Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector: laboratory and test beam campaigns

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ON BEHALF OF ATLAS-HGTD COLLABORATION

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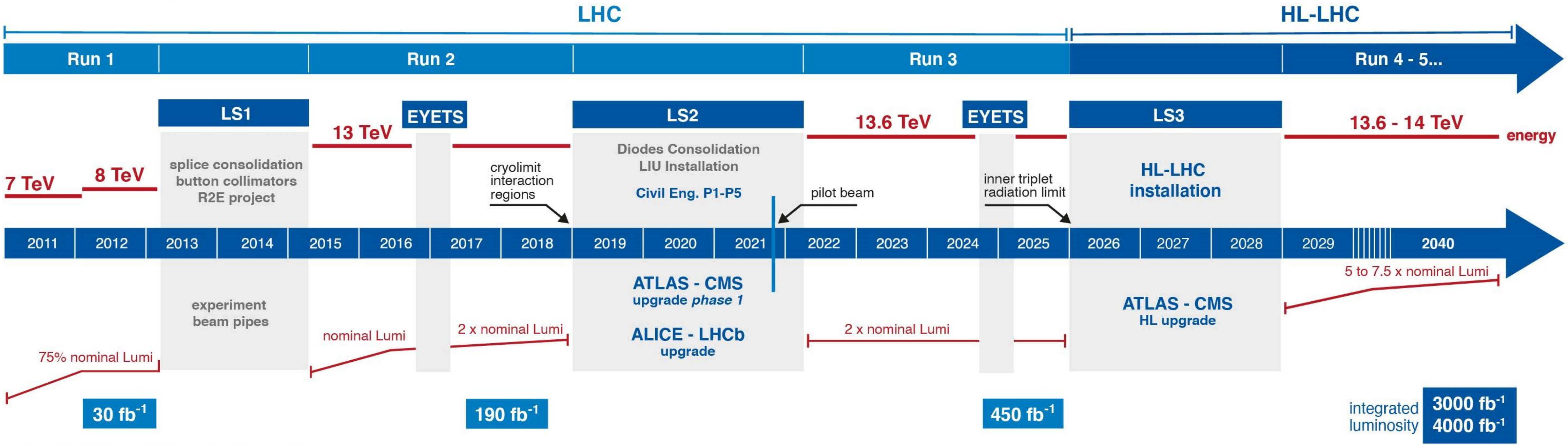
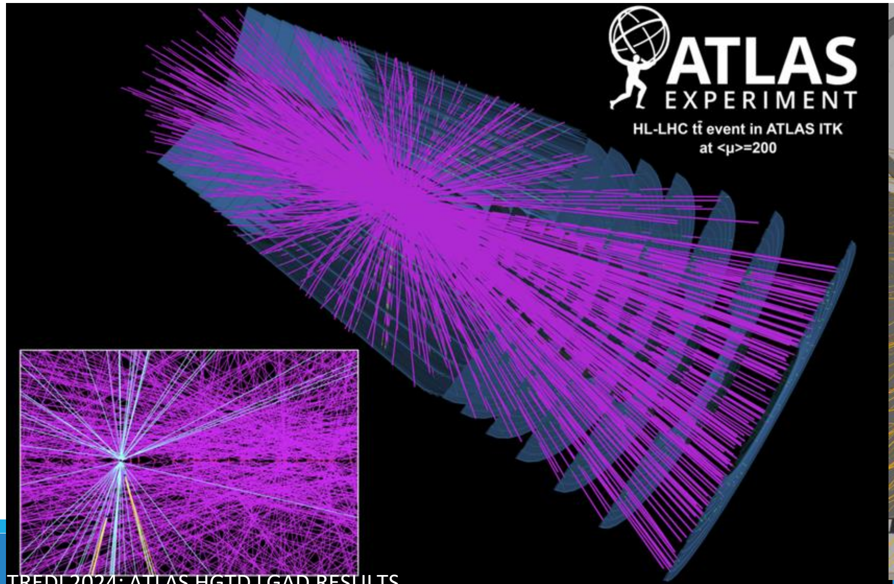
High Luminosity LHC (HL-LHC)

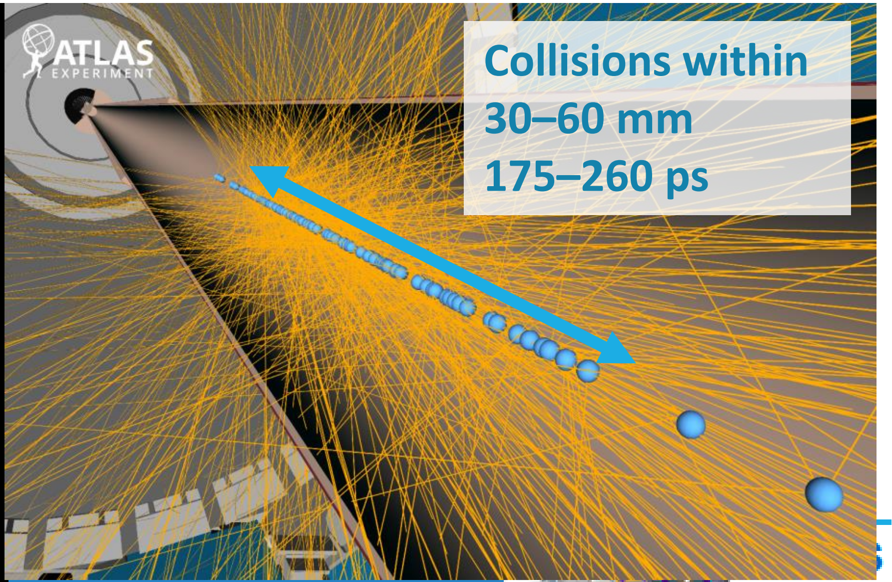

LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
inner triplet
radiation limit
HL-LHC
installation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
experiment
beam pipes
ATLAS - CMS
upgrade *phase 1*
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
5 to 7.5 x nominal Lumi
30 fb^{-1}
190 fb^{-1}
450 fb^{-1}
integrated
luminosity
3000 fb^{-1}
4000 fb^{-1}

ATLAS experiment pileup:

LHC run 3: $\langle\mu\rangle_{max} = 55$

HL-LHC: $\langle\mu\rangle = 200$





Collisions within
30–60 mm
175–260 ps

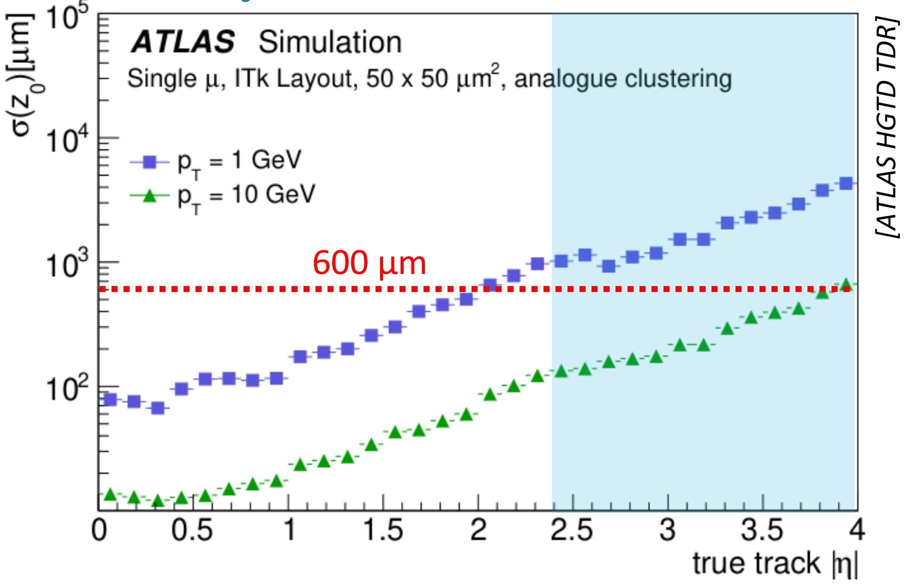
[ATLAS Collaboration]

ATLAS High Granularity Timing Detector

- **Pile-up a big experimental challenge at HL-LHC**
  - At <μ> = 200 vertex spacing ≈ 0.6 mm
  - Vertex separation in forward direction not possible with only ATLAS ITk (new inner tracking detector)

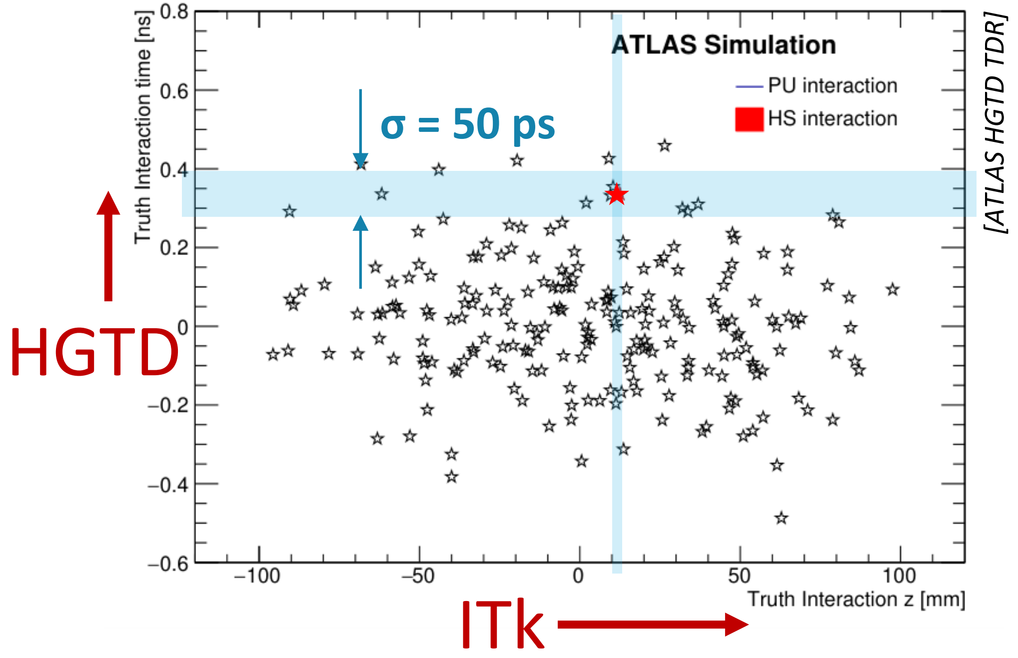
- **ATLAS High Granularity Timing Detector (HGTD)**
  - Time information, track time resolution 50 ps
  - In addition luminosity measurement by particle counting (target 1 % precision)

z_0 resolution with ITk only



600 μm

[ATLAS HGTD TDR]



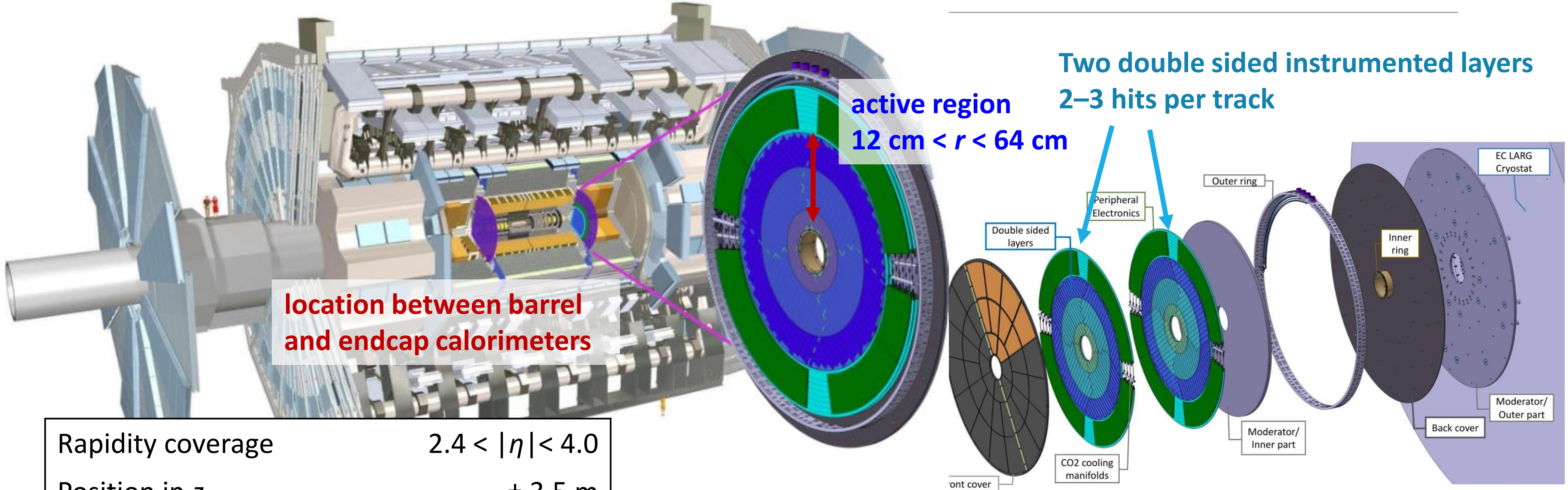
σ = 50 ps

HGTD

ITk

[ATLAS HGTD TDR]

