The ATLAS HGTD - Status and Updates and Exploring the response of LGADs for time resolved synchrotron applications

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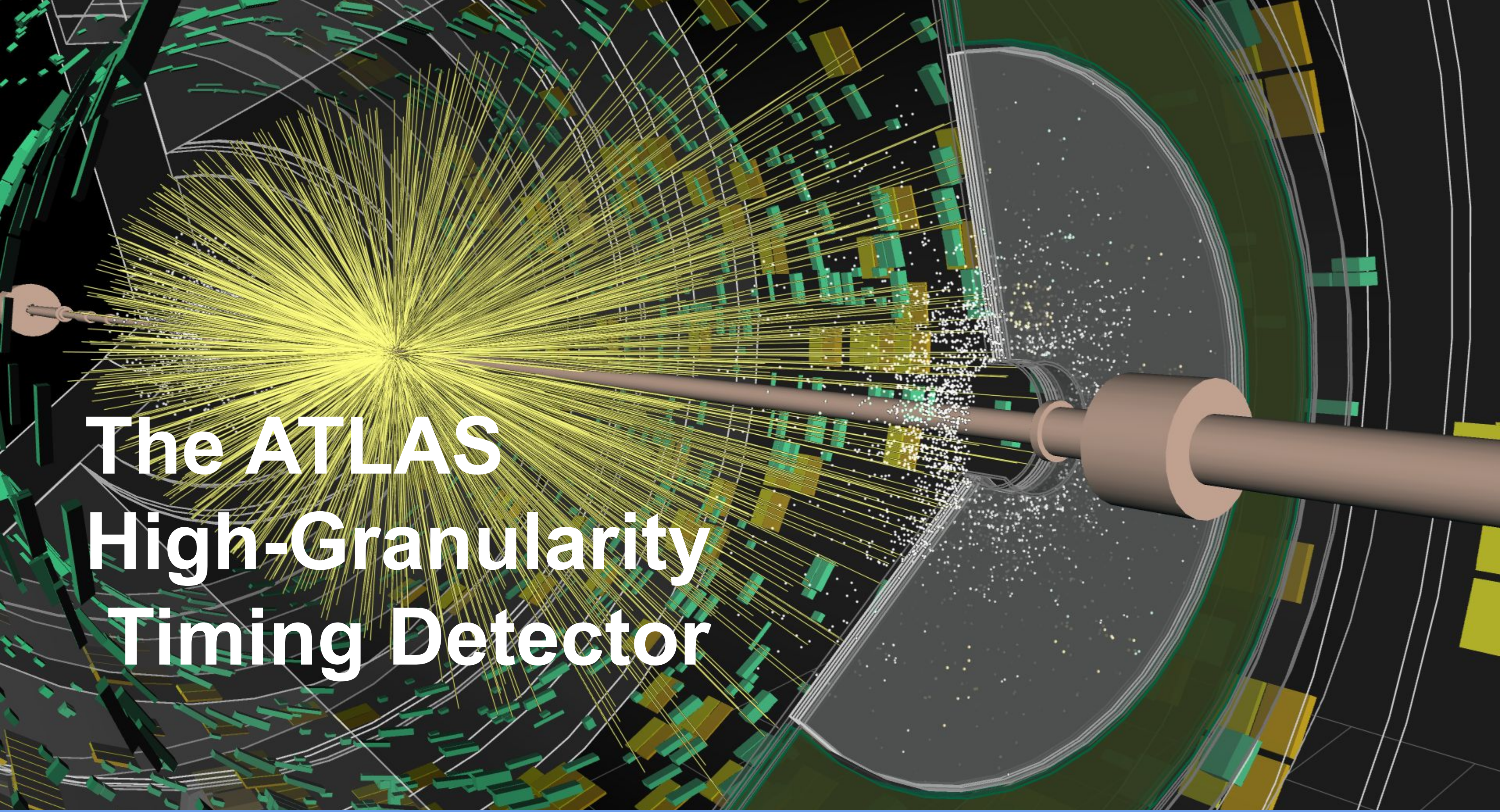
IX Reunião Geral - Projeto Especial FAPESP "Física e Instrumentação de Altas Energias com o LHC-CERN"

27 May 2026

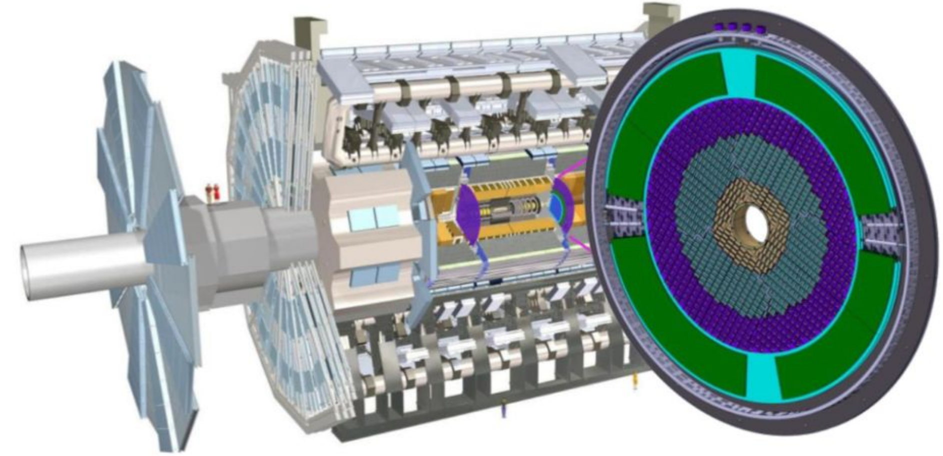
On this presentation

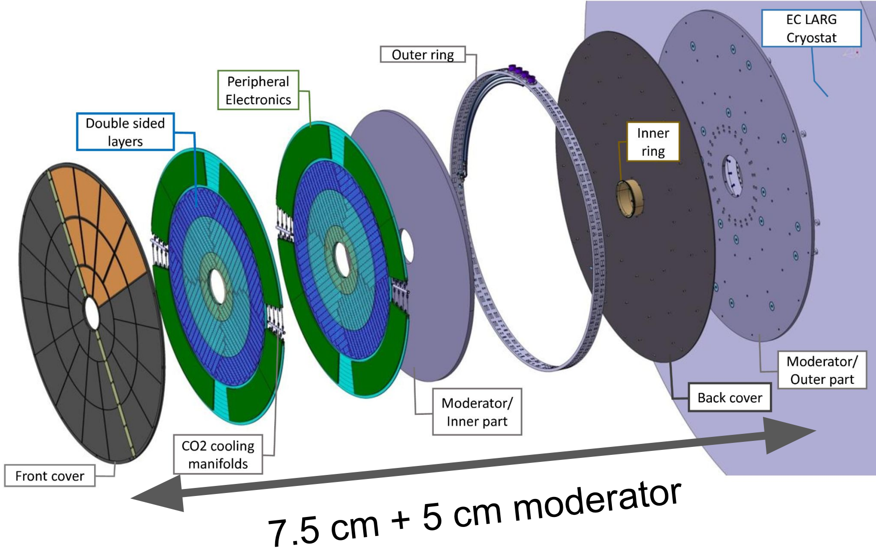
- The ATLAS High-Granularity Timing Detector
  - Project status
  - Sensor delivery
    - Sensors and wafers quality control at USP and CERN
- LGADs for time resolved Synchrotron X-ray applications
  - Beam testing campaigns in Sirius
  - New results



The ATLAS High-Granularity Timing Detector

High-Granularity Timing Detector





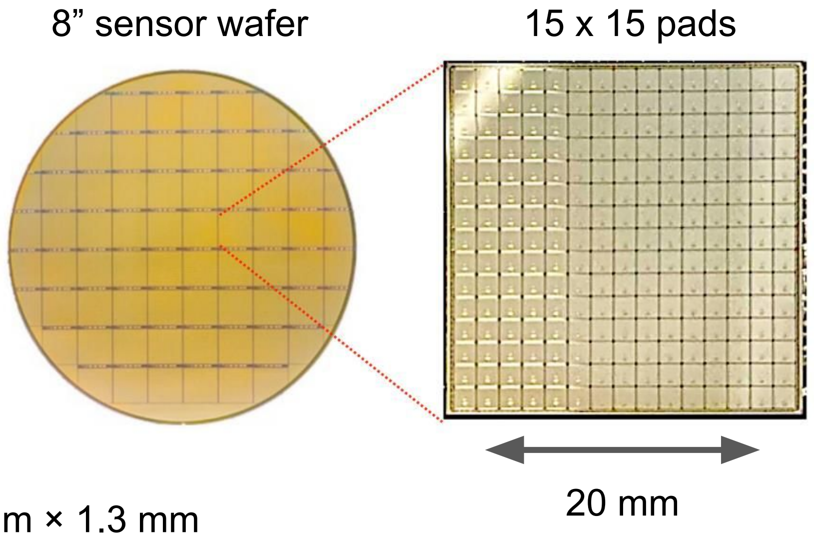
Mitigate pileup using 4D information on hits/tracks

- See Rodrigo's talk for more on pileup mitigation

- ➔ Placed between ITk and LAr Calorimeter
- ➔ Active area coverage: $2.4 < |\eta| < 4.0$
- ➔ Track-time resolution: **30 ps** (start) - 50 ps (end)
- ➔ **6.4 m^2 of silicon** sensors
- ➔ **8032 modules** (2 LGAD sensors arrays + 2 ASICs)

