A HIGH-GRANULARITY TIMING DETECTOR FOR THE PHASE-II UPGRADE OF THE ATLAS CALORIMETER SYSTEM: BEAM TEST RESULTS

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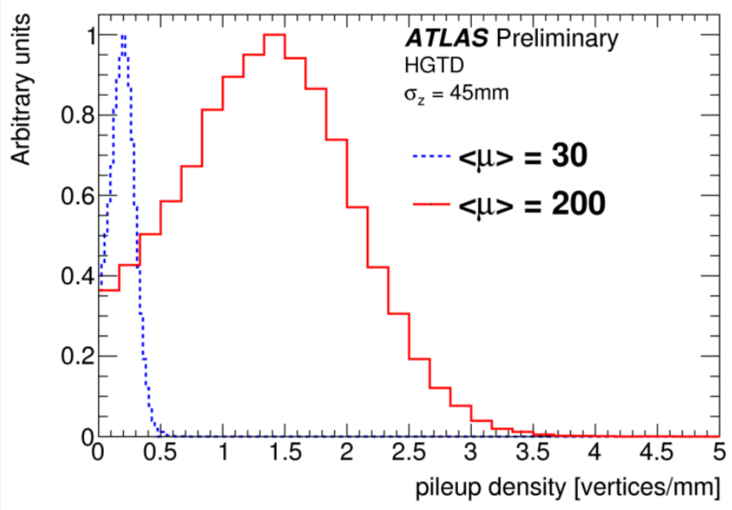
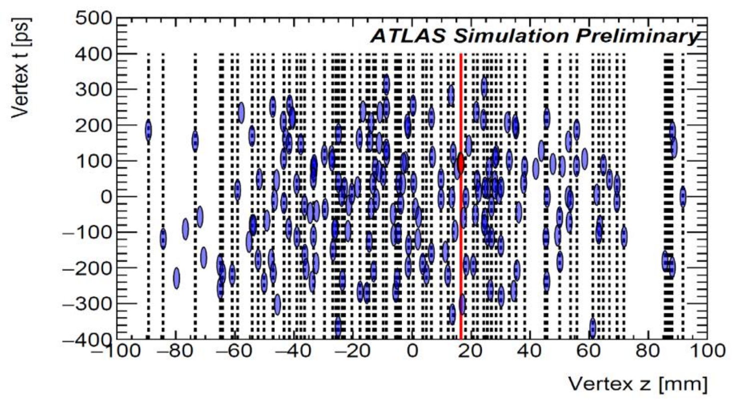
Motivation

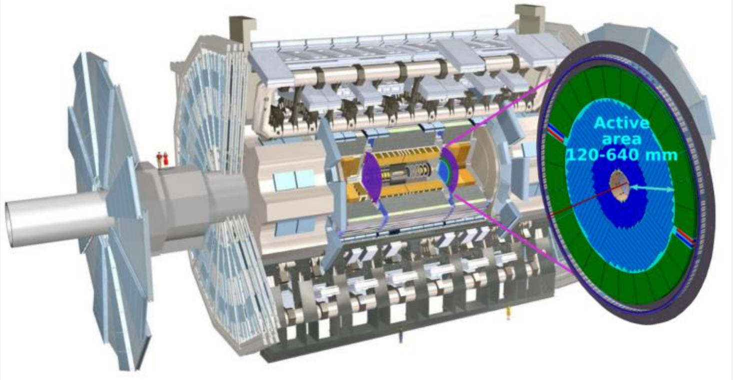
- At the High-Luminosity phase of LHC (HL-LHC)
  - Instantaneous luminosities up to $L \simeq 7.5\times10^{34}$ cm^{-2} s^{-1} (×5 current L_{inst})
  - Pile-up: $<\mu>$ = 200 interactions per bunch crossing → 1.5 vertex/mm on average
  - Vertex reconstruction and physics objects performance will be significantly degraded in the forward region where compared to the central region
    - Liquid Argon based electromagnetic calorimeter has coarser granularity
    - Inner tracker has poorer momentum resolution
- A **H**igh **G**ranularity **T**iming **D**etector (HGTD) is proposed in front of the Liquid Argon end-cap calorimeters for pile-up mitigation
  - Improve performance in the forward region by combining
    - HGTD precise timing
    - ITk (new ATLAS tracker) position information



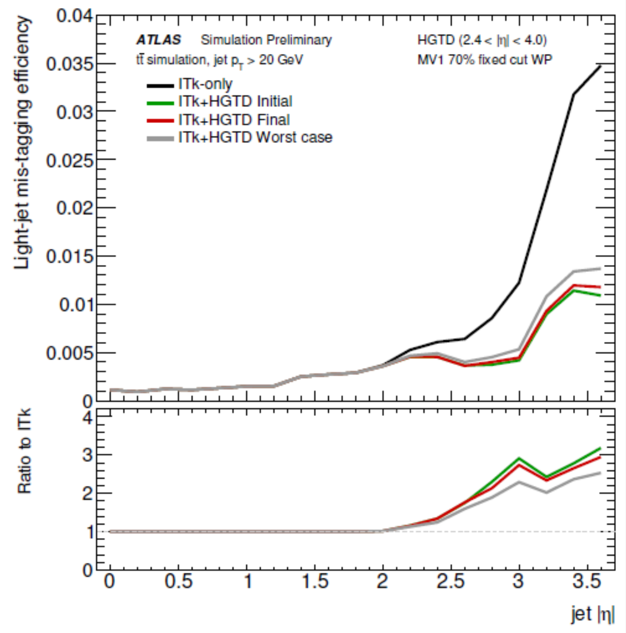


HGTD requirements

- Detector quite constrained by the space available and the harsh environment
- Time resolution better than 30 ps per track (50 ps per hit in a 2 layer geometry)
  - Recovers electron ID, track & jet reconstruction and b-tagging
- **L**ow **G**ain **A**valanche **D**etectors (LGAD) technology has been chosen
  - It provides an internal gain good enough while providing a large S/N ratio
- Design optimized for <10% occupancy



Pseudorapidity coverage	$2.4 < \lvert\eta\rvert < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	3435 mm $< z <$ 3485 mm
Radial extension:	
Total	110 mm $< R <$ 1000 mm
Active area	120 mm $< R <$ 640 mm
Time resolution per track	30 ps
Number of hits per track:	
$2.4 < \lvert\eta\rvert < 3.1$	2
$3.1 < \lvert\eta\rvert < 4.0$	3
Pixel size	1.3×1.3 mm^2
Number of channels	3.54M
Active area	6.3 m^2

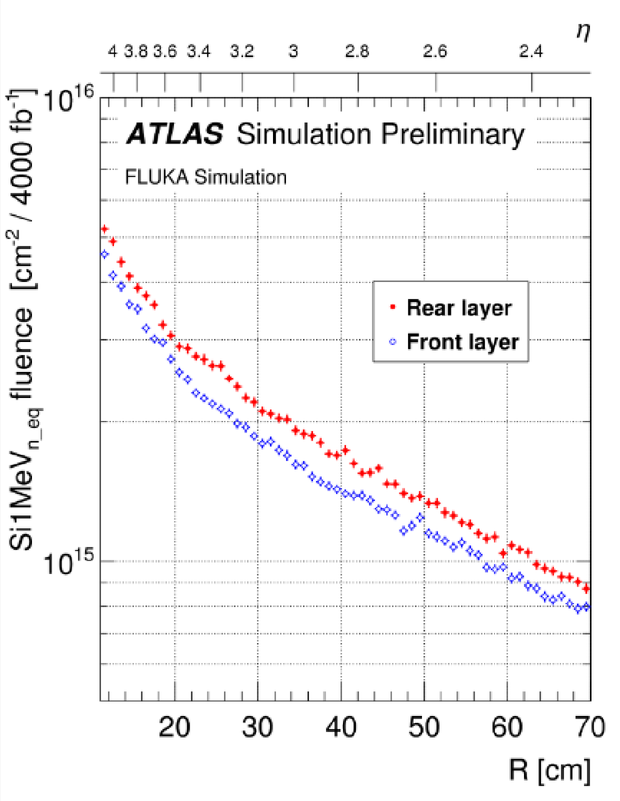


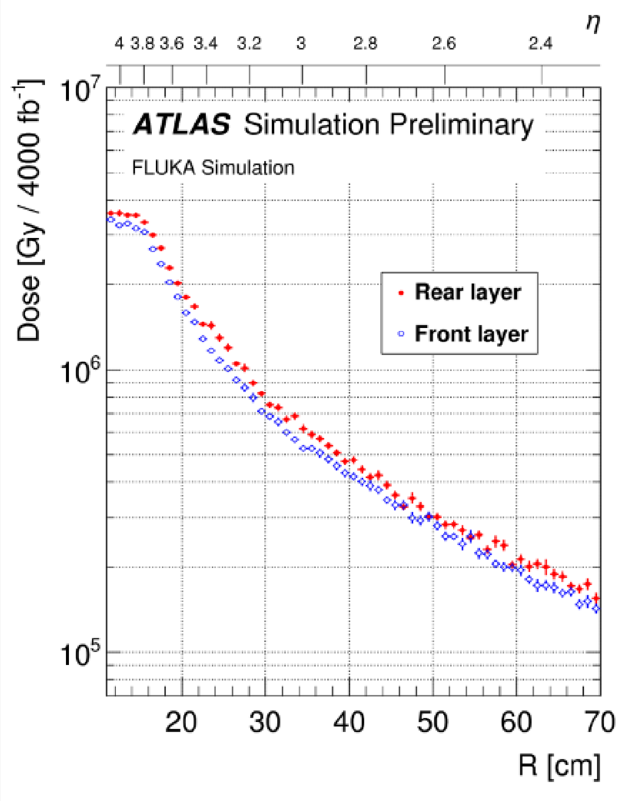
Radiation levels in HGTD

- Maximum n_{eq} fluences and dose for HL-LHC
  - R< 32 cm → 3.7×10^{15} n_{eq}/cm^2 and 4.1 MGy
  - R> 32 cm → 3×10^{15} n_{eq}/cm^2 and 1.6 MGy
  - A safety factor of ~2 and replacement of inner ring at half life time are taken into account