ATLAS HGTD basic information



active region
$12\text{ cm} < r < 64\text{ cm}$

Two double sided instrumented layers
2–3 hits per track

location between barrel and endcap calorimeters

[ATLAS HGTD TDR]

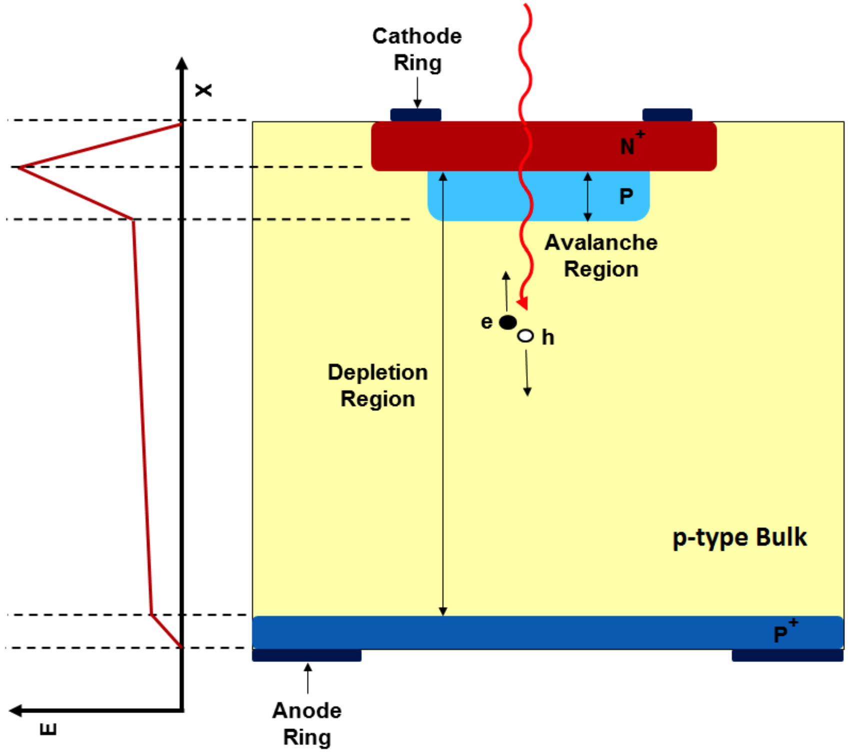
total thickness 75 mm

Rapidity coverage	$2.4 < \lvert\eta\rvert < 4.0$
Position in z	± 3.5 m
Number of channels	3.6 M
Pad size	1.3 mm × 1.3 mm
Operating temperature	–30 °C (CO_2)
Track time resolution	≤ 50 ps

HGTD radiation hardness:
Design for **End-of-Life (EOL) fluence 2.5×10^{15} n_{eq} cm^{-2}, TID 2 MGy**
Plan to replace Inner sections after this radiation level

HGTD Sensors: Low Gain Avalanche Detector (LGAD)

- Hit time resolution $\sigma_{\text{hit}} \leq 70$ ps per layer is required - beyond standard HEP devices
  - $\sigma_{\text{track}} = \sigma_{\text{hit}}/\sqrt{N_{\text{hits}}}$
- **Low Gain Avalanche Detector (LGAD)**
  - n-on-p silicon sensor with additional **p^+ Gain Layer**
  - Charge multiplication by impact ionization – improved Signal-to-Noise
  - Operation in linear regime with typical gain factor 10–20
- Active sensor thickness in ATLAS HGTD 50 µm, pad size 1.3 mm × 1.3 mm, 15 × 15 channels

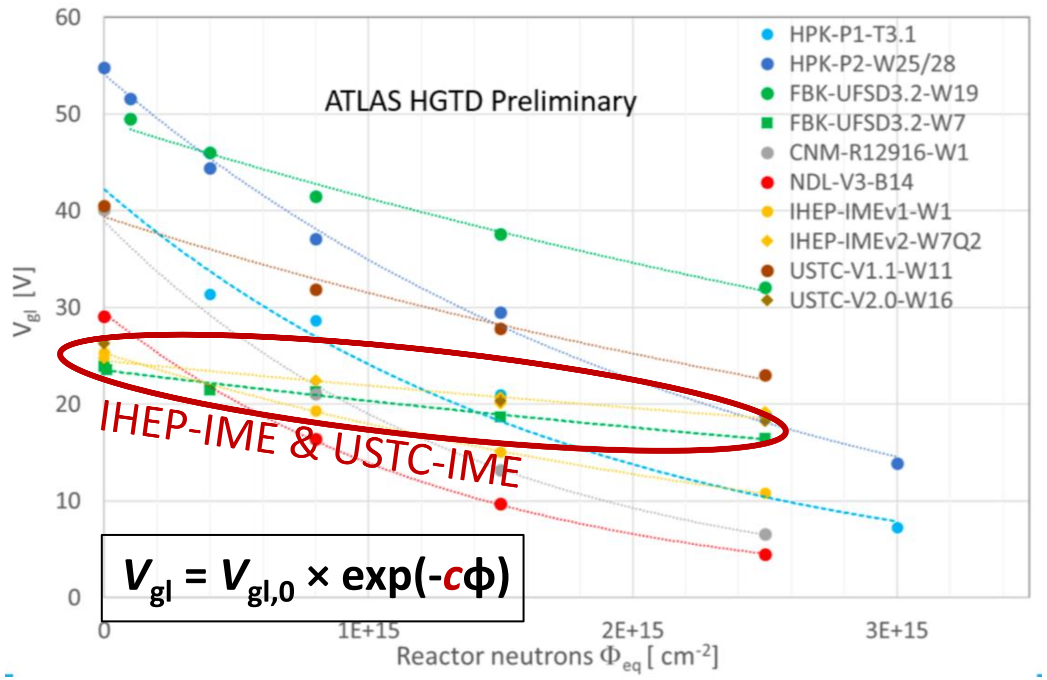


LGAD radiation hardness

- HGTD requirements after EOL fluence 2.5×10^{15} n_{eq} cm^{-2} :
  - **Collected charge:** 4 fC (25 ke$^-$) at V_{bias} = 550 V
  - **Time resolution:** 50 ps

1 fC = 6250 e$^-$

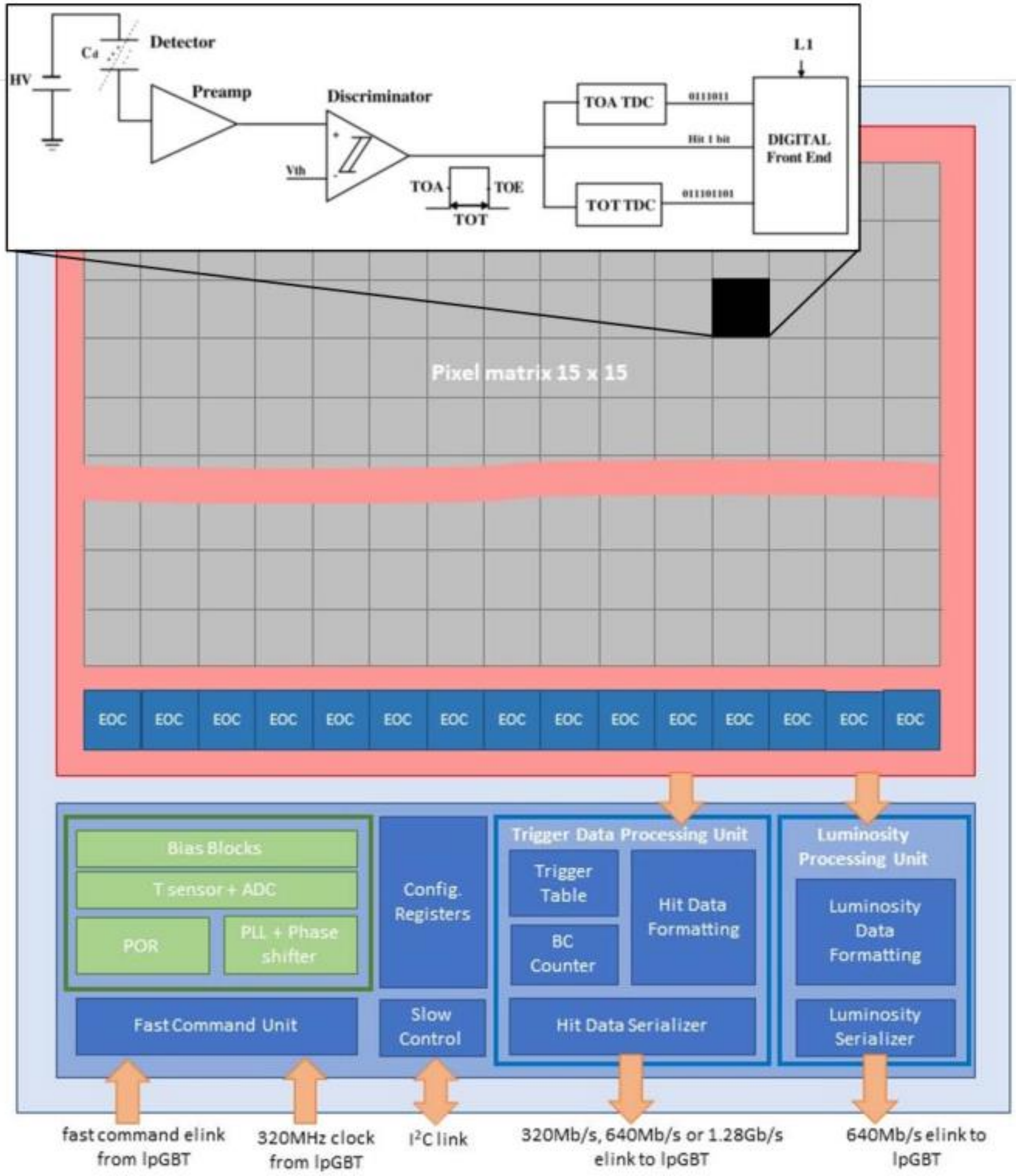
- **V_{gl}** (gain layer depletion voltage ∝ $N_{Acceptor}$)**: V_{gl} ↑, Gain ↑**
- Electrical deactivation of Boron dopants in gain layer – **acceptor removal – *c***: smaller V_{gl}, *E*-field, Gain
  - **$B_s + I \rightarrow Si + B_i$; $B_i + O \rightarrow B_iO_i$**
  - Compensated for by higher bias voltage … but safe operating voltage limited, E_{avg} **≤ 11 V/µm** due to destructive **Single Event Breakdown**
- Carbon implantation reduces acceptor removal rate
  - C shielding substitutional boron – improved radiation hardness
- **Two sensor designs selected for HGTD:**
  - **IHEP** (Beijing, China), **USTC** (Hefei, China), both produced by **IME**
  - Preproduction started in 2023



$$V_{gl} = V_{gl,0} \times \exp(-c\phi)$$

ALTIROC: HGTD readout chip

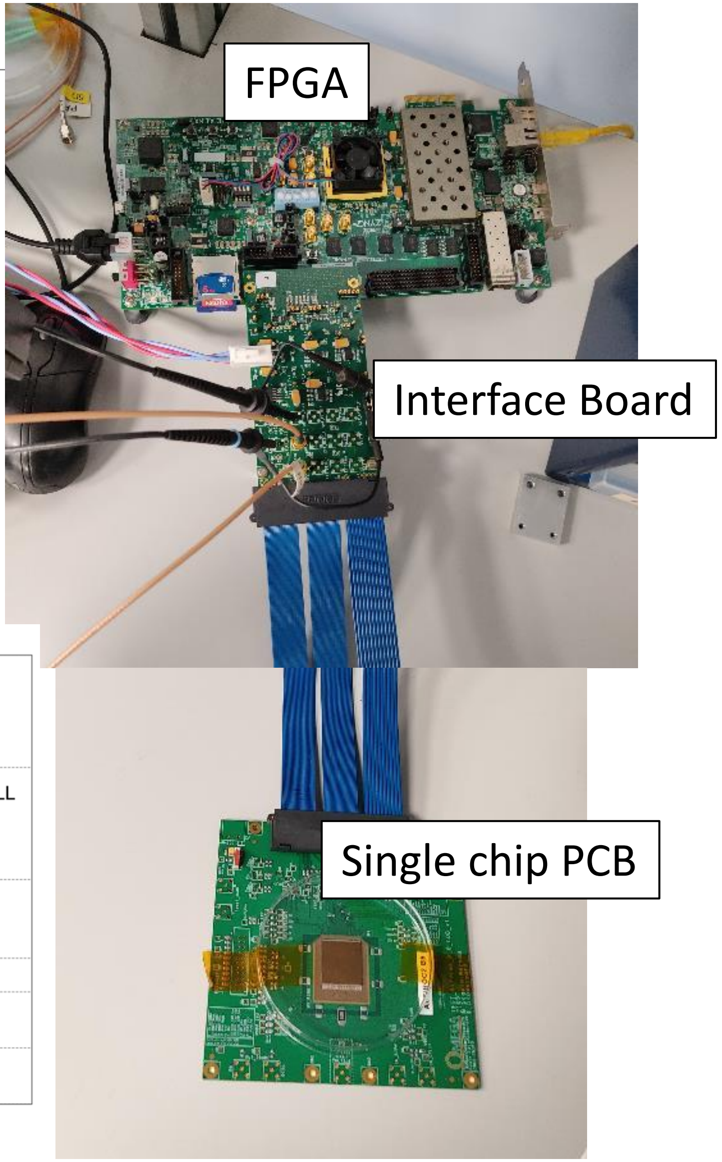
- **ASIC produced in 130 nm CMOS process by TSMC (radhard)**
- Pixel chip with low number of channels optimized for timing
  - Small jitter: 25 ps at 10 fC (< 70 ps at 4 fC)
  - 2 fC minimum discriminator threshold
- **Time-to-Digital Converters (TDC)** for measurements of
  - **Time of Arrival**, w.r.t. LHC clock
  - **Time over Threshold**, for time walk correction (approximating constant fraction discrimination)
- **Development status**
  - **ALTIROC 0 & 1**: small prototypes for analog front end tests
  - **ALTIROC 2**: First full size prototype (15 × 15 pixels) with full electronic chain
  - **ALTIROC 3**: Current version, performance up to specifications on testbench and after irradiation
  - **ALTIROC A**: Planned production version, minor fixes to ALTIROC 3 design, planned submission February 2024

