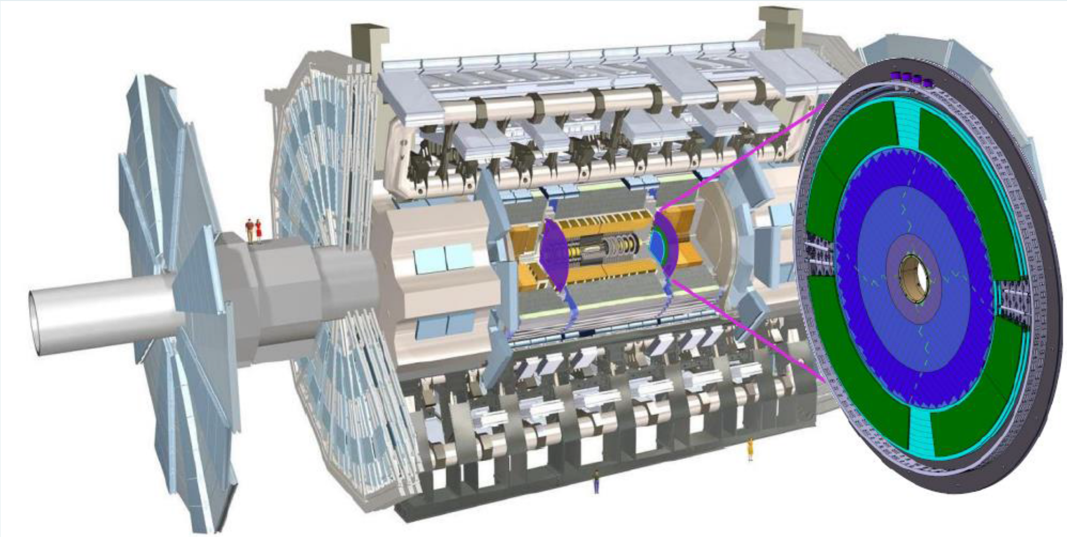


Performance of LGAD sensors for the ATLAS High-Granularity Timing Detector HGTD

Irena Nikolic, on behalf of the ATLAS High Granularity Timing Detector Group
TIPP 2021 Conference

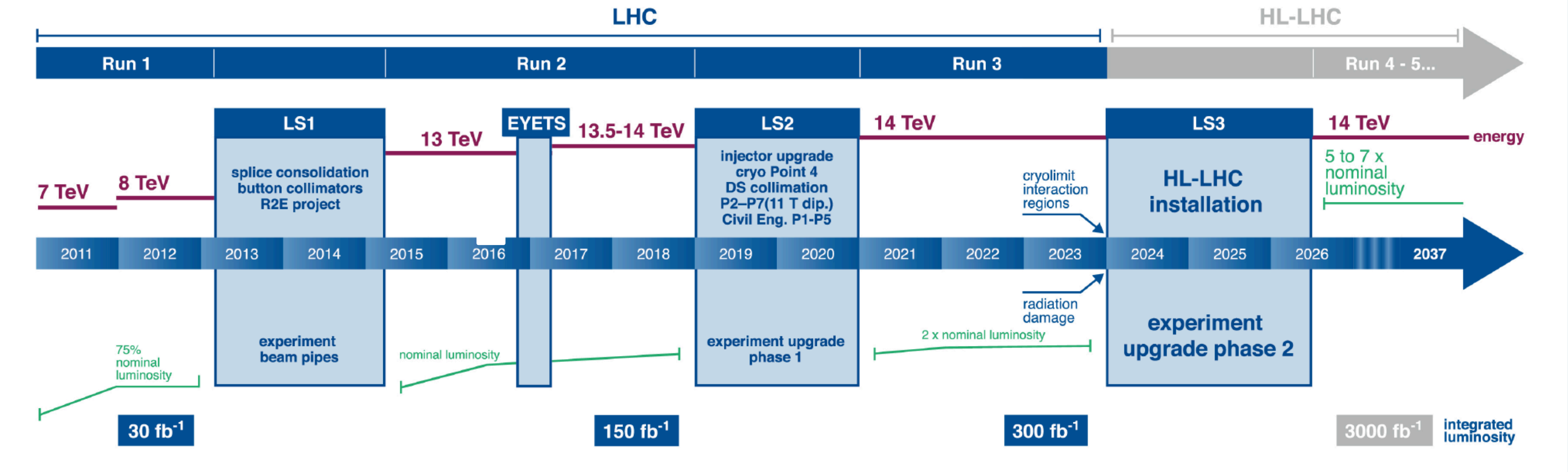
LPNHE PARIS

Université de Paris

cnrs IN2P3 Les deux infinis

Towards the High-Luminosity LHC

- To extend the discovery potential, both the LHC accelerator and experiments are scheduled for an upgrade.
- "HL-LHC" is expected to start ~ 2027, reaching 5 to 7 times the nominal luminosity



ATLAS detector will need major upgrades due to:

- Pile-up challenge : <μ> ~ 30 in Run 2 up to <μ> ~ 200
- More radiation damage
- Higher Trigger rates

Among upgrades: High-Granularity Timing Detector: HGTD

See also the HGTD talk by Abdellah Tnourji at TIPP-2021

Motivations for HGTD: Pileup challenge

- Main challenge for HL-LHC is pile-up:

  $\mathcal{L}_{inst} = 7.5 \times 10^{34}\ cm^{-2}\ s^{-1}$ and $\langle\mu\rangle = 200$

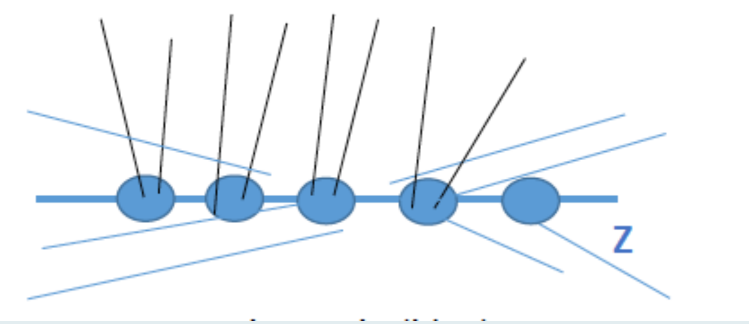
  Interaction region will spread out over 50 mm in z direction.
- ITk provides good resolution on track impact in the central region.
- To discriminate between pile up and hard scattering interaction, HGTD is added in the forward region with the goal is to have 30-50 ps per track time resolution (beginning-end).

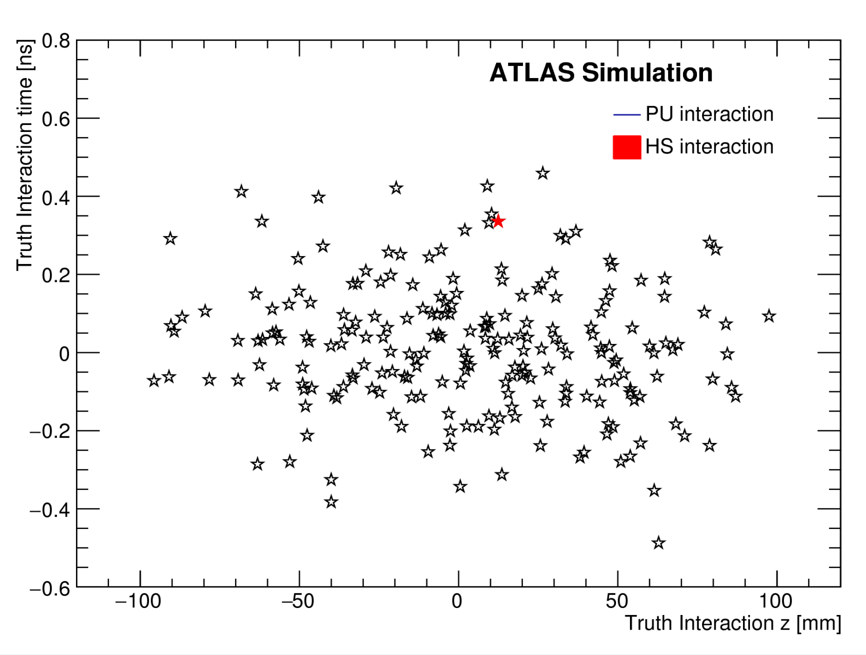
  Impact on physics: track/jet reconstruction, electron ID, b-tagging.
- Requirements for the detector:

  Compact and

  Radiation Hard

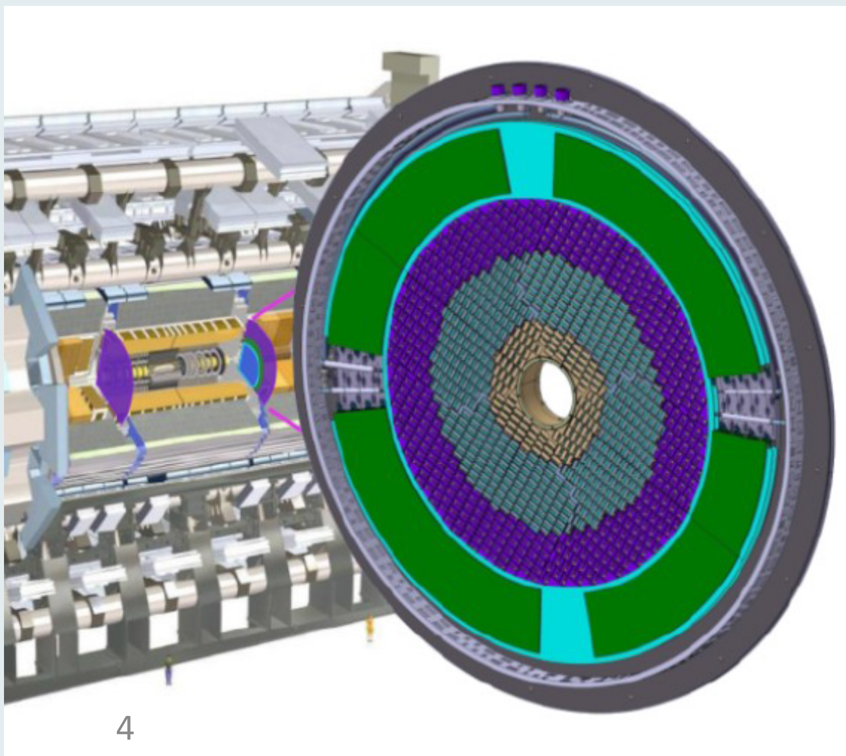
Choice of Silicon-based timing detector with LGAD sensors





HGTD System

- $|z|$=3.5 m, 7.5 cm width
- Coverage $2.4 < \eta < 4.0$
  12 cm < R < 64 cm
- 2 disks/side, 2 sensor layers/disk
- 2-3 hits/track
- Nu of channels : 3.6 M



Baseline:

- Time resolution :
  σ_t = 35 - 70 ps per hit
  σ_t = 30 - 50 ps per track
  over the lifetime of HL-LHC
- Maximum fluence:
  $2.5\times10^{15}\ n_{eq}/cm^2$
  TID of 2MGy by end of HL-LHC,4000 fb^{-1}

Sensors will be operated at -30°C using a common CO_2 cooling system with ITk

HGTD provides also a luminosity measurement : gives the number of hits per ASIC in two time windows per bunch crossing

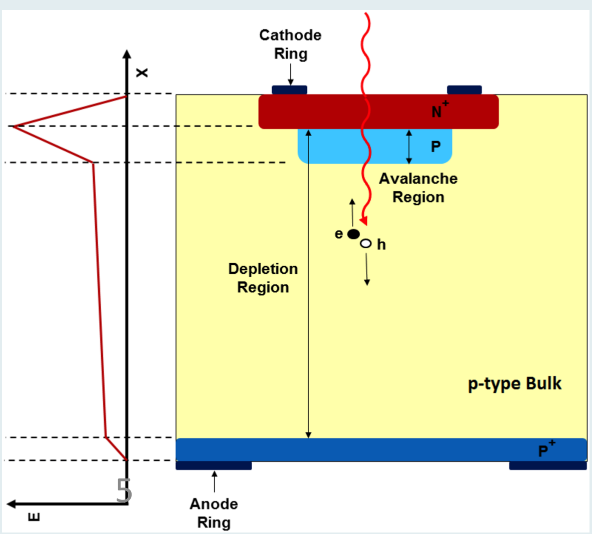
HGTD detection technology: LGAD sensors

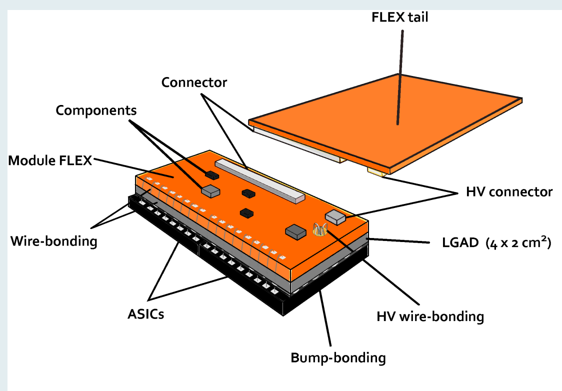
- **Low Gain Avalanche Detectors**

  n-in-p Si detector with an additional p-type doped layer inducing charge multiplication.
  - Sensor internal gain >20 before irradiation and > 8 at the end of lifetime. V_{bias}<800 V
  - Sensor gain controlled by doping level, depth and material
  - Fast rise time: 0.5 to 0.8 ns
  - Excellent timing resolution: 35 - 70 ps per hit
  - For good timing: minimum collected charge 4 fC /MIP/hit after 2.5×10^{15} n_{eq} cm^2
  - Hit efficiency > 95 % at the end lifetime
  - Pad size: 1.3x1.3 mm^2 (occupancy <10%).

  8032 modules of 15x30 pads (each sensor bump-bonded to 2 ALTIROC ASICS)

  Threshold of the ALTIROC electronic discriminator: Q_{coll} > 2 fC.





