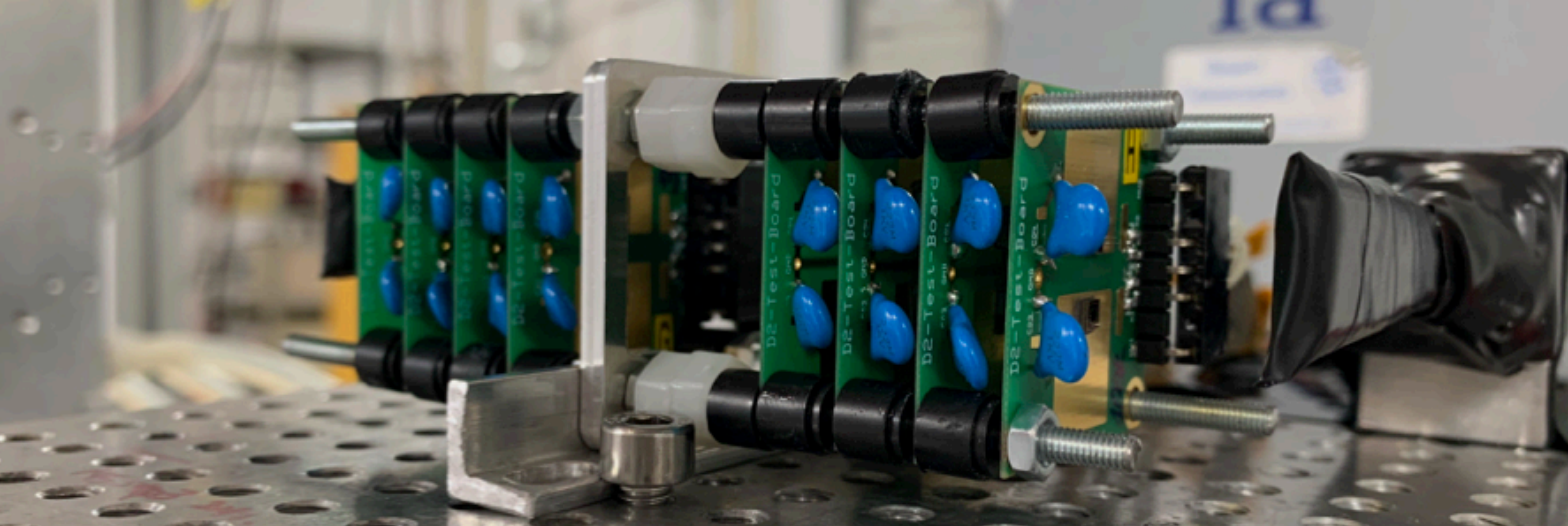


The ATLAS High-Granularity Timing Detector:

test beam campaigns and results

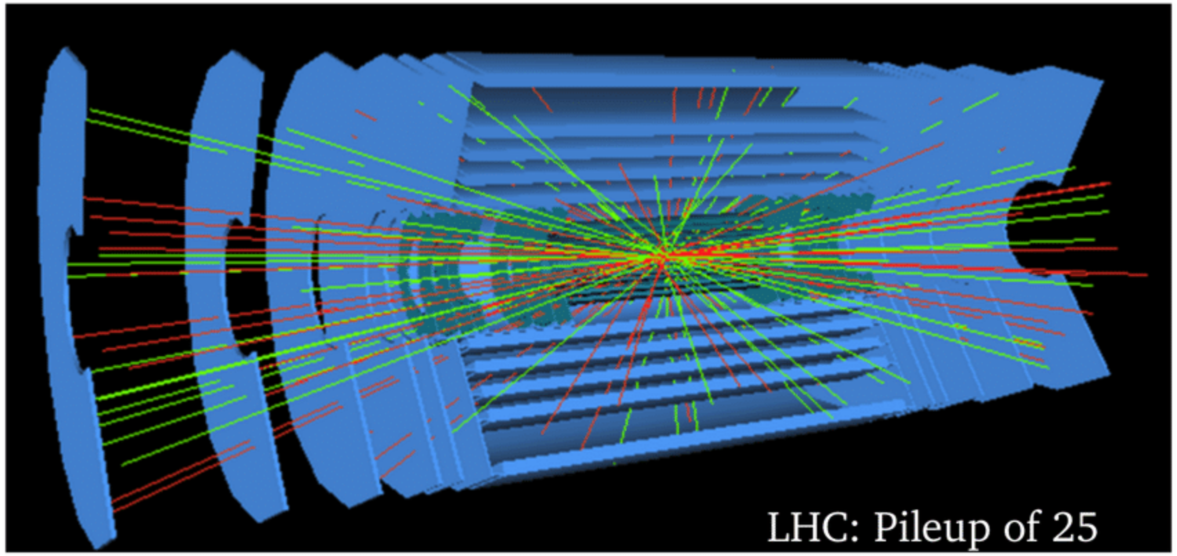
10th Beam Telescopes and Test Beams Workshop
June 2022, Lecce

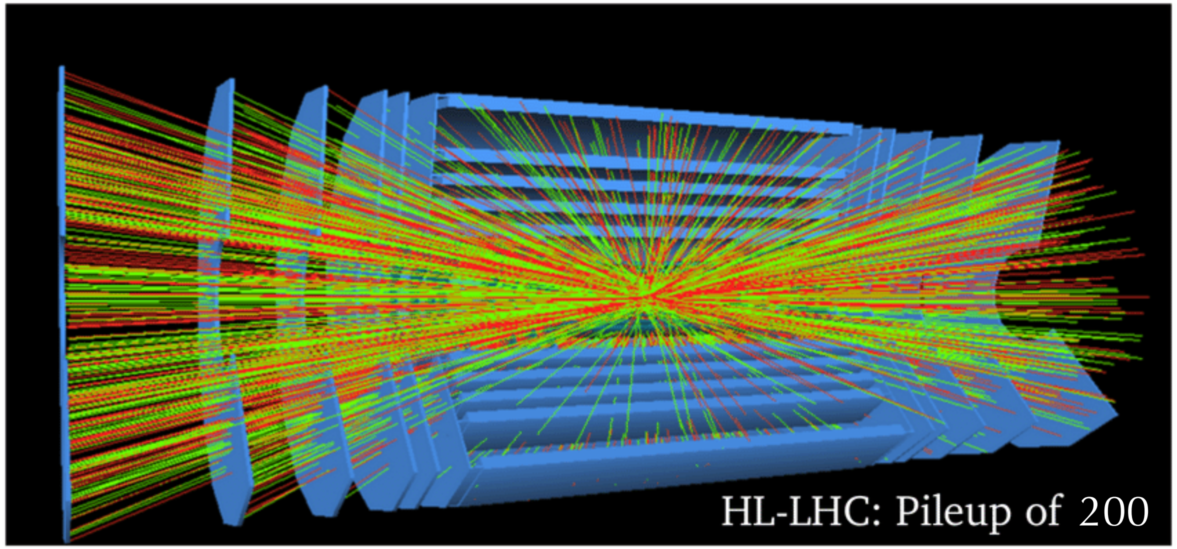
Dr. Louie Dartmoor Corpe (CERN) on behalf of the ATLAS HGTD Group

The HL-LHC: challenges and opportunities

- From ~2029, LHC will operate in **"high luminosity"** mode
- Collisions will occur with **~5x higher intensity than at present**
- This will allow us to collect ~**x10 more data than Run3** in the long term...
- But with ~**10x more interactions per proton bunch crossing**
- *Pileup* of ~200 vertices per interaction !
- Track reconstruction: complexity increases **exponentially or worse with pileup**

