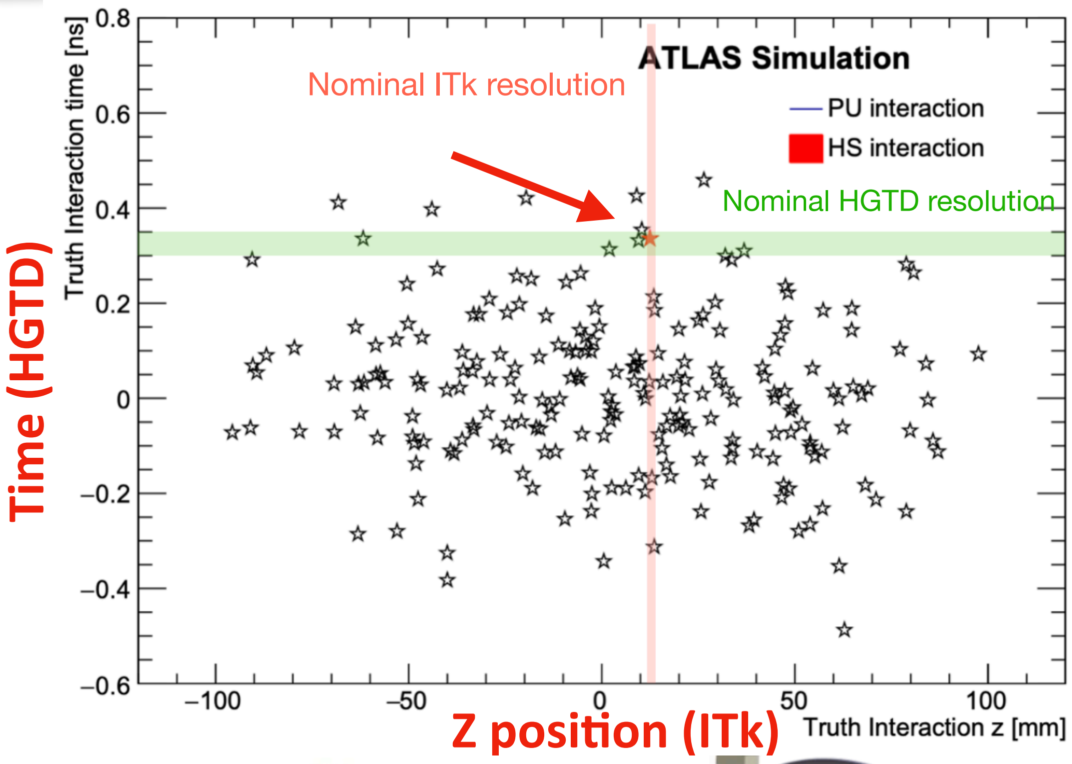
Overview

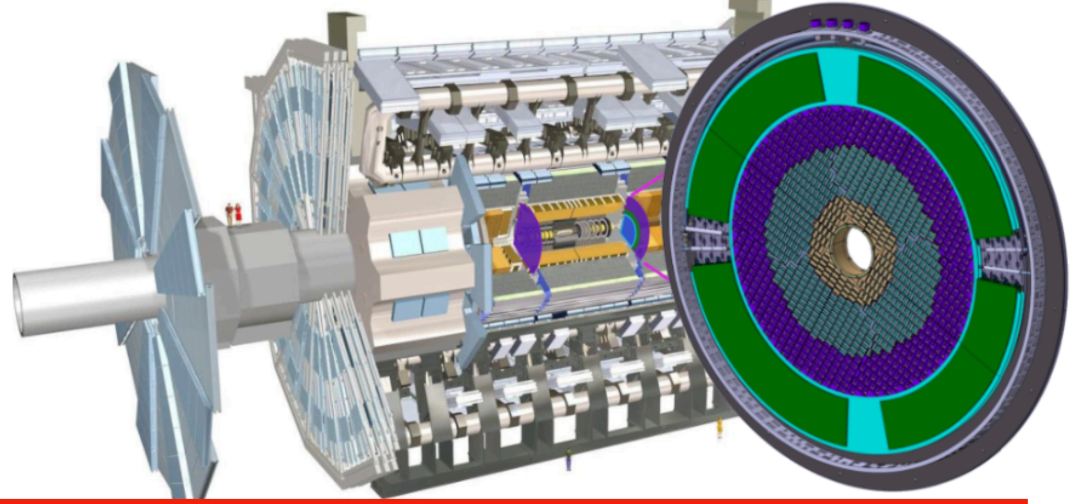
- ***ATLAS HGTD upgrade and LGAD technology***
- ***LGAD performance in laboratory***
- ***LGAD performance in test beam at DESY and CERN***
- ***Pre-production plan and QA/QC***
- ***Summary and outlook***

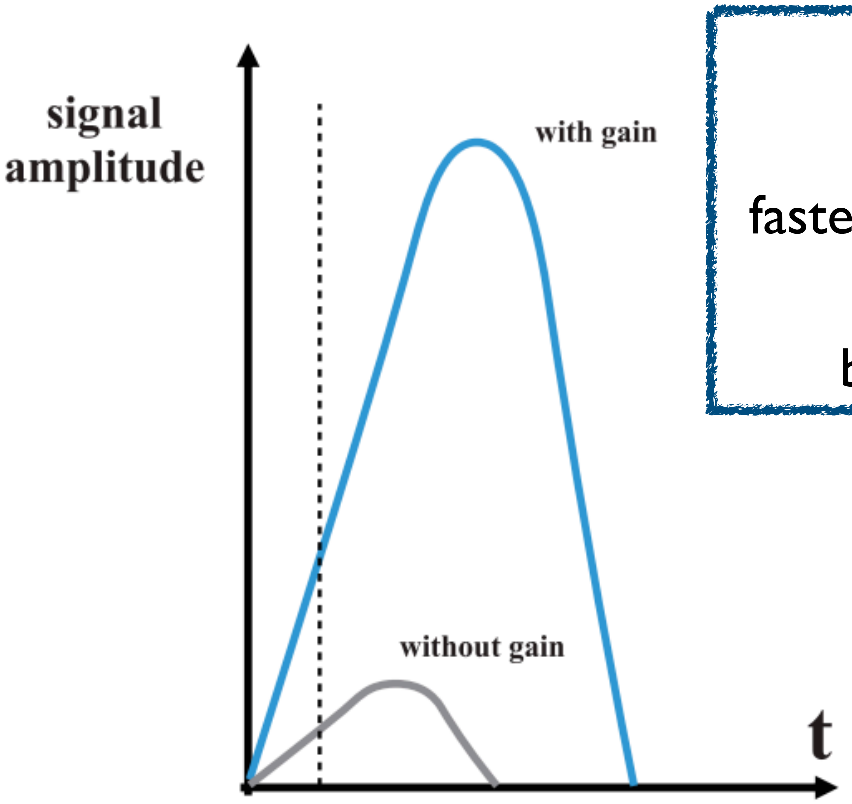
High-Granularity Timing Detector for ATLAS Phase-II

- In the HL-LHC, pile-up density at ATLAS will get so high (1.6 vertices/mm) that track to vertex association will be very hard, especially in the forward region (2.4 <|η|< 4.0).
- Having a timing detector with the inner tracker (ITk) in the forward region will allow us make the matching in "4-D" space. => **HGTD**
- The LGAD (**Low-Gain Avalanche Detector**) can achieve promising S/N and σ_t by introducing a local internal gain layer on a planar silicon diode.

* *More details can be found in the poster by Marion Missio*







larger gain
↓
faster rise time and larger S/N
↓
better time resolution

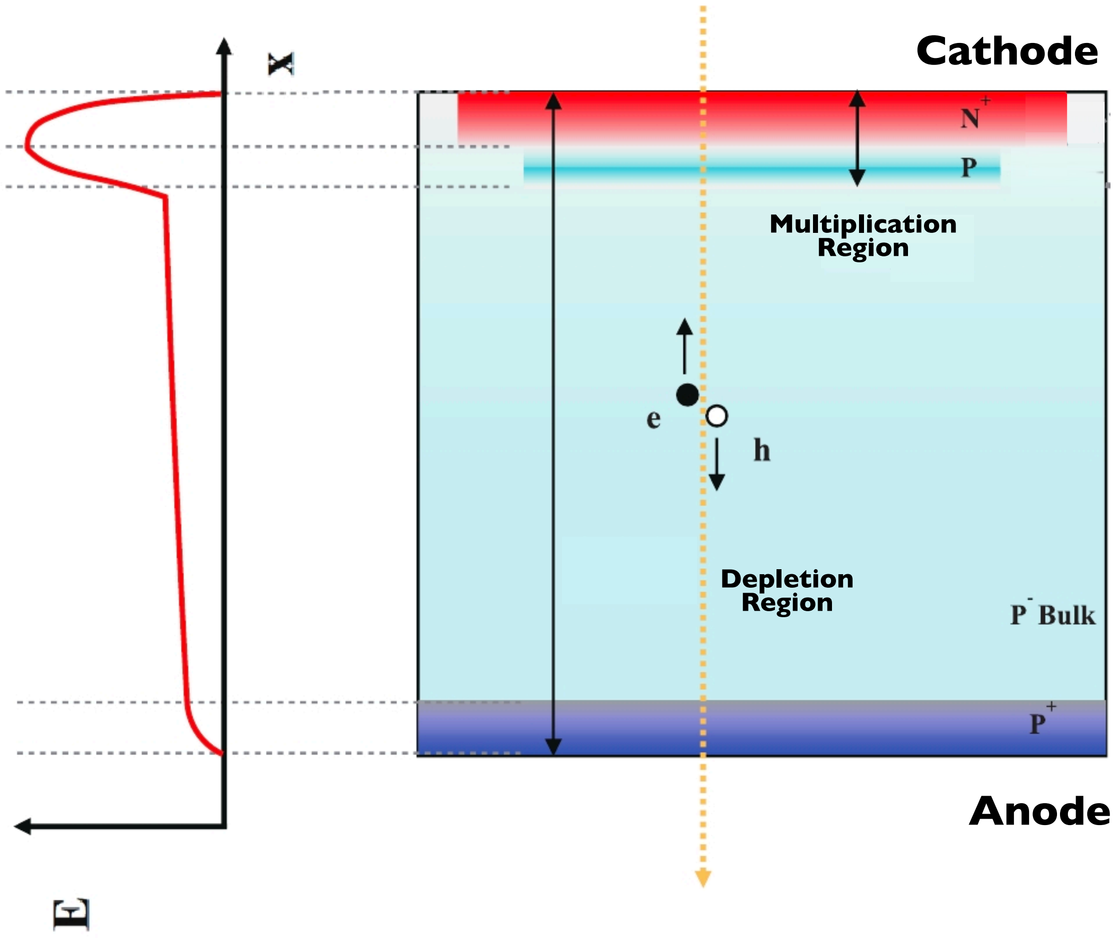
Detector requirements:

- 3 ring layout with 6.4 m^2 total area
- Harsh radiation environment: 2.5×10^{15} n_{eq}/cm^2 and 2 MGy TID in the end
- Operated at -30 °C
- Collected charge > 4 fC
- σ_t ~30 (50) ps per track and 35 (70) ps per hit at the start (end)
- Hit efficiency: 97% (95%) at the start (end)

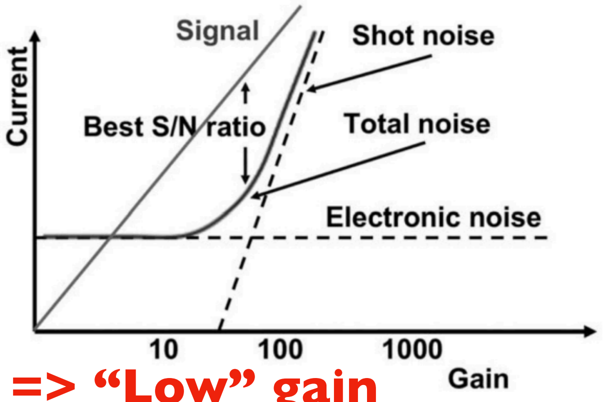
Low Gain Avalanche Detector (LGAD)

- N-in-P diode structure, with extra p-type gain layer to produce moderate gain (10 ~ 20) and ps-level time resolution (30 ps before irradiation)
- LGAD size for HGTD: 1.3 mm × 1.3 mm pad in 15 × 15 array with 50 µm thickness.

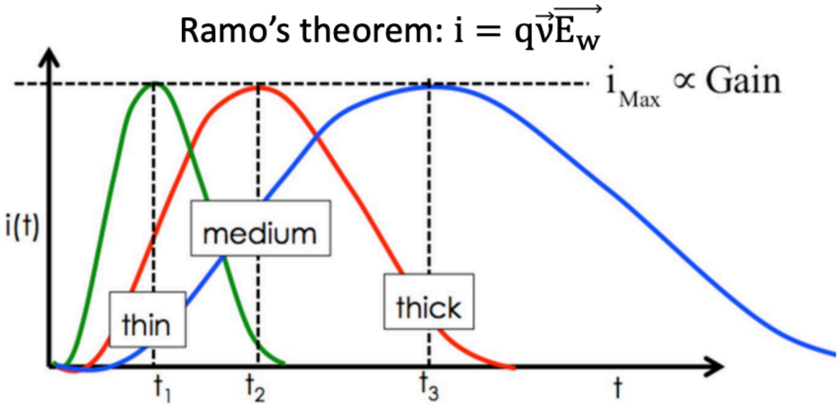
$$\sigma_t^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{Time walk}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TDC}}^2$$



- $\sigma_{\text{Jitter}} \sim \dfrac{t_{\text{rise}}}{S/N}$
- $\sigma_{\text{Time walk}} \sim [\dfrac{V_{\text{th}}}{S/t_{\text{rise}}}]_{\text{RMS}}$ (V_{th}: threshold)
- σ_{Landau}: caused by non-uniform energy deposition
- $\sigma_{\text{Distortion}}$: caused by non-uniform weighting field E_w
- σ_{TDC} : TDC binning resolution: 7.2 ps (25/√12)



=> “Low” gain

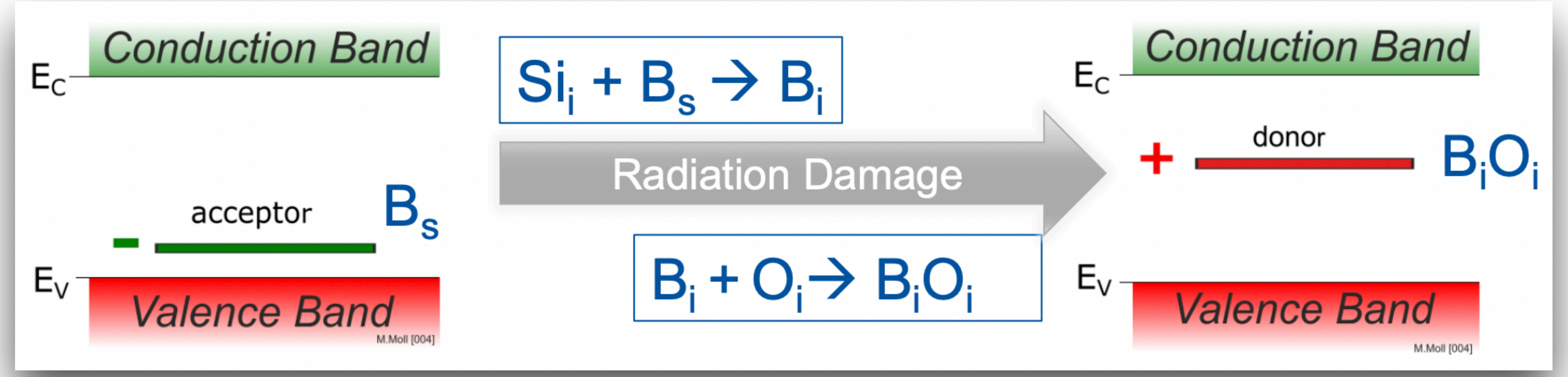


=> Thin detector: 50 µm

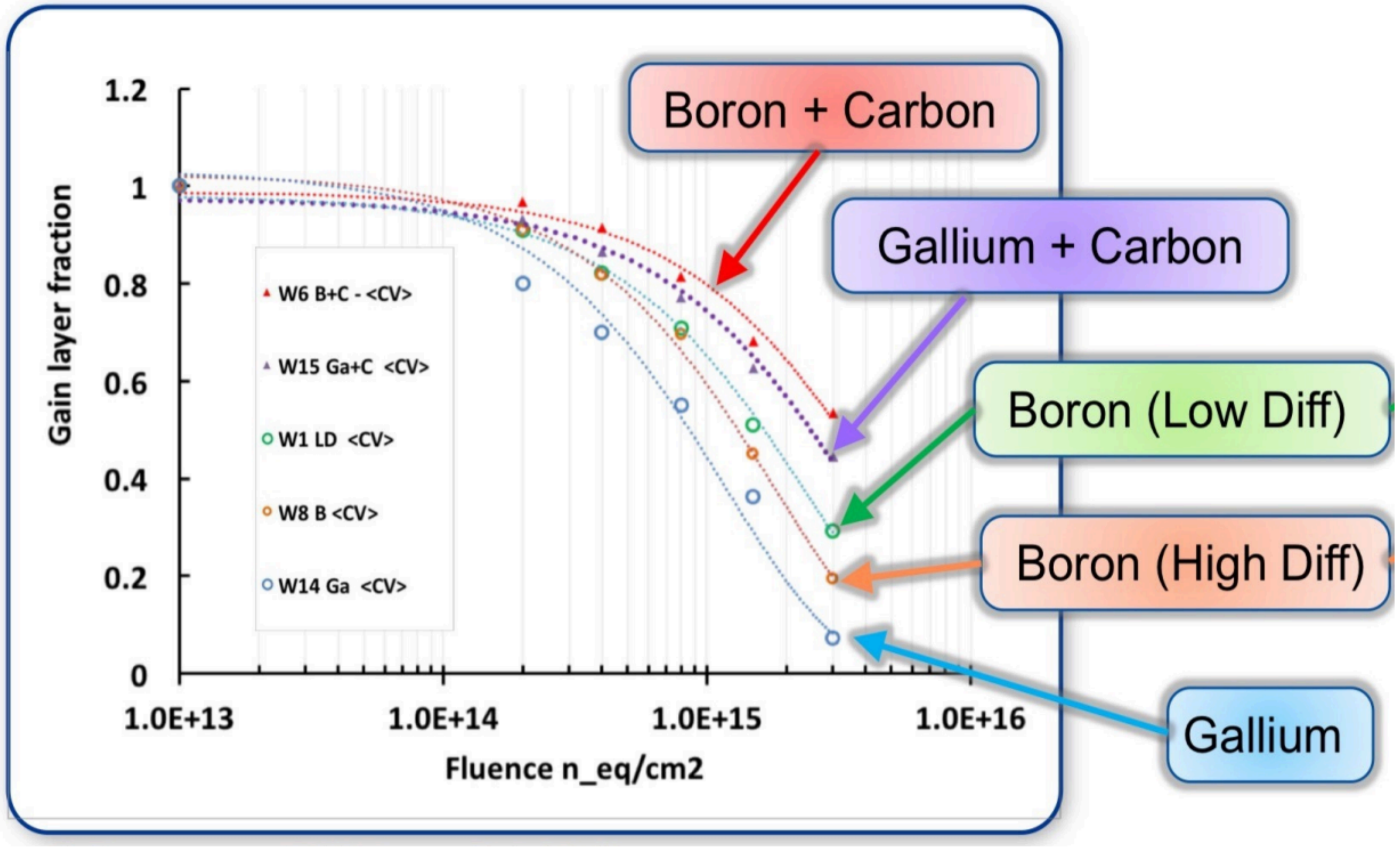
Radiation hardness of LGAD

- The reduction of effective doping in the gain layer is caused by the "acceptor removal" process →LGAD gain reduction after non-ionizing radiation damage.

[M.Moll, VERTEX2019]



- Explored use of different gain layer designs, doping materials and C-enriched substrates → **B + C** shows largest gain after irradiation ($C_i + O_i \rightarrow C_iO_i$ competes with $B_i + O_i \rightarrow B_iO_i$)

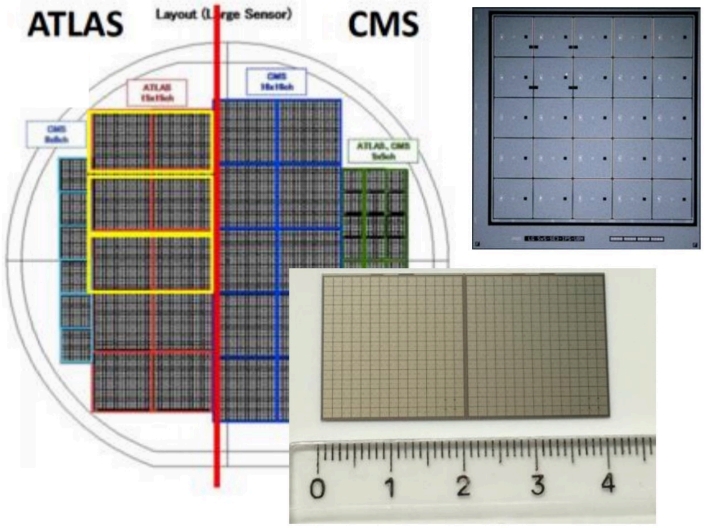


G.Paternoster, TREDI 2019

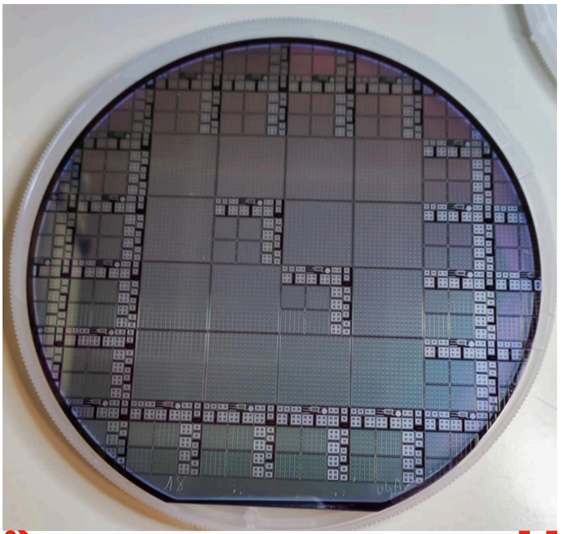
LGAD prototypes produced by different vendors

- LGADs from many producers have been widely studied over the last few years, including:
  CNM (Spain), FBK (Italy), HPK (Japan), IHEP-IME (China), USTC-IME (China), IHEP-NDL (China)
- For each vendor, the prototypes include **small-array** sensors (1×1, 2×2, 5x5) and **large-array** sensors (15×15 full-size sensor for ATLAS HGTD)

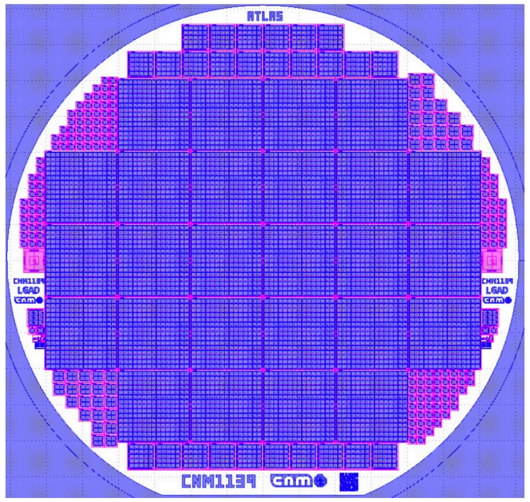
HPK-P2 (2022, 6”)



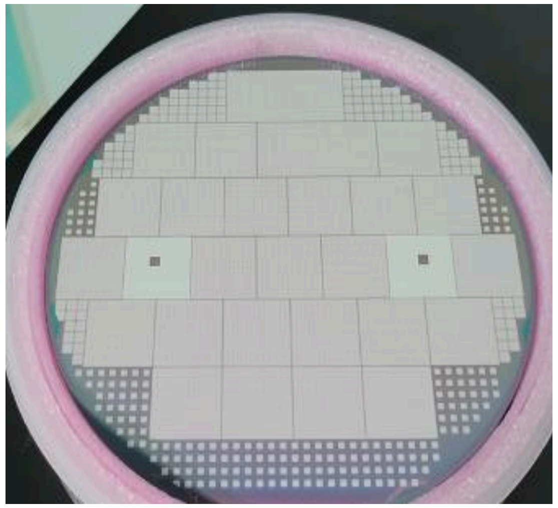
FBK-UFSD 4.0 (2022, 6”)



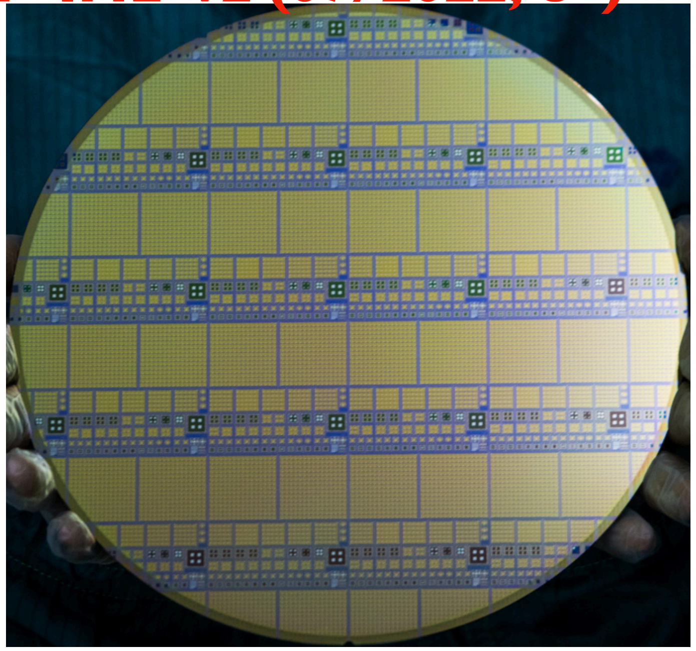
CNM-Run15973 (2022, 6”)



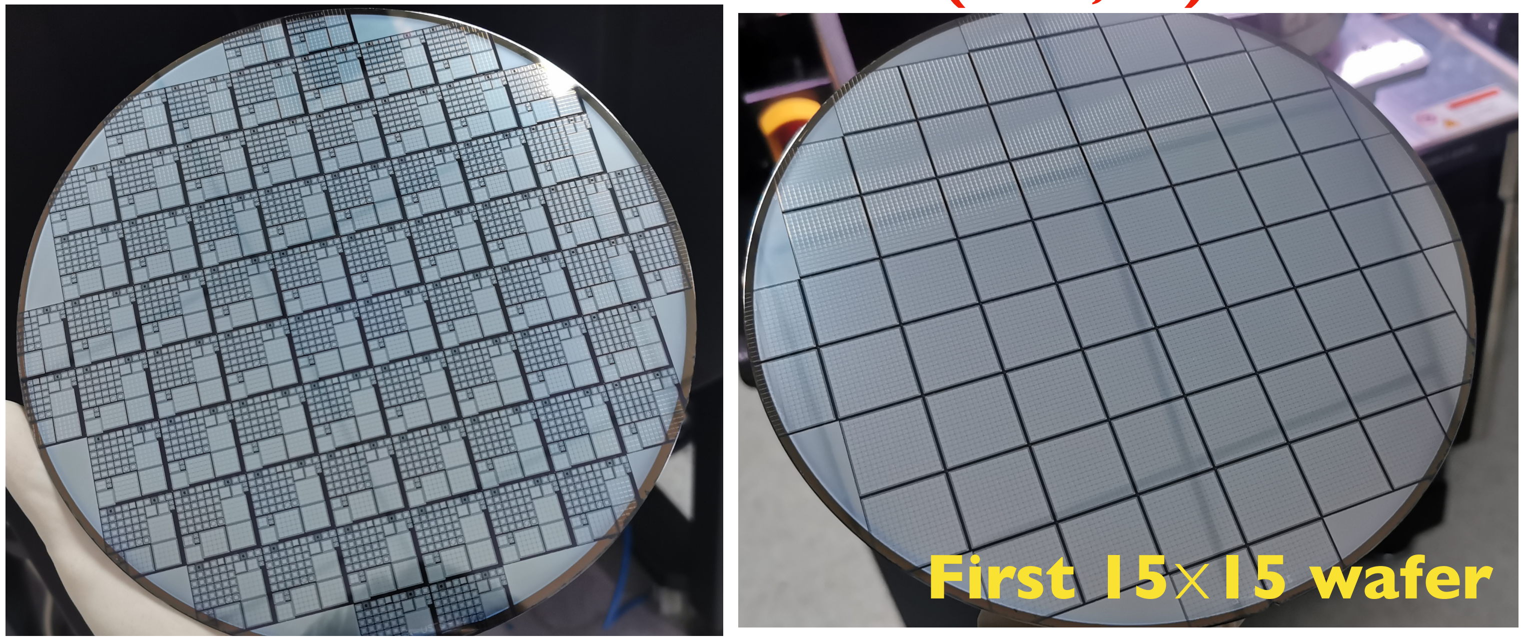
NDL-v4 (2021, 6”)



IHEP-IME-v2 (07/2022, 8”)



USTC-IME-v2.0/2.1 (2021, 8”)