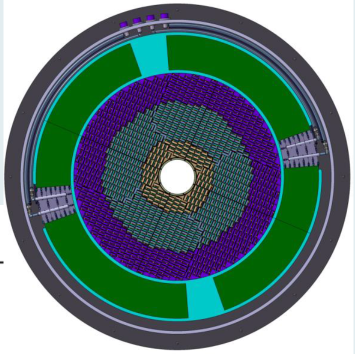
- LGAD originally developed by CNM and RD50
- HGTD tested prototypes from CNM (Spain), HPK (Japan) BNL (USA), FBK (Italy) IME, NDL (China)

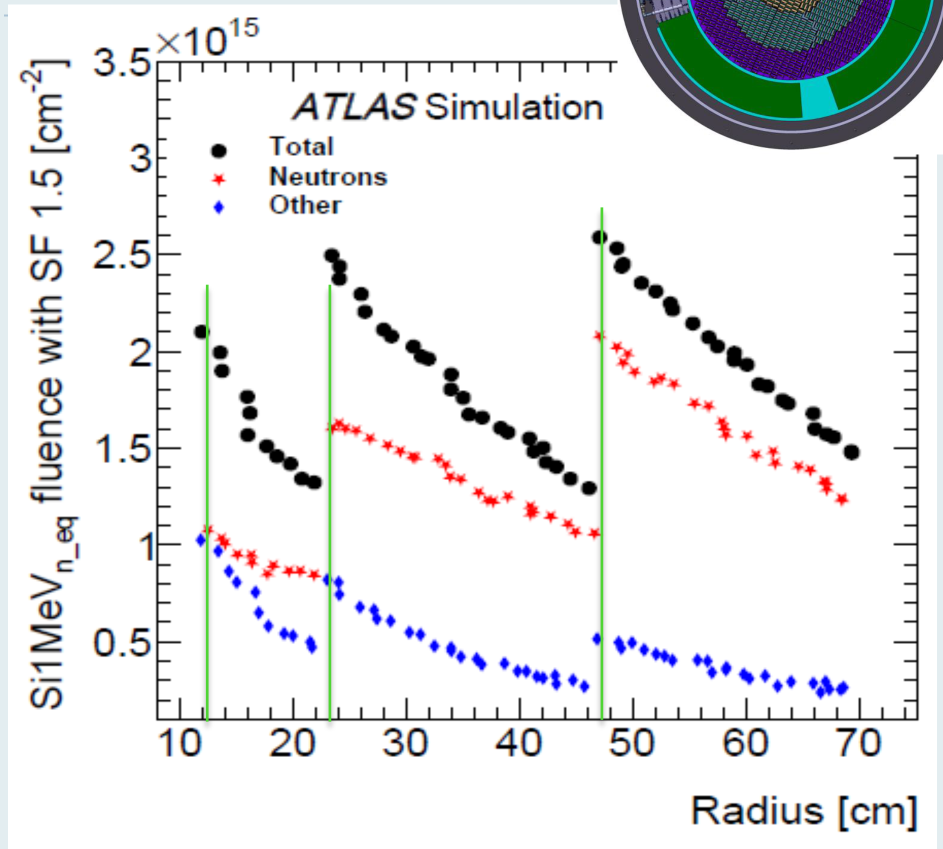
HGTD Radiation Hardness

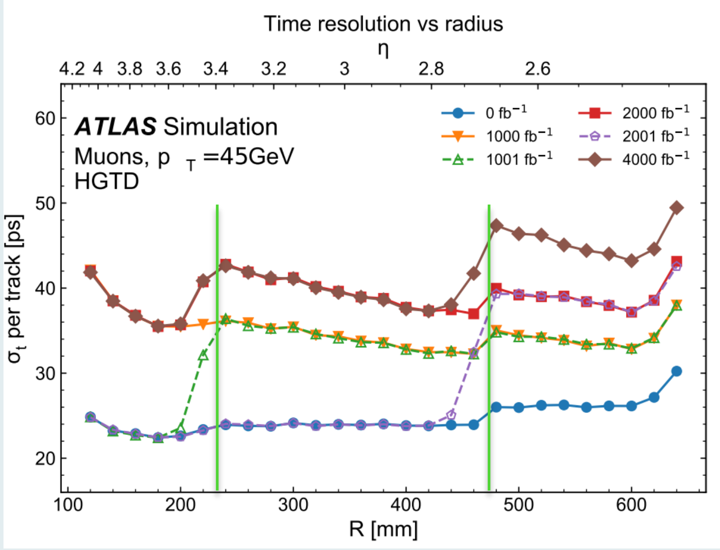
Requirements for good time resolution:
- maximum fluence: $2.5 \times 10^{15}\ n_{eq}/cm^2$
- TID: 2 MGy

Coping with high radiation environment: segment the HGTD detector into 3 replaceable rings:

- Inner (12-23 cm) every 1000 fb^{-1}
- Middle (23-47 cm) every 2000 fb^{-1}
- Outer (47-64 cm) never replaced







Safety factors applied:
x 1.5 for sensors
x 2.25 for the electronics

Strong timing constraints on sensor choice

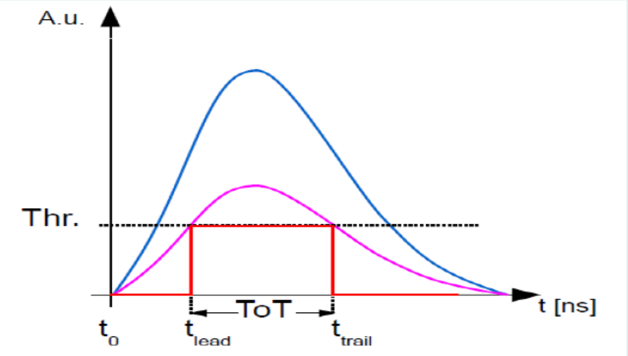
- **Time resolution**

Time resolution less than 70 ps/hit after irradiation level $2.5\times10^{15}\ n_{eq}/cm^2$ is beyond standard HEP silicon devices

$$\sigma_{tot}^2 = \sigma_{Landau}^2 + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{\mathrm{TDC}_{bin}}{\sqrt{12}}\right)^2 + \sigma_{clock}^2$$

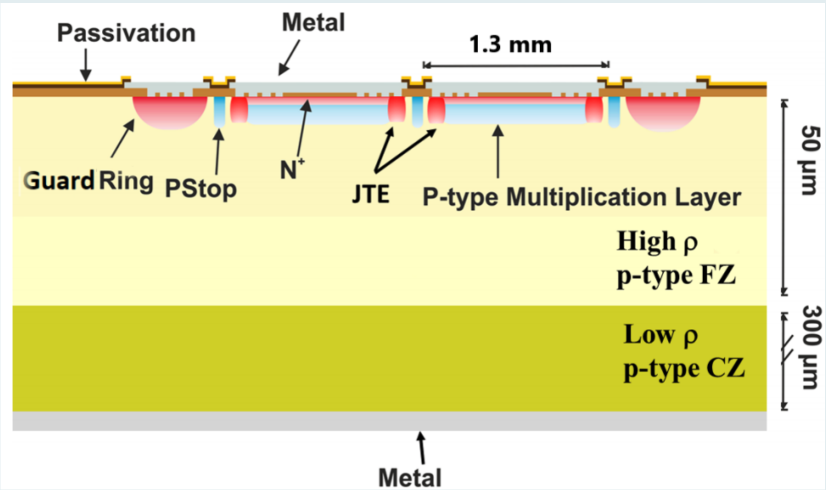
Jitter *Time-walk* *(negligible)*

- ➢ $\sigma_{Landau} < 25$ ps. Intrinsic Landau contribution coming from charge deposition non-uniformities is reduced for thin sensors: choice of 50 μm in HGTD
- ➢ $\sigma^2_{Jitter} + \sigma^2_{TimeWalk} < 25$ ps (70 ps at 4000 fb^{-1}) -> fast signal and excellent S/N
- ➢ $\sigma_{clock} < 15$ ps
- ➢ Time-walk contribution can be corrected with the Time of Arrival (TOA) and the Time over Threshold (TOT)
- ➢ At low S/N, noise jitter is dominating and Landau term takes over at high S/N



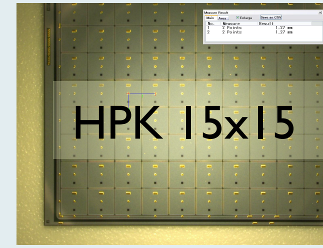
HGTD detection technology : LGAD tests

Sensor with a 2x2 array of pads
(1 pad : 1.3x1.3 mm²)



Manu-facturer	Wafer Size [inch]	Thick-ness [μm]	C Implant	Array 5 × 5	Array 15 × 15	Array 30 × 15
CNM	4-6	30 - 300	x	x	(x)	(x)
FBK	6	(50) 60 - 300	x	x		
HPK	6	20 - 80		x	x	(x)
BNL	4	50				
Micron	4	100 - 300				
NDL	6	33 (50)		x	(x)	

Arrays tested:
5x5
15x15



Sensor tests

- In laboratory:

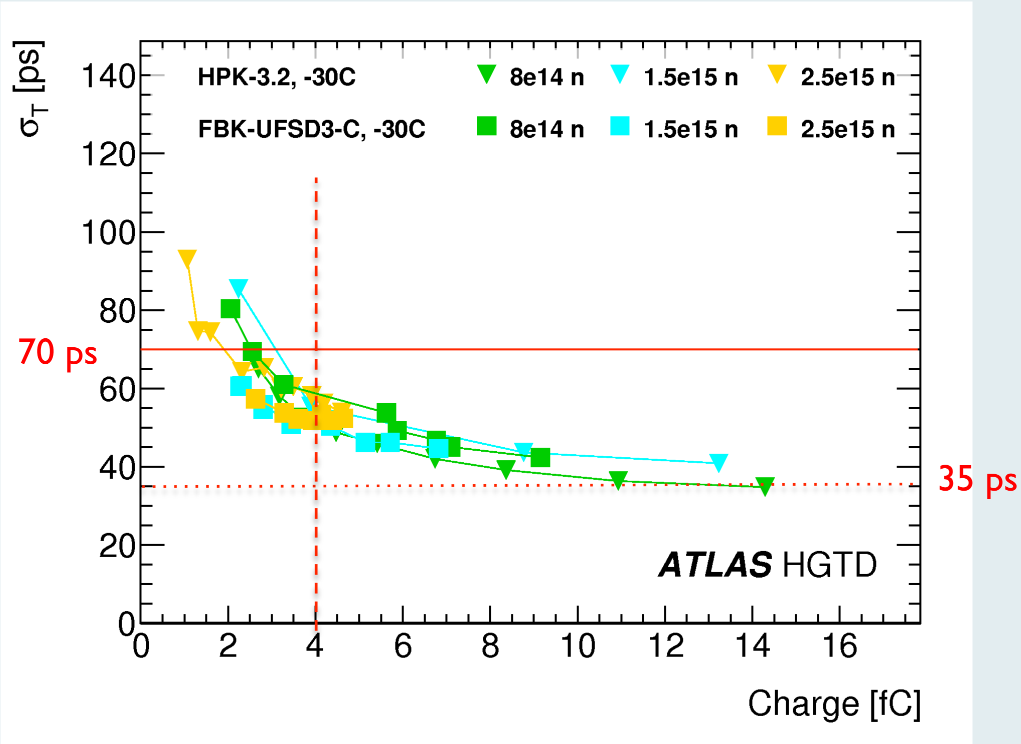
with β-source (^{90}Sr) or lasers in control environment and in climate chamber for irradiated sensors.
Custom made HGTD-specific readout boards.
Electrical measurement: I-V, C-V, Gain, time-resolution, rise time and inter gap

- In test beams:
  - ✓ at CERN (120 GeV Pions)
  - ✓ at DESY (5 GeV e-).

Sensors integrated into a beam telescope providing track position with 3μm resolution

Sensors irradiated at various fluencies. Results for 3×10^{15} n_{eq}/cm^2 max are shown here.
C-enriched sensors: promising idea to improve radiation hardness.

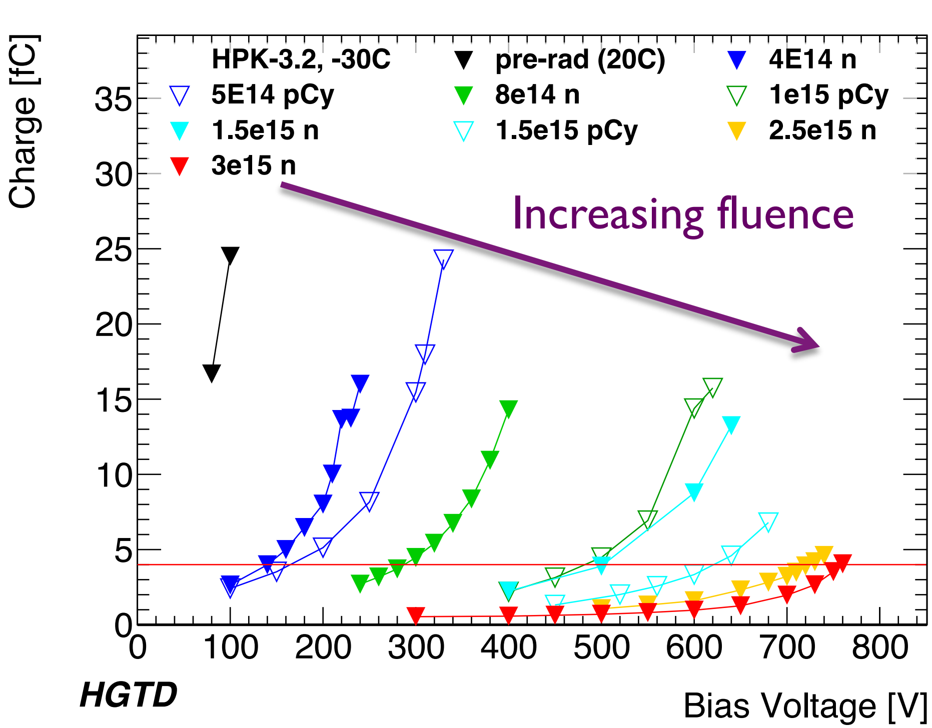
Sensor performance in lab: σ_t vs charge

