ATLAS EXPERIMENT

JSI
Ljubljana
Slovenia

Slovenian
Research
Agency
arrs

ATLAS High Granularity Timing Detector and Production Activities at F9

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JOŽEF STEFAN INSTITUTE

SEMINAR, FEBRUARY 2024

ATLAS
HGTD

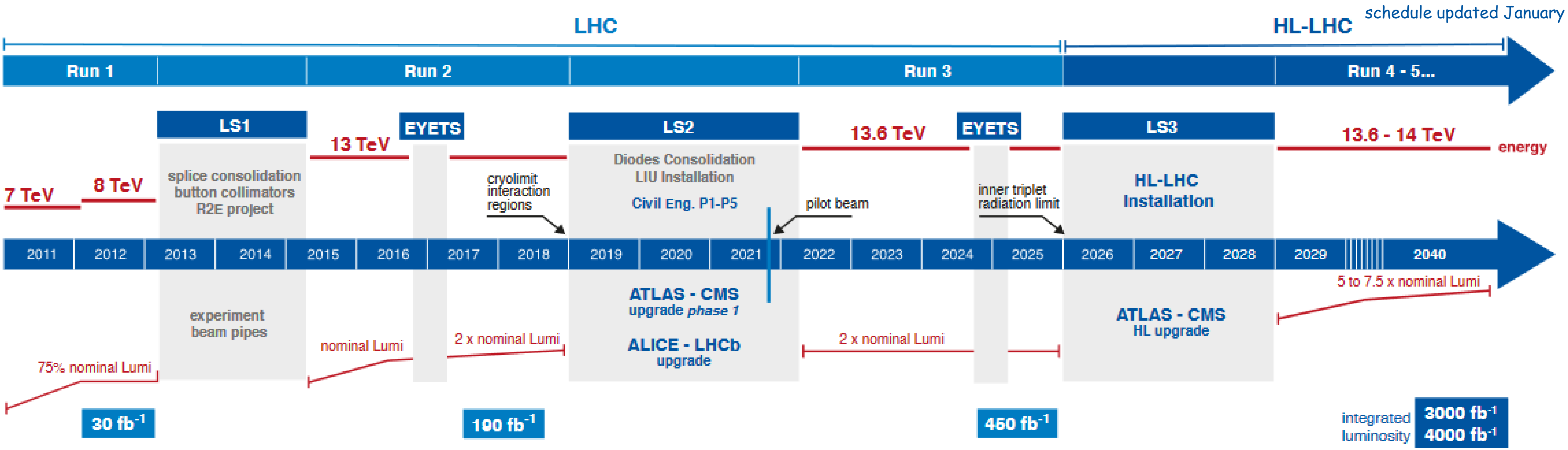
Outline

- **Part 1:** *ATLAS-HGTD at HL-LHC*
  - HL-LHC and motivation for ATLAS-HGTD
  - HGTD detector components
    - LGAD Sensors
    - Readout chip
    - Integration into experiment
- **Part 2:** *ATLAS-HGTD production activities at JSI F9*
  - Sensor Process Quality Control
  - Sensor Irradiation Tests
  - Production of Flex Tail circuits

Part 1: *ATLAS-HGTD at HL-LHC*

High Luminosity LHC (HL-LHC)

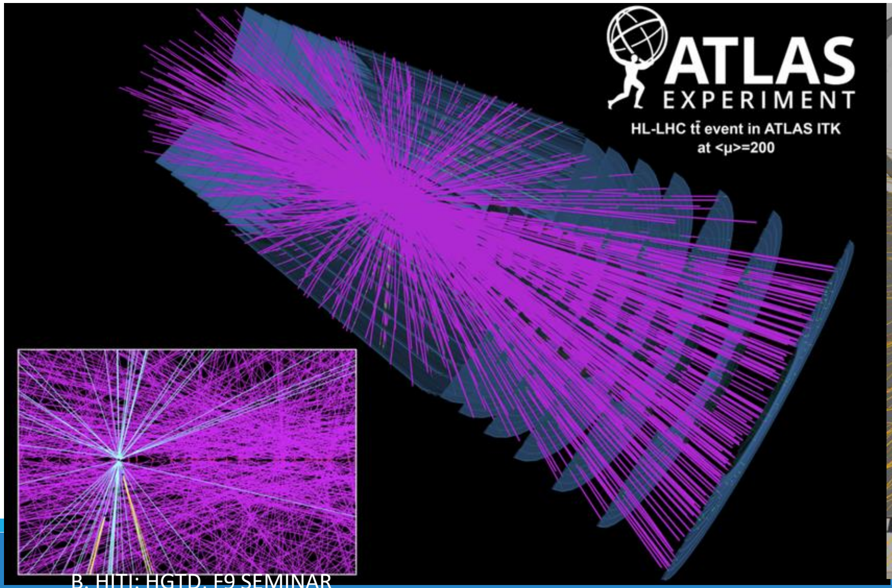
schedule updated January 2022

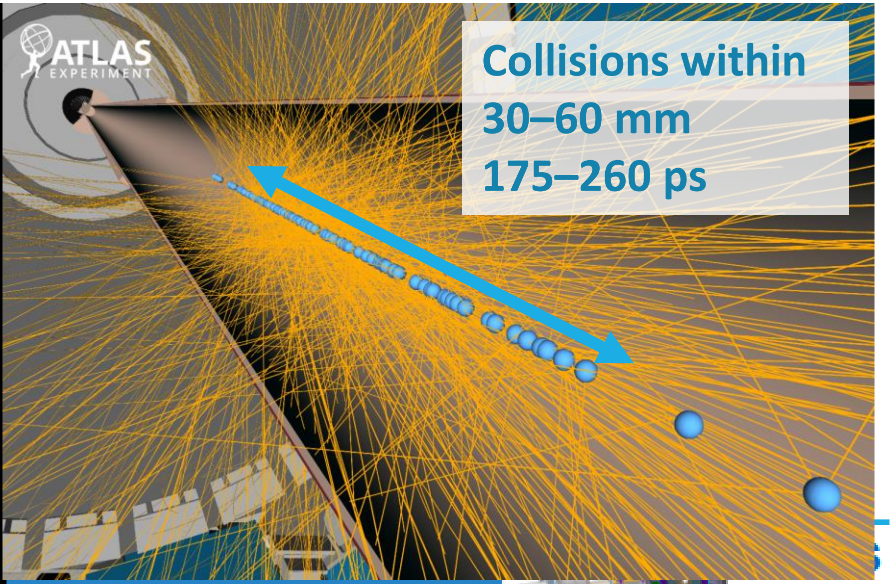


ATLAS experiment pileup:

LHC run 3: <μ> = 40

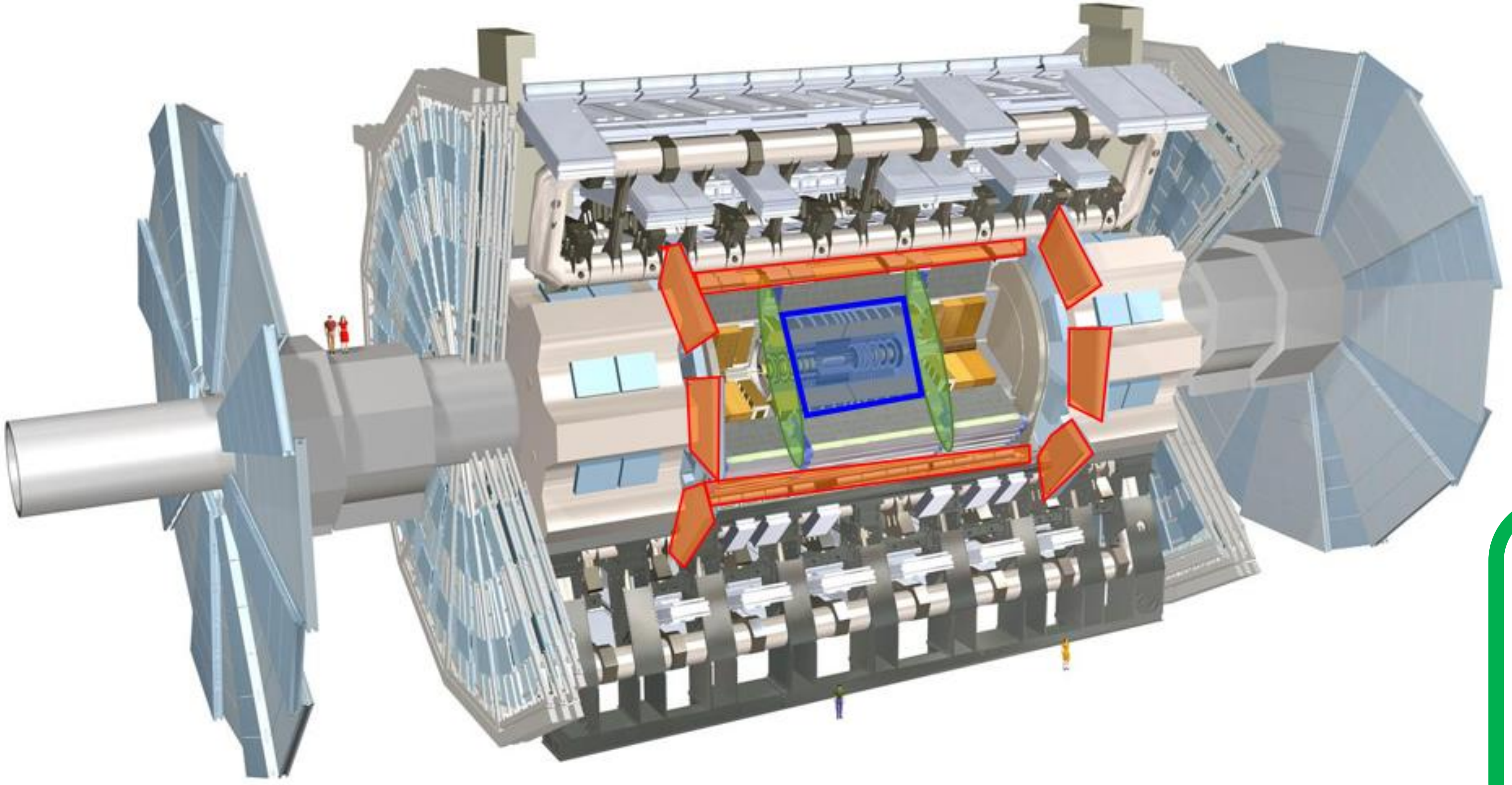
HL-LHC: <μ> = 200





Collisions within
30–60 mm
175–260 ps

ATLAS phase II upgrade



Upgraded Trigger and Data Acquisition System

- Single Level Trigger with 1 MHz output
- Improved 10 kHZ Event Farm

Electronics Upgrades

- On-detector/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors
- 40 MHz continuous readout with finer segmentation to trigger

High Granularity Timing Detector (HGTD)

- Precision time reconstruction (30 ps) with Low-Gain Avalanche Detectors (LGAD)
- Improved pile-up separation and bunch-by-bunch luminosity

New Muon Chambers

- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate

New Inner Tracking Detector (ITk)

- All silicon with at least 9 layers up to $|\eta| = 4$
- Less material, finer segmentation

Additional small upgrades

- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

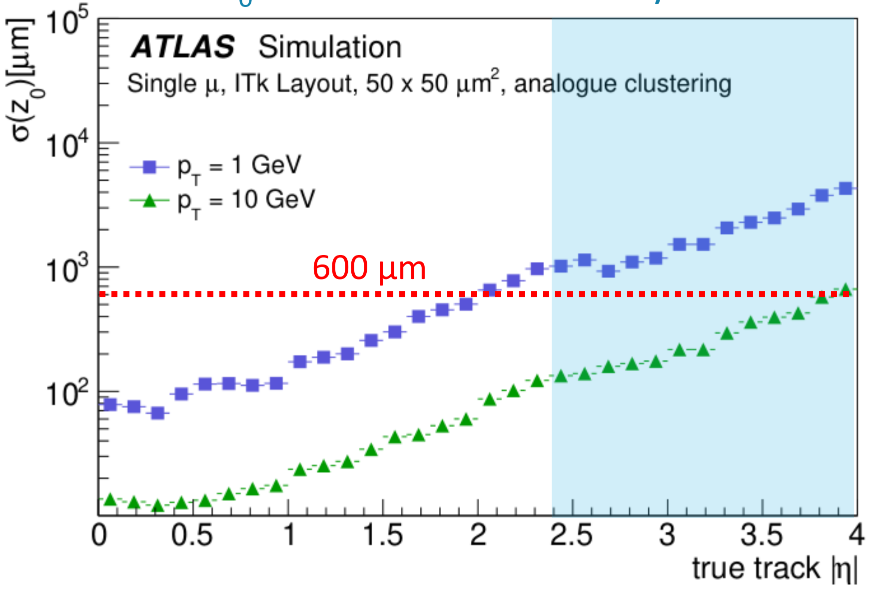
[slide from T. Affolder, Lepton Photon 2021]

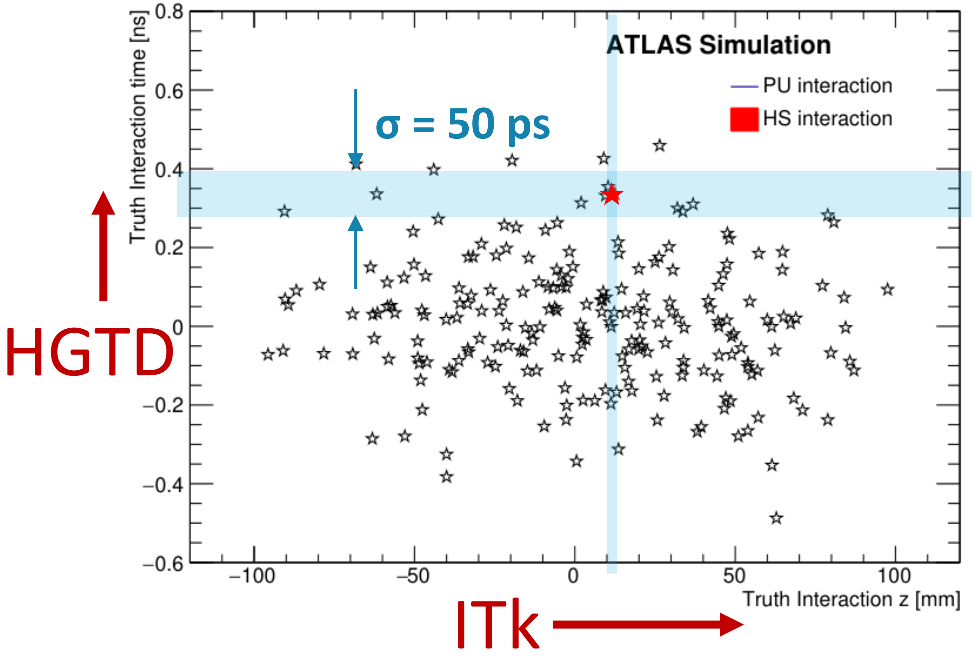
ATLAS High Granularity Timing Detector

- **Pile-up a big experimental challenge at HL-LHC**
  - At <μ> = 200 most probable pile-up density 1.44 vertices/mm → vertex spacing 0.6 mm
  - New tracker ATLAS ITk alone not sufficient for vertex separation in forward direction