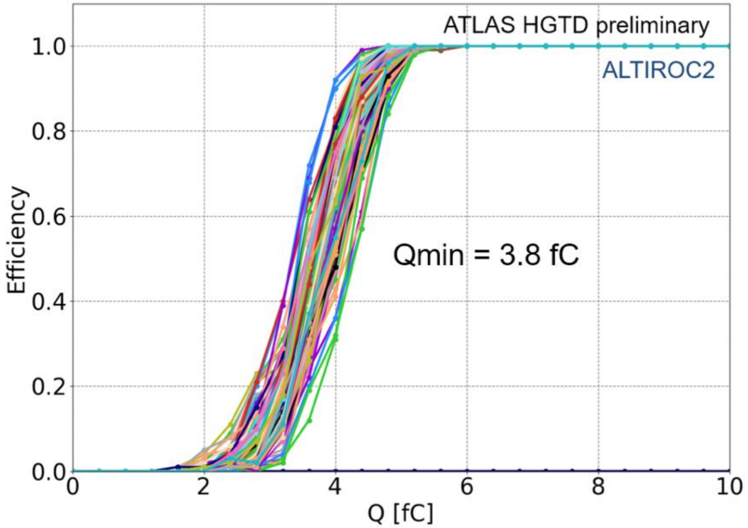


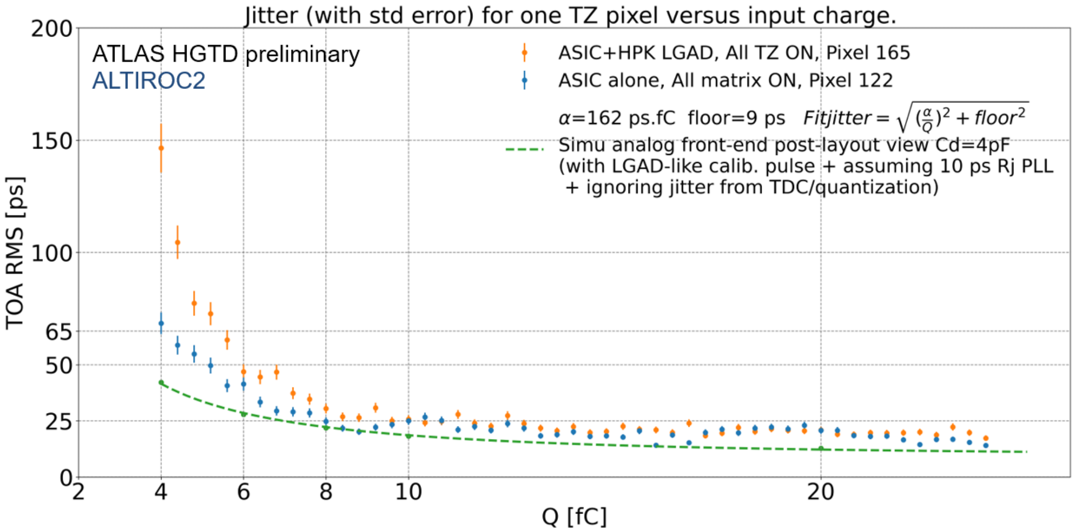
[ATLAS HGTD TDR]

ALTIROC performance

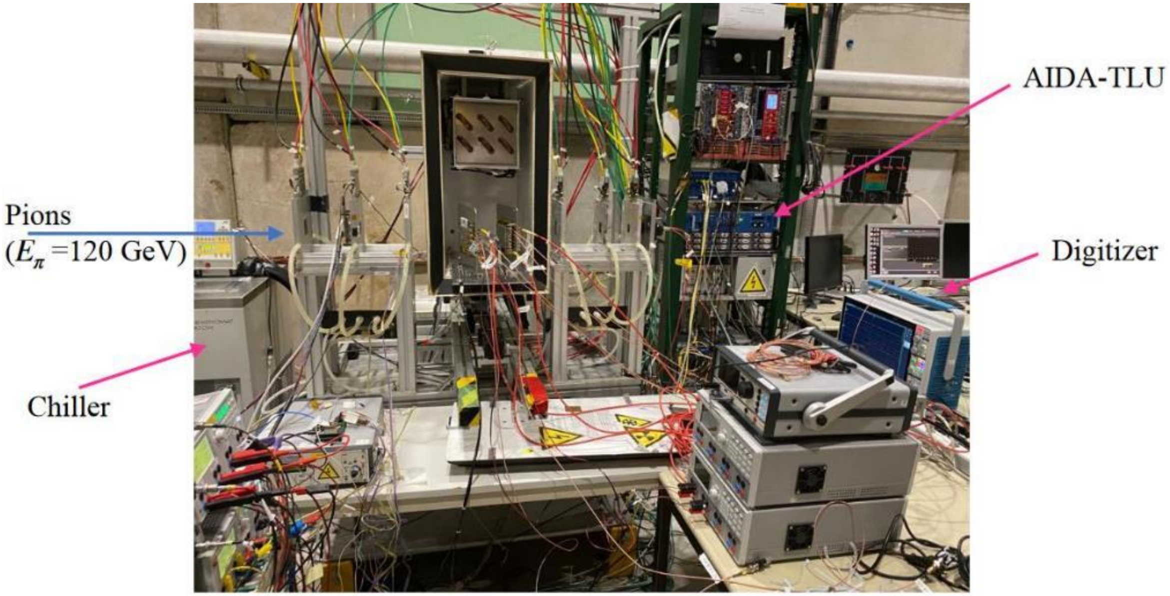
- ASICs extensively studied with dedicated setups
  - Tests with ASIC-only and ASIC+LGAD (hybrid)
  - Tests with hybrids with 90Sr and in testbeams
- ALTIROC 2: minimum threshold with LGAD 3.8 fC
  - Improved in ALTIROC 3
  - Jitter close to 25 ps @ 10 fC (with sensor)







HGTD testbeam campaigns



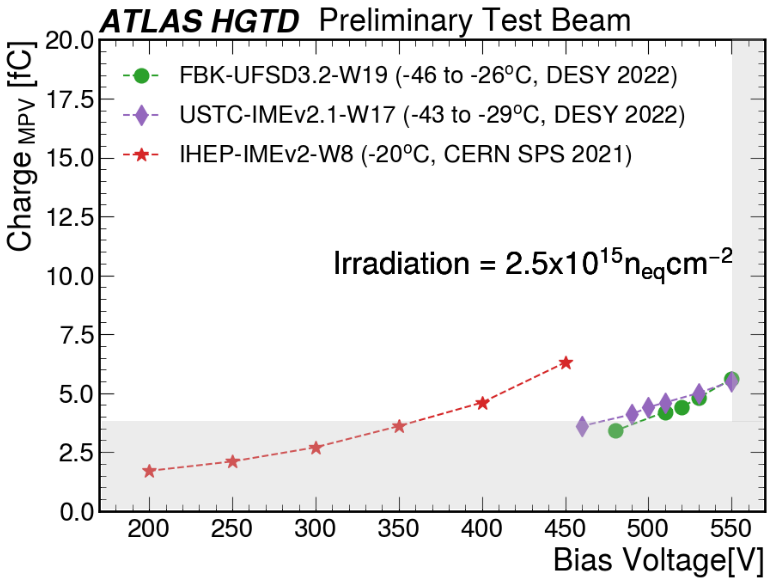
DESY
5 GeV electron beam
EUDET beam telescope

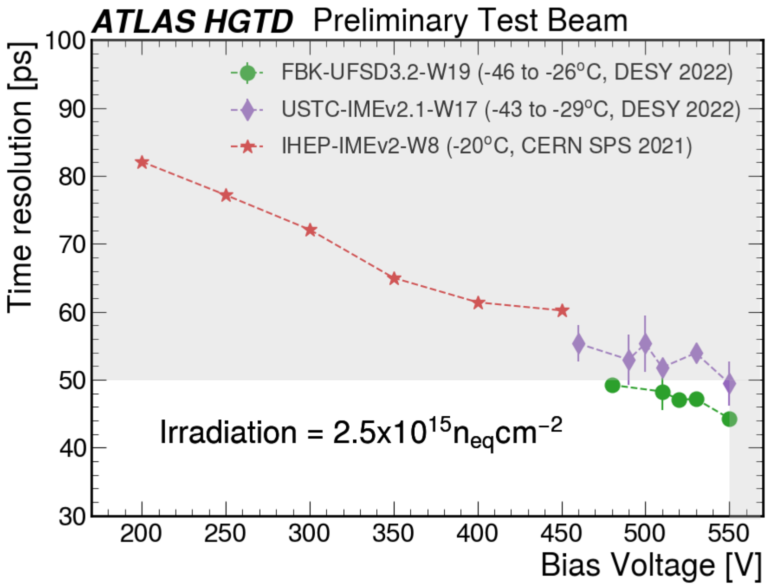
CERN SPS
120 GeV pion beam
AIDA beam telescope

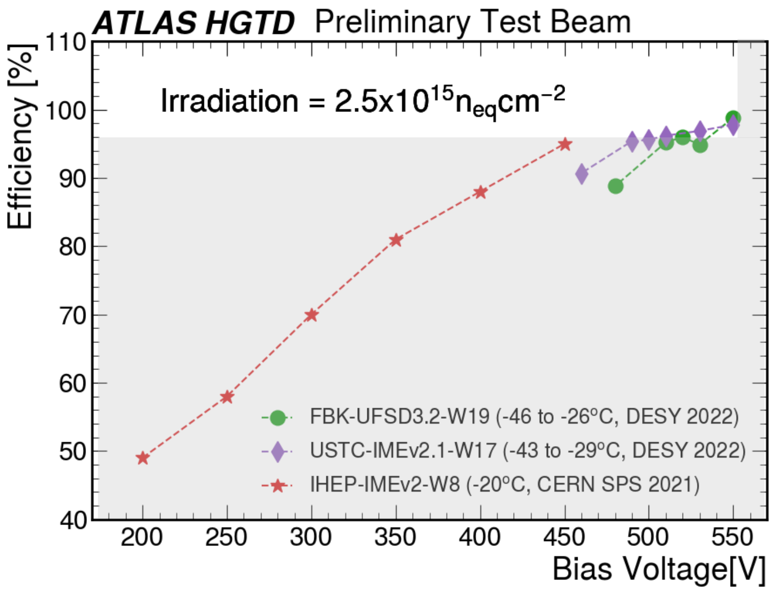
Analysis based on Corryvreckan

2022: sensor R&D tests (irradiated)
2023: preproduction sensor tests (irradiated), hybrid tests (unirradiated) – analysis ongoing
2024: in addition irradiated hybrids

Testbeam sensor results 2021/2022







Collected charge

4 fC collected at EOL fluence for all tested sensors

Time resolution

Resolution **< 70 ps** achieved with prototype sensors

Efficiency

Hit efficiency > 95 % (within specs)