- ➔ Radiation hardness requirements (with replacements):
  - ◆ Maximum fluence: **2.5×10^{15} n$_{eq}$/cm^2** with SF=1.5
  - ◆ TID: **2 MGy** with SF=2.25
- ➔ Two instrumented double layers per side
- ➔ Layout optimised to have **~2 hits per track**
- ➔ Unique capability for **bunch-by-bunch luminosity determination**

HGTD Sensors

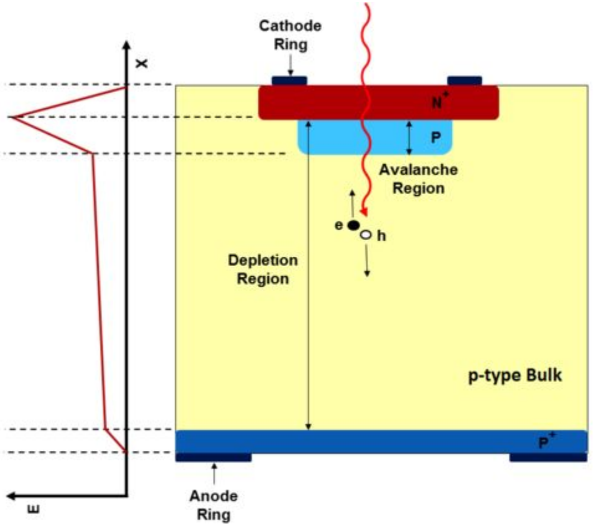


Low Gain Avalanche Detector (LGAD):

- n-in-p diode structure
  - Extra p-type gain-layer enabling
  - Moderate gain 10-20

➔ Larger signal-to-noise ratio and fast rise time

= Excellent time resolution



HGTD LGAD:

➔ 15 × 15 pads

➔ Pad size: 1.3 mm × 1.3 mm

➔ 3.6 M channels

➔ Active thickness: 50 μm

➔ Carbon implanted gain-layer to withstand radiation

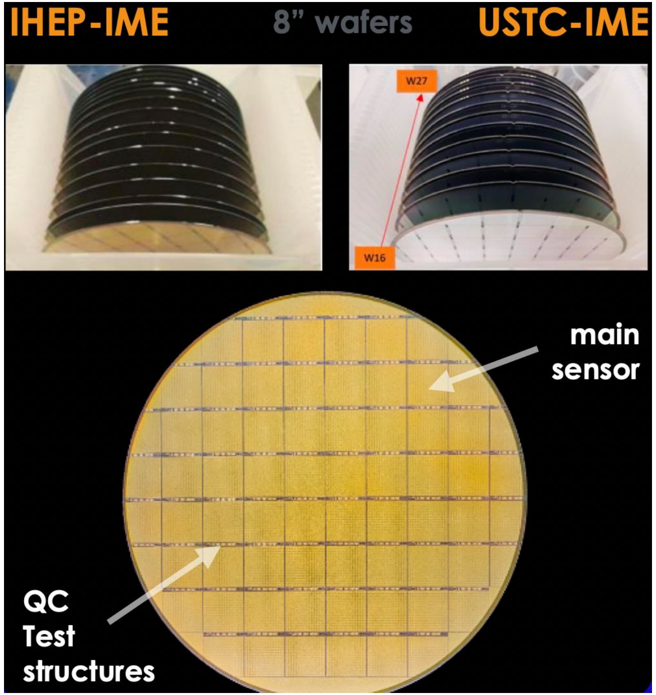
Requirements:

➔ Hit-time resolution: 40 ps (start) - 70 ps (end)

➔ Collected charge per hit: 10 fC (start) - 4 fC (end)

HGTD Sensors Production

- O(600) 8” wafers to be produced for HGTD by IME (Chinese Academy of Science)
- 16000 sensors to be delivered to HGTD:
  - 90% IHEP-IME (China)
  - 10% USTC-IME (China)
- 569 sensors already delivered (Pre-Production)
  - Pre-production of 24 wafers already performed, checked and validated
- Yield on the pre-production wafers was 40-50%
  - But, HGTD buys sensors not wafers



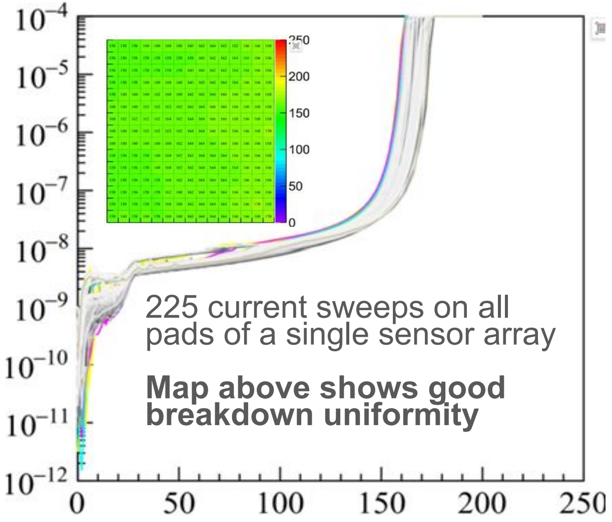
Sensor and Wafer Quality Control

Quality control on **sensor level**:

- ➔ Only measure Breakdown Voltage and Leakage Current
  - ➔ Before company delivery: **on all sensors** with probe card
  - ➔ On selected sensors: **pad by pad** (at IHEP and USTC)

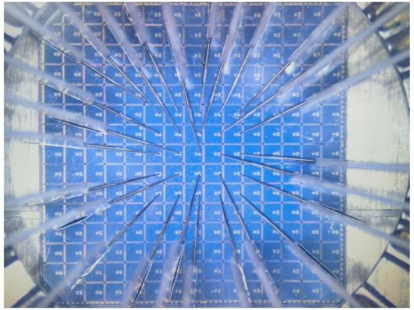
Quality control on **wafer level**:

- ➔ Dedicated Quality Control Test Structures (QC-TS)
  - ➔ **Monitor all available electrical parameters** across the wafer (USP and CERN - 50% each)
  - ➔ **Ensures LGAD performance** after irradiation (at JSI)

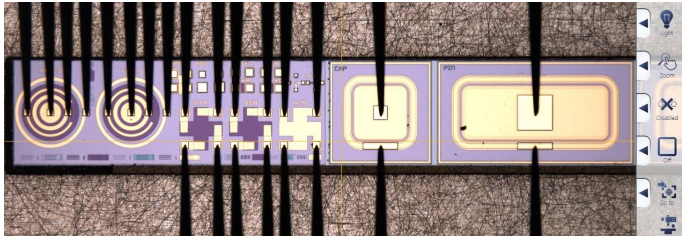


225 current sweeps on all pads of a single sensor array

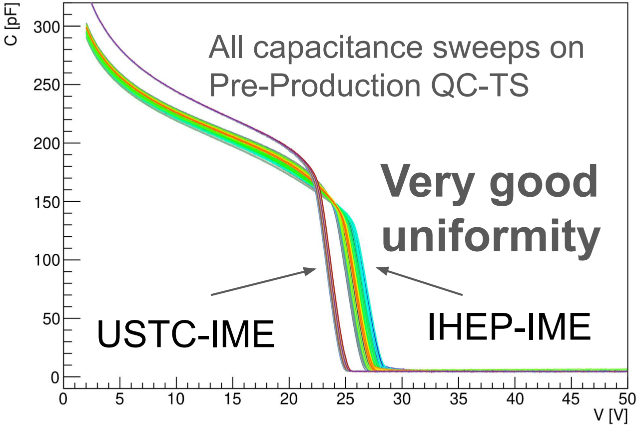
Map above shows good breakdown uniformity



Probe-card measurement on **main sensor**



Probe-card measurement on **QC-TS**



All capacitance sweeps on Pre-Production QC-TS

Very good uniformity

Sensor and Wafer Production

- As of May 2026:
    - USP and CERN qualified >220 wafers [⅖ of total]
        - Batches of ~100 wafers
    - >2000 Quality Control Test Structures at each site
    - ~6000 good sensors delivered to the HGTD collaboration
- Every batch results from USP, CERN and JSI are fed back to the vendor in dedicated meetings
- Different kinds of excursions:
    - Singular outlier wafers and production trends observed
- No public results yet, all internal until paper publication