- ~30% sensors and ASIC (R< 32 cm) need to be replaced at half HL-LHC running period because of radiation damage

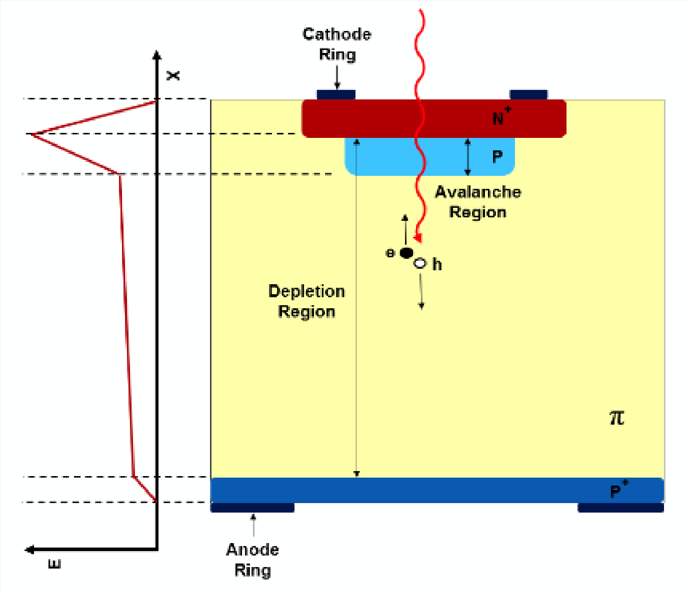
- Sensors will be operated at -30 °C using a common CO_2 cooling system with the inner detector (ITk)

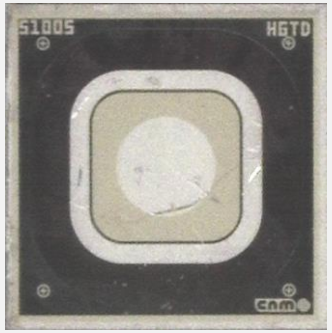




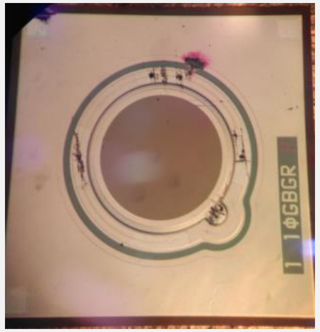
Detection technology: LGAD

- **L**ow **G**ain **A**valanche **D**etectors (LGADs) originally developed by CNM
  - n-p silicon planar detector + multiplication layer that amplifies the signal
  - High E field
  - Moderate internal gain (10-50)
  - Typical rise time 0.5ns
  - Excellent time resolution <30 ps before irradiation
- R&D programme to deliver thin sensors to provide the required time resolution (30 ps per track), fine segmentation, radiation hardness
  - New doping materials, substrates and new geometries
  - Prototypes tested from CNM, HPK, BNL, FBK





CNM LGAD for HGTD

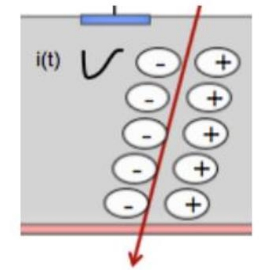


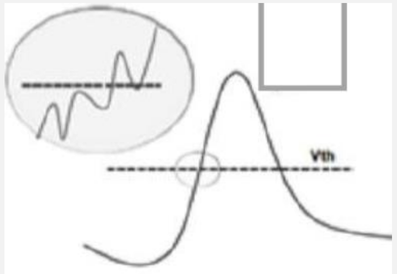
HPK LGAD for HGTD

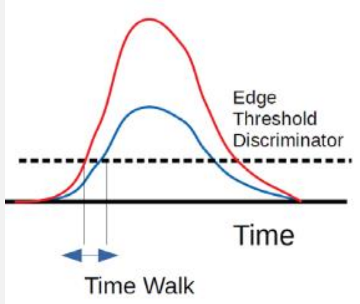
Contributions to timing

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

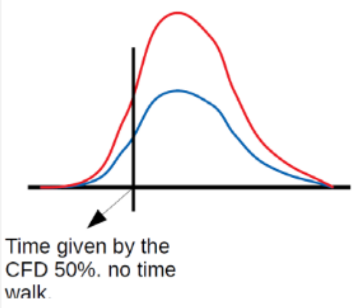
- Landau term <25 ps
  - Reduce for thin sensors: 35-50 μm
- Jitter term <15 ps and time walk term <10 ps
  - Low noise and fast signals
- Digitization granularity ~5 ps
- Clock distribution <10 ps





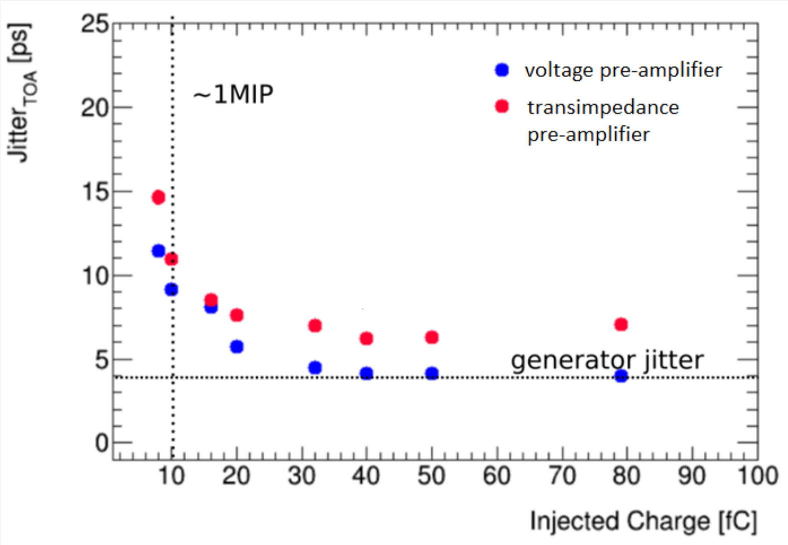


- Time walk corrections on beam test data using the **C**onstant **F**raction **D**iscriminator (CFD) technique
  - Considering the time at a fraction of 50% of the amplitude



Readout electronics: ALTIROC ASIC

- **A**TLAS **L**GAD **T**iming **I**ntegrated **R**ead**O**ut **C**hip (ALTIROC)
  - Minimize noise and power consumption
  - Provide **T**ime **O**f **A**rrival (TOA) and **T**ime **O**ver **T**hreshold (TOT) measurements
  - Target time resolution <25 ps
  - Developed in various phases
    - ALTIROC0: single-pixel analog readout (pre-amplifier + discriminator)
      - Test bench measurements satisfactory
      - Beam tests → see next slides
    - ALTIROC1: full single-pixel analog readout (analog + digital) in 5×5 arrays
      - Test bench measurements on-going
      - Irradiation campaigns and beam tests in Q1 2019
    - ALTIROC2: final 15×15 version
      - Submission expected end of 2019



Beam test campaigns

- CERN North Area SPS H6A & B beamlines (120 GeV pion beam)
  - ACONITE telescope in H6A and AIDA telescope in H6B