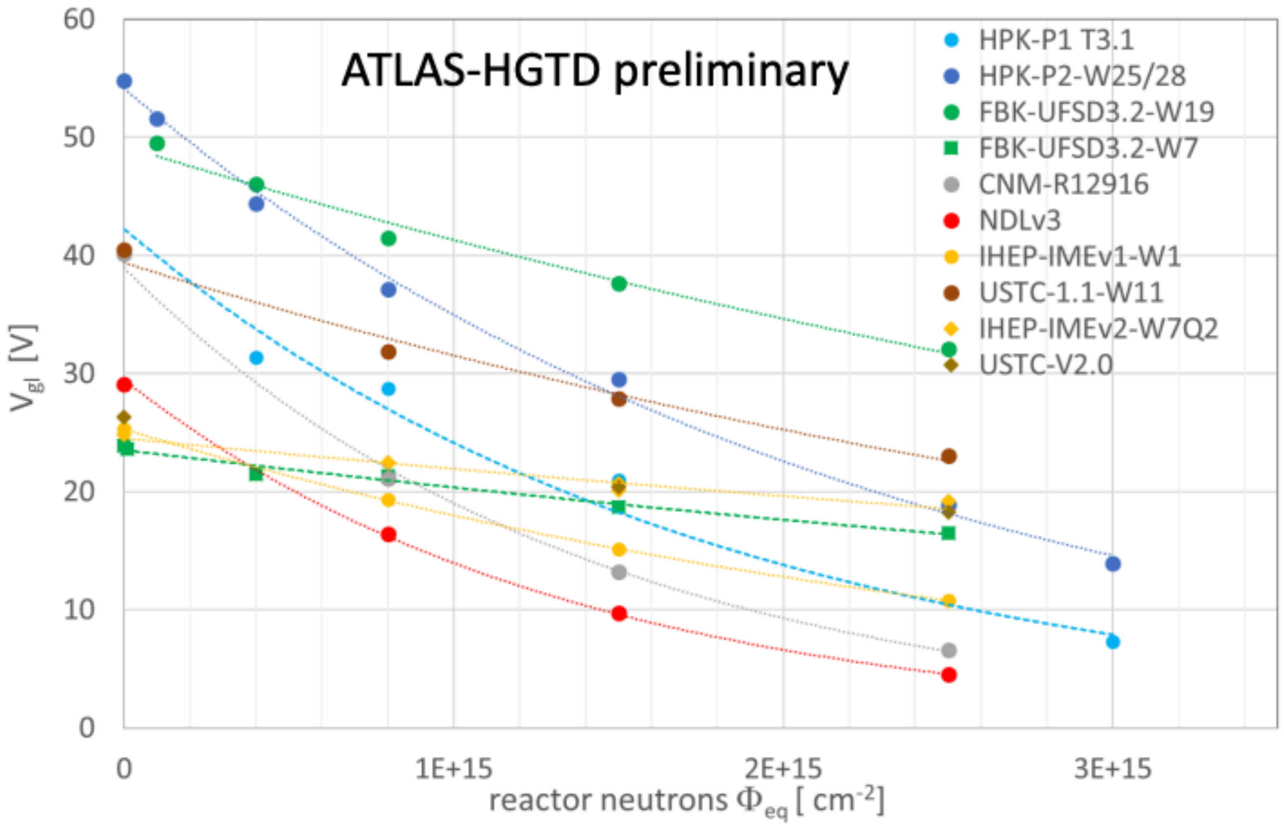


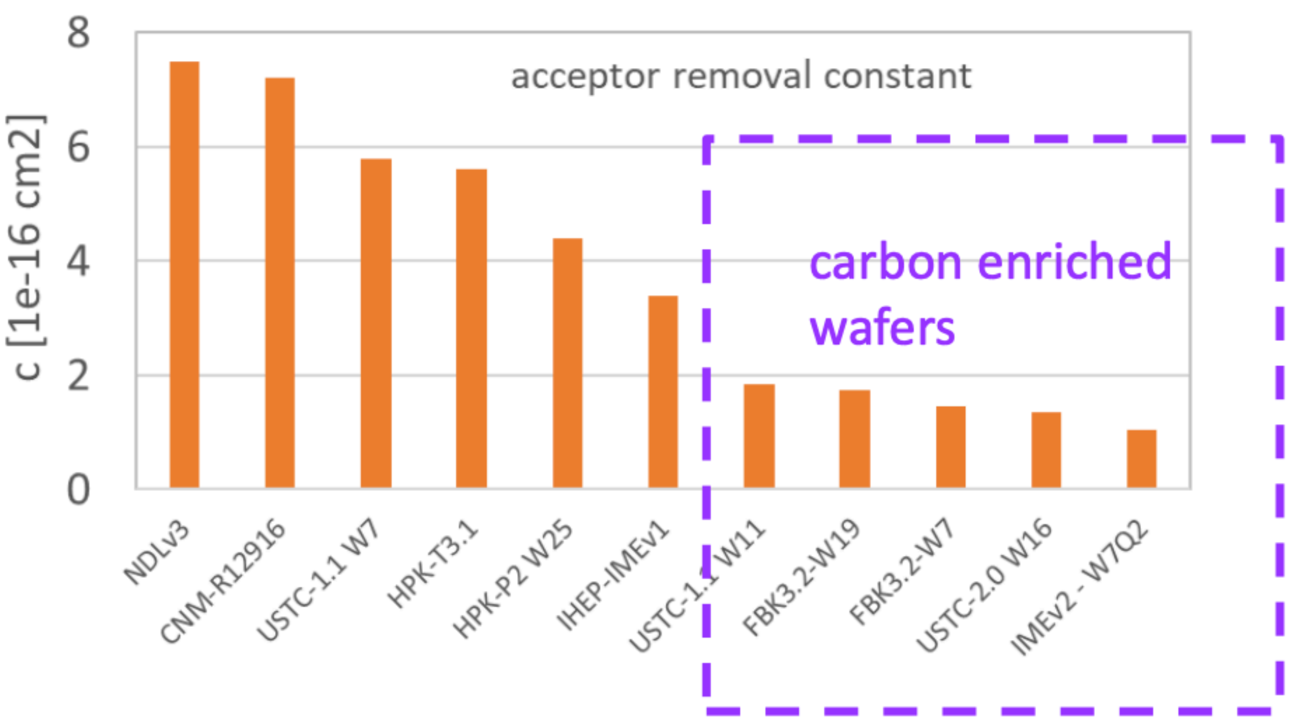
Evaluation of radiation hardness

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots

- Acceptor removal coefficient (c-factor) is extracted from the gain layer depletion voltages (V_{GL}) obtained from CV curves:

$$V_{GL,\Phi_{eq}} = V_{GL,0}\,\exp(-c \cdot \Phi_{eq})$$



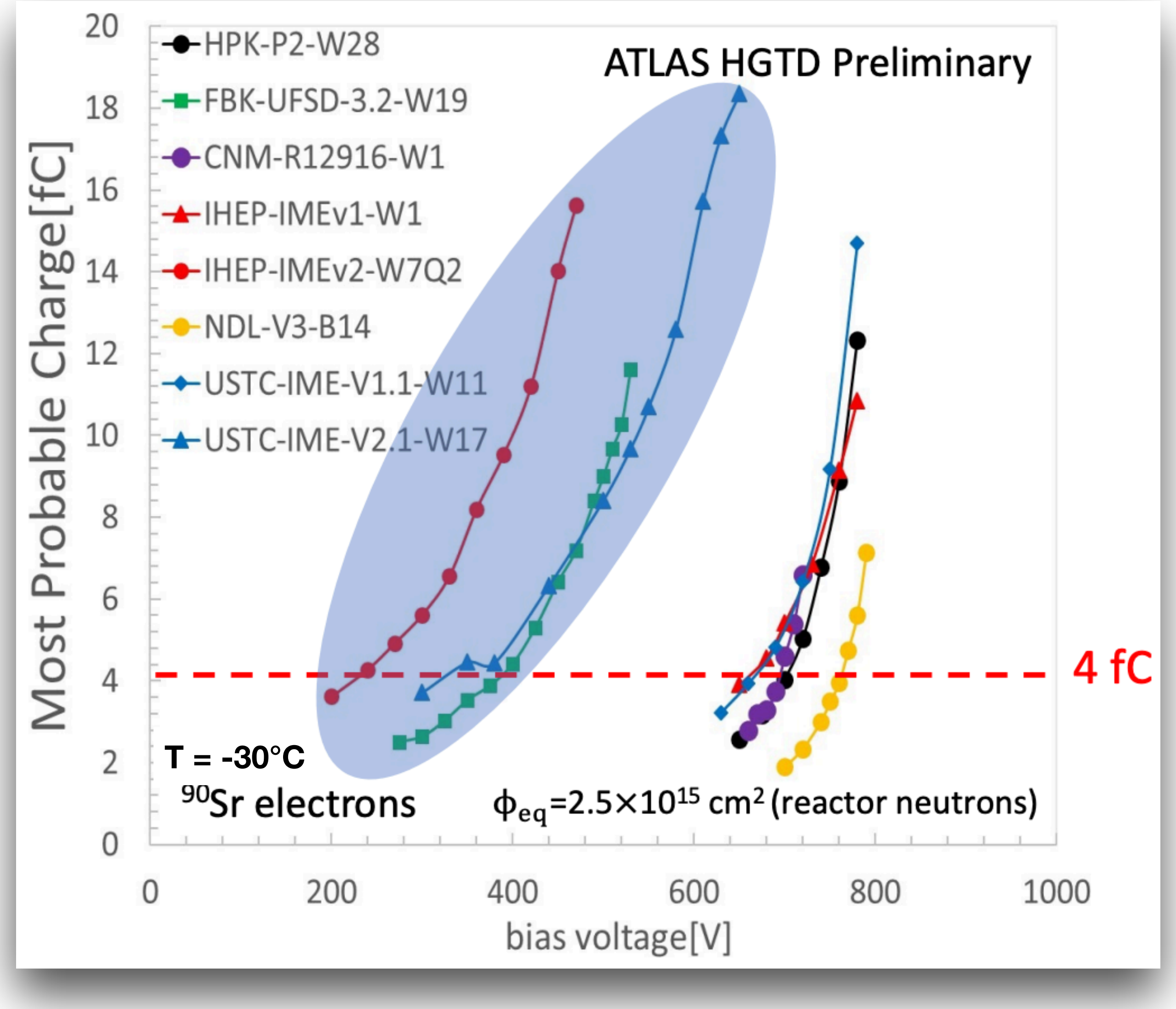


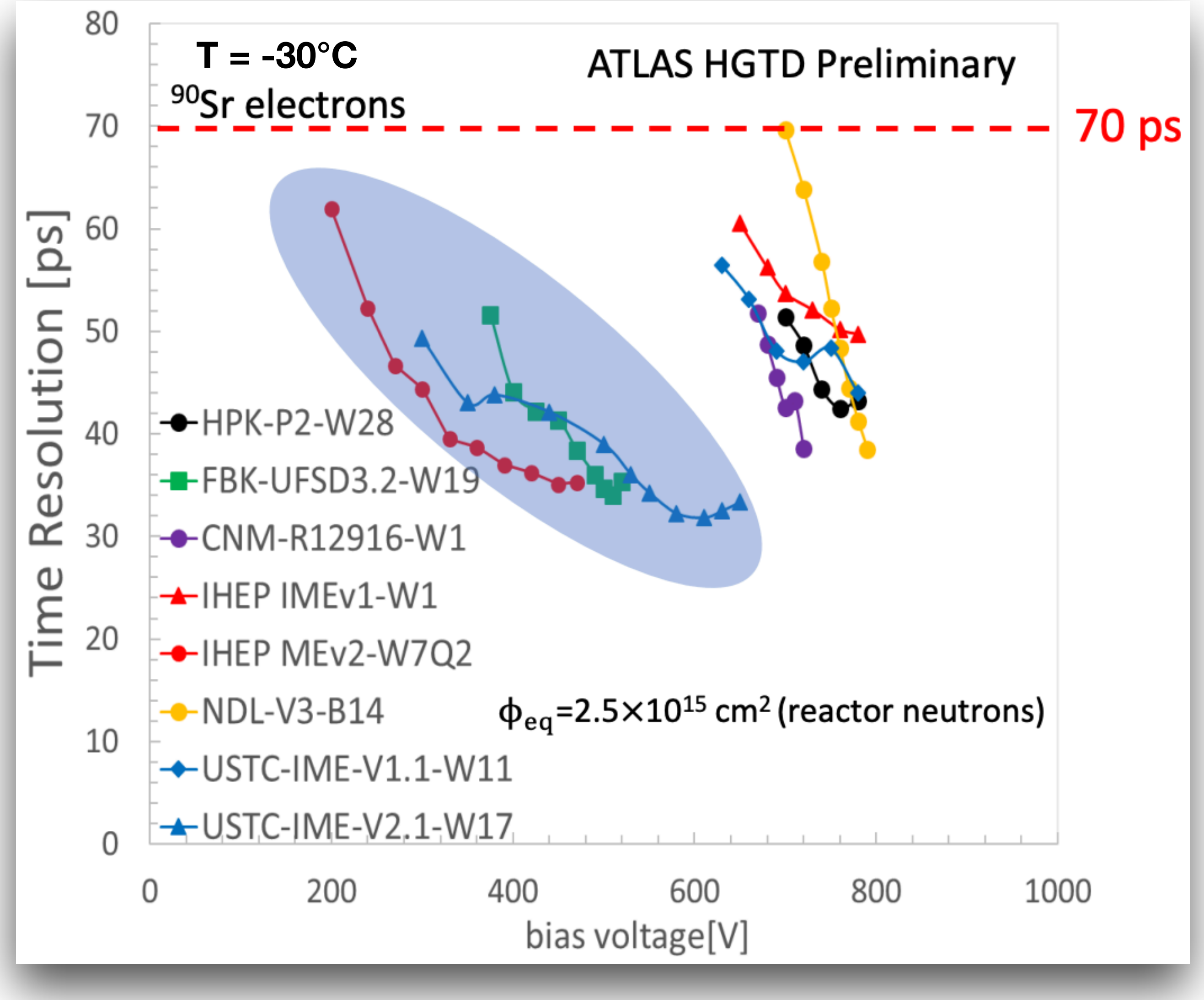
- Optimization: adjust the configuration of the gain layer (carbon/boron) to achieve a lower acceptor removal coefficient.
- Samples from FBK, IHEP-IME, USTC-IME have shown sufficiently small c values.

Collected charge and time resolution with Sr^{90} source

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots

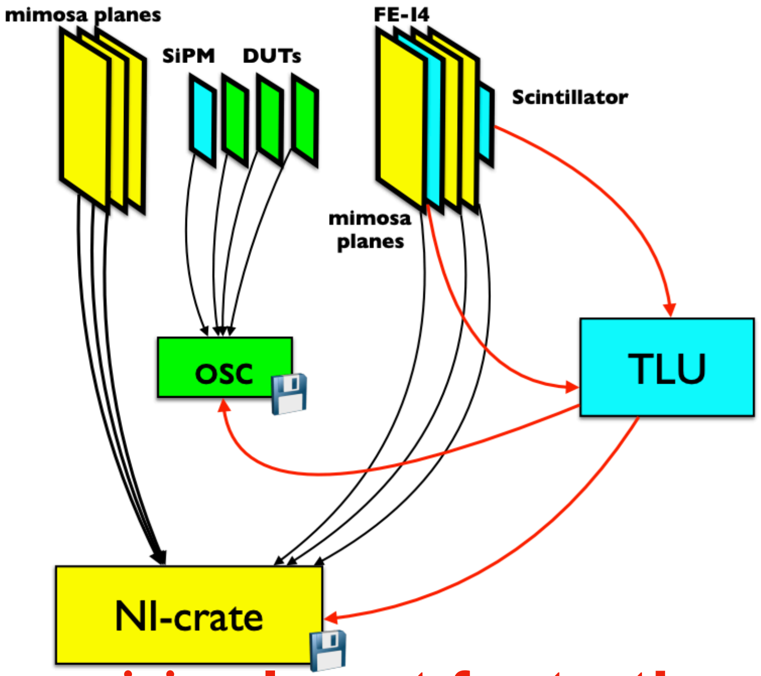
- Sensors were exposed to fast neutrons with fluences up to **2.5×10^{15} n_{eq}/cm^2** at the TRIGA reactor in Ljubljana, Slovenia.
- After irradiation the bias voltage is increased to compensate the LGAD performance degradation due to the loss of gain.
- **Carbon-enriched** LGADs (blue region) allow for the sensor operation at lower voltages.



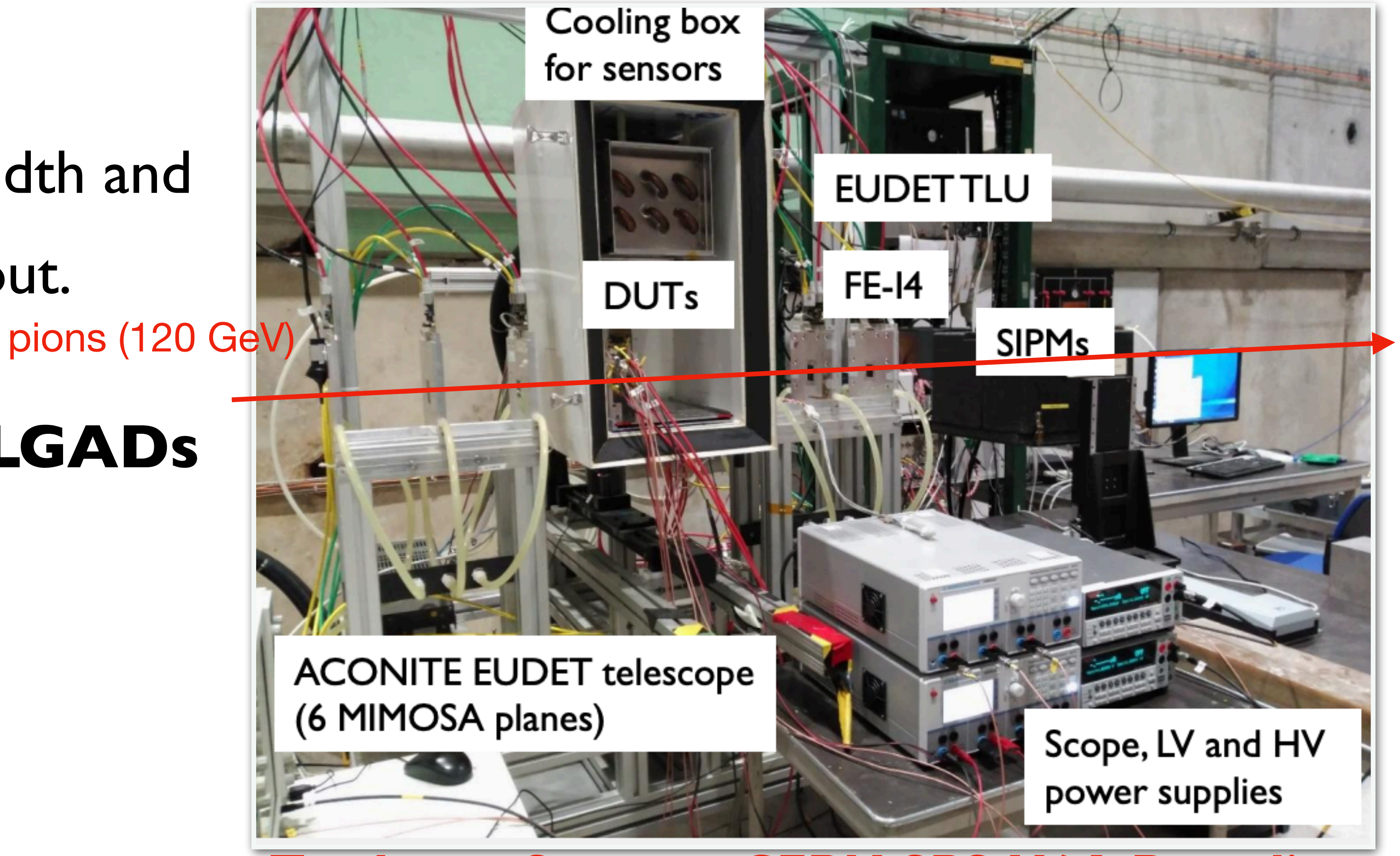


Testbeam campaigns

- Performed at **CERN SPS** H6A and **DESY.**
- Use EUDET telescope with **6 MIMOSA26** planes for tracking and with **FEI4** for triggering the region of interest.
- **Oscilloscope** with 1 GHz bandwidth and 10 GS/s is used for waveform readout.
- The **SiPM/MCP-PMT/35um-LGADs** are used as time reference.



Data acquision layout for testbeam

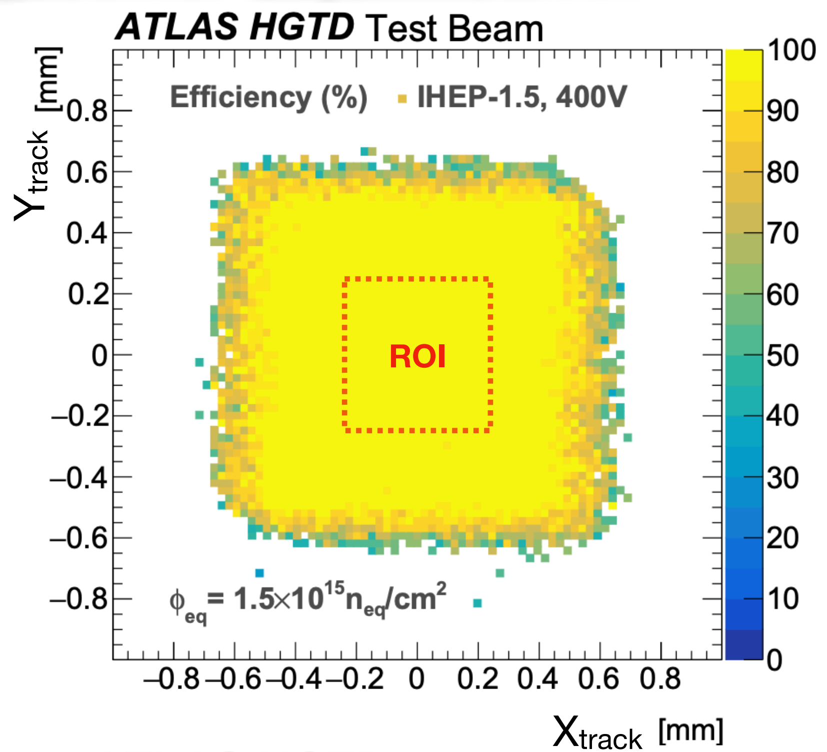


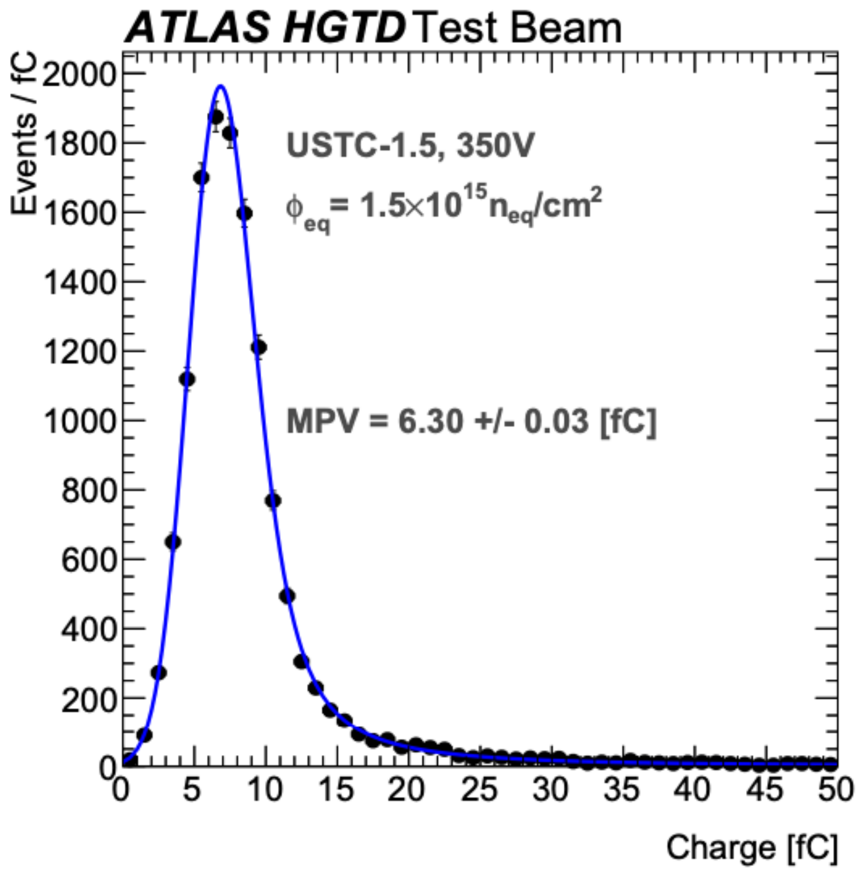
Testbeam Setup at CERN SPS H6A Beamline

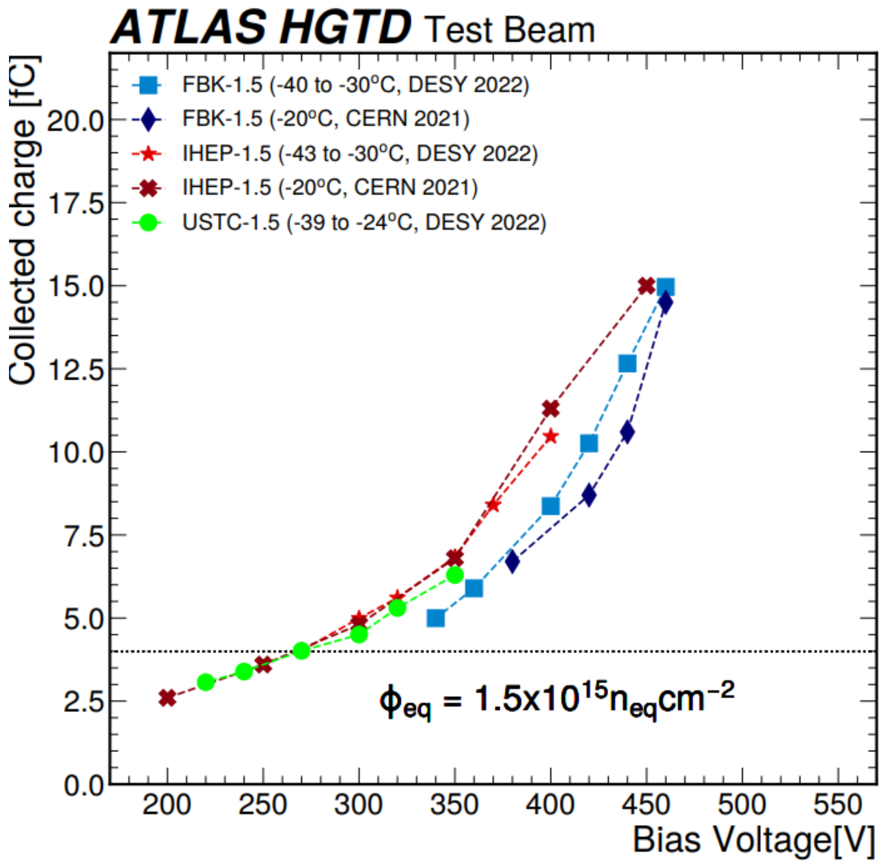
Collected charge

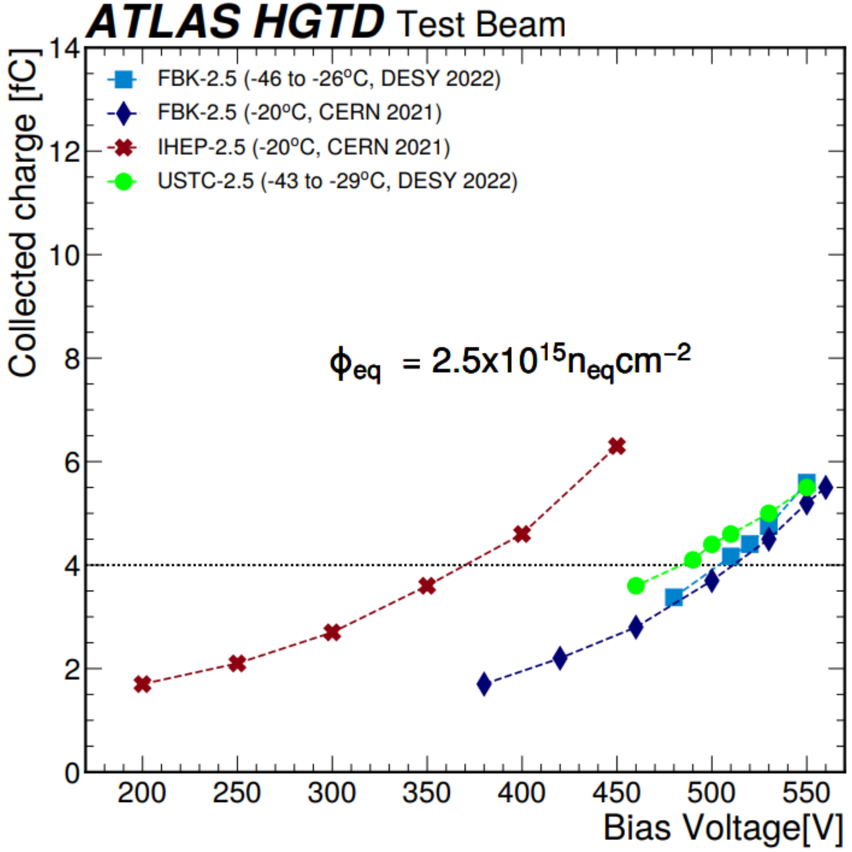
S.Ali et al 2023 JINST 18 P05005

- Distribution of charge in the Region of Interest (ROI) was fitted with a Landau-Gaussian convoluted function
- Collected charge:
  - Defined as the Most Probable Value (MPV) from fit
  - Above the minimum required charge of 4 fC needed for a sufficient timing resolution