3rd Batch of HGTD LGAD Wafer structures sent to USP

Exploring LGADs for time resolved synchrotron applications

Sirius Carnaúba Beamline

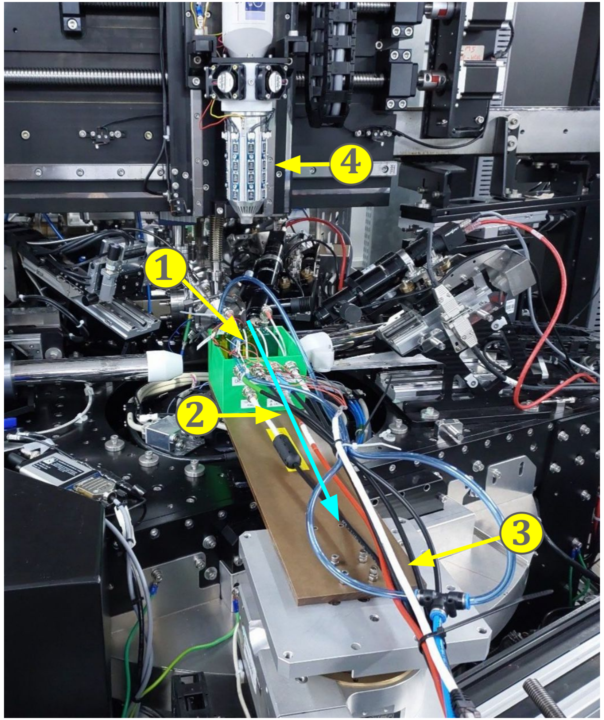
- ATLAS HGTD HPK and IHEP and FBK TI-LGAD sensors tested
- Beam size 350 μm or 150 nm
- Detector can move and rotate wrt to the beam
- Energy/timing resolution wrt X-ray energy, bias and temperature
- EPIC by Sirius to control/store conditions

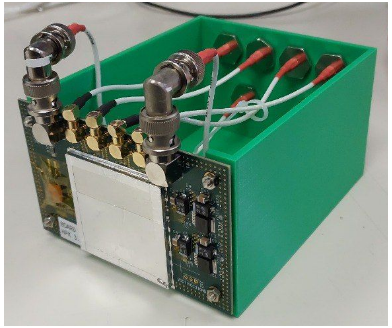
① **LGAD**

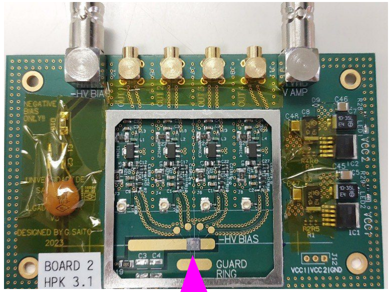
② **Beam direction**

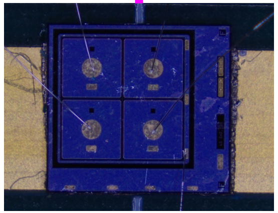
③ **Linear stage**

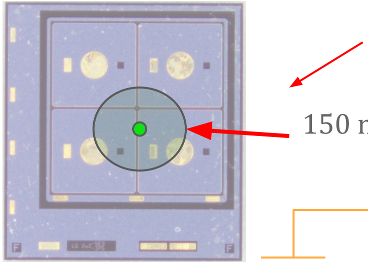
④ **Cooling nozzle**





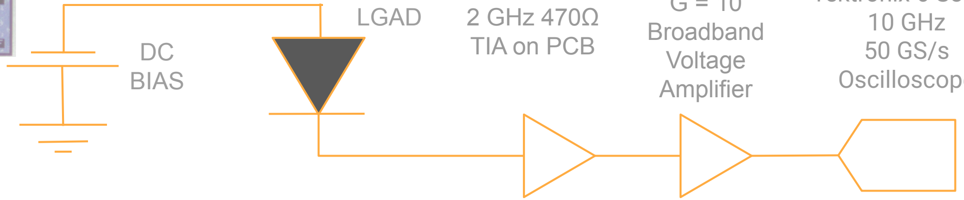






2x2 HPK 3.1 LGAD array

150 nm or 350 μm X-ray beam



DC BIAS

LGAD

2 GHz 470Ω TIA on PCB

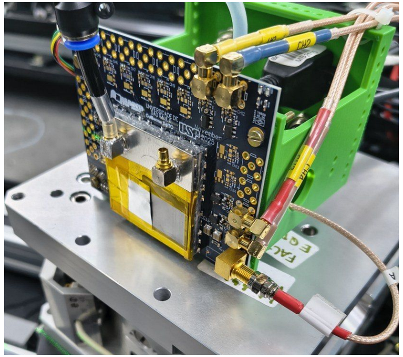
G = 10 Broadband Voltage Amplifier

Tektronix 6 Series 10 GHz 50 GS/s Oscilloscope

Beam tests

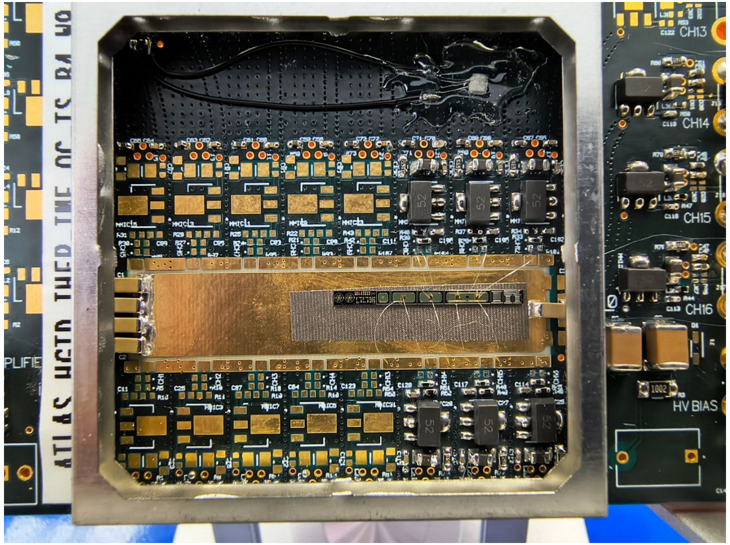
Last 12 months beam tests:

- October 2025 - 2 days
  IHEP HGTD LGAD
  HPK HGTD LGAD
  FBK TI-LGAD
  - Energy resolution and response/linearity as function of bias voltage / X-ray energy
  - Absolute and relative time resolution as function of bias voltage / X-ray energy
  - **Spatial resolution scan** of TI-LGAD
    - **new result - first with <1um beam**
  - **Full beam intensity illumination**
    - **new result - first LGAD ~500MHz response**
- May 2026 - 12 hours
  IHEP HGTD LGAD
  - **2.1 keV using a Be window**
  - Non uniform SIRIUS electron bunch filling
    - useful for baseline correction calibration
  - **High intensity large statistics run**
    - **new result - very precise non-linearity from 5keV~30keV**

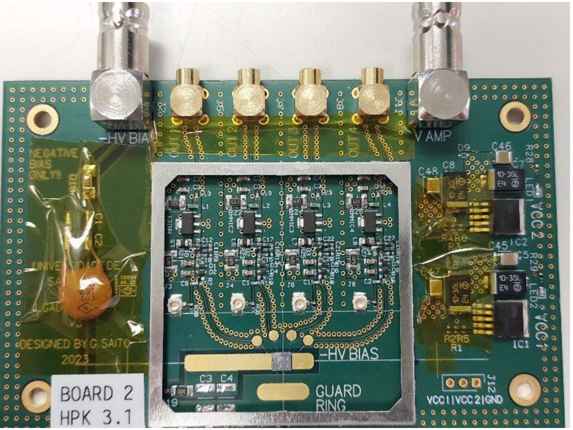


New version of readout board

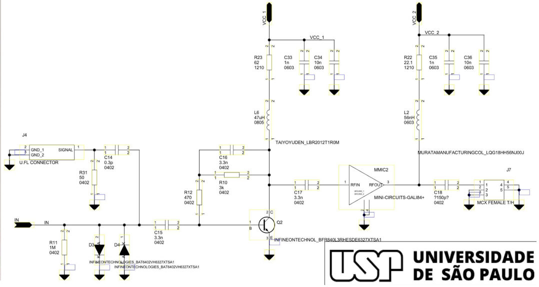
- 16 channels
- Better amplifier design
  - Better energy estimation
  - Improved jitter
- Optimal for many pixels sensor