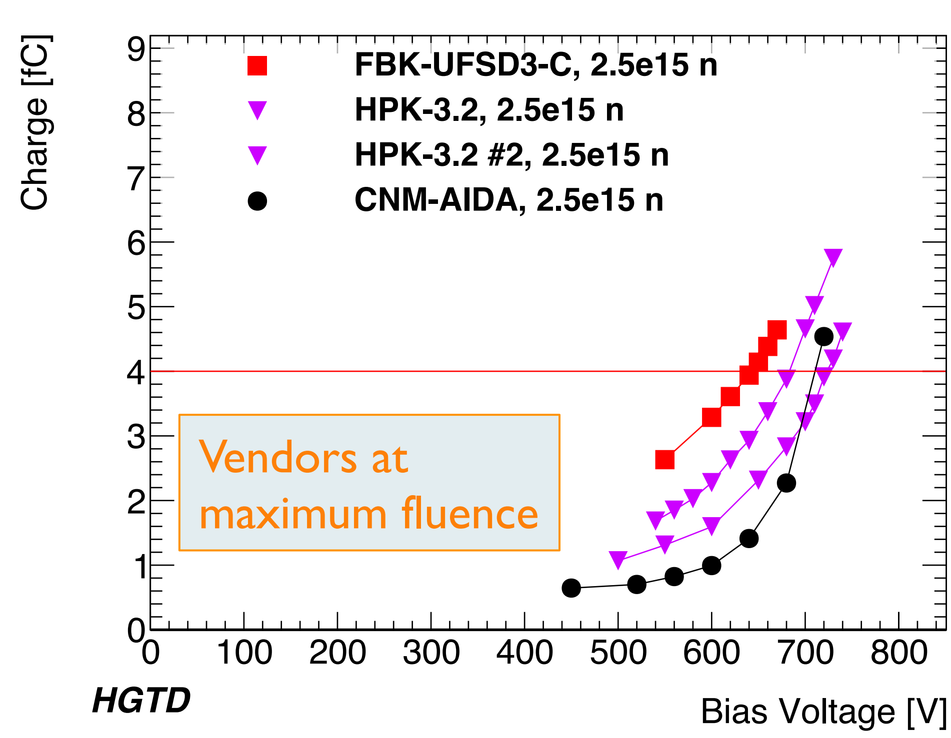


- Time resolution vs collected charge, for HPK 3.2 and FBK sensors at various fluencies and up to 2×10^{15} n_{eq}/cm^2
- 4fC corresponds to a gain = 8
- Results obtained with dedicated electronics. Time walk is corrected.
- Typical error bar ~ 3ps
- 50 μm thickness

- Sensors from different vendors have different operation voltage.
- Similar σ_t can be achieved with sensors while biased at different voltages.
- Time resolution improves with increasing gain.

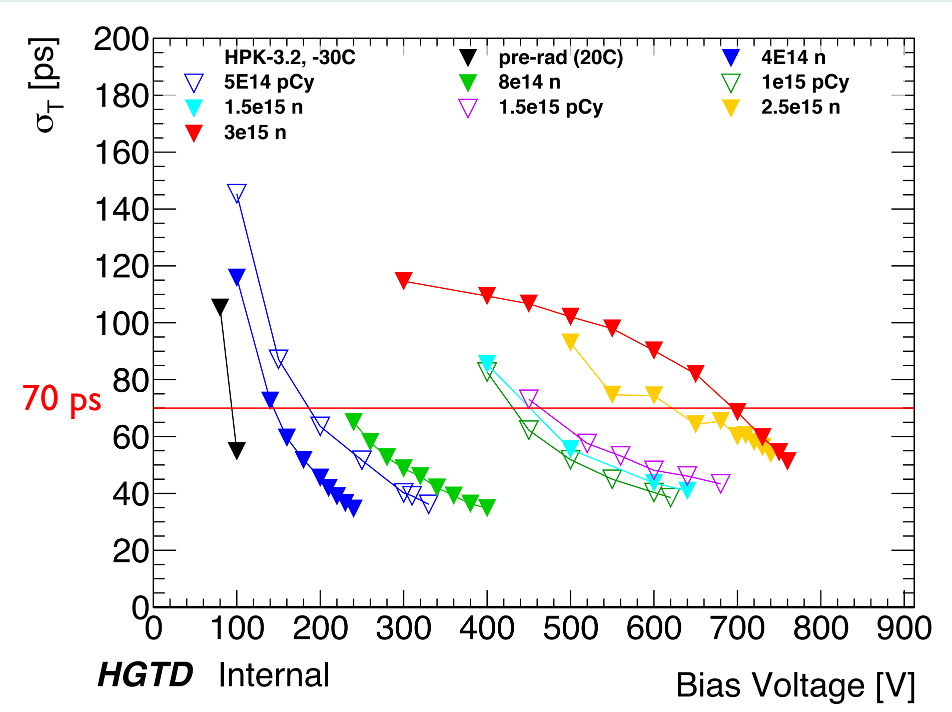
Sensor performance in lab: charge

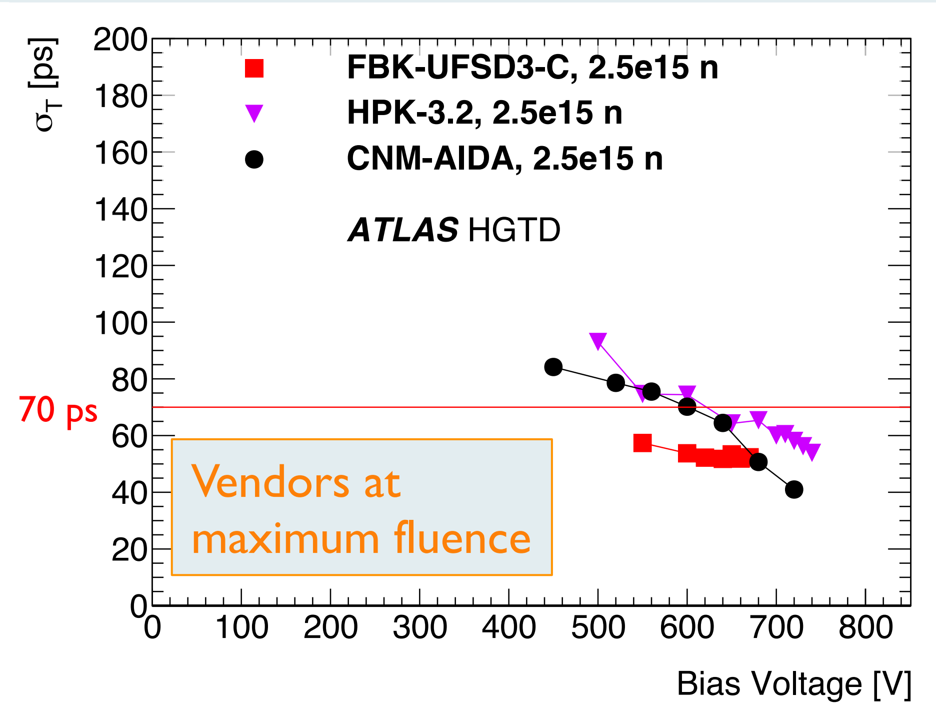




- Collected charge as a function of bias voltage from various vendors.
- Sensors from a variety of vendors satisfy collected charge requirement
  HPK 3.2 : Collected Charge > 4 fC after irradiation to $3x10^{15}$ n_{eq}/cm^2 with neutrons.
- Superior performance for FBK sensors with C enriched gain layer. Same charge for lower bias voltage. Testing continues.

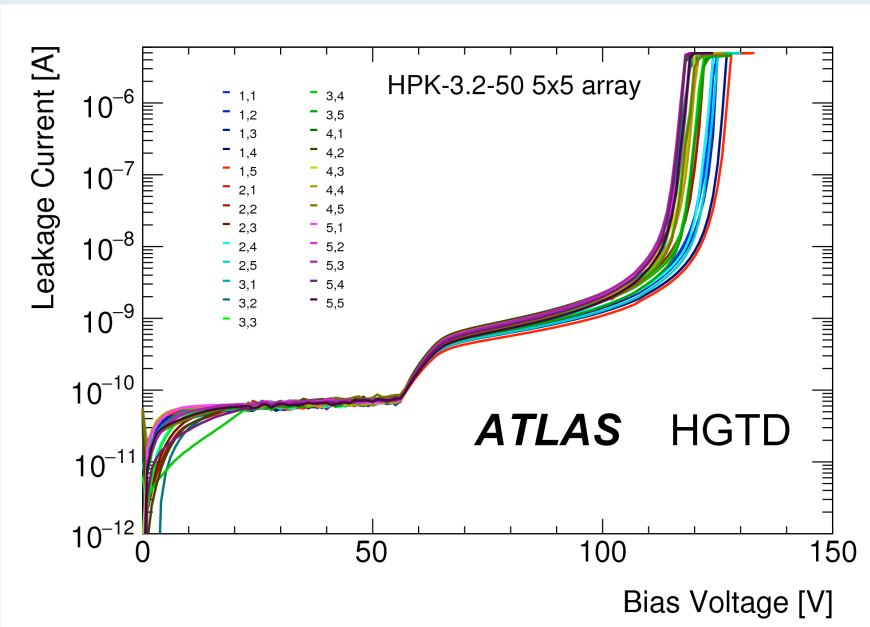
Sensor performance in lab: time resolution

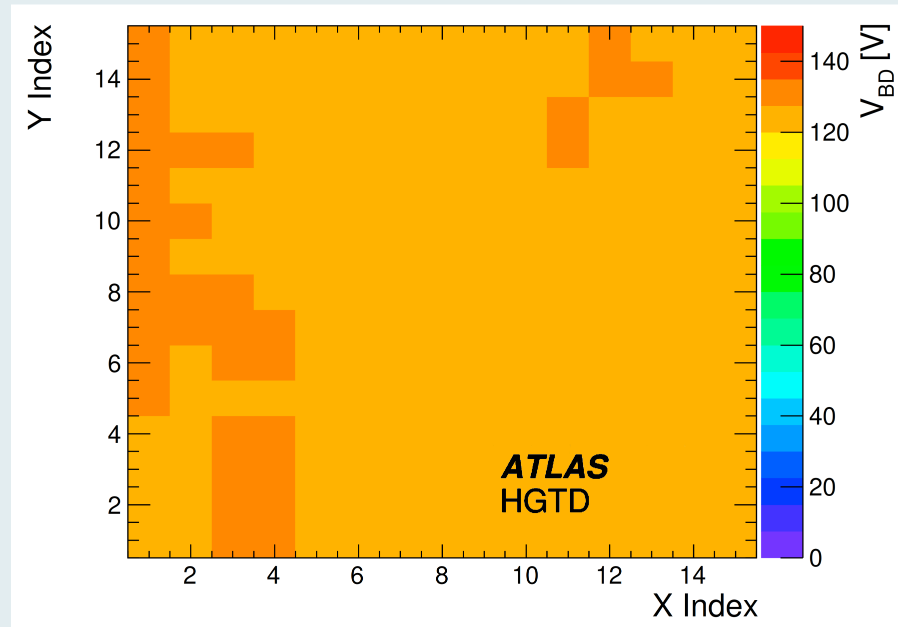




- Time resolution as a function of bias voltage for different fluencies and vendors
- Maximum allowed resolution of 70 ps is achieved for HPK 3.2 at $3 \times 10^{15}\ n_{eq}/cm^2$
- Superior performance for FBK sensors with C enriched gain layer

IV and V_{BD} map in HPK non irradiated arrays





- 25 pads from a 5x5 non irradiated HPK 3.2 array, measured in laboratory by a probe card and at room temperature.
- Uniform behavior of pads: V_{BD} variations ~ few Volts

HGTD Test Beam campaigns

Measure Q_{coll} ,σ_t , efficiency, uniformity for sensors from different vendors, with different dopings, and irradiated with n or p, at different fluencies up to $3x10^{15}$ n_{eq}/cm^2

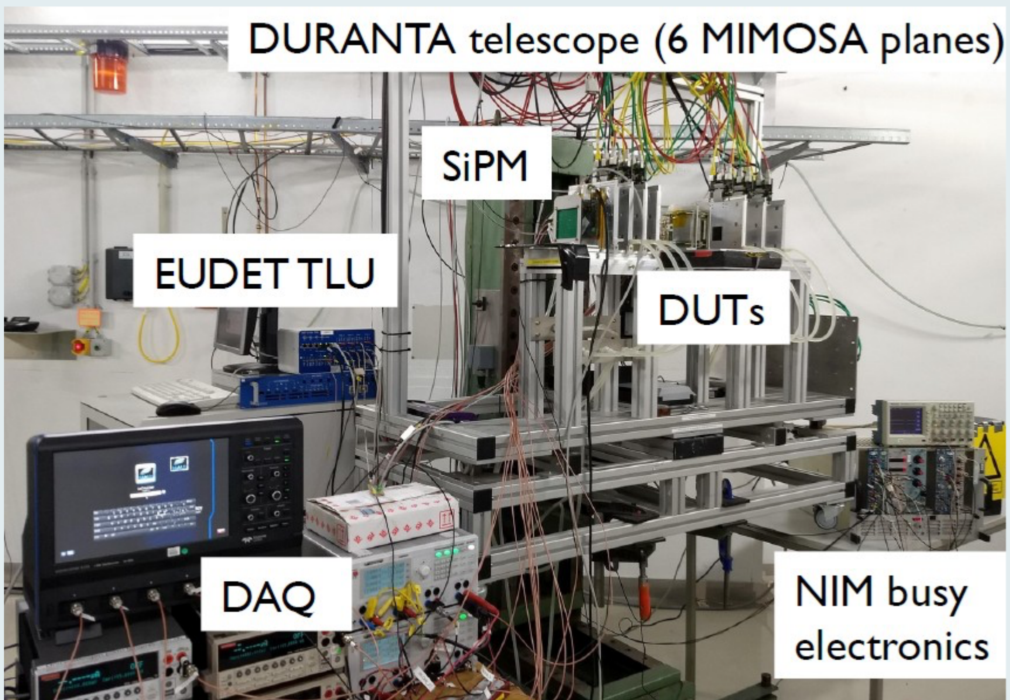
- 2016 - 2018: CERN, 120 GeV pions
  - 2016+2017: Unirradiated CNM and HPK. Irradiated CNM
  - 2018 : Unirradiated and irradiated CNM and HPK
    - CNM sensors:
      - Boron implanted
      - Boron implanted with Carbon diffused
      - Gallium implanted
    - HPK sensors:
      - doped with Boron, different doping profiles
    - FBK Boron+ Carbon infused
    - 2x2 array ALTIROC 0
- 2019 : DESY, 5 GeV electrons : mostly irradiated sensors
  - single pad HPK
  - CNM sensors doped with Boron; Boron + Carbon; Gallium
  - 5x5 ALTIROC1 coupled to non irradiated HPK 3.2
- 2020 : only one campaign at DESY with HPK, NDL, FBK and CNM sensors
  others campaigns cancelled due to pandemic
- 2021: Hope for a DESY test beam in June and at CERN at end of 2021