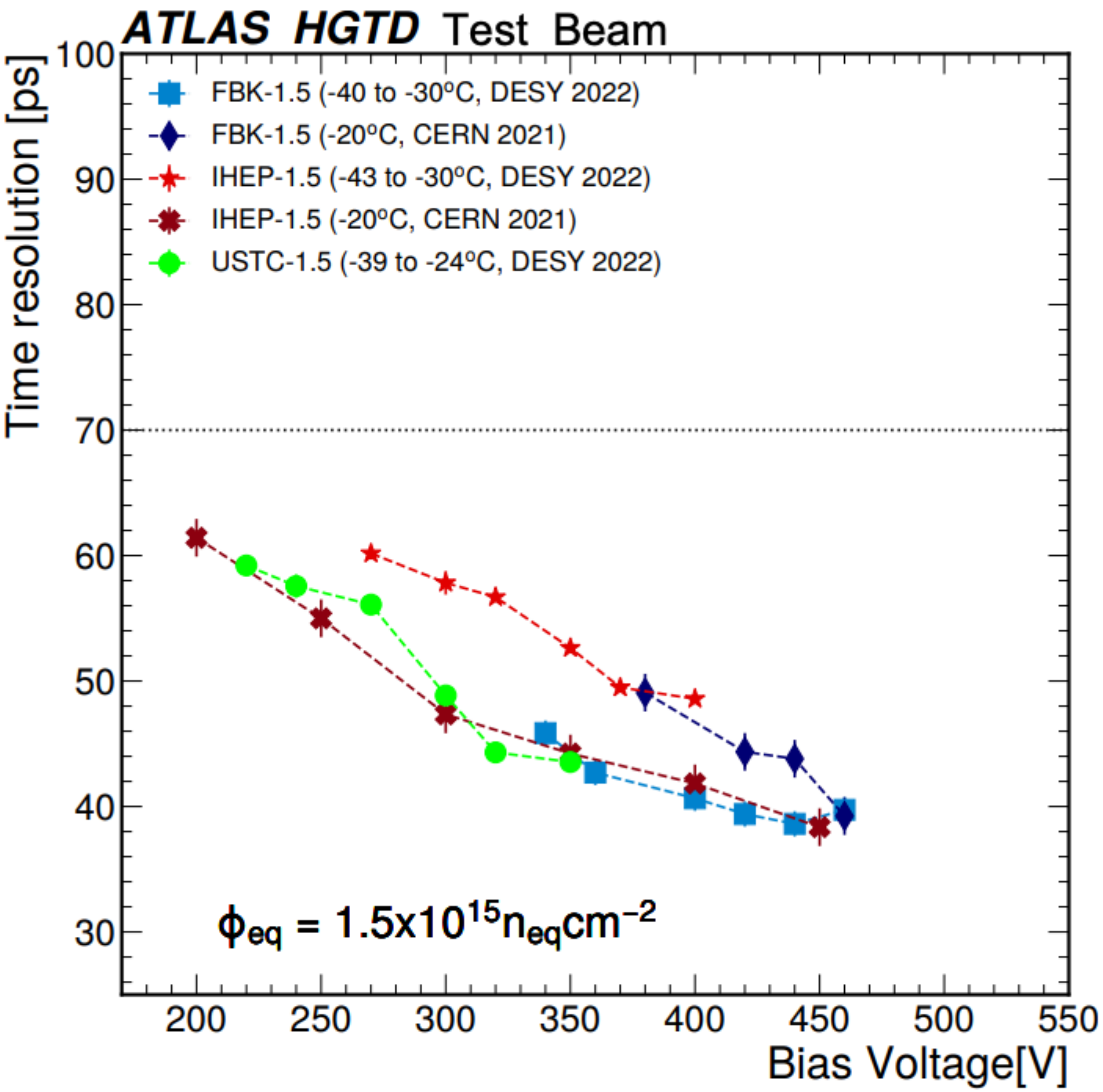


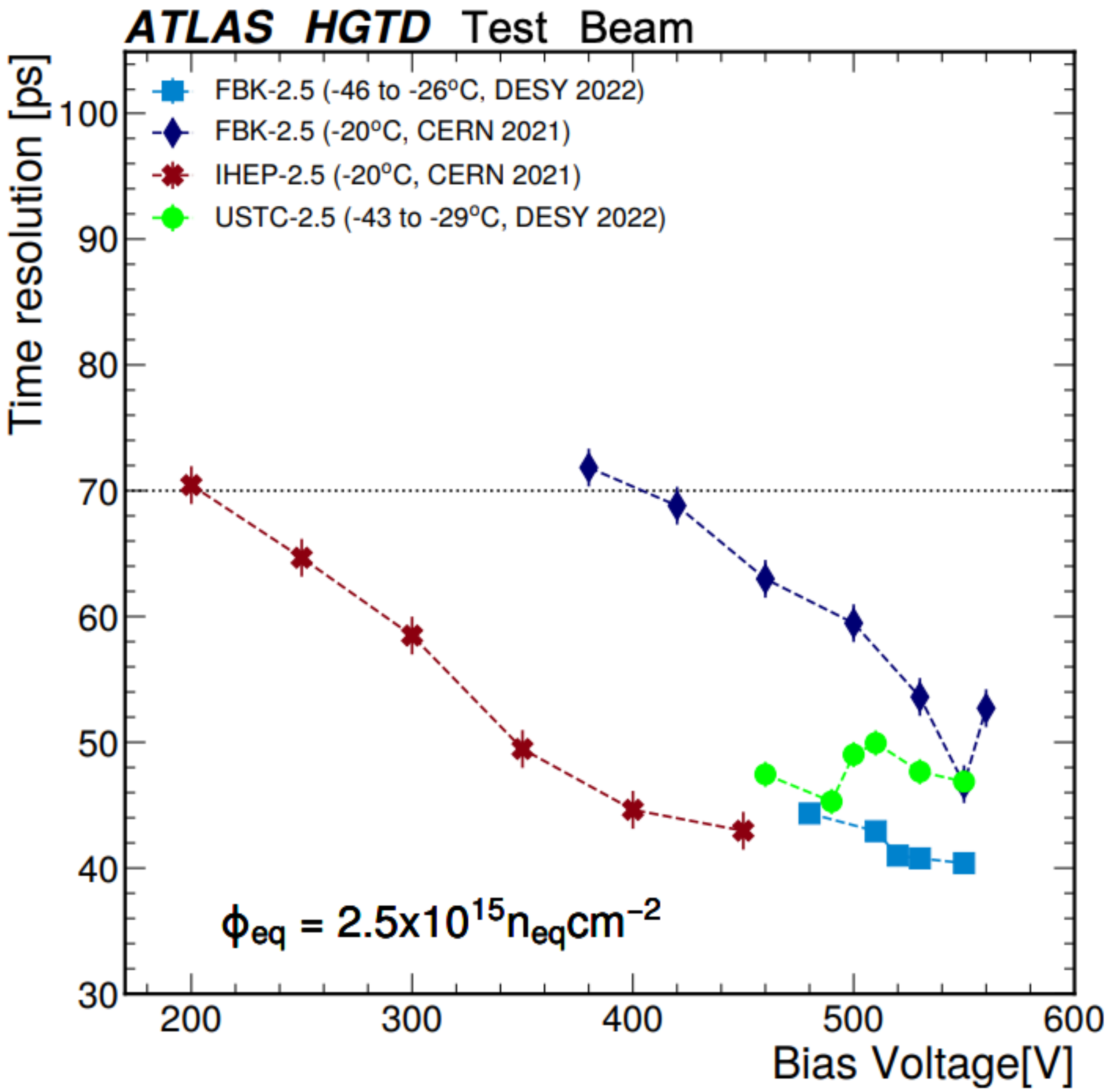
- All sensors tested fullfill the HGTD requirement (**4 fC**) after being irradiated to maximum fluence.

Time resolution

S.Ali et al 2023 JINST 18 P05005

- Time resolution is obtained by unfolding the time resolution with reference detectors.





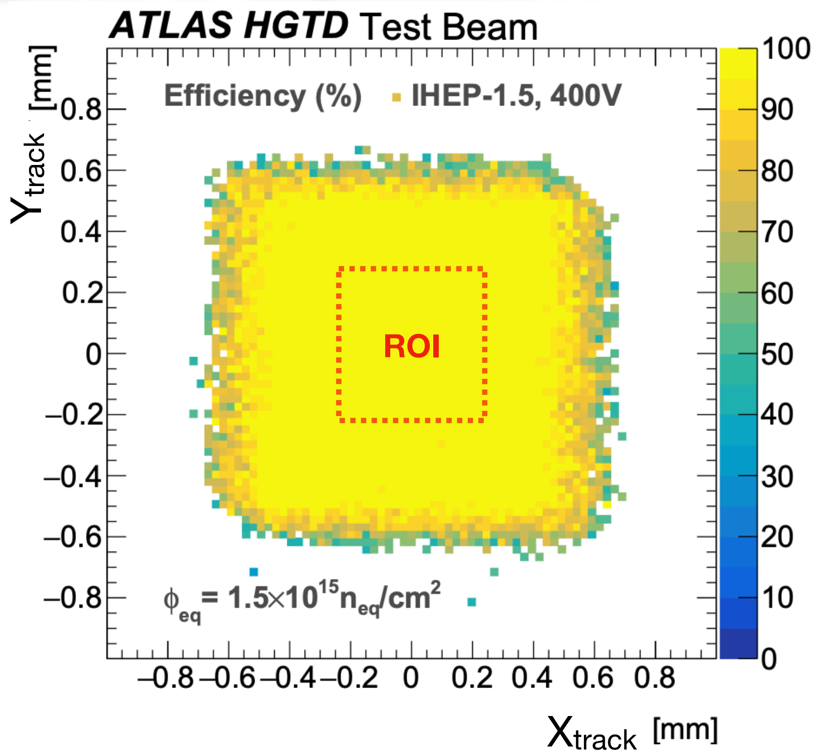
- All sensors tested fulfil the HGTD requirement (**70 ps**) after being irradiated to maximum fluence.

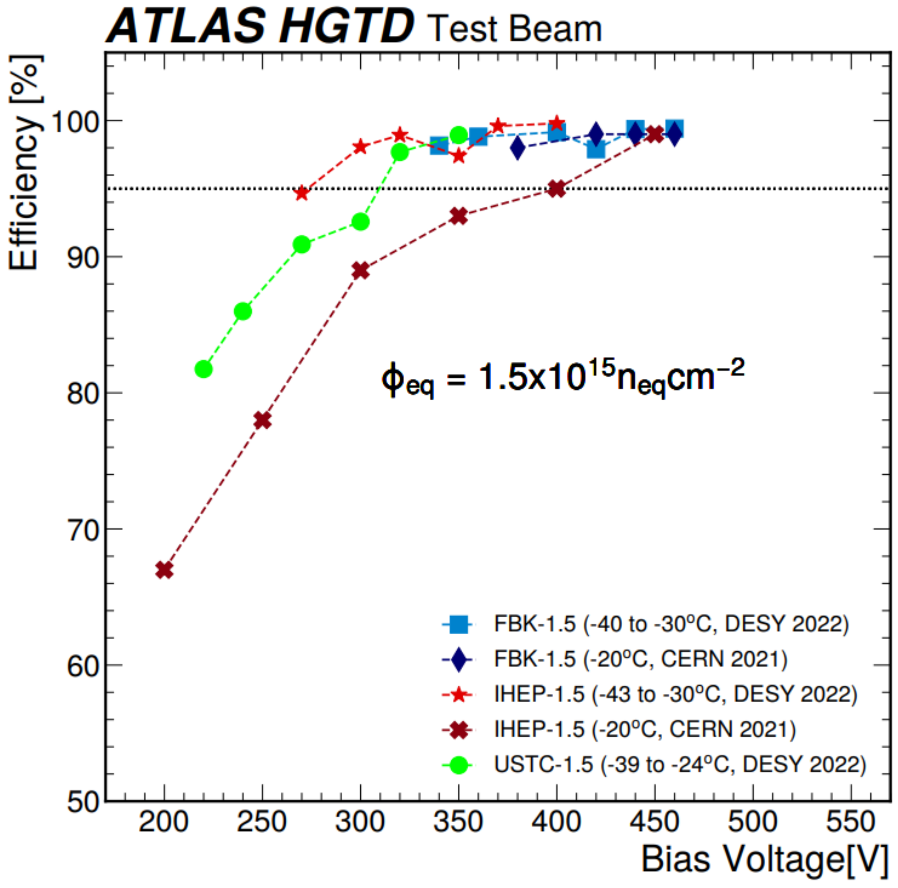
Hit efficiency

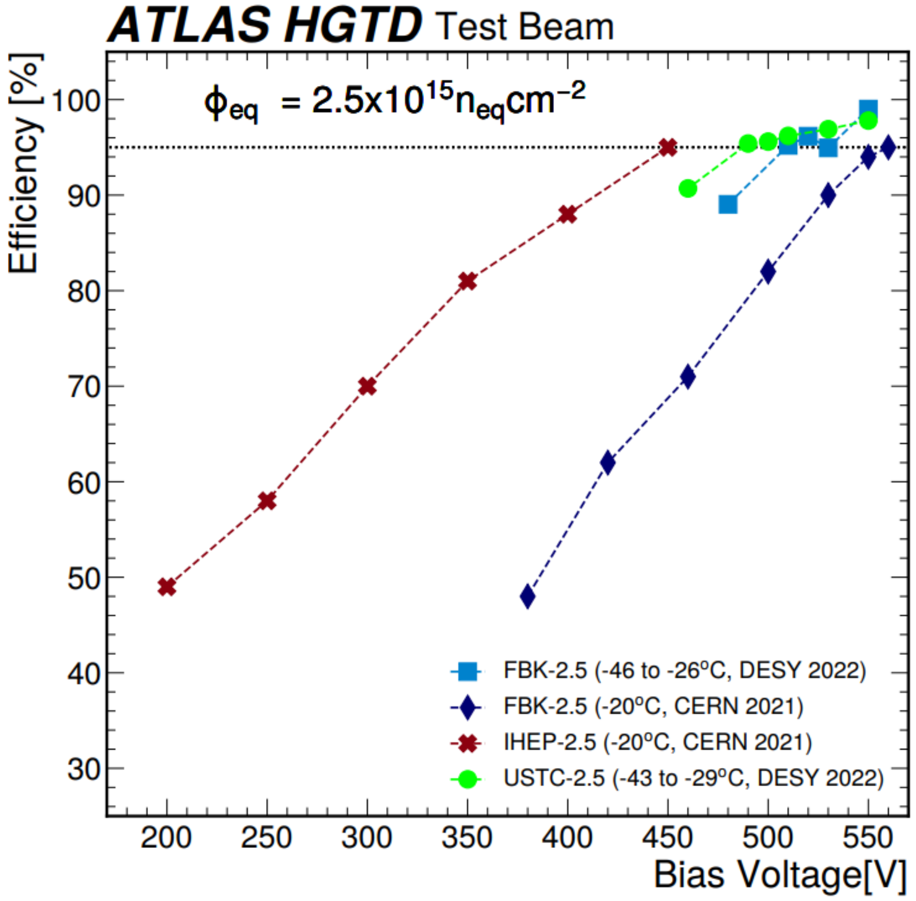
S.Ali et al 2023 JINST 18 P05005

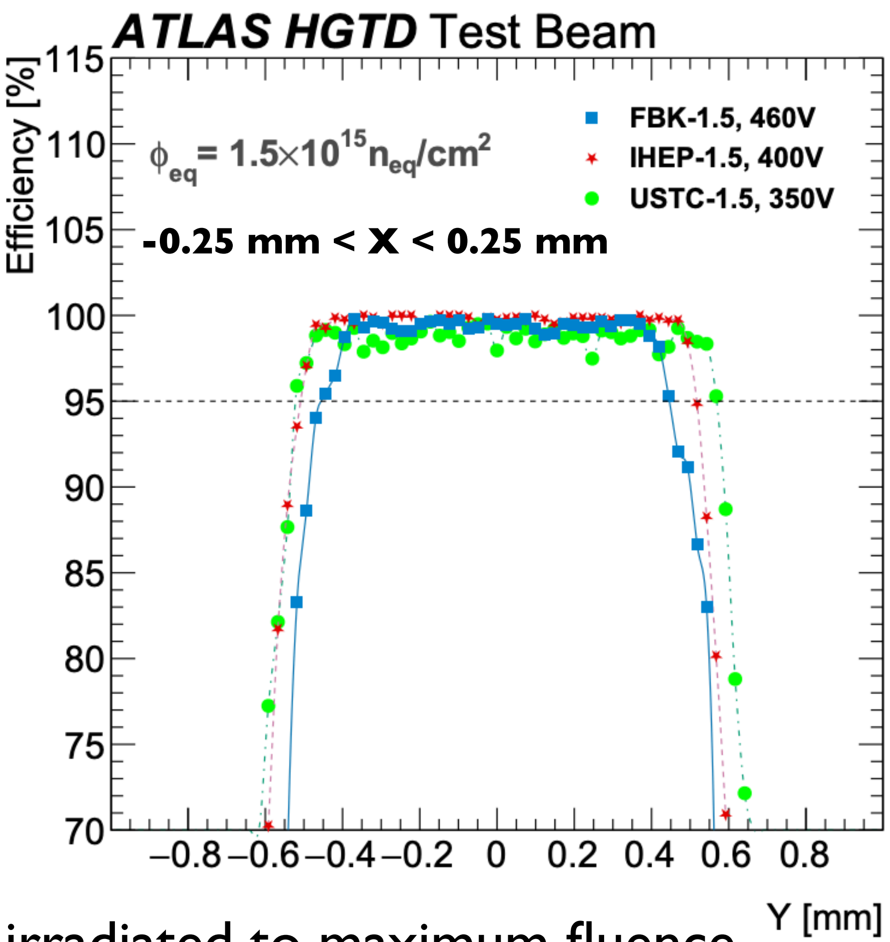
$$\textbf{Hit Efficiency} = \frac{\textbf{Reconstructed tracks with } q > Q_{cut}}{\textbf{Total reconstructed tracks}}$$

- Q_{cut} = 2 fC (minimum achievable threshold of the readout ASIC)
- Achieved efficiency of 95% required for HGTD after irradiation



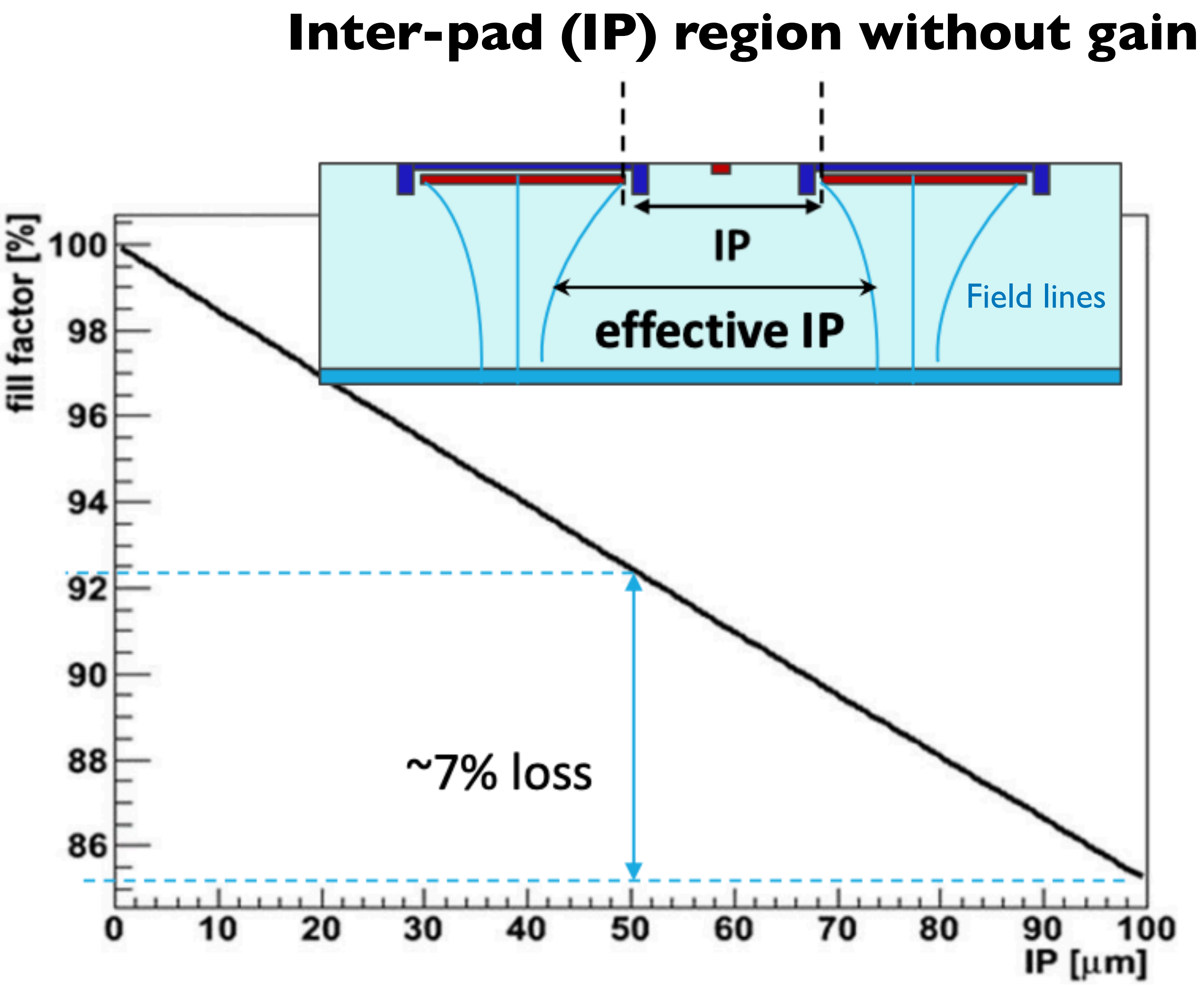






- All sensors tested fullfill the HGTD requirement (**95%**) after being irradiated to maximum fluence.

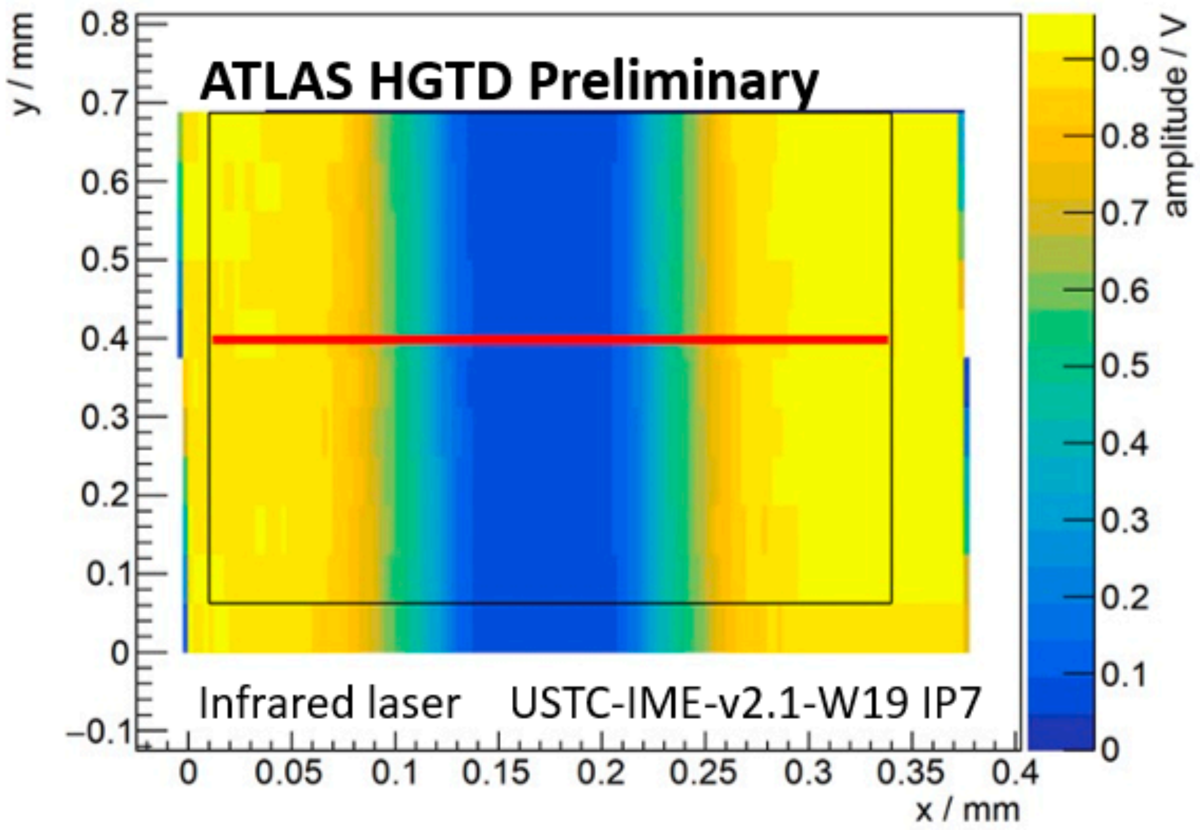
Inter-pad (IP) gap of LGAD

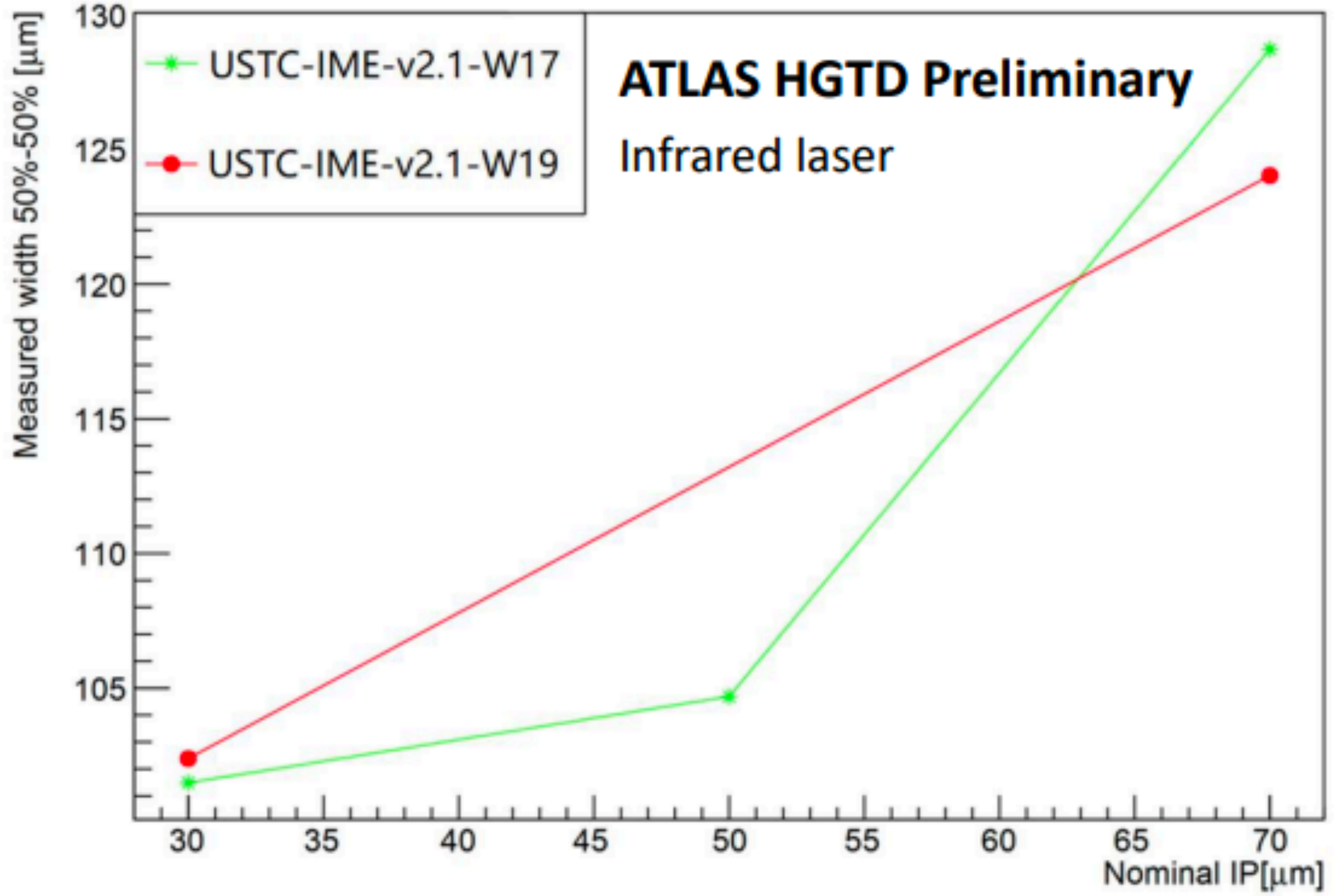


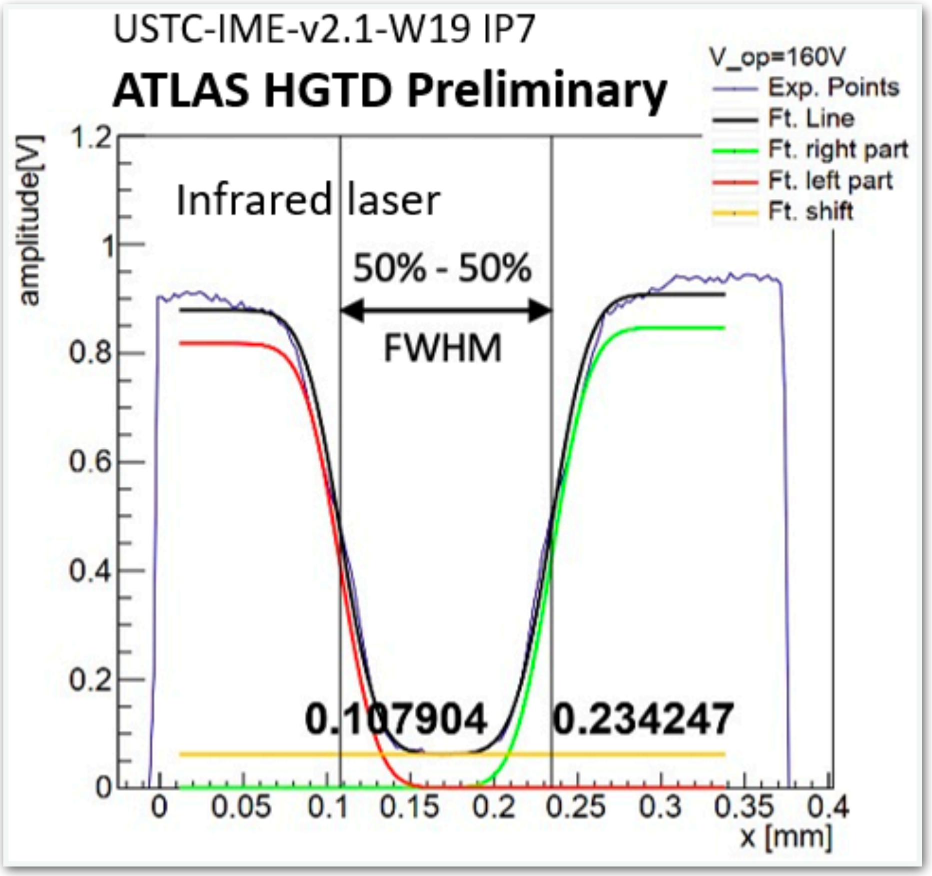
G. Kramberger, CERN Detector Seminar

- Current LGAD sensors show **~50-60 μm larger effective IP gap** with respect to the nominal one → **loss of fill factor**
- The inter-pad gap has been measured in recent HGTD test-beam campaigns with **tracks reconstructed by the beam telescope software**.