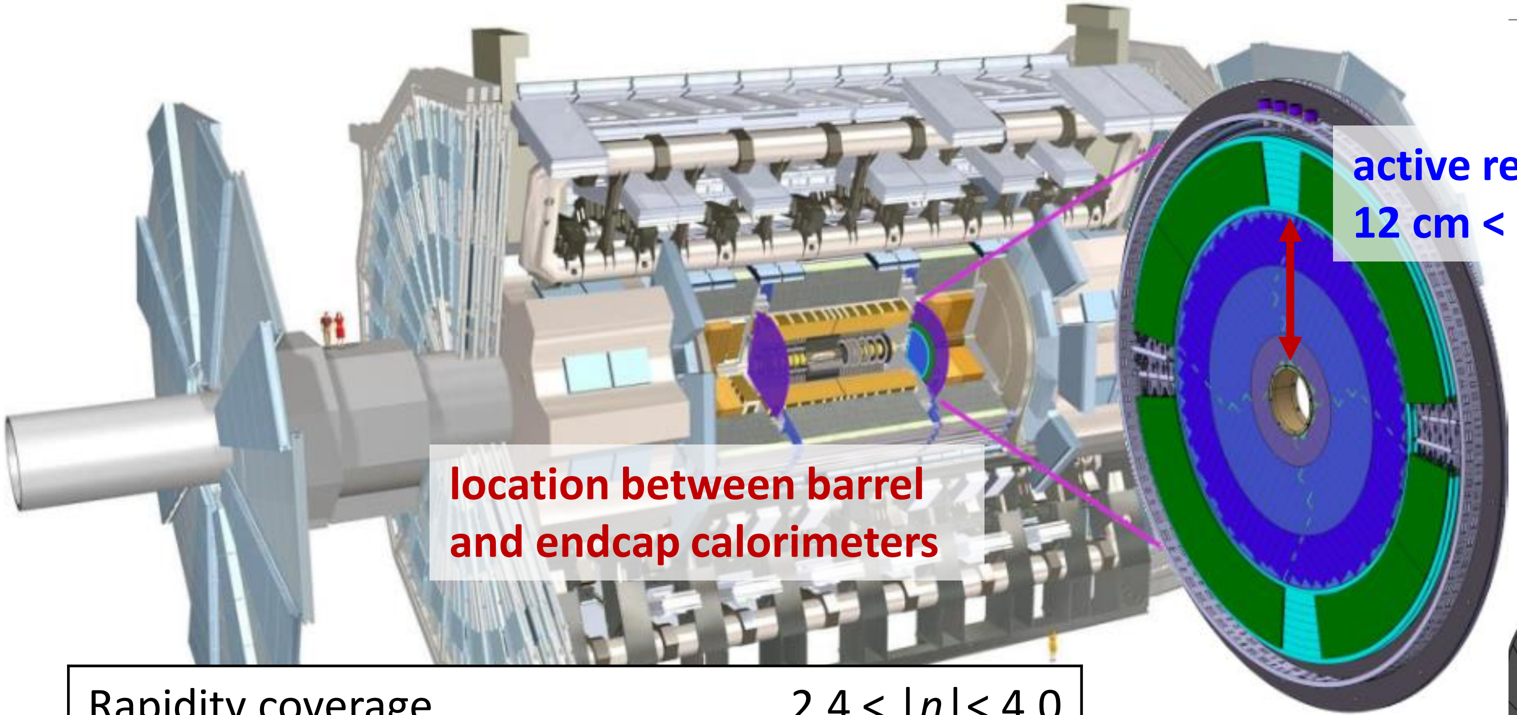
- **ATLAS High Granularity Timing Detector (HGTD)**
  - Track time information, resolution 50 ps
  - In addition luminosity measurement by particle counting (target 1 % precision)

z_0 resolution with ITk only





ATLAS HGTD basic information

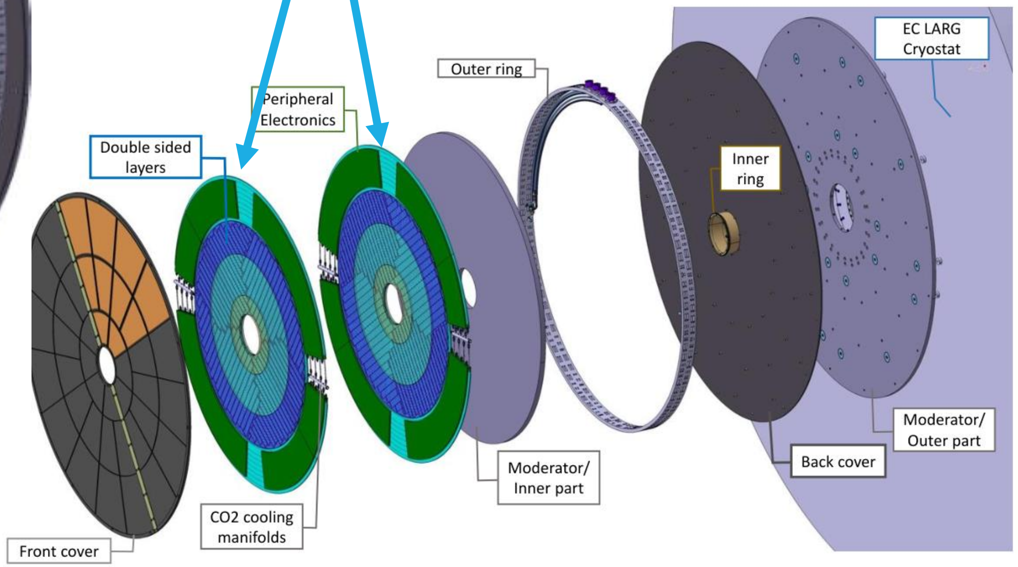


active region
12 cm < r < 64 cm

location between barrel and endcap calorimeters

Rapidity coverage	2.4 < $\|\eta\|$ < 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)
Time resolution (beginning)	30 ps
Time resolution (End-Of-Life)	50 ps

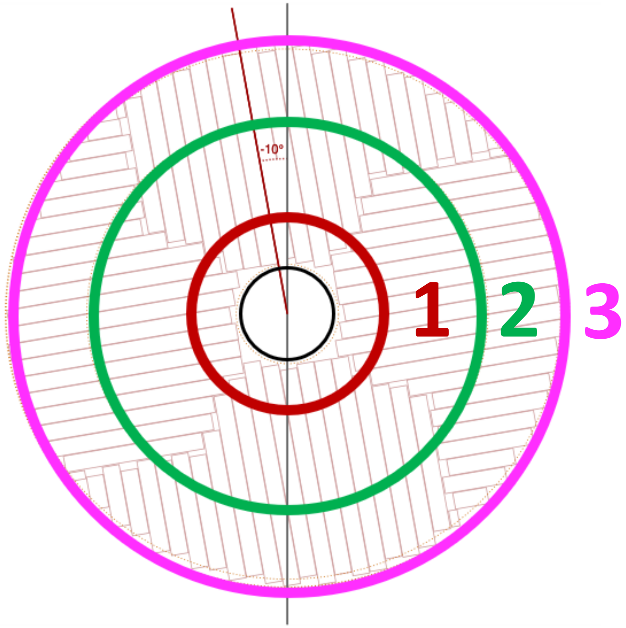
Two double sided instrumented layers (= 4 sensor layers)

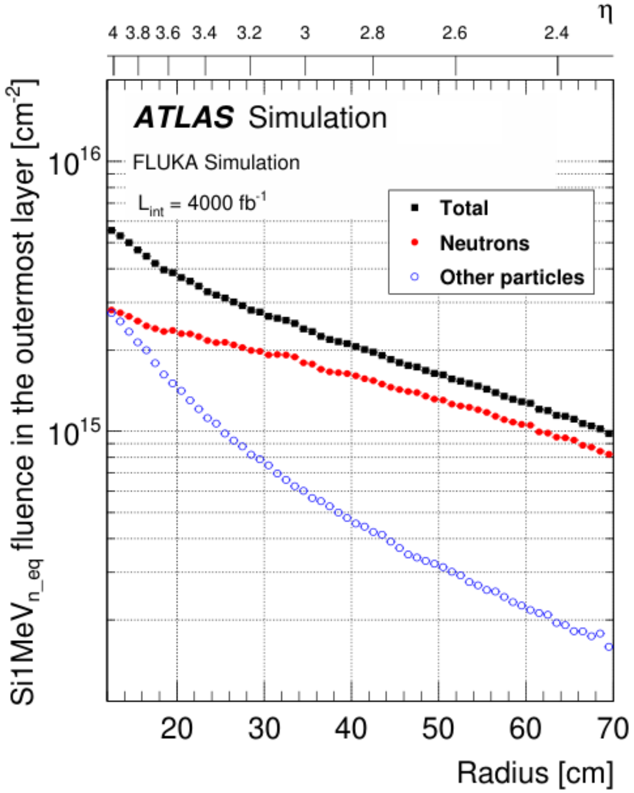


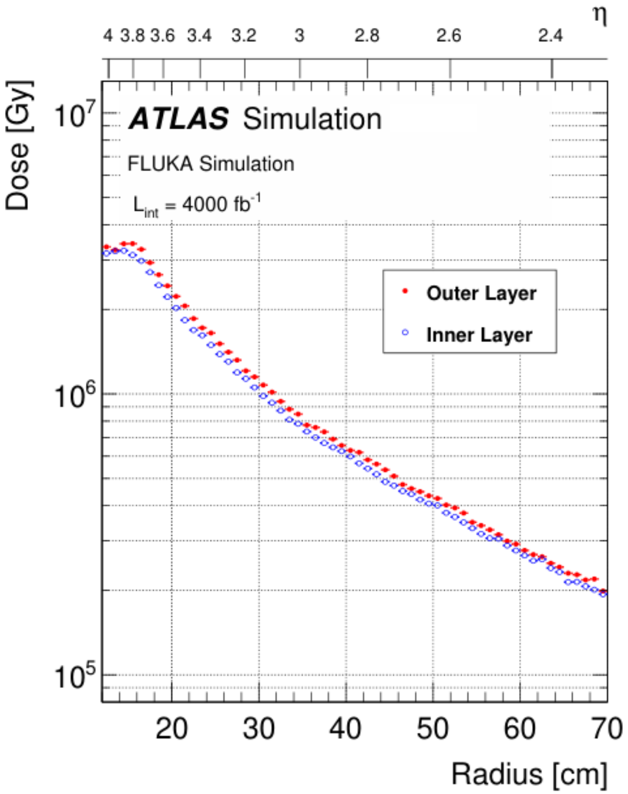
total thickness 75 mm

HGTD Radiation Environment

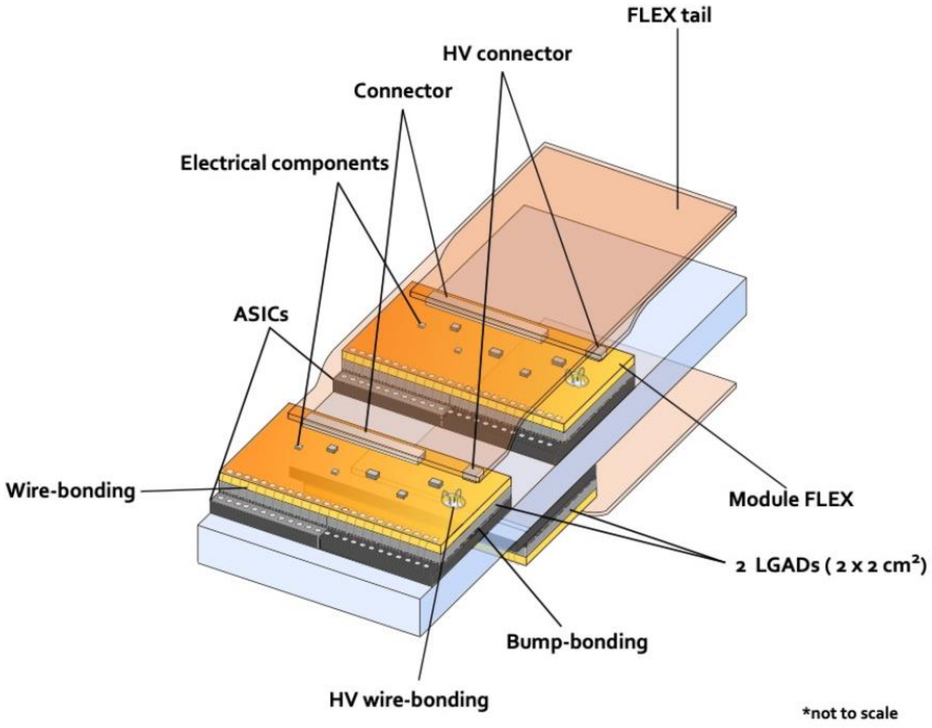
- Radiation damage in HGTD after 4000 fb^{-1} up to 8.3e15 n_{eq} cm^{-2}, 7.5 MGy (including safety factors)
- HGTD designed for **End-of-Life (EOL) fluence 2.5 × 10^{15} n_{eq} cm^{-2}, TID 2 MGy** → detector replacements planned
- Segmentation in three concentric rings:
  - **Inner ring (*r* ≤ 230 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



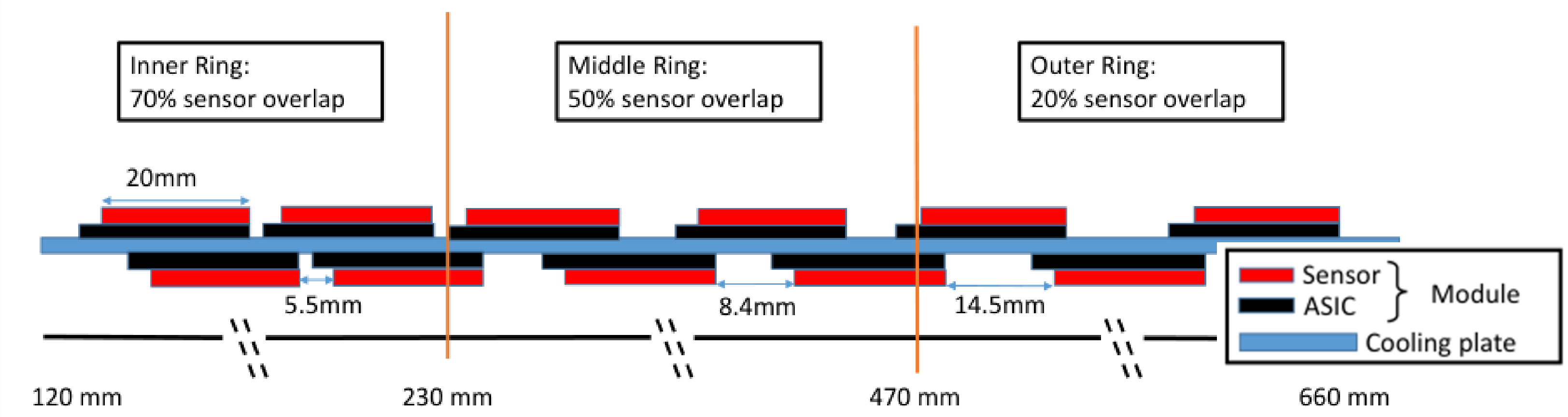


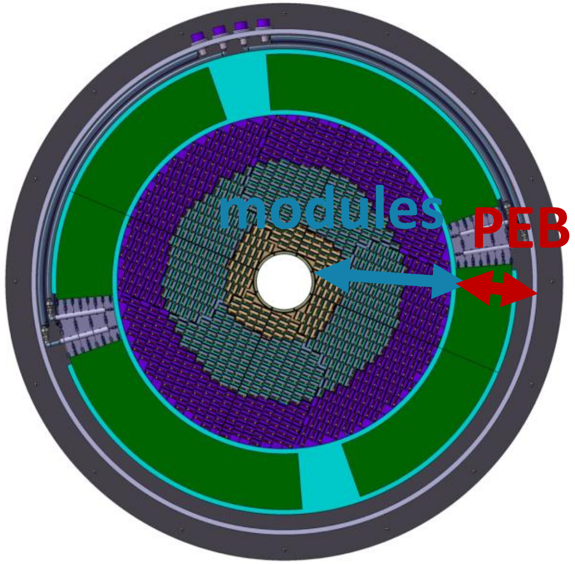


HGTD Modules



- **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), 1.3 mm × 1.3 mm channel size
- 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





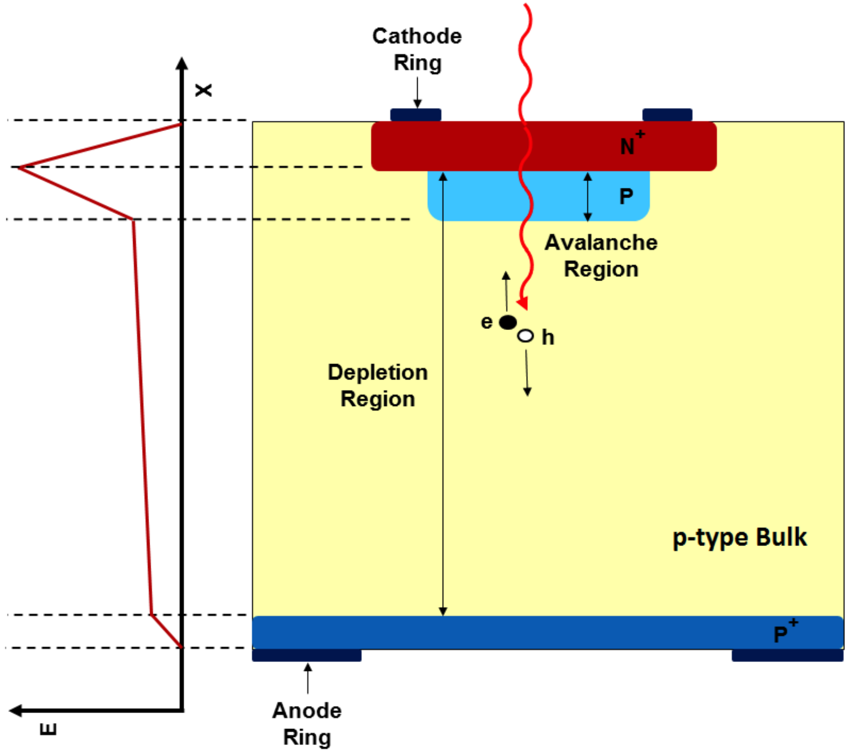
HGTD Sensors: Low Gain Avalanche Detector (LGAD)

- 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)** – new silicon sensor technology pioneered by CNM Barcelona and CERN-RD50
  - 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 50 µm, physical thickness of silicon 300 µm

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

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

[**G. Pellegrini, G. Kramberger et al.:** Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications, NIM A, 2014]



Why gain?