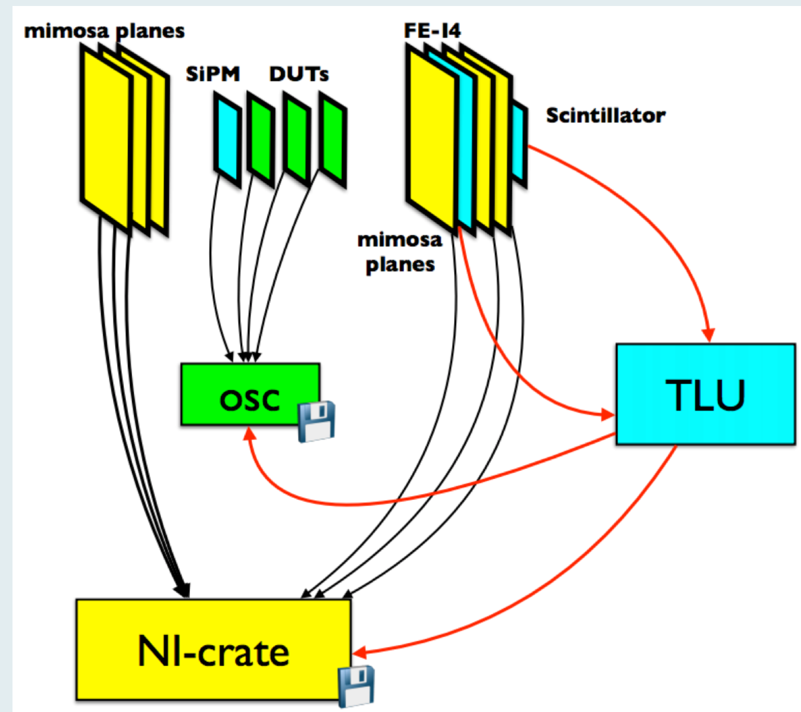
CNM
HPK
FBK
IHEP/NDL

Test beam setup

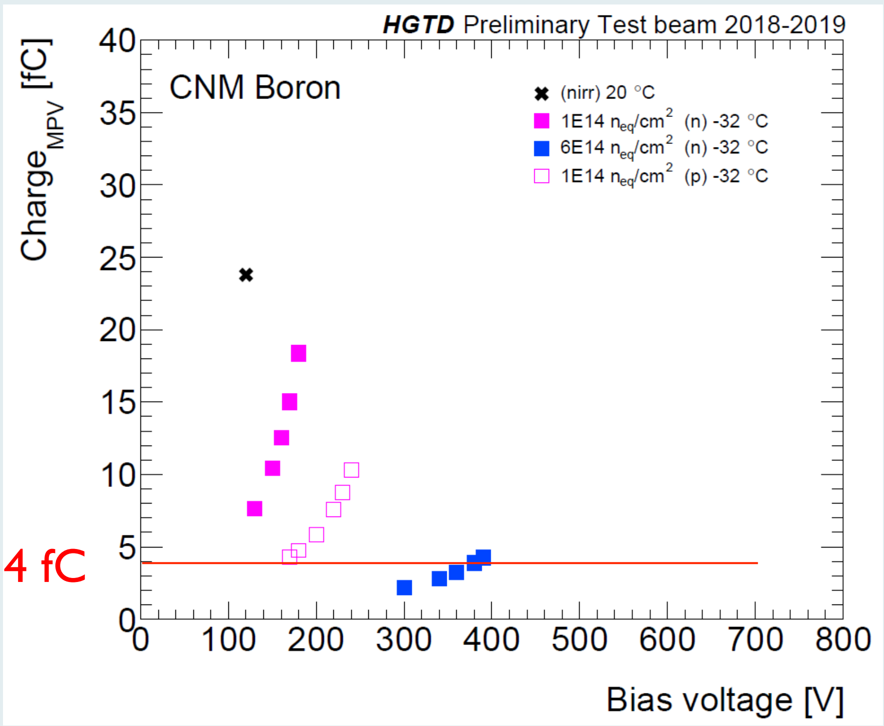
Test beam with pion/electron beams (CERN/DESY)

- Telescope Mimosa planes to provide track reconstruction
- Inside a cooling device
- Oscilloscope records wave-forms to perform analysis
- Cerenkov Quartz bar and SiPM (σ = 10-40 ps) for independent time reference
- ASIC + sensor testing: ALTIROC chip is used for readout + oscilloscope for debug





Collected charge measurement in test beam

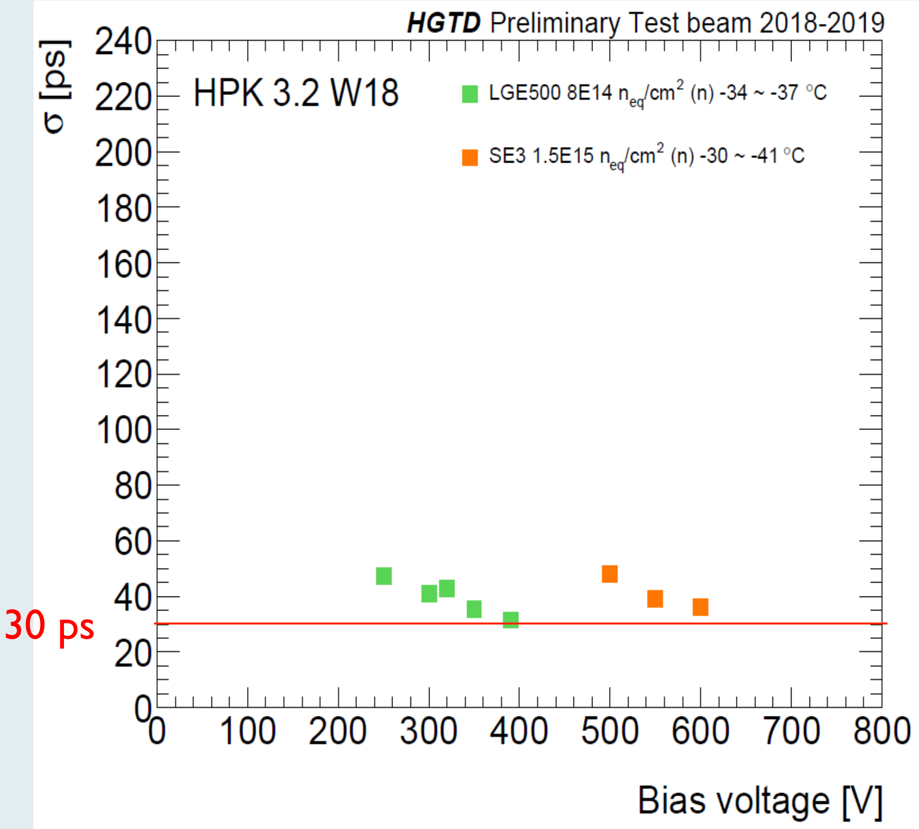


Boron doped CNM sensors, irradiated with neutrons

- Charge computed as the integral of signal waveform divided by the transimpedence of the readout circuit
- For each bias voltage, the collected charge is given by the MPV of the Landau-Gaussian fit of the charge distribution
- For Boron doped CNM sensor irradiated with neutrons at 6×10^{14} n_{eq}/cm^2 and V=390V
  Q = 4.2 fC
- For Gallium doped CNM sensor irradiated with neutrons at 3×10^{15} n_{eq}/cm^2 at HV=740V
  Q = 5.3 fC
- Achieved HGTD requirement of 4fC

Time resolution measured in test beam

Boron doped HPK 3.2 sensors, irradiated with neutrons

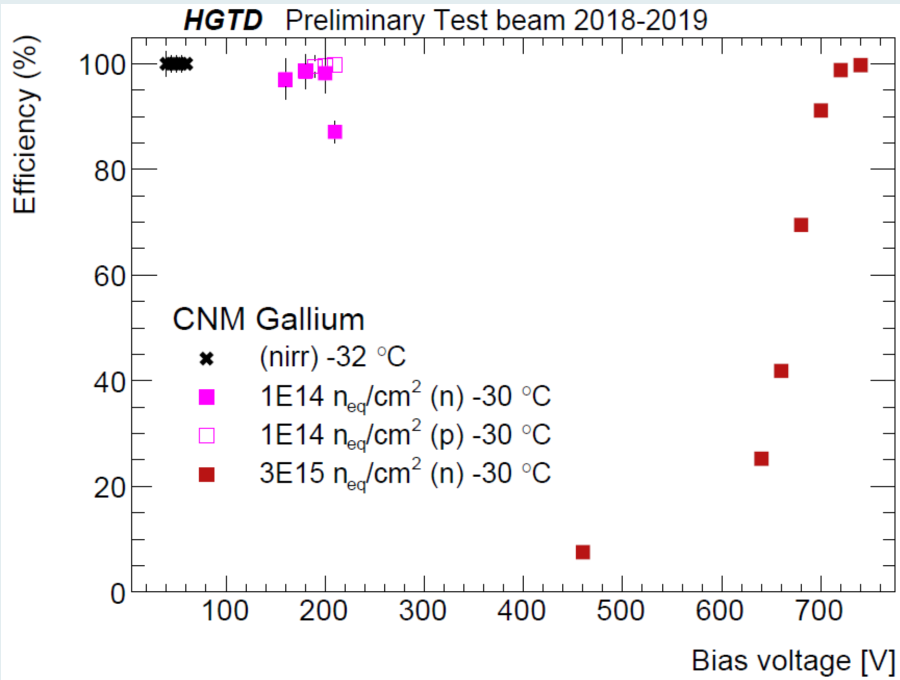


- Time resolution is computed from time difference between the sensor and SiPM time (or with another sensor):
  $$\sigma^2 (t_i - t_j) = \sigma^2(t_{sensor\ i}) + \sigma^2 (t_{sensor\ j})$$
  4 sensors/SIPM give a constrained system

- HPK n-irradiated at $1.5\times10^{15}\ n_{eq}/cm^2$
  σ = 36 ps
  at 600 V and for Q coll = 22.8 fC .

- Tested sensors that have a collected charge greater than 4 fC have a time resolution better than 40 ps at higher bias voltage

Efficiency measurement in test beam



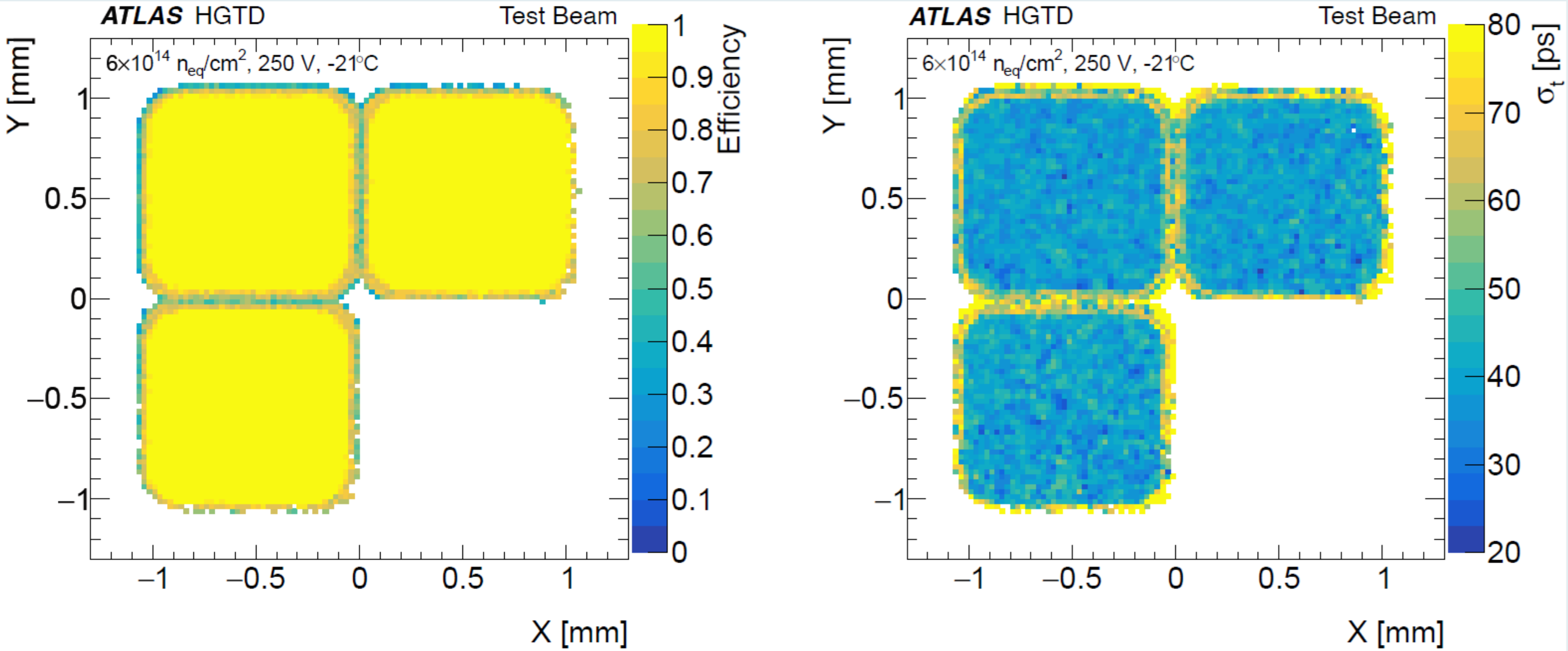
$$\varepsilon = \frac{\textit{Tracks with } Q>2fC \textit{ in central part}}{\textit{Total Tracks in the central part}}$$

- The threshold at 2 fC for the collected charge corresponds to the threshold of the ALTIROC.