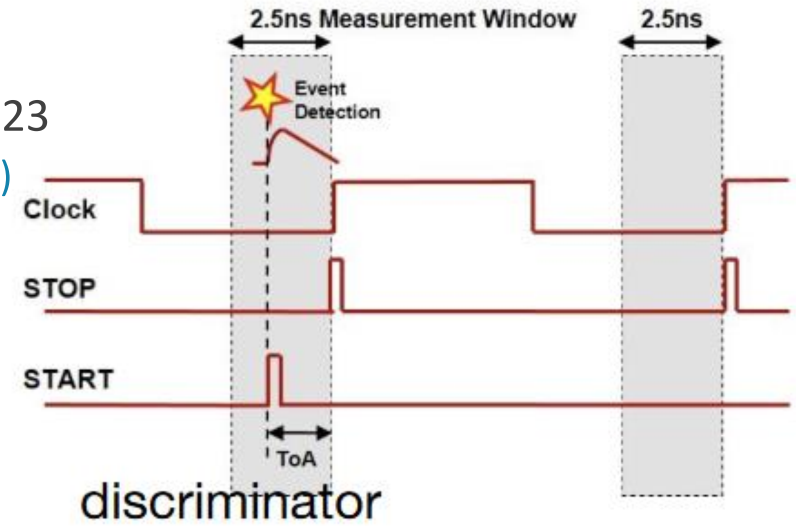
Analog efficiency at Q_{thr} = 2 fC (nominal min. ASIC threshold)

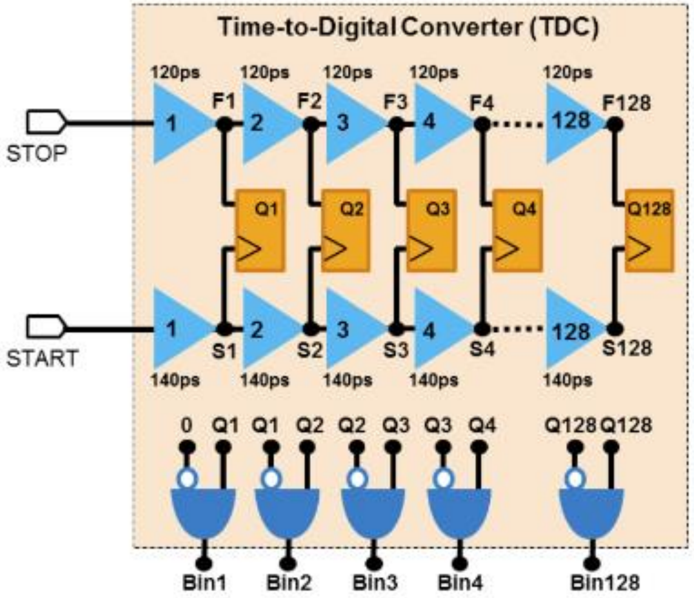
$$\text{Efficiency} = \frac{\text{Ntracks } (q > Q_{\text{thr}})}{\text{Total Ntracks}}$$

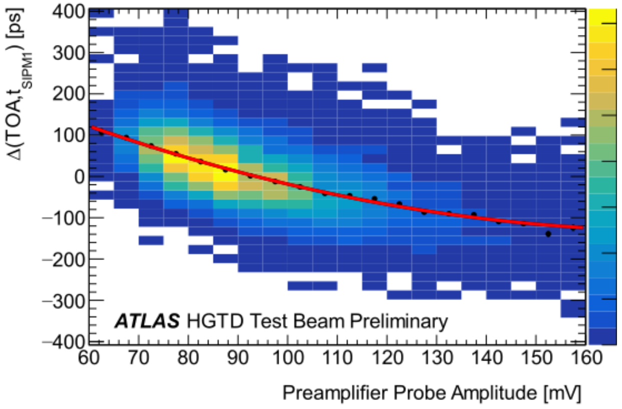
Measurements & Analysis with preproduction sensors ongoing

Testbeam measurements with LGAD + ALTIROC hybrids

- Measurements of time resolution with unirradiated hybrids (Sensor + ALTIROC) in 2023
    - Asynchronous hits (in ATLAS in sync with LHC clock)
- Tests of ALTIROC TDC functionality
    - Slow and Fast delay lines (START & STOP)
    - Properties of Least-Significant-Bit size
    - Design improvements in ALTIROC 3 & A
- Time-walk correction procedure using ToT
- Analysis ongoing
- First hybrids prepared for irradiation, testbeam in 2024

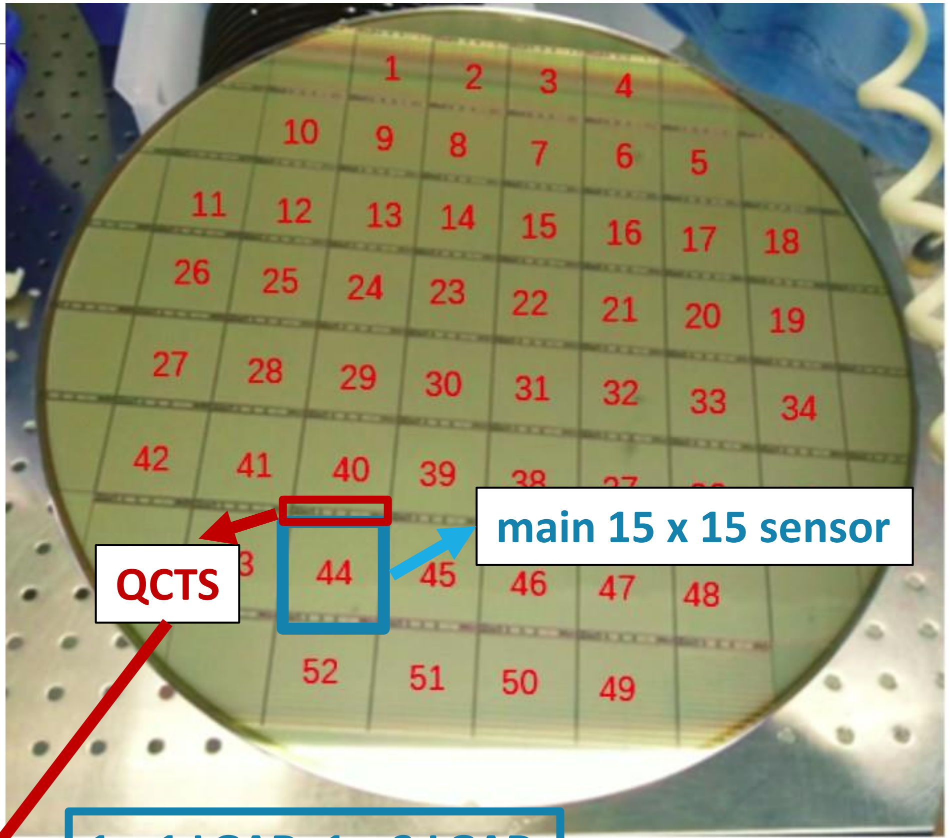






HGTD Sensor production

- HGTD will be built from 16,064 sensors produced by IHEP-IME and USTC-IME
- 8-inch wafers with 52 Main Sensors (2 cm × 2 cm, 15 × 15 channels)
- Quality Control Test Structure (QCTS) next to each Main Sensor
- Sensor preproduction started in 2023
  - 130+ preproduction wafers being processed
  - 7 wafers available for preliminary testing
  - Main production starts in first half of 2024



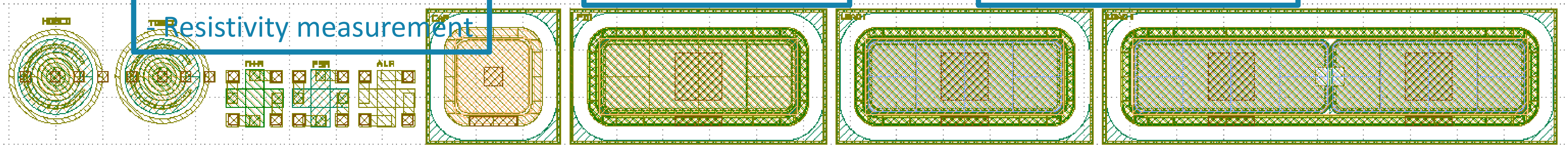
Gate Controlled Diodes
- Surface currents

MOS Capacitor
- SiO_2 properties

PIN diode
- Si bulk properties

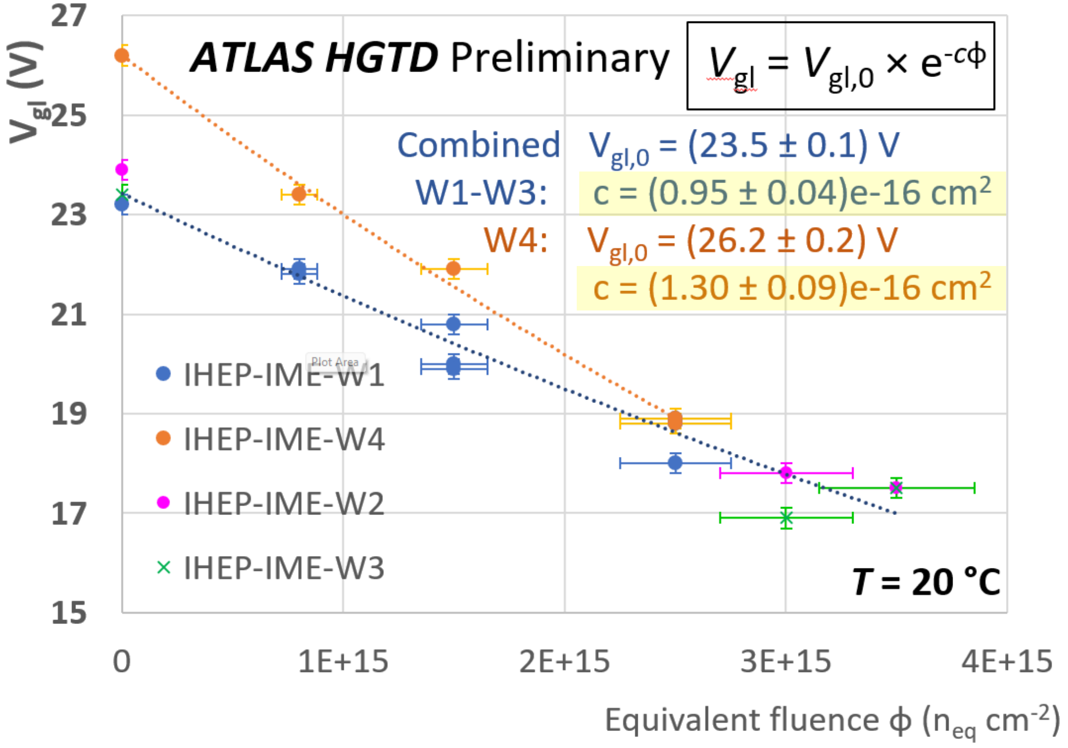
1 x 1 LGAD, 1 x 2 LGAD
- LGAD performance