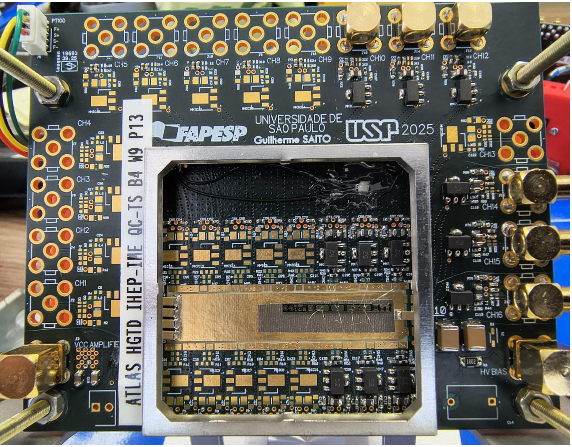


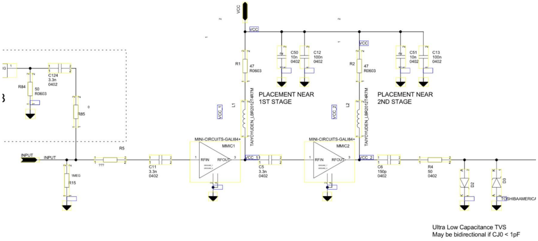
New amplifier design



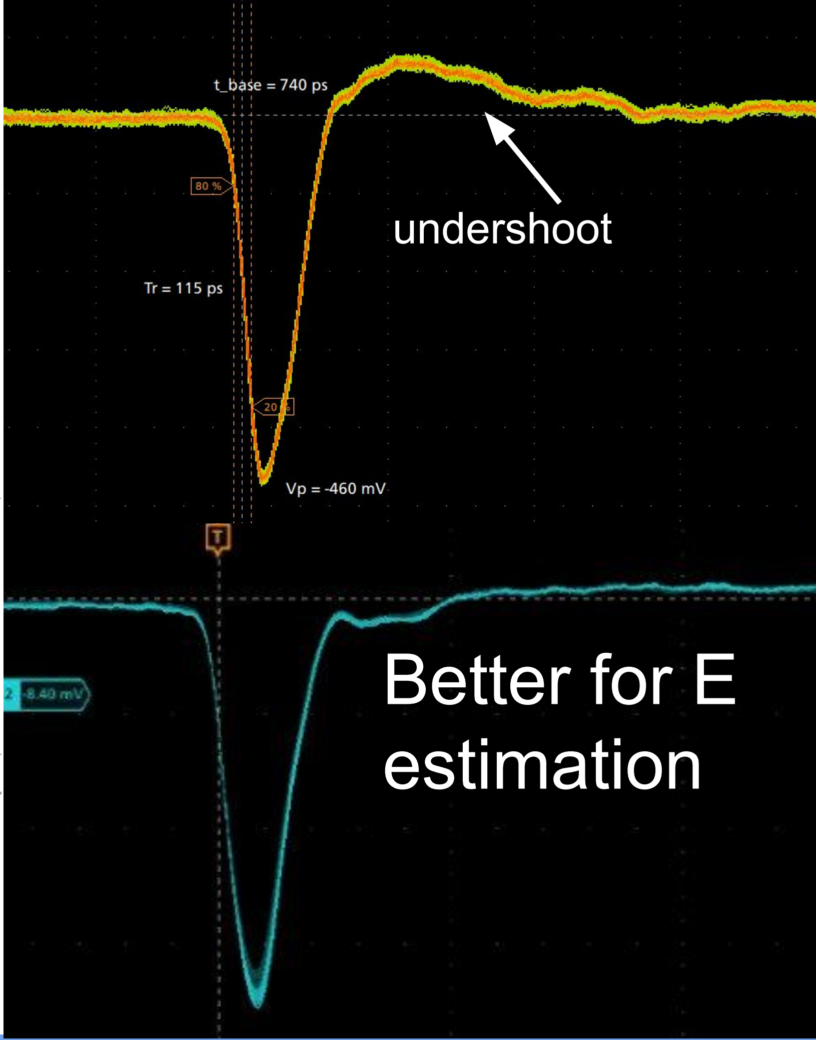
Old design







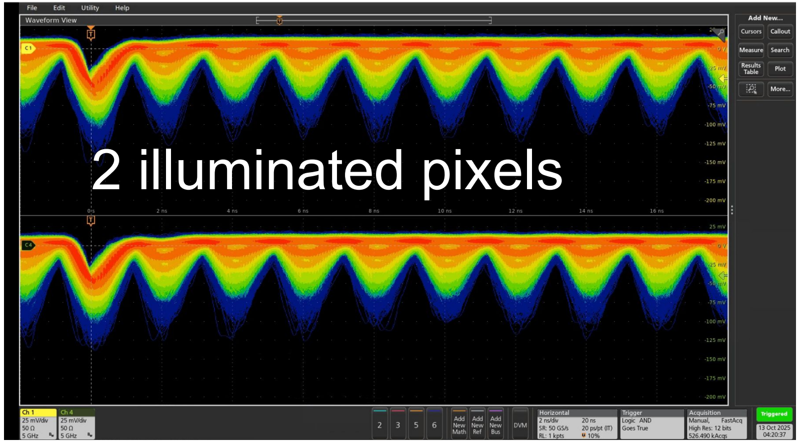
New design



undershoot

Better for E estimation

Selected results



2 illuminated pixels

Ch 1: 25 mV/div, 50 Ω, 5 GHz

Ch 4: 25 mV/div, 50 Ω, 5 GHz

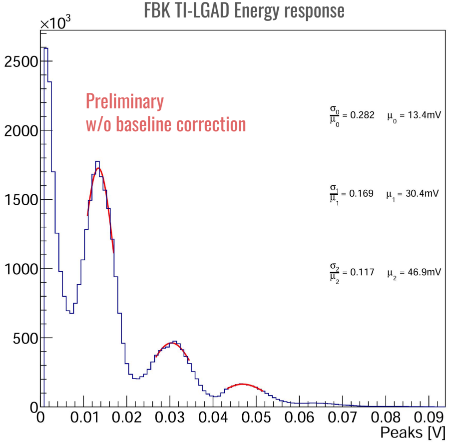
Horizontal: 2 ns/div, 20 ns, SR: 50 GS/s, 20 ps/pt (IT), RL: 1 kpts, 10%

Trigger: Logic AND, Goes True

Acquisition: Manual, FastAcq, High Res: 12 bits, 526.490 kAcqs

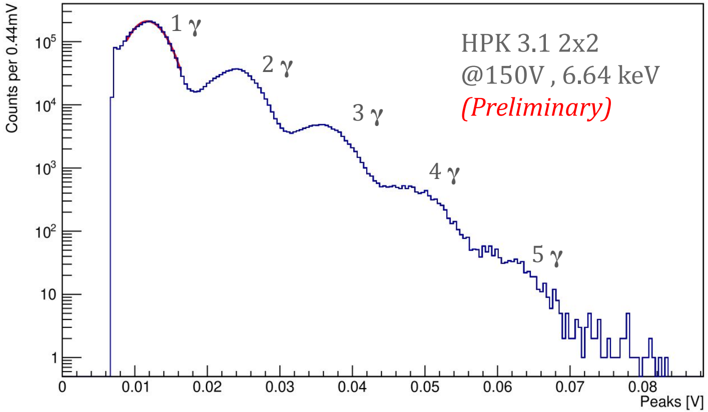
Triggered

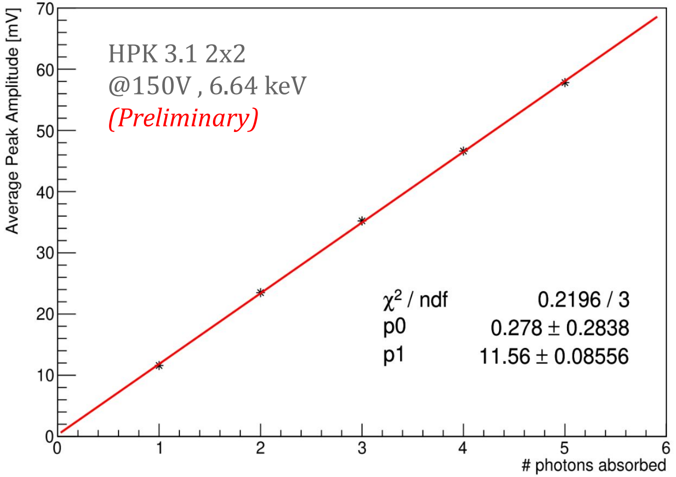
13 Oct 2025 04:20:37



FBK TI-LGAD Energy response

High intensity large statistics run - Linearity





Selected results

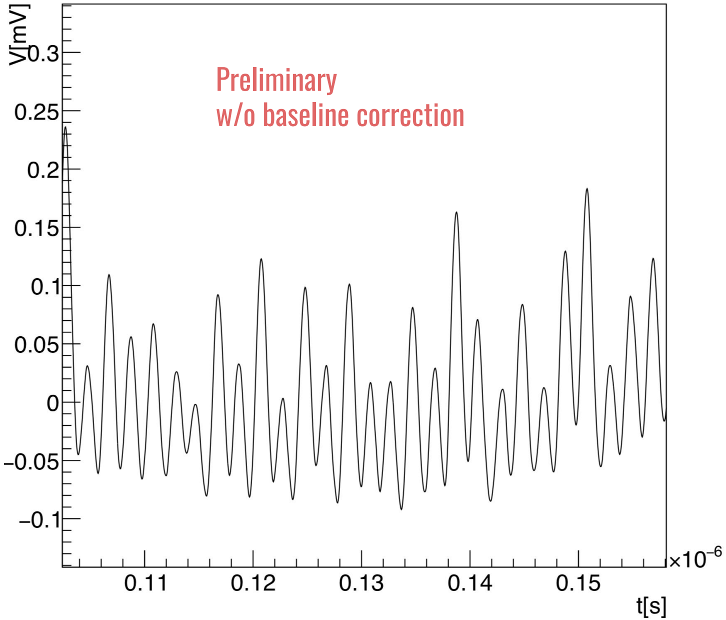
Attempt to kill the sensor ….