- For CNM n-irradiated, Ga doped sensors, at $3\text{x}10^{15}$ n_{eq}/cm^2
  $\varepsilon = 99.7\%$
  for V = 740 V and Q_{coll}=5.3 fC

Gallium doped CNM sensors
- unirradiated
- irradiated with neutrons or protons

2D efficiency maps at test beam



CNM with 2x2 arrays, irradiated with neutrons at $6x10^{14}$ n_{eq}/cm^2 .

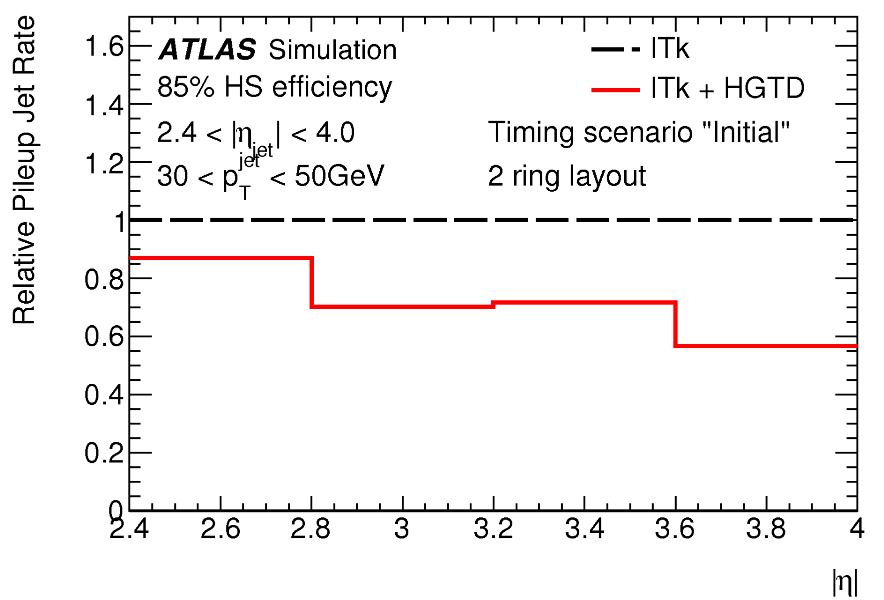
- A mean efficiency in the pad center is maintained up to the threshold of 5 times the noise level.
- Time resolution has 3ps variations across the pad center

Conclusions

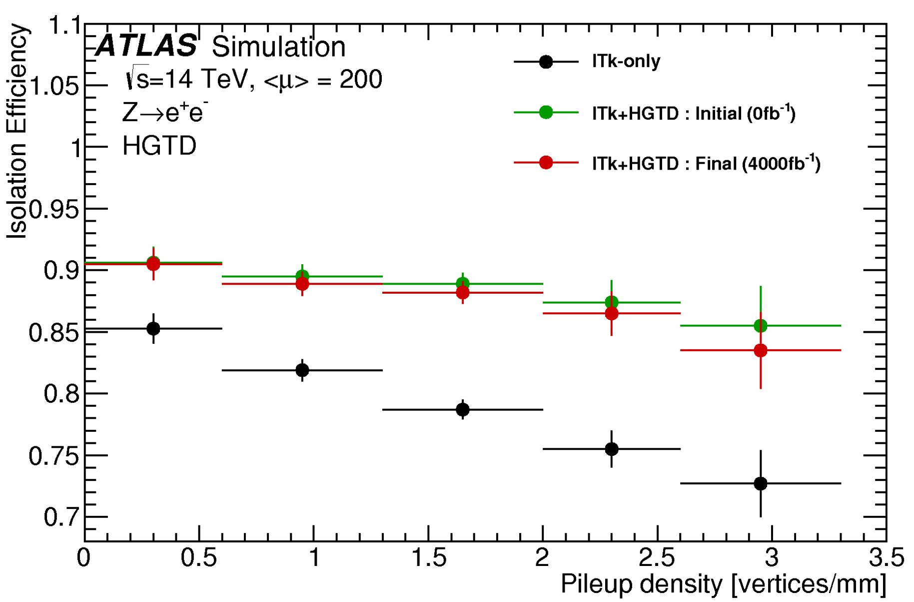
- Timing information from ATLAS-HGTD is expected to play a key role in mitigating the impact of pile-up in the forward region and for very challenging HL-LHC conditions
- HGTD will use the LGAD technology to improve ATLAS performance in forward region
- LGAD technology and layout for HGTD are optimized to reach a per-track resolution of 30 - 50 ps up to the end of the detector lifetime.
- Irradiated LGAD sensors with different doping profiles and irradiation levels were tested in test beams and in laboratories. Required performances are reached for several vendors.
- The overall design and construction works are progressing. Intense R&D ongoing to improve radiation hardness. Installation is foreseen in 2026-27
- The HGTD Technical Design Report has been approved in Sept 2020
  ATLAS-TDR-031 https://cds.cerncern.ch/record/2719855

Backup

Impact of HGTD

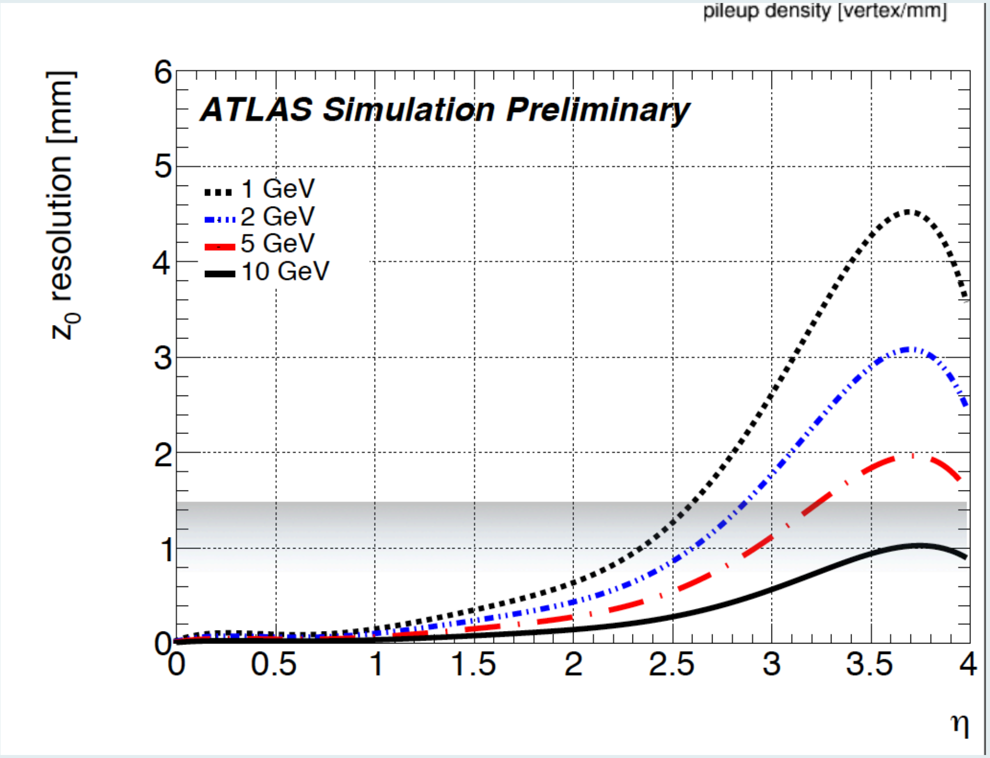


Relative pileup jet rate as a function of jet pseudorapidity, for jets with 30GeV < p_T < 50GeV, with and without HGTD



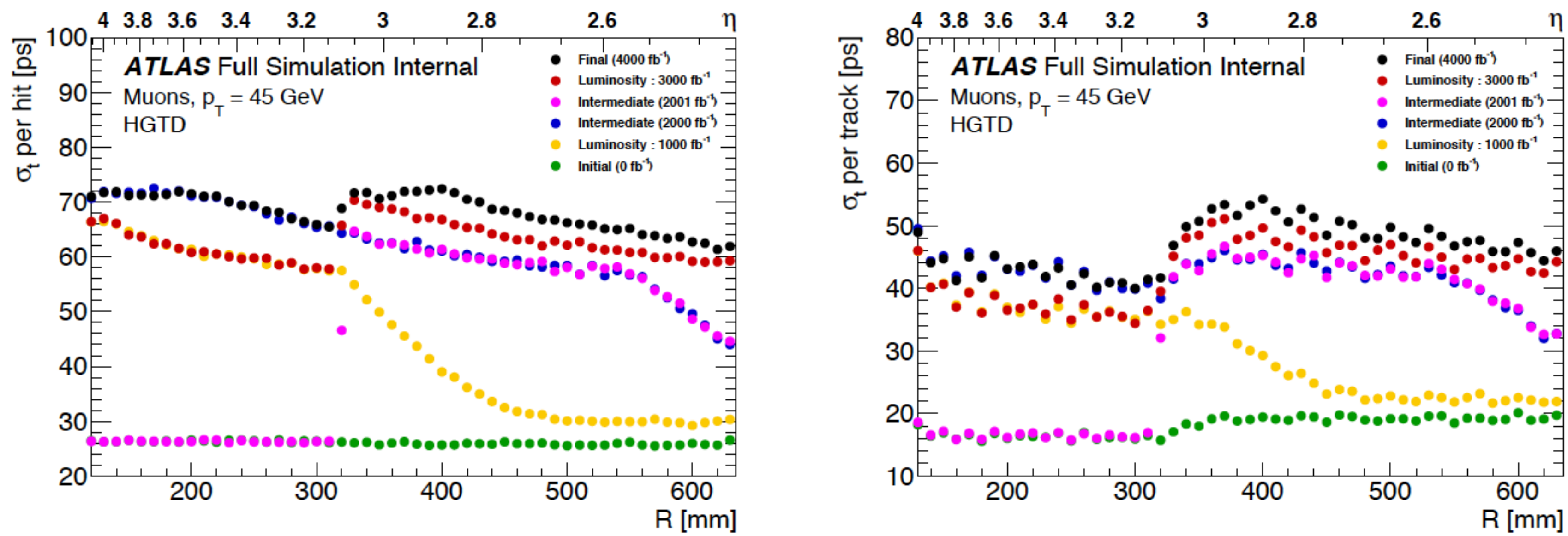
Efficiency for electrons to pass track-isolation criteria, denoted as ε (p_T^{iso}), as function of the local vertex density with or without HGTD.

ITK



At 1GeV and η=3, σ_{Z0} =2.5 mm: selection window of 5 mm around vertex position.
The forward track is compatible with 13 vertices :
Significant pile-up contamination.

Resolution per track 50 ps with several hits and 70 ps per hit



(a) Resolution per hit.

(b) Resolution per track.

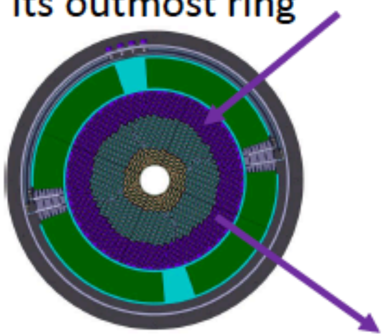
Figure 3.6: The HGTD timing resolution is shown as function of the radius for four timing scenarios. The sensor resolution and the contribution from the electronics are considered, added in quadrature.

TDR plots

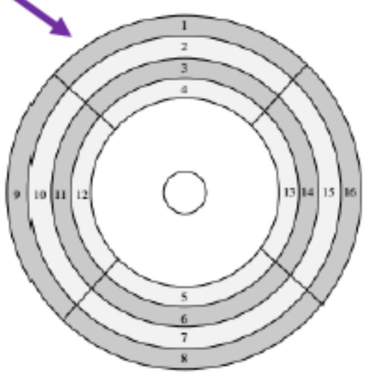
Luminosity measurement

Precise knowledge of luminosity is a key to many physics studies

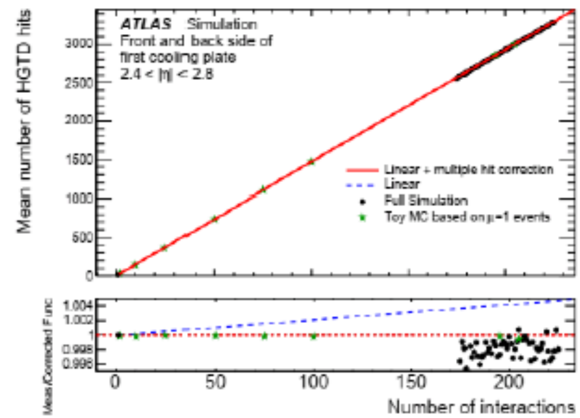
HGTD provides precise bunch-by-bunch luminosity measurement in its outmost ring



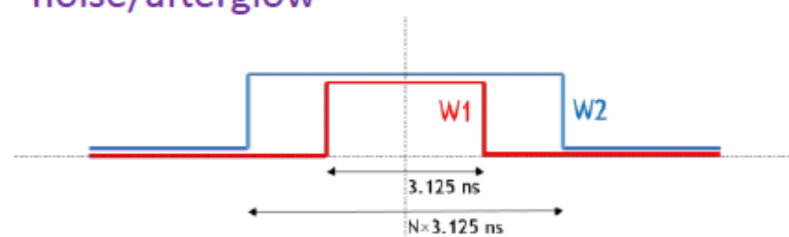
Planned for 16 partitions with independent measurements



High granularity → great linearity between measurements and luminosity



Unique two timing window scheme at ASIC level give in-situ measurement of noise/afterglow