Van der Pauw structures
- Resistivity measurement

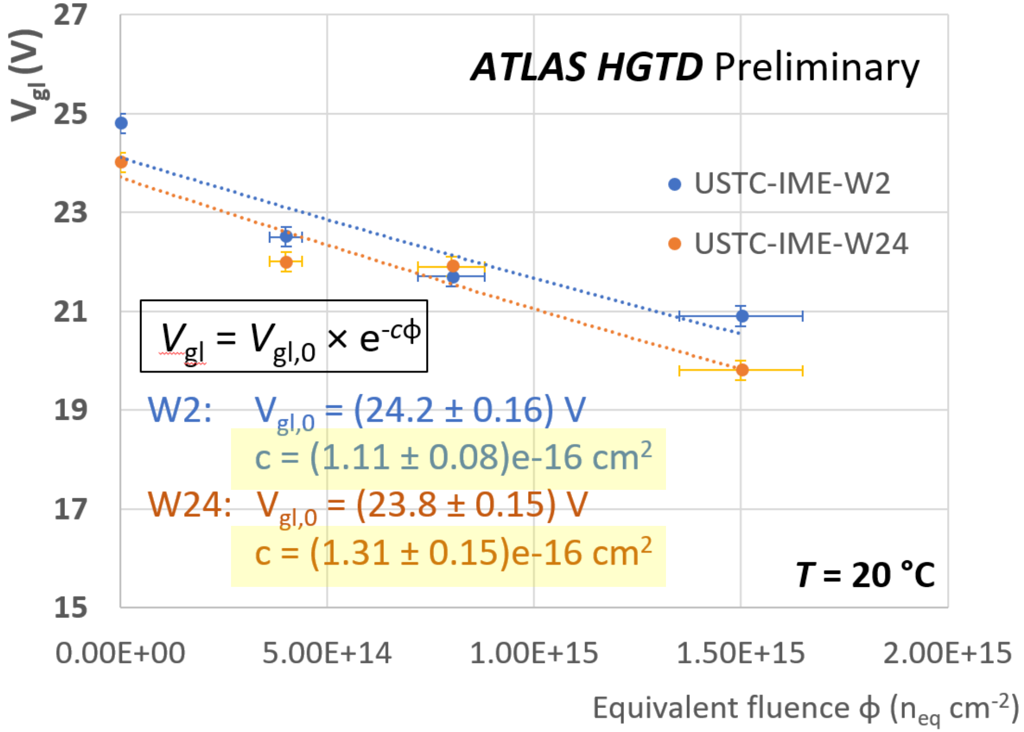


CV: Acceptor removal parameter in HGTD preproduction sensors

IHEP-IME



USTC-IME

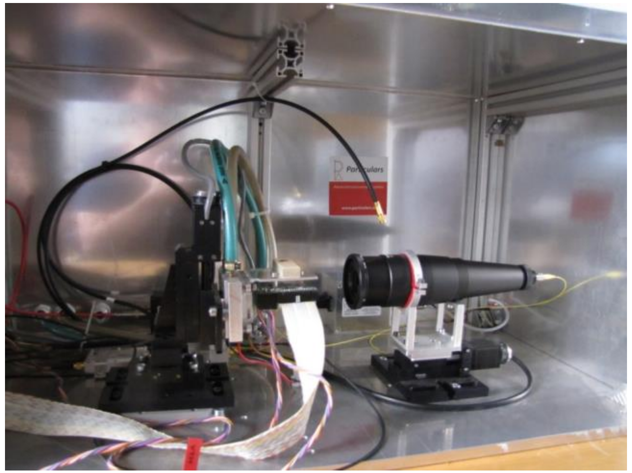


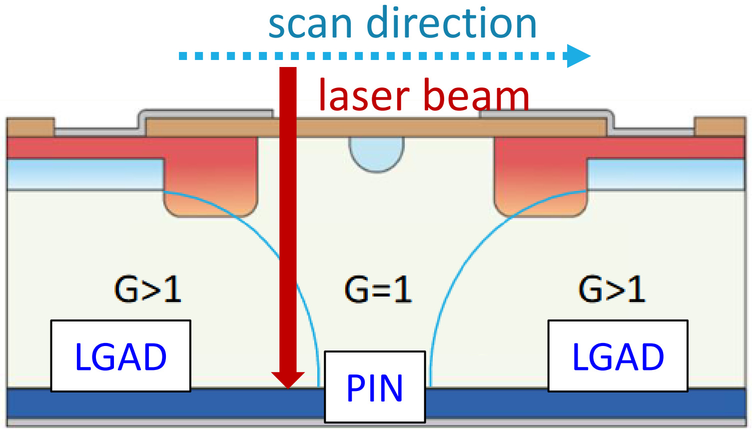
- CV: Acceptor removal parameter *c* in all IHEP-IME and USTC-IME wafers is around 1e-16 cm^{-2} (slight differences)
- **Promising result in terms of acceptor removal → indicates good radiation hardness**

HGTD Irradiation Tests

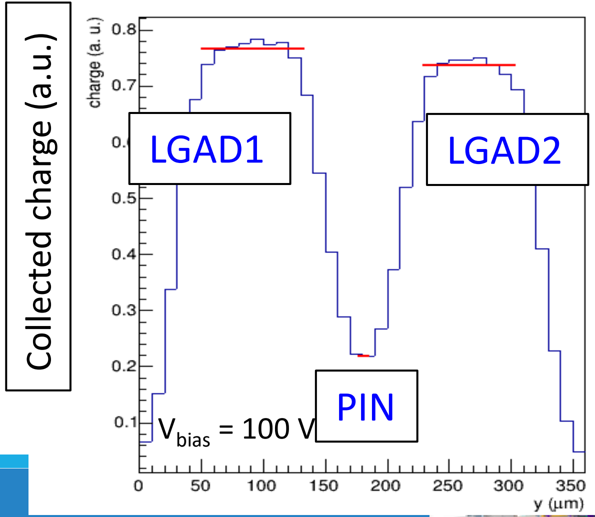
- **Irradiation tests (IT)** to monitor sensor radiation hardness throughout production
  - Main test site is JSI Ljubljana – neutron irradiation (TRIGA) and tests on Quality Control Test Structure
  - 1–2 tests per wafer (total ≈ 1000 tests) – need fast method, extract many parameters with a single measurement

- New Transient Current Technique (TCT) test method – **TCT-IT**
  - Top-TCT within interpad region between two LGADs using focused infrared laser (MIP-like charge deposition)
  - Measure response of **LGAD** and **interpad** region (no gain →**PIN diode**)
  - Extract **V_{gl}, Gain as function of V_{bias}, Interpad Distance, Leakage Current**
  - Wafer acceptance criteria to be defined on preproduction statistics based on results from several methods (TCT, Sr90, IV/CV)



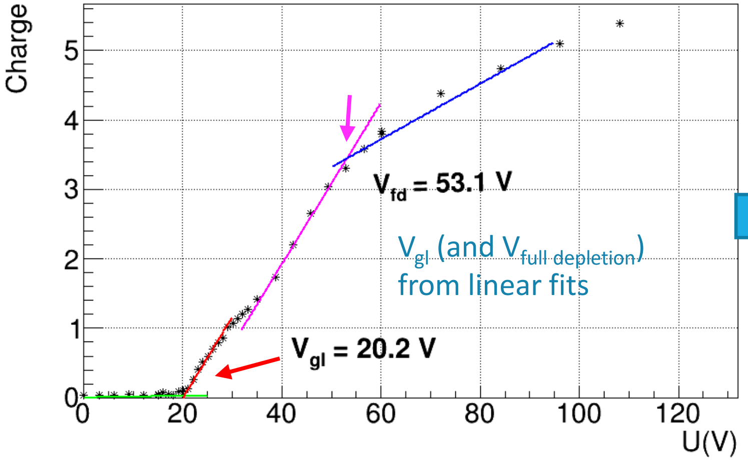


[TCT-IT method working plot example]

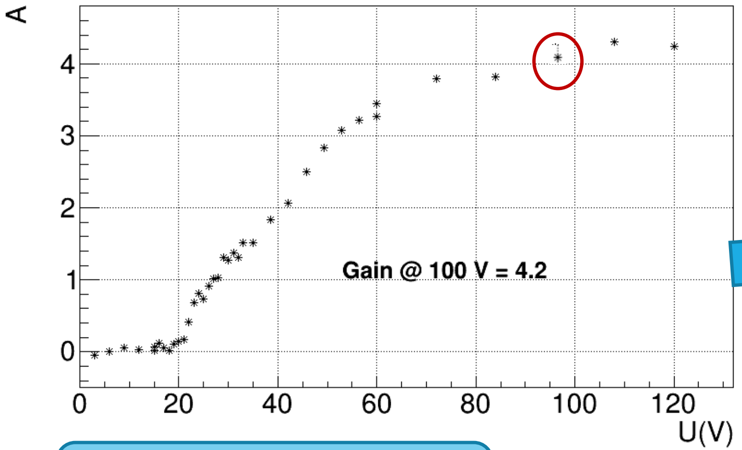


TCT-IT Results: V_{gl} and Gain

[TCT-IT method working plot example]

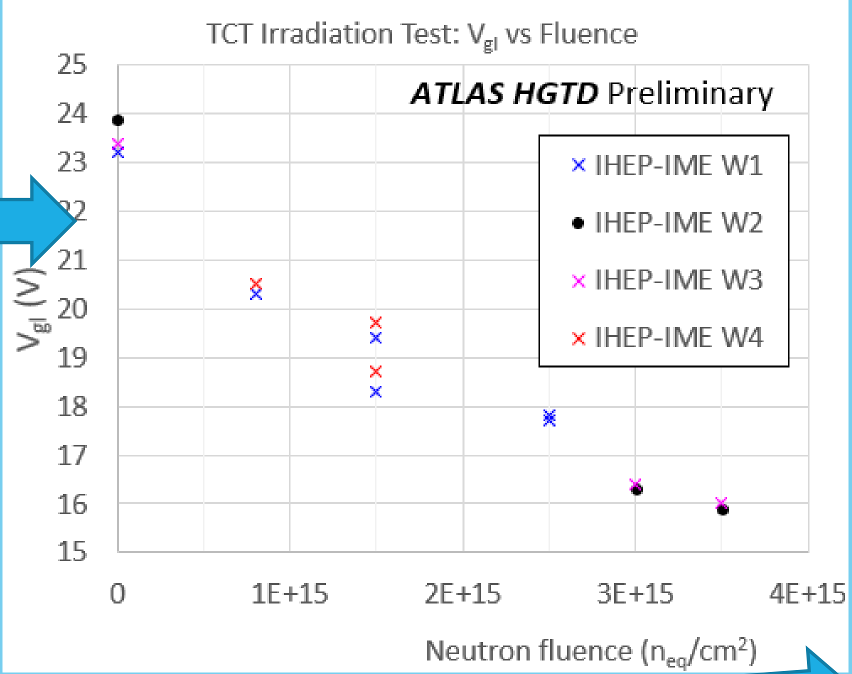


[TCT-IT method working plot example]

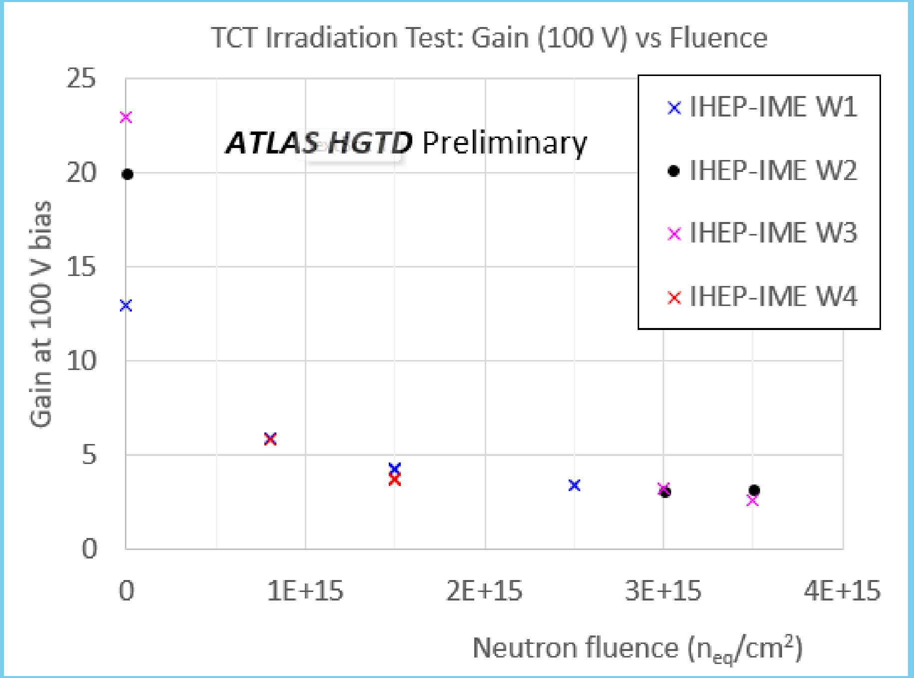


$$\text{Gain} = \frac{\text{Signal (LGAD)}}{\text{Signal (PIN)}}$$

TCT Irradiation Test: V_{gl} vs Fluence



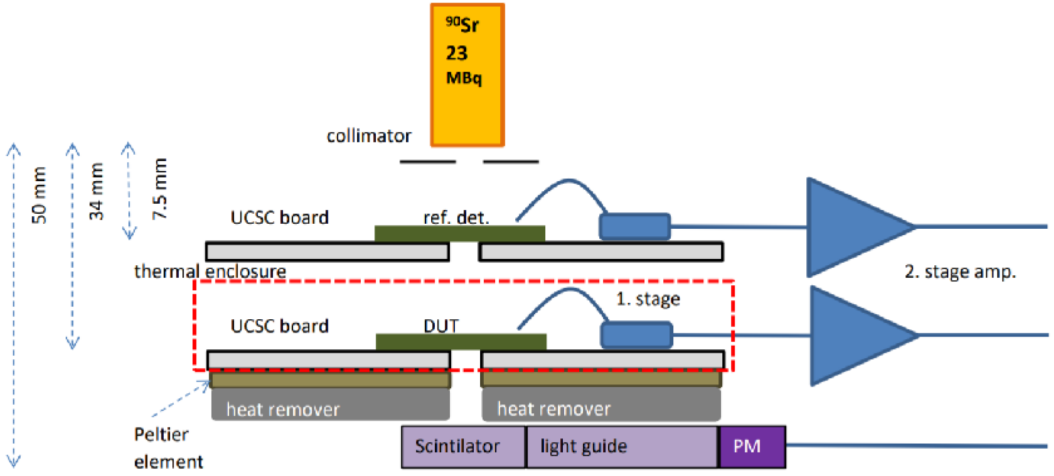
TCT Irradiation Test: Gain (100 V) vs Fluence



- V_{gl} and Gain at 100 V (= fixed voltage) well separated for different fluences
  - **Good method sensitivity**
- Consistent behavior between different wafers
- Gathering more statistics to derive selection criteria