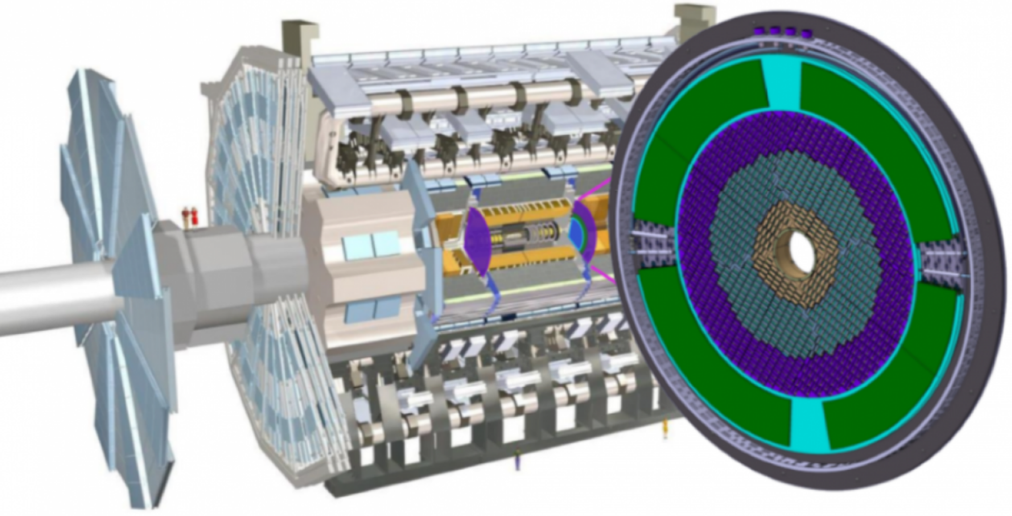
- **<u>How can ATLAS do physics in these conditions?</u>**





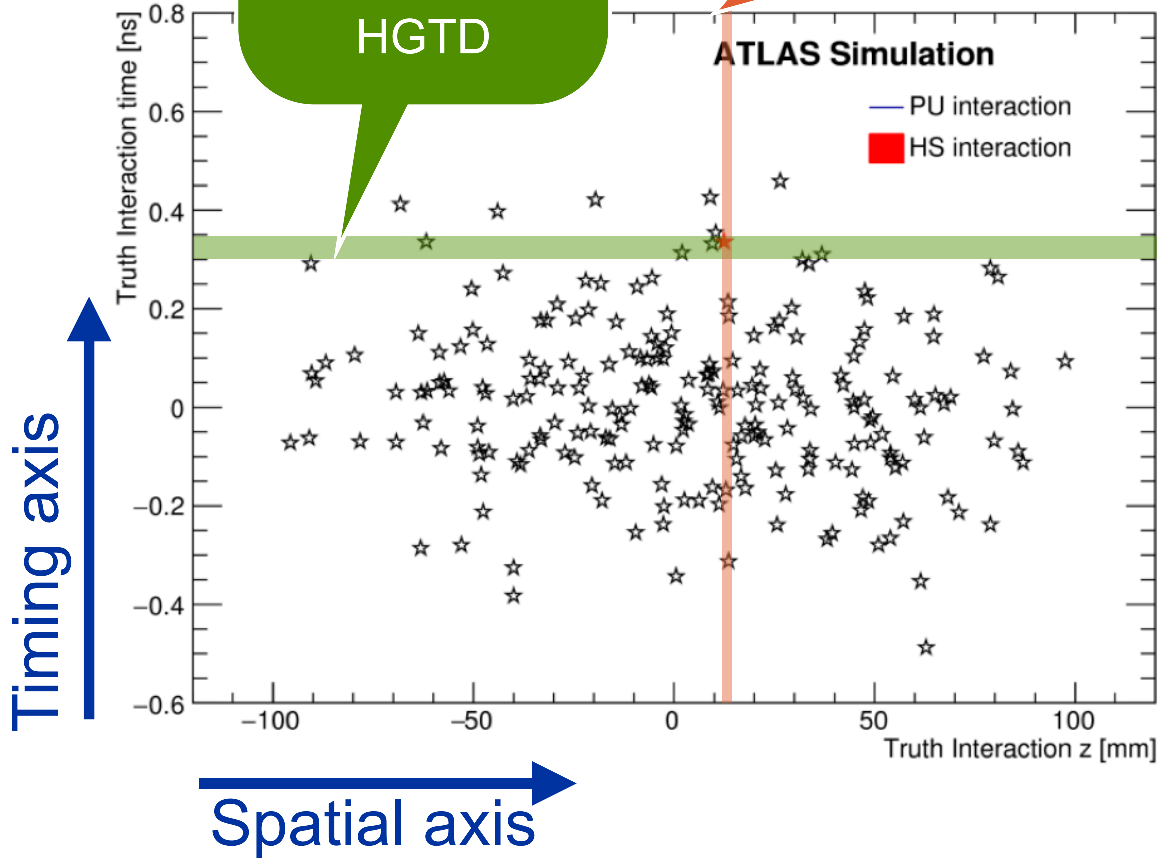
Exploiting the 4th dimension: time

- Additional vertices resolved using **timing information!**
- Solution: a new sub-detector with extremely precise time resolution
- Enter the High-Granularity Timing Detector (HGTD): **resolution ~40ps**!