IP gap measurement



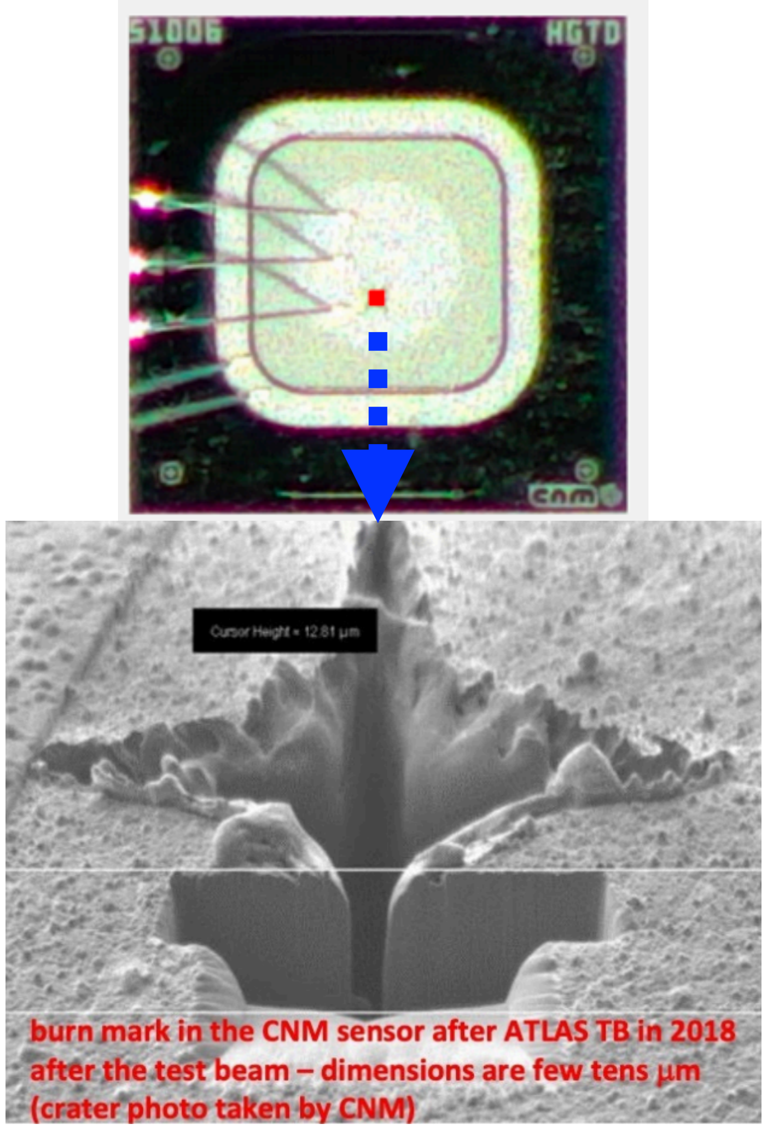




- **Inter-pad gap** measurements are performed at different bias voltages with 1064nm laser TCT scan.
- The sum of two sigmoids are used in the fitting.
- The measured IP gap from the TCT is better than **105 µm**, comparable with the HGTD requirement (100 µm).

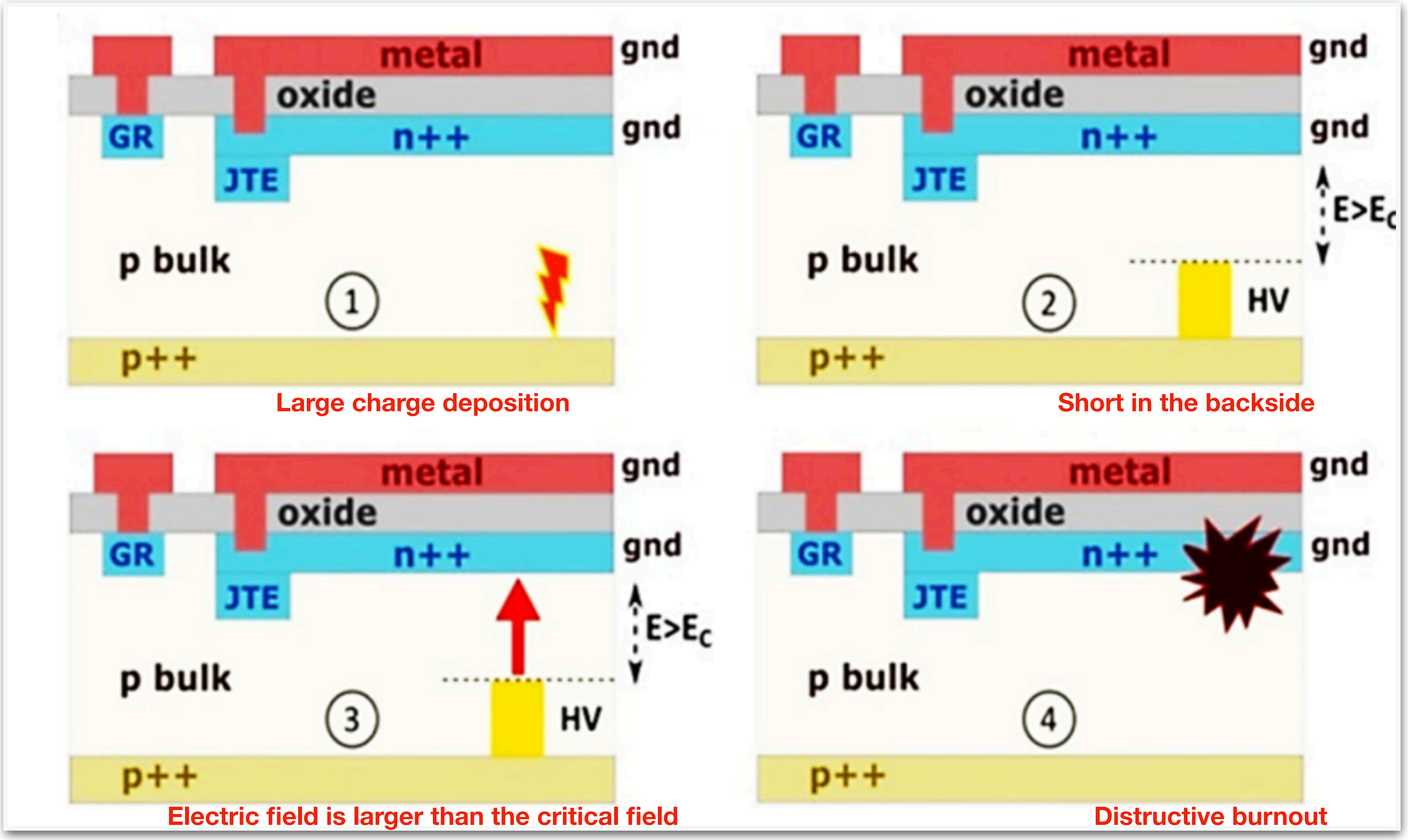
LGAD Single Event Burnout

- Single Event Burnout (SEB) has been observed in several test beam campaigns
  - **Irreversible breakdown** triggered by a large charge deposition while operating at high voltage.
  - Observed by CMS/ATLAS/RD50 teams.
  - Systematically studied by the HGTD group in beam tests.



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)

L.A. Beresford et al. JINST 18 P07030



Large charge deposition

Short in the backside

Electric field is larger than the critical field

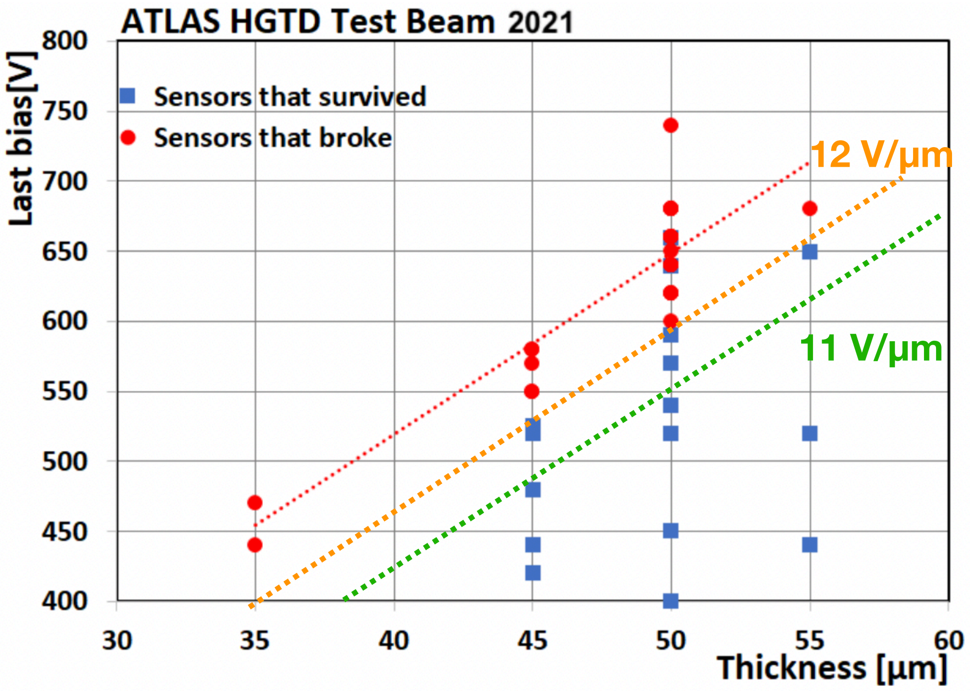
Distructive burnout

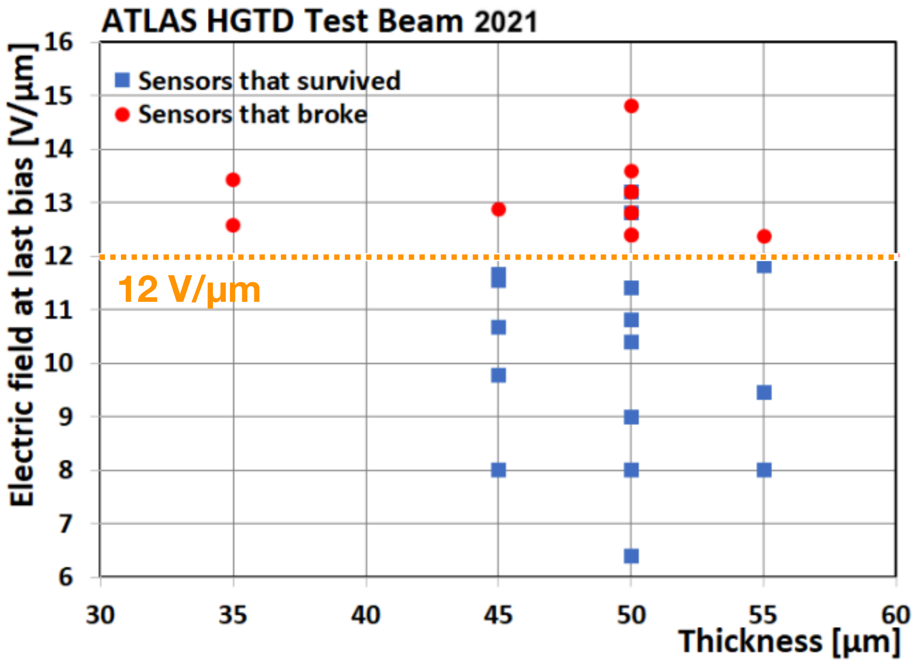
Mechanism of SEB

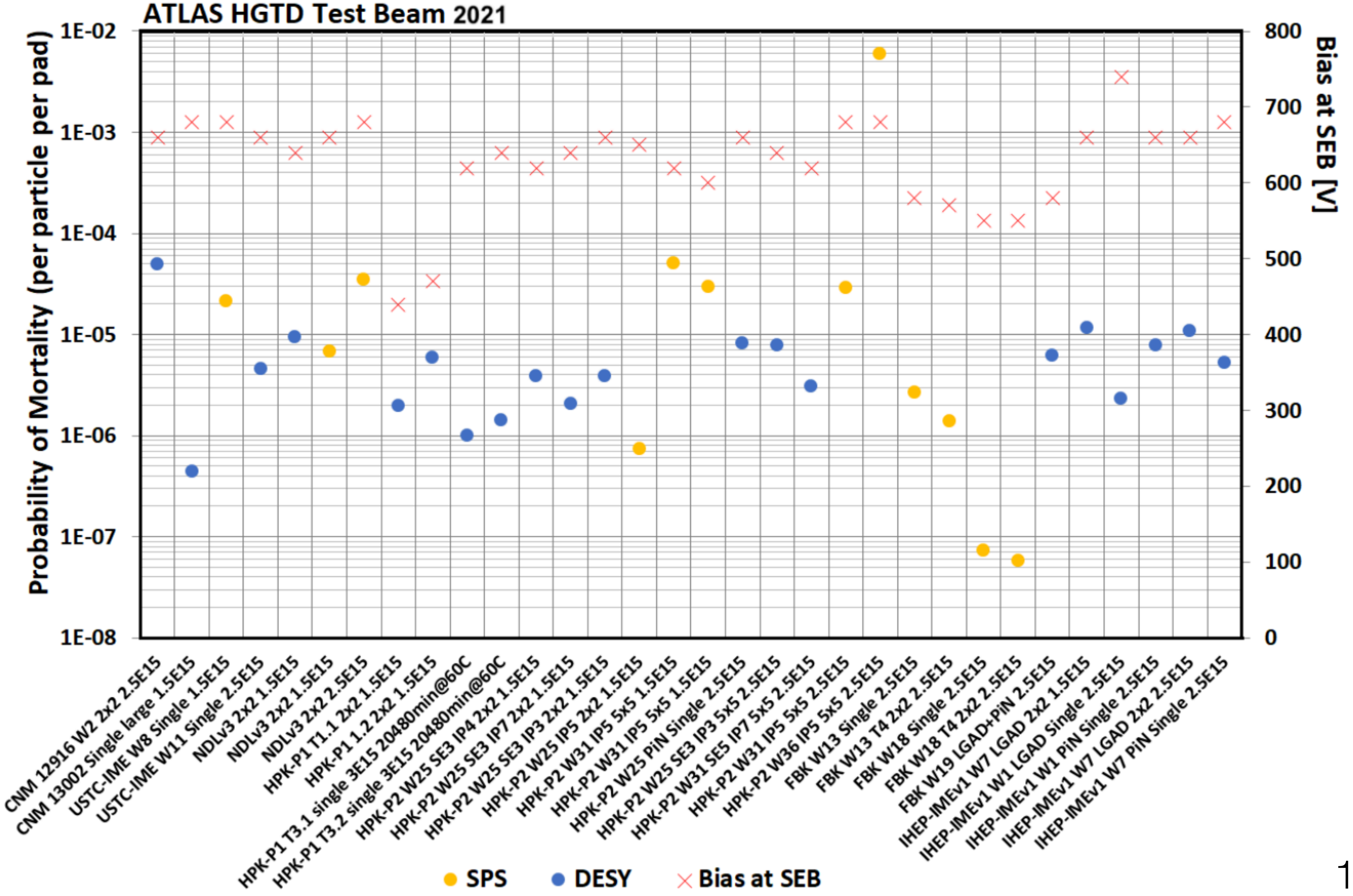
Single event burnout

- The SEB effect is studied by operating the LGADs of different **thicknesses** at several **bias voltages**.
- A clear **correlation** between the SEB bias and sensor thickness has been found.
- The **electric fields** for the bias at which the SEB occurs (last bias point) are compared.
- **12 V/µm** is obtained as the minimum electric-field for the SEB.
- **Safe zone**: |E| < **11 V/µm** (Max bias voltage is 550 V for 50 µm thick LGADs)

L.A. Beresford et al. JINST 18 P07030



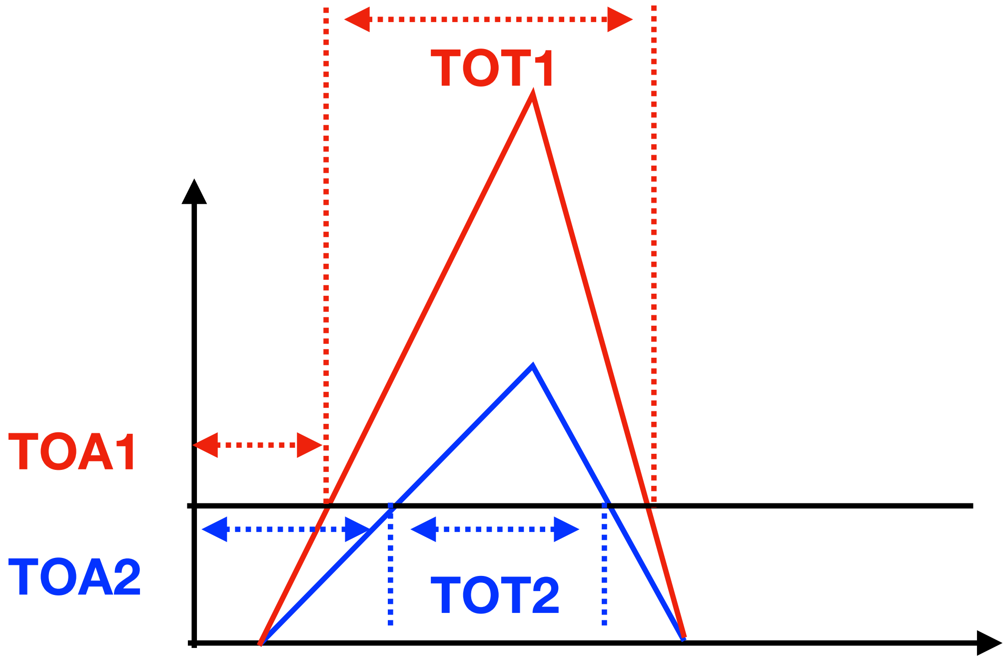


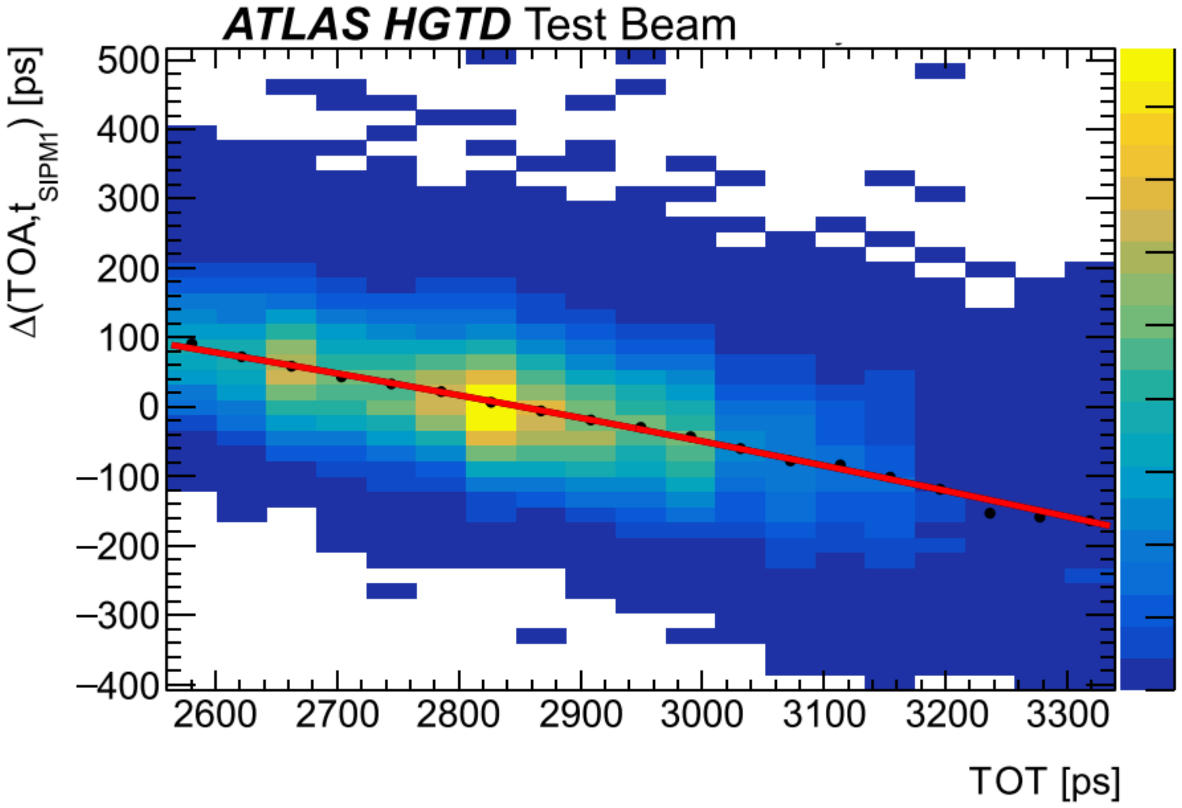


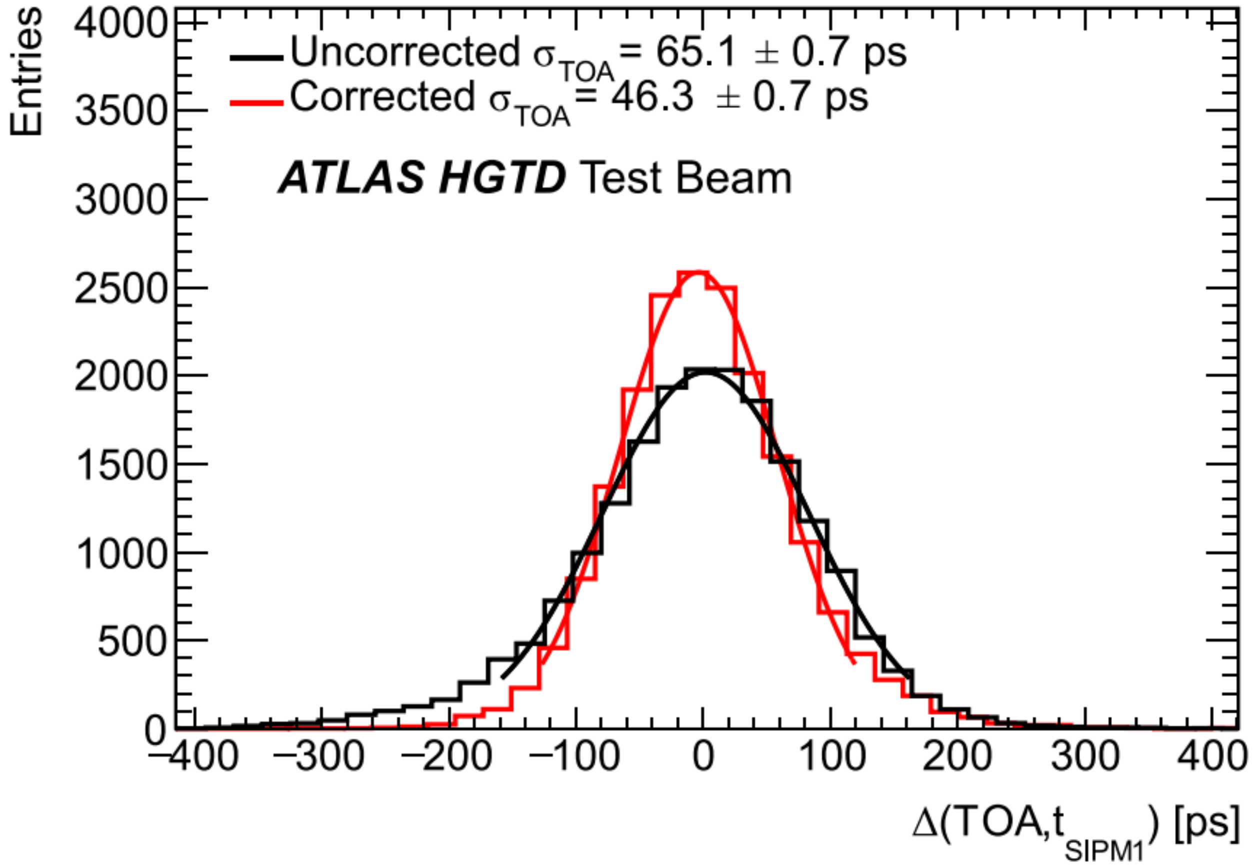
Performance with front-end readout chip (ALTIROC1)

C. Agapopoulou et al. JINST 18 P08019

- The time resolution is also measured with a **5×5 mini-module** (Sensor+ALTIROC1 ASIC)
- Time resolution of **46 ps** is achieved after TOA-TOT correction.
  (Fulfilled HGTD requirement: **50 ps** per hit before irradiation)