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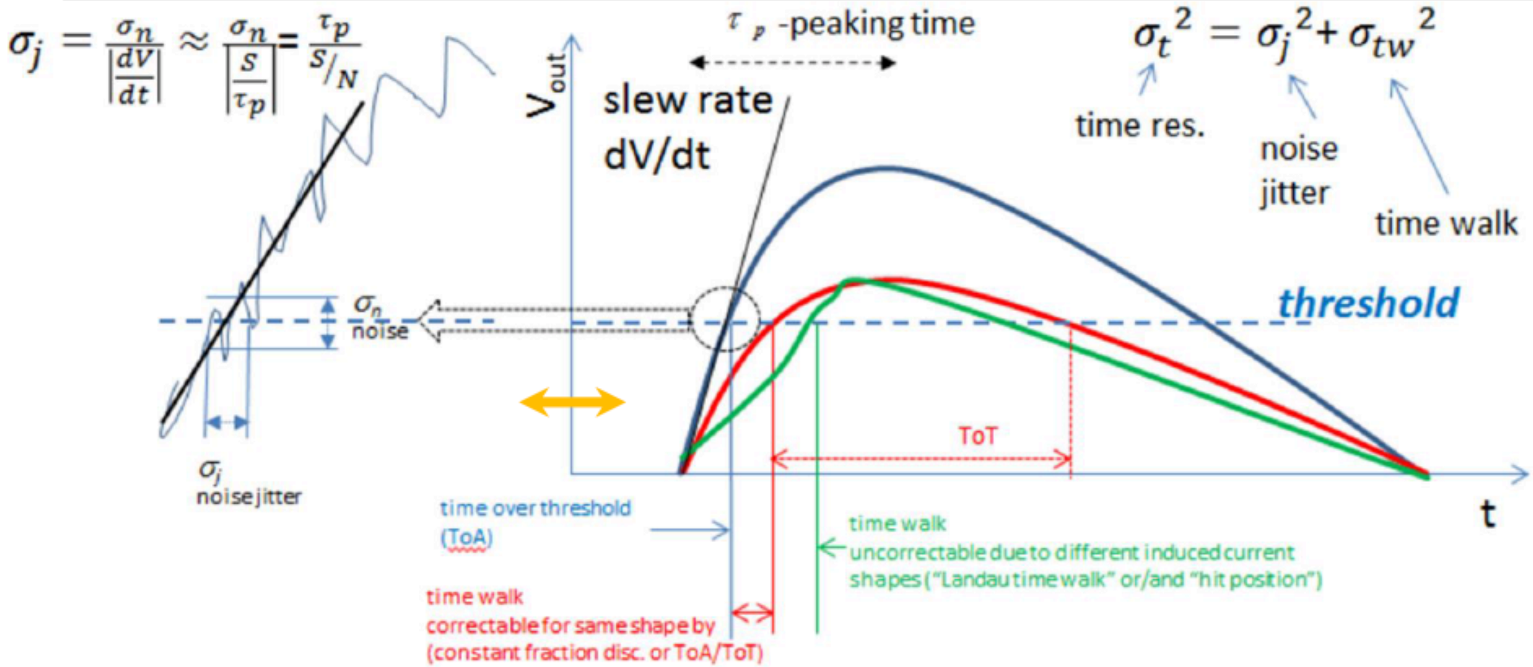
Measuring time



Time resolution defined by **jitter** and **time walk** and clock stability (defining t0).

short collection (τ_p), large signal S/N

not in the domain of sensor

10/11/2020 S. GRINSTEIN, G. KRAMBERGER, SPR - LGAD TECHNICAL SPECIFICATIONS 4

Sensor parameters and requirements

Technology	Silicon Low Gain Avalanche Detector (LGAD)
Time resolution	≈ 35 ps (start); ≈ 70 ps (end of lifetime)
Time resolution uniformity	No requirement
Min. gain	20 (start); 8 (end of lifetime)
Min. charge	4 fC
Min. hit efficiency	95%
Granularity	$1.3\,\text{mm} \times 1.3\,\text{mm}$
Max. inter-pad gap	100 µm
Max. physical thickness	300 µm
Active thickness	50 µm
Active size	$39\,\text{mm} \times 19.5\,\text{mm}$ (30×15 pads)
Max. inactive edge	500 µm
Radiation tolerance	$2.5 \times 10^{15}\,n_{eq}\,\text{cm}^{-2}$, 1.5 MGy
Max. operation temperature on-sensor	–30 °C
Max. leakage current per pad	5 µA
Max. bias voltage	800 V
Max. power density	$100\,\text{mW/cm}^2$

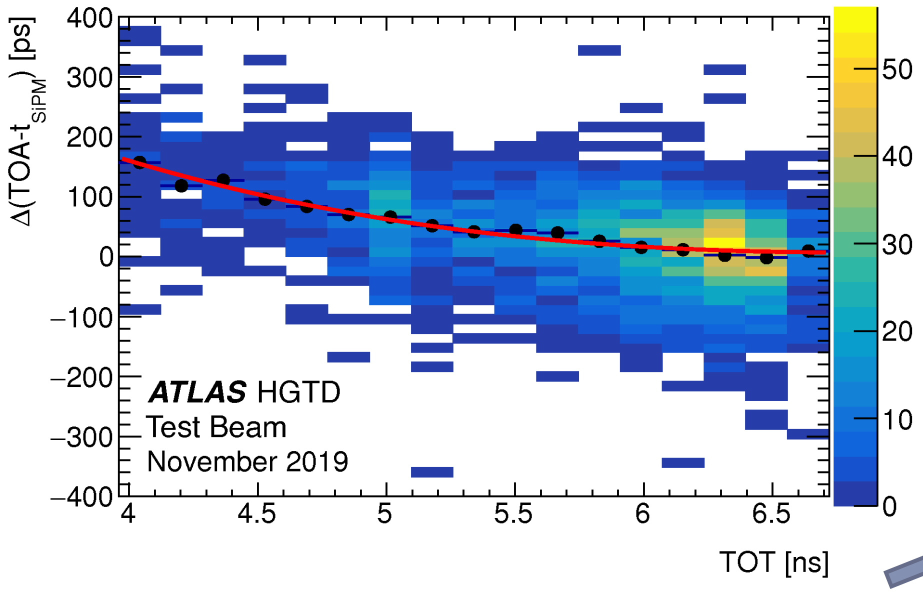
Irradiation Facilities/sensor properties

Manu-facturer	Name	Thickness [µm]	Gain layer dopant	C implant	Gain layer depth [µm]	Gain layer depletion [V]
HPK	HPK-3.1	50	Boron	No	1.6	40
HPK	HPK-3.2	50	Boron	No	2.2	55
FBK	FBK-UFSD3-C	60	Boron	Yes	0.6	20
CNM	CNM-AIDA1/2	50	Boron	No	1.0	45
NDL	NDL-33µm	33	Boron	No	1.0	20
Manu-facturer	**Name**	**Full depletion [V]**	**V_{BD} $-30\,^{\circ}$C [V]**	**Nominal IP [µm]**	**Nominal SE [µm]**	**Max. Array Size**
HPK	HPK-3.1	50	200	30-95	200-500	15×15
HPK	HPK-3.2	65	70	30-95	200-500	15×15
FBK	FBK-UFSD3-C	25	170	37	200-500	5×5
CNM	CNM-AIDA1/2	50	220/50	37-57	200-500	5×5
NDL	NDL-33µm	35	70	55	450	15×15

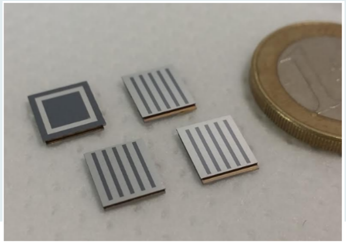
Facility & Abbreviation	Particle Type	Hardness Factor	TID [MGy] / 10^{15} n_{eq} cm^{-2}	Max. Fluence [10^{15} n_{eq} cm^{-2}]	Max. TID [MGy]	LGAD Types Irradiated
JSI Ljubljana (*n*)	≈1 MeV n	0.9	0.01	6	0.06	all
CYRIC (*pCY*)	70 MeV p	1.5	0.81	2.5	4.0	HPK-3.1/3.2, NDL FBK-UFSD3-C
Los Alamos (*pLA*)	800 MeV p	0.7	0.43	6	0.4	early prototypes
CERN PS (*pPS*)	23 GeV p	0.6	0.44	6	2.7	early prototypes

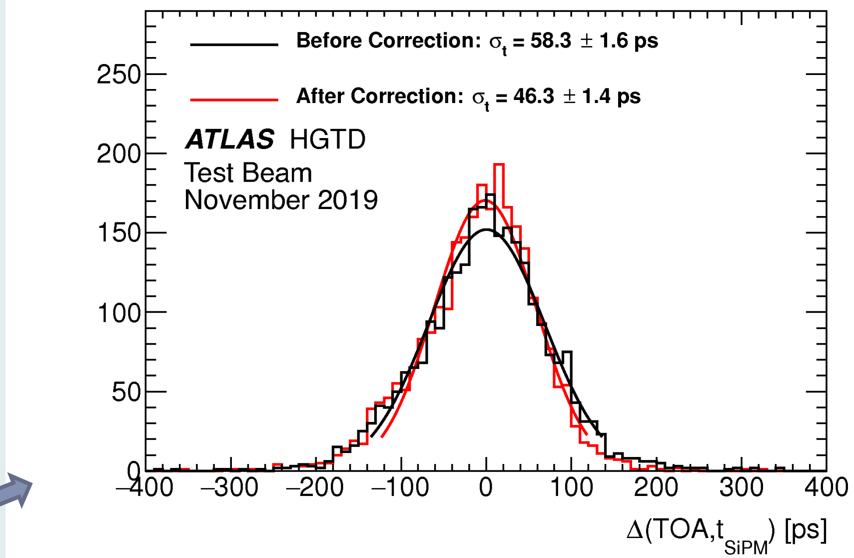
ALTIROC front end chip in test beam

Test beam measurement at DESY in 2019 for unirradiated ALTIROC1 modules
-> TOA corrected for time-walk



5x5 ATLIROC1 devices with HPK and CNM sensors





Estimated resolution of **46 ps** after time-walk correction and including Landau contribution (25 ps). Estimated jitter contribution: **39 ps**

In test beam configuration, improved DAQ (with FPGA) should improve jitter resolution by 35% achieving ~25 ps target

Road to specifications – many prototypes

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TDR samples

Manu-facturer	Name	Thickness [µm]	Gain layer dopant	C implant	Gain layer depth [µm]	Gain layer depletion [V]
HPK	HPK-3.1	50	Boron	No	1.6	40
HPK	HPK-3.2	50	Boron	No	2.2	55
FBK	FBK-UFSD3-C	60	Boron	Yes	0.6	20
CNM	CNM-AIDA1/2	50	Boron	No	1.0	45
NDL	NDL-33µm	33	Boron	No	1.0	20
Manu-facturer	**Name**	**Full depletion [V]**	**V_{BD} −30 °C [V]**	**Nominal IP [µm]**	**Nominal SE [µm]**	**Max. Array Size**
HPK	HPK-3.1	50	200	30-95	200-500	15 × 15
HPK	HPK-3.2	65	70	30-95	200-500	15 × 15
FBK	FBK-UFSD3-C	25	170	37	200-500	5 × 5
CNM	CNM-AIDA1/2	50	220/50	37-57	200-500	5 × 5
NDL	NDL-33µm	35	70	55	450	15 × 15

NEW SAMPLES

Manufacturer	Name	W [µm]	GL [µm]	V_{gl} [V]	Dopant/C	SE [µm]	IP [µm]	Max. Array Size
HPK (HPK-P2)	P2 (4 splits)	50	2.2	50.5-54.5	B/NO	300-500	30-70	Single,2x2,3x3,5x5, 15x15,15x30
FBK	UFSD 3.2	50	2	35-50	B/YES		28	Single, 2x2
NDL	V3	50	~1	29	B/NO			2x2

FBK prototype run – very ambitious – 19 wafers processed exploring wide range of parameters (C,B, depth, width)

Gain layer – crucial for LGAD operation

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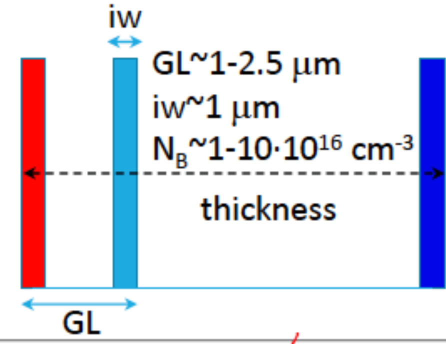
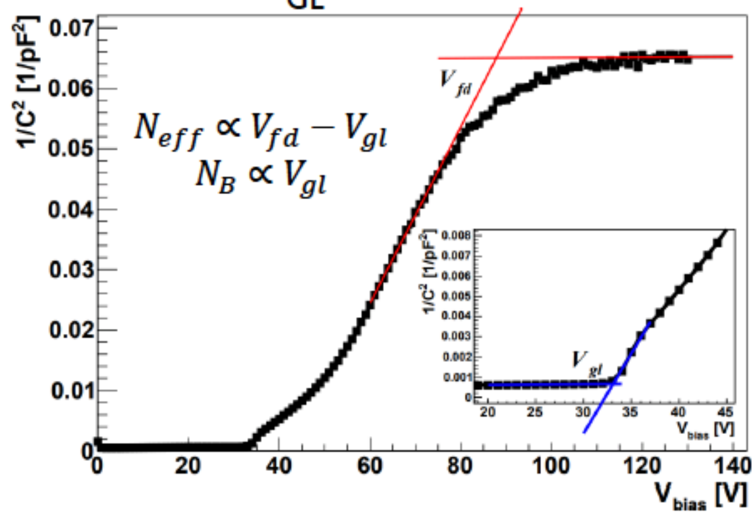
- Gain decreases as boron substitutional atoms get deactivated ("acceptor removal") –> reduction of the field
- Ways to mitigate degradation of gain layer:
  - Make the implant thinner (IW) and more doped N_B (~1e17 cm^{-3}), reduces the acceptor removal constant (c~2-7·10^{-16} cm^2)
  - Increase the bias voltage -> after depletion increase of electric field in the GL is $\Delta E \sim \Delta V_{bias}$/thickness
  - Make the implant deeper (increase of GL)
    - Larger multiplication region
    - Easier to recuperate the electric field ΔV_{gl}/GL compensated by ΔV_{bias}/thickness
  - Replacement of gain layer implantation material or co-implantation of material that decreases the acceptor removal rate (carbon)



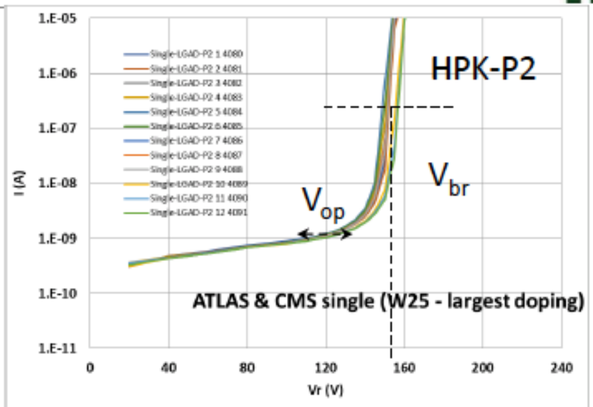


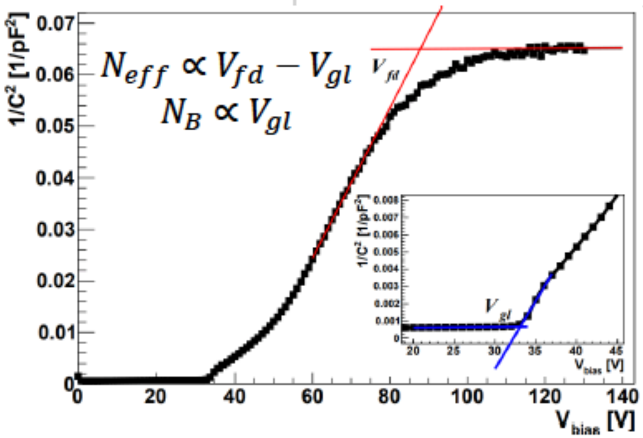
We do not specify these parameters, but work closely with producers for them to establish the most effective way of reaching our requirements.