Possible ITk position resolution in forward region, ~2mm for soft particles

Expected time resolution of HGTD

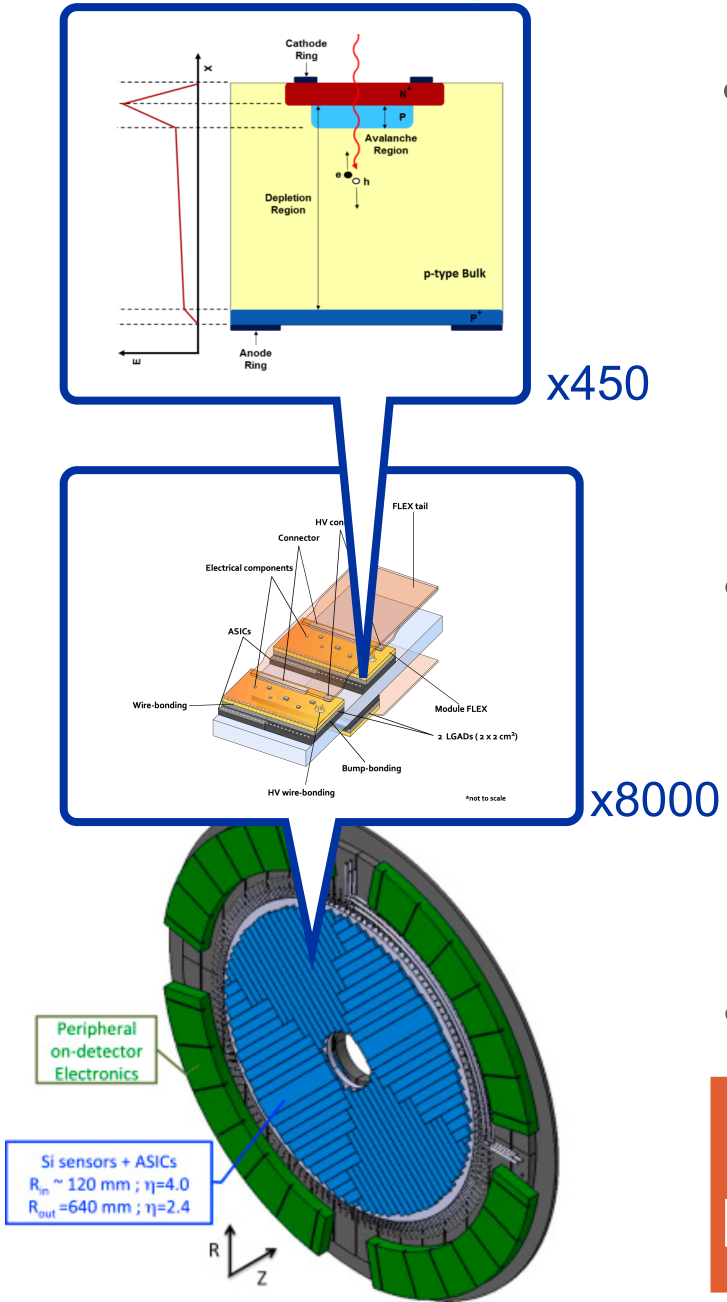


Using both spatial and timing information, will be able to **unambiguously associate tracks to vertices** in the forward region

Exploiting new technologies for HGTD

- **Low-Gain Avalanche Detector (LGAD)**
  - **Radiation-hard** + **Excellent timing resolution**
  - **Design specifications:** Most probable value of 4fC collected charge, <70ps time resolution and >95% efficiency at irradiation of $2.5 \times 10^{15}\ n_{eq}/cm^2$

Exploiting new technologies for HGTD



- **Low-Gain Avalanche Detector (LGAD)**
  - **Radiation-hard** + **Excellent timing resolution**
  - **Design specifications:** Most probable value of 4fC collected charge, <70ps time resolution and >95% efficiency at irradiation of $2.5 \times 10^{15}\ n_{eq}/cm^2$

- **ALTIROC**: readout using ASIC integrated circuits
  - ASIC time resolution ~25ps, minimum threshold 2fC
  - Reading 15x15 = 225 LGAD channels
  - 2 ASICs + 2 LGAD arrays = 1 module
  - HGTD = 2 x ~4000 modules
- HGTD design constrained by available space

Impact on pileup rejections, track/jet reconstruction, b-tagging... critical to success of ATLAS programme

HGTD milestones and testbeam objectives

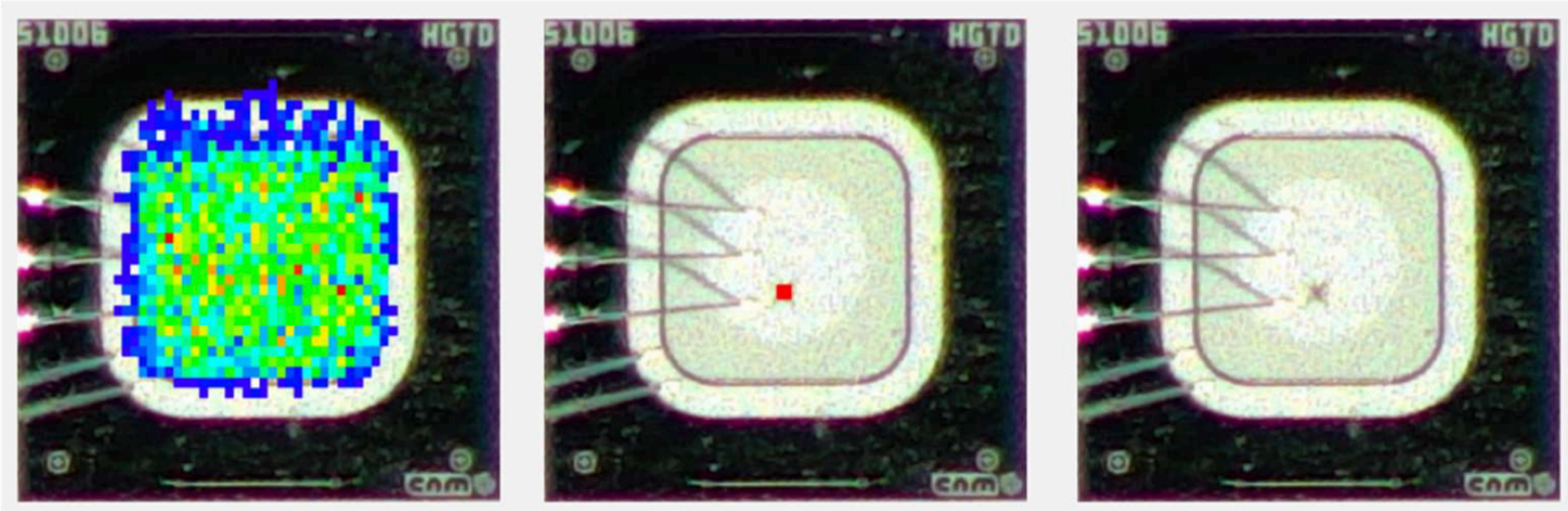
- In past year, the main objectives of the HGTD testbeam campaigns have been to work towards our **sensor Final Design Review** (FDR)

- In other words, two main objectives:
  - **Qualify sensor performance** (timing resolution, efficiency, collected charge) from different manufacturers
  - Determine **safe bias voltages** to avoid "single event burnout" (SEB) (see next slide)

- Objectives reached over **4 testbeam campaigns** in 2021 and early 2022:
  - SEB studies at DESY in June 2021 and SPS in November 2021 (no telescope)
  - SEB + performance studies at SPS in July-Nov 2021 using MALTA telescope
  - Sensor performance studies at DESY in March 2022 using DATURA telescope

SEB: what is it and why do we care?

- **"Single Event Burnout"** destructive **breakdown of irradiated LGAD** at high voltages, seen by CMS/ATLAS/RD50 teams