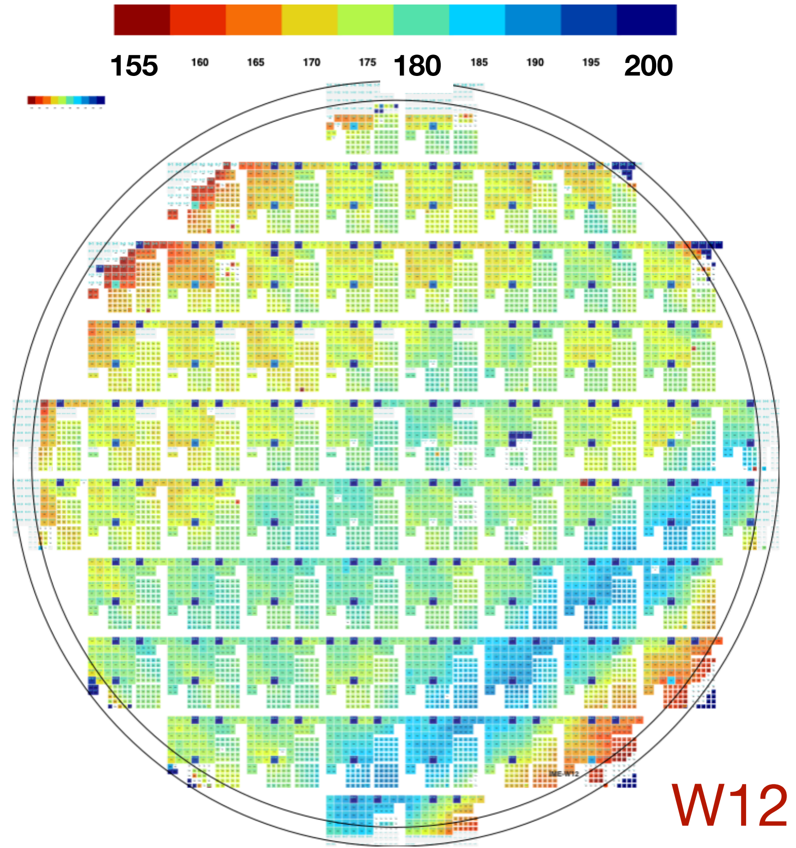


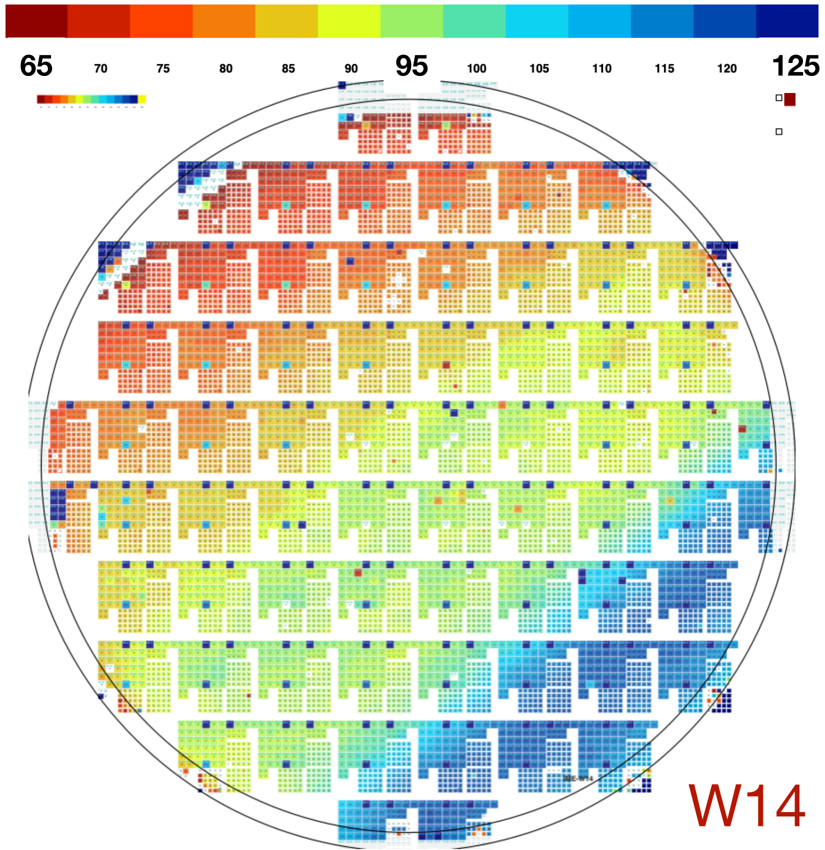


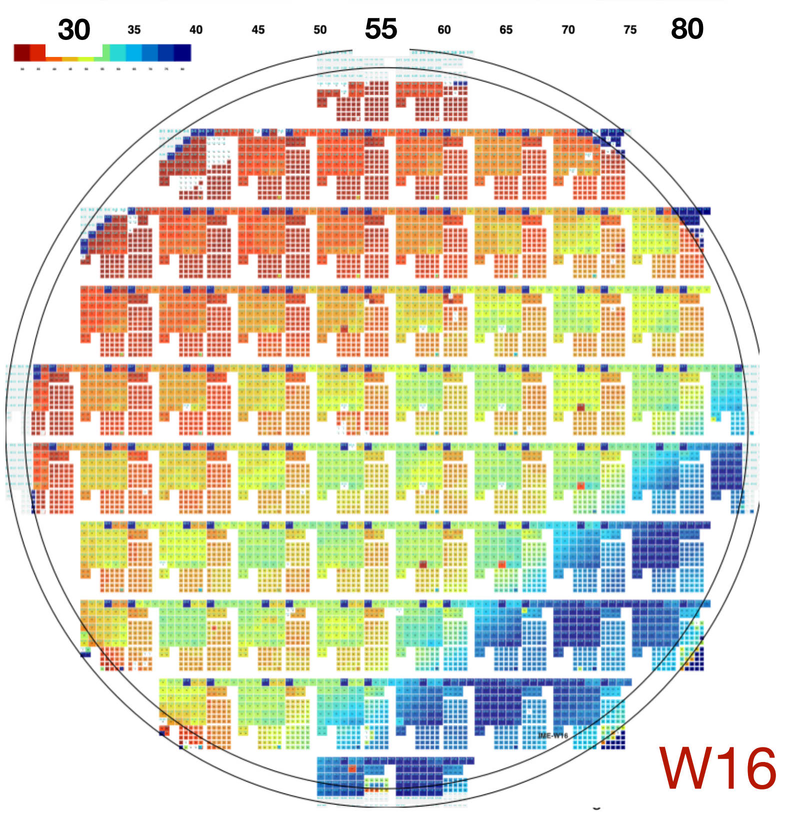


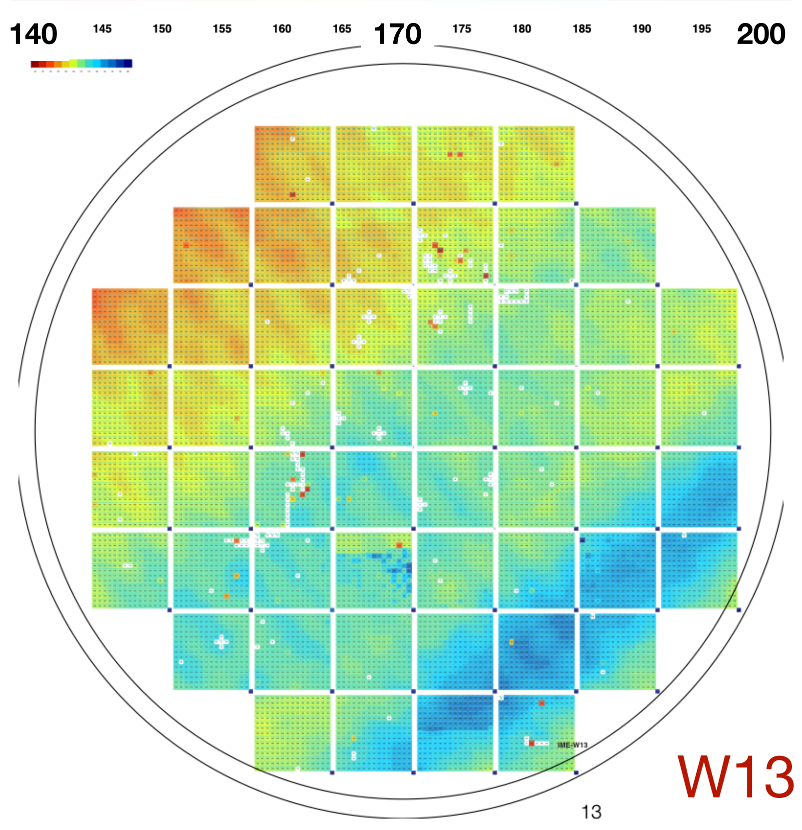
LGAD uniformity for large array production

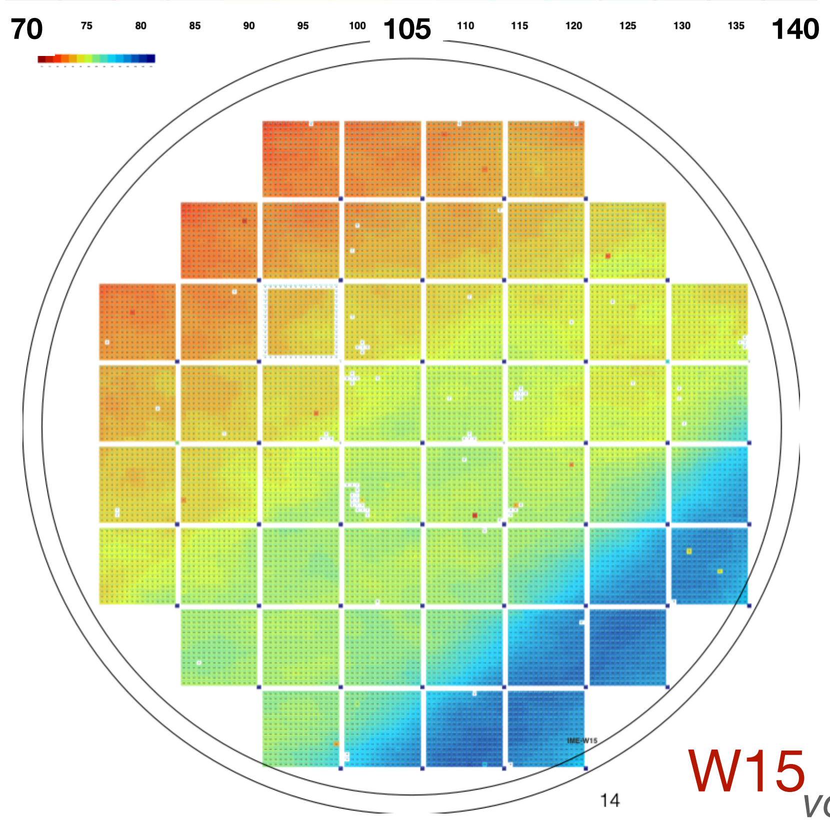
X.Yang et al, 40th RD50 Workshop











Breakdown voltage (VBD) distribution on USTC-IME v2.0 8" wafers

- With a wafer level single pad I-V test, the wafer level variation on VBD is obtained.
- ~ **12V** variation on the VBD
  → ~ **1%** variation on gain layer dose [X.Yang et al, 980, 2020, 164379]
- Will be **further monitored** and studied during the production for HGTD.

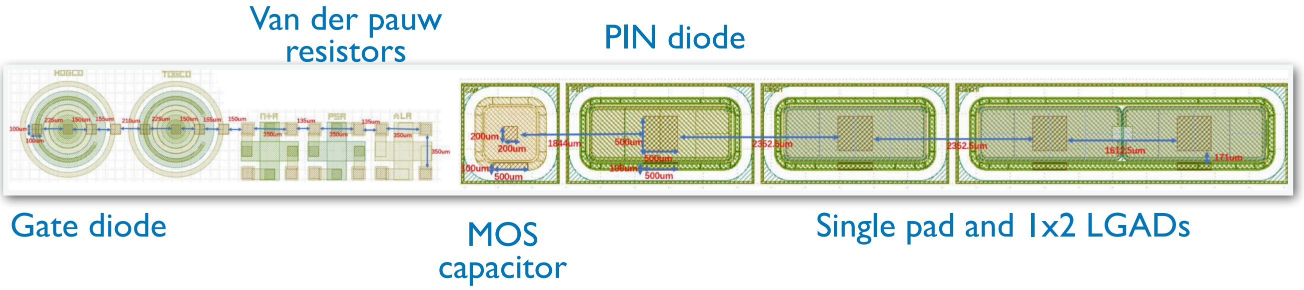
**Breakdown voltage: voltage when current reach the threshold (500 nA)*

Pre-production status and QA/QC

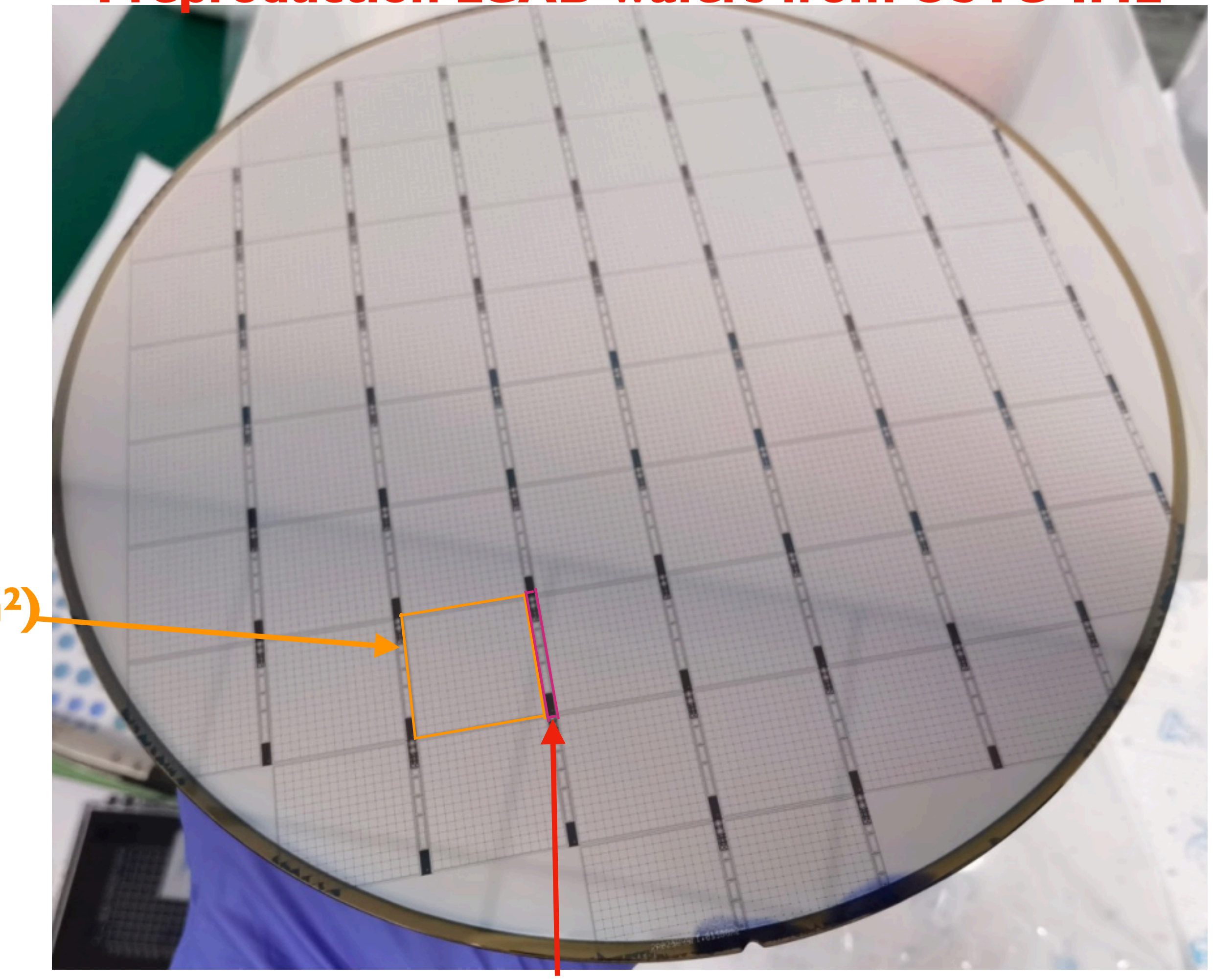
- In order to control the quality of the sensor fabrication process, dedicated **test structures (QC-TS)** are placed on the wafer. Test systems have been setup at 5 different QA/QC sites.

Plan:

- Measure 4-5 QC-TS for each wafer.
- **Correlate sensor performance with QC-TS** and define the acceptance criteria.
- Rely on sensor IV by vendors during the production.



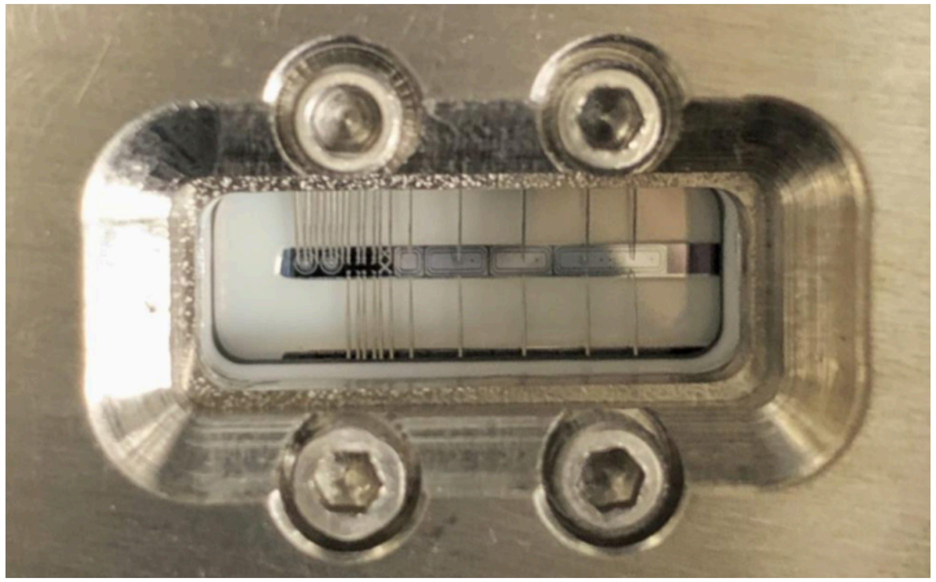
Preproduction LGAD wafers from USTC-IME



Main 15×15 LGAD array (20.1×20.3 mm²)

QC-TS

Automatic test system at CERN with dedicated probe-card and DAQ software



HGTD QC-TS under probe card

Summary and outlook

- The LGAD sensor technology has **reached a mature state** in recent years and moving from R&D towards production.
- **Carbon**-enriched LGADs from three vendors (FBK, IHEP-IME and USTC-IME) have shown **sufficient radiation hardness** and performance.
  - >4 fC, >95% and <70 ps @ 2.5×10^{15} n_{eq}/cm^2
  - 46 ps obtained with ASIC readout
- Results confirmed the **feasibility of an LGAD-based timing detector** for HL-LHC
- Outlook:
  - The IHEP-IME and USTC-IME sensor **pre-production** has started and laboratory and beam tests are ongoing.
  - **QA/QC** programme is being commissioned, to ensure a high **quality** and **uniformity** of the sensors during the production.

Thanks for your listening!

Acknowledgement *:**Some of** the measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).*

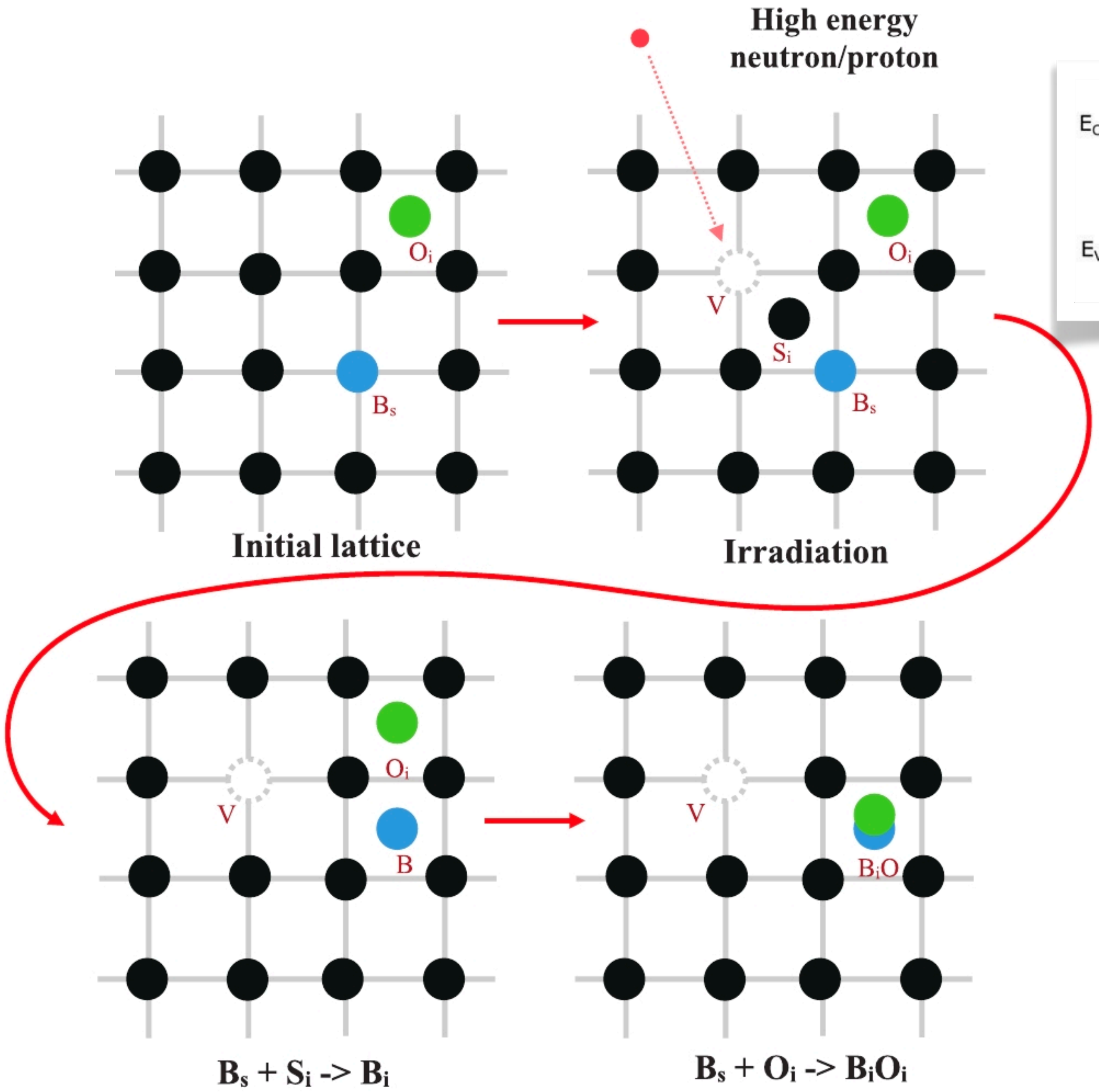
Backup

Summary and outlook

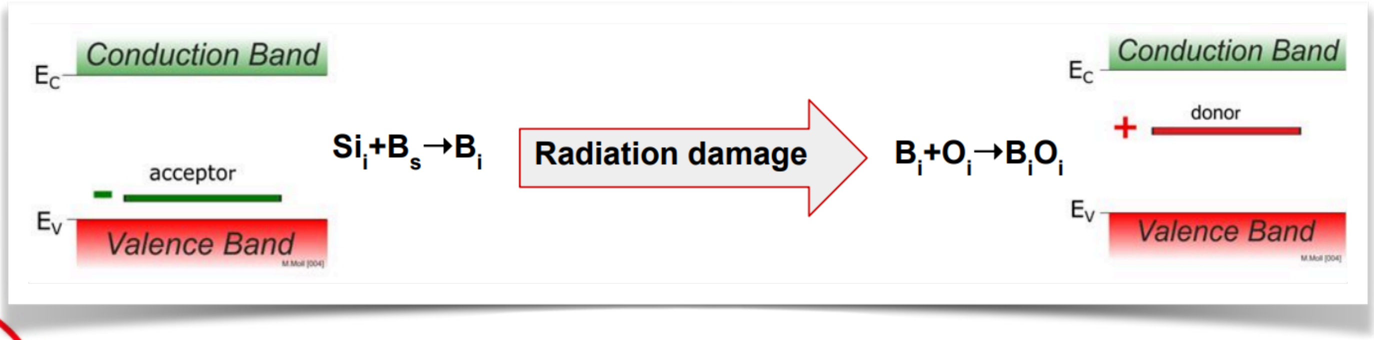
- The LGAD sensor technology has **reached a mature state** in recent years and moving from R&D towards production.
- Carbon-enriched LGADs from three vendors (FBK, IHEP-IME and USTC-IME) have shown sufficient radiation hardness and performance.
  - Irradiated at fluences of 1.5 - 2.5×10^{15} n_{eq}/cm^2, the LGADs were operated at voltages below 550 V
  - Under these conditions, LGADs achieved the objectives of:
    - Collected charge of more than 4 fC while guaranteeing a time resolution better than 70 ps
    - An efficiency larger than 95% uniformly over sensor surface is obtained with a charge threshold of 2 fC
- Time resolution of 46 ps is obtained by the module test with ALTIROC ASIC readout with the TOA-TOT correction applied.
- These results confirm the feasibility of an LGAD-based timing detector for HL-LHC
- Outlook:
  - The IHEP-IME and USTC-IME sensor pre-production has started and laboratory and beam tests are ongoing.
  - QA/QC programme is being commissioned, to ensure a high quality and uniformity of the sensors during the production.

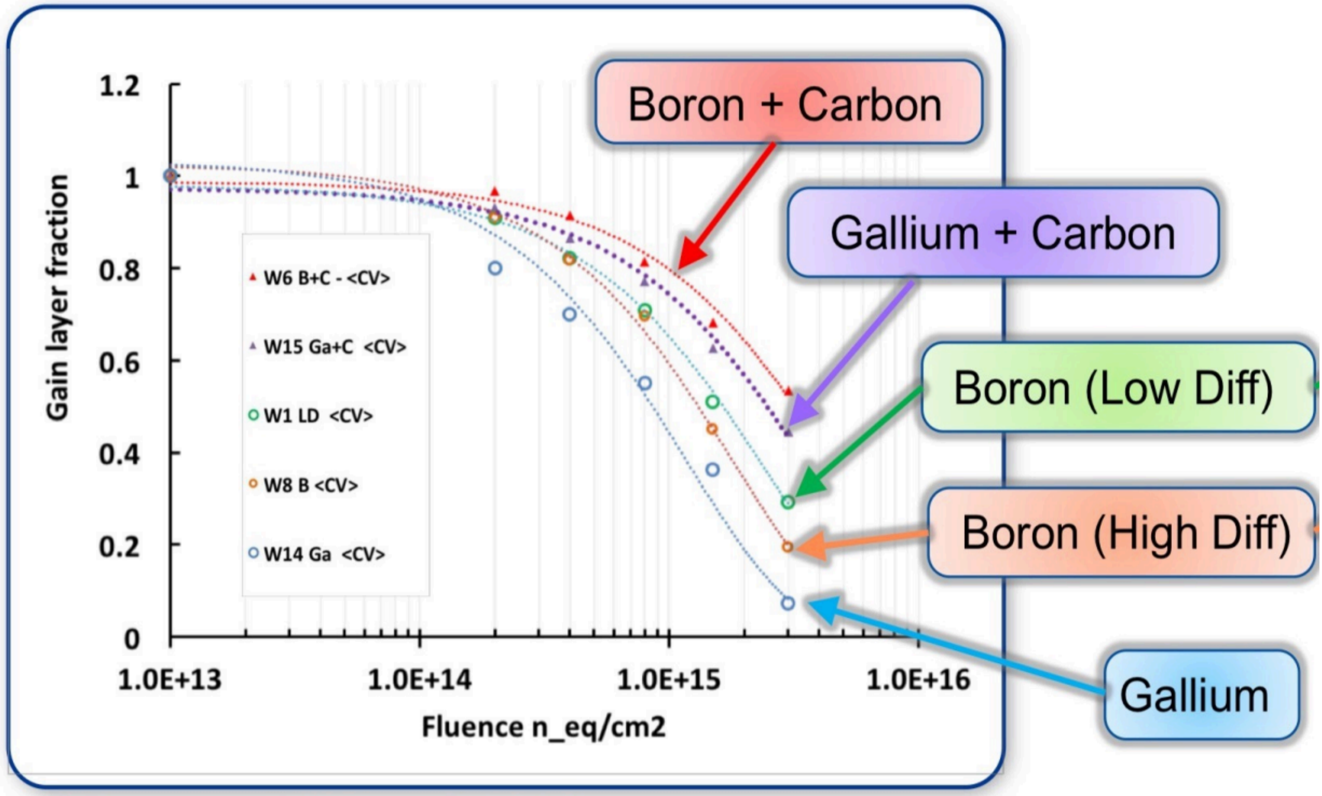
Radiation hardness of LGAD

- The reduction of effective doping in the gain layer is caused by the “acceptor removal” process →LGAD gain reduction after non-ionizing radiation damage.
- Explored use of different gain layer designs, doping materials and C-enriched substrates → **B + C** shows largest gain after irradiation ($C_i + O_i \rightarrow C_iO_i$ competes with $B_i + O_i \rightarrow B_iO_i$)