Specifications - terminology

TERMINOLOGY:

- V_{gl} - gain layer depletion voltage
- V_{fd} - full depletion voltage
- V_{bd} - break down voltage
- I_{gen} - generation current
- I_{leak} – leakage current -> Ileak=Igen Gain
- V_{op} - operation voltage :
  - S/N>7
  - Increase of noise <20% low Vbias
  - Q>4 fC
  - long term operation assured
  - no/low rate ghost/spurious hits

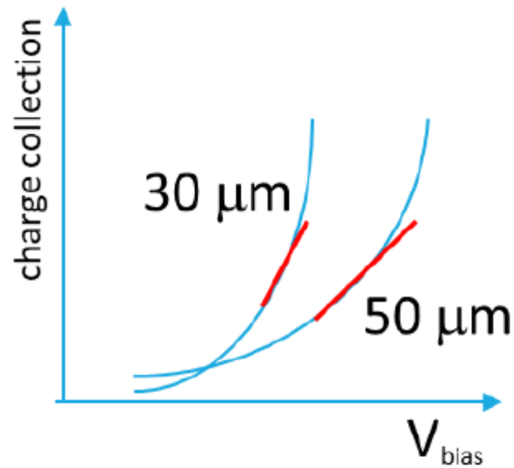




Optimization of sensor thickness

We investigated sensors of different thickness

- Smaller thickness – faster signal – less Landau fluctuations
- Smaller bias voltage required for given gain after irradiation – less power
- Larger capacitance
- Less charge generated by mip particle
- Steeper dQ/dV – difficult to control the V_{op} particularly for sensors where the variation of fluence is significant over the sensors



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ATLAS EXPERIMENT

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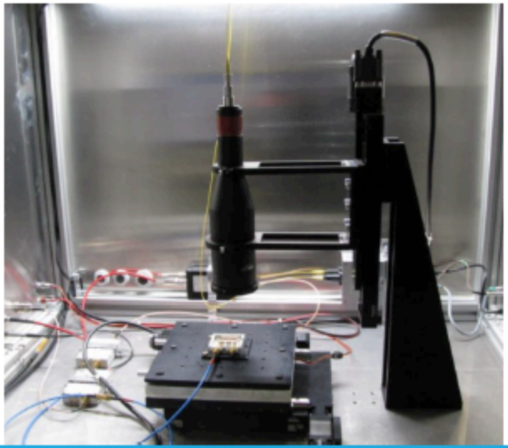
Main tools used to evaluate detectors

CV/IV – probe station (V_{gl}, V_{fd}, I_{gen})

- most of the capacitance measurements done at 20ºC and 2-10 kHz
- current measurements done also at lower temperatures
- probe card measurements for large arrays

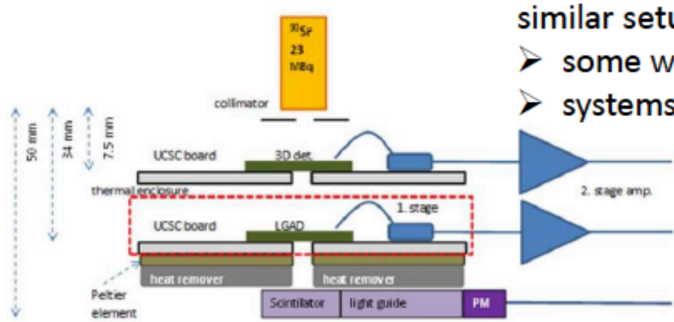
Laser/TCT measurement

convenient to study multi electrode arrays in absence of readout ASIC



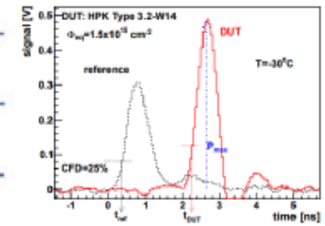
Beta scope

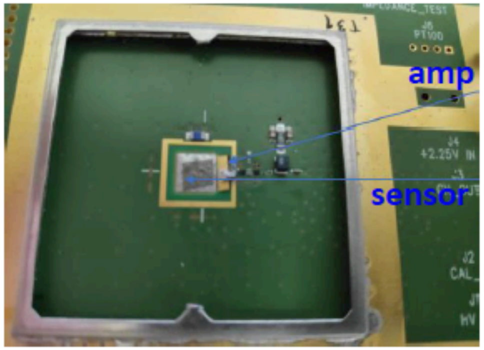
Timing and Charge measurements



similar setups at different labs

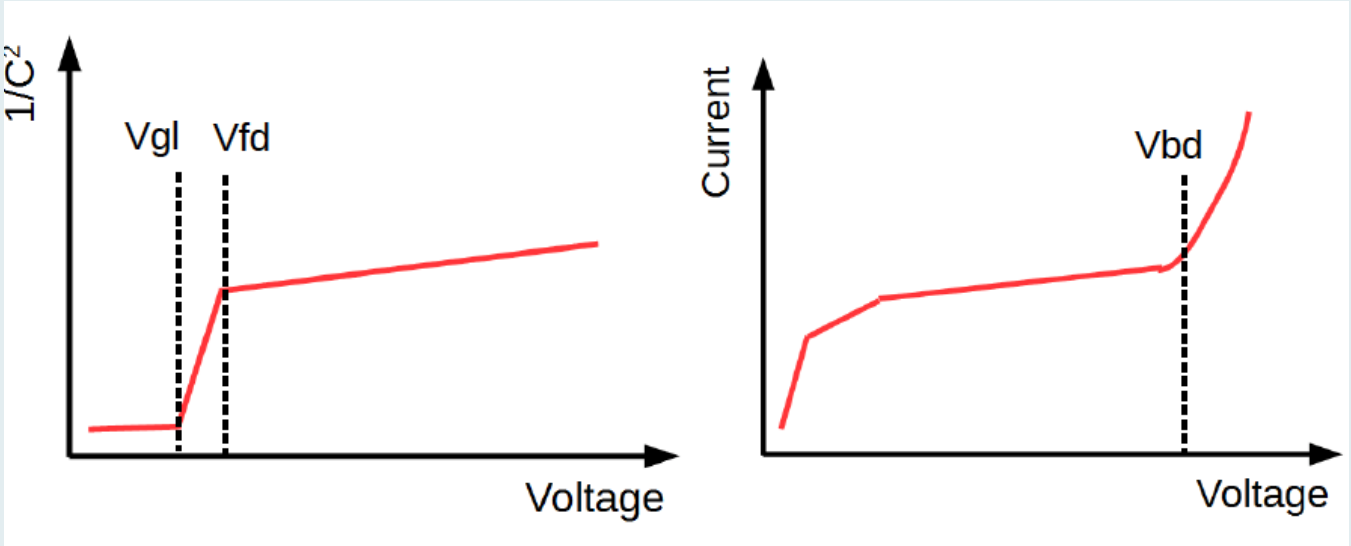
- some without Sci+PM
- systems inter-calibrated

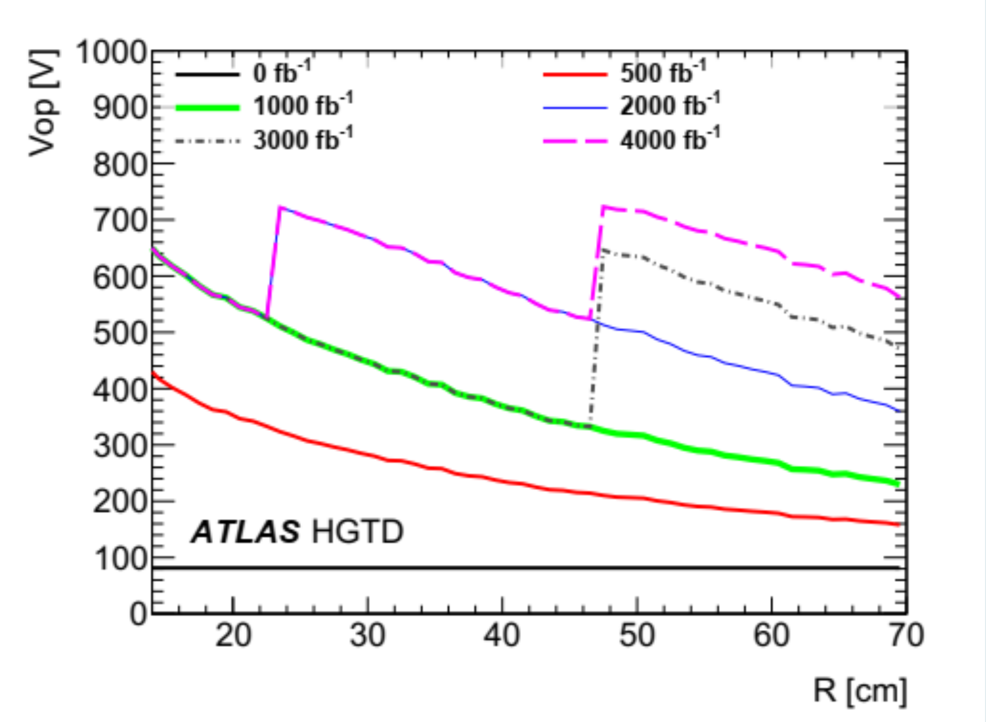




UCSC boards is mostly used

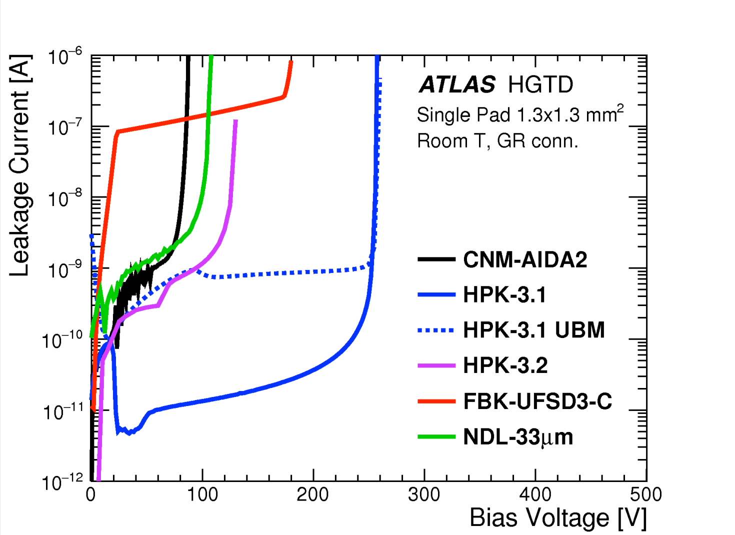
- transimpedance amp (470Ω)
- wideband width >3 GHz
- 4 Ch. version exists

