A High Granularity Timing Detector for the ATLAS Phase-II Upgrade

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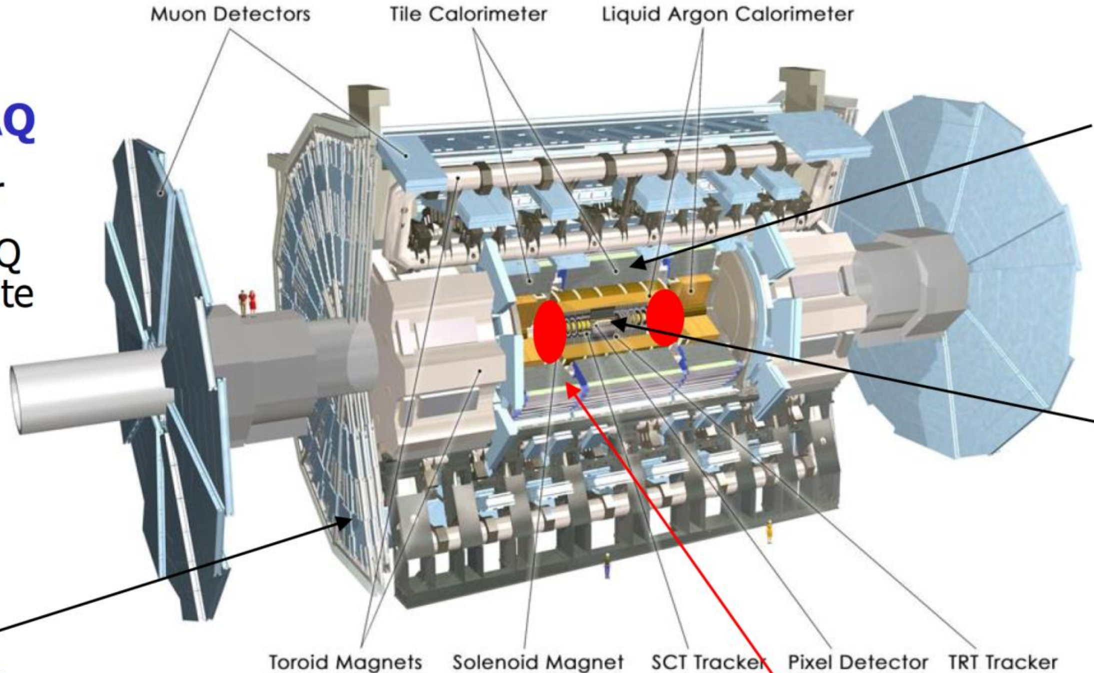
Outline

- The ATLAS detector phase II upgrade
- The case for the ATLAS High Granularity Timing Detector
- Description of the HGTD system
  - HGTD layout and properties
  - Low Gain Avalanche Detector technology
- Measurements of LGAD sensors and electronics performances
- HGTD readout
  - ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC)
  - ALTIROC1 test
- HGTD Module and radiation hardness
- HGTD project status

The ATLAS Detector Phase-II upgrade for HL-LHC

- The ATLAS detector is undergoing a significant upgrade program for all subsystems to operate in challenging HL-LHC conditions
  - Luminosity up to 7.5×10^{34} $cm^{-2}s^{-1}$, pileup $\langle\mu\rangle \sim 200$, irradiation level TID ~2MGy
  - L1 trigger rate of 1 MHz. Additional 15 years of operation and maintenance



Trigger + DAQ
- Track trigger
- Upgrade DAQ for higher rate

Calorimeters
- Upgrade electronics

Inner Tracker
- Full replacement: all-Si extended to $|\eta|=4$

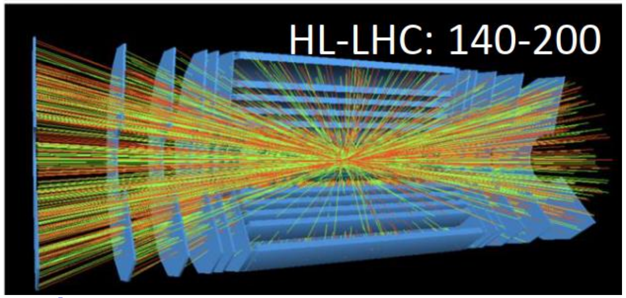
Muon System
- New trigger chambers in barrel

- High Granularity Timing Detector
- Silicon-based novel detector

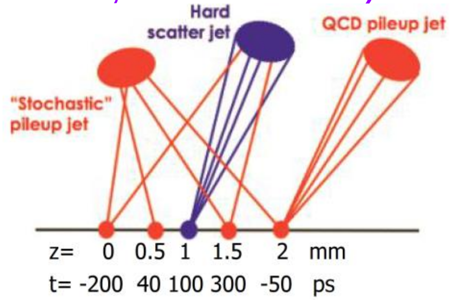
The case for the HGTD: Pile-up challenge

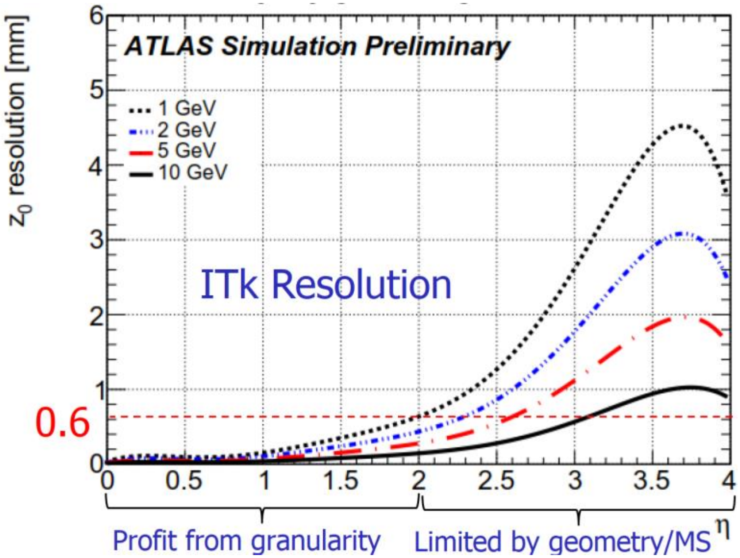
- Main challenge for detectors at the HL-LHC is pile-up

	Energy	Instantaneous $\mathcal{L}$	Integrated $\mathcal{L}$	Pileup
Run 2 LHC	13 TeV	2×10^{34} cm^{-2}s^{-1}	300 fb^{-1}	37
HL-LHC (Nominal)	14 TeV	5×10^{34} cm^{-2}s^{-1}	3000 fb^{-1}	140
HL-LHC (Ultimate)	14 TeV	7.5×10^{34} cm^{-2}s^{-1}	4000 fb^{-1}	200



  - With ~7 pileup jets (p_T>30GeV)
- Need to identify if particles or jets come form hard scattering vertex
  - Misidentification affects reconstructed physics objects (efficiency, fakes, resolution…)
- Vertices spread out with σ_Z=45mm, over ~175 ps
  - With 1.6 vertices/mm ⇒ <0.6 mm ITk resolution