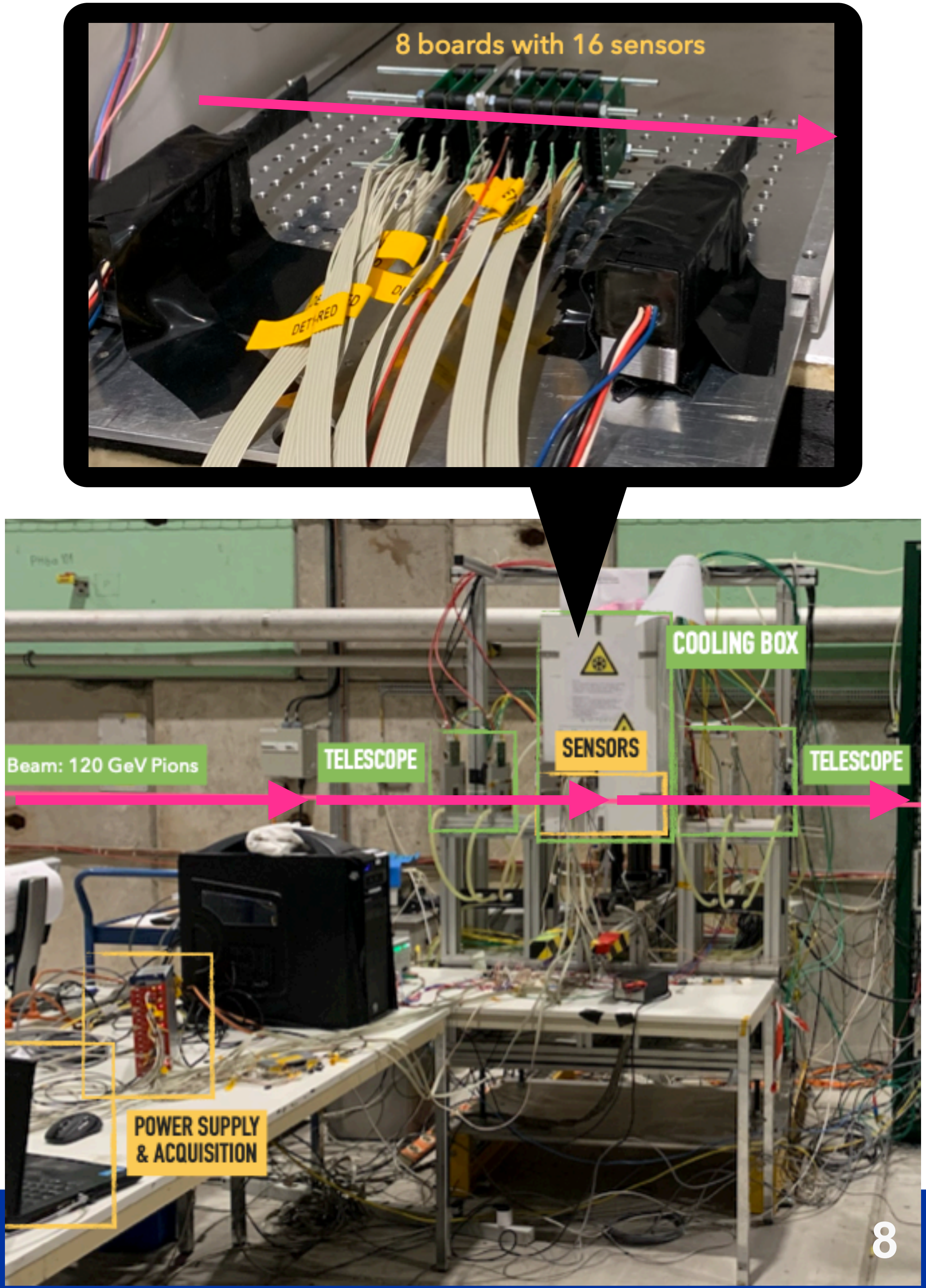
- Usually triggered by single particle: visual **"crater"** on device, and complete **irrecoverable failure**
- Likely a **effect of rare large energy deposits:** Electric field (V/thickness) is key parameter determining the fatality. E field collapse in present of high concentration of free carriers. See here for more information and details.
- Implication for HGTD: **ensure sensors can be operated** at biases reaching design specs **without risk of SEB**

SEB testbeam setup

- Several testbeam campaigns dedicated to:
  - Gain **more information on SEB** mechanism
  - Check candidate **sensors are safe from SEB** at biases meeting HGTD specifications

- Experimental setup (DESY and SPS):
  - Mount **16 sensors on 8-board train** at a time
  - High voltage: **CAEN N472** Power Supply
  - Readout: 3 **NI-USB 6001**

- Procedure: expose irradiated sensors to beam, keeping track of rate, at **8h per bias point**. Increase bias until SEBs occur, check if above **required voltage for 4fC collected charge**



SEB testbeam results

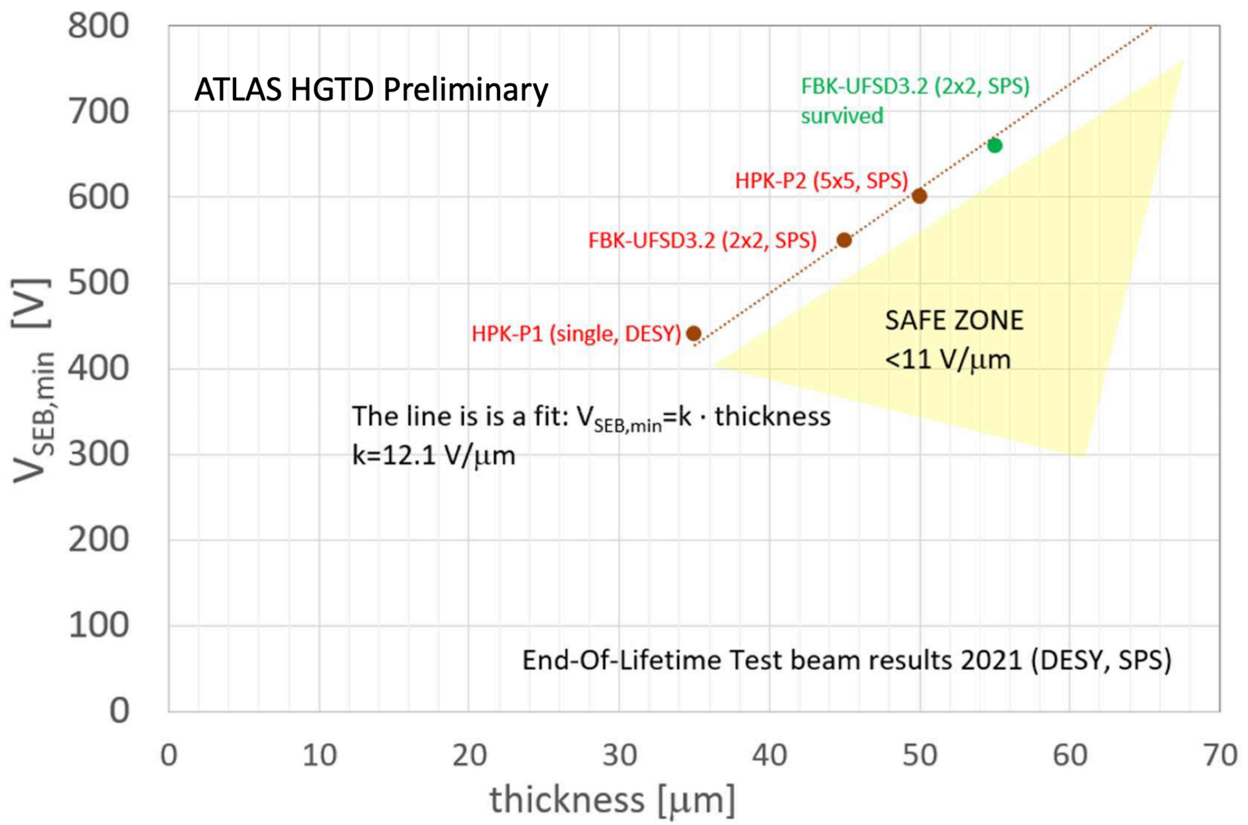
- Can determine SEB prob: scale particle rate measured from scintillator in beam to sensor size. SEB probability studies conducted during two campaigns:

- **DESY in June 2021 (6 GeV electrons)**
  - 32 sensors tested, **24 survived to voltages expected to meet HGTD specs**
  - **SEB probability ~ 10^{-6} to ~10^{-5}** depending on irradiation, for ~12V/μm
  - Agrees with results from GEANT

- **SPS in November 2021** (120 GeV pions)
  - 42 sensors tested, **31 survived to voltages expected to meet HGTD specs**
  - **More recent sensors than at DESY testbeam**
  - >100k pions per bias point (**10^6 to 10^7 particles / mm^2 per per exposure**)
  - **SEB probability typically below 10^{-5}**, often much less for latest sensors