2016
Un-irradiated sensors

2017
Un-irradiated and irradiated CNM sensors
- Single pads and arrays

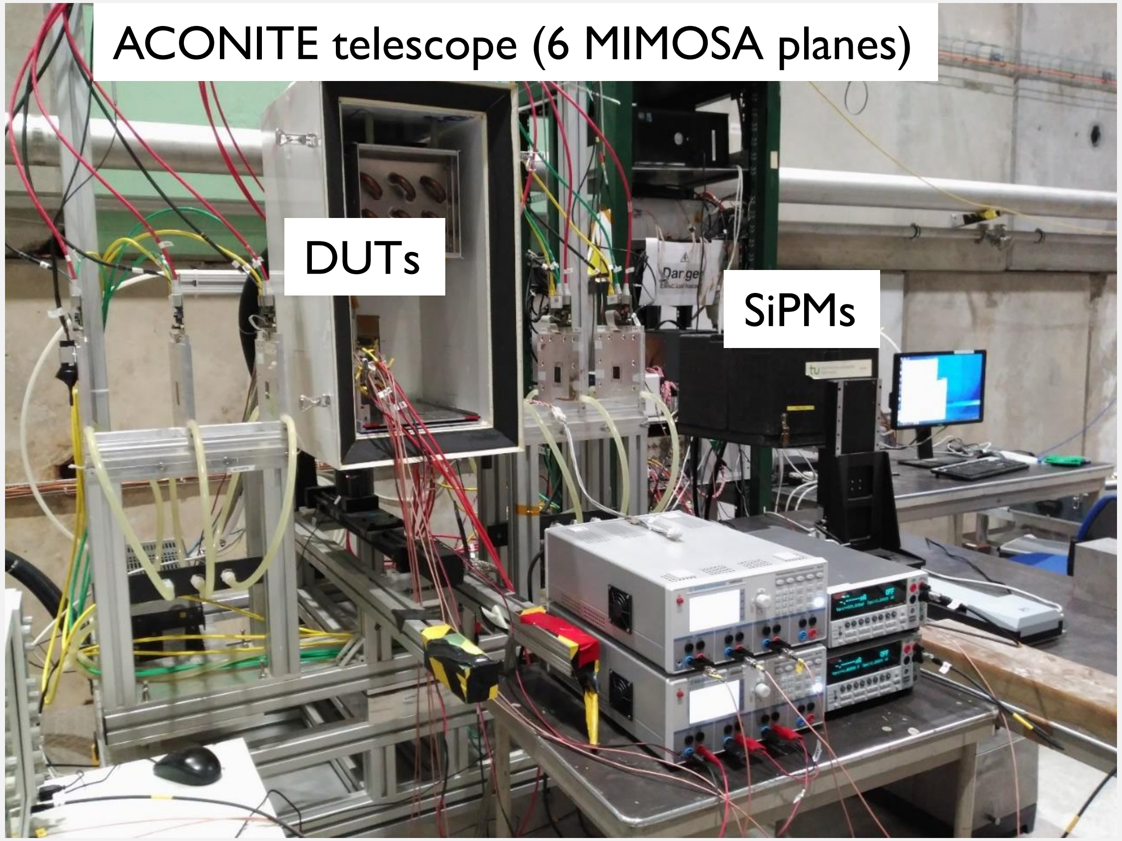
Un-irradiated HPK sensors

2018
Un-irradiated CNM, HPK, BNL

Neutron vs Proton irradiated
- Boron implanted CNM sensors
- Carbon diffused CNM sensors
- Gallium implanted CNM sensors
- HPK sensors

2×2 array sensors with ALTIROC0_v2

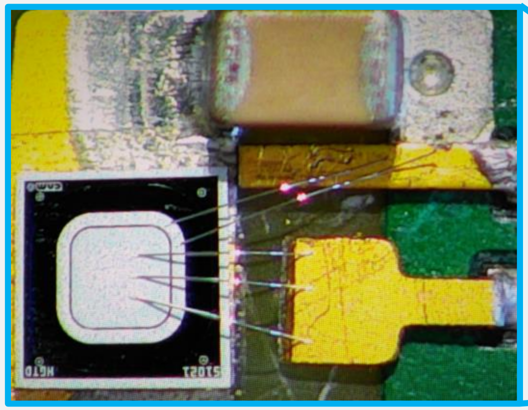
Arrays with different inter-pad gaps

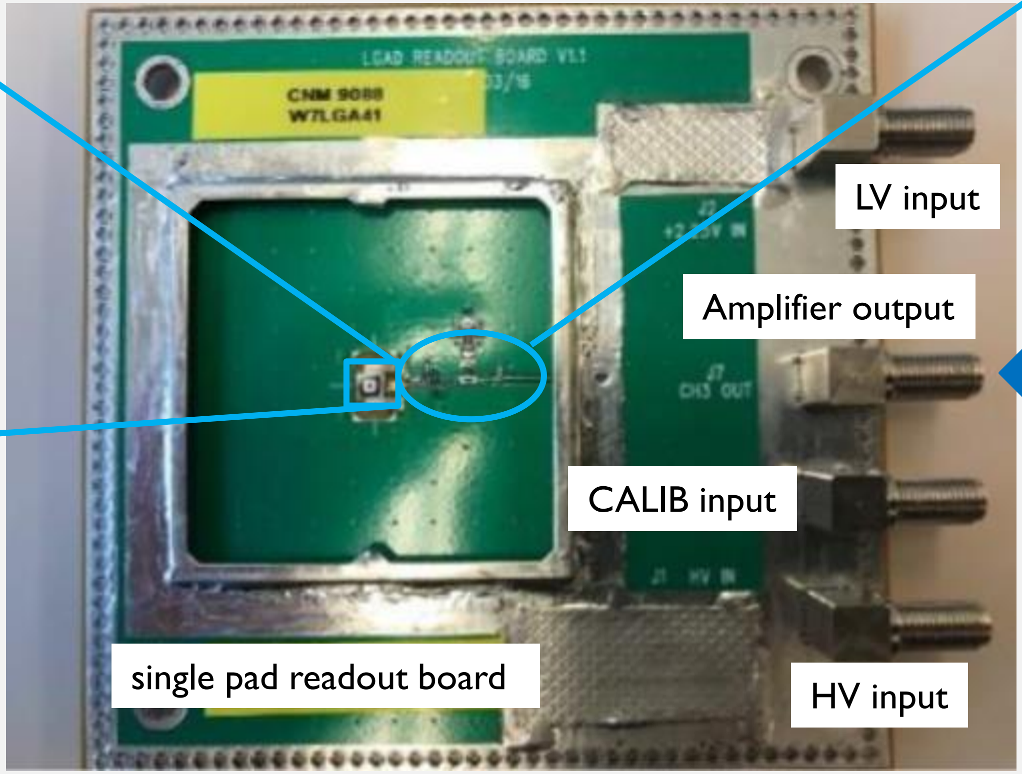


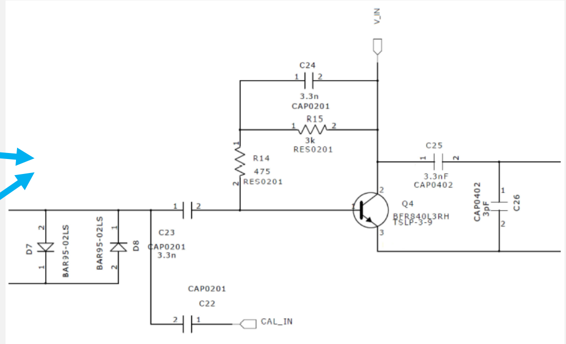
- SLAC beam tests → See talk "HGTD testbeam at the SLAC beamline" by S. Mazza

Sensor + Readout board

- 50 sensors (un-irradiated, p- and n-irradiated) tested so far
- LGAD readout boards with trans-impedance first stage amplifier
- Voltage second stage amplifiers with hermetic E/B cover design







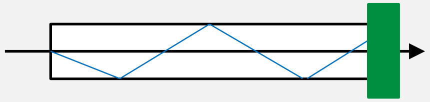
- Sensor attached to board using double-sided conductive tape
- Amplifier input coupled to metallization layer via wire bonds
- Guard ring grounded

Second stage amplifier output to oscilloscope

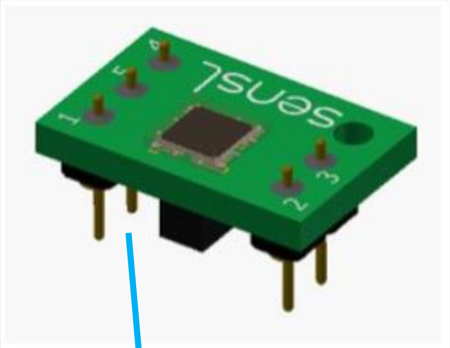
- Gain of ~10
- 2 GHz Bandwidth

Timing reference system

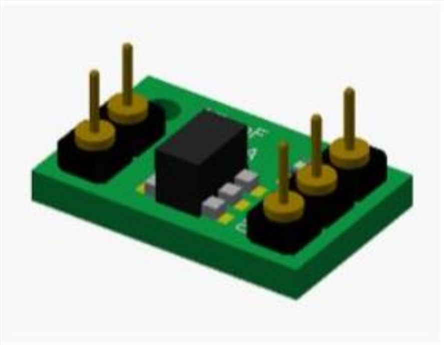
- 4 quartz bars
  - UVFS window
  - $3{\times}3{\times}10\ mm^3$
  - 6 side-polished
- Translucent optical grease
- 4 single channel SIPMs from sensL
  - $4{\times}4\ mm^2$ base
  - 0.7 mm thickness
- 4 SIPM readout and amplification boards
  - Shielding for amplification circuitry
- 3D printed quartz light-tight enclosure
  - Main cover and top plate
  - Holes for pins, screws, bar and SIPM