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}$$

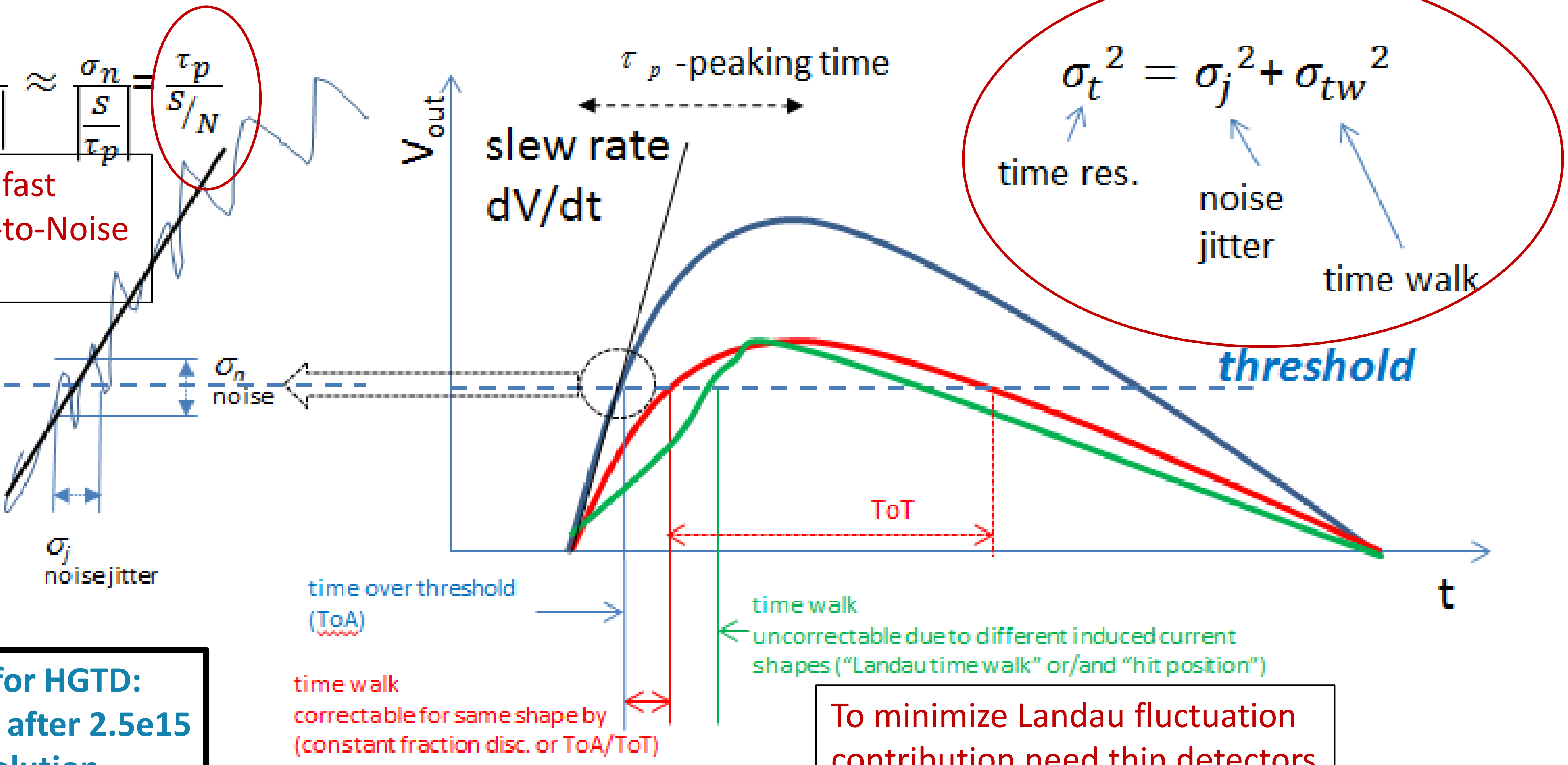
To minimize noise jitter fast signals with high Signal-to-Noise ratio are required

$$\sigma_t^{\,2} = \sigma_j^{\,2} + \sigma_{tw}^{\,2}$$

time res.

noise jitter

time walk



To minimize Landau fluctuation contribution need thin detectors
→but less signal, need Gain

LGAD requirements for HGTD:
4 fC collected charge after 2.5e15
50 ps LGAD time resolution

1 fc = 6250 e$^-$

LGAD radiation effects

- LGAD internal gain vital for a good time resolution
- Impact ionization increases exponentially with electric field in gain layer
  → LGAD performance critically depends on voltage drop in Gain Layer

$$V_{\mathrm{gl}} = \frac{e_0 w^2}{2\epsilon\epsilon_{\mathrm{Si}}} N_{\mathrm{B}}$$

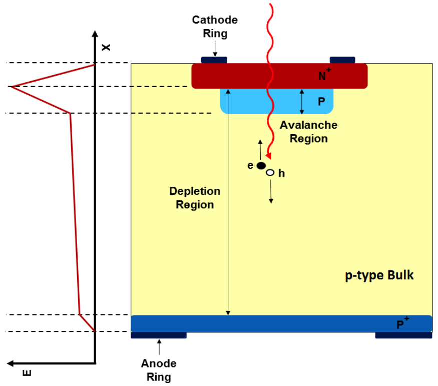
V_{gl} .. gain layer depletion voltage
→depends on Gain Layer doping N_B

10s of Volts

From sensor overdepletion
100s of Volts

$$E_{\text{gain layer}} \approx \frac{V_{\mathrm{gl}}}{w} + \frac{V_{\mathrm{od}}}{d}$$

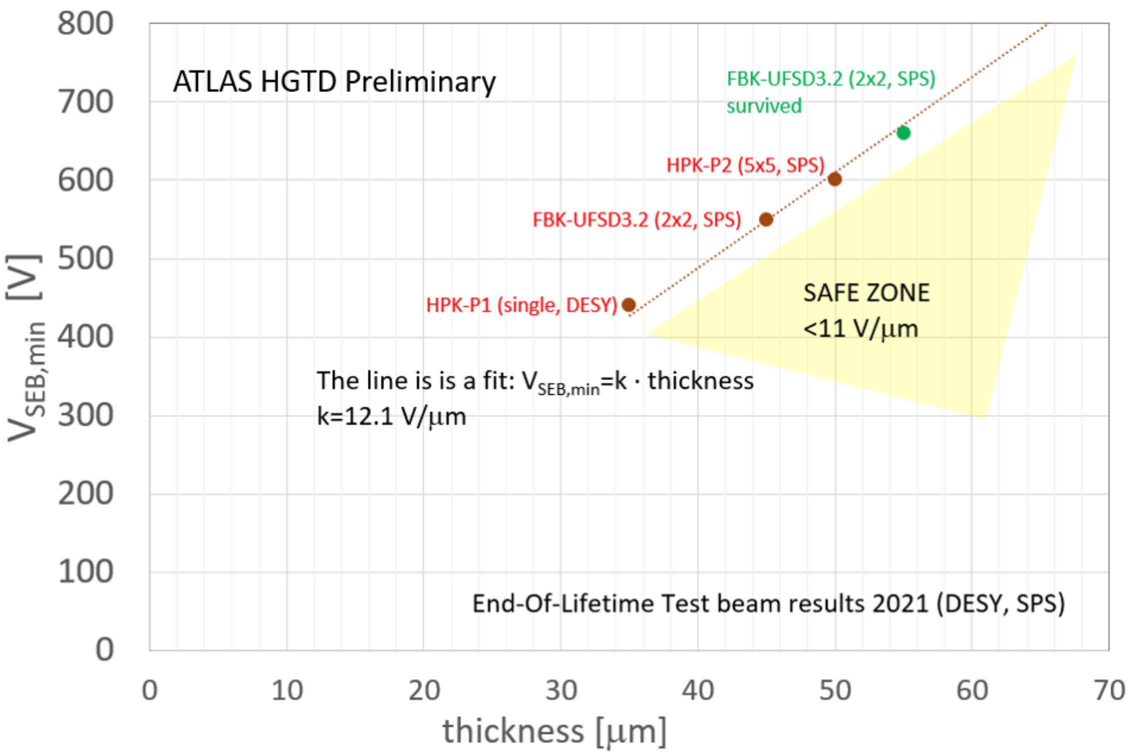
N_b .. effective acceptor concentration
w .. gain layer thickness (1–2 μm)
d .. active device thickness (50 μm)



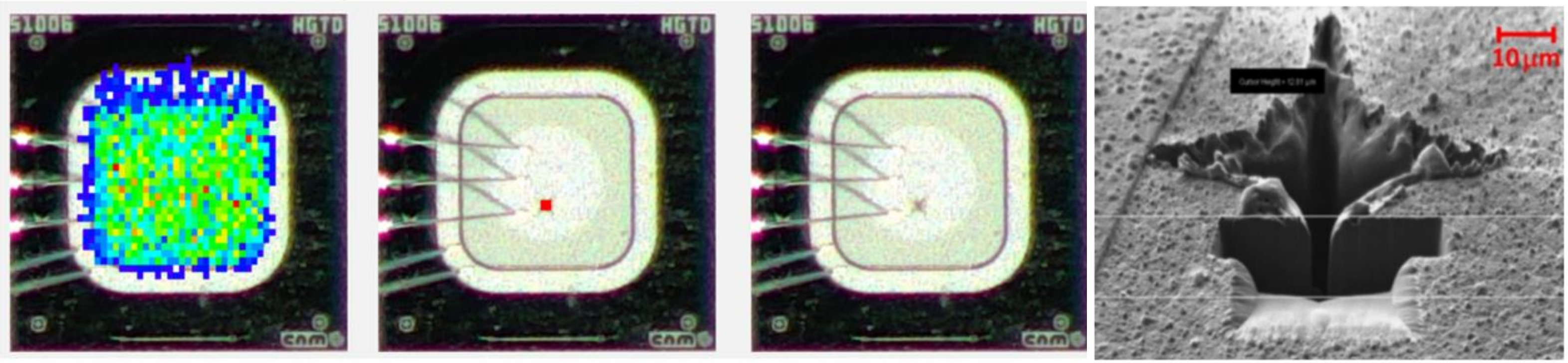
- Displacement damage by irradiation reduces effective doping concentration in p-type silicon
  - **Acceptor removal**: electrically active Boron gets deactivated by formation of the B_iO_i defect → ***N_B*, *V_{gl}* reduces**
  - Larger bias voltage needed to sustain the same *E*-field/Gain → but physical limits
- Defect engineering to improve radiation hardness
  - Carbon coimplantation to screen Boron in the lattice → slower removal

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

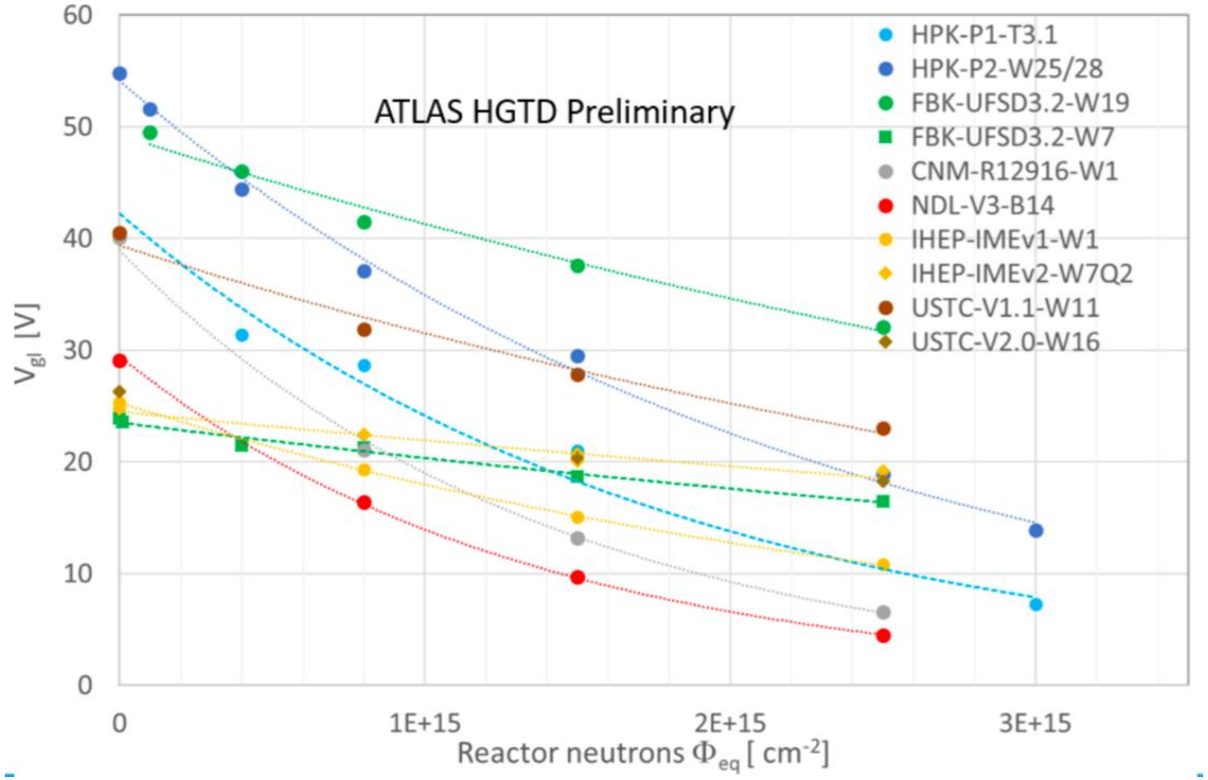


ATLAS HGTD Preliminary



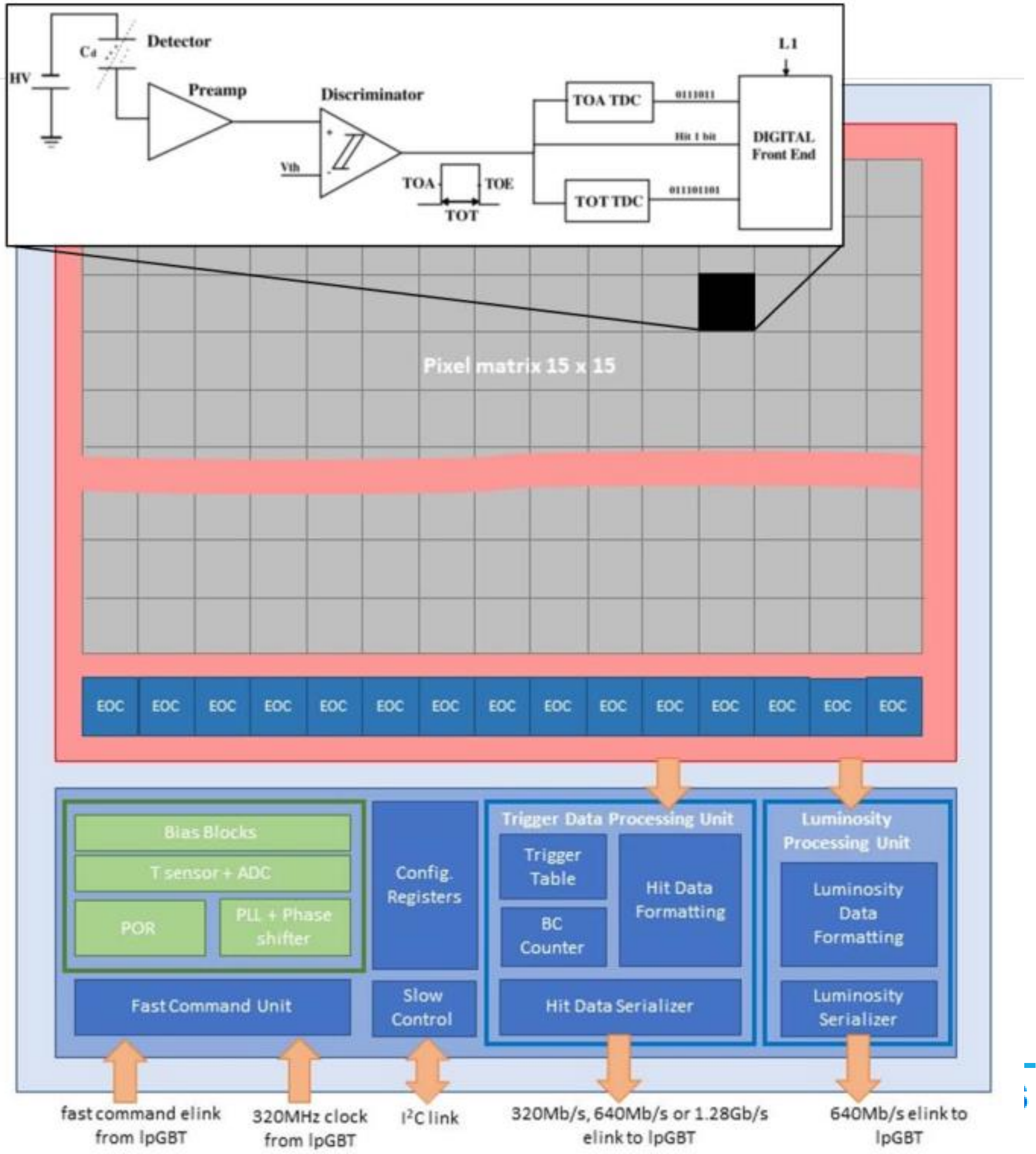
LGAD radiation hardness

- Since 2014 extensive R&D program for development and optimization of LGAD devices for HL-LHC
- Evaluated prototypes from 5+ manufacturers
- Carbon enriched designs meet HGTD radiation hardness specifications
- For HGTD production selected two Chinese designs:
  - **IHEP-IME (Beijing, China)**
  - **USTC-IME (Hefei, China)**
- LGAD sensor preproduction started in 2023