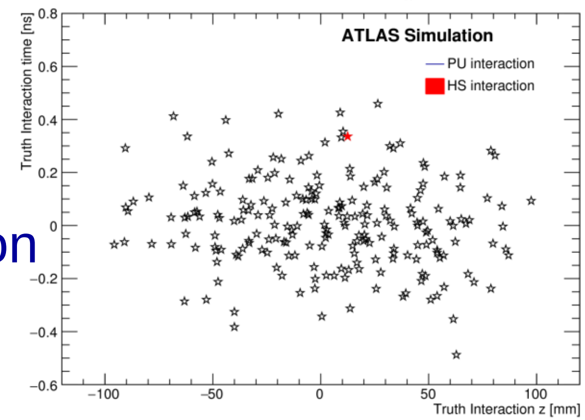




ITk performs well only up to |η| ~ 2-2.7

Assign time to each track in 2.7<|η|<4.0

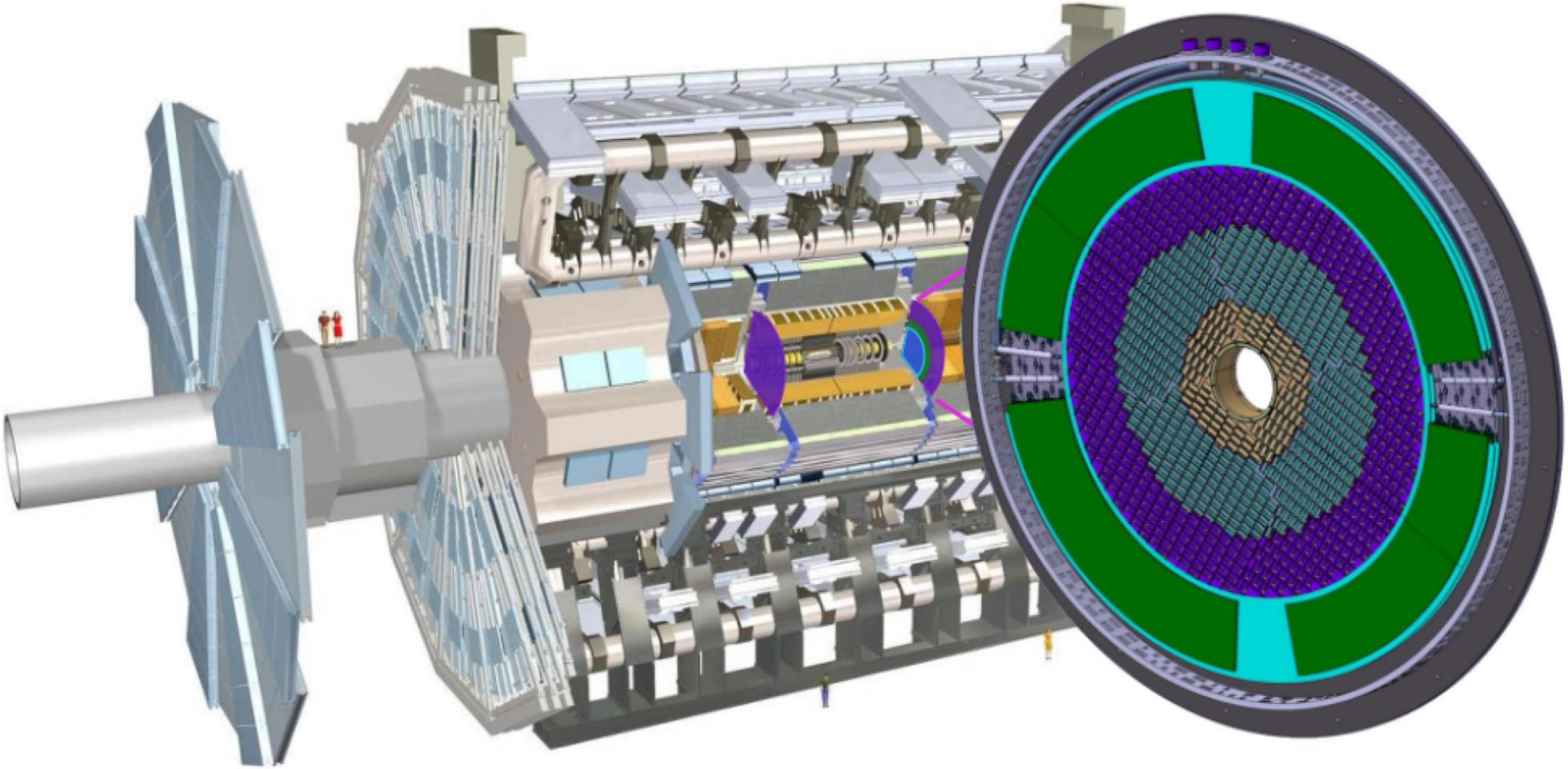
30-50 ps time resolution per track would give ~x6 pile-up rejection



The HGTD system

Compact: limited space, maximum thickness: 12.5 cm

Radiation hardness: Fluence $2.5 \times 10^{15} n_{eq}/cm^2$, TID 2 MGy

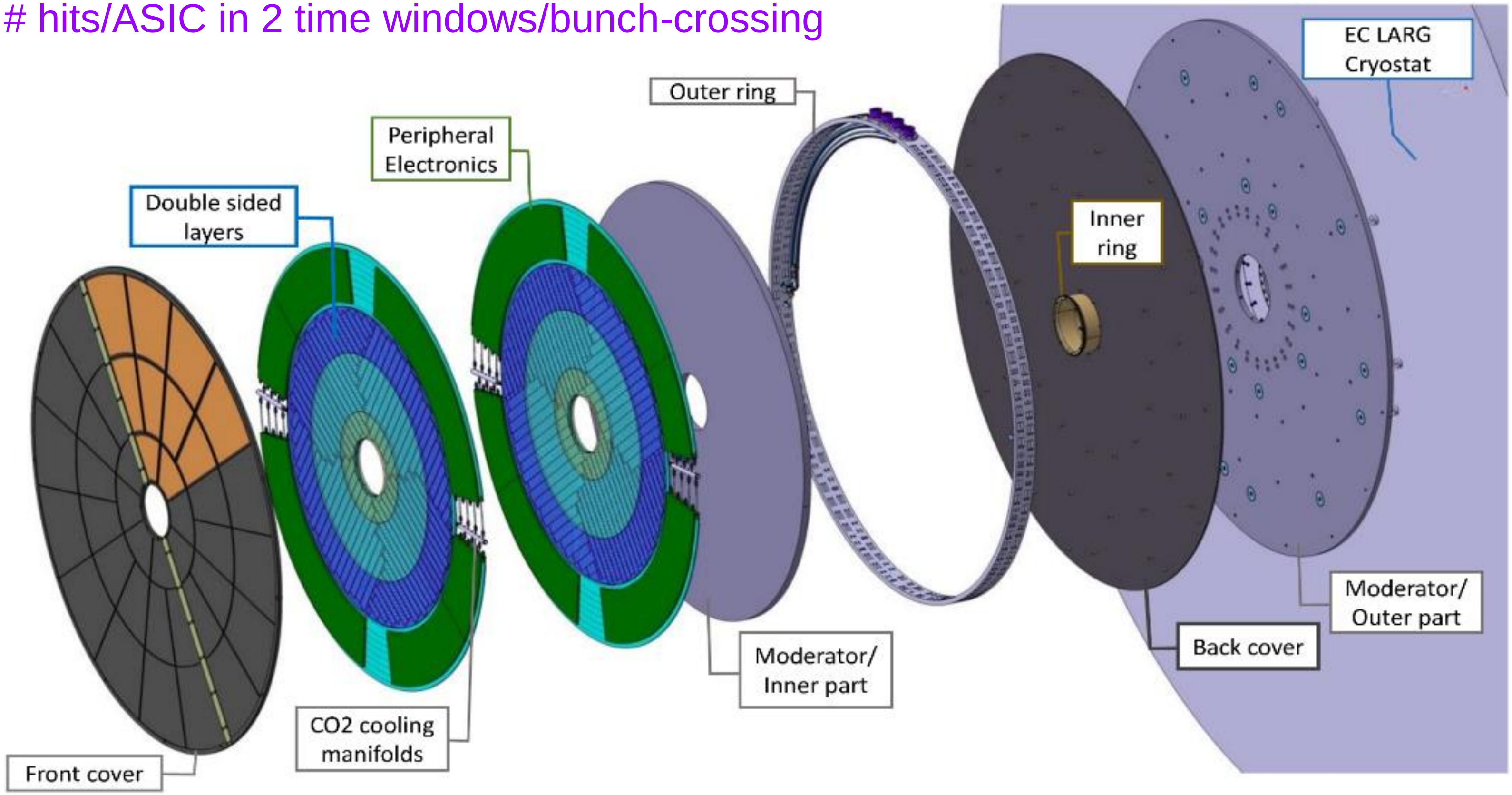


The HGTD Layout

- To satisfy all requirements and constraints: Silicon-based detector:
  - 2 disks/side, 2 sensor layers/disk. Active area 2.4 < |η} < 4.0
  - Total number of channels: 3.6 M
  - Sensors operated at -30 °C