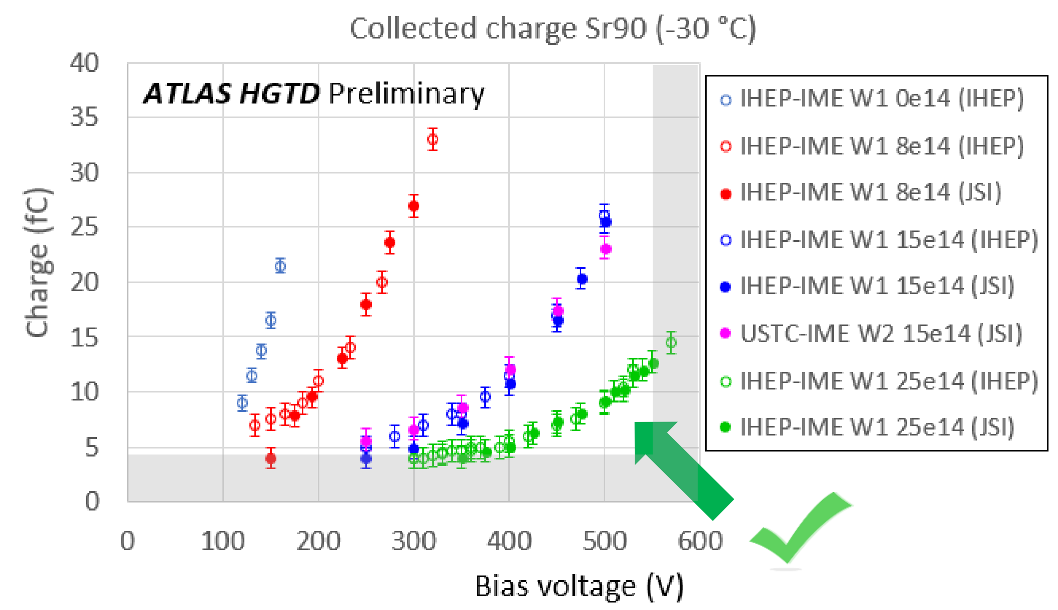
HGTD IT ^{90}Sr measurements

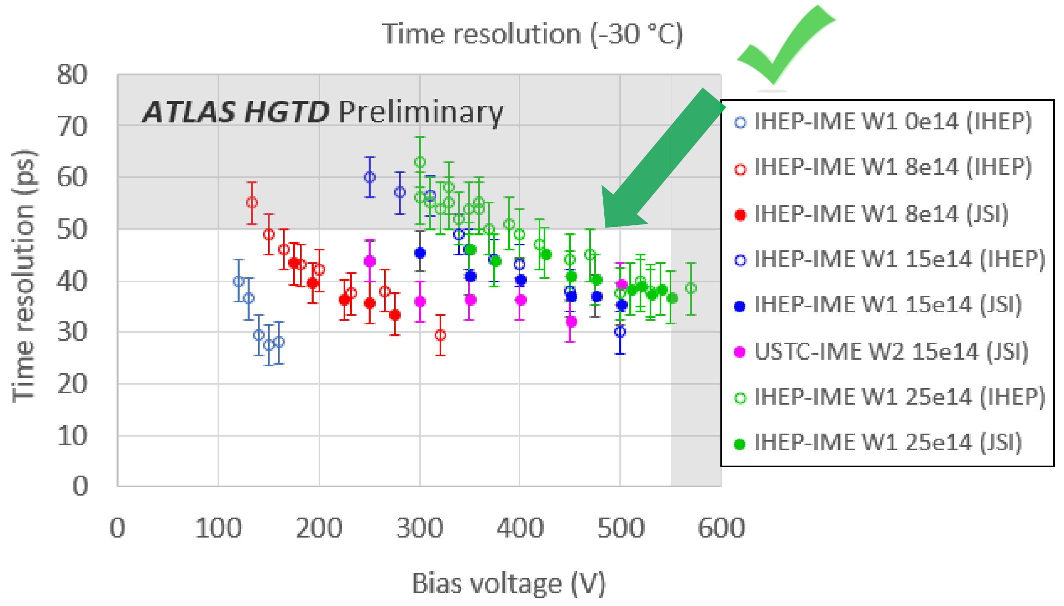
- TCT-IT not directly measuring **MIP charge** and **time resolution – calibration by Sr90**
- Setup with two LGADs (time reference and DUT)
  - Trigger on reference LGAD + PMT ("MIP" selection)
  - DUT cooled to –30° C, not part of the trigger



Preproduction sensors well within radiation hardness specifications

TCT-IT results for 2.5e15 a rough outline for **selection criteria**:
Vgl > 17 V, Gain(100 V) > 3 after EOL fluence





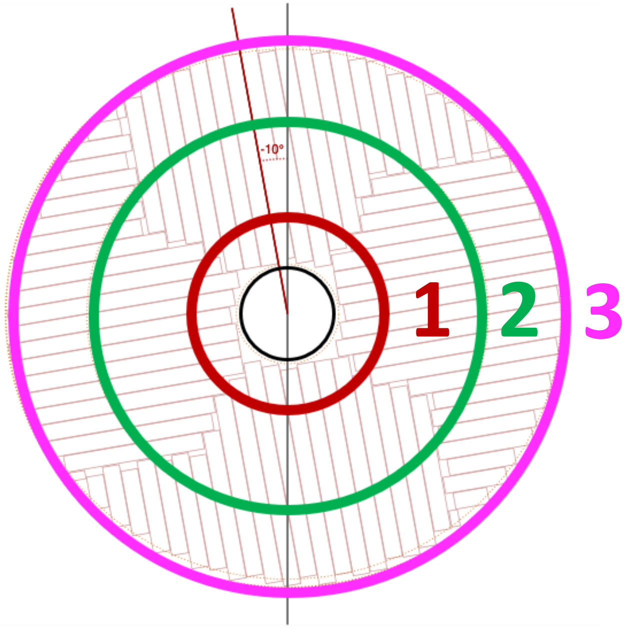
Summary

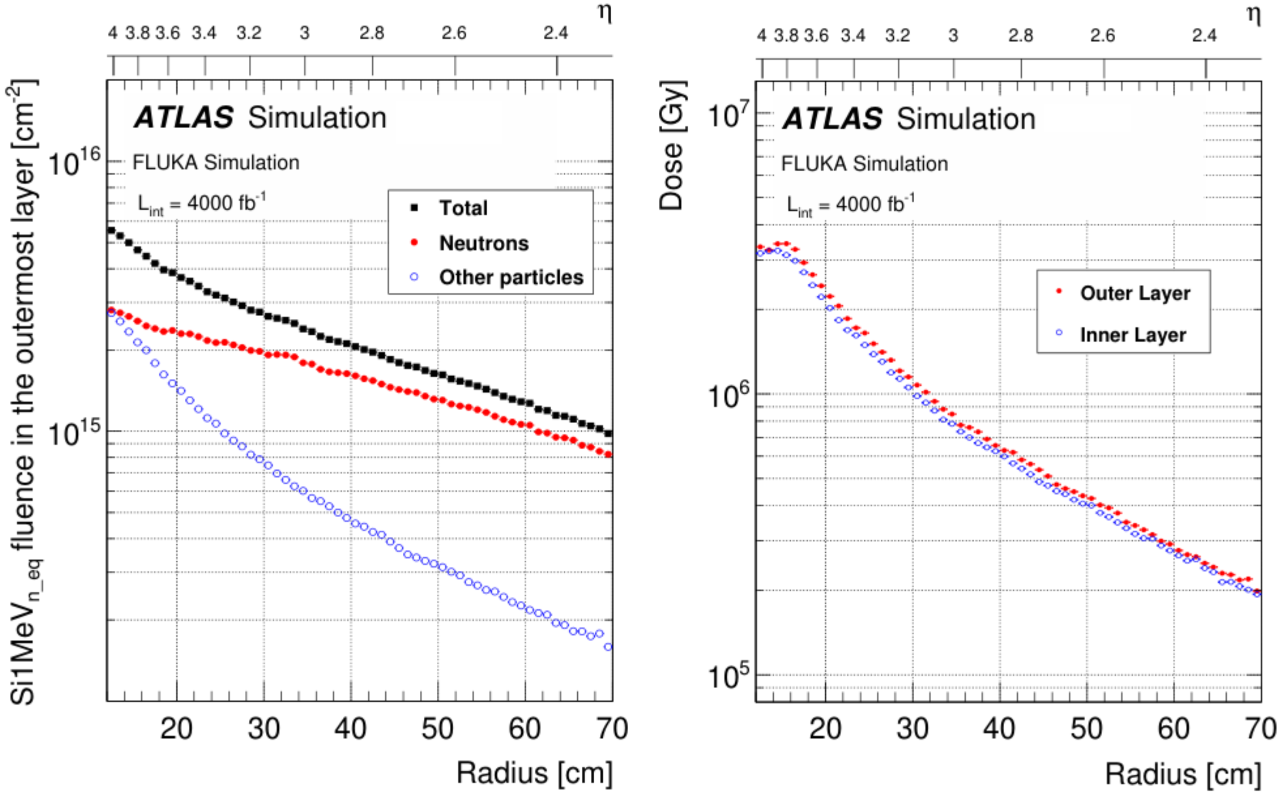
- **ATLAS HGTD** will provide **precise timing information (50 ps)** and **luminosity measurement (1 %)** at HL-LHC
- Challenging radiation environment: **2.5×10^{15} n_{eq} cm^{-2}, 2 MGy**
- **LGAD sensors** by **IHEP-IME** and **USTC-IME**
  - Carbon implantation for improved radiation hardness – acceptor removal parameter ≈ **1e-16 cm^{-2}**
  - Operation within specification in test beam (DESY, CERN)
- **ALTIROC readout chip** – final version ALTIROC A to be submitted soon
  - Timing performance within specifications 25 ps (10 fC), 70 ps (4 fC)
  - First tests with unirradiated LGAD + ALTIROC 3 hybrids in test beam
- **Sensor preproduction** currently ongoing
  - Very promising performance in terms of radiation hardness
  - Introduced new **TCT method for wafer Irradiation Test Quality Control**, working on **wafer acceptance criteria** (statistics)

BACKUP

HGTD Radiation Environment

- Radiation damage in HGTD after 4000 fb^{-1} up to 8.3×10^{15} n_{eq} cm^{-2}, 7.5 MGy (including safety factors)
- HGTD designed for **End-of-Life (EOL) fluence 2.5×10^{15} n_{eq} cm^{-2}, TID 2 MGy** → detector replacements planned
- Segmentation in three concentric rings:
  - **Inner ring ($r \leq 230$ mm)** replaced every 1000 fb^{-1}
  - **Middle ring ($r < 470$ mm)** replaced at 2000 fb^{-1}
  - **Outer ring ($r < 640$ mm)** will not be replaced