SEB testbeam: results

- DESY and SPS studies confirmed:
  - For many sensors, **SEB issue occurs only above required operational bias voltage** for the 4fC collected charge target, even after irradiation
  - For many of the more **modern sensors, SEB did not occur** even high above the required bias
  - There is a "safe zone" at <11V/µm

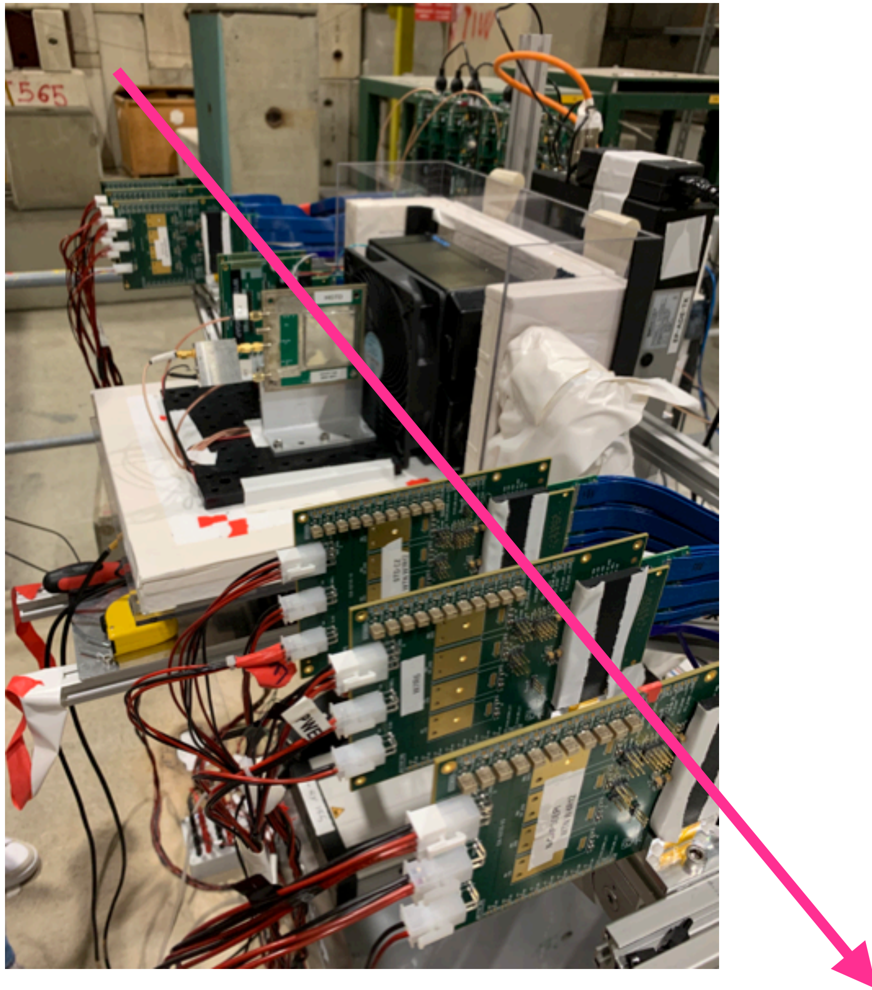


But what are the sensor performances wrt the HGTD specs in this safe zone?

Sensor performance: MALTA telescope at SPS
(more info: JINST 15 P02005 2020 or this talk)

- **MALTA monolithic CMOS sensor prototype produced in 180nm TowerJazz technology**

- Matrix of 512 x 512 pixels of 36.4 x 36.4 μm^2 size
  - Tracking resolution of ~5 μm (6 layers)
  - Efficiency of almost 100 %
  - Also take high intensity beams *(unlike MIMOSA)*



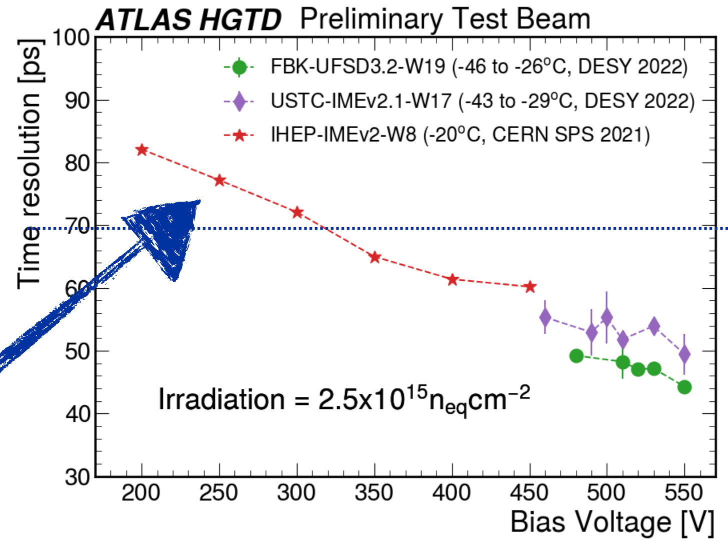
At SPS: permanent parasitic setup in H6A
- 6 Malta Planes
- Cold box with climate chamber
-Special supports made for LGAD sensors

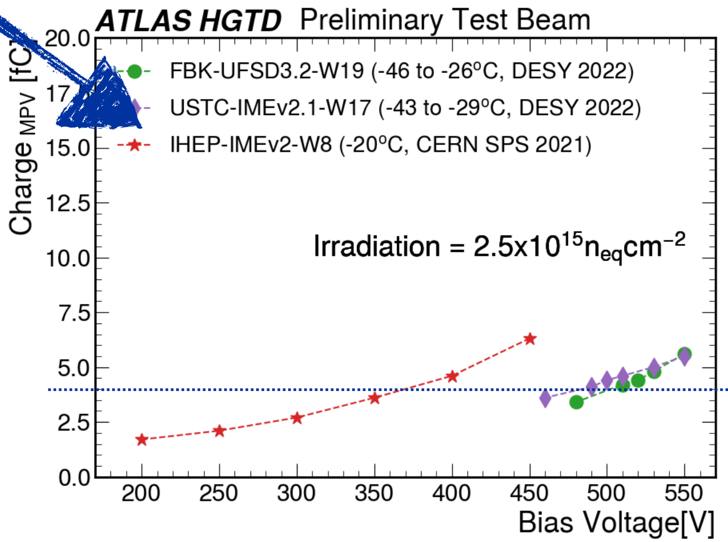
Special MALTA runs performed July-Nov 2021

SEB and sensor performance: MALTA telescope at SPS

- **HGTD MALTA testbeam:**
  - Oscilloscope to measure waveforms/collected charge
  - MALTA tracking for efficiency calculation
  - Reference LGAD (known 35ps resolution): extract time resolution
- Test **sensors of most promising varieties**
- Only **one SEB**, for non-Carbon sensor
- **Non-carbon samples** hit specs for 1.5×10^{15} n_{eq}/cm^2 at >600V
- **Carbon samples** hit specs for 2.5×10^{15} n_{eq}/cm^2 at <550V