Acceptor (B_s) removal in the gain layer after irradiation





G.Paternoster, TREDI 2019

Time resolution

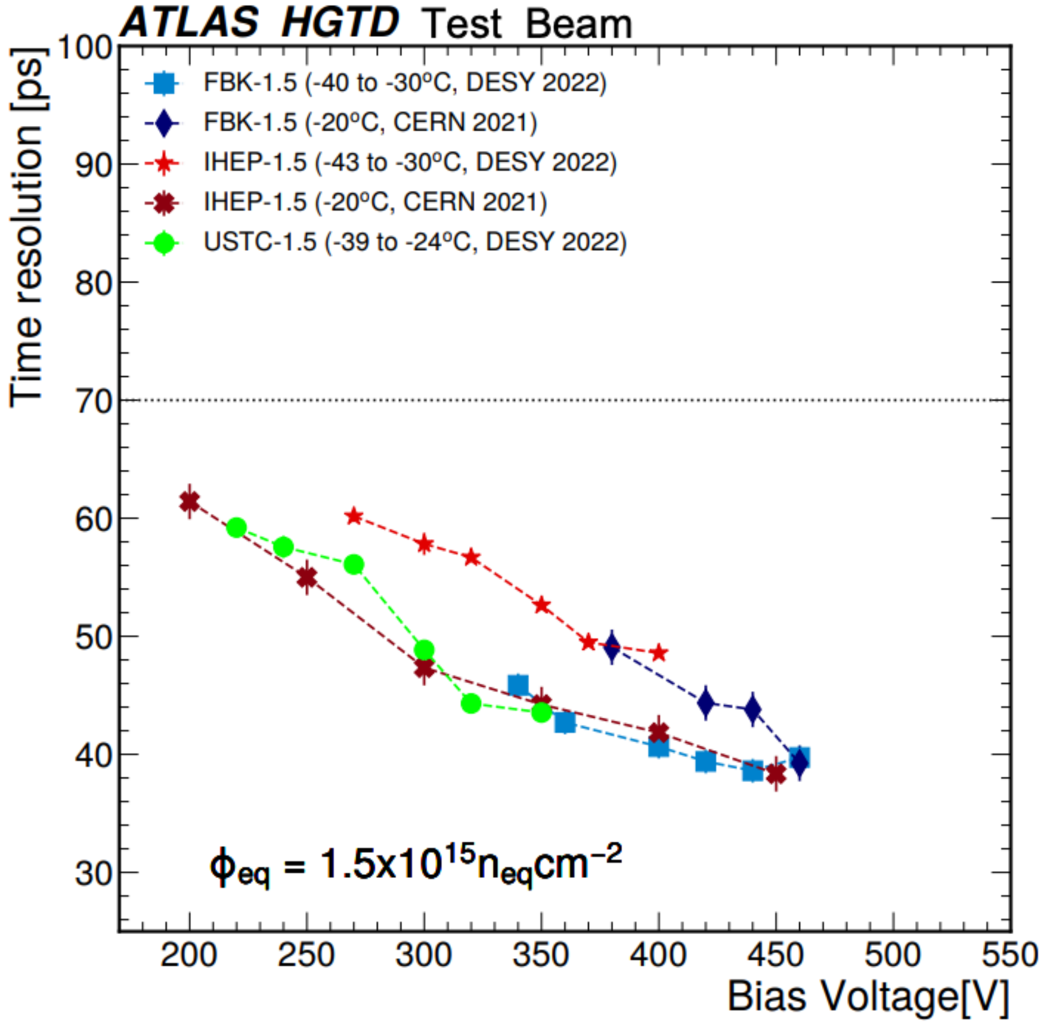
S.Ali et al 2023 JINST 18 P05005

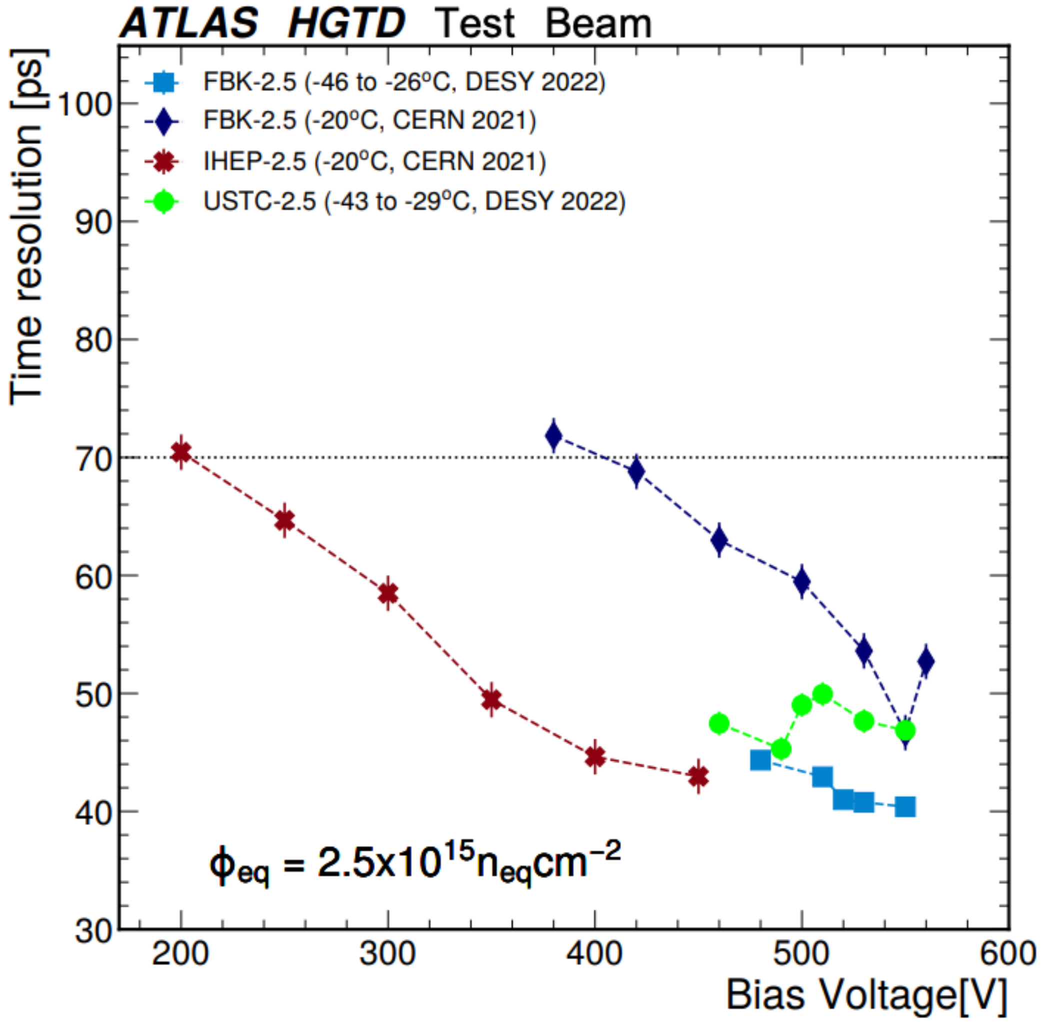
- Time resolution is obtained by unfolding the time resolution with reference detectors.
  - For DESY: 1: DUT1, 2: DUT2, 3: SiPM (σ_t = 62.6 ps)

$$\begin{cases} \sigma_{1,2}^2 = \sigma_1^2 + \sigma_2^2 \\ \sigma_{1,3}^2 = \sigma_1^2 + \sigma_3^2 \\ \sigma_{2,3}^2 = \sigma_2^2 + \sigma_3^2 \end{cases}$$

  - For CERN:
    1: Reference LGAD (σ_t = 55.0 ps)
    2: DUT

$$\sigma_{\mathrm{DUT,ref}}^2 = \sigma_{\mathrm{DUT}}^2 + \sigma_{\mathrm{ref}}^2$$

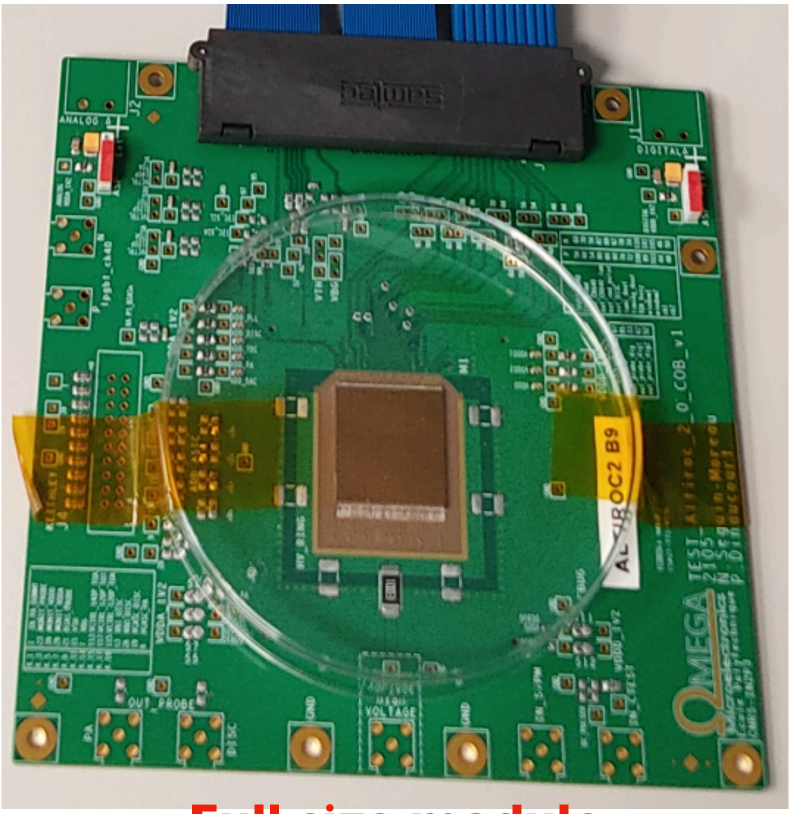




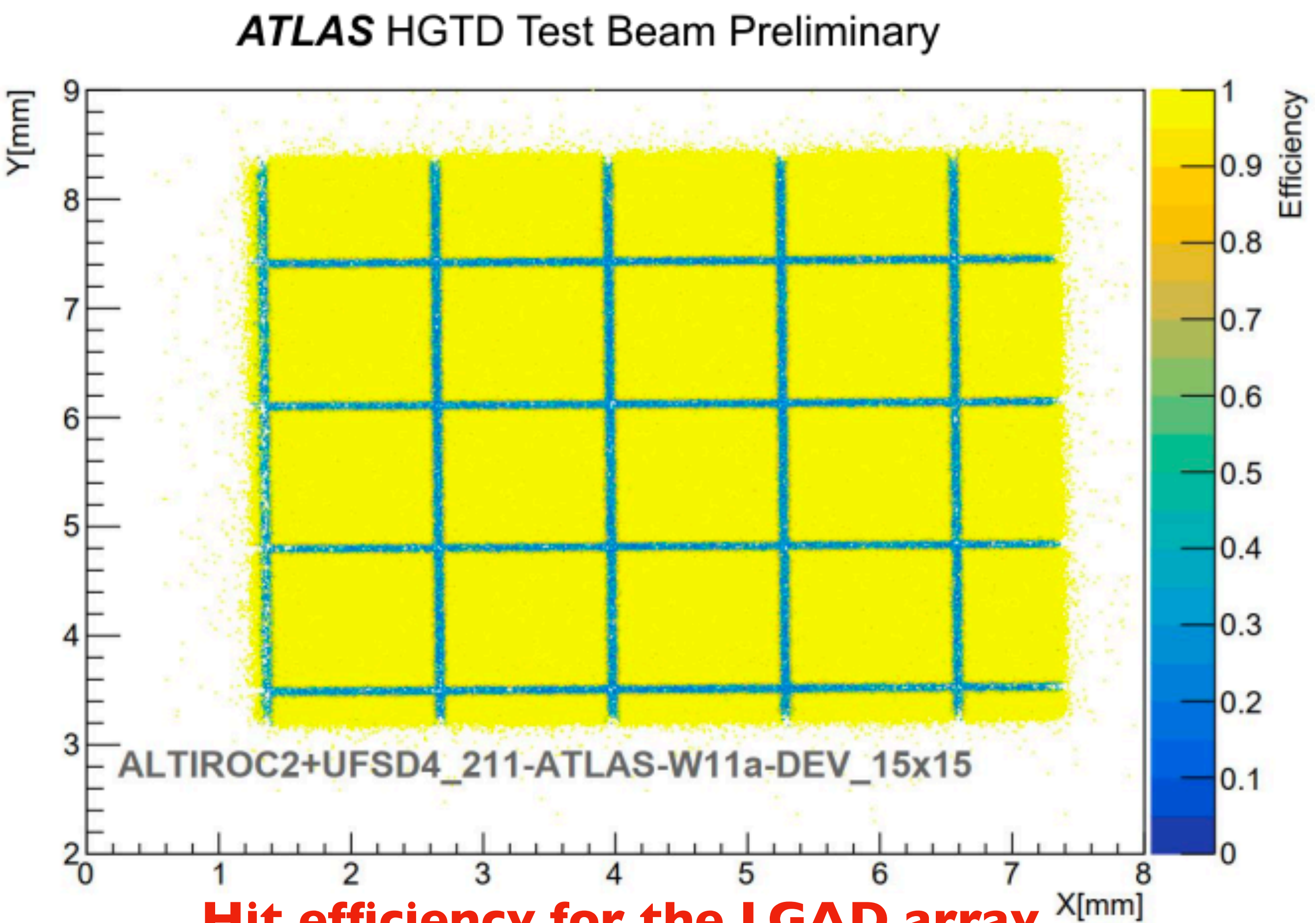
- All sensors tested fulfil the HGTD requirement (**70 ps**) after being irradiated to maximum fluence.

Performance with front-end readout chip (ALTIROC2)

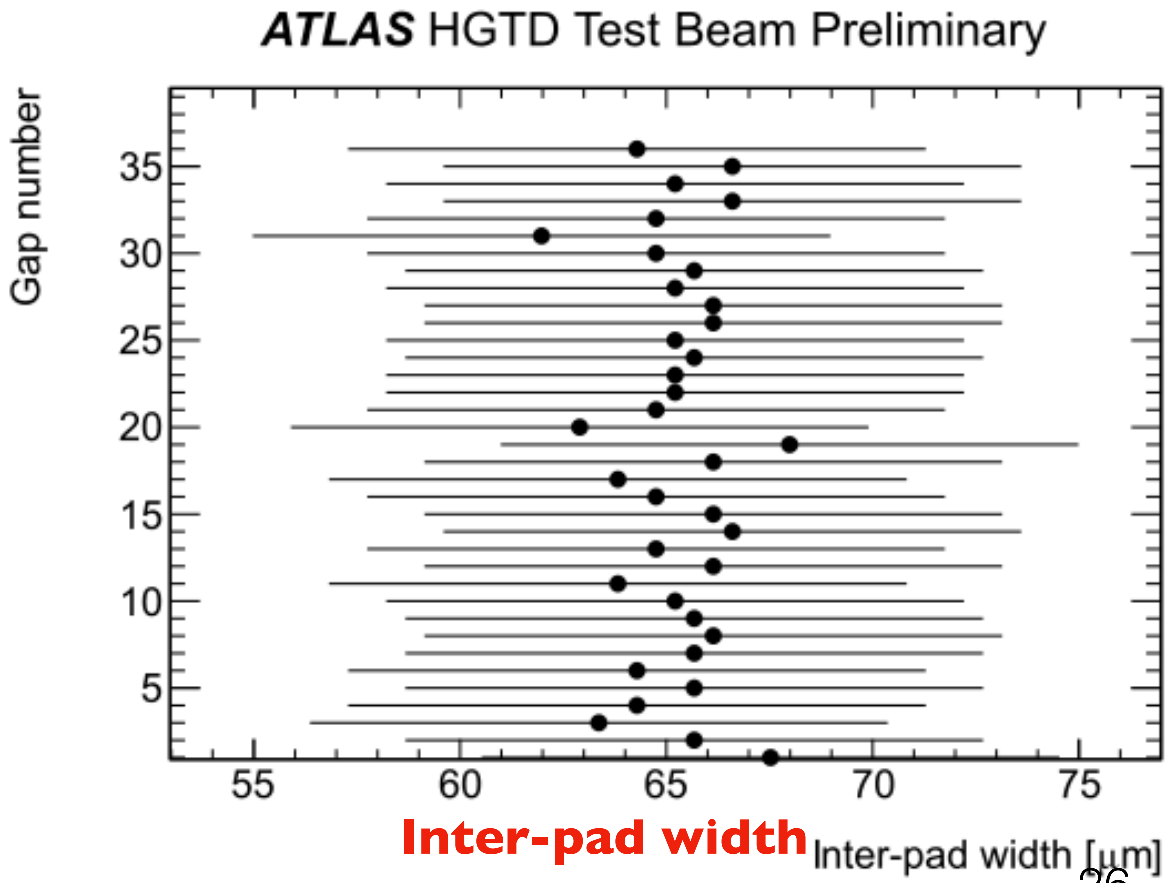
- The efficiency and inter-pad gap is measured with the full size 15×15 module. (Sensor+**ALTIROC2** chip)
- An efficiency of better than **95%** and inter-pad gap < **70 μm** is validated on module level.
- An improved version of ASIC: **ALTIROC3** has been produced and is currently being tested.



Full size module



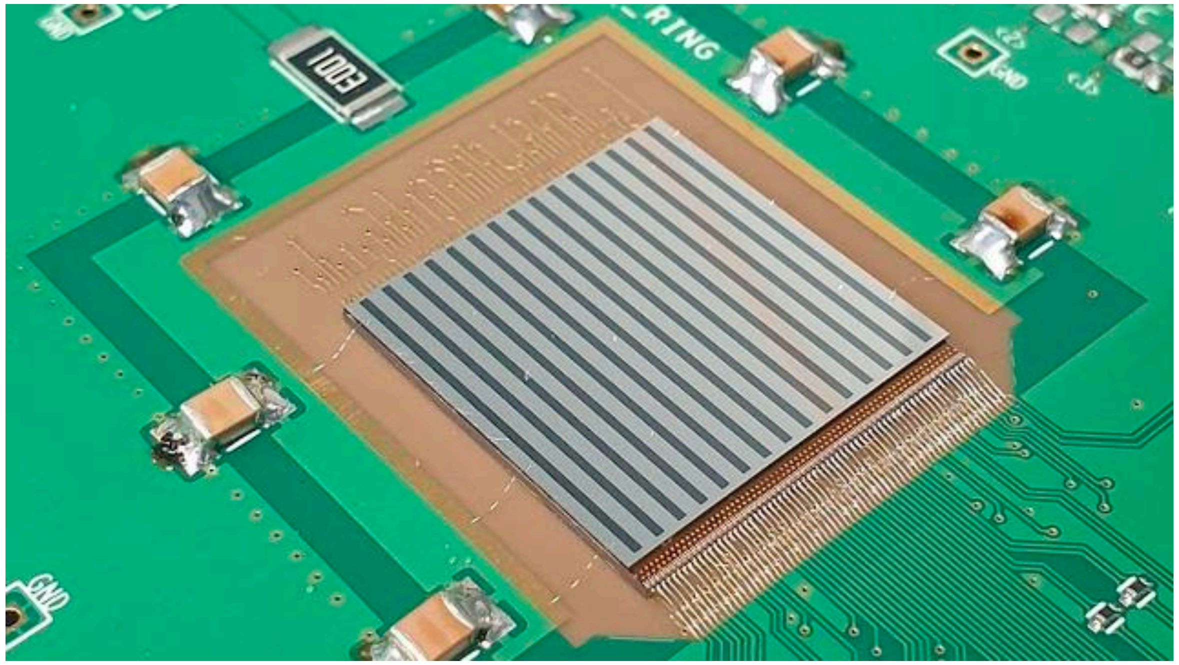
Hit efficiency for the LGAD array



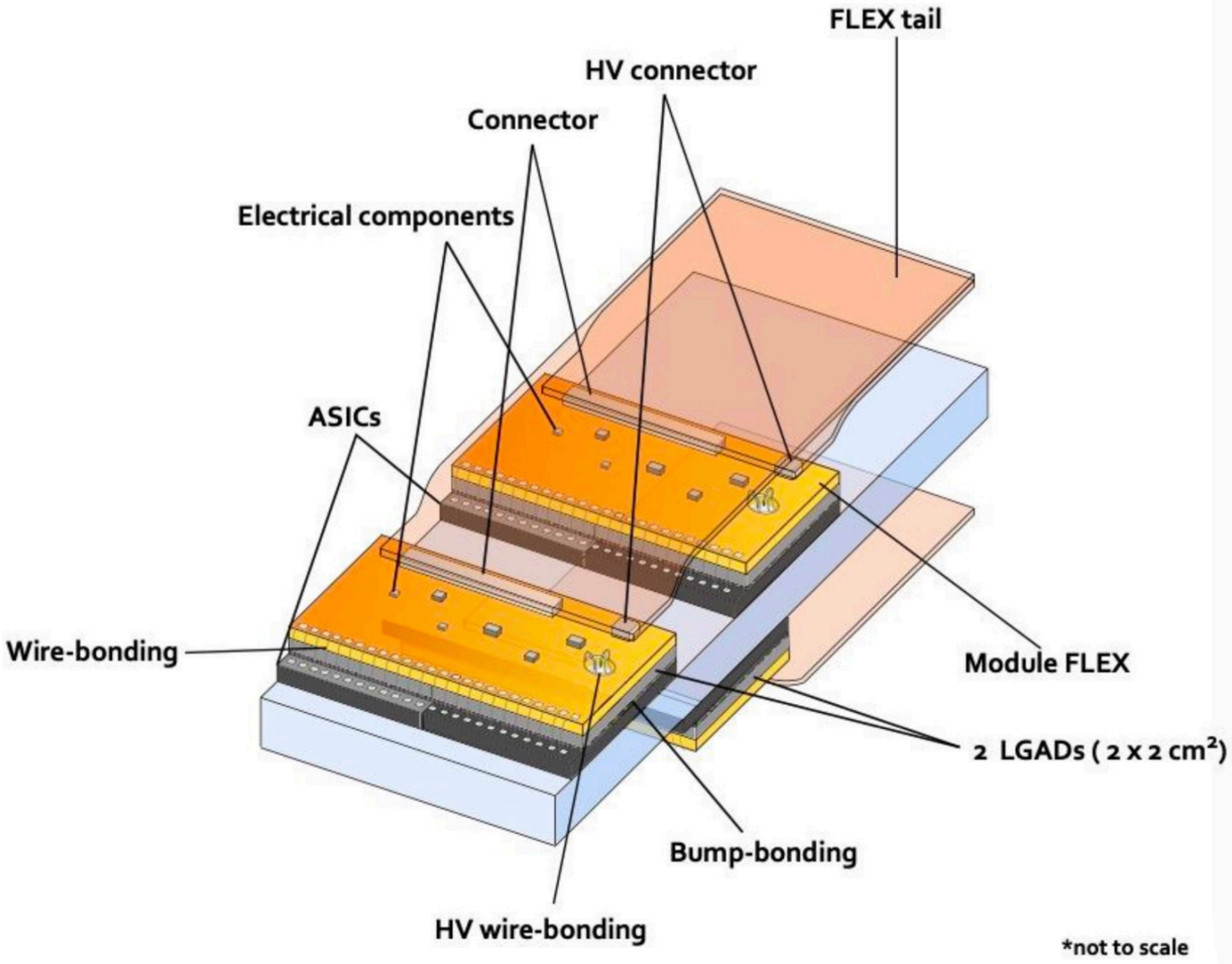
Inter-pad width

Module

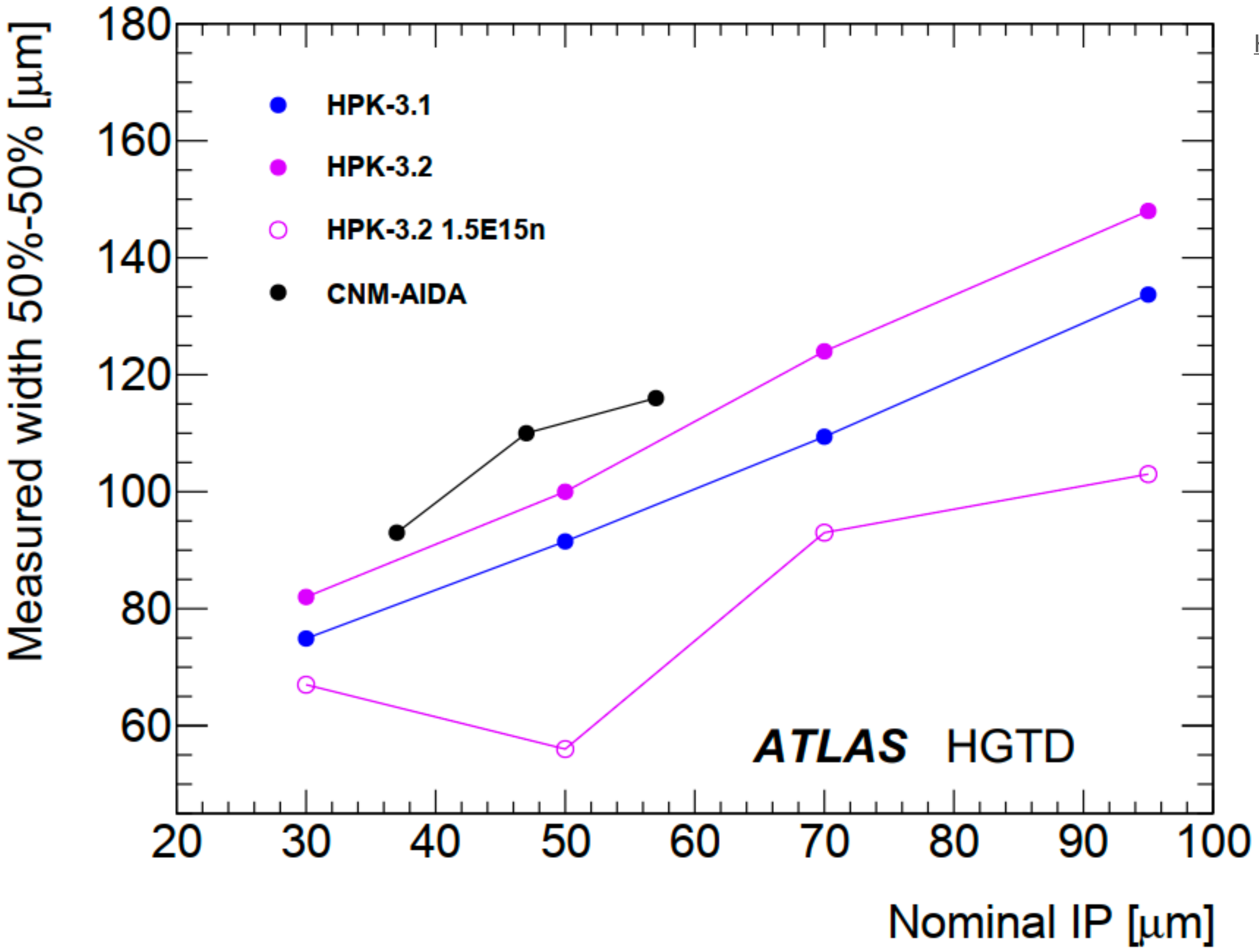
15x15 full size hybrid



HGTD module

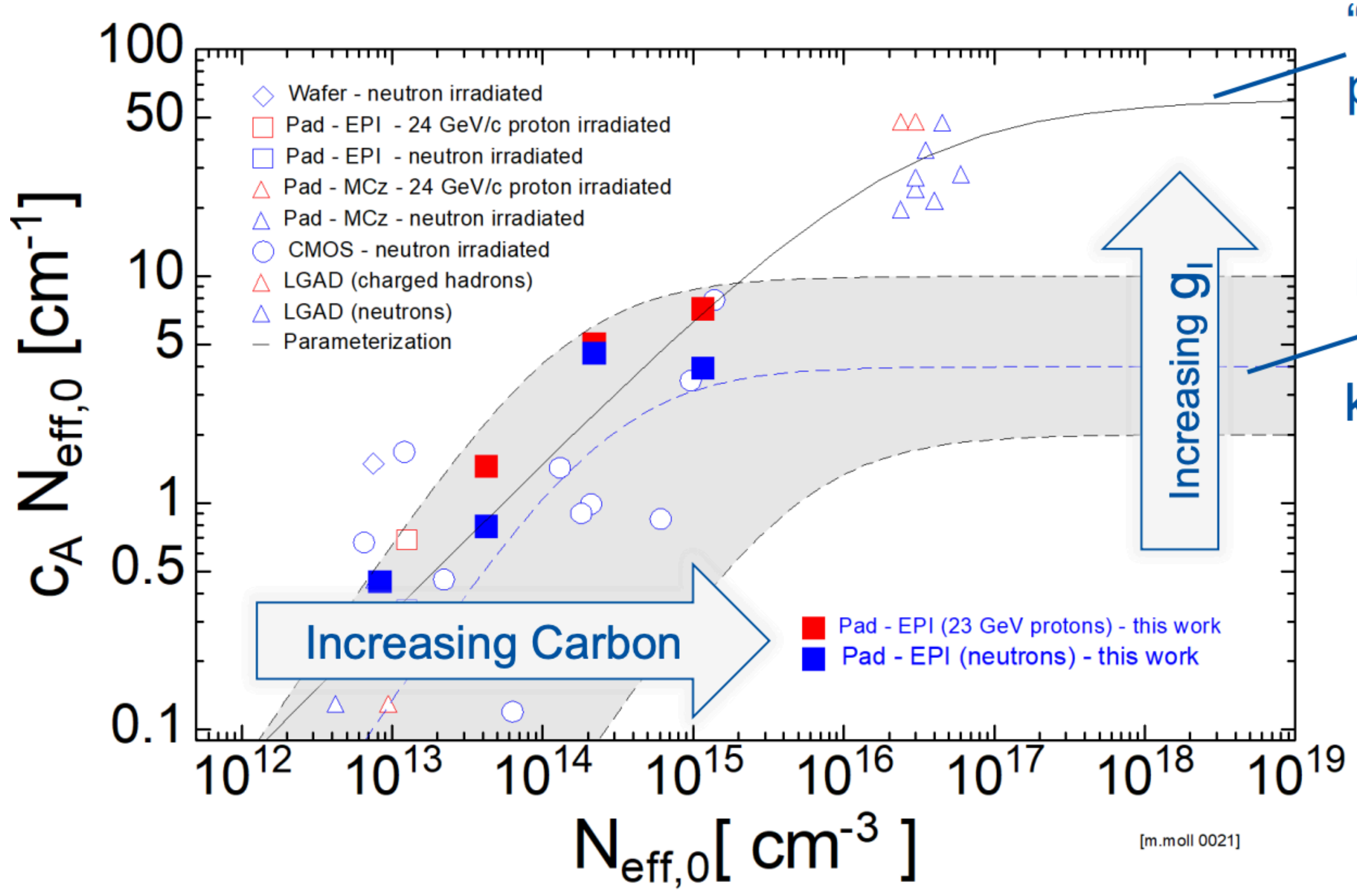


Inter-pad gap for HGTD LGADs



HGTD TDR

Acceptor removal parameterisation



“Torino parameterization”