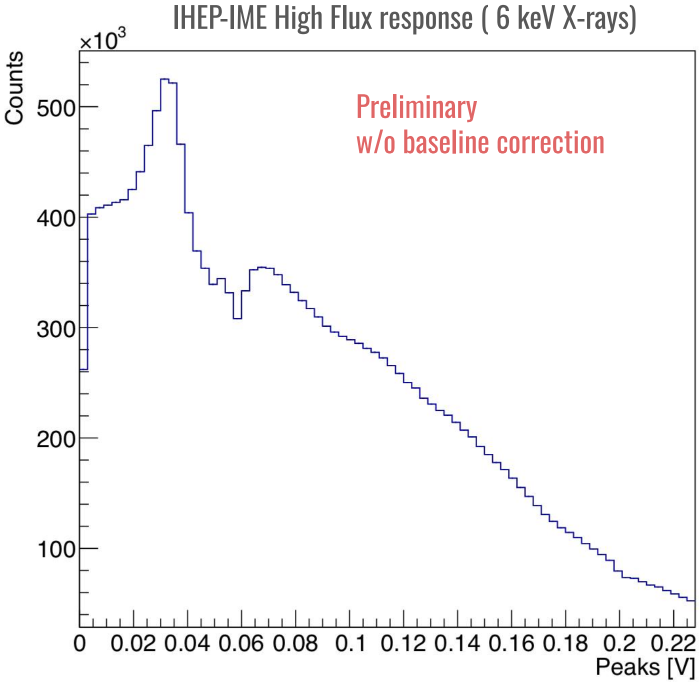
Maximum flux from beam line @ 6 keV, (350 μm spot size)

18uA current from sensor ⇛ no increase in the current in ~10min operation

500 MHz rate

Signal recorded at every bunch

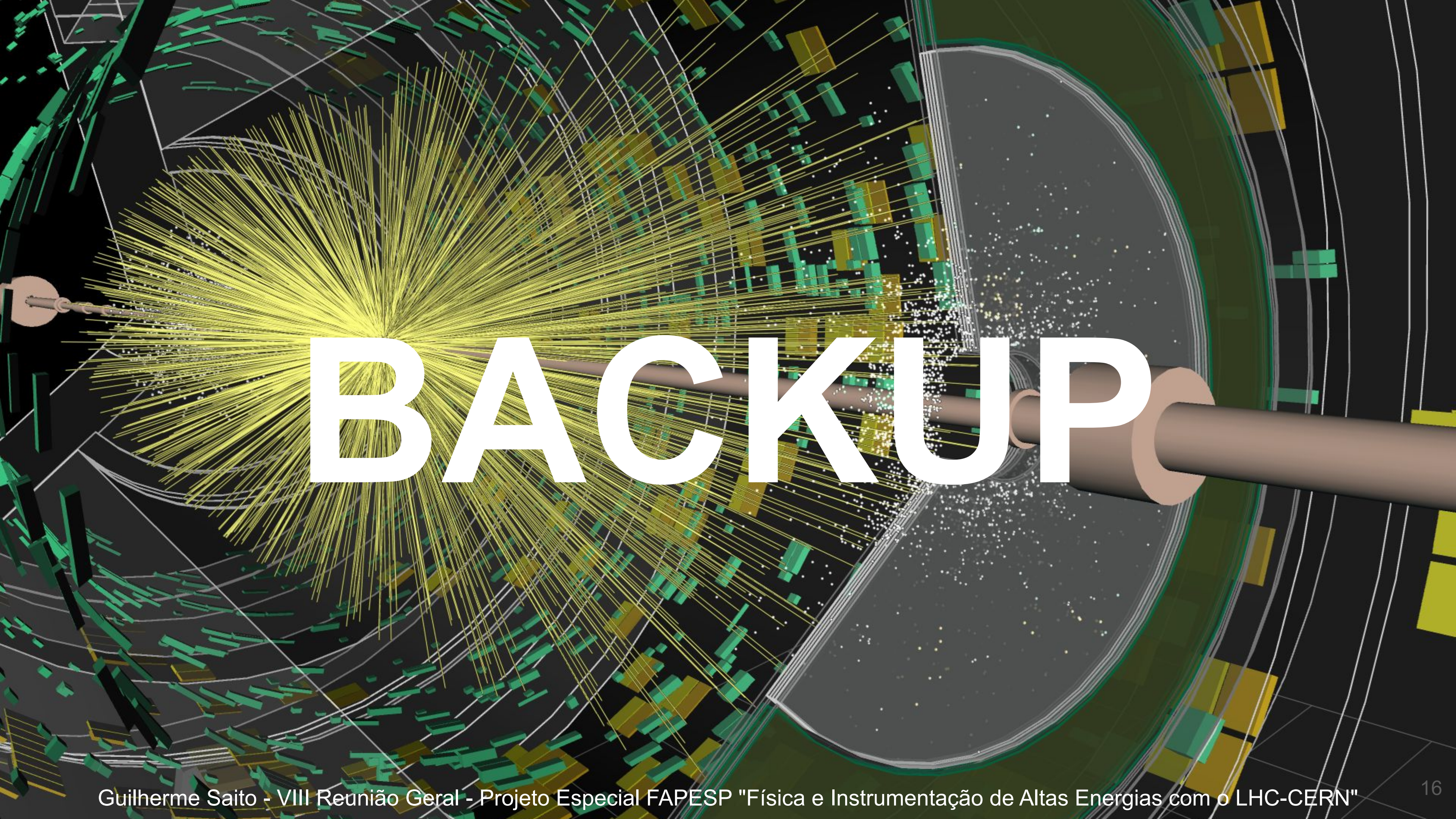




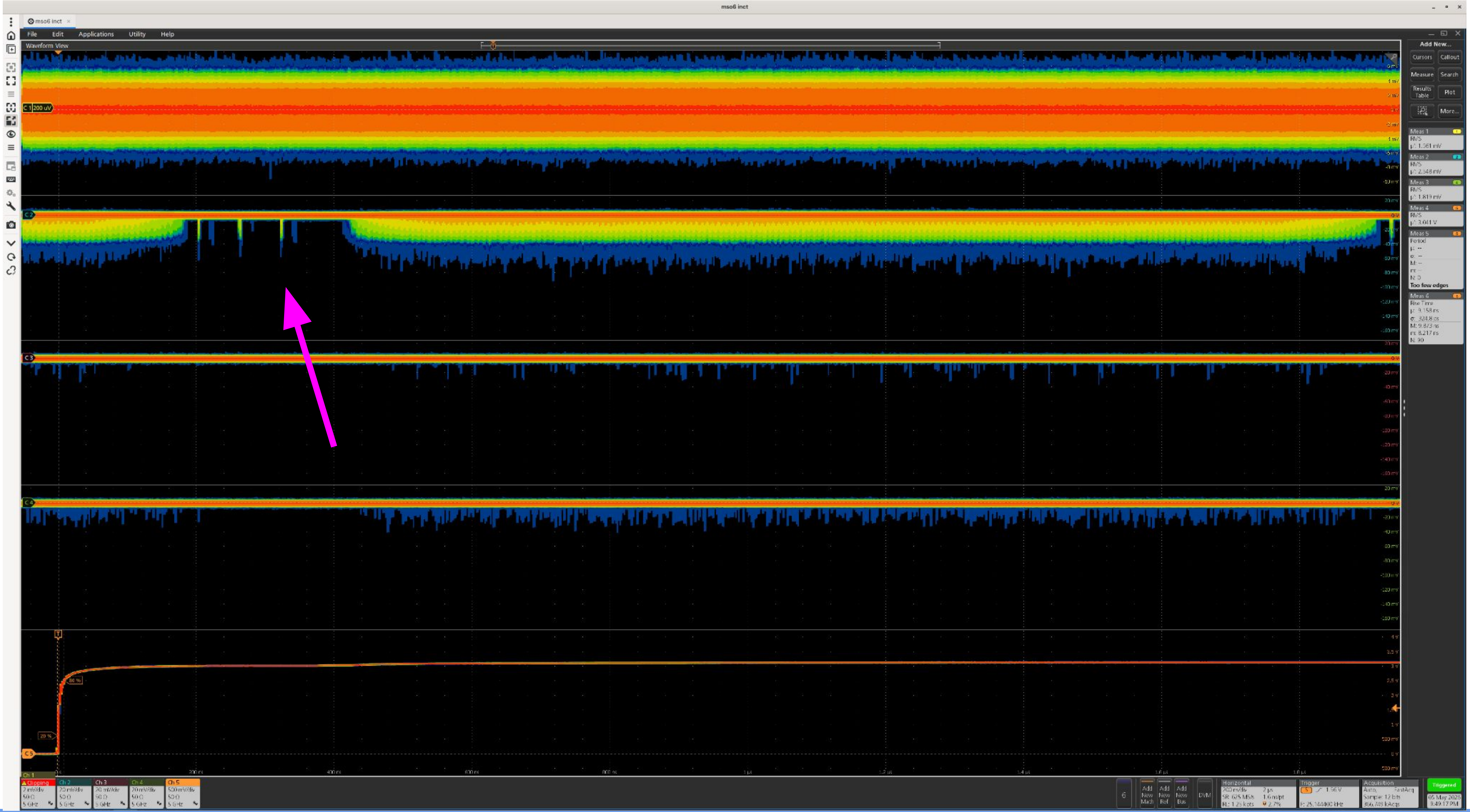
Summary

- Work on ATLAS HGTD Sensor development and qualification presented by G. Saito
  - 2025 IEEE NSS MIC RTSD, 5 November 2025 - Yokohoma, Japan
  - Short paper already published
- Dedicated USP+CERN full paper on wafer production quality control on internal review with HGTD collaboration
- All production testing procedures are being performed at IHEP, CERN, USP and JSI
- **Production is under way!**
  - On 3rd delivery
  - Almost 6000 good sensors already delivered (2/5 of total)