Examples of results obtained with MALTA

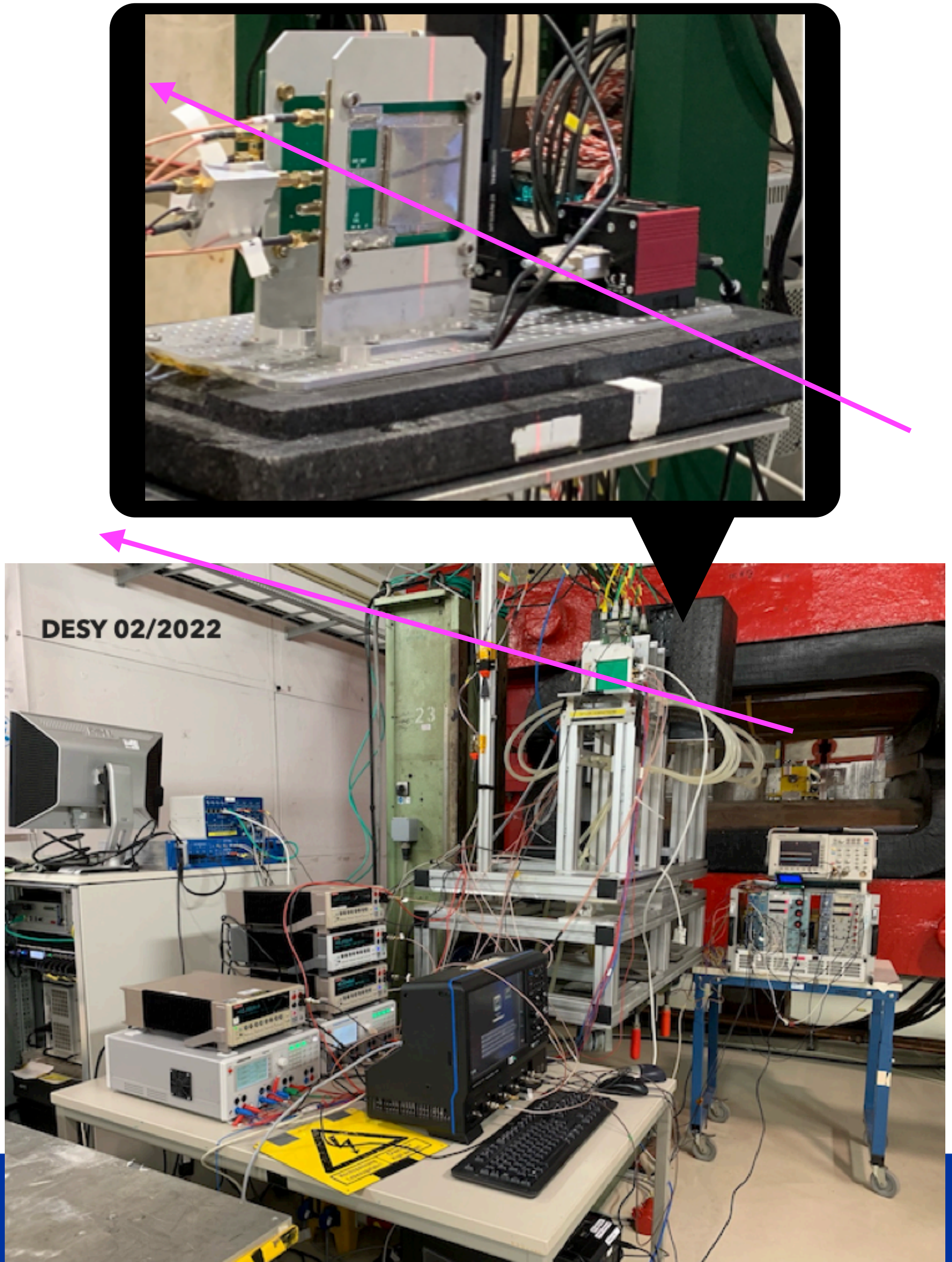




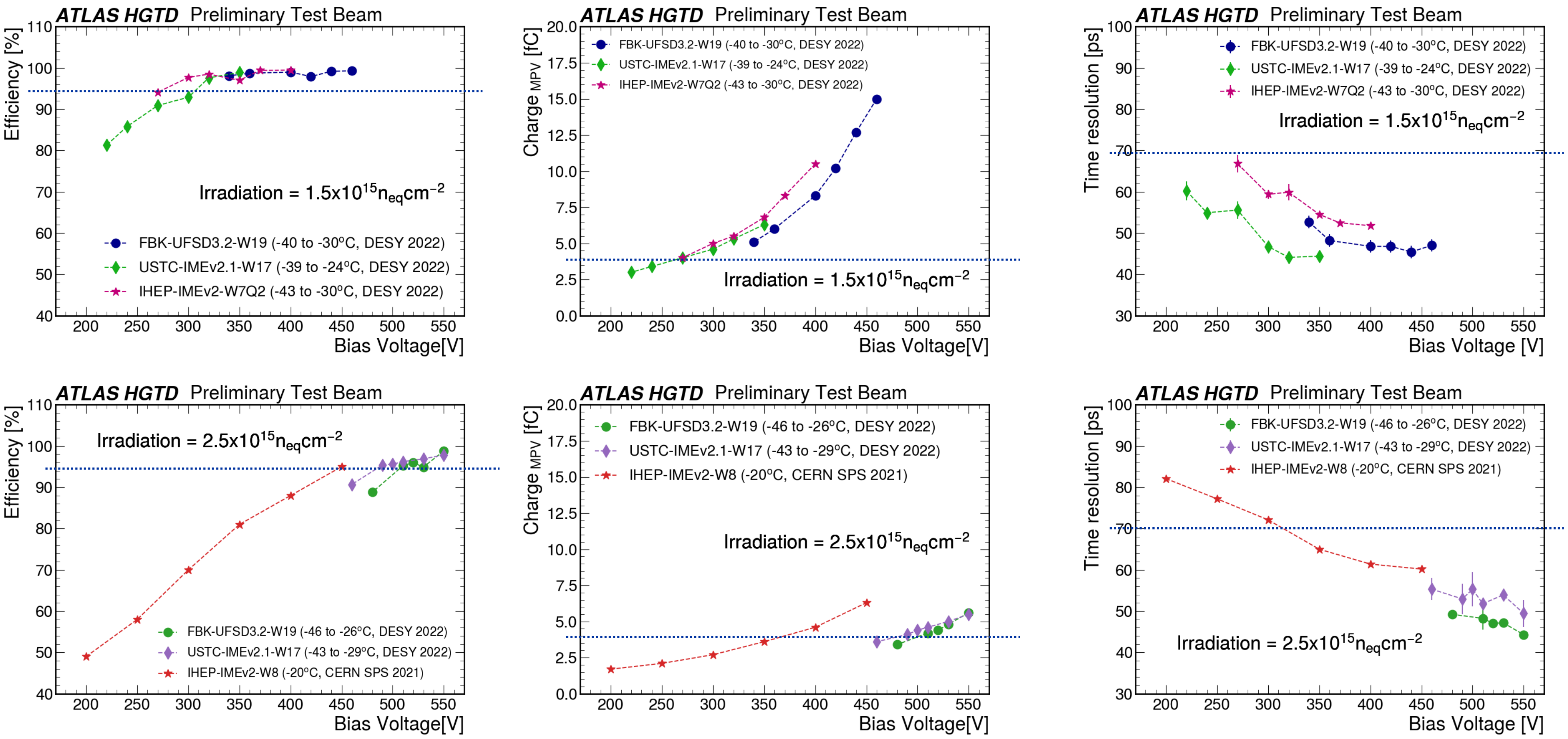
Conclusions: Recent HGTD testbeam results indicate that LGADs exist which ***can*** be operated to meet HGTD specifications while at low-enough biases to avoid SEB.