Expectation from simple defect kinetics modelling

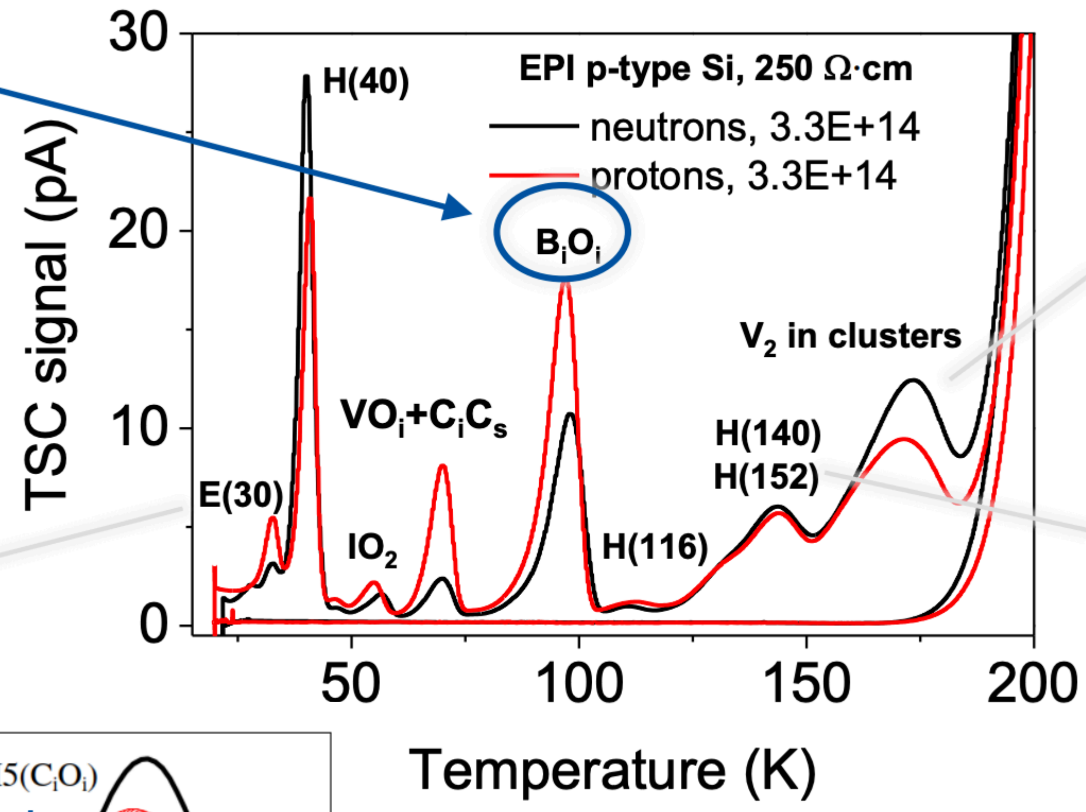
M.Moll for RD50, VERTEX 2019,
https://indico.cern.ch/event/806731/contributions/3516709

Defect characterization with DLTS or TSC

M.Moll for RD50, VERTEX 2019,
https://indico.cern.ch/event/806731/contributions/3516709

- *Example: TSC (Thermally Stimulated Currents) measurement*
  - Comparing damage after proton and neutron exposure

More about defects: see talk of F.R.Palomo: RD50 TCAD simulations

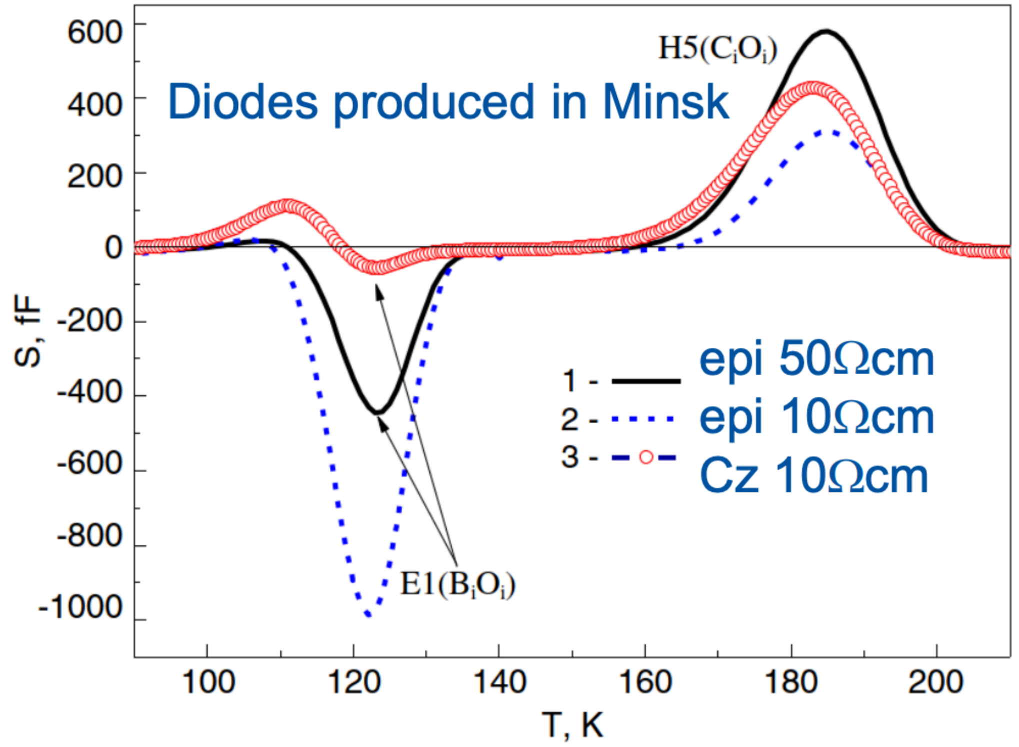


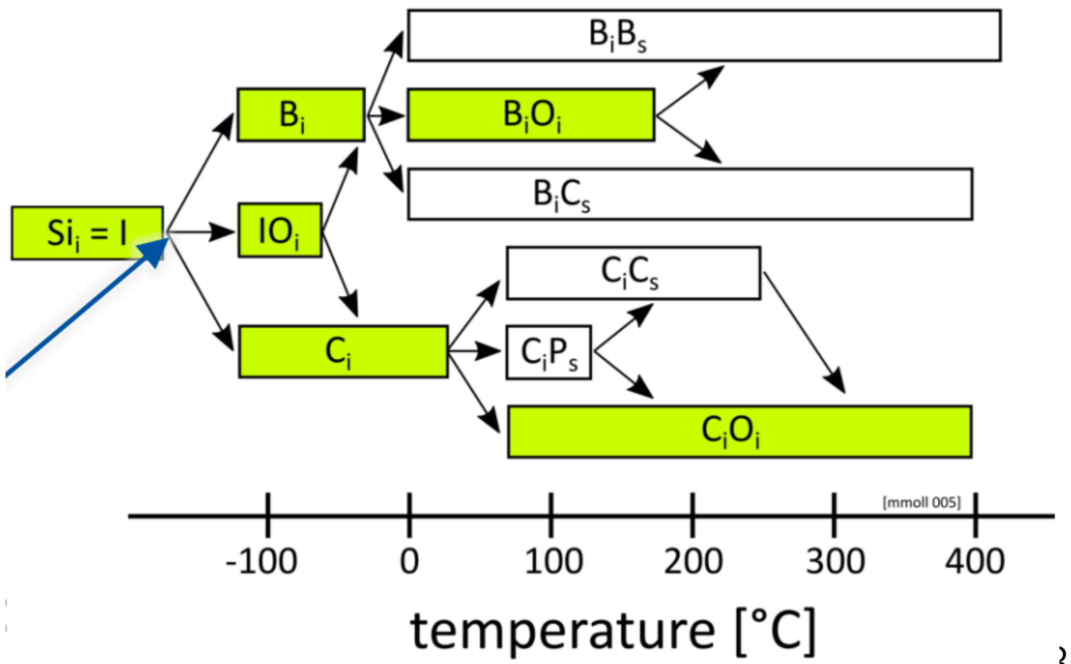
B_iO_i defect (acceptor removal)

E30 donor (positive charge) proton vs. neutron damage

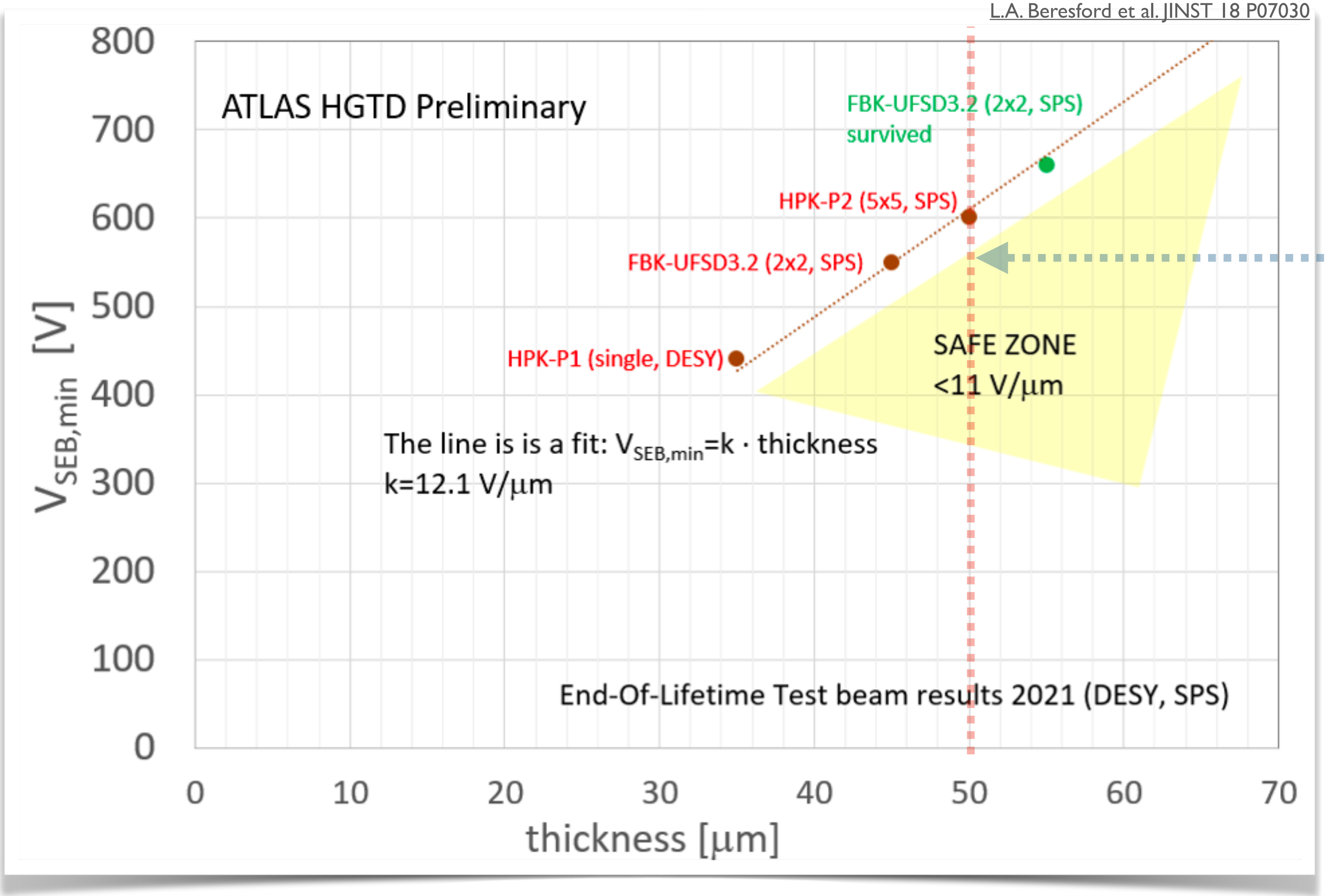
Cluster related defects (leakage current)

H(1xx) - acceptors (reverse annealing)





“Safe zone” for SEB

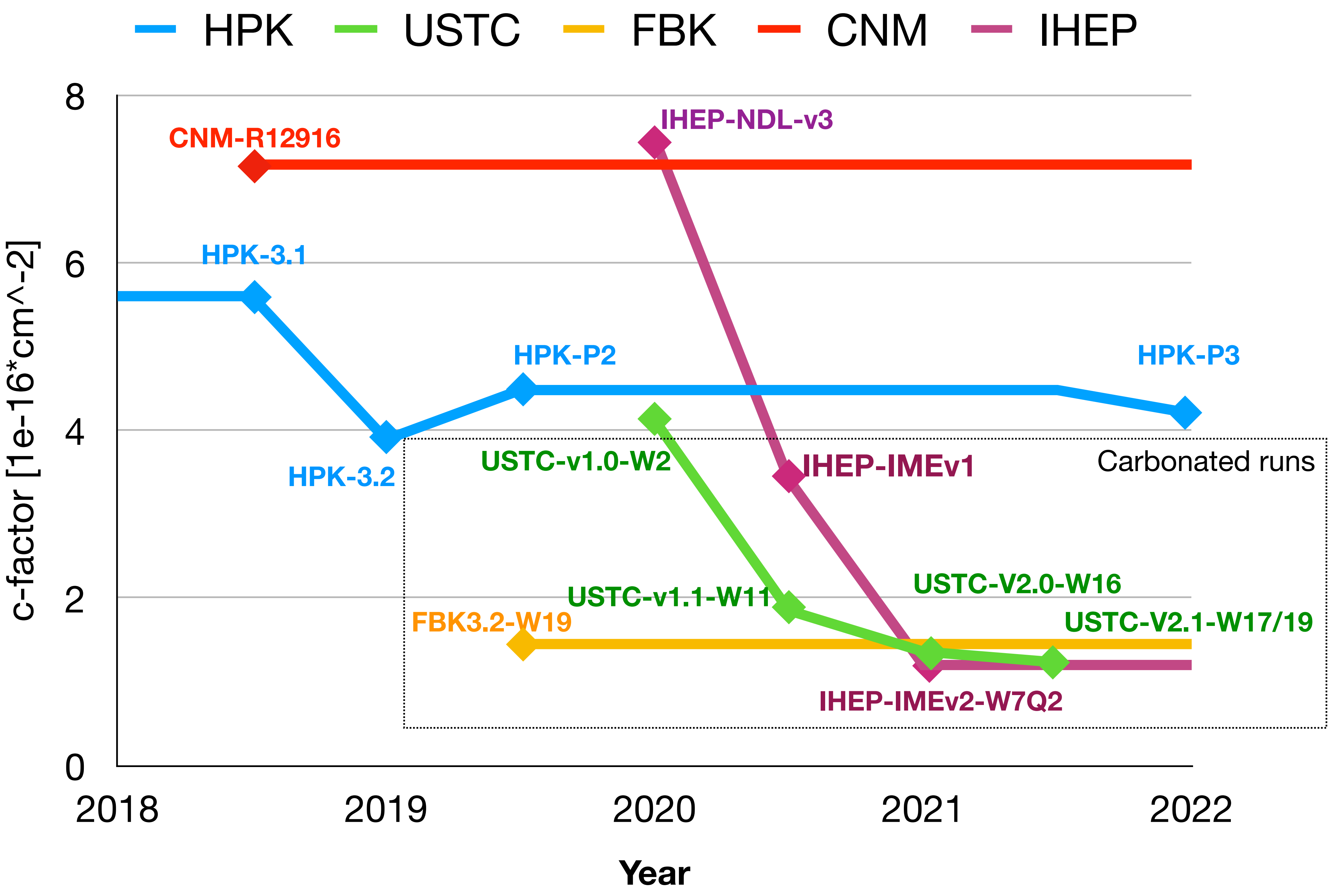


V_{max} = 550 V

- A safe zone has been defined with the results:
  - **Safe zone**: electric field < 11 V/μm (50 μm → Max bias voltage is 550 V)

Evolution of the c-factor from different vendors

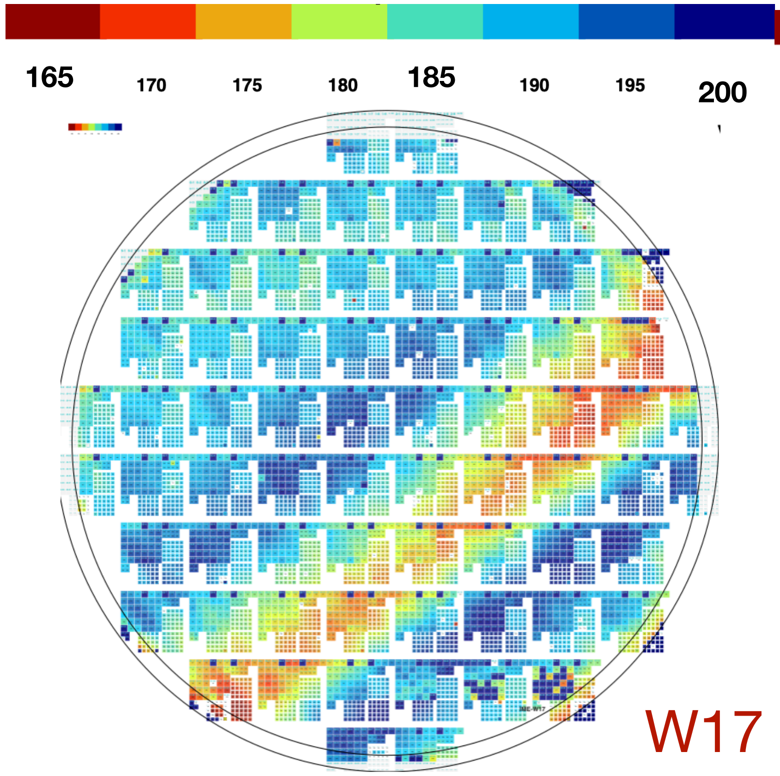
X.Yang et al, 40th RD50 Workshop



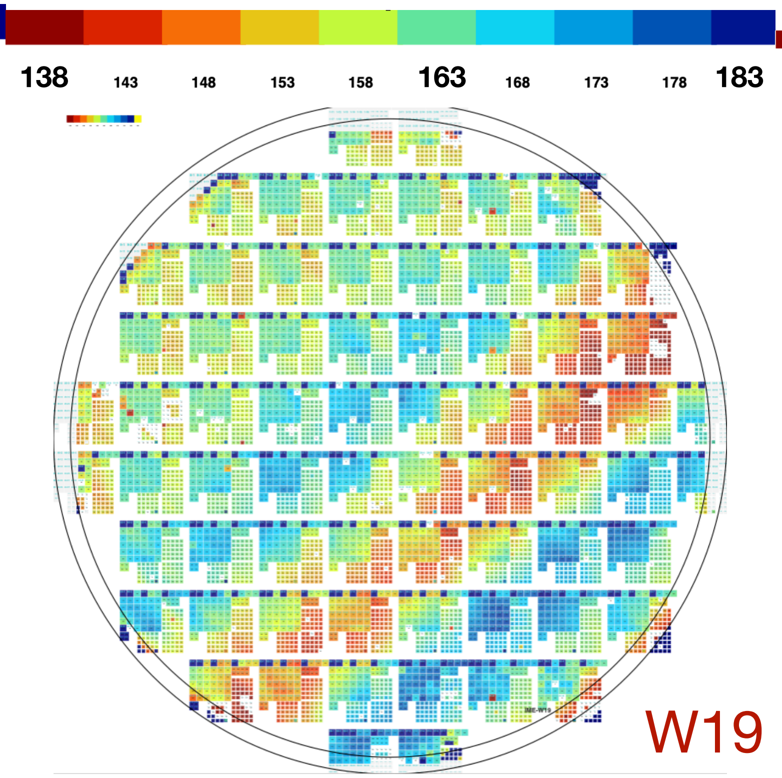
- c factor measured with CV method on the most promising wafer (rad. hard) for each vendors' run.