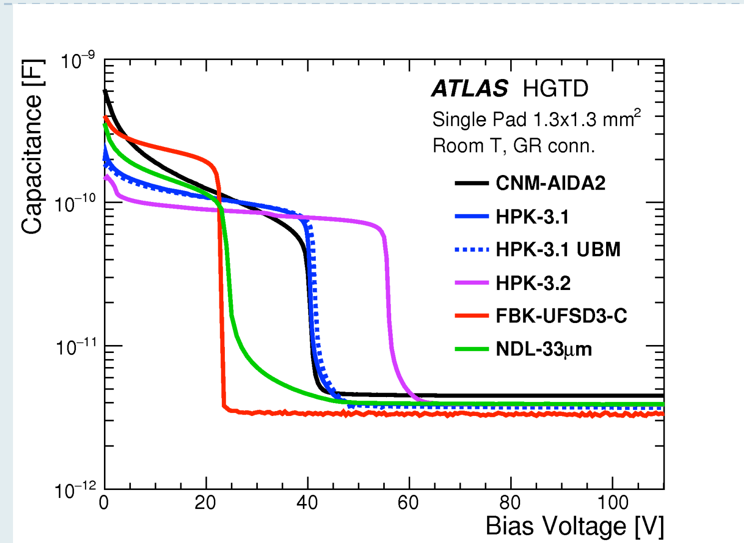


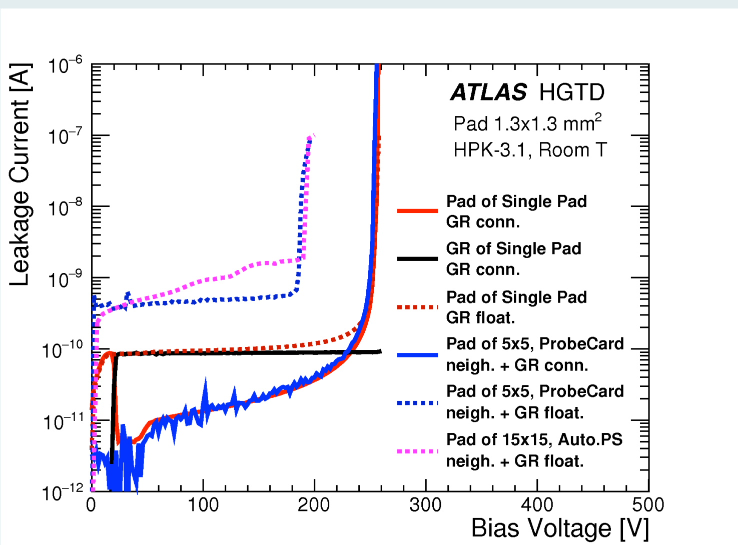


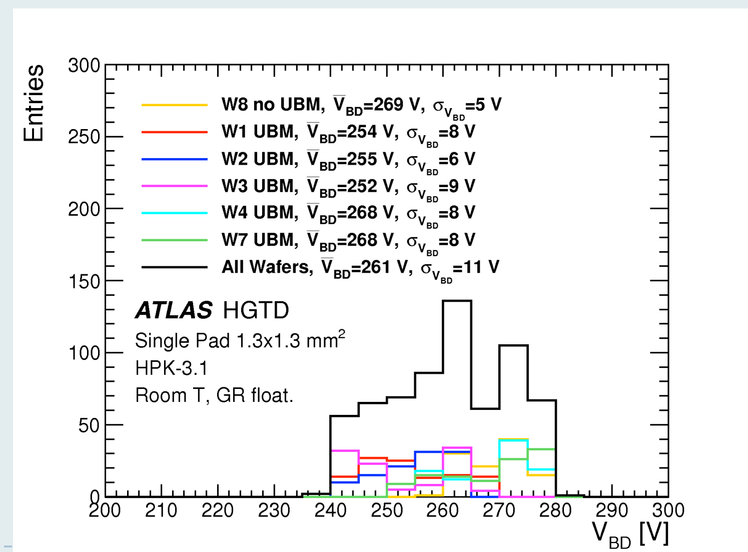
Planned operation voltage for LGAD
vs luminosity / R

IV,CV and V_{BD} curves

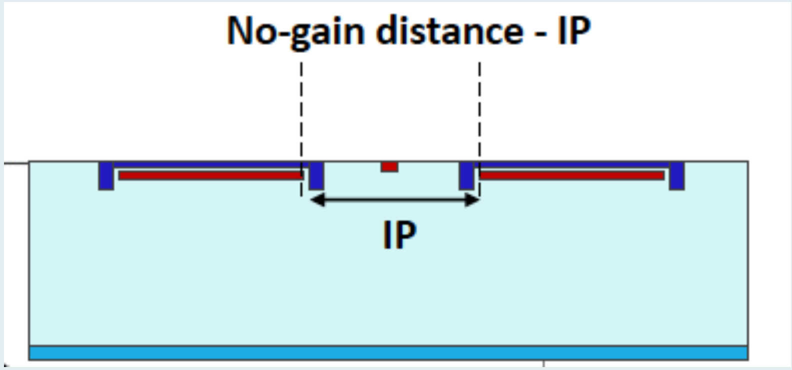


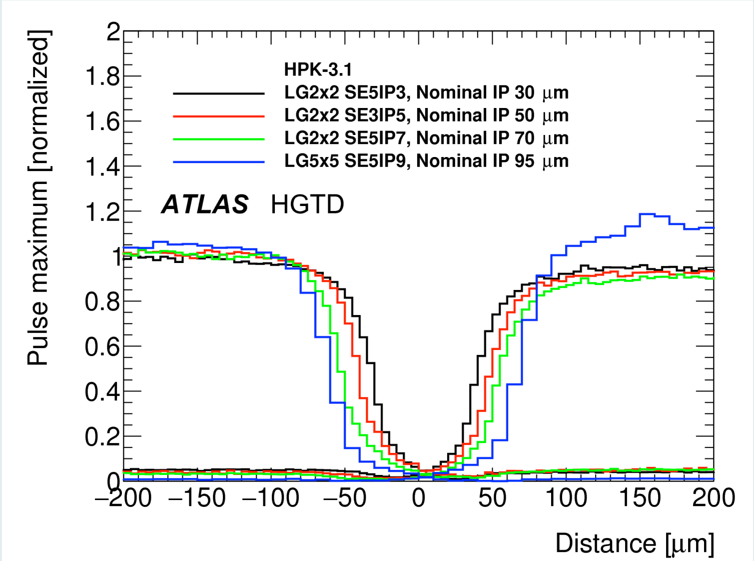




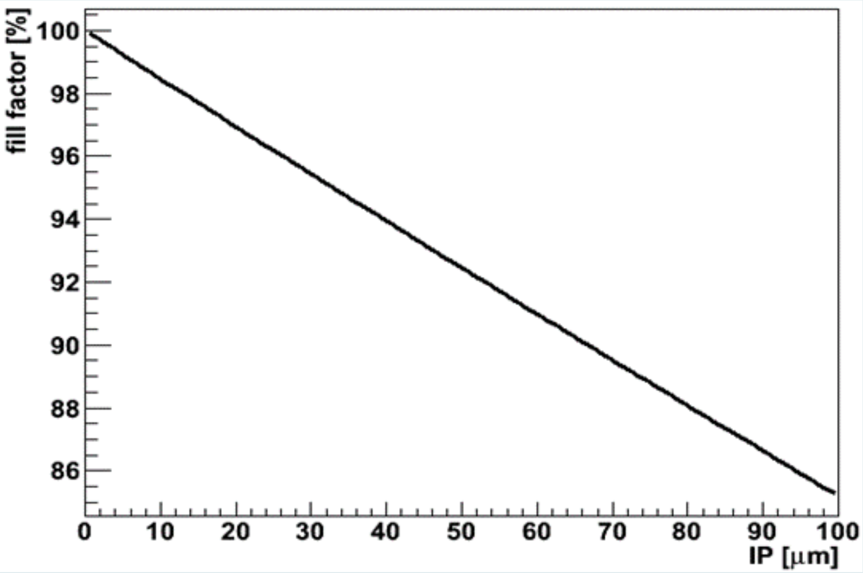


Sensor Inter pad

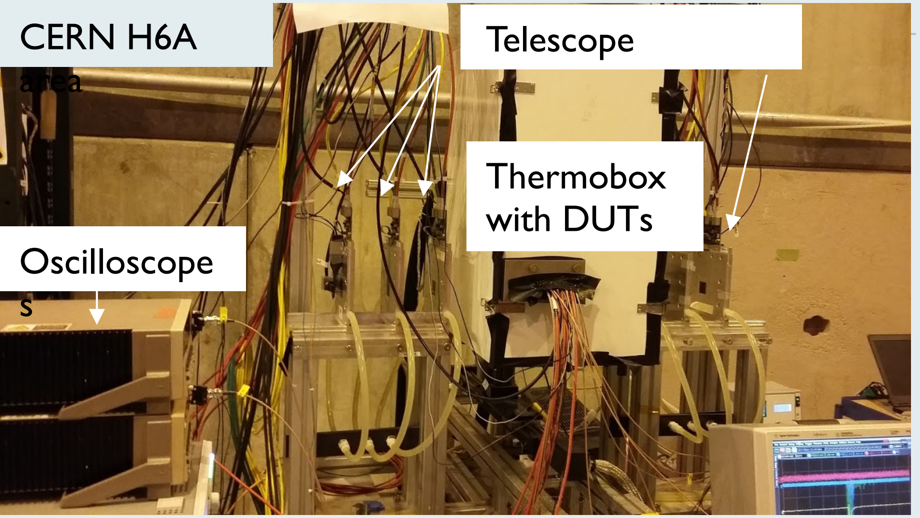


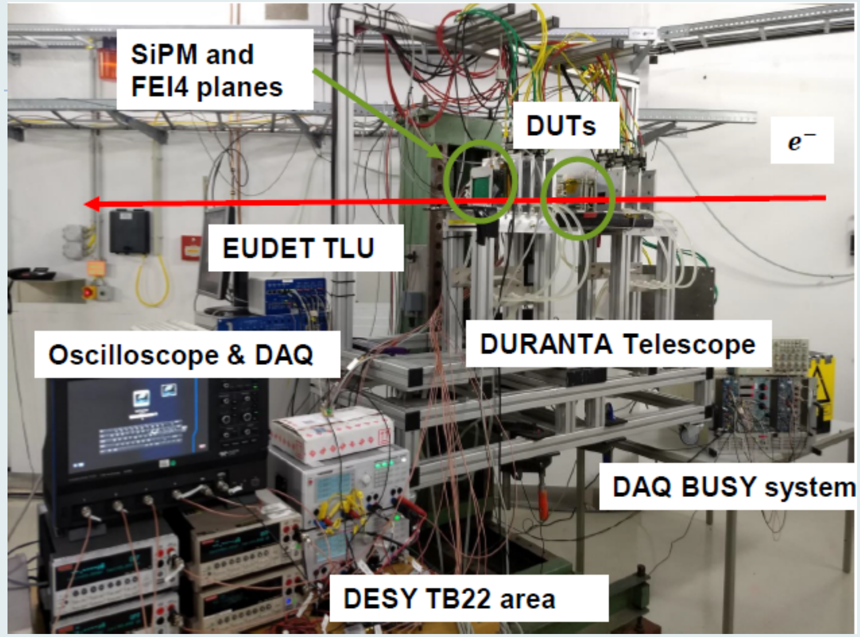


Inter pad with laser for several HPK-3.3



Test beam setup





- ✓ **Sensors -** between 2 arms of a **TELESCOPE EUDET-type** (3 MIMOSA planes per arm) inside a **cooling**
  readout by **oscilloscopes** (2 oscilloscopes at CERN, 1 at DESY)
- ✓ On same oscilloscope, a Cerenkov light Quartz bar + Si PM provide **independent time reference**
- ✓ **Trigger by FE-I4** plane with a ROI geometrically optimized around sensors position
- ✓ Two plastic **scintillators** at each extremity of the telescope is also part of the TLU

Data analysis scheme

Data from telescope

Tracking program

Noisy pixels removal
Clustering
Telescope plane alignment
Tracks fitting
⇨ Hit position in DUT plane

Root-tuple for user analysis

DUT signal information
hit position

Data from oscilloscope

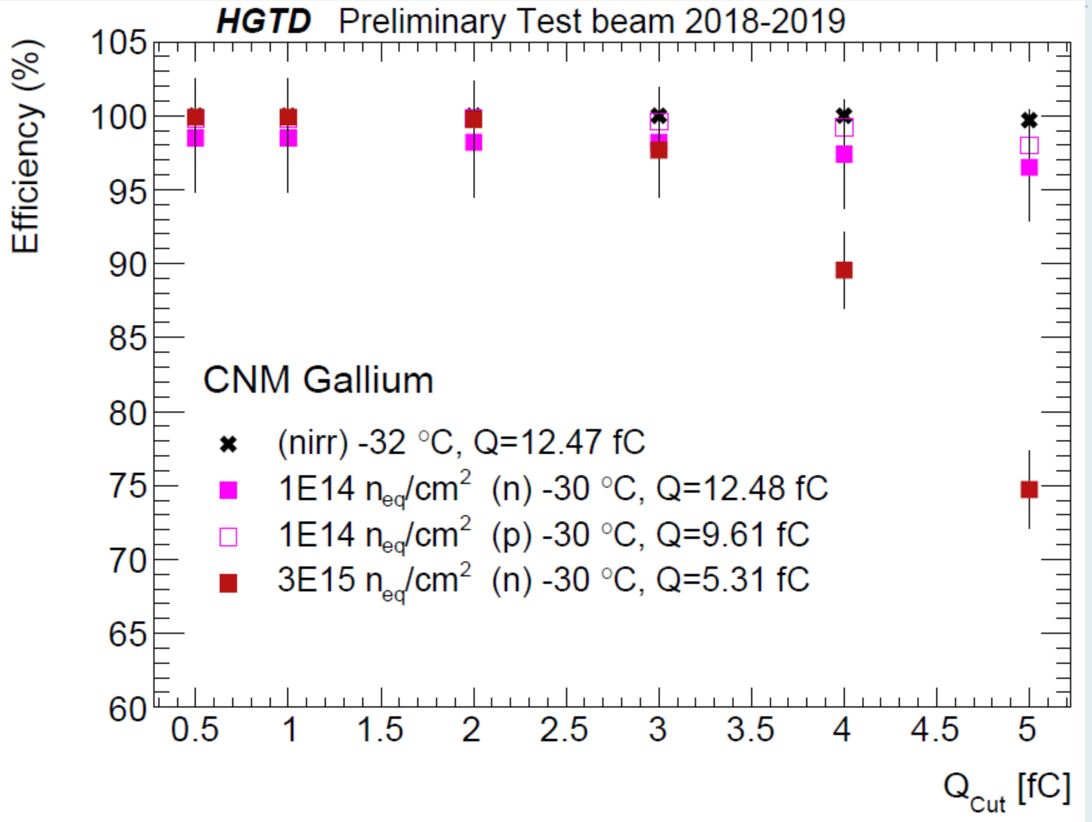
LGAD waveform processing

Pedestal substraction
Signal start and stop
Compute noise, charge,
rise time, time at different CFD fraction or with CTD…

Tracks reconstructed asking exactly one hit in FE-I4 plane.

Tracks fitting : - straight lines for CERN data (120 GeV Pions)
- multiple scattering for DESY data (5 GeV electrons) with EUTelescope

Efficiency vs charge threshold



CNM sensors doped with Gallium

- unirradiated
- irradiated with neutrons or protons

✓ For the highest bias voltage point of a given sensor, efficiency is computed for different charge thresholds.

$$\varepsilon = \frac{\textit{Tracks in the central area (0.5x0.5 mm}^2\textit{) with Q> threshold}}{\textit{Tracks in the sensor center}}$$

✓ The threshold at 2 fC for the collected charge corresponds to the threshold of the electronic discriminator