- Work on LGADs for Synchrotron X-ray applications presented by M. Leite
  - 4th Hiroshima Symposium on the Development and Application of Semiconductor Tracking Detectors - 16 November 2025, Taiwan
  - Proceedings on review with journal
- New beam testing campaign on October 2025 and May 2026 @ Sirius with HPK, FBK and IHEP sensors
  - Data still being analysed
- FAPESP SPRINT USP + IHEP ongoing



BACKUP



Meas 1
RMS
µ: 1.361 mV

Meas 2
RMS
µ: 2.348 mV

Meas 3
RMS
µ: 1.819 mV

Meas 4
RMS
µ: 3.041 V

Meas 5
Period
µ: --
σ: --
M: --
m: --
N: 0
Too few edges

Meas 6
Rise Time
µ: 9.158 ns
σ: 324.8 ps
M: 9.873 ns
m: 8.217 ns
N: 90

Ch 1
Clipping
2 mV/div
50 Ω
5 GHz

Ch 2
20 mV/div
50 Ω
5 GHz

Ch 3
20 mV/div
50 Ω
5 GHz

Ch 4
20 mV/div
50 Ω
5 GHz

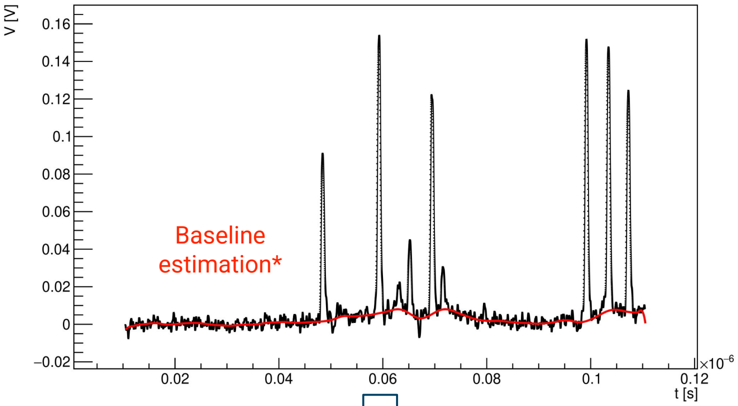
Ch 5
500 mV/div
50 Ω
5 GHz

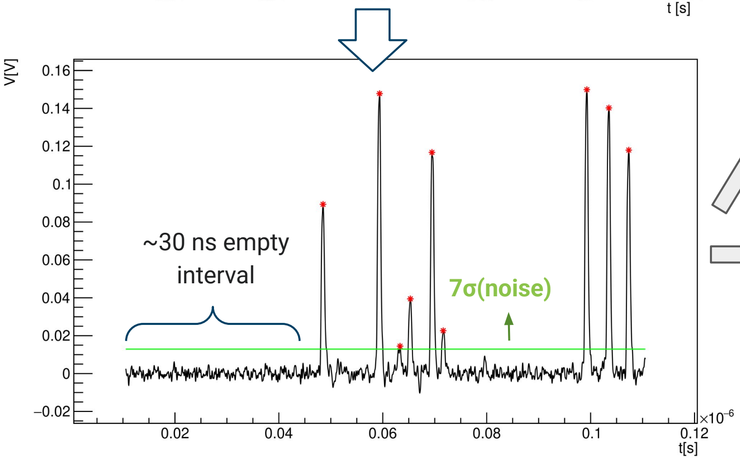
Horizontal
200 ns/div 2 µs
SR: 625 MS/s 1.6 ns/pt
RL: 1.25 kpts 2.7%

Trigger
5 1.56 V
F: 25.144400 kHz

Acquisition
Auto, FastAcq
Sample: 12 bits
366,749 kAcqs

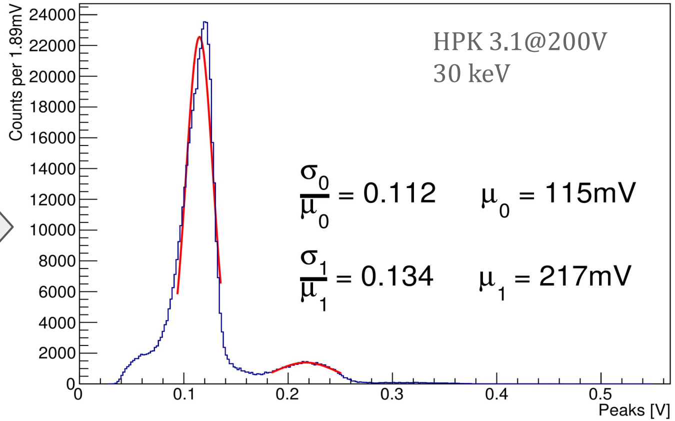
05 May 2025
9:49:17 PM





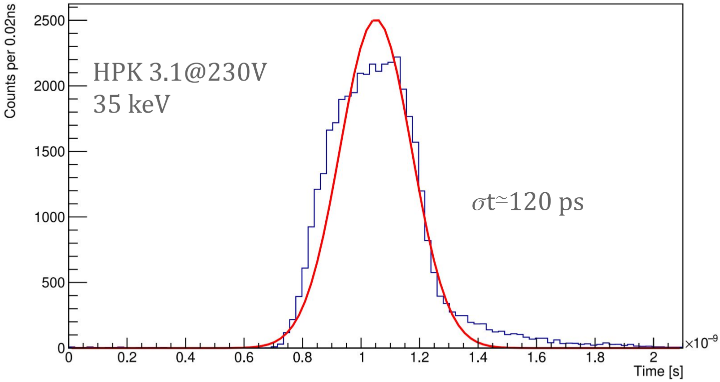
Energy

σE/E from Amplitude distribution



Timing

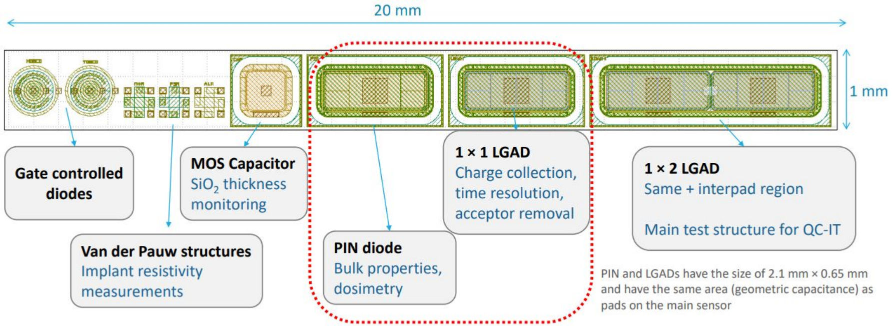
σt based on 2.1 ns interval (20% CFD)



III - New Devices

- ATLAS HGTD IHEP-IME QCTS structure with carbon-enriched "standard" DC-LGADs (and PiN)

- FBK TI-LGAD sensor from RD50 production, test structures 2x1 (*Paternoster et al*)



20 mm

1 mm

Gate controlled diodes

MOS Capacitor
SiO_2 thickness monitoring

1 × 1 LGAD
Charge collection, time resolution, acceptor removal

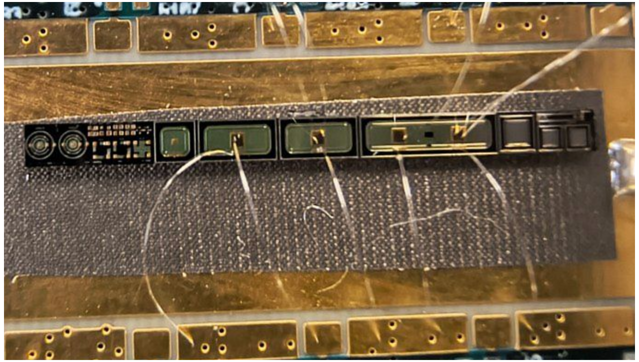
1 × 2 LGAD
Same + interpad region

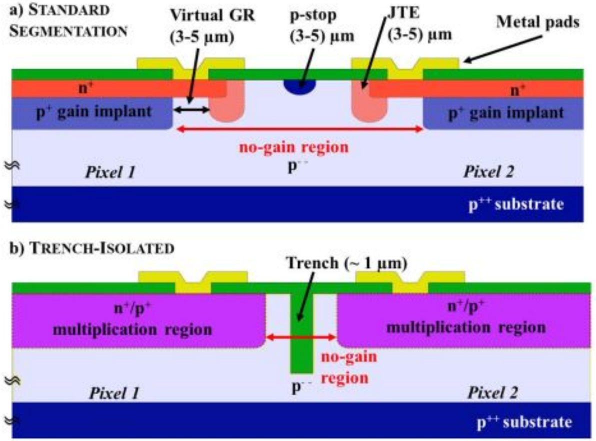
Main test structure for QC-IT

Van der Pauw structures
Implant resistivity measurements

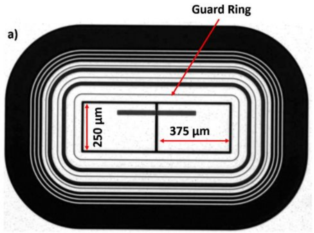
PIN diode
Bulk properties, dosimetry

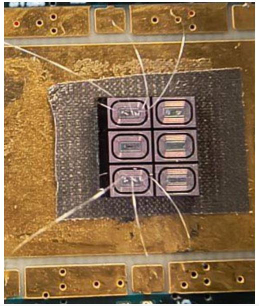
PIN and LGADs have the size of 2.1 mm × 0.65 mm and have the same area (geometric capacitance) as pads on the main sensor