Uniformity comparison of the USTC-IMEv2.1 wafers

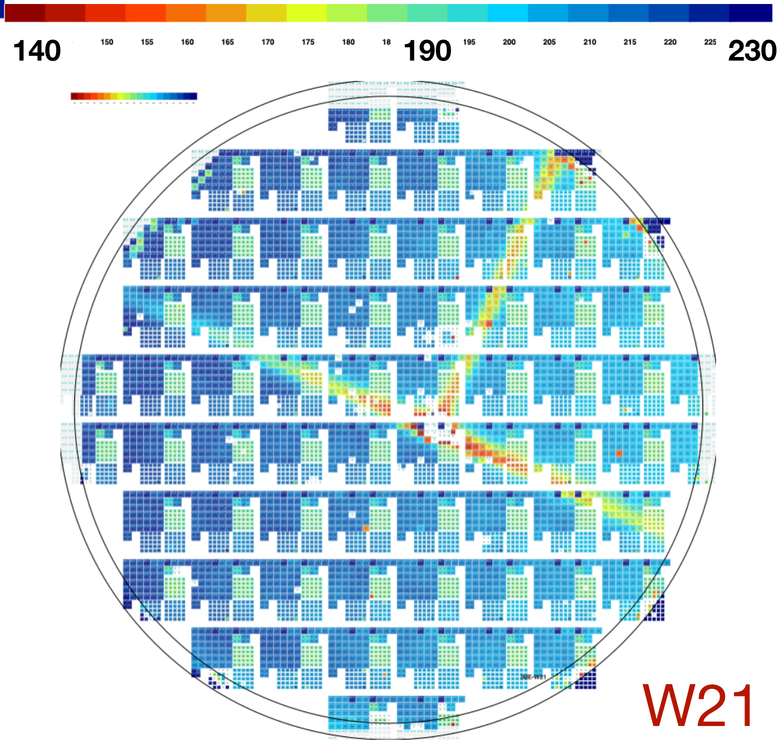
X.Yang et al, 40th RD50 Workshop



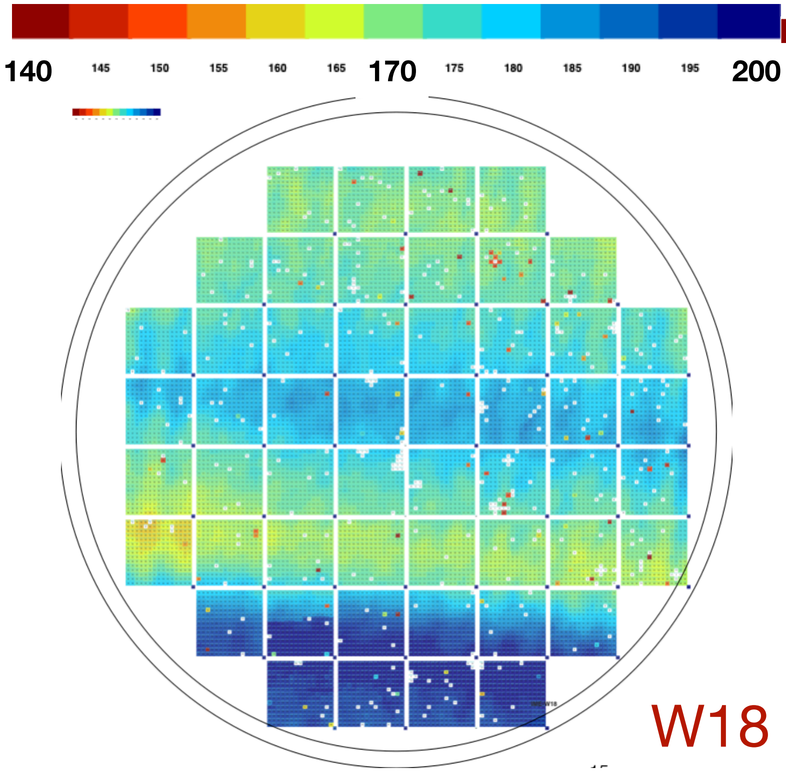
W17



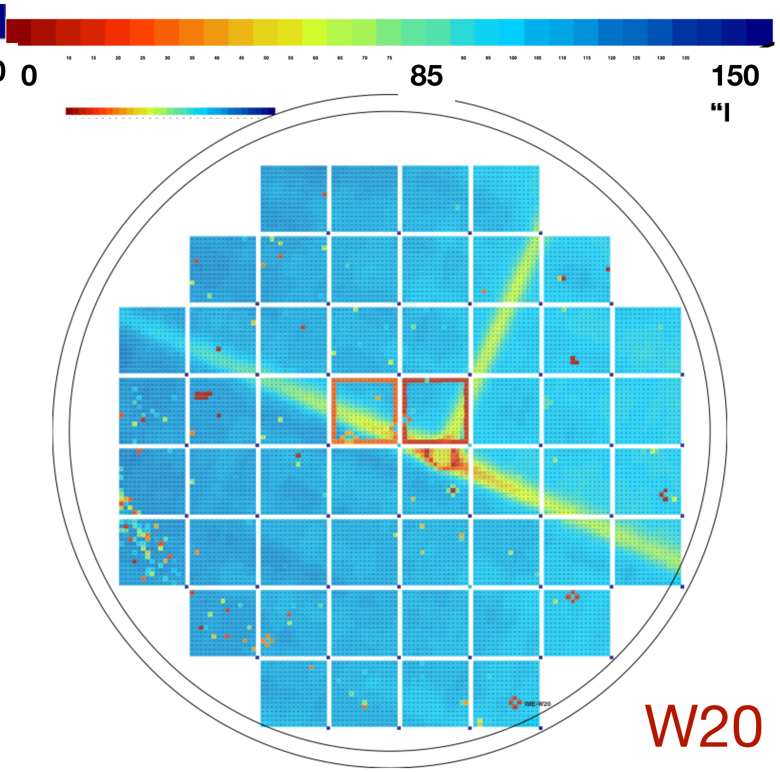
W19



W21



W18

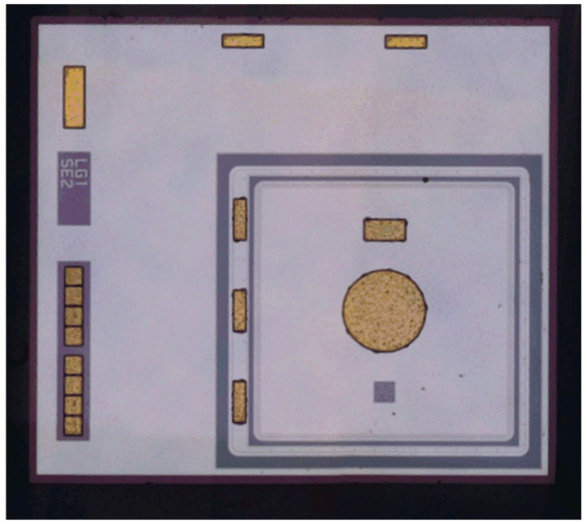


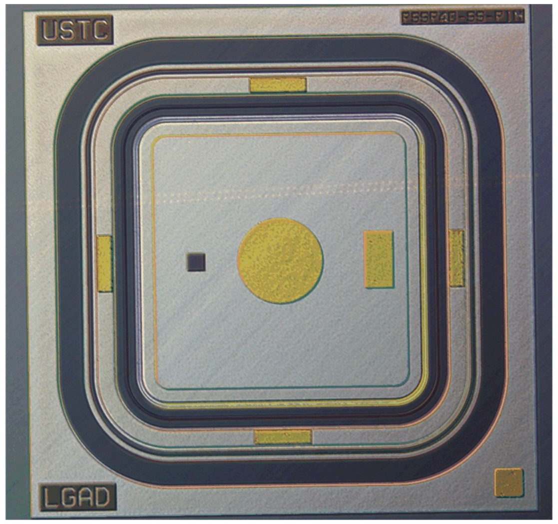
W20

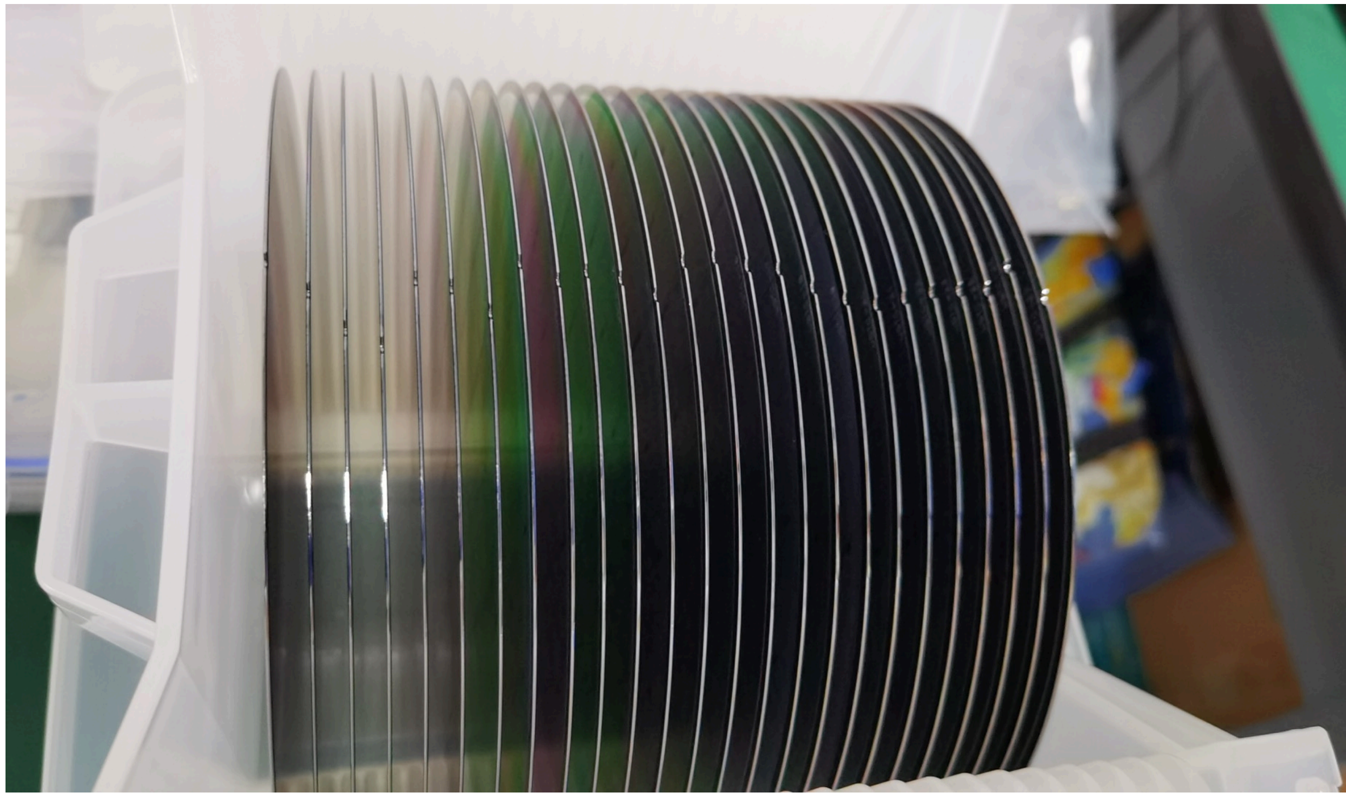
VBD distribution on wafer

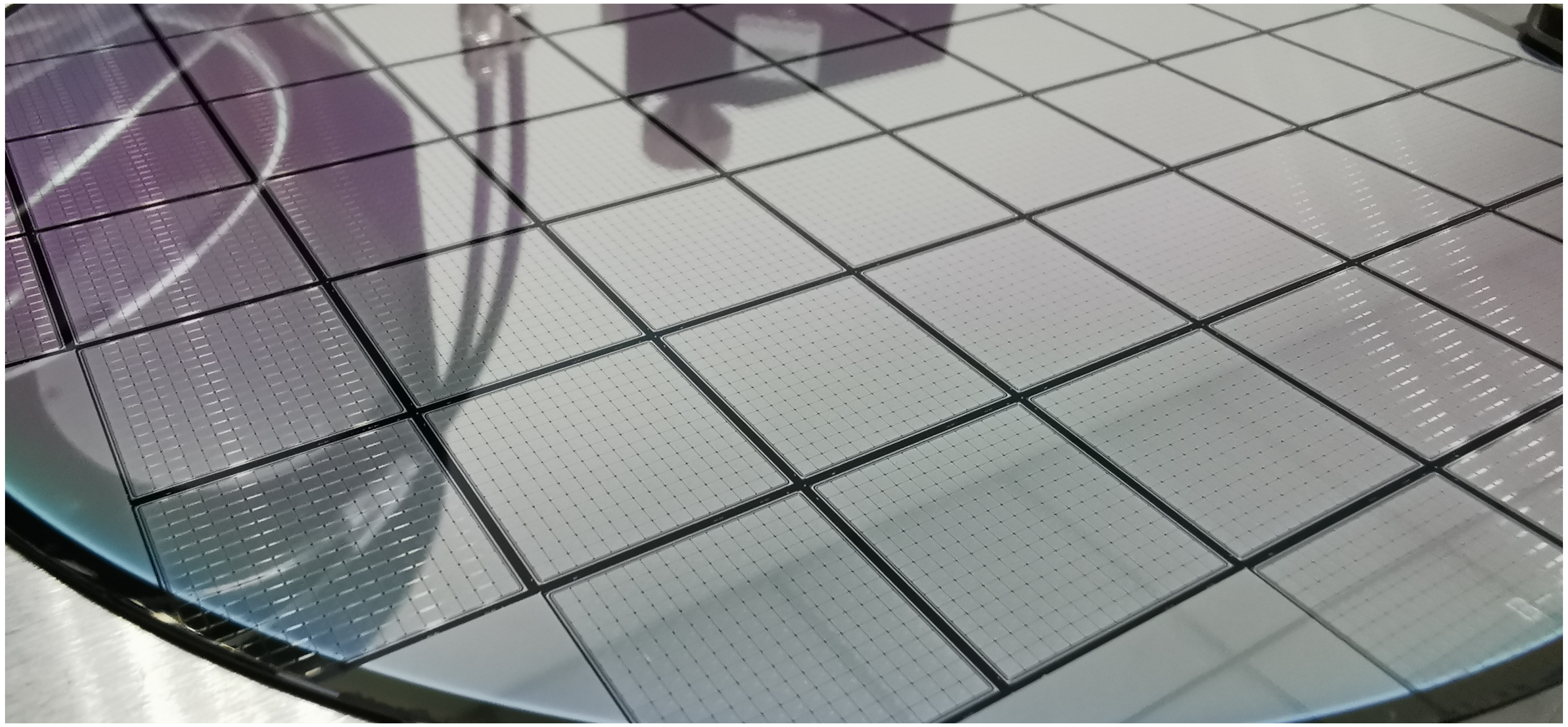
- The wafer W18 have 45 degree counterclockwise rotation before gain layer implementation
- The W20 and W21's gain layer are made with a different machine, thus have different variation

HGTD LGAD layout









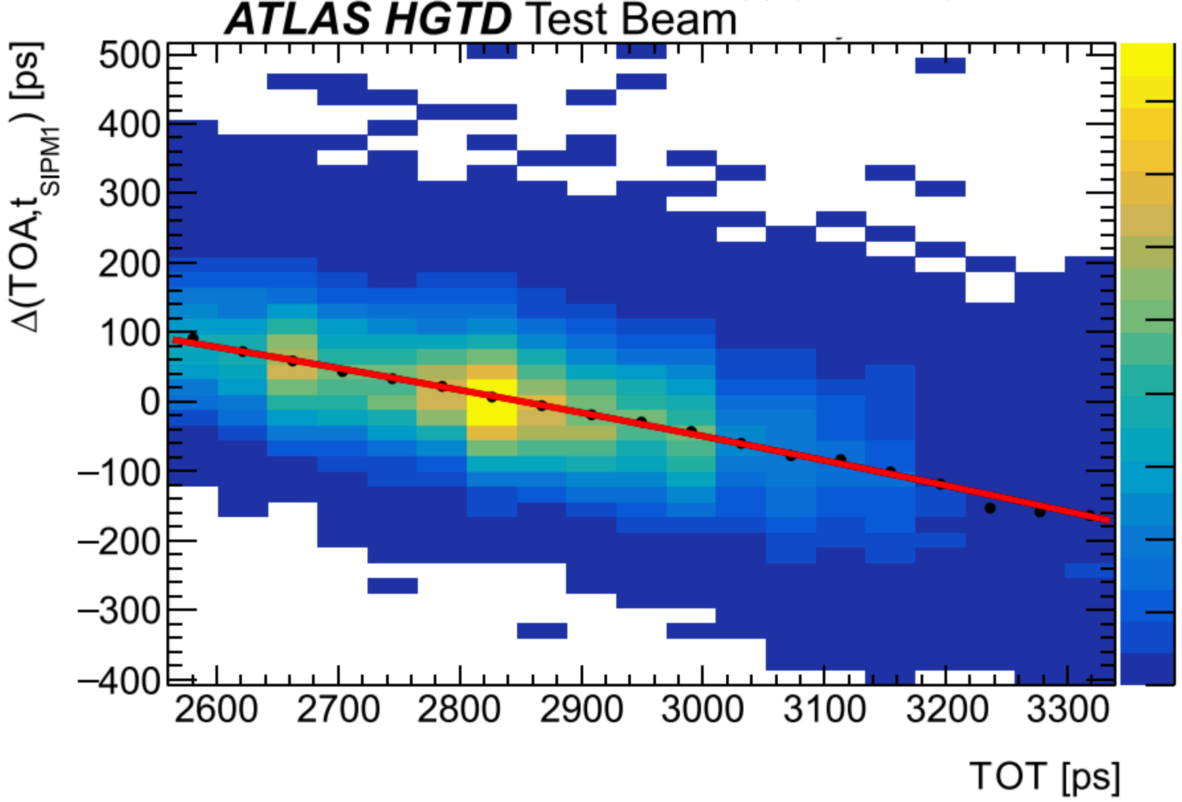
Performance with front-end readout chip (ALTIROC1)

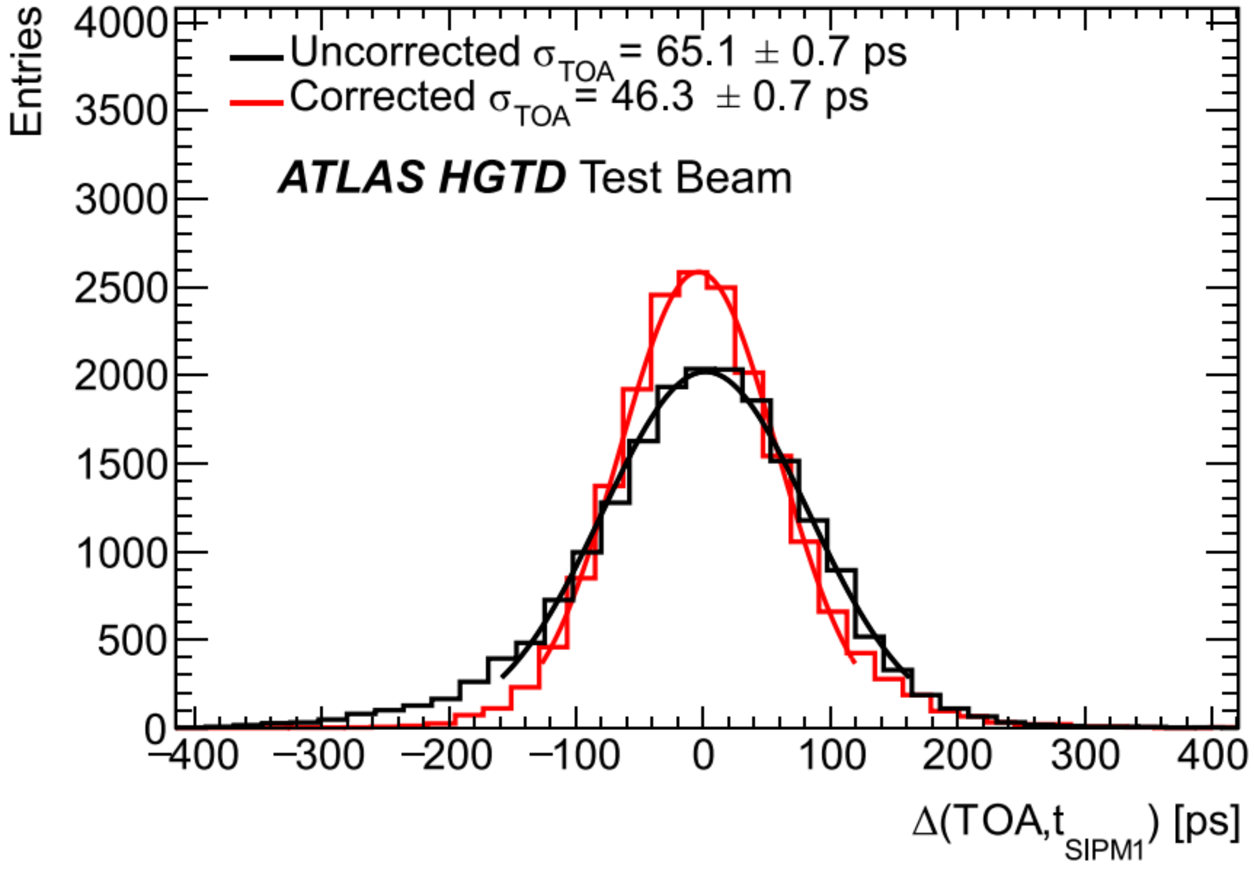
- The time resolution is also measured with a **5×5 mini-module** (Sensor+ALTIROC1 ASIC)
- Different time walk corrections are compared.
- Time resolution of **46 ps** is achieved after on-chip TOA-TOT correction.
  (Fulfilled HGTD requirement: **50 ps** per hit before irradiation)

Time-walk correction method	Time resolution
No correction	65.1 ± 0.7 ps
Preamplifier probe amplitude	40.2 ± 0.7 ps
Preamplifier probe TOT	55.0 ± 0.7 ps
ALTIROC1 TOT	54.2 ± 0.7 ps
Corrected ALTIROC1 TOT	49.6 ± 0.7 ps
ALTIROC1 TOT for TOA 1600 ps	46.3 ± 0.7 ps

Comparison of the time resolution with different TOA-TOT correction for time walk.

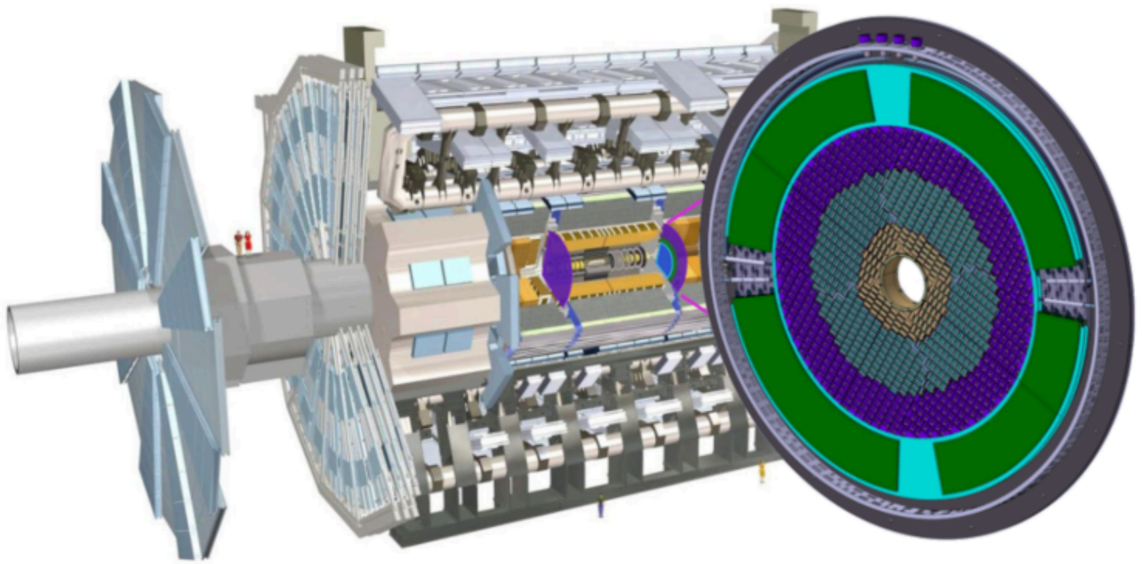
C. Agapopoulou et al. JINST 18 P08019





HGTD Overview

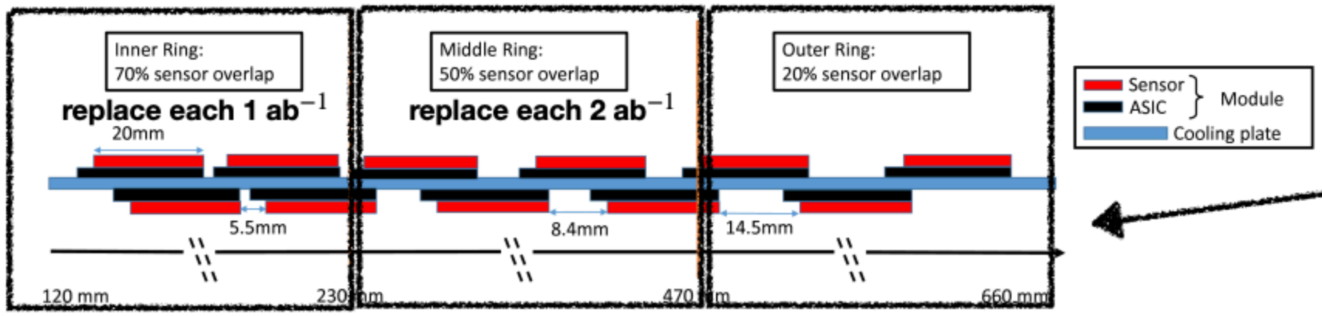
[X. Jia, PSD13]



Designed to provide **time** information to suppress pileup effect in forward region

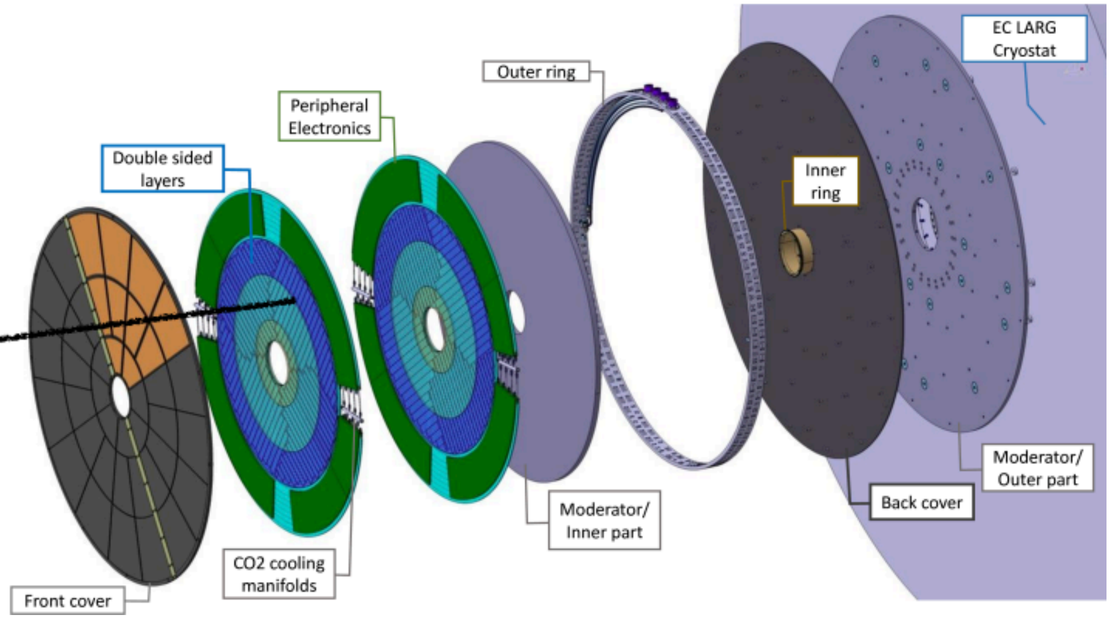
- 30 - 50 ps time resolution per track
- Two disks between barrel and end-cap calorimeter
- Coverage 2.4 $< |\eta| < 4$, ± 3.5 m from nominal interaction point along z axis, radius 11 - 100 cm.
- Also contribute to luminosity measurement

Each double-sided layer mounted on cooling plate



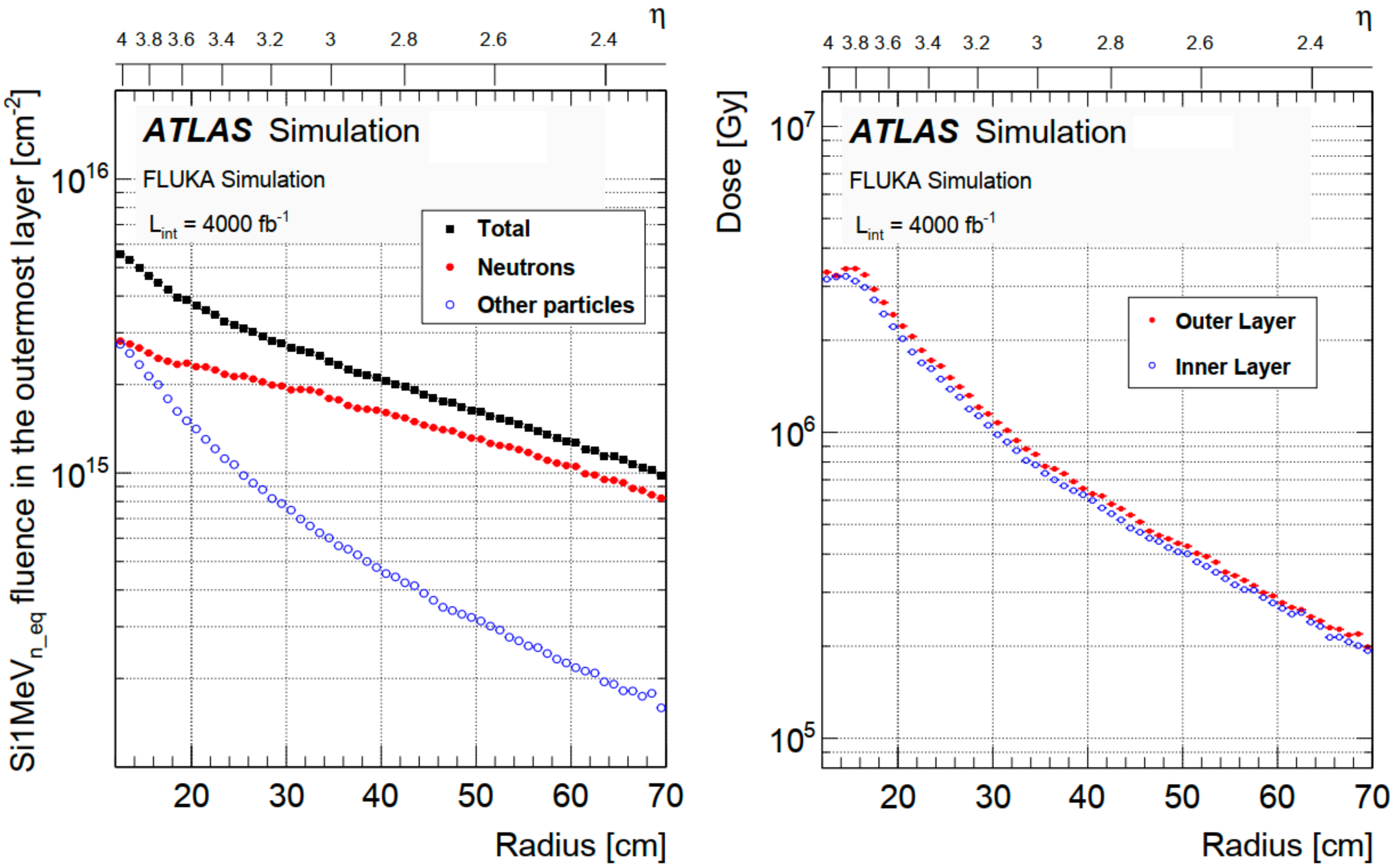
Total 8032 modules, > 3.6 M pads (channels)

Total detector withstand 8.3×10^{15} $n_{eq} \cdot cm^{-2}$, 7.5 MGy radiation



HGTD irradiation

HGTD TDR



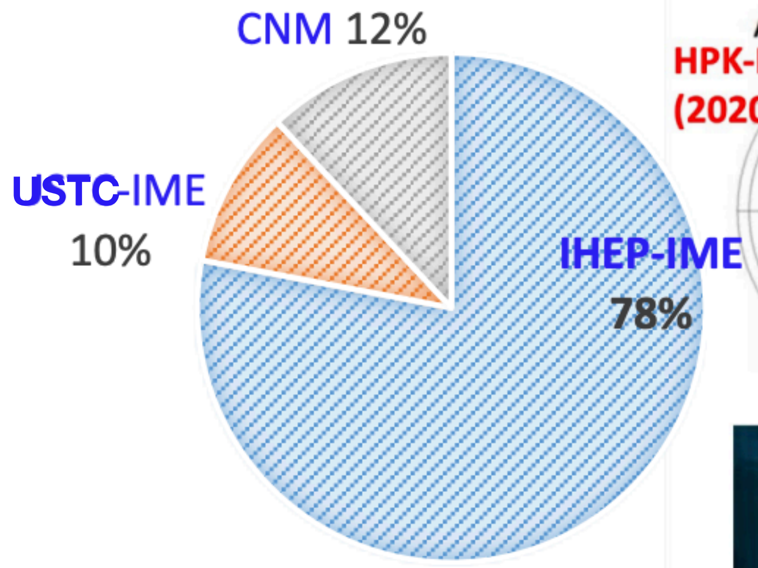
(a) Nominal Si1MeV$_{n_{eq}}$ fluence for HL-LHC. (b) Nominal ionising dose for HL-LHC.

HGTD LGADs Prototypes

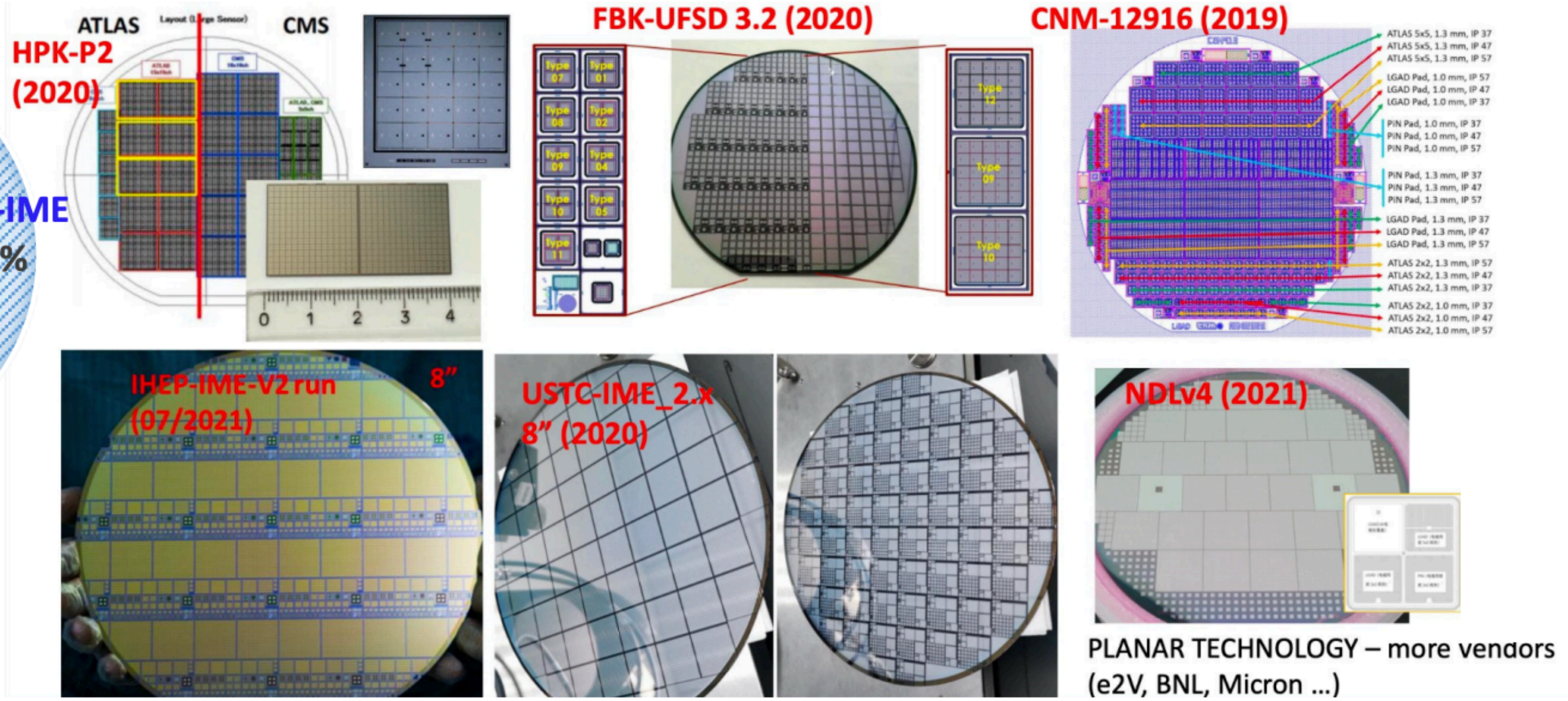
[X. Jia, PSD13]

Lots of prototypes R&D in LGAD, vendors includes:

- IHEP-IME (China), USTC-IME (China), IHEP-NDL (China), FBK (Italy), CNM (Spain), HPK (Japan)



Share of production between vendors



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