SIPM detects Cherenkov photons generated by charged pions in quartz

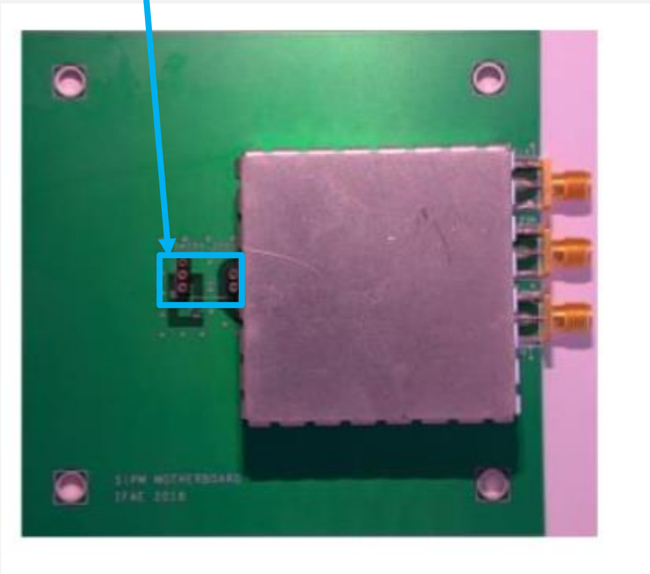


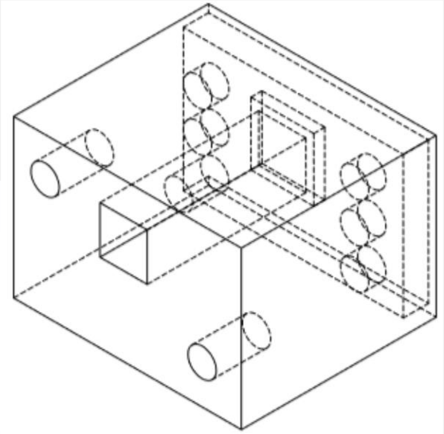
Top View

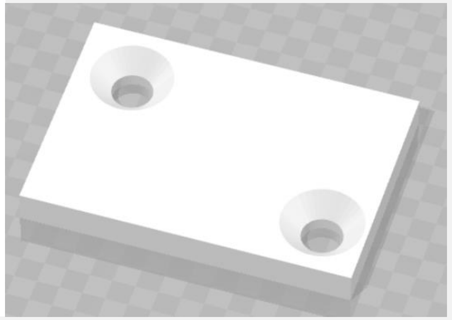


Bottom View

Pin Assignments	
Pin #	C Series
1	Anode
2	Fast Output
3	Cathode
4	PCB Ground
5	Jumper to PCB Ground (0 Ohm)

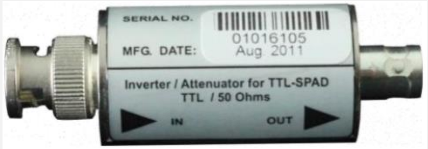


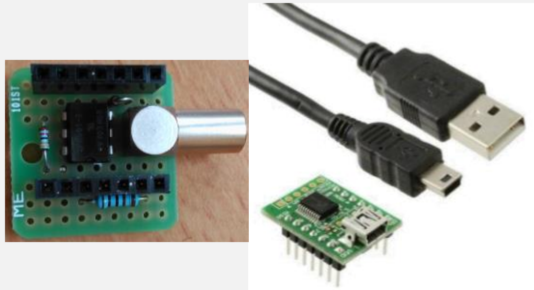




Beam test equipment

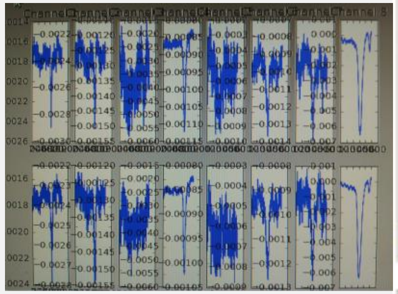
- L-shape support mechanics for sensors → easy installation and good board alignment
- Cooling box for sensors and light-tight boxes for timing reference system
- Chillers
  - 1 for sensors in H6A
  - 2 room temperature for SIPMs
  - Cooling loops
- PI x-y translation stages
- Low (HMP4040) and high voltage (Keithley 2410) power supplies
- Agilent Infinium (10 Gs/s @ 5 GHz) series and Lecroy WaveRunner oscilloscopes
- Trigger pulse converter (TTL to NIM)
- SPS cycle USB catcher
- Storage array → Lacie RAID array with 4×2 TB Seagate hybrid drives

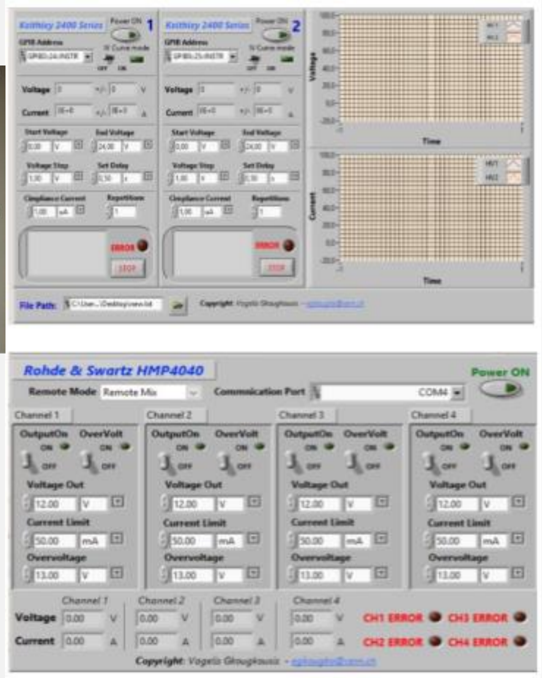




Beam test software and running conditions

- Software:
  - DAQ script compatible with all versions of Agilent and Lecroy oscilloscopes
  - Low voltage and SIPM high voltage controls LabVIEW based
    - Continuous monitoring
    - Compliance and voltage adjustment
  - ISEG control for LGADs bias voltage
  - Run EUDAQ for combined data taking (RunControl, STcontrol)
  - Use standalone dataMonitor.py and EUDAQ OnlineMon.exe for data sanity checks
- Running conditions:
  - IV measurements performed in the laboratory before sensor on-board assembly
  - Select highest operating voltages using IV derivative method (8 std. dev. from stable region)
    - 4 operating voltages 1M events
    - Highest operating voltage 3M events for efficiency maps
  - Run at -20 °C and -30 °C