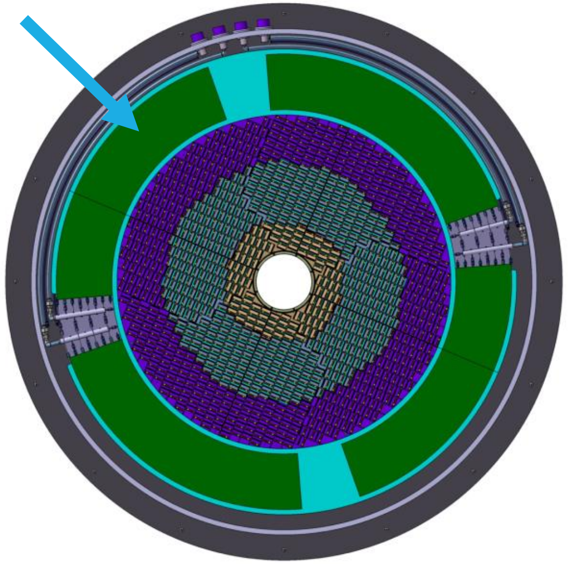


ALTIROC: HGTD readout chip

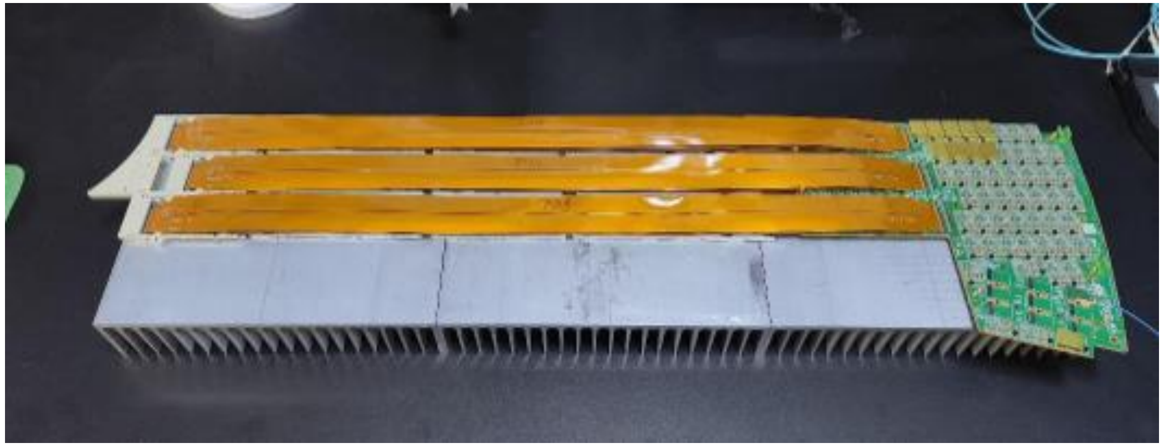
- **ASIC produced in 130 nm CMOS process by TSMC (radhard)**
- Pixel chip with low number of channels optimized for timing
  - Small jitter: 25 ps at 10 fC (< 70 ps at 4 fC)
  - 2 fC minimum discriminator threshold
- **Time-to-Digital Converters (TDC)** for measurements of
  - **Time of Arrival**, w.r.t. LHC clock
  - **Time over Threshold**, for time walk correction using 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

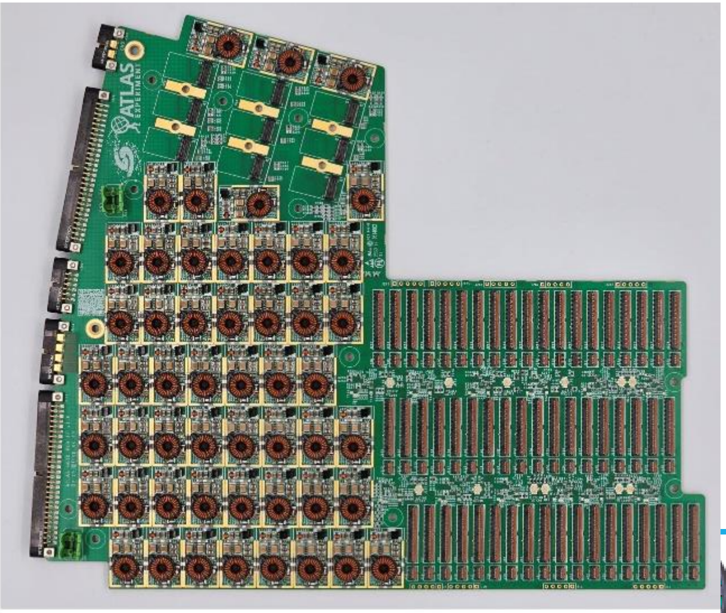


Peripheral Electronics Board (PEB)



- 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





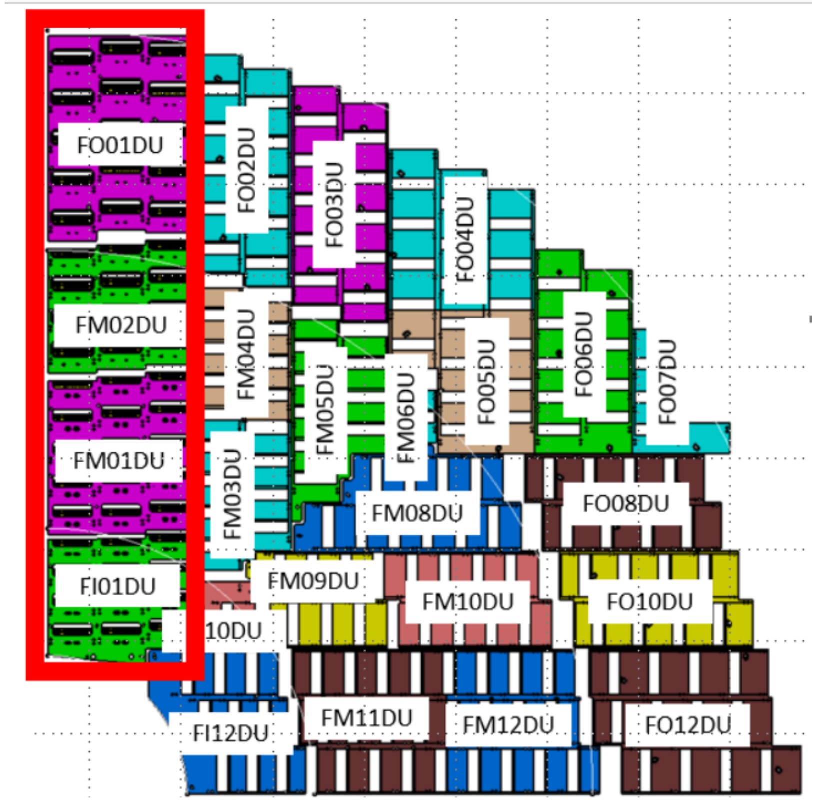
HGTD module and detector assembly

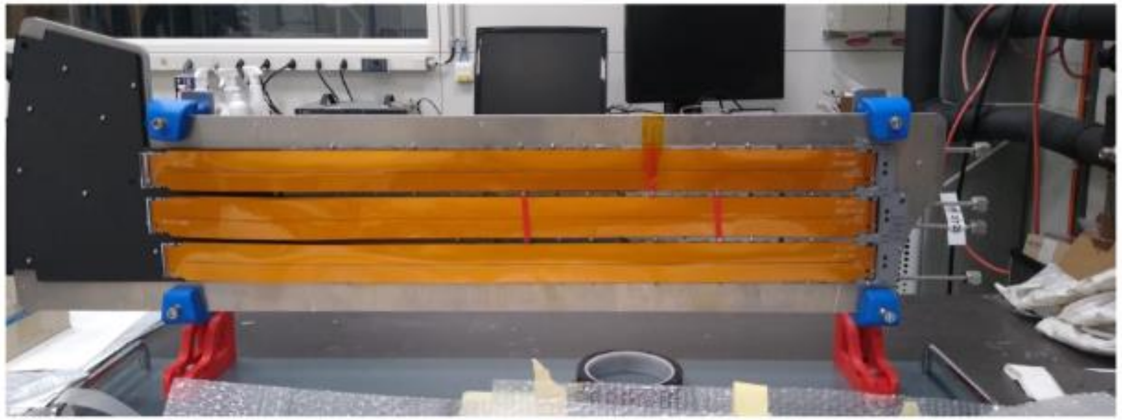
- Module Production: **Hybridization → Flex gluing →Metrology → Wire bonding → Module testing**
  - 6 assembly sites – Europe, Morocco, China

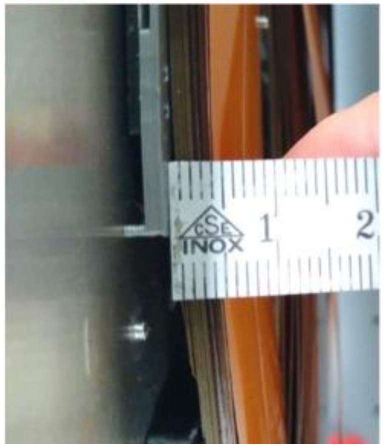
- 10s of Modules grouped into **Detector Units** – mechanical support and cooling
  - 24 Detector Units per quarter disk

- **Flex tails** to connect modules with Peripheral Electronic Boards

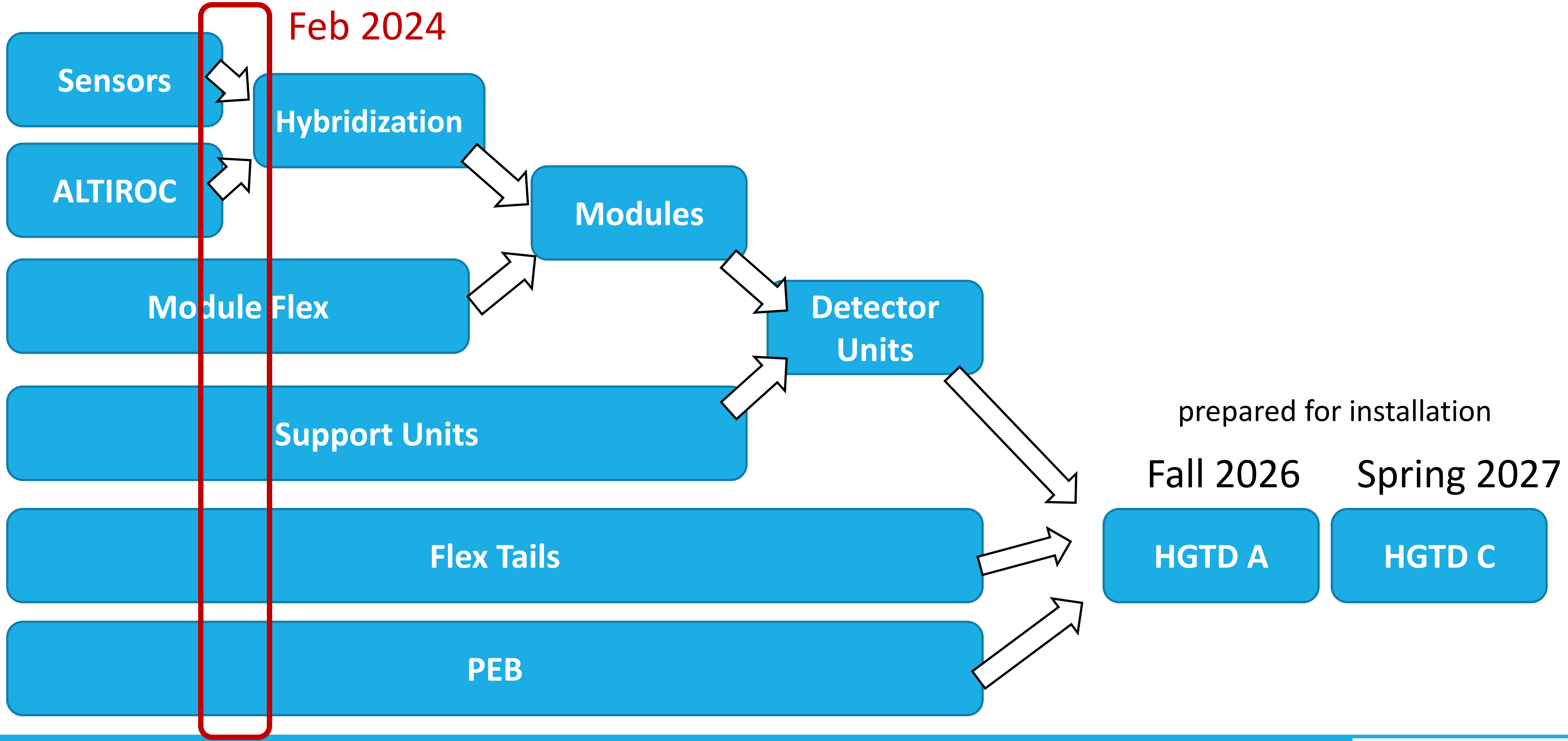
- 54-Module Demonstrator being assembled at CERN
  - Two out of four Detector Units delivered







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

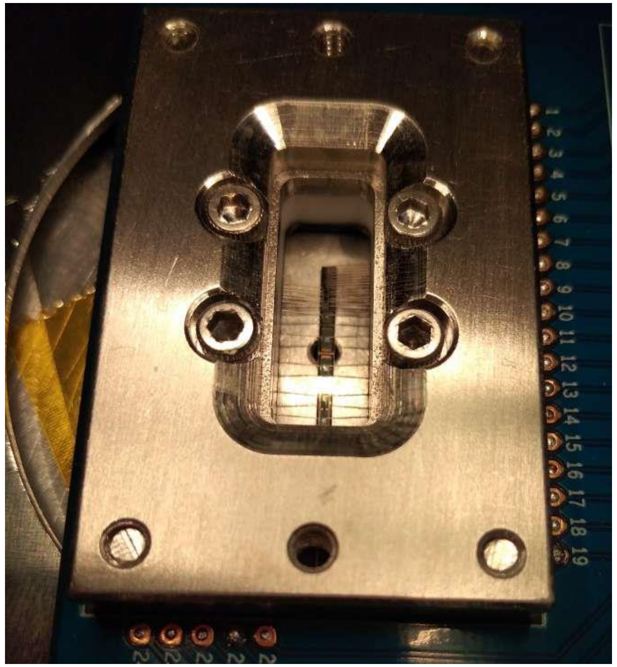
HGTD C

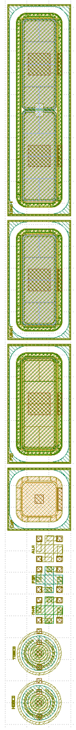
Part 2: *ATLAS-HGTD at F9*

ATLAS HGTD at F9 – 3 activities

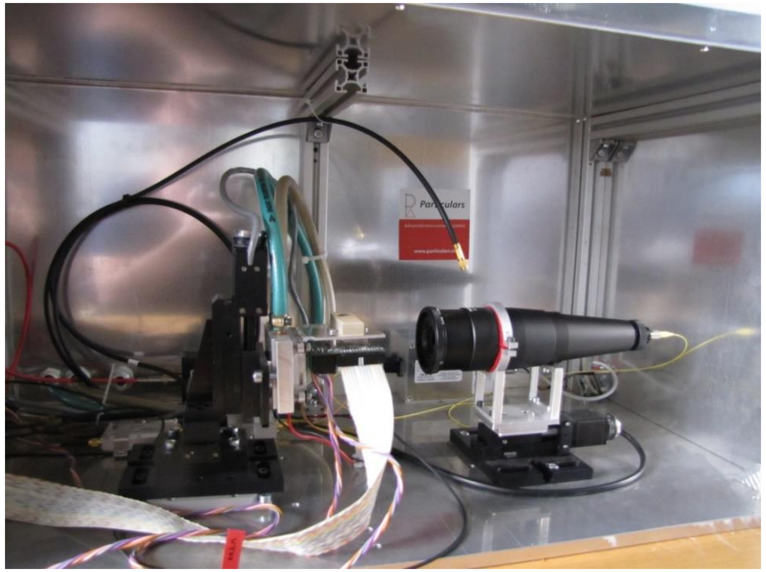
Current HGTD team:
G. Kramberger, B. Hiti, I. Velkovska, J. Debevc, M. Terglav
Past Members:
A. Howard, Ž. Kljun, L. Potočnik