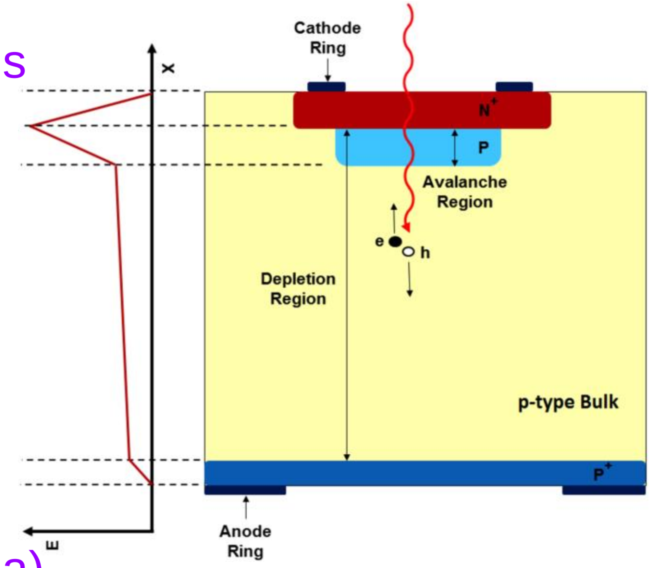
Target time resolution: 30-50 ps/track up to 4000 fb^{-1}

- HGTD will provide also a luminosity measurement:
  - # hits/ASIC in 2 time windows/bunch-crossing



The LGAD sensors for the HGTD

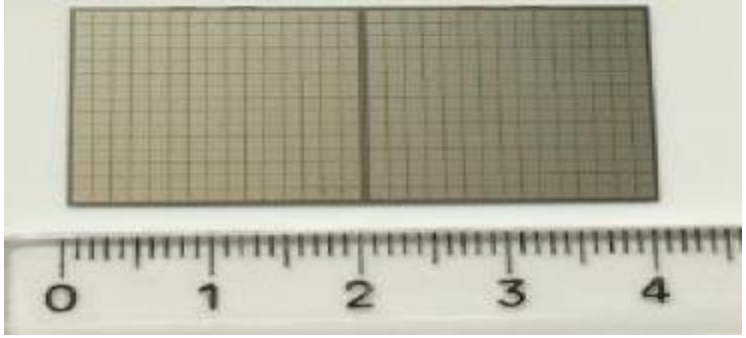
- Low Gain Avalanche Detectors: Originally developed by CNM and RD50
  - Standard n-p Si detector with an additional p-type doped laying producing additional charge multiplication
    - 6” and 8” wafers, 50 μm active thickness. B-dopant for highly p-doped multiplicative layer. Considered Ga as well as pursuing additional C-spray.
    - High E field. Internal gain (V_{bias} < 800 V) > 20 before irradiation, and > 8 at the end of lifetime
  - Small rise time: ~0.5ns, fast charge collection ~1 ns
  - Good timing requires a minimum collected charge of 4 fC/mip/hit
  - Hit efficiency > 95% at the end of lifetime



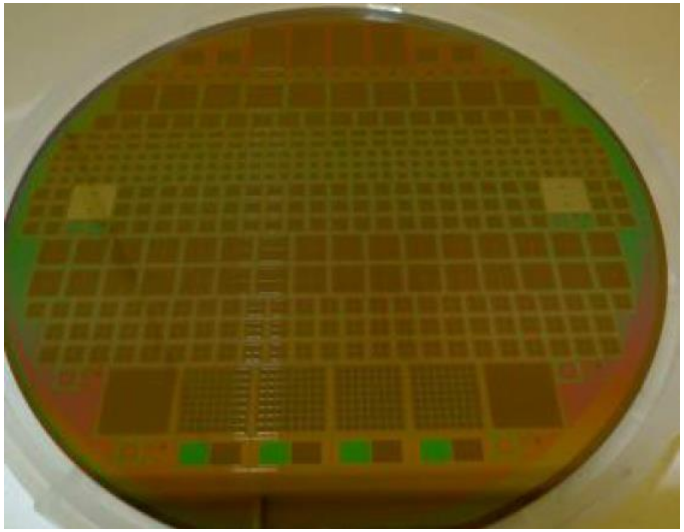
- Several prototypes are being tested:
  - CNM (Spain), HPK (Japan), FBK (Italy), IME (China), NDL (China)