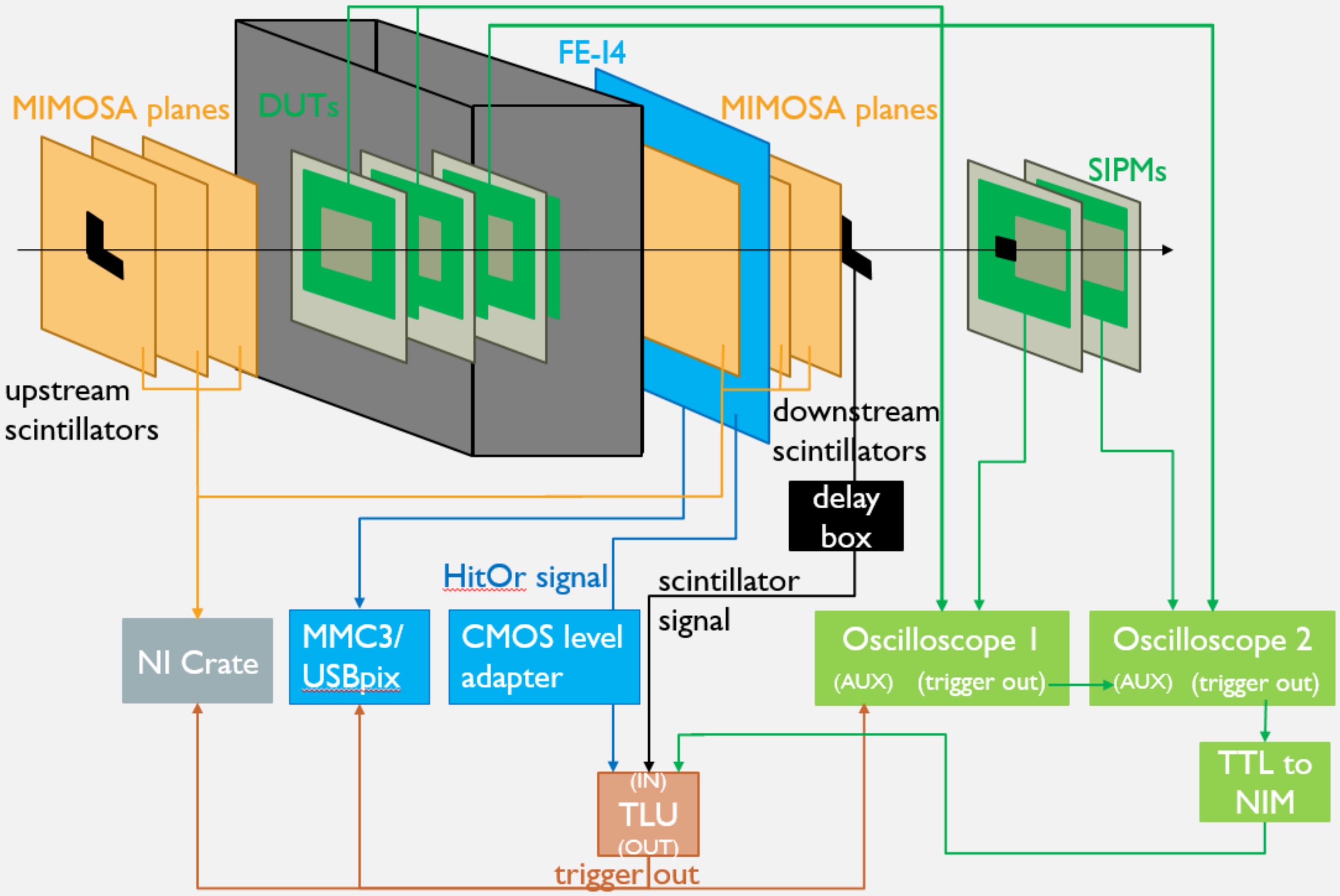




[LGAD safety and stability talk by V. Gkougkousis](#)

HGTD beam test DAQ and trigger system

- Definition ROI mask in FE-I4 → only accept tracks passing through small area covering all LGADs
- Use inverted signal from HitOr (TTL → NIM)
- Delay (~100 ns) scintillator NIM signal to match in TLU trigger window with HitOr signal
- 5 ns trigger window in TLU → triggers oscilloscope, MIMOSA readout, MMC3/USBpix
- A track on LGAD → look back in time and a waveform is recorded
- Data are saved in two separated files (oscilloscope, MIMOSA + FE-I4)

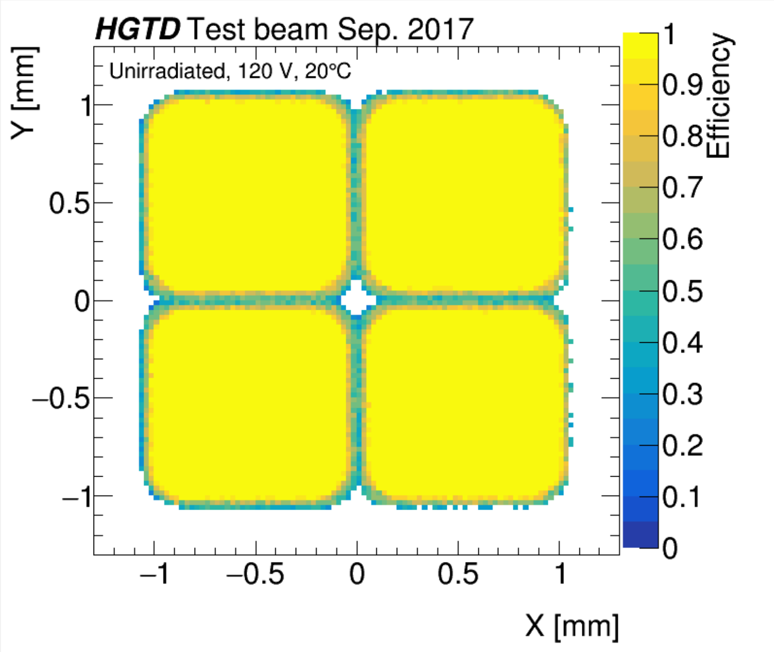


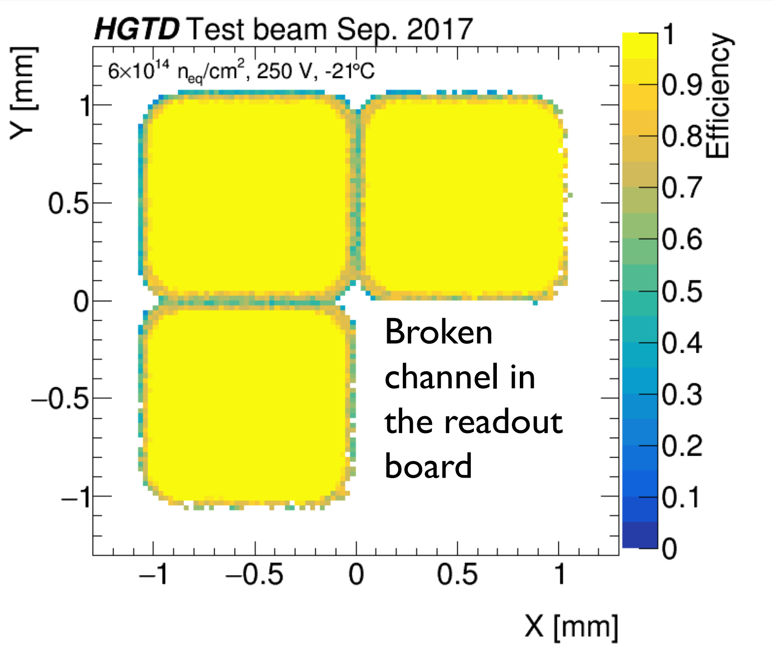
Results from 2017 campaigns

- Comparison between un-irradiated and irradiated at fluence 6×10^{14} n_{eq}/cm^2 arrays of four LGAD sensors of 1.1×1.1 mm^2 each

Efficiency using standalone tracking software

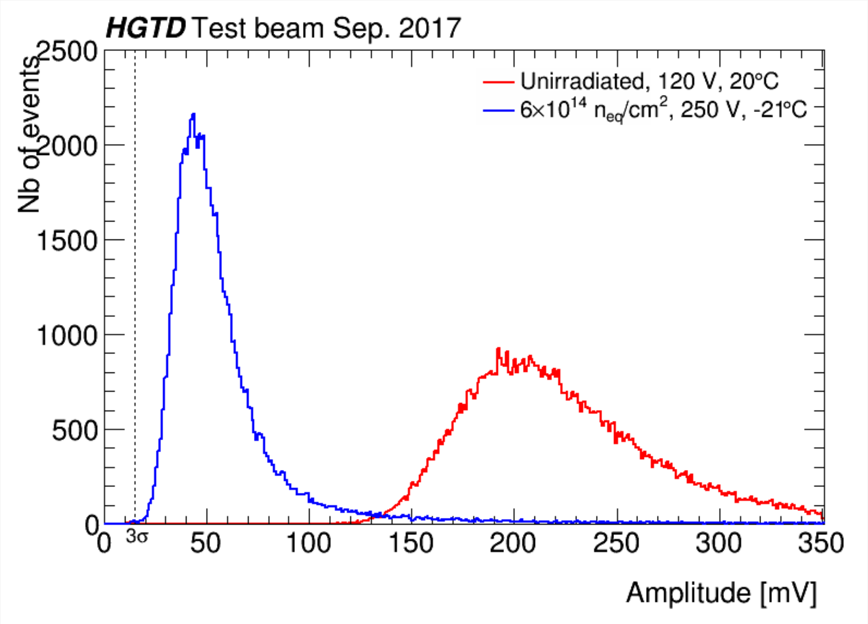
- Standalone tracking software developed to reconstruct tracks in raw data from telescope and match event information with oscilloscope data
- Efficiency is obtained as $\frac{tracks\ on\ LGADs\ with\ signals\ larger\ than\ a\ threshold}{all\ reconstructed\ tracks\ on\ LGADs}$
- Efficiency in the bulk is larger than 98-99%