Paternoster et al

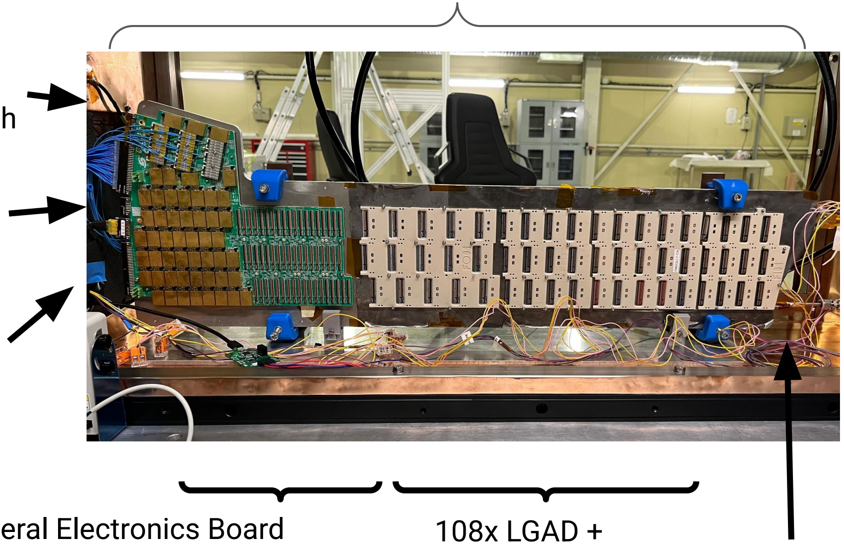




USP Activities at CERN

HGTD Demonstrator

- Exercise module loading and mechanical assembly
- Verify thermal runaway situations
- Full Readout chain



1/160 of whole HGTD

9x transceivers
10.24 Gbps each

High Voltage
for LGADs

Low Voltage
for Electronics

Peripheral Electronics Board
Power + Readout
22 layers

108x LGAD +
ASIC Modules

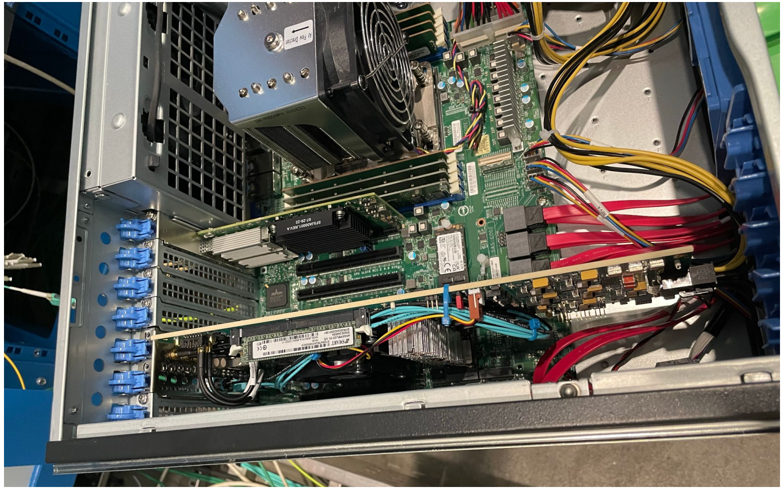
Triple Point
CO_2 Cooling

HGTD Readout

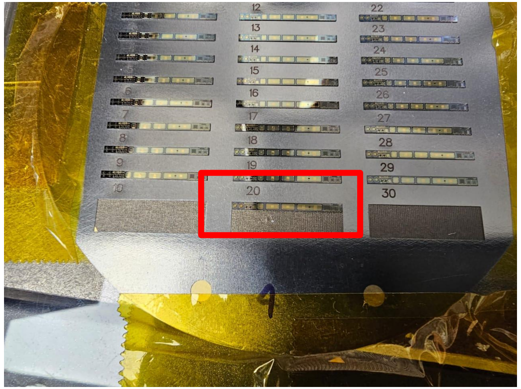
FELIX:

- ATLAS Data Acquisition System
- Custom 24 layer PCB
- 48x 10.24Gbps links

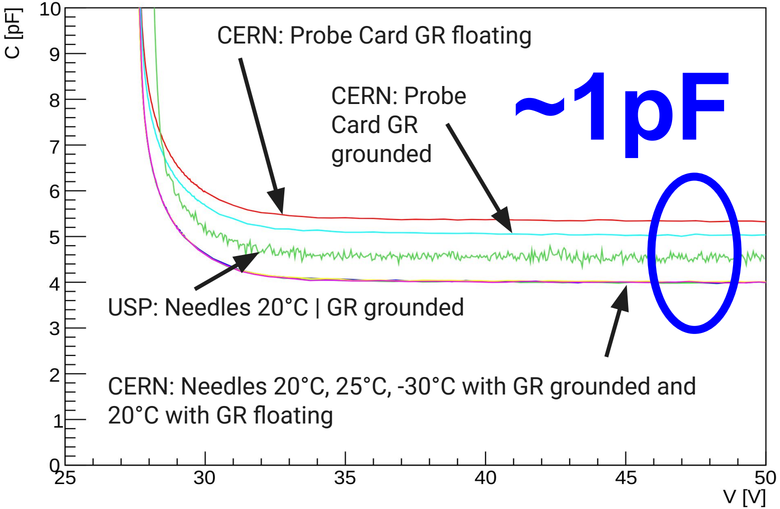
System being replicated @USP



Systematics between USP - CERN



Same device measured @CERN and @USP



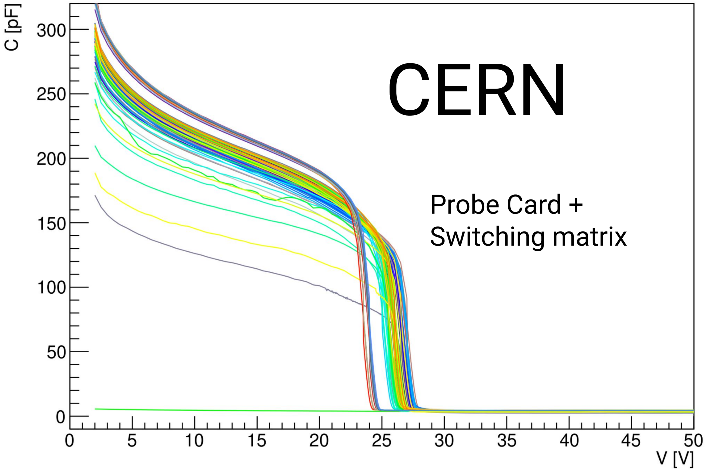
CERN: Probe Card GR floating

CERN: Probe Card GR grounded

~1pF

USP: Needles 20°C | GR grounded

CERN: Needles 20°C, 25°C, -30°C with GR grounded and 20°C with GR floating

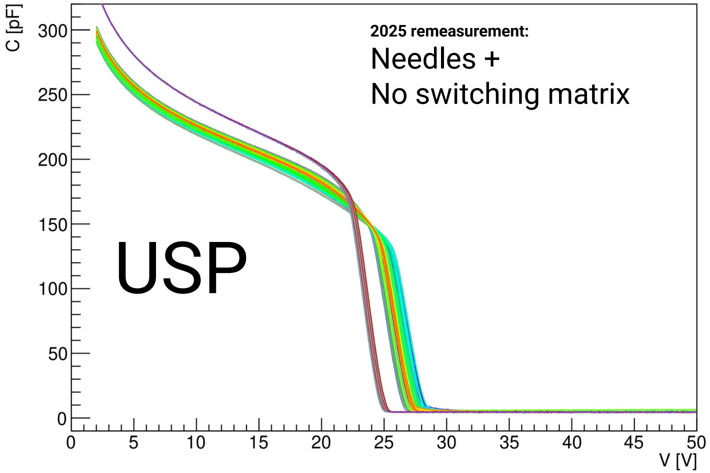


CERN

Probe Card +
Switching matrix

Different devices

Same wafers

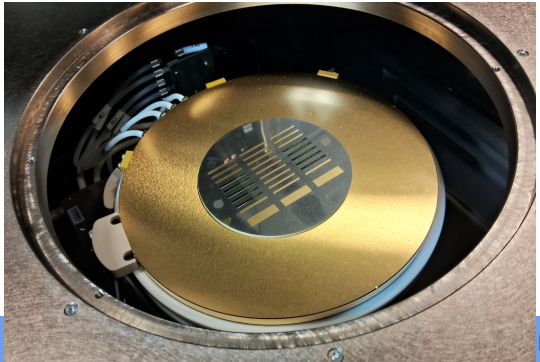


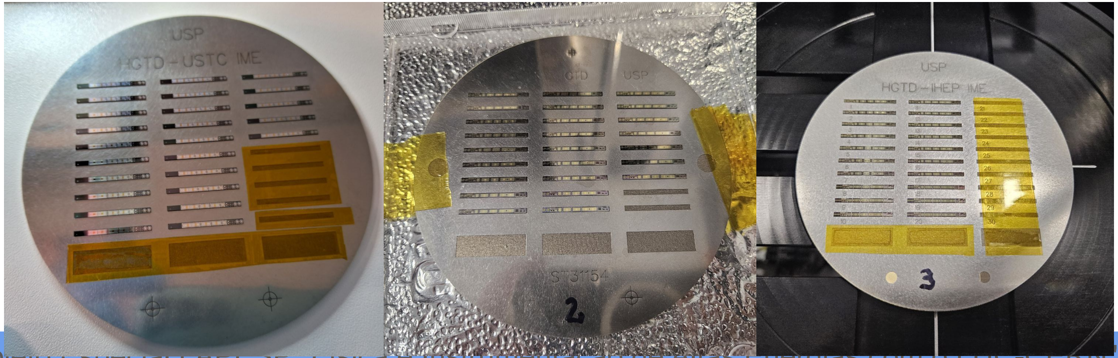
2025 remeasurement:
Needles +
No switching matrix