Sensor performance: DESY testbeam Mar 2022

- Use DATURA EUDET telescope with 6 MIMOSA planes for tracking
- FEi4 with MMC3 for trigger/ROI
- AIDA v1 (Bristol) TLU
- EUDAQ1 for DAQ
- WaveRunner Oscilloscope for waveform readout
- Use NIM-logic crate to count 4096 events and send busy signal to block new events during Scope readout
- Cooling provided by dry ice in cold box
- 2 DUTs per run
- Use SiPM as time reference



Sensor performance: DESY testbeam Mar 2022



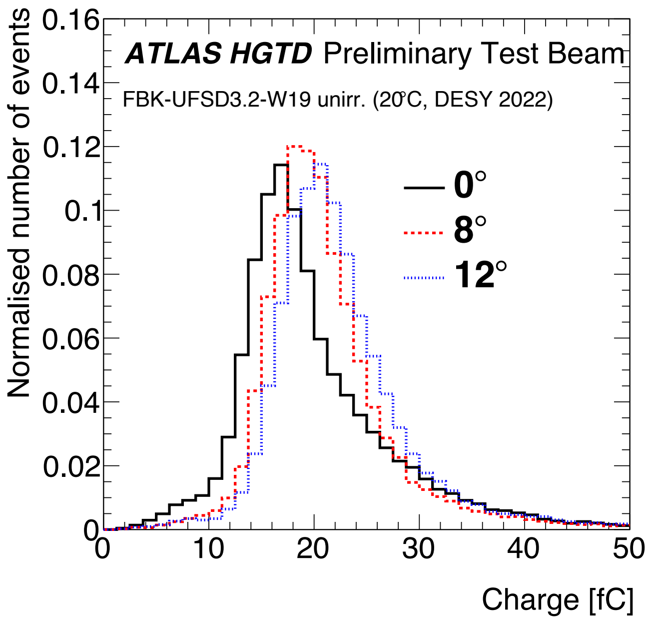
All sensors are with Carbon.

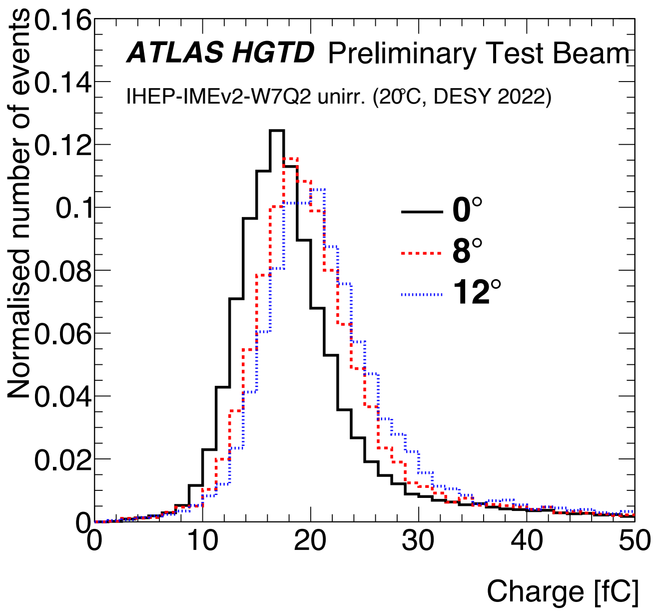
All properties calculated assuming 2fC cut.

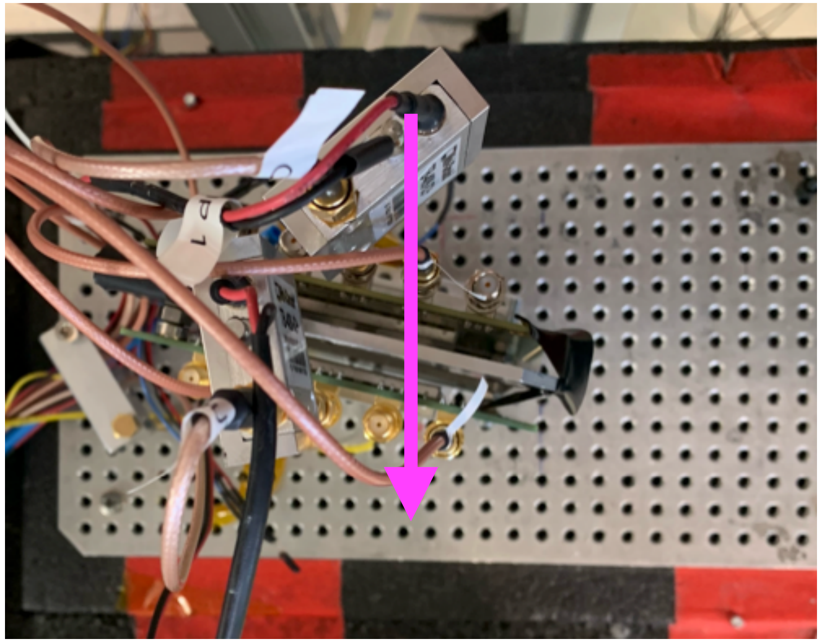
At highest biases, DUTs irradiated up to 2.5E15, have efficiency > 95%, charge > 4 fC and time resolution < 70 ps. **Meet HGTD specifications !**

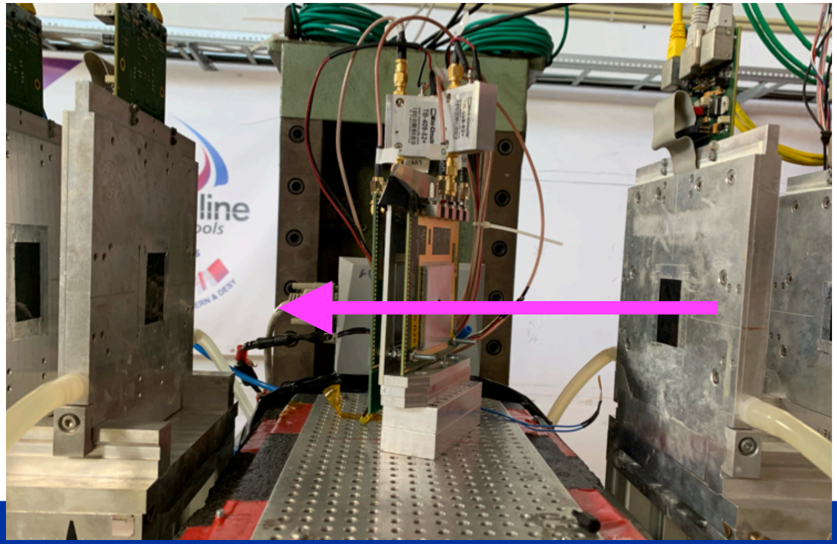
Sensor performance: DESY testbeam Mar 2022

- **Incident angle around 12°** expected in final HGTD without track curvature effects
- **Angular effects investigated** in final days of testbeam after main programme completed
  - FBKW19 and IMEv2 (IHEP) at room temp









Significant dependence of amplitude on the angle

Summary and other testbeam activities

- HGTD Sensor FDR passed in June 2022: relied on results presented today:
  - **Allayed concerns about SEB** at voltages required to meet HGTD specs
  - **Qualified performance of latest generation** of LGADS