LGADs Performance measurements

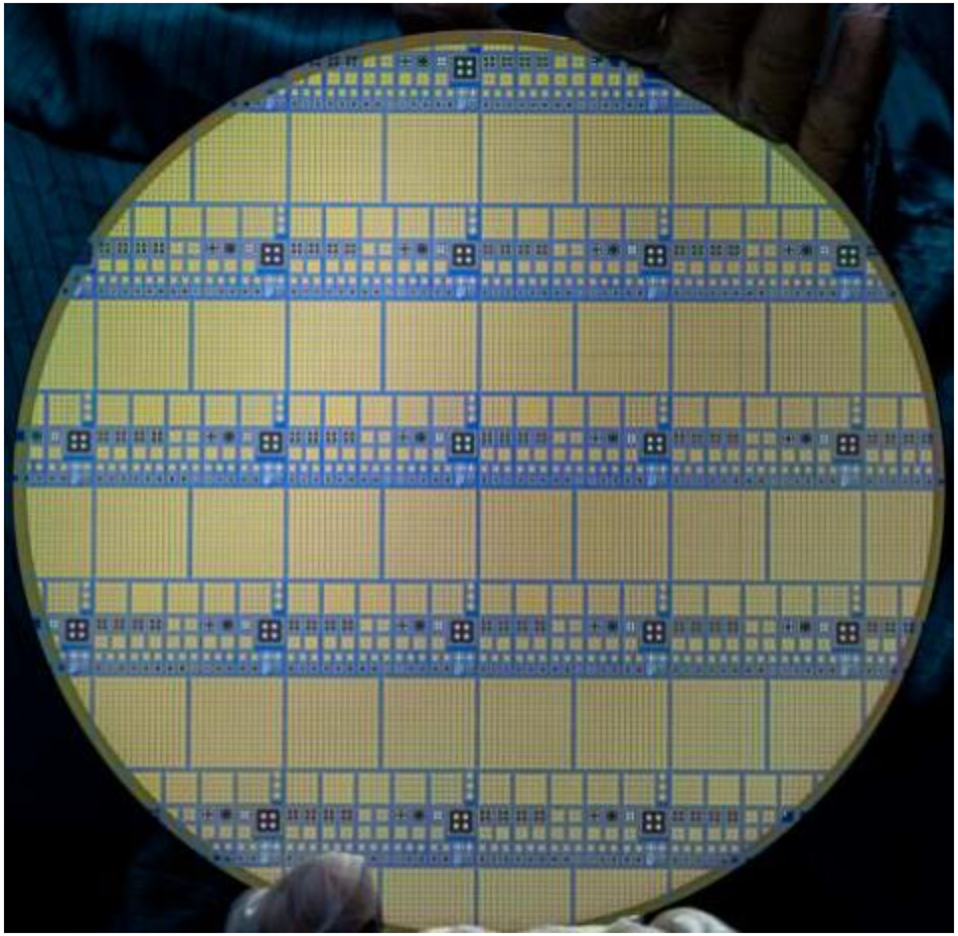
HPK-P2



CNM

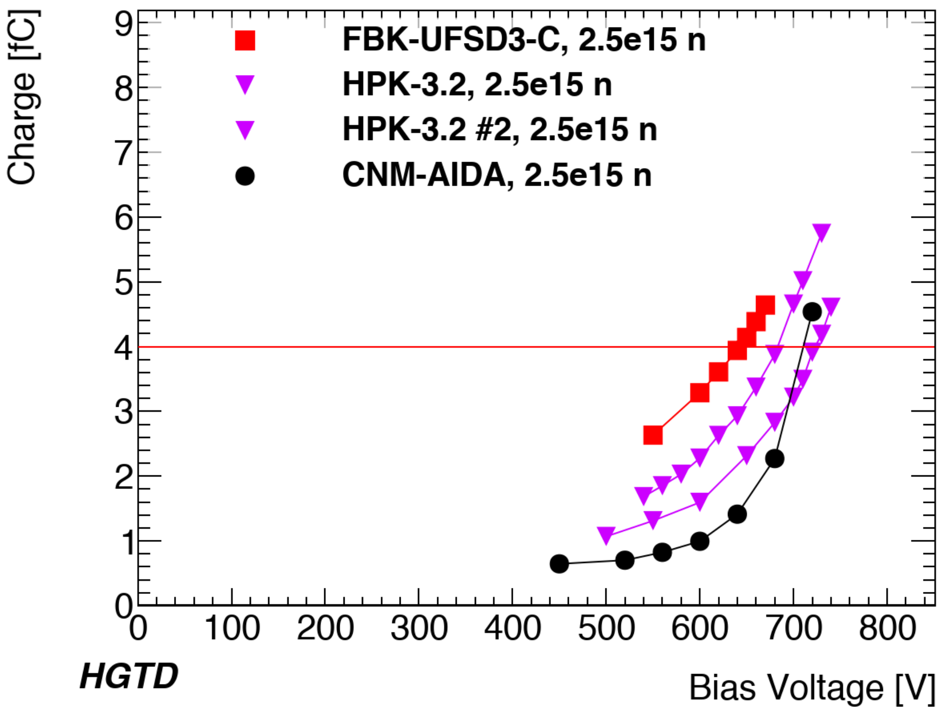


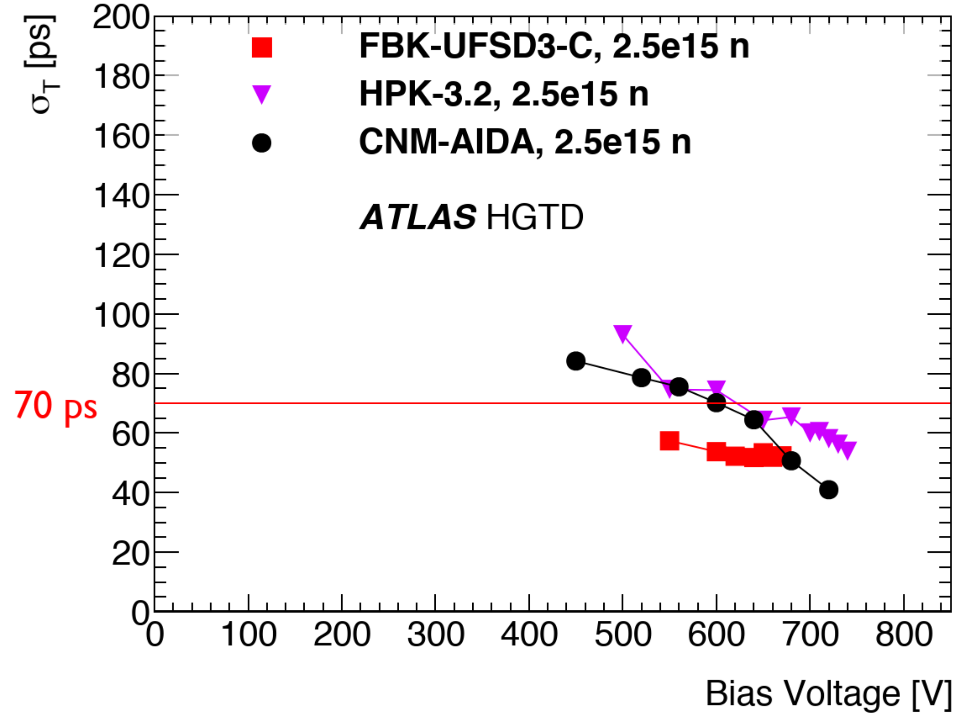
IHEP-IMEv2



LGAD Sensors Laboratory Measurements

- Using ^{90}Sr β to measures LGAD dynamic characteristics
- Collected charge and time resolution as a function of bias voltage from various manufacturers.
  - Better performance for sensors with C enriched gain layer. Same charge for lower bias voltage.

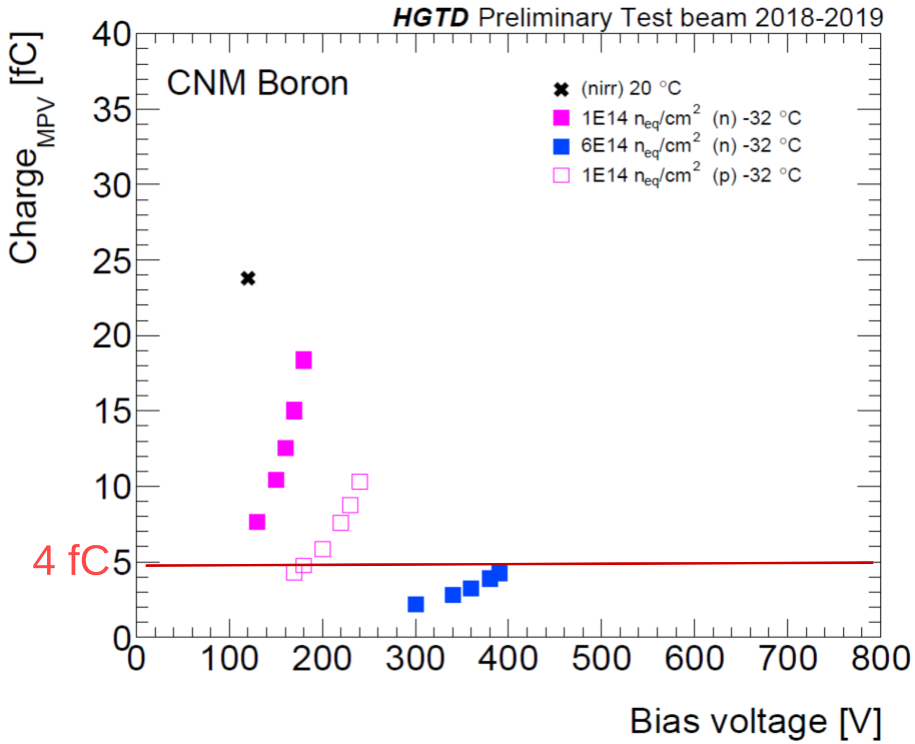




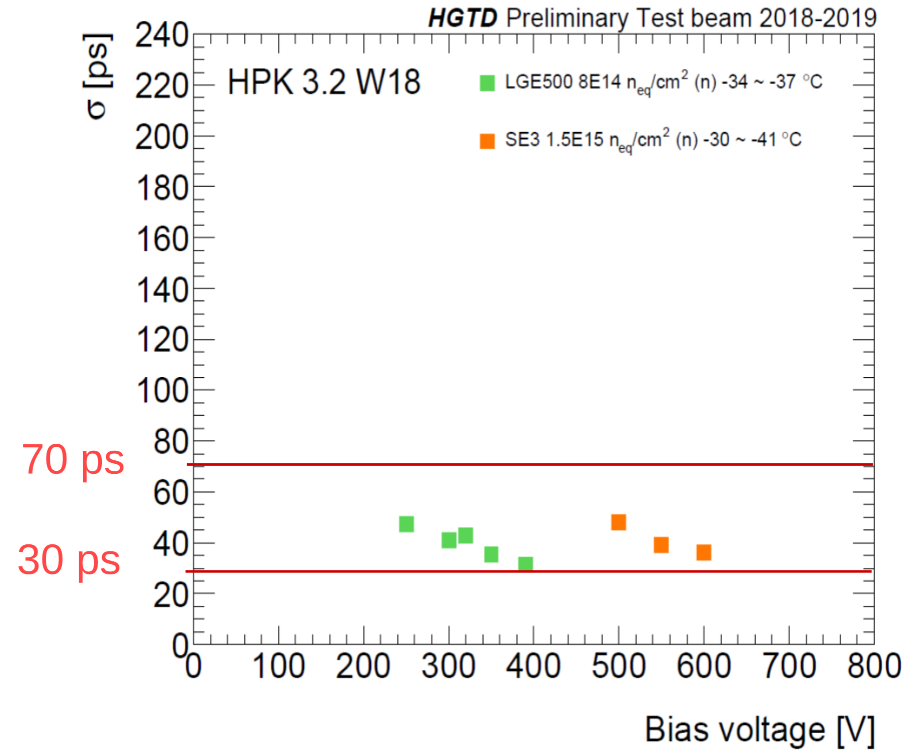
LGAD sensors from a variety of vendors satisfy both collected charge and time resolution requirements after irradiation to $2.5E^{15}$ n_{eq}/cm^2

LGAD sensors test beam results

- Collected charge:



- Time resolution:



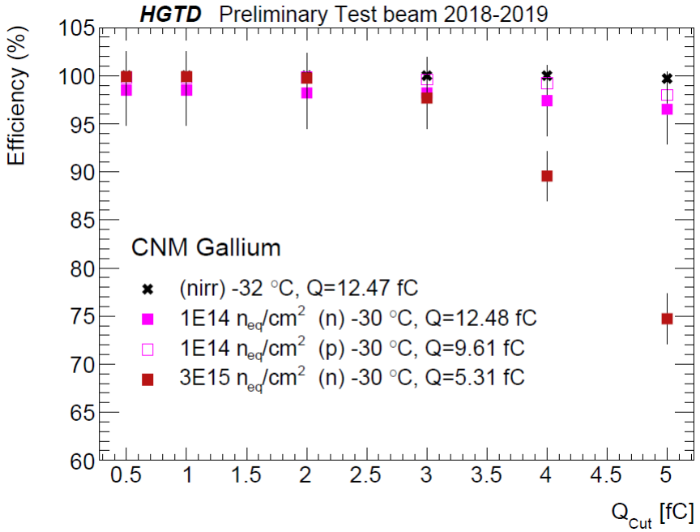
- Collected charge = MPV of the Landau-Gaussian fit of charge distribution
  - CNM B-doped Q = 4.2 fC (V=390 V, 6×10^{14} n_{eq}/cm^2)
- HPK n-irradiated at 1.5×10^{15} n_{eq}/cm^2
  - σ = 36 ps (600 V and for Q coll = 22.8 fC)
- Tested sensors that have Q coll >4 fC have a time resolution better than 40 ps at higher bias voltage

LGAD sensors test beam results

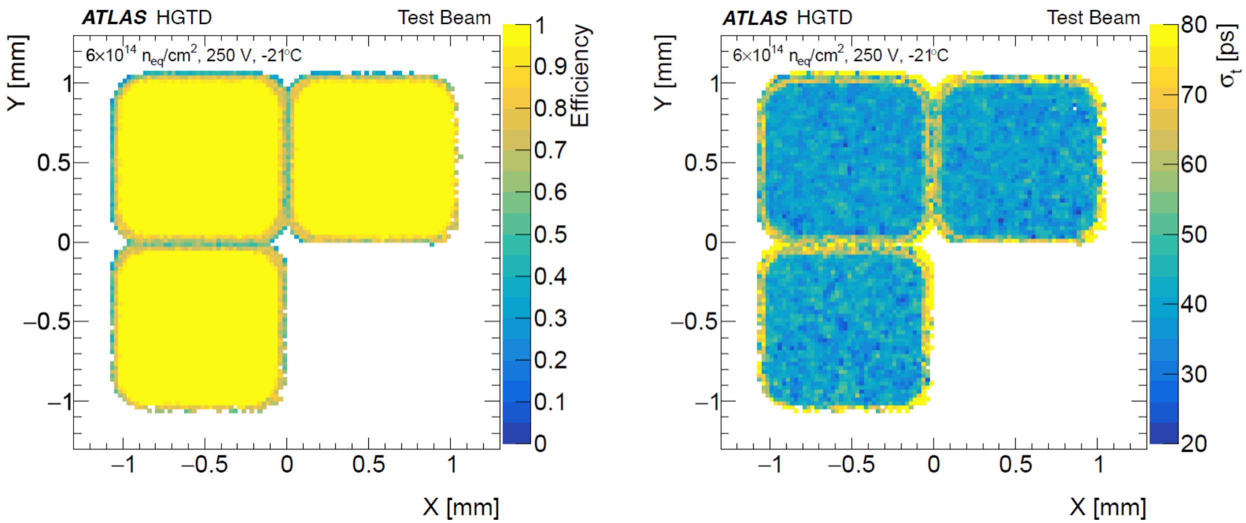
- Efficiency measurements:

$$\varepsilon = \frac{\text{Number of tracks with } Q > 2fC \text{ in central region}}{\text{Total number of tracks in central region}}$$

- $Q > 2fC$ corresponds to the ALTIROC threshold
- For CNM n-irradiated, Ga doped sensors, at $3\text{x}10^{15}$ neq/cm^2
  - ε = 99.7% for V = 740 V and Q coll=5.3 fC



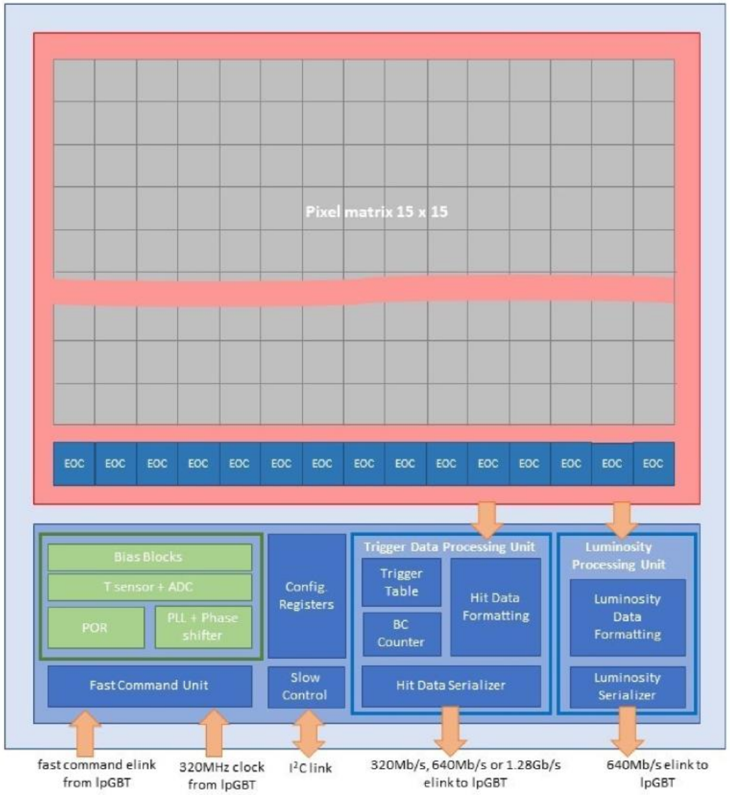
- 2-D efficiency map: CNM with 2x2 arrays, n-irradiated at $6\text{x}10^{14}$ n_{eq}/cm^2



- Time resolution has 3ps variations across the pad center.

ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC)

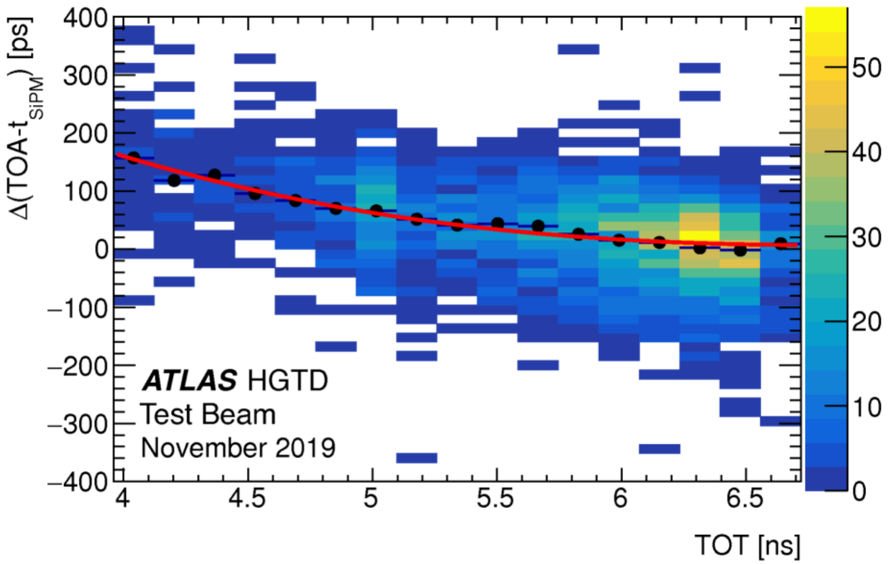
- Signal from each LGAD sensor will be read out using the ALTIROC chip.
  - TSMC CMOS 130nm technology. Total of 225 readout channels (15x15)
  - Pre-amplifier followed by TOA and TOT (for time-walk correction)
  - Threshold for ALTIROC Discriminator 2 fC
- Two prototypes of ALTIROC chips produced and tested:
  - ALTIROC0: 2016
    - four channels in a 2x2 array. Each channel 200x100 μm^2 = Preamplifiers + TOT and CFD
  - ALTIROC1: 2018
    - 25 channels in 5x5 array
    - Preamplifiers,TOT, CFD + digital components
- Ongoing development:
  - ALTIROC2: 2020-2021
    - 225 channels. All functionalities of final ASIC
  - ALTIROC3:
    - Radiation hard version of ALTIROC2