USP

USP Setup Status

- ➔ USP constructed a new facility for the HGTD Sensors PQC
- ➔ Probe Station MPI TS2000-HP
  - ◆ Same as CERN
  - ◆ No temperature control, but capable of operation up to 10kV
  - ◆ Installed and Commissioned
- ➔ Already measured 120 test structures from 24 pre-production wafers for HGTD
- ➔ HGTD sensors production **first delivery now**



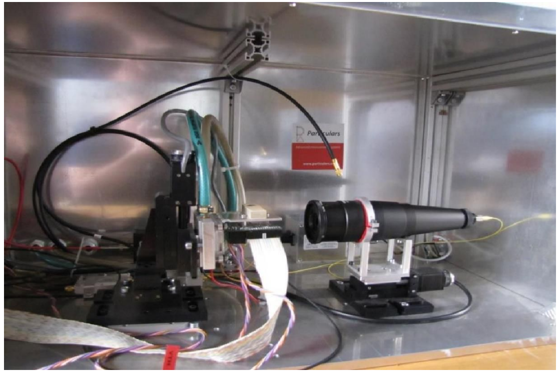


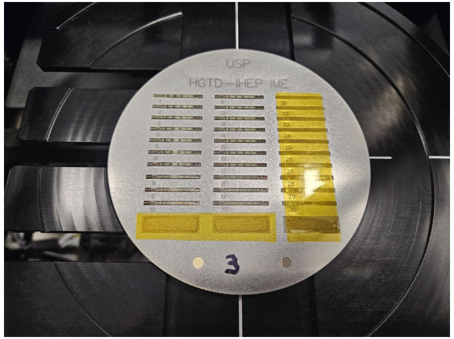
Sensor and Wafer Quality Control

Probe Station setup at USP

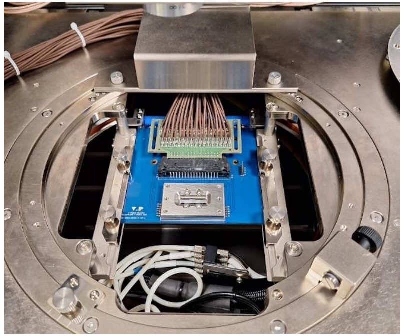
Probe Station setup at CERN

TCT Laser setup at JSI





Many QC-TS loaded on
Probe Station



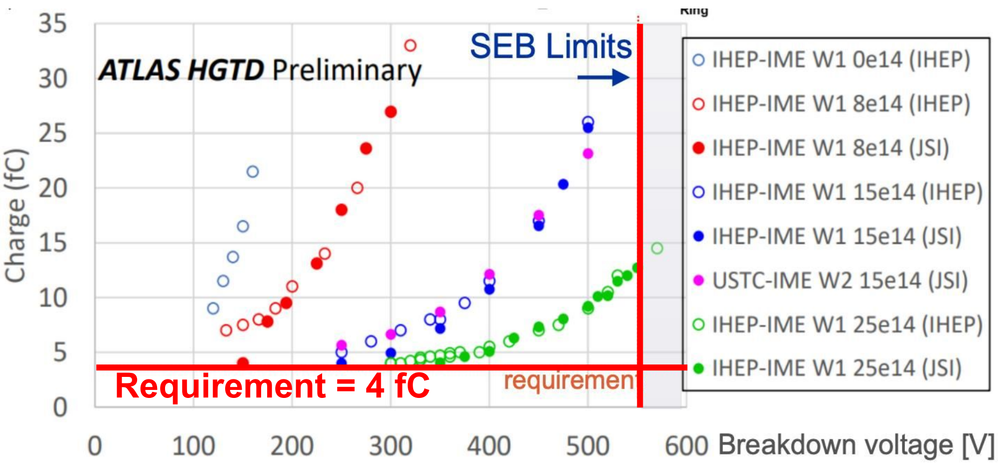
QC-TS Probe Card

Performance

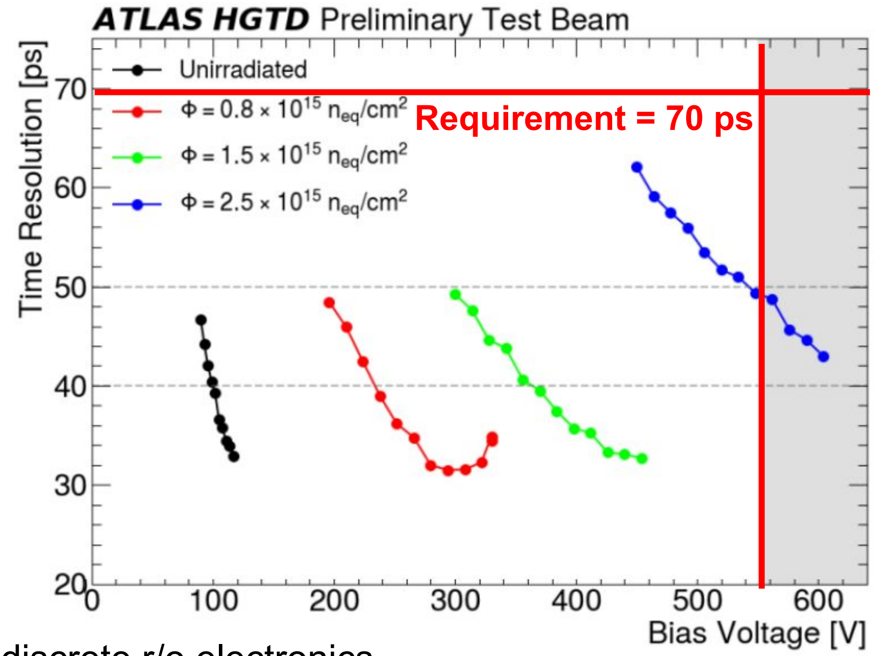
LGAD performance **degrades with radiation** exposure due to a loss of gain

- ➔ Radiation induced **removal of Boron** from gain layer
  - ➔ Improved by **addition of Carbon** on gain layer
- ➔ Recovered by **increasing the bias** during operation
- ➔ **Limit imposed** by *Single Event Burnout* (SEB)
  - ➔ Safe operation <550V (more on backup slides)

LGAD Signal vs. Bias Voltage

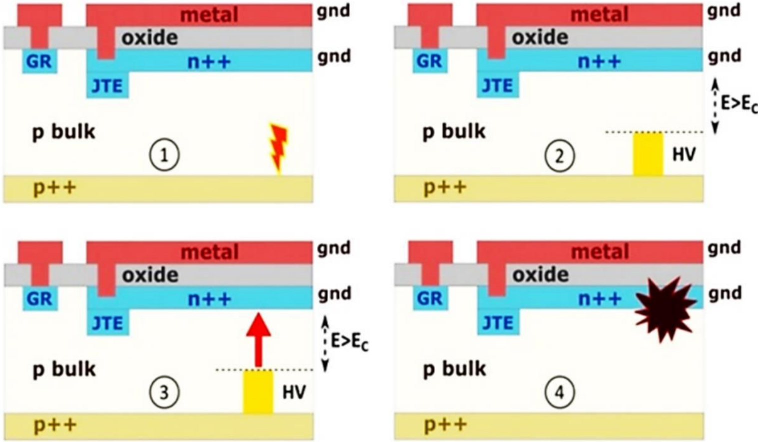


LGAD Time Resolution vs. Bias Voltage



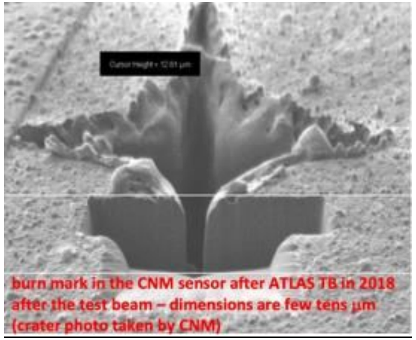
Both measured with discrete r/o electronics

Single Event Burnout (SEB)



- ➔ **Irreversible breakdown** triggered by a large charge deposition at high operation voltages
- ➔ Triggered by a single particle
- ➔ Large energy deposits: **electric field collapse** in presence of high concentration of free carriers
- ➔ Observed in several test beam campaigns
- ➔ Common effort of ATLAS/CMS/RD50 collaborations: determine a safe operating voltage
- ➔ Systematically studied at HGTD test beams
- ➔ **Safe operating zone: 11V/µm**

For 50µm sensor thickness:
Maximum safe bias voltage = 550V



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)