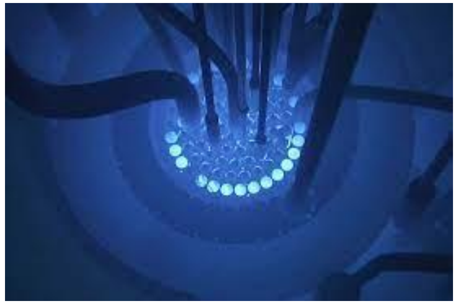
1 Process Quality Control



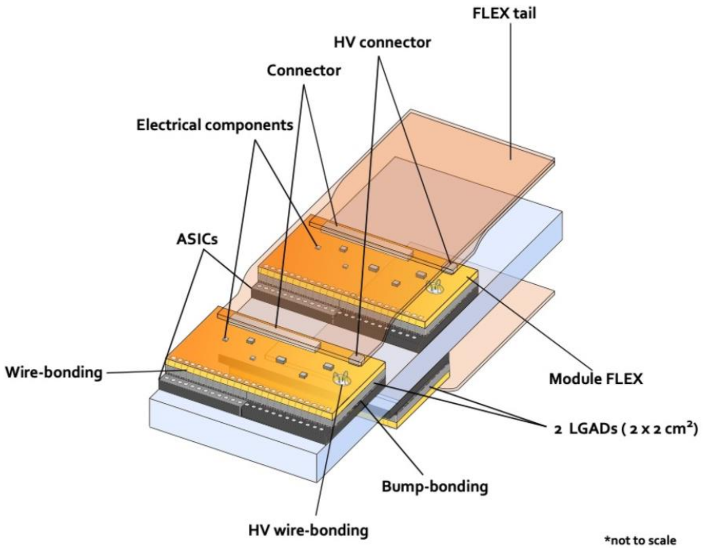


2 Sensor Irradiation Tests



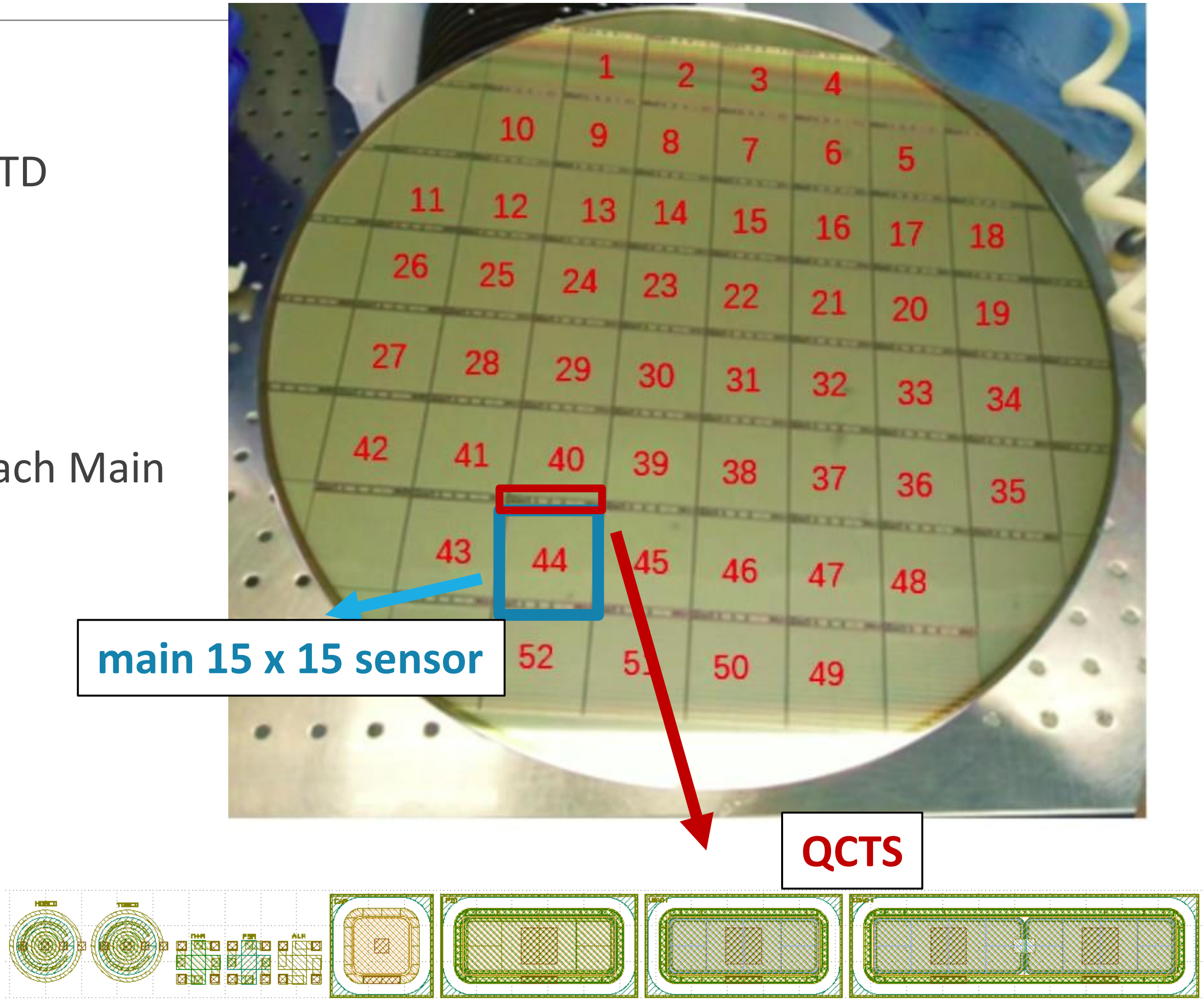


3 Flex tail production



HGTD Production Sensor & QCTS

- **> 21.000 good Sensors (≈ 1000 wafers)** will be required for HGTD
- Produced on 8-inch wafers
  - 90 % IHEP-IME design, 10 % USTC-IME design
  - Each wafer holds 52 Main Sensors (15×15, 2×2 cm)
- Dedicated **Quality Control Test Structure (QCTS)** adjacent to each Main Sensor
  - Used for Quality Control throughout production
- Current status of HGTD preproduction (5 % of total):
  - 7 wafers distributed for preliminary testing
  - 130+ wafers in last stages of processing (UBM deposition)
  - 5 sites involved in sensor Quality Control testing:
    - IHEP (China), USTC (China), CERN, Sao Paulo (Brazil), JSI

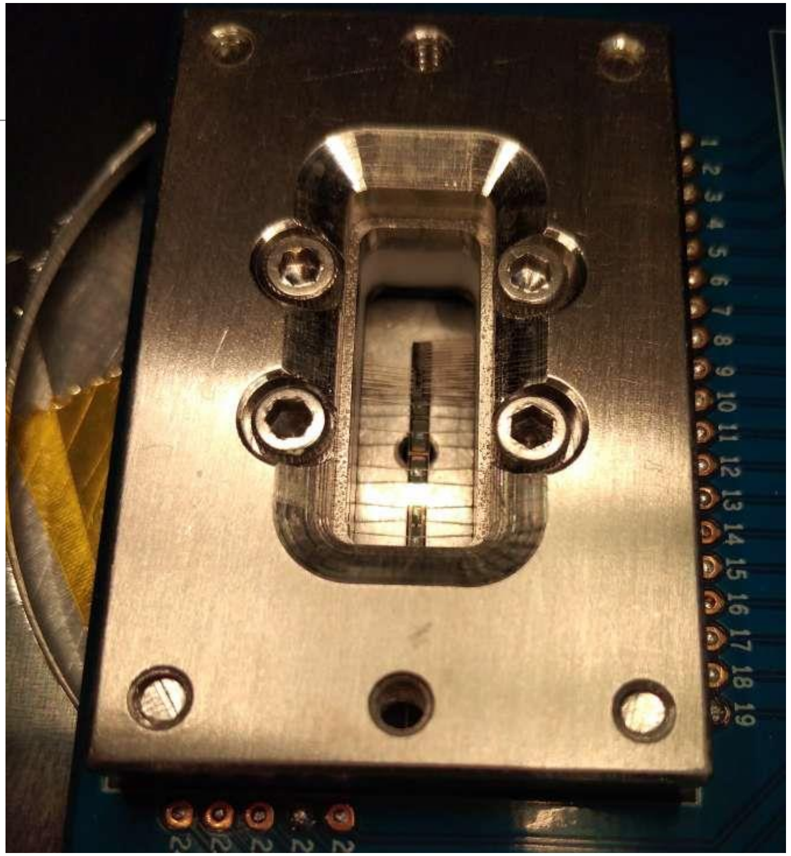


main 15 x 15 sensor

QCTS

F9 HGTD Process Quality Control

- Standardized monitoring of sensor properties on each wafer via QCTS
  - Check if manufacturing process parameters within specification – PQC
  - **Probe card (30 needle)** used to contact all structures simultaneously
  - Automated electrical test performed
- Baseline: PQC with unirradiated samples from each wafer
- Main test sites are Sao Paulo (also DAQ development) and CERN
- JSI is backup site in case of problems
  - Jernej Debevc working on setup commissioning



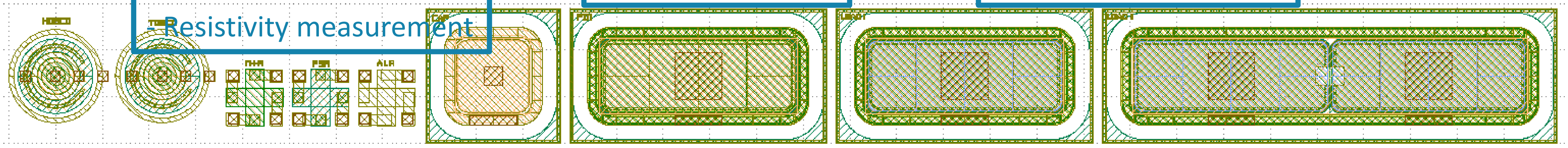
Gate Controlled Diodes
- Surface currents

MOS Capacitor
- SiO_2 properties

Van der Pauw structures
- Resistivity measurement

PIN diode
- Si bulk properties

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

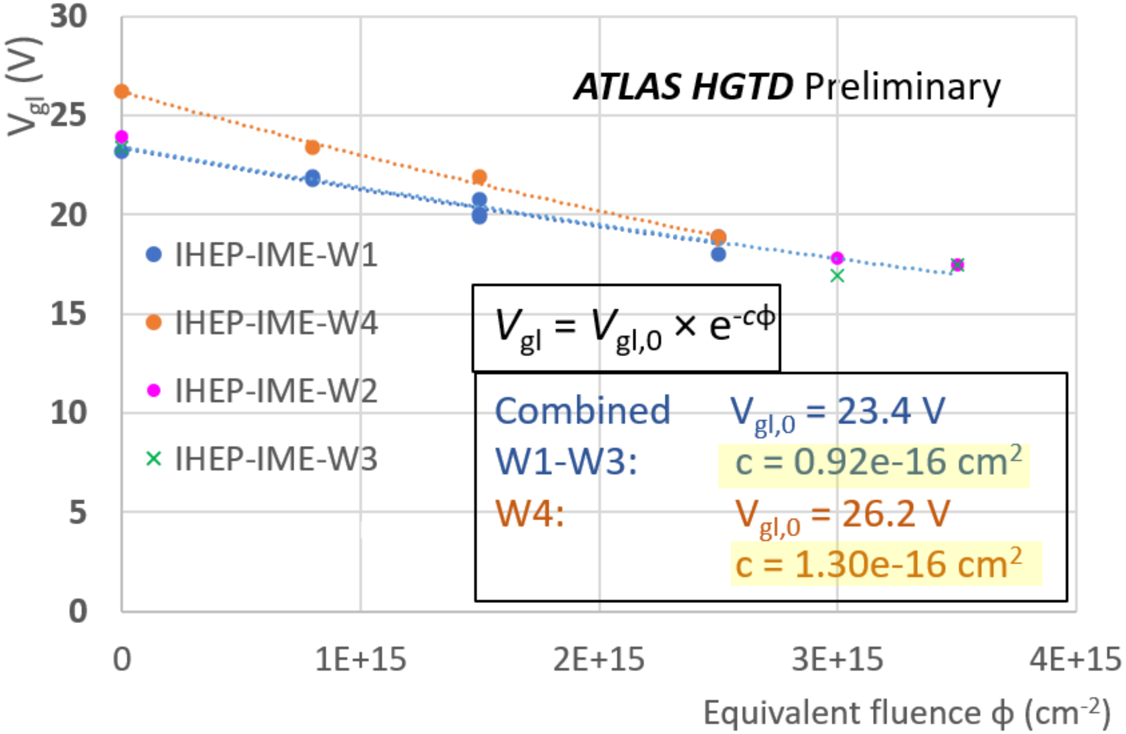


F9 HGTD Irradiation Tests

- **Irradiation Tests (IT)** to monitor sensor radiation hardness throughout production
  - LGAD radiation hardness very sensitive to manufacturing variations (1 % variation in [B] makes a difference)
  - Neutron irradiation at JSI TRIGA reactor and performance characterization at JSI → JSI is the main test site
  - Run 1–2 tests on each wafer (total ≈ 1000 tests)
  - Must be fast and well understood – **new TCT method developed**
  - **Wafer acceptance criteria** – will be based on statistics from multiple samples
- Goals:
  - Check that sensor performance within specifications after EOL fluence of 2.5×10^{15} n_{eq} cm^{-2} (4 fC @ 550 V, 50 ps)
  - Also group similar wafers for building modules (in ATLAS two sensors will share same high voltage)
- Samples tested in HGTD preproduction:
  - 5 + 2 wafers (IHEP + USTC)
  - Neutron fluences 4e14 – 3.5e15 n_{eq} cm^{-2}, annealing 80 min at 60° C
  - Some samples irradiated above EOL fluence to ensure they fail IT
- IT in scope of ATLAS Qualification Task by Iskra Velkovska, measurements also by student Matic Terglav

CV: Acceptor removal parameter

IHEP-IME

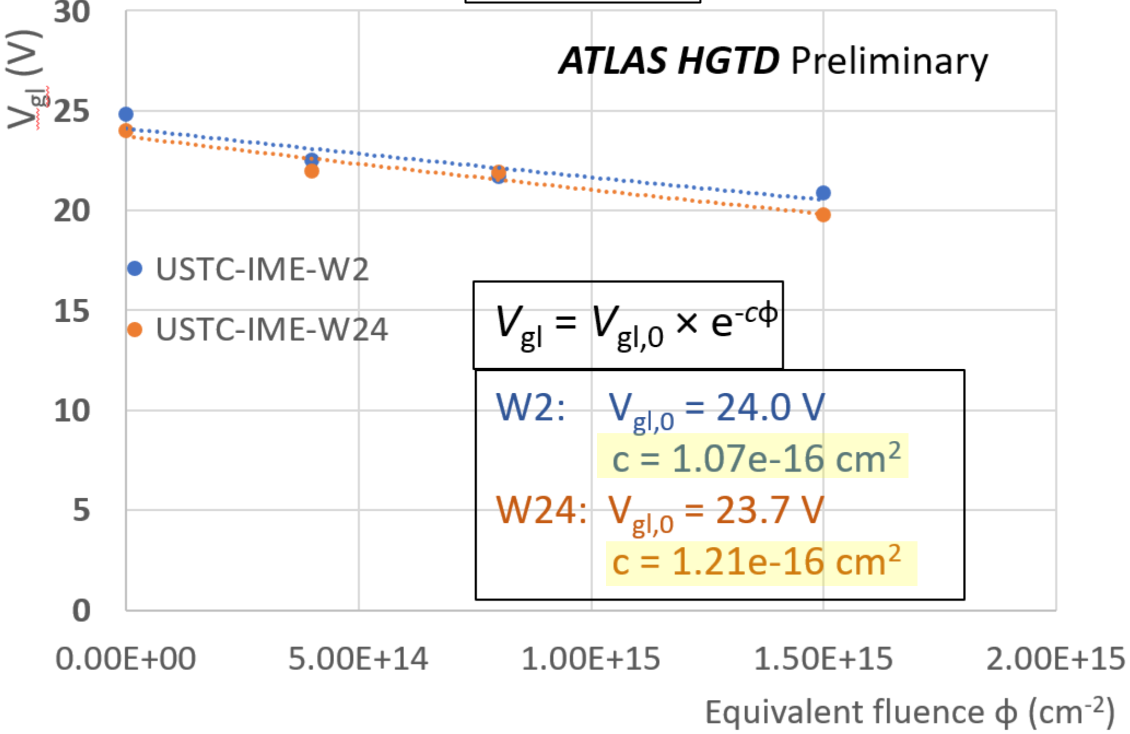


$V_{gl} = V_{gl,0} \times e^{-c\phi}$

Combined W1-W3: $V_{gl,0} = 23.4$ V, c = 0.92e-16 cm^2

W4: $V_{gl,0} = 26.2$ V, c = 1.30e-16 cm^2

USTC-IME



$V_{gl} = V_{gl,0} \times e^{-c\phi}$

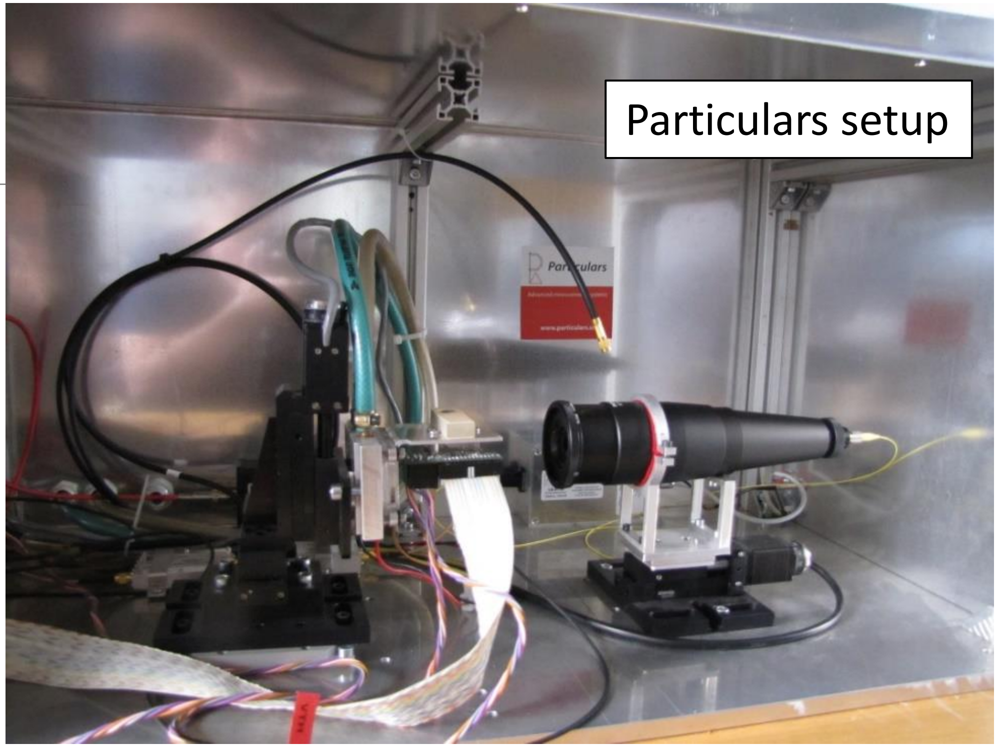
W2: $V_{gl,0} = 24.0$ V, c = 1.07e-16 cm^2