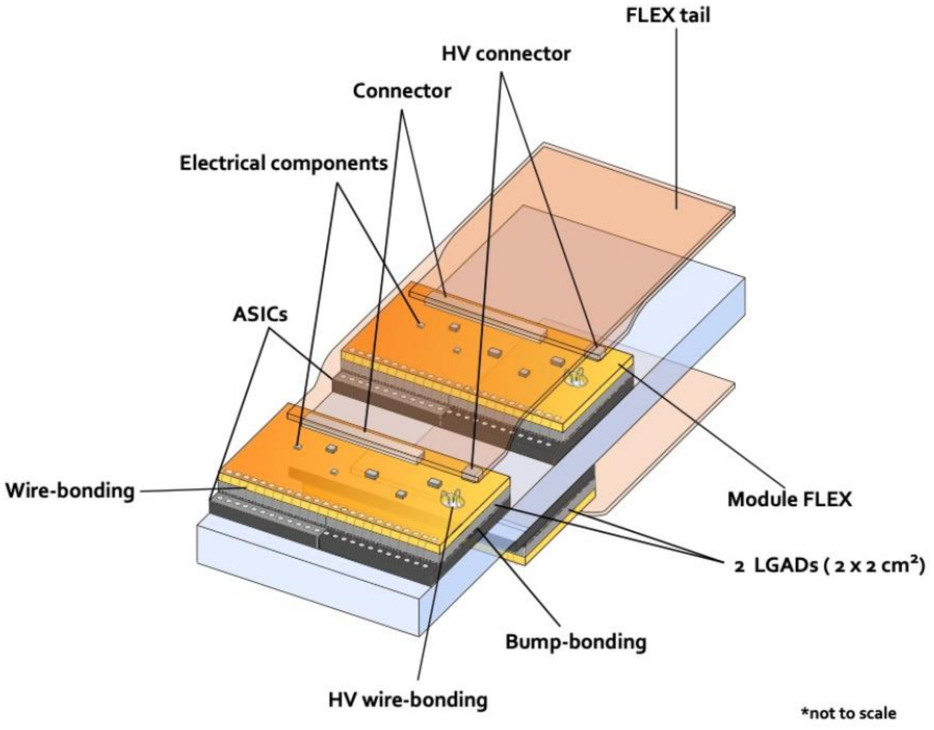


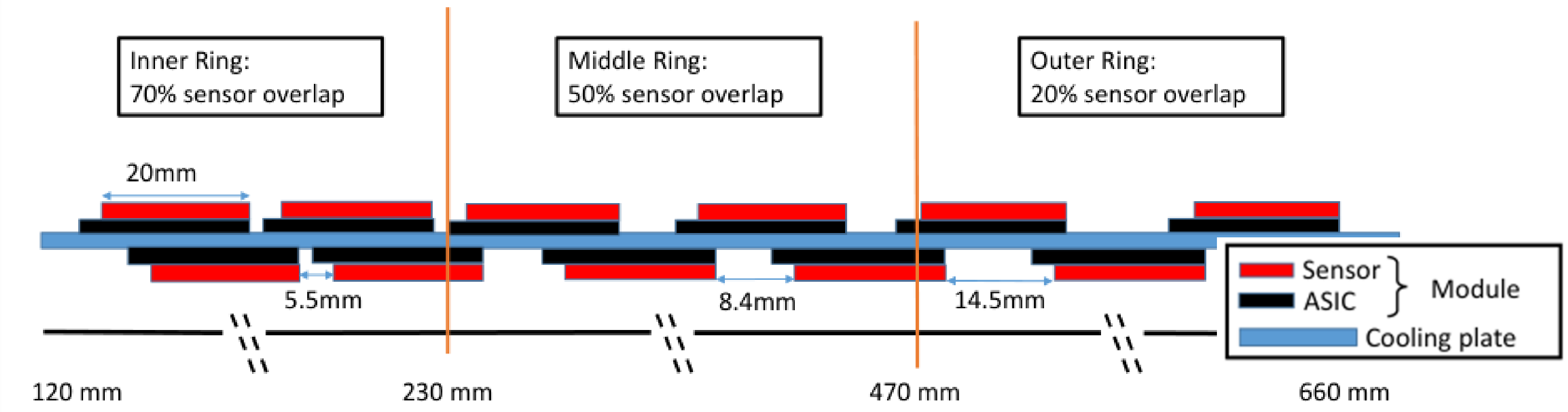


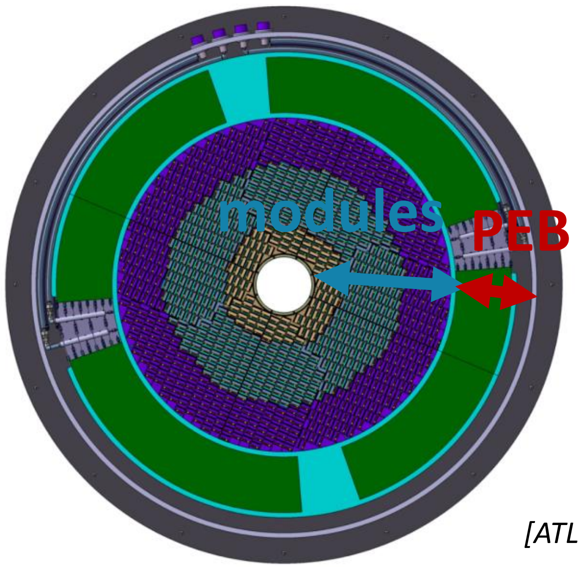
[ATLAS HGTD TDR]

HGTD Modules

- HGTD Module = Two single-chip Hybrids (sensor + readout chip) connected to the same flex PCB (Module Flex)
    - Total dimension 2 cm × 4 cm, 15 × 30 channels (15 × 15 per Hybrid)
    - Bump bond interconnections
    - Two sensors sharing same high voltage → need sensors with similar evolution with fluence, fluence gradient along *r*
- Total of 8032 modules
    - Rows of hybrids connected via Flex Tails to the Peripheral Electronics Boards (PEB) @ 660 < *r* < 920 mm
- Module overlap optimized on each ring, ensure 2–3 hits per track

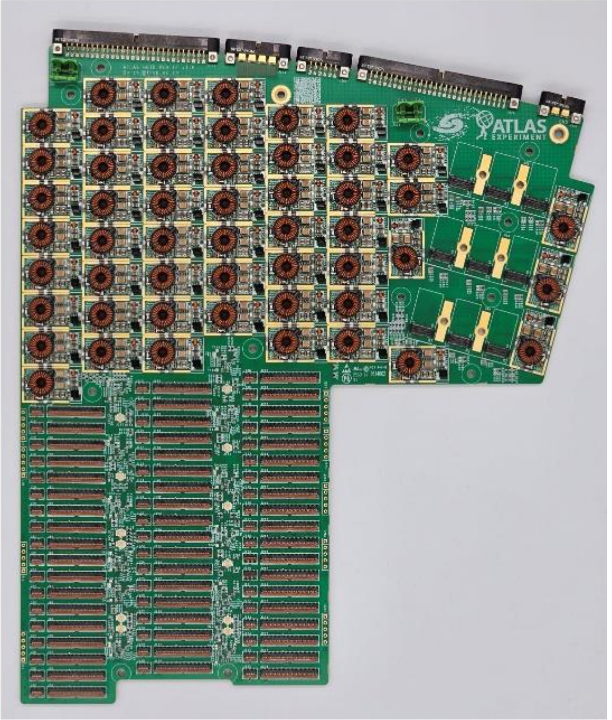




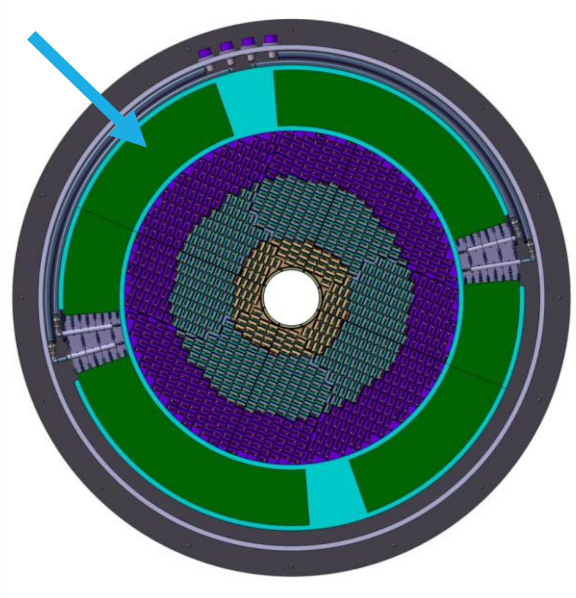


[ATLAS HGTD TDR]

Peripheral Electronics Board (PEB)

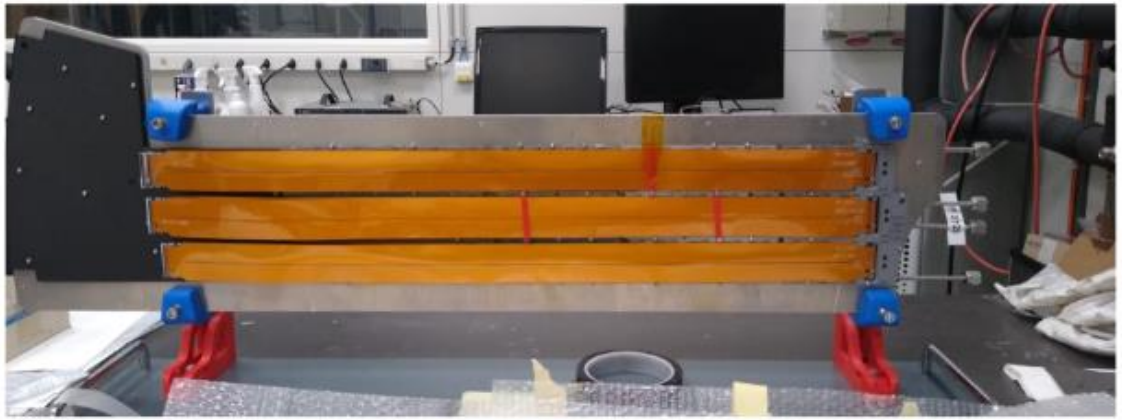


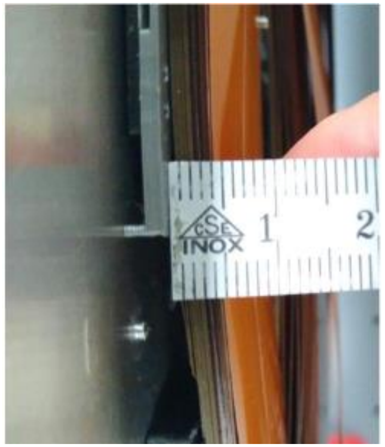
- Circuit for distribution of services & control to modules, data aggregation and optical links
- Located at $660 < r < 920$ mm
- "The most complex electrical circuit of high energy physics"
  - Up to 9 groups with 12 lpGBTs, 52 Bpol12v, support up to 55 front-end modules per PCB
  - 22 layer PCB, Micro-via size down to 0.1 mm – difficult manufacturing