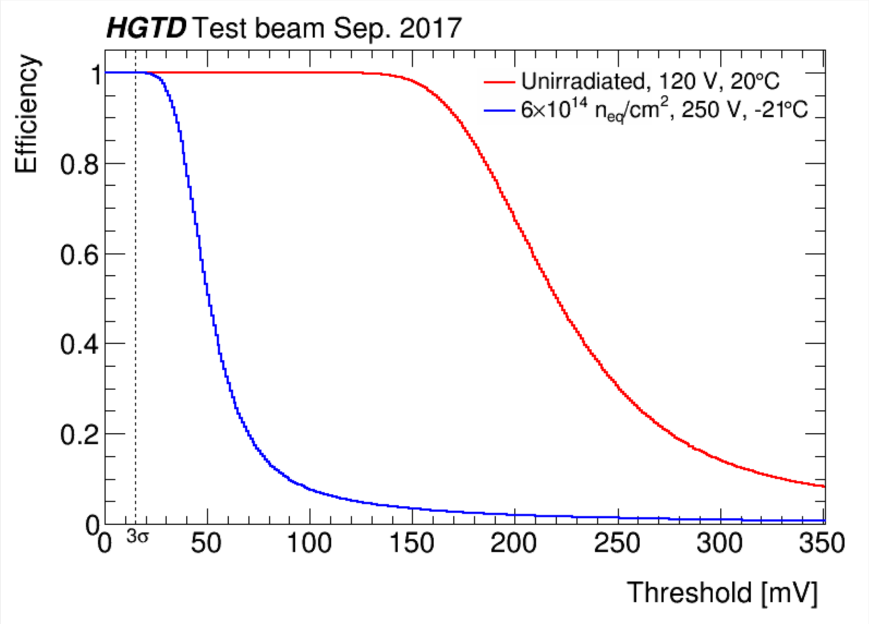




Efficiency vs threshold

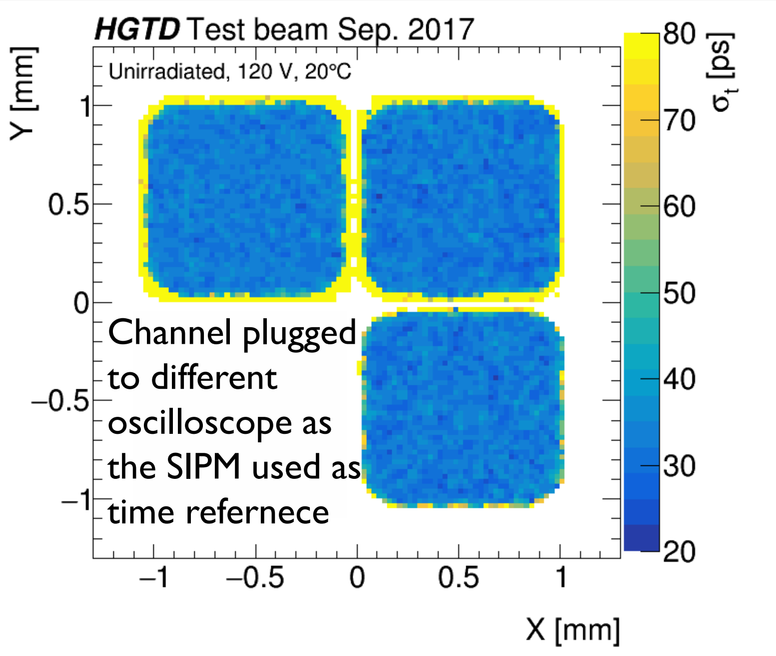
- Signal amplitude in the bulk of LGAD pads
- Signal efficiency in the bulk of LGAD pads as a function of the voltage threshold
- Dashed line shows the default threshold corresponding to 3 times the noise

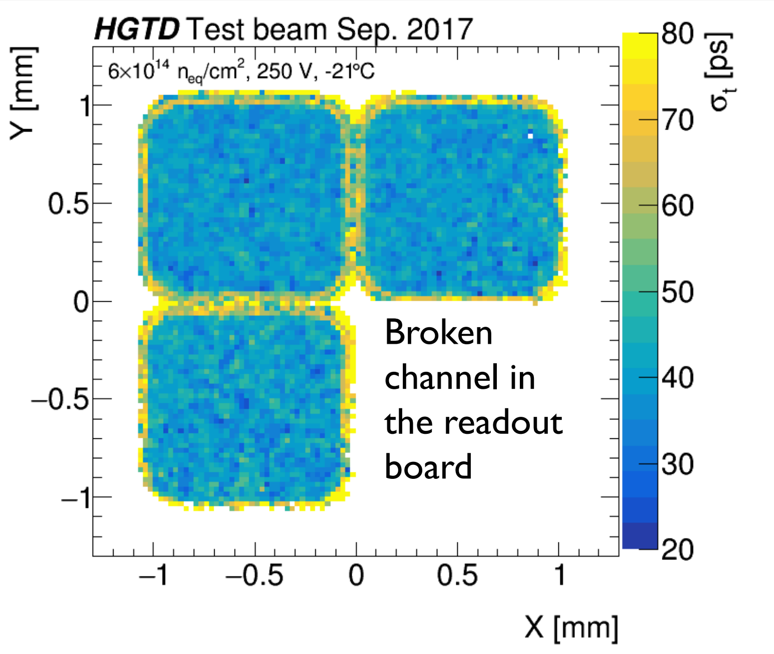




LGAD timing performance

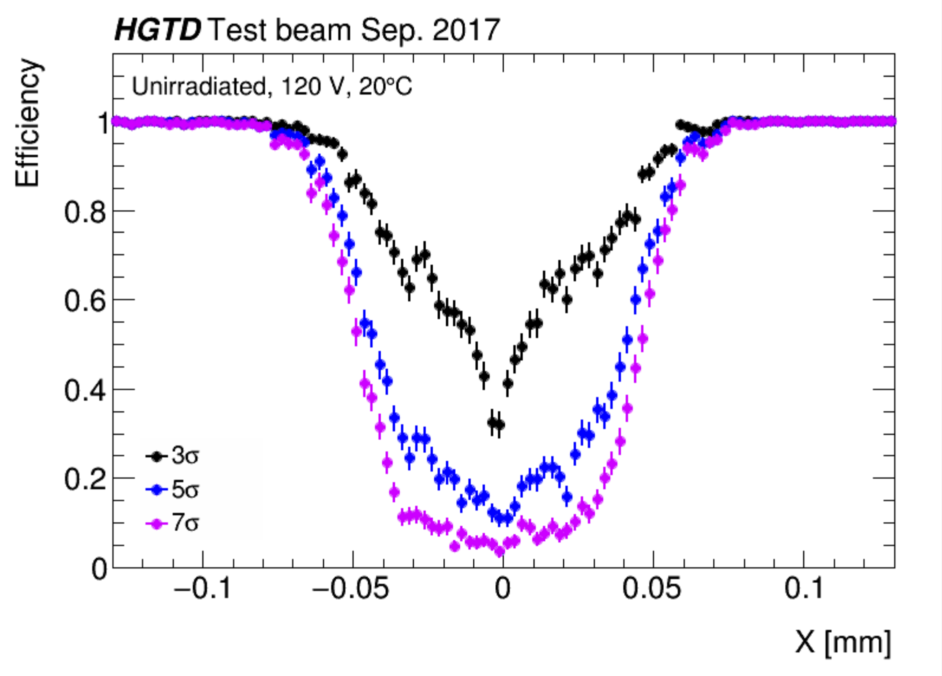
- Time resolution as a function of the X and Y coordinates (in mm)
- The time resolution is larger in the guard rings around the pads where there is no multiplication of the charge
- The fluctuations are dominated by statistical fluctuations since very small bins are used in order to show the structure around the pad

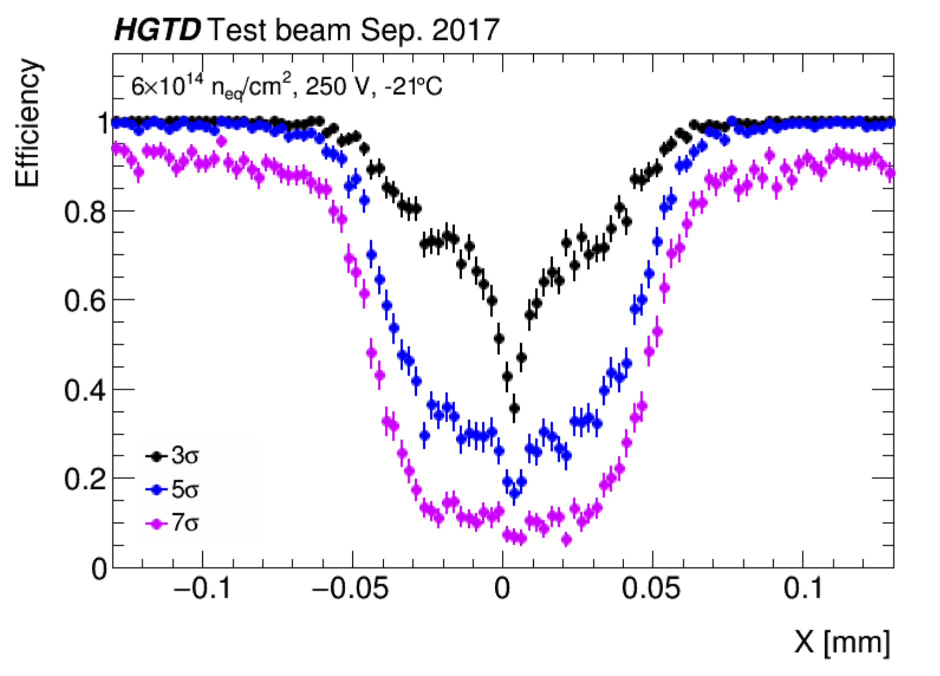




Inter-pad studies

- Signal efficiency in the inter-pad region as a function of X (in mm) for 3 different voltage thresholds