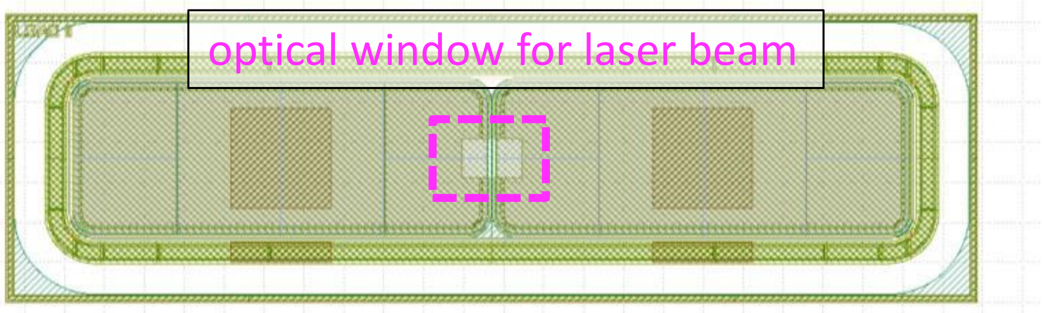
W24: $V_{gl,0} = 23.7$ V, c = 1.21e-16 cm^2

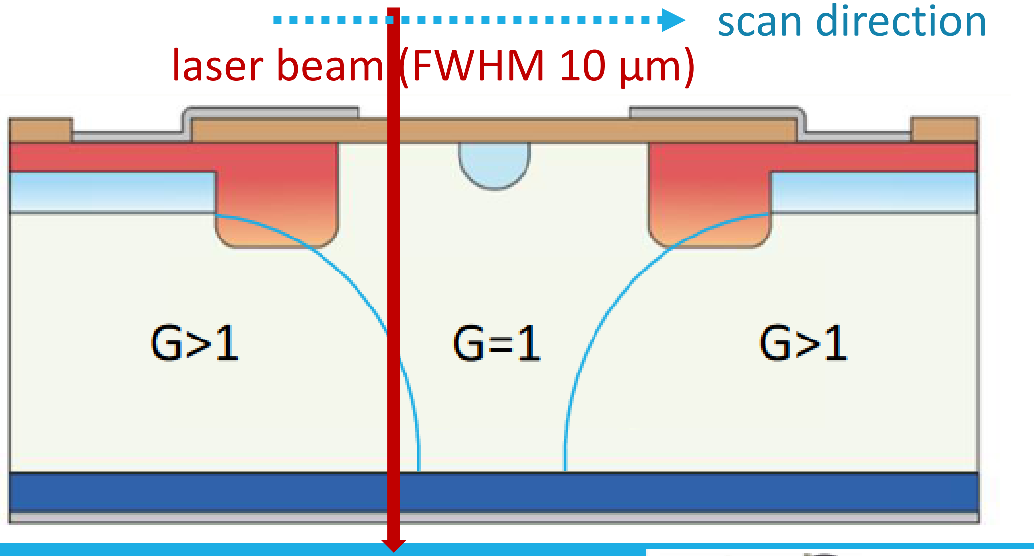
- CV: Acceptor removal parameter *c* in all IHEP-IME and USTC-IME wafers is around 1e-16 cm^{-2} (slight differences)
- **Promising result in terms of acceptor removal → indicates good radiation hardness**

IT – TCT test method

- New laser TCT based test method developed for IT
- Charge collection measurement with a focused infrared laser
  - Top-TCT, room temperature
- Test structure 1 × 2 LGAD on QCTS
  - **Interpad region: LGAD–PIN–LGAD**
  - No gain in interpad region – **PIN diode** (= standard silicon pad sensor)
  - Measure LGAD performance and calibrate it against PIN



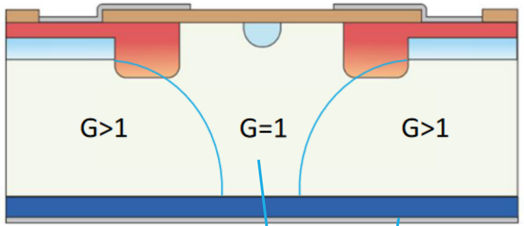


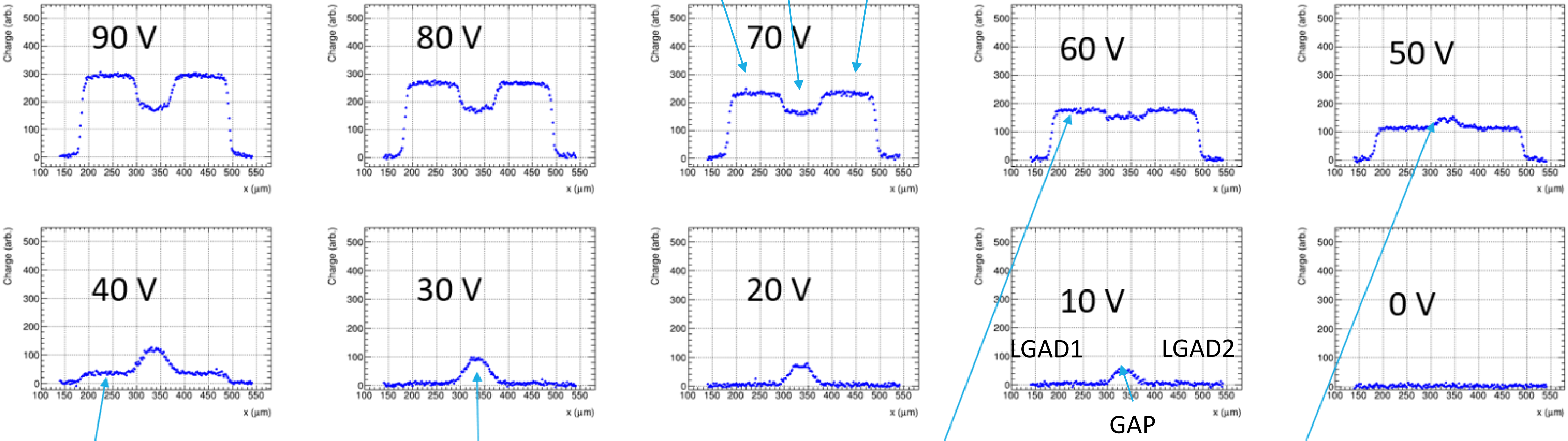


TCT-IT concept

FBK4.0 W18, 20°C, Voltage scan

both LGADs connected to same readout channel





2. Depletion of gain layer – appearance of signal in GL (agrees with CV)

1. Depletion of "no gain" region – full depletion of active layer

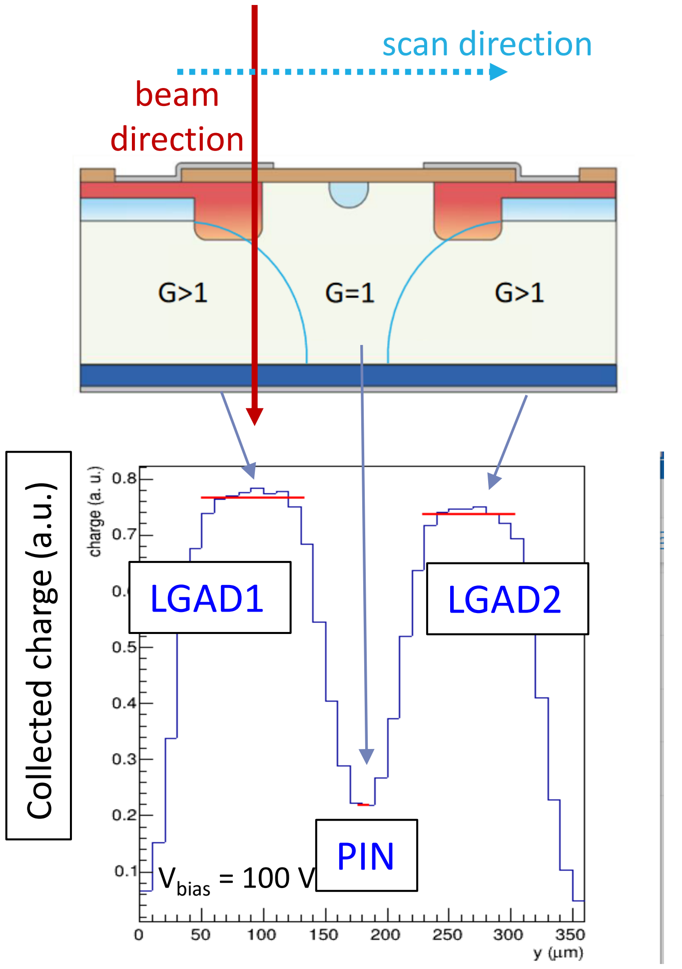
4. Gain increases

3. Full depletion of the device

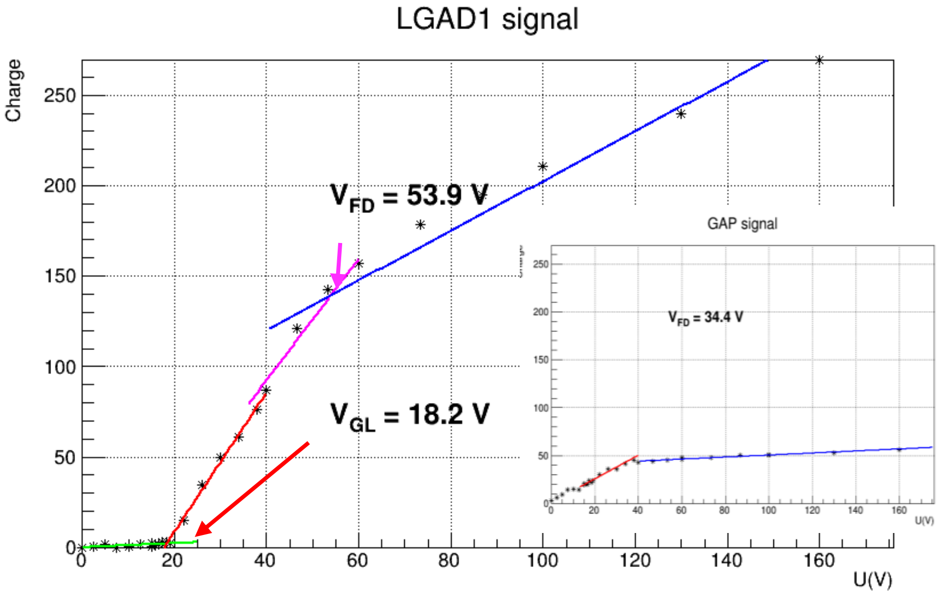
Slide taken from P. Skomina, 42nd RD50 Workshop

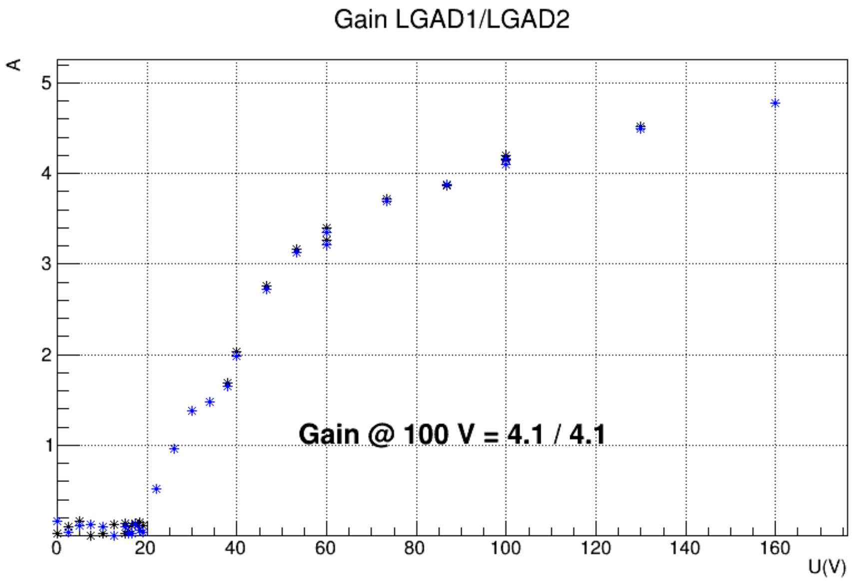
TCT-IT method

- Measure collected charge as a function of voltage in LGADs and PIN and determine:
  - **Gain layer depletion voltage V_{gl}** – onset of observable signal
  - **Sensor depletion voltage V_{fd}** – end of sharp signal increase
  - **Gain vs. bias voltage A** – ratio of LGAD and PIN collected charge
  - **Interpad distance –** between both LGADs
  - **Leakage current**
- These parameters are used to qualify sensor performance/radiation hardness
- Indirect method – calibration against other methods



charge = signal integral [0, 3 ns]

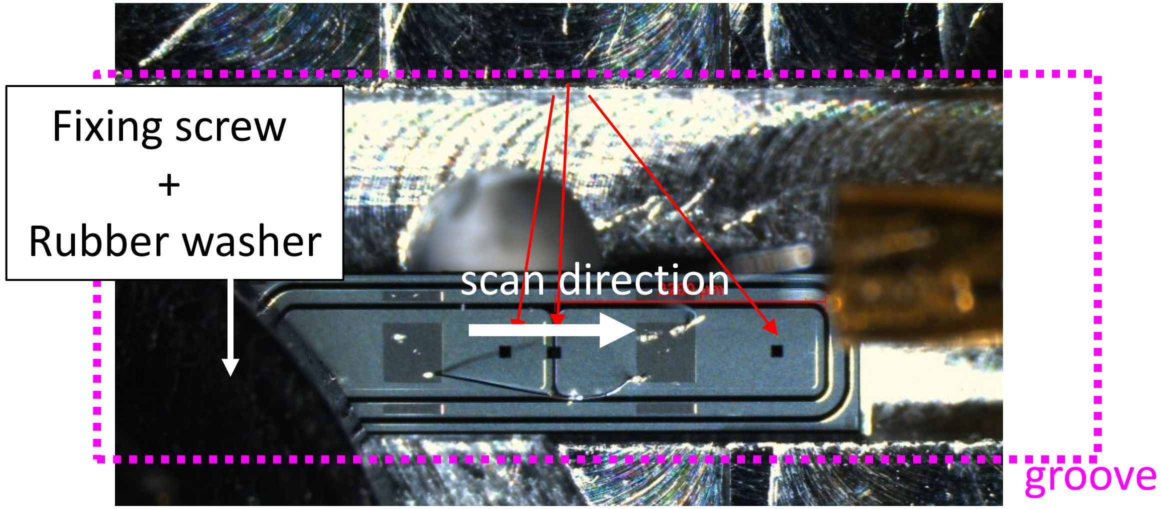




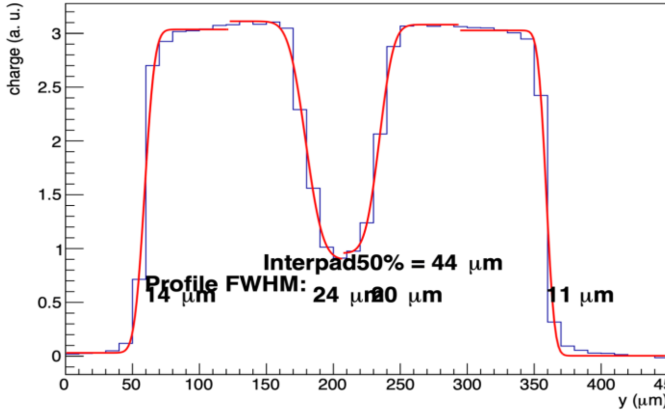
TCT-IT Quality of Life improvements

Sample placement: dedicated Al holder with a groove for precise placement

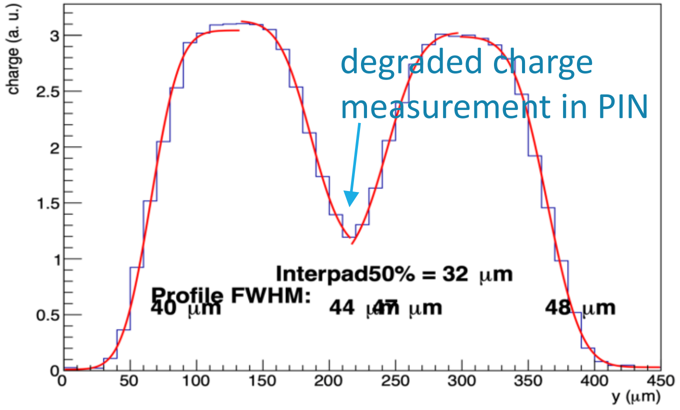
Precise orientation and known position
(simpler & faster measurement preparation)