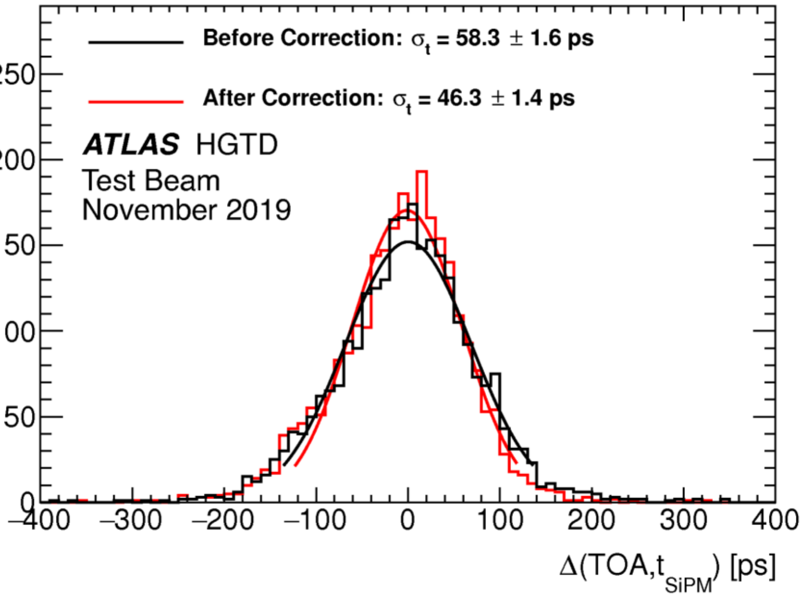


ALTIROC1 with 4pF input capacitance can achieve ~25ps jitter at 4fC input charge

ALTIROC1 measurements in test beam

- Test beam measurement at DESY in 2019 for unirradiated ALTIROC1 modules. 5x5 ALTIROC1 devices with HPK and CNM sensors
  - Fit of TOA variation as a function of the TOT is used to calculate time-walk corrections



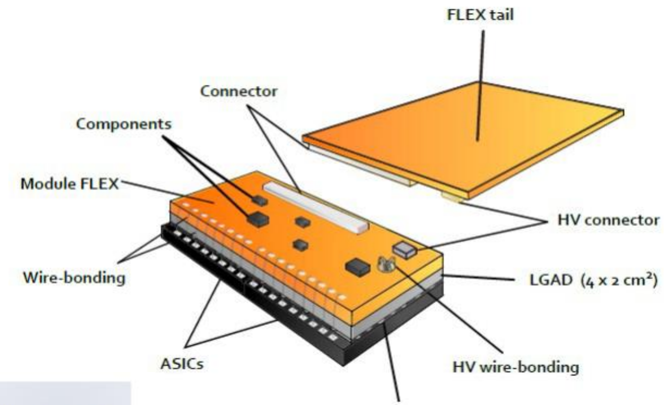


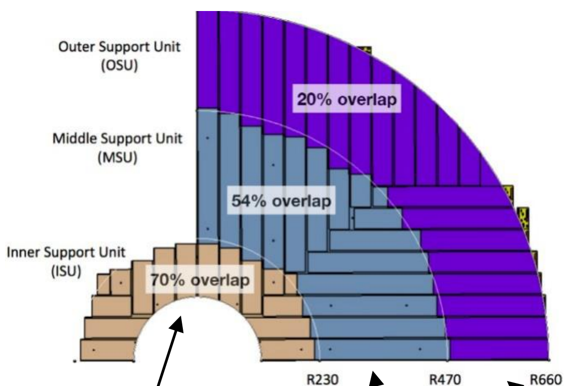
$t_{\mathrm{LGAD+ALTIROC}} - t_{\mathrm{Quartz+SiPM}}$

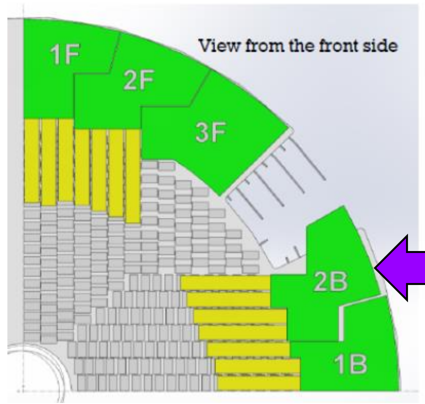
- Estimated resolution of 46 ps after time-walk correction and including Landau contribution (25 ps). Estimated jitter contribution: **39 ps**
- In test beam configuration, improved DAQ (with FPGA) should improve jitter resolution by 35% achieving ~25 ps target

HGTD Module

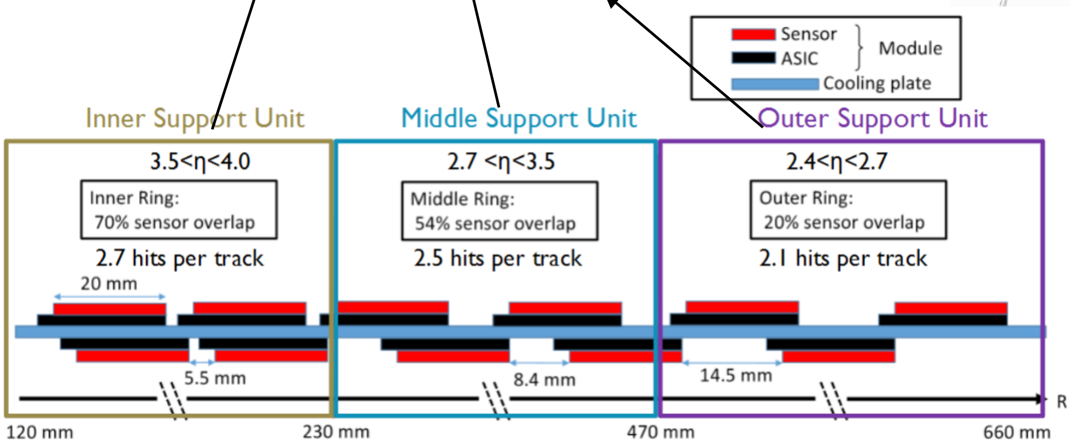
- Module made of 15x30 pads of 1.3x1.3 mm^2
- LGADs Bump-bonded to ALTIROCs
  - Hybridization process. 8032 modules, 6.4 m^2
- Flex-PCB glued on top
- Flexible tail to outer radius electronics







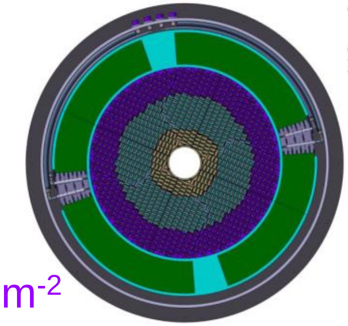
Peripheral Electronics Board transfer data between the detector modules and DAQ system