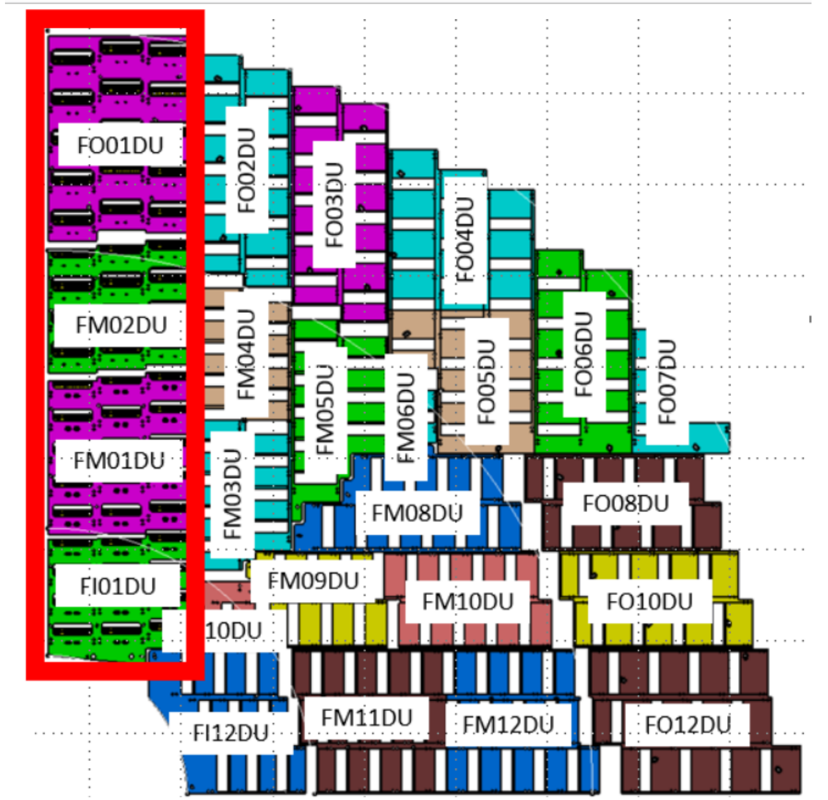


Module and detector assembly

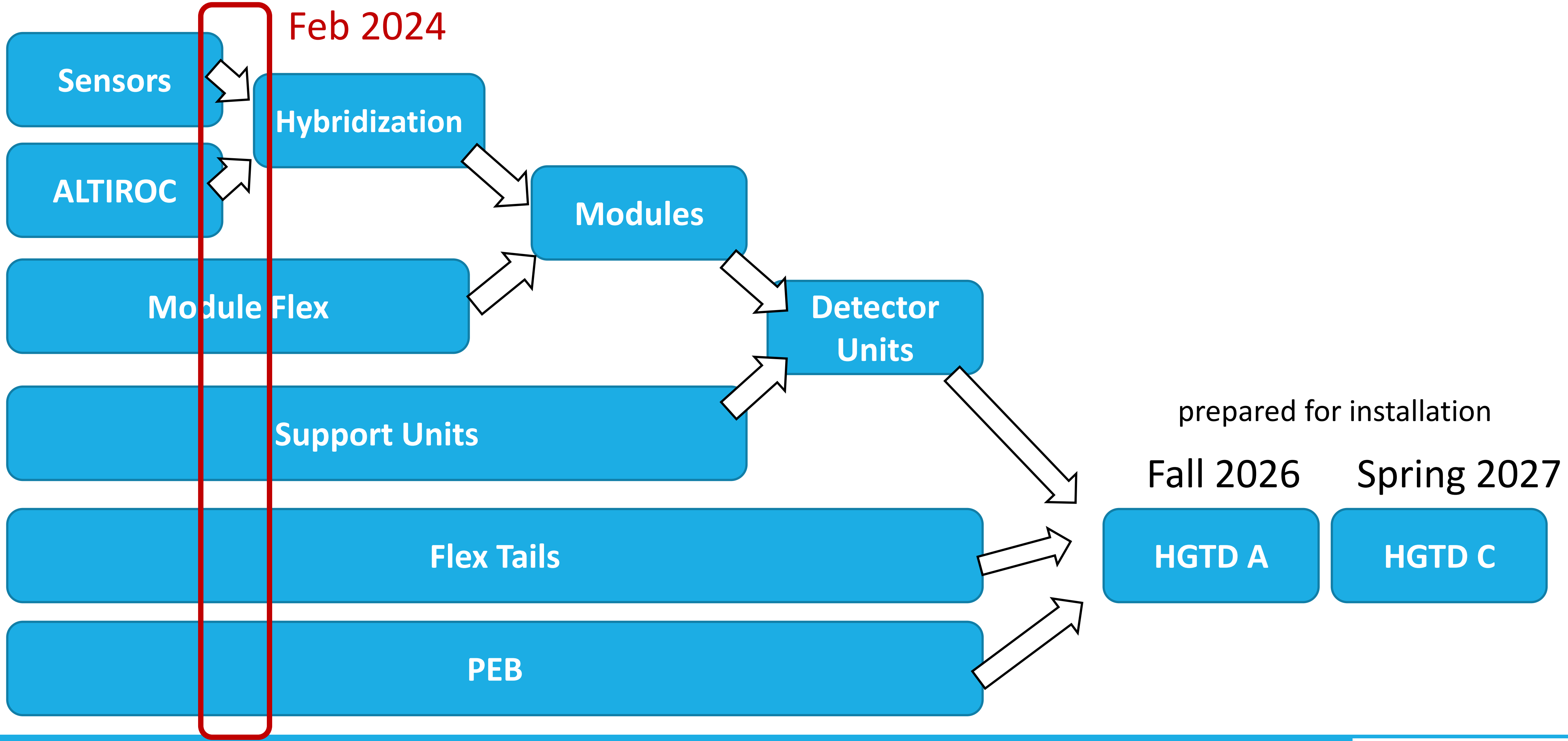
- Module Production: Hybridization → Flex gluing →Metrology → Wire bonding → Module testing
  - 6 assembly sites – Europe, Morocco, China
- 10s of Modules grouped into Detector Units – mechanical support and cooling
  - 24 Detector Units per quarter disk
- Flex tails to connect modules with Peripheral Electronic Boards
- 54-Module Demonstrator being assembled at CERN
  - Two out of four Detector Units delivered







HGTD production timeline



Feb 2024

Sensors

ALTIROC

Hybridization

Module Flex

Modules

Support Units

Detector Units

Flex Tails

PEB

prepared for installation

Fall 2026

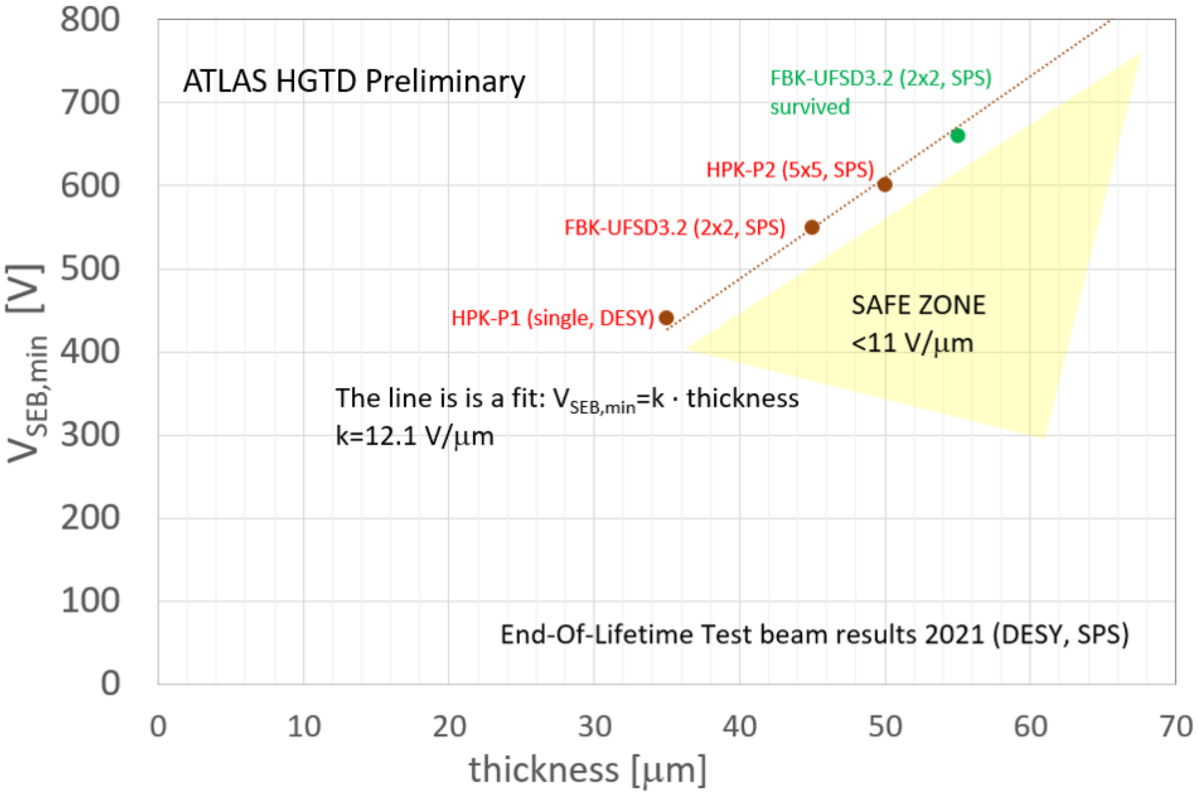
Spring 2027

HGTD A

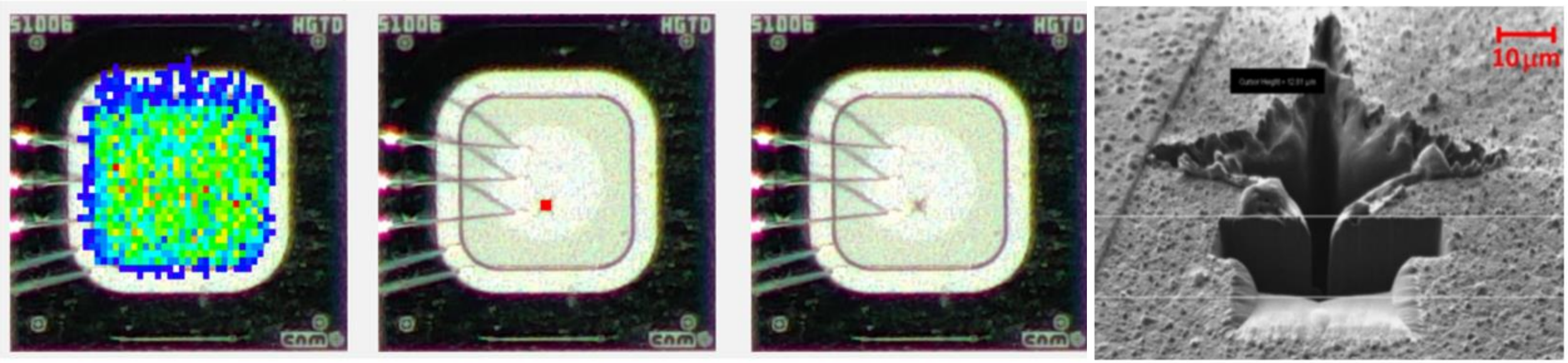
HGTD C

LGAD Single Event Burnout (SEB)

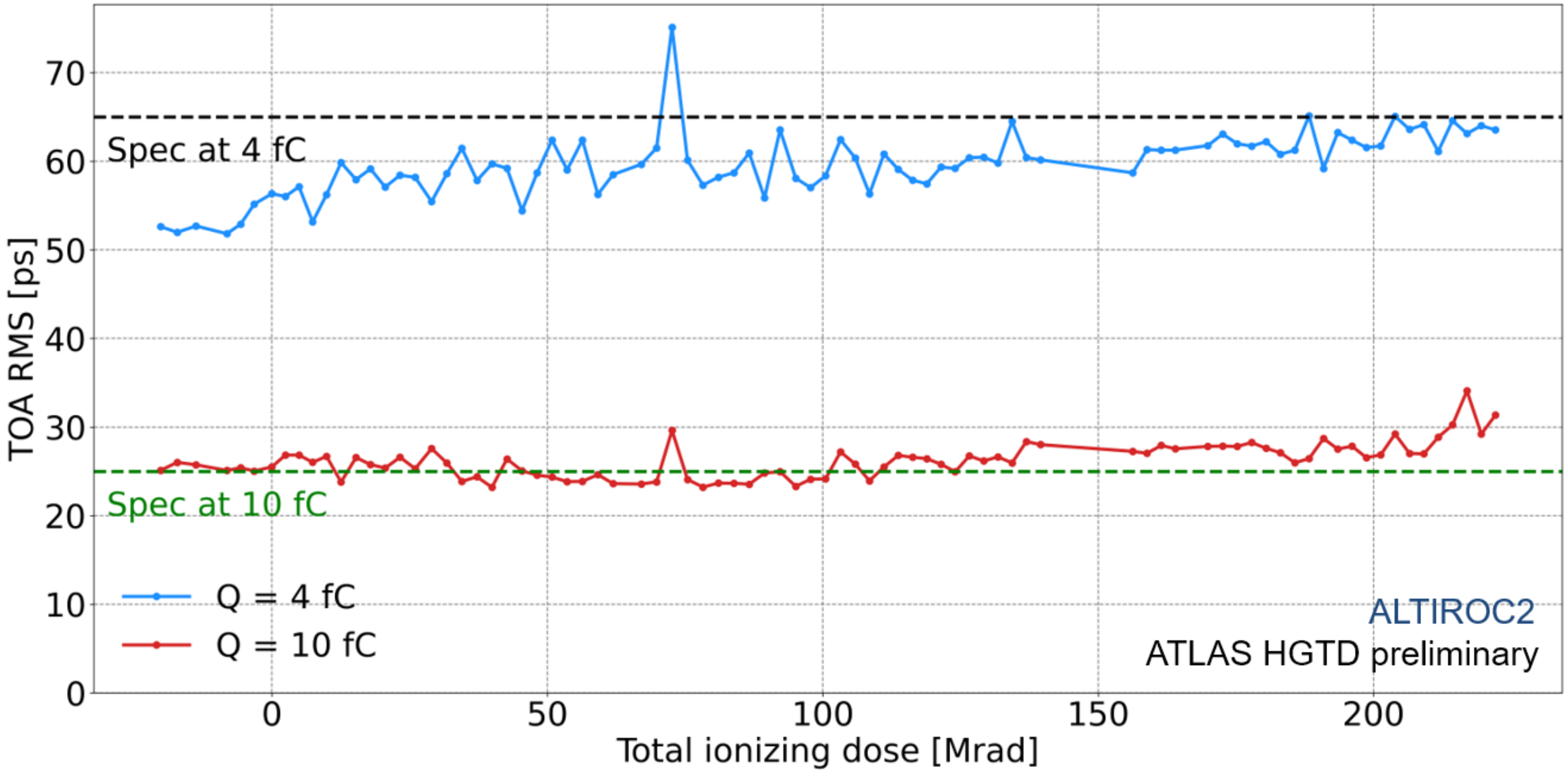
- Single Event Burnout – Catastrophic failure in highly irradiated LGAD devices
  - Caused in particle beam by rare events with massive charge deposition (10s MeV)
  - Localized destructive electrical breakdown, “crater”
- Threshold at average electric field in LGAD exceeding 11 V/µm (550 V for 50 µm thick devices)
- “Natural limit” for LGAD radiation hardness
  - Cannot further increase bias voltage to mitigate gain loss due to radiation damage



ATLAS HGTD Preliminary



ALTIROC radiation hardness – TID



TID Dose rate: 3 Mrad/h
Temperature: 22°C
Jitter stays stable with the increasing TID

Time resolution – why gain?

$$\boldsymbol{\sigma_{\mathrm{det}}}^{2} = \boldsymbol{\sigma^{2}_{\mathrm{Landau}}} + \boldsymbol{\sigma^{2}_{\mathrm{elec}}} + \boldsymbol{\sigma^{2}_{\mathrm{clock}}}$$

σ_{Landau} .. non uniform charge deposition by MIP (limit 25 ps in 50 µm thick sensors)
σ_{Elec} .. from readout electronics (25 ps/70 ps – start of HL-LHC/4000 fb^{-1})
σ_{Clock} .. LHC clock jitter (15 ps)

$$\sigma^{2}_{elec} = \left(\frac{t_{rise}}{S/N}\right)^{2} + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^{2} + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^{2}$$

Jitter

Need high Signal-to-Noise ratio to minimize

Time walk

Corrected by constant fraction discrimination / ToT correction

TDC Quantization error

TDC bin 20 ps in ALTIROC