Sample in focus



Sample out of focus

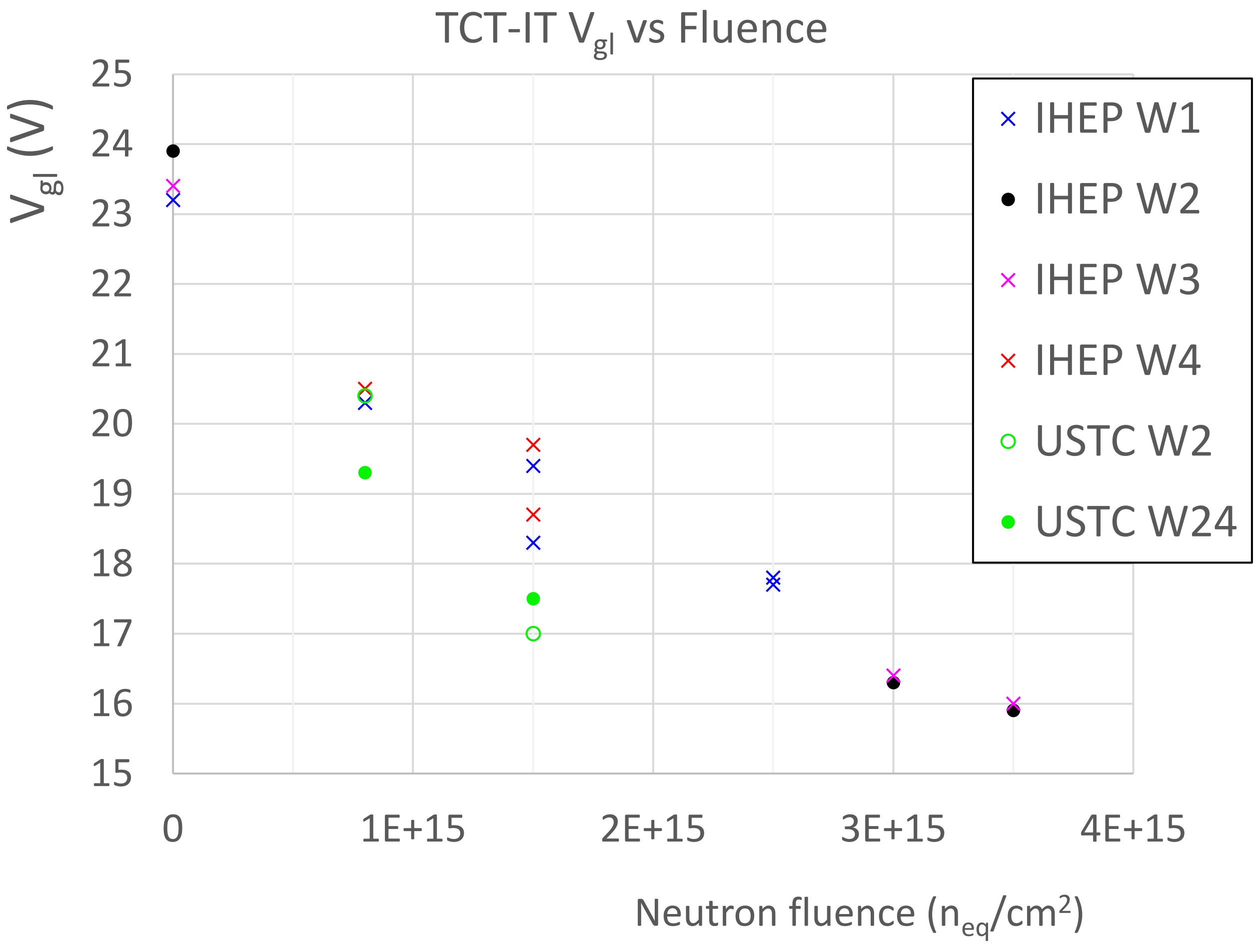


Data quality test

Automated check that sample is in beam focus

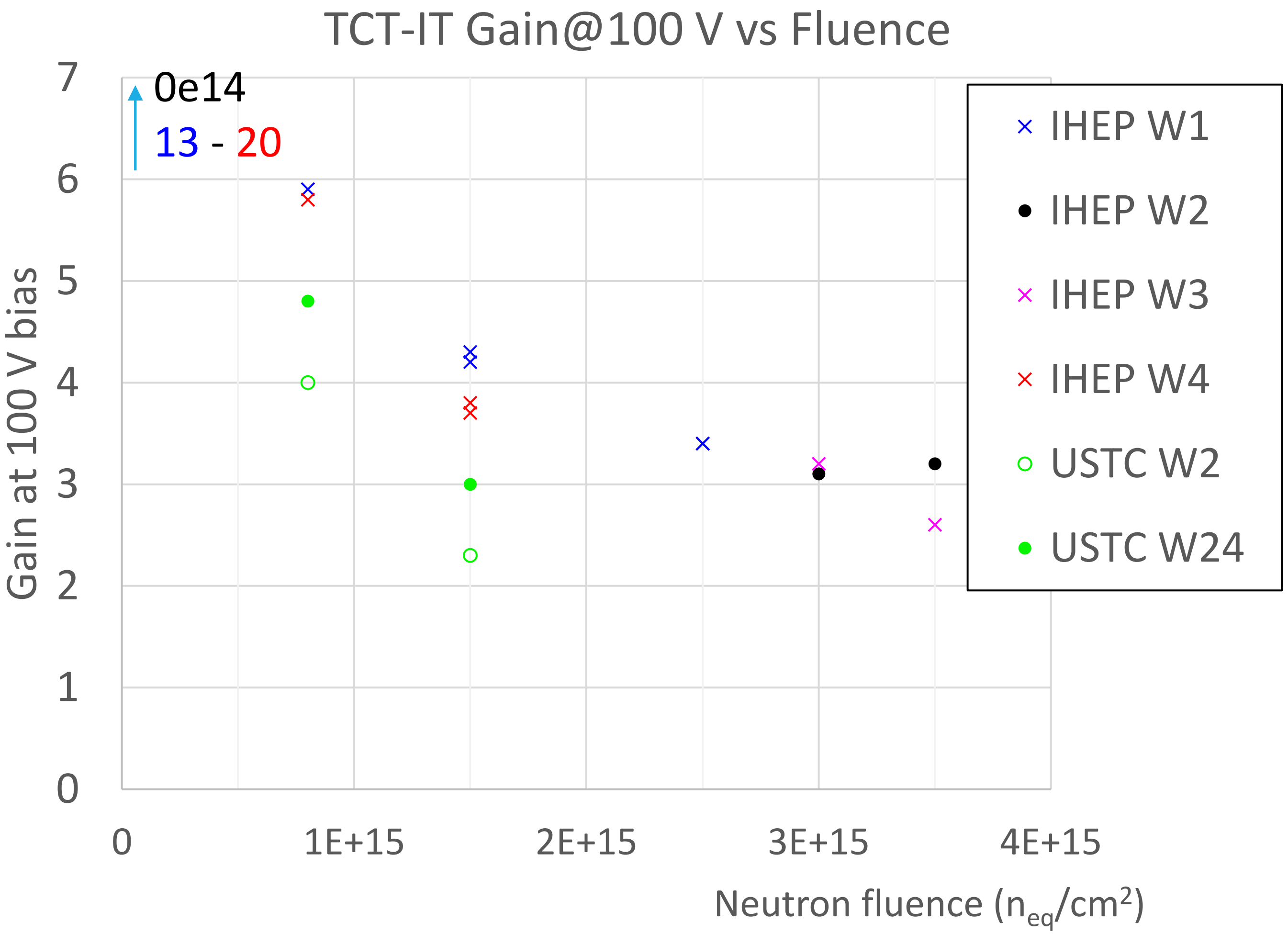
Automated analysis scripts and uploading of results in CERN production database

TCT-IT Results: V_{gl}



- V_{gl} as a function of fluence for different wafers
- Falling consistently with fluence (acceptor removal)
  - Clear separation between fluences – good sensitivity
- Results reasonably consistent between wafers
- USTC-IME samples do not follow the trend of IHEP-IME
  - Data comes from first measurements during method commissioning – learning curve
  - More statistics required when samples available

TCT-IT Results: Gain

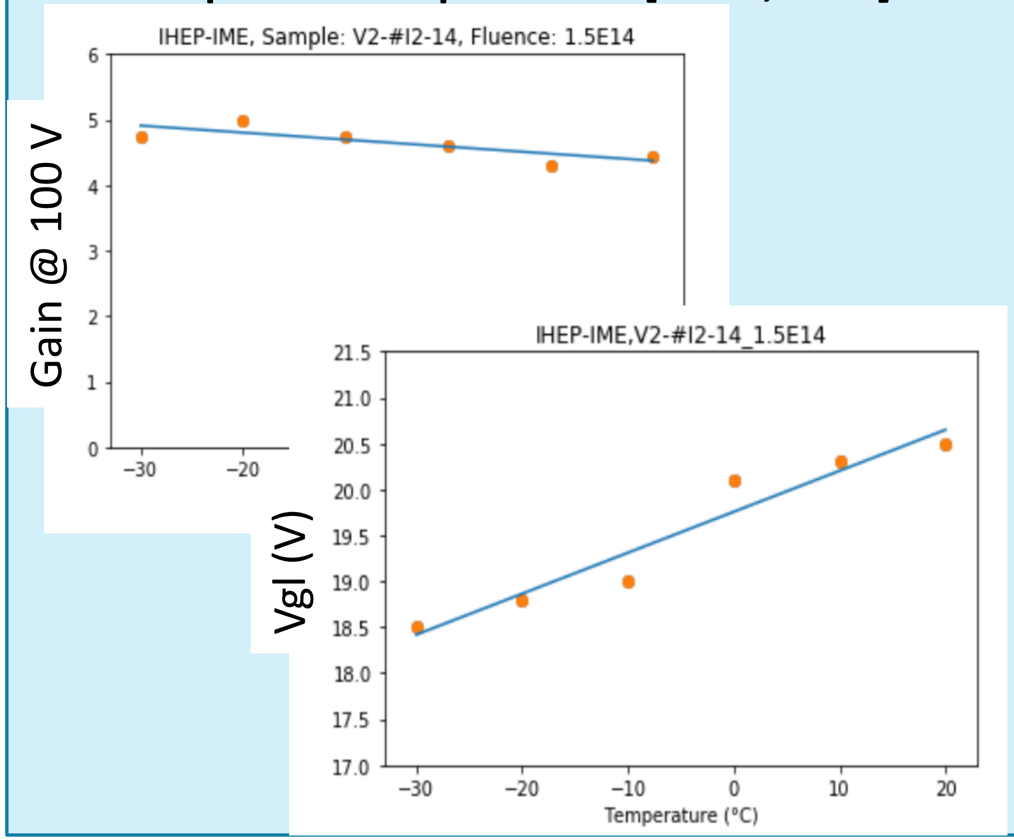


- LGAD Gain at 100 V (= fixed voltage)
- Falling consistently with fluence (due to smaller V_{gl})
  - Relatively good separation between fluences – sensitivity
- More statistics needed for fluences ≥ 2.5e15 to determine measurement uncertainty
- More statistics required, especially with USTC-IME

IT: systematic effects

- Extensive setup validation studies during TCT-IT commissioning to evaluate systematic effects
- No nasty systematic effects found

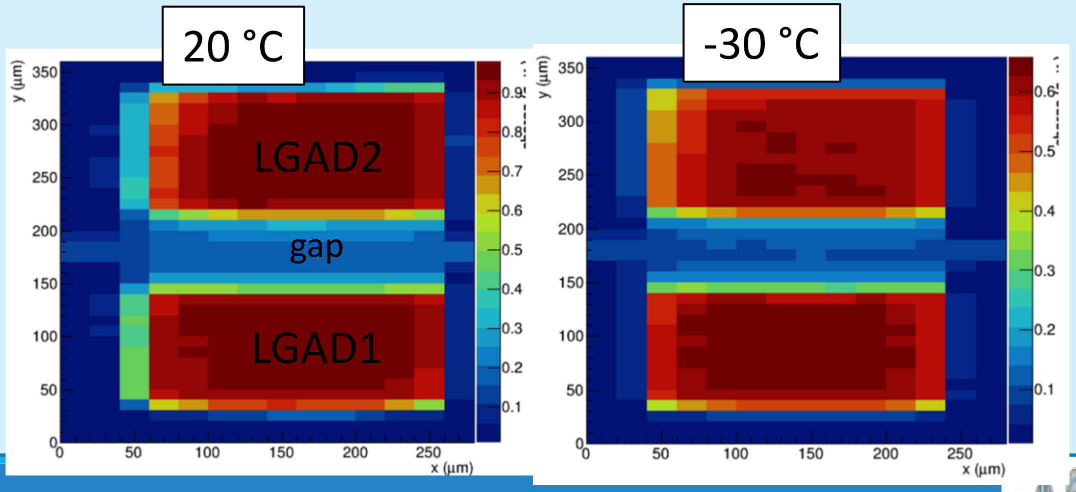
Temperature dependence [-30°C, 20°C]



Reproducibility (3× same test)

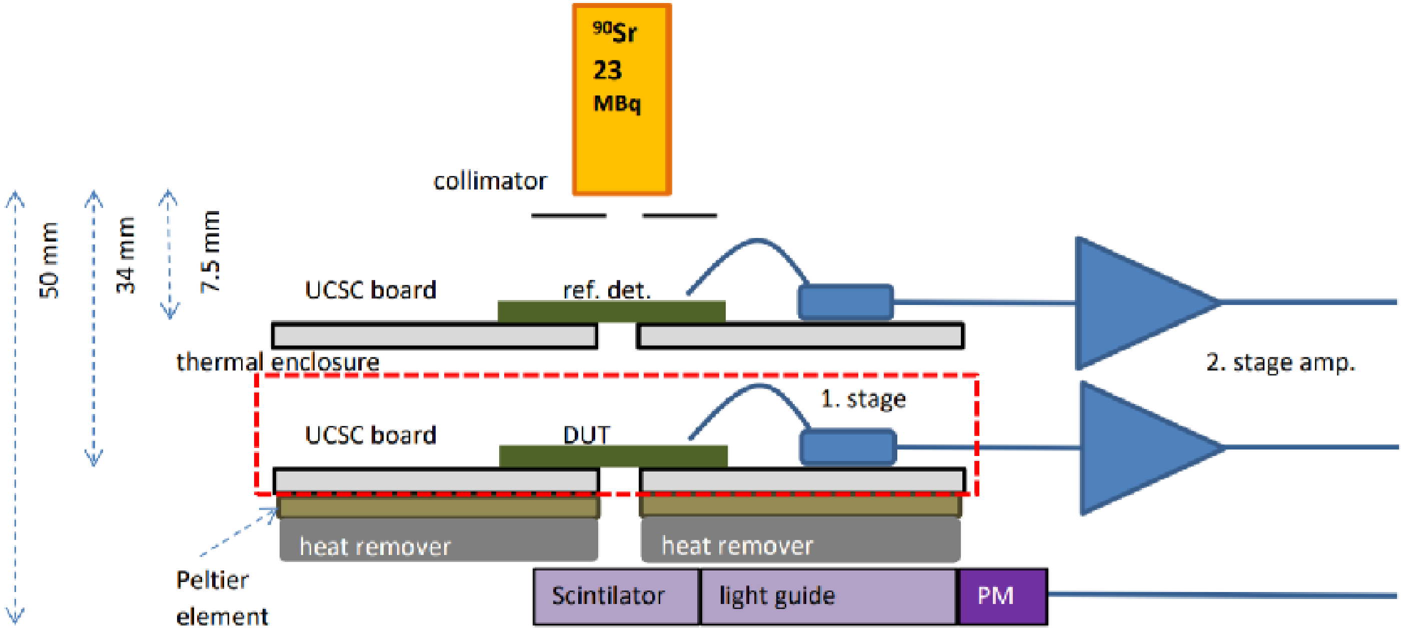
Sample	T (K)	Vgl (V)	Gain at 100 V
V1R2-21_1.5e15	293	18.1 / 18.2	4.2/4.1
		18.3 / 18.3	4.1/4.2
		18.4 / 18.4	4.2/4.2

Mechanical shifts with temperature

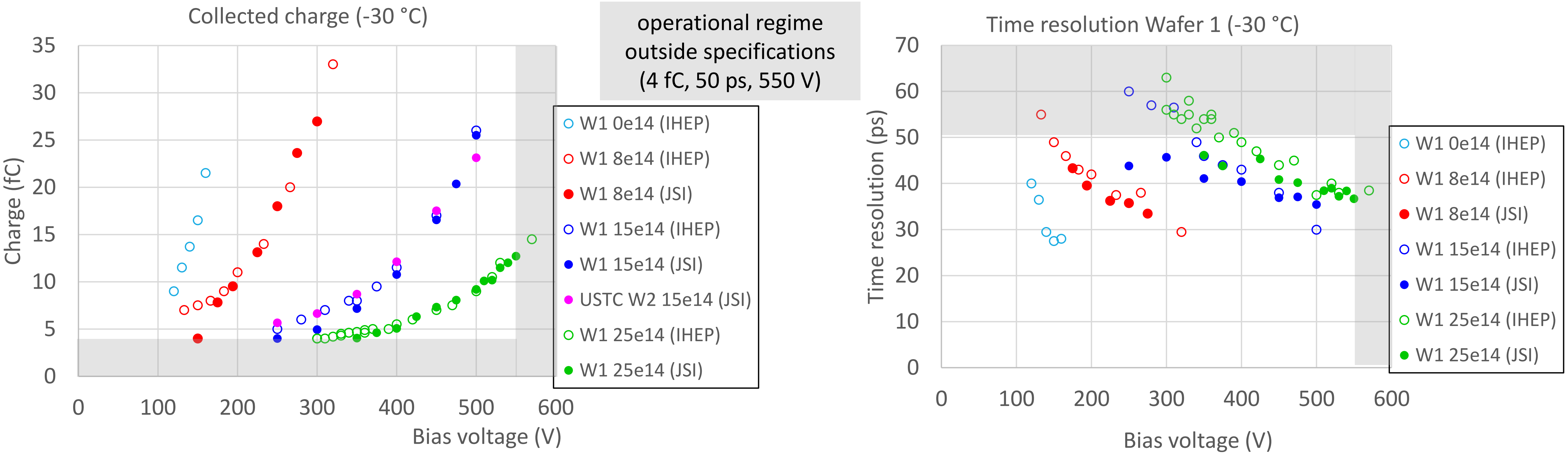


^{90}Sr measurements

- TCT-IT not directly measuring **MIP charge** and **time resolution**
- Charge Collection and Time Resolution measured with Sr90 and used for TCT-IT calibration
  - Sr90 is a pure β emitter – laboratory MIP source
- Setup with two LGADs (time reference and DUT)
  - DUT cooled to –30° C
  - Trigger on reference LGAD + PMT (“MIP” selection)
  - DUT not part of the trigger
- Up to 2 measurements per day, relatively time consuming
  - In production will only be used for diagnostics of problematic wafers / occasional calibration