Preliminary results from 2018 campaigns

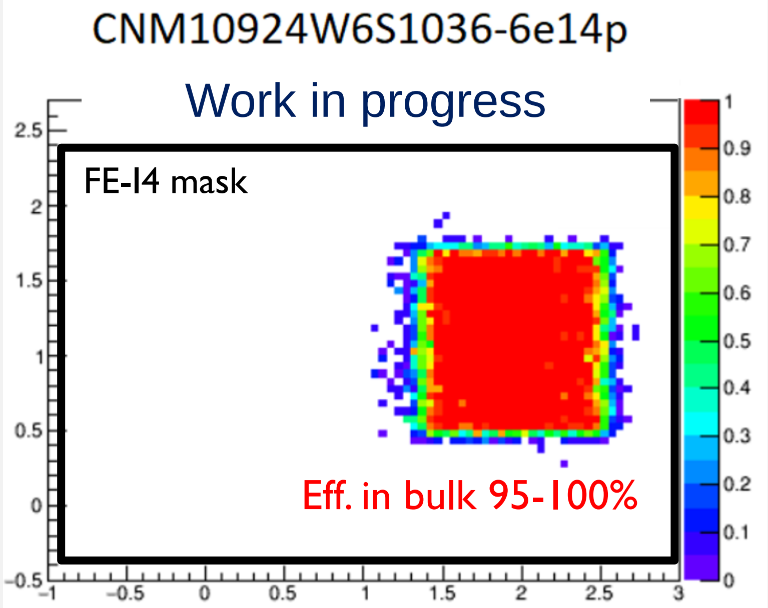
- First efficiency results using EUTelescope tracking software
- ALTIROC preliminary results

Efficiency using EUTelescope tracking software

- Motivation using EUTelescope software
  - Crosscheck results with standalone tracking software
  - Algorithm providing better resolution and to be used for analysis of future DESY beam test data
- Reconstruction procedure using iLCsoftware v01-19-02, EUTelescope version master, EUDAQ version branch/1.x-dev

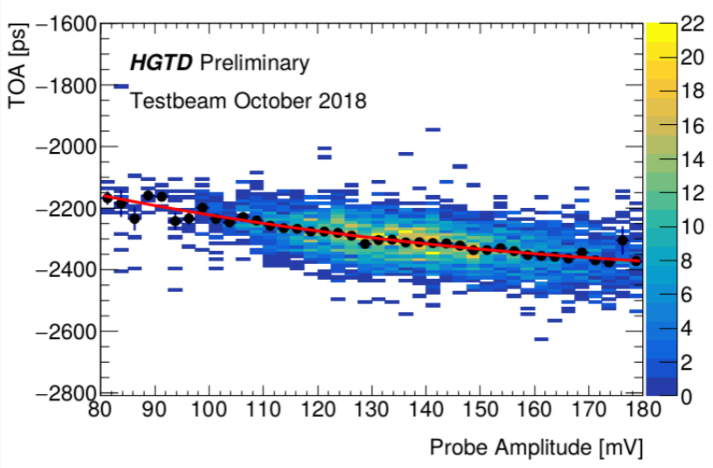
Native data from telescope → Geometry in gear file: 6 MIMOSA + 1 FE-I4 → EUTelescope jobtasks: converter, clustering, hitmaker, align, fitter → Ntuple containing track info at MIMOSA and FE-I4 planes

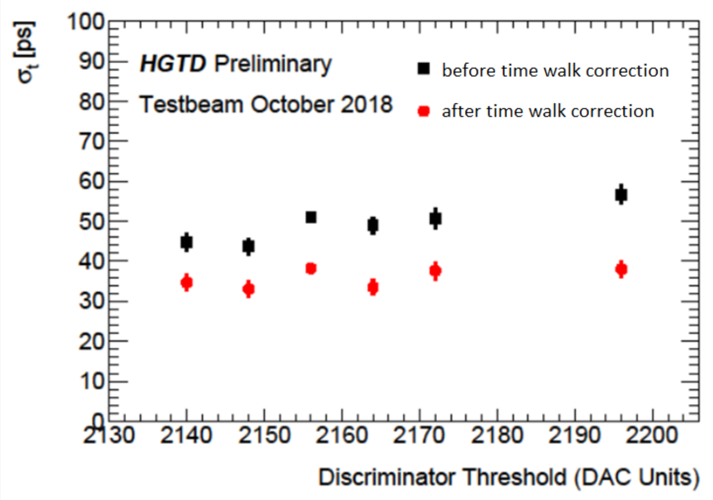
  - Match event information between oscilloscope and telescope ntuples
  - Fit track x-z and y-z points on all MIMOSA planes and extrapolate to LGADs z position
- Conditions to calculate the efficiency:
  - Select tracks passing through FE-I4 within the defined ROI mask
  - Have a hit on LGAD (waveform is recorded in oscilloscope)
  - LGAD signal amplitude > threshold



ALTIROC preliminary results

- ALTIROC0v2 bump bonded to a un-irradiated CNM 2×2 LGAD array
- TOA of signal corrected for time walk effects
  - TOA vs amplitude of pre-amplifier probe
  - Black points correspond to profile of 2D distribution
  - Red line corresponds to polynomial fit use to correct for time walk effects
- Best achieved time resolution 35 ps after time walk correction
  - Time resolution vs discriminator threshold (in DAC units) **before** and **after** time walk correction
  - Amplitude of pre-amplifier probe use to correct for time walk
  - 30% improvement
  - A SIPM is used as time reference where its 40 ps contribution is subtracted





Summary and perspectives

- The HGTD is proposed to mitigate pile-up effects and improve the performance in the ATLAS forward region
  - Challenging requirements
  - Technical proposal was approved [link to HGTD Technical Proposal]
- After a fluence 6×10^{14} n_{eq}/cm^2 (test-beam 2017)
  - Efficiency in the bulk is still ~100%
  - Time resolution of 40-50 ps is achieved
  - More results published on HGTD testbeam paper [link to HGTD beam test paper]
- A 4 period test-beam campaign in 2018 is complete
  - An extensive list of LGAD prototypes have been tested from different technologies and manufacturers
  - First efficiency results using EUTelescope software are presented
  - ALTIROC results look promising
  - Lots of data recorded and analysis is on-going
  - A paper with 2018 beam test results is in preparation
- Next beam tests at DESY are scheduled in March and May 2019
  - Investigate the integration of LGAD and ALTIROC readouts in EUDAQ

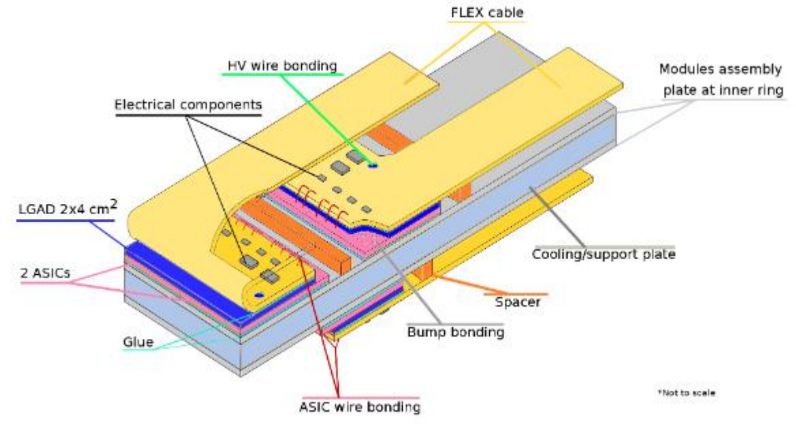
BACKUP SLIDES

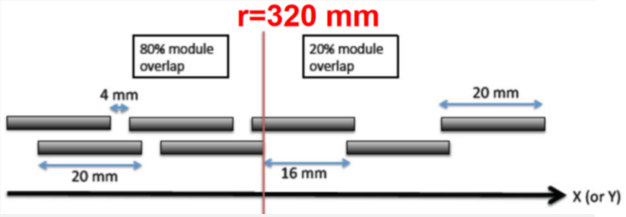
HGTD module and stave

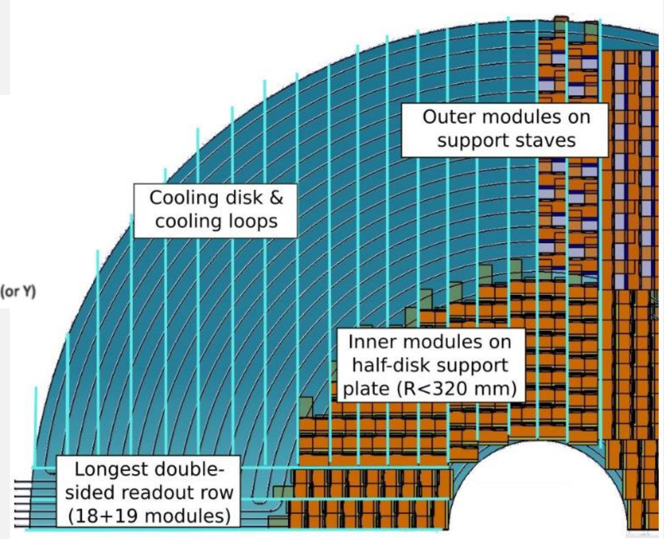
- 7984 modules:
  - 2 15×15 pixels ALTIROC ASIC (2×2 cm^2)
  - 1 15×30 pixels LGAD with 1.3×1.3 mm^2 pads (2×4 cm^2)