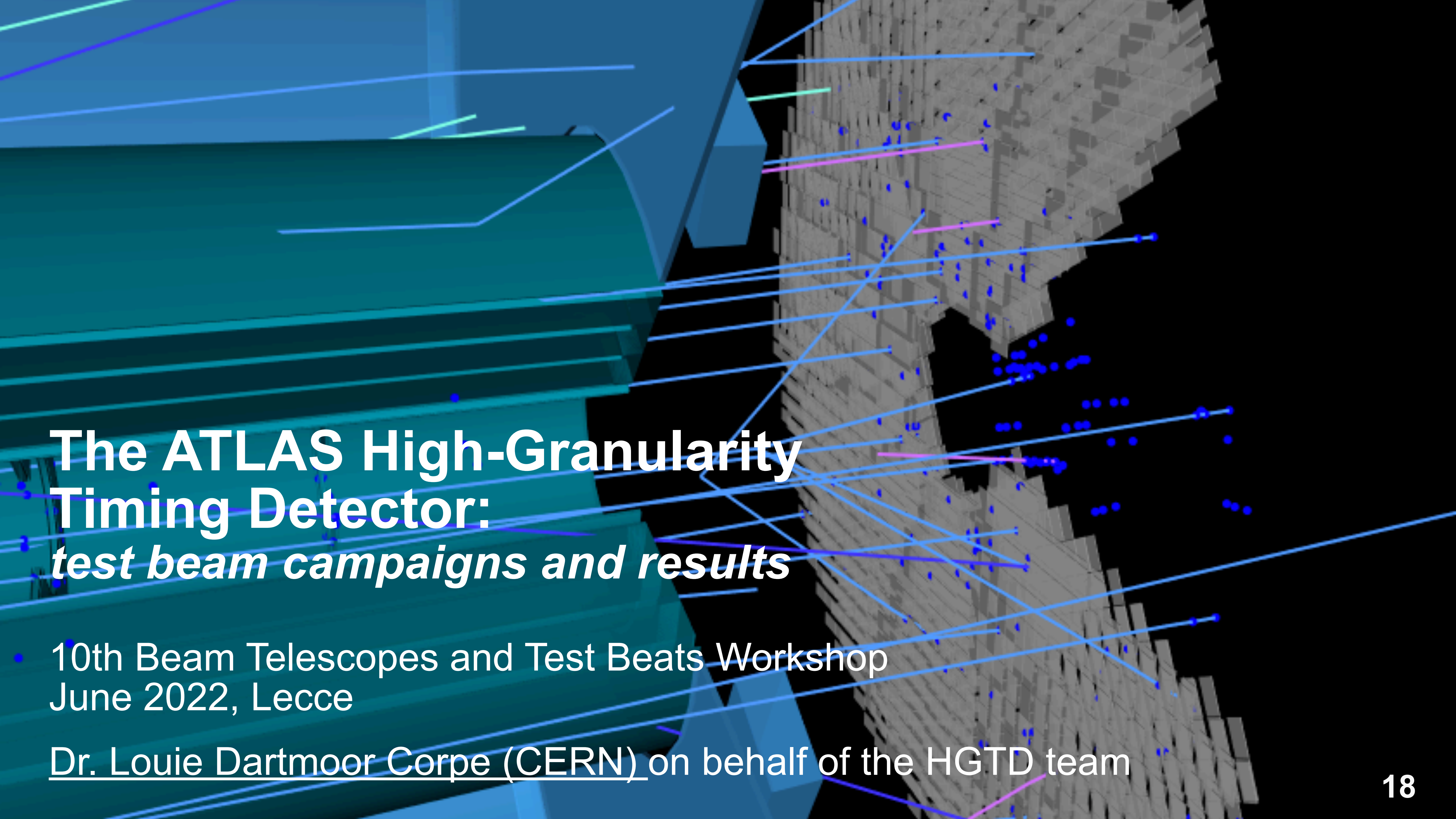
- Other ongoing testbeam work:
  - **Migration to EUDAQ2**, AIDA2 TLU
  - **Further qualification** of latest batches of sensors
  - Ongoing analysis and **tests of ASIC**: ALTIROC1.3

- In the near future:
  - Tests of **ALTIROC2 on PCB in beam (July 2022)**
  - Tests of **full detector module in beam**

Watch this space!

Thank you!

home.cern



The ATLAS High-Granularity Timing Detector:

test beam campaigns and results

- 10th Beam Telescopes and Test Beats Workshop
June 2022, Lecce

Dr. Louie Dartmoor Corpe (CERN) on behalf of the HGTD team

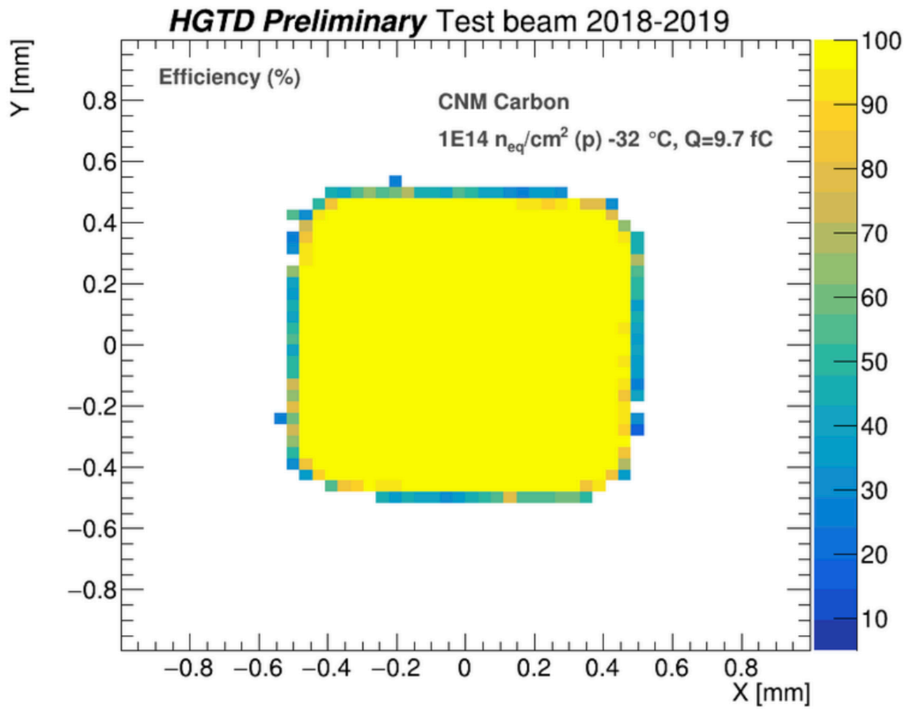
Calculation of efficiency for LGAD sensors

5.3 Hit reconstruction efficiency

The hit reconstruction efficiency is defined as the reconstructed tracks giving a signal on the sensor for which the charge in the sensor is greater than a given threshold value, Q_{cut}, divided by the total number of reconstructed tracks crossing the sensor:

$$\text{Hit Efficiency} = \frac{\text{Reconstructed tracks with } q > Q_{cut}}{\text{Total reconstructed tracks}} \quad (5.6)$$

To avoid the effect of the edge of the sensor, the global efficiency values sensor are computed in the central 0.5×0.5 mm^2 region of the DUT, representing a quarter of its surface for the CNM sensors and less than a quarter of its surface for the HPK sensors.



For further info: https://cds.cern.ch/record/2753590/files/ATL-COM-HGTD-2021-003.pdf