Sr90 results: charge and time resolution

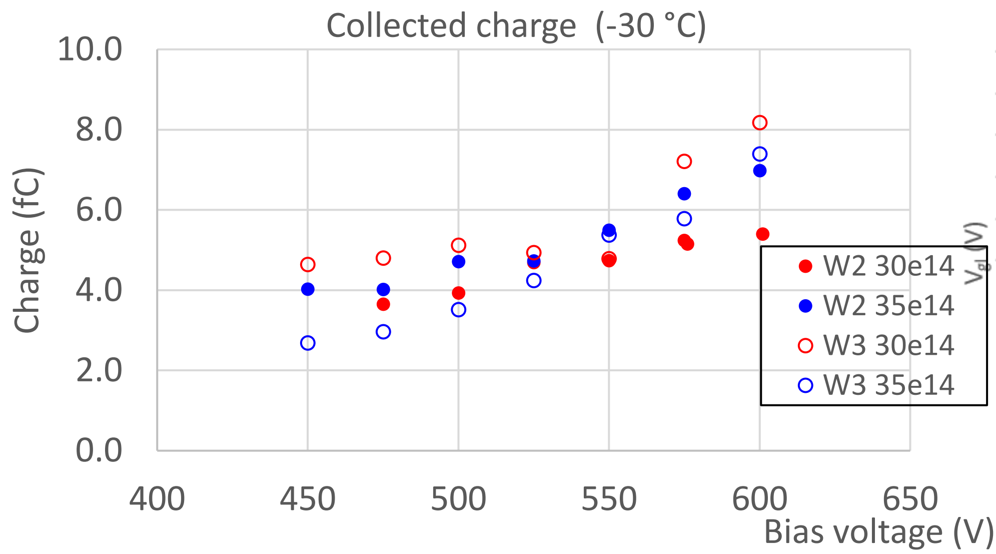


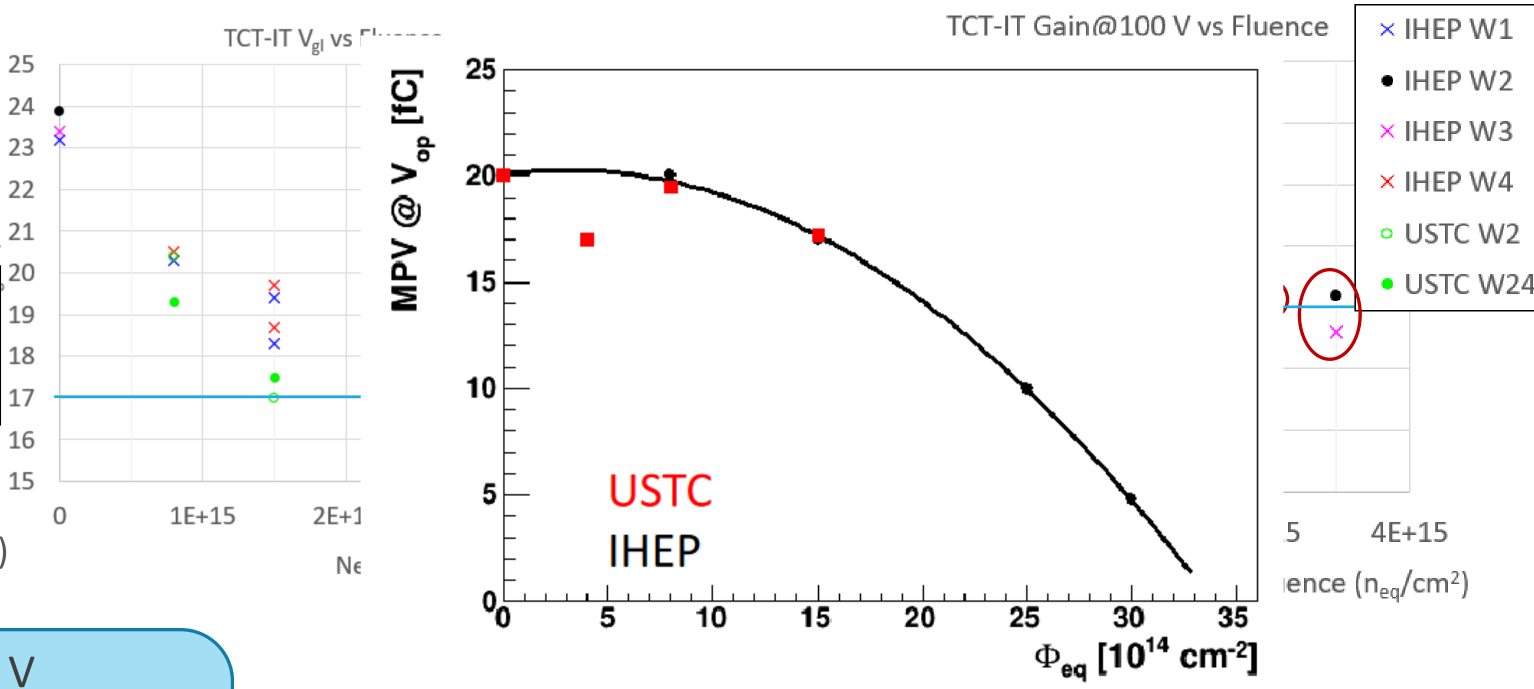
- Results between wafers and manufacturers very similar (do not see the discrepancy from TCT-IT)
- Same sample measured first at JSI, then IHEP → excellent agreement
- **HGTD Preproduction: Collected charge and time resolution well within specifications even at EOL fluence**

Sr90 results at extreme fluences (3e15, 3.5e15)

Excellent performance of all wafers up to now. How do we know what IT failure will look like?

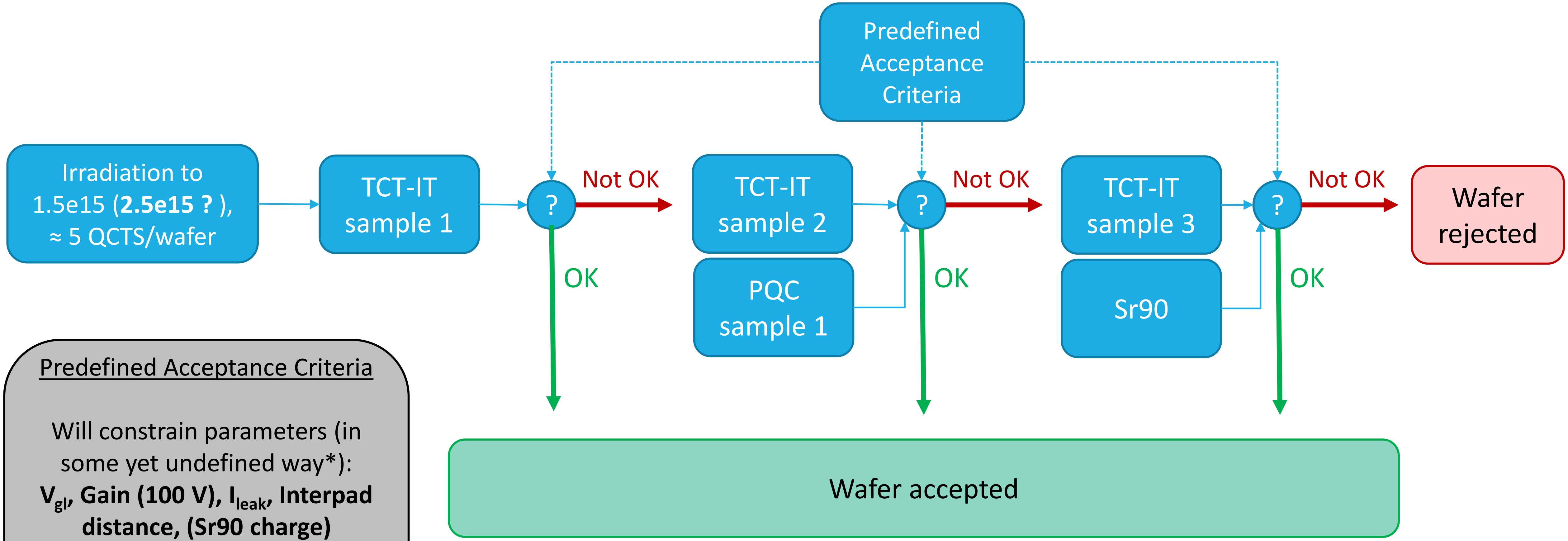
→ **Sample irradiation above EOL fluence: 3e15, 3.5e15 n_{eq}/cm^2**





- Collected charge just above 4 fC at 550 V
- This indicates rough acceptance criteria in TCT-IT:
  - **Vgl > 17 V @ 2.5e15 (for IHEP-IME)**
  - **Gain(100 V) > 3 @ 2.5e15 (for IHEP-IME)**

Outlook: Wafer Acceptance/Rejection process



Predefined Acceptance Criteria

Irradiation to 1.5e15 (**2.5e15 ?**), ≈ 5 QCTS/wafer

TCT-IT sample 1

TCT-IT sample 2

PQC sample 1

TCT-IT sample 3

Sr90

Wafer rejected

Wafer accepted

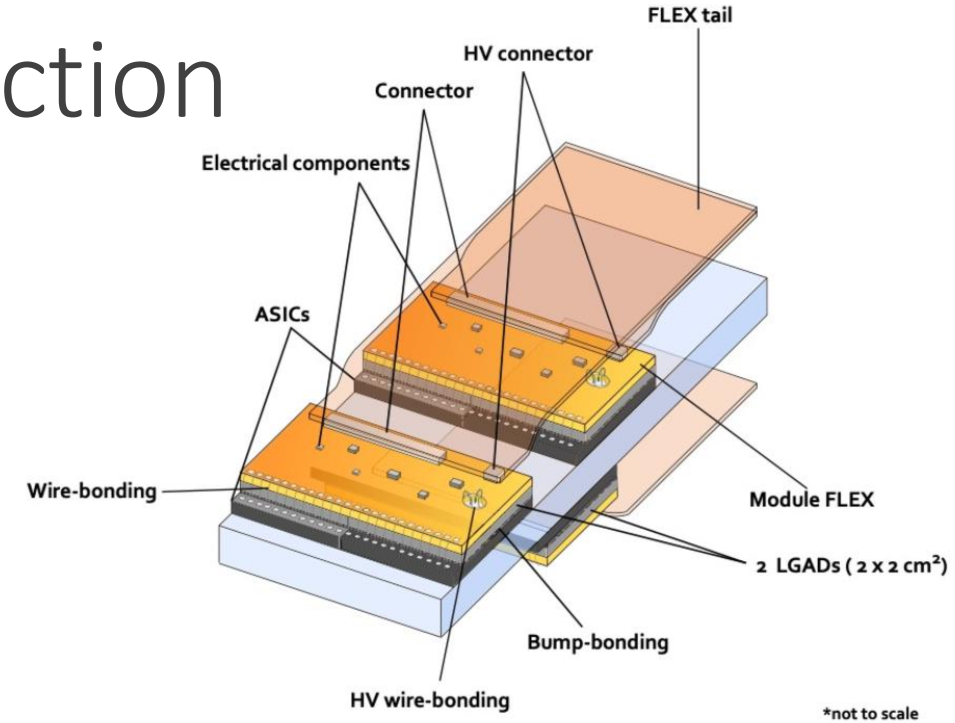
<u>Predefined Acceptance Criteria</u>

Will constrain parameters (in some yet undefined way*): **V_{gl}, Gain (100 V), I_{leak}, Interpad distance, (Sr90 charge)**

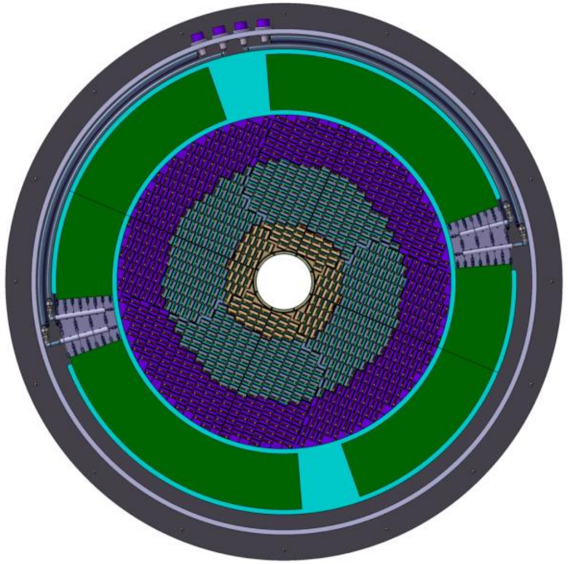
*Based on statistical distributions of tested samples, for example 2σ

Occasional full (irradiated) sensor test on probe station, compare to specs (Maybe)

ATLAS HGTD Flex Tail production



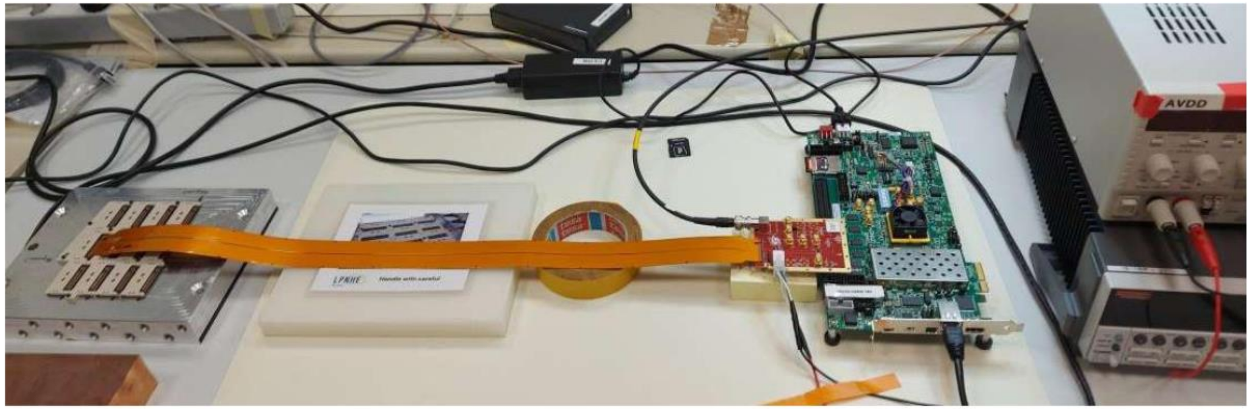
- **Flex Tails**: lightweight multichannel cables connecting HGTD modules with Peripheral Electronic Boards
  - Built on Polymide (Kapton) substrate – flexible
  - Many stacked on top of each other → small thickness
- ≈ 10,000 pieces, 79 flavors (lengths)
  - 5 cm–70 cm, same connector ends, different body length
- JSI has experience with **flex cable production for ITk strip** endcap modules – collaboration with SLO industry (**Elgoline**)
  - Potential for further collaboration in HGTD
- Current activity status
  - HGTD 54-module Demonstrator being built
  - JSI provided 5 prototype flex cables – work OK
  - Vendor selection and production orders not yet done



HGTD Flex Tail MoU

	Flex PCB	Certification test benches	Total
	8.4.5.1	8.4.5.2	8.4.5
Brazil			
China NSFC+MSTC	33.6%		33.2%
France IN2P3			
France CEA			
Germany BMBF	41.7%	33.33%	41.6%
Morocco	16.2%	33.33%	16.4%
Netherlands			
Russia			
JINR			
Slovenia	8.5%	33.33%	8.8%
Spain			
Sweden			
Taipei			
Turkey			
CERN			
Total	100.0%	100.0%	100.0%

- JSI to provide:
  - 8.5 % of total Flex Tails
  - 33.3 % of total Flex Tail testing
  - Irradiation tests
- FPGA based test setup copied from Uni Mainz for testing



Summary

- **ATLAS HGTD for HL-LHC** is a step forward in particle detector technology
- It will provide:
  - Precise particle timing information **≤ 50 ps (!)**
  - Bonus: **Luminosity measurement (1 %)**
- LGAD sensors – technology developed in HEP (including JSI) for HL-LHC detectors
- Preproduction currently ongoing, planned completion of HGTD A/C in Fall 2026/Spring 2027

- Production activities at F9
  - **Process Quality Control** – backup site
  - **Irradiation Test Quality Control** – main site, new test method developed
  - **Flex tail production** – cooperation with Slovenian industry