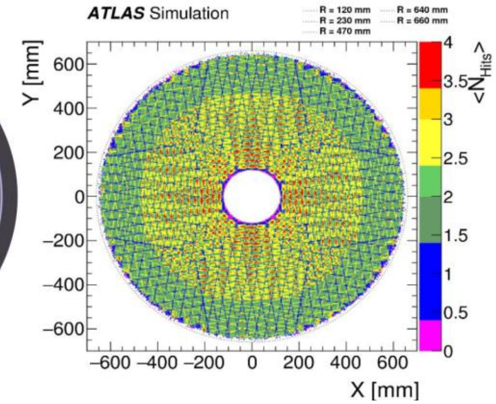


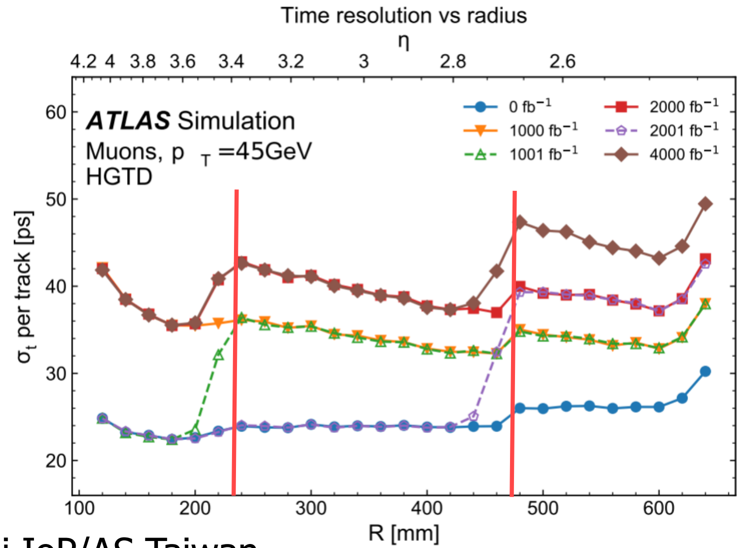
Overlap decreases with radius to maintain average Nhits per track 2≳

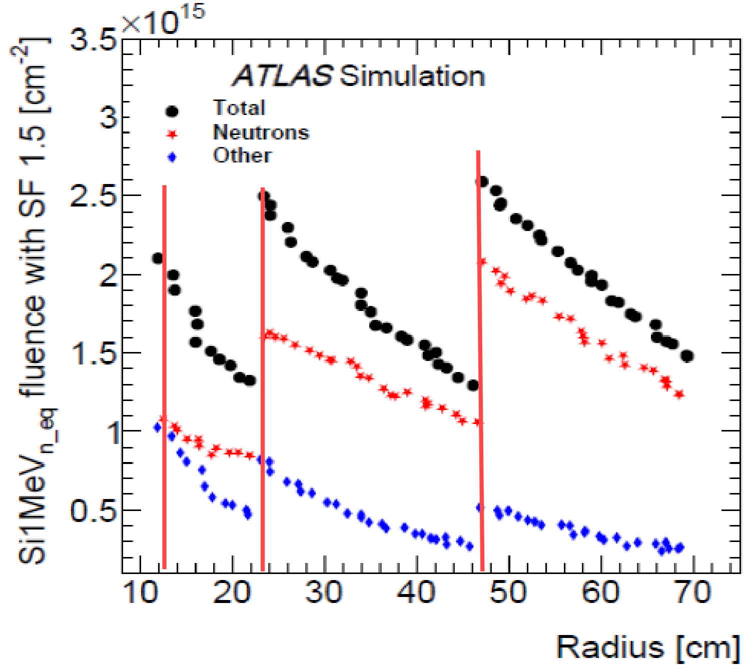
Radiation Hardness

- High radiation levels in the forward region requires specific optimization for HGTD design to keep stable performance:
  - Each disk is divided into 3 rings:
    - Inner (12-23 cm) replaced every 1000 fb^{-1}
    - Middle (23-47 cm) replaced every 2000 fb^{-1}
    - Outer (47-64 cm) never replaces
  - Limitations: TID 2MGy, fluence $2.5x10^{15}$ MeV/$n_{eq}cm^{-2}$
  - Safety factors:
    - x 1.5 for sensors
    - x 2.25 for readout electronics









HGTD project status and prospects

- Sensors
  - Many full size sensors in hand. Many full size sensors in hand
- Active R&D in ATLAS/CMS/RD50 to understand destructive breakdowns of some sensors observed at very high bias voltages and very high fluence
    - Most promising: Carbon diffusion, which allows lower HV operation for the same collected charged. R&D with manufacturer
- Electronics
  - ALTIROC2 design submitted. 20 8″ wafers will be produced
    - sensor/hybridization/module studies
- Module assembly
  - Preparations for first full-size hybrid prototyping. Tests with dummy modules
  - Studies on design on the PEB ongoing, choice of electronics components
- Mechanics
  - Design ongoing for hermetic vessel, cooling plate, outer ring
- Demonstrator
  - Heaters (cooling plates). DAQ with FELIX, ALTIROC2 emulator.
  - Full demonstrator (loading and testing of modules)

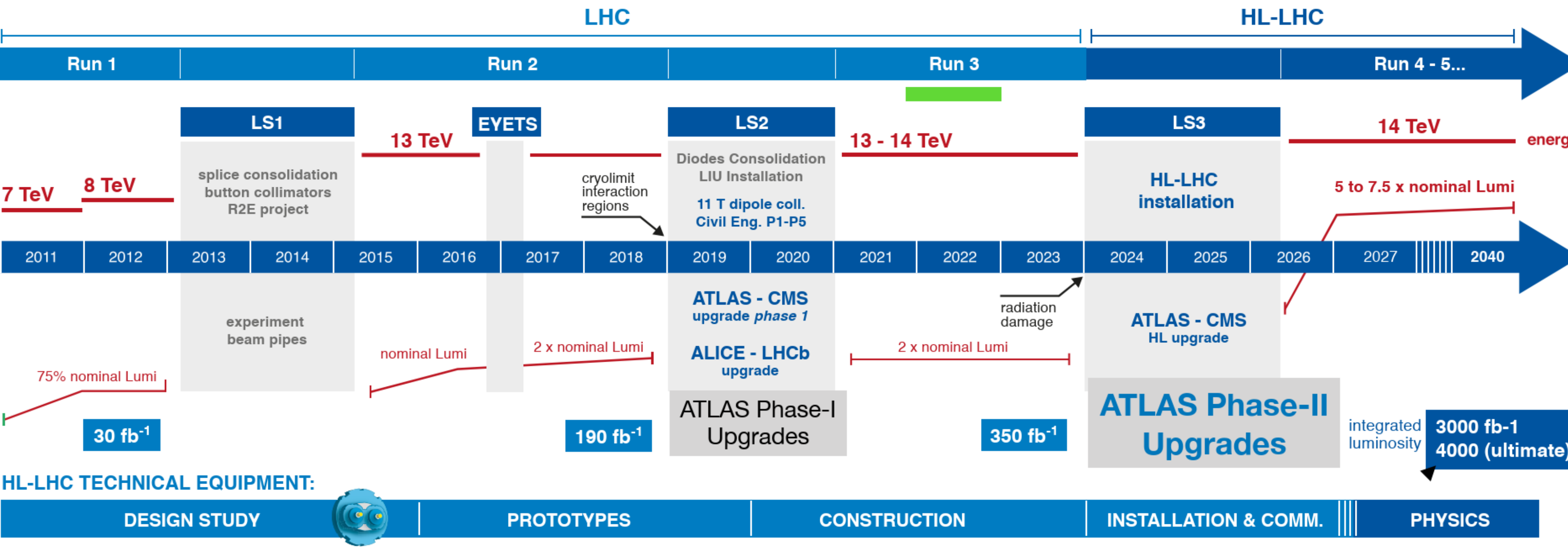
Conclusions

- With the HL-LHC challenging conditions, the timing information from ATLAS-HGTD is expected to play a key role in mitigating the impact of pile-up in the 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/are tested in test beams and in laboratories. Required performances are reached for several manufacturers
- The overall design and construction works are progressing. Intense R&D ongoing to improve radiation hardness. Installation is foreseen in 2026-27

Back-up slides

The High Luminosity LHC

- Upgrade program for the LHC accelerator aims to extend discovery potential with higher statistics and precision for rare processes



- HL-LHC presents definite challenges to the detector and its electronics
  - High luminosity: up to 7.5×10^{34} $cm^{-2}s^{-1}$, requiring a L1 trigger rate of 1 MHz
  - High pile-up conditions with $\langle\mu\rangle \sim 200$ producing very large occupancies
  - Increased radiation dose: up to 20x increase, reaching TID ~2MGy for 4000 fb^{-1}
  - 15 additional years of operation and subsequent maintenance

The HGTD Layout

Technology	Silicon Low Gain Avalanche Detector (LGAD)
Time resolution	$\approx$ 35 ps (start); $\approx$ 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 mm $\times$ 1.3 mm
Max. inter-pad gap	100 µm
Max. physical thickness	300 µm
Active thickness	50 µm
Active size	39 mm $\times$ 19.5 mm (30 $\times$ 15 pads)
Max. inactive edge	500 µm
Radiation tolerance	$2.5 \times 10^{15}\ n_{eq}\ cm^{-2}$, 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 mW/cm^2

LGAD time Resolution

- HL-LHC environment requires fast signal and excellent S/N as well as stability w-r-t irradiations level
- Time resolution less than 70 ps/hit is needed.

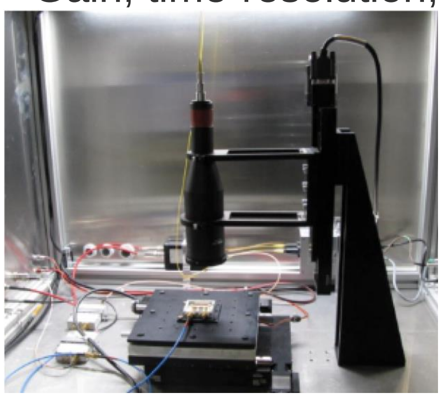
$$\sigma^2_{tot} = \sigma^2_{Landau} + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + \sigma^2_{clock}$$

Jitter Time-walk (negligible)

- Intrinsic Landau contribution from non- uniformities charge deposition is reduced for thin sensors: choice of 50 µm in HGTD. σ_{Landau} < 25ps
- $\sigma^2_{Jitter} + \sigma^2_{Time\text{-}Walk} < 25$ ps (70 ps at 4000 fb^{-1}) ⇒ fast signal and good S/N
- σ_{clock} < 15 ps
- Time-walk contribution can be corrected with the Time of Arrival (TOA) and the Time over Threshold (TOT)
  - Negligible with CFD
- Noise jitter dominates at low S/N while σ_{Landau} does at high S/N
- Several LGAD prototypes satisfy time resolution requirements

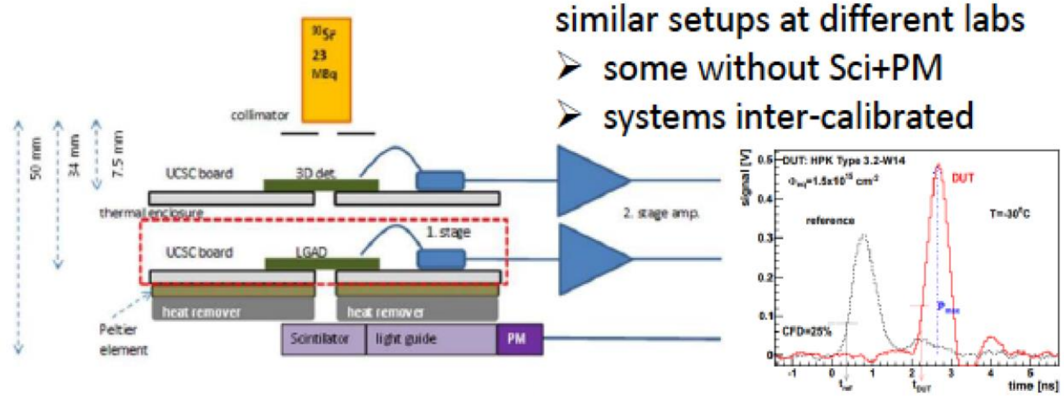
LGAD sensors tests

- Several LGAD sensors prototypes have been tested
  - Single pad, 2x2, 5x5 and 15x15 pads
- Sensors tests in laboratory
  - Using ^{90}Sr β-source or lasers in controlled environment using a climate chamber for irradiated sensors.
    - Custom made HGTD-specific readout boards. Electrical measurement: I-V, C-V, Gain, time-resolution, rise time and interpad gap



similar setups at different labs

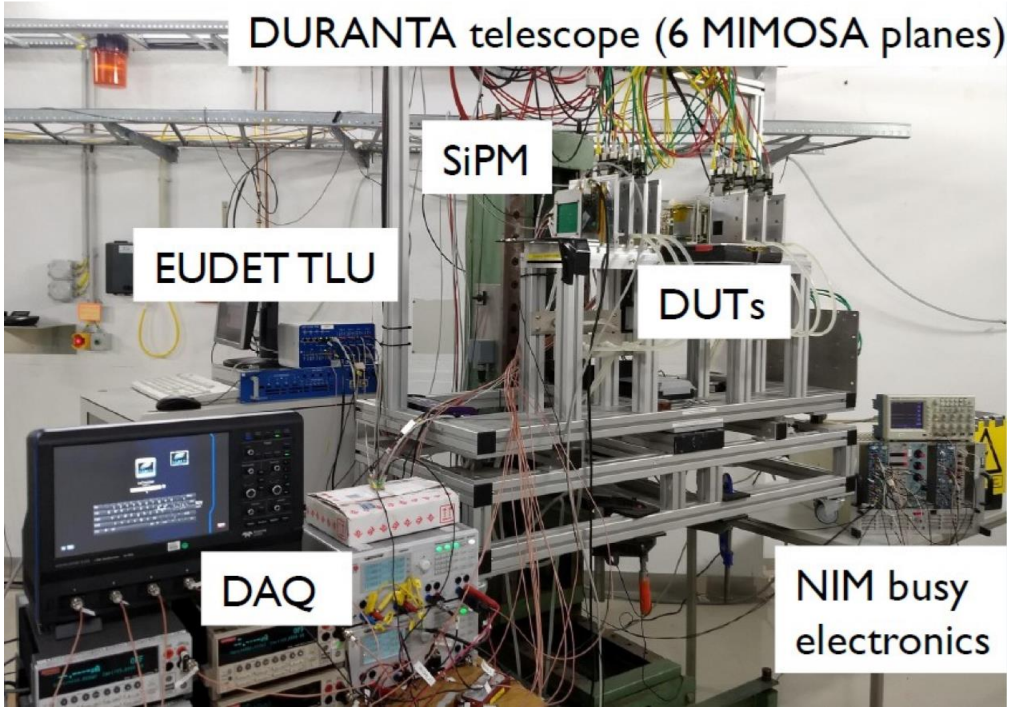
- some without Sci+PM
- systems inter-calibrated

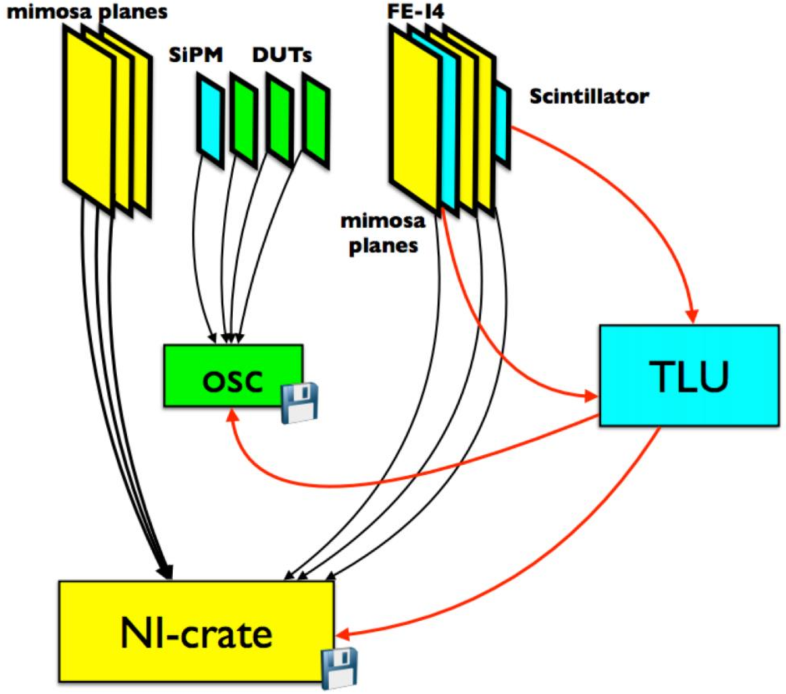


- Sensors test with beams
  - CERN SPS (120 GeV pions) and DESY (5 GeV electrons), FNAL, SLAC
  - Sensors integrated into a beam telescope providing track position with 3µm resolution

HGTD LGAD sensors test beam setup

- Test beam with pion/electron beams at CERN and DESY.





- Sensors, inside a cooling volume, are located between 2 arms of aTelescope Mimosa planes to provide track reconstruction
- 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

LGADs Performance measurements

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

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