  } bump bonded together

  - Schematic drawing of two adjacent modules
  - Double sided layer with a cooling plate in between
  - Modules mounted on thin support plates → up to 18 on a stave
  - Wire bonded to flex cables going to peripheral electronics

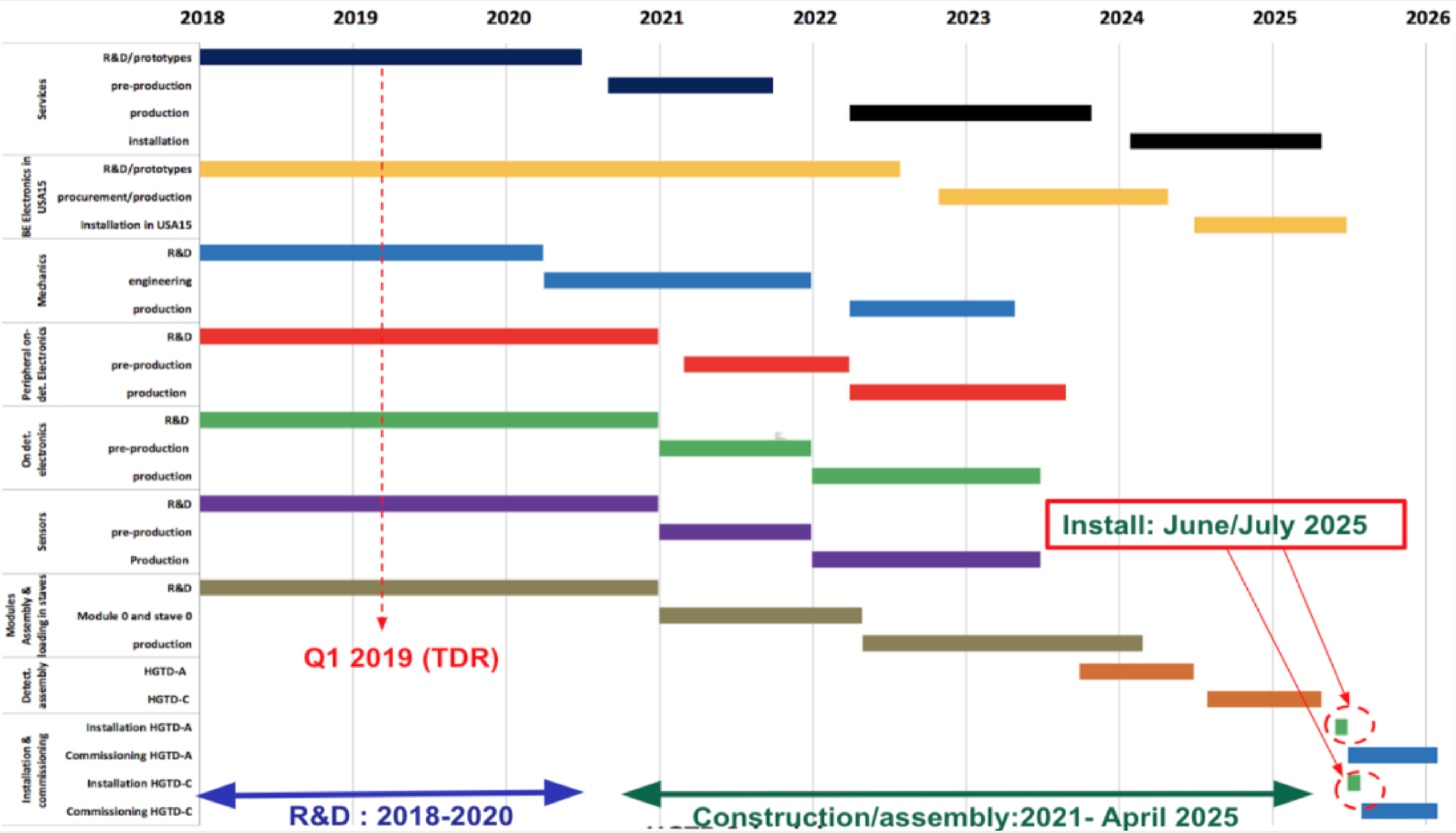






- Layout:
  - For R< 32 cm → stave designed to have 3 hits with a 80% module overlap
  - For R> 32 cm → stave designed to have 2 hits with a 20% module overlap

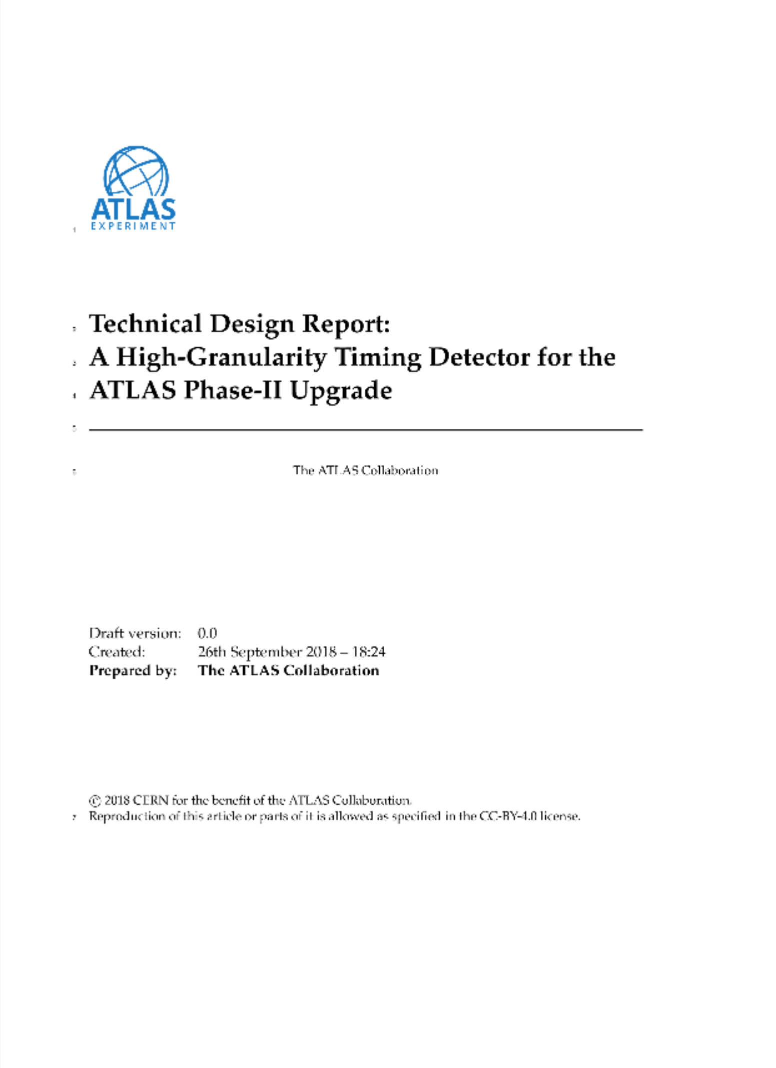
Timeline



2018
2019
2020
2021
2022
2023
2024
2025
2026
Services
R&D/prototypes
pre-production
production
installation
BE Electronics in USA15
R&D/prototypes
procurement/production
installation in USA15
Mechanics
R&D
engineering
production
Peripheral on-det. Electronics
R&D
pre-production
production
On det. electronics
R&D
pre-production
production
Sensors
R&D
pre-production
Production
Modules Assembly & loading in staves
R&D
Module 0 and stave 0
production
Detect. assembly
HGTD-A
HGTD-C
Installation & commissioning
Installation HGTD-A
Commissioning HGTD-A
Installation HGTD-C
Commissioning HGTD-C
Q1 2019 (TDR)
Install: June/July 2025
R&D : 2018-2020
Construction/assembly:2021- April 2025

Summary

- The HGTD group is working hard to deliver TDR by 5th April 2019
  - LGAD from CNM, HPK,FBK up to 15×15 channels (½ final size)
  - Complete 2018 test beam campaigns
  - Performance with final detector layout and full simulation
  - ASIC-ALTIROC1 up to 5×5 channels w/ analog+dig. part
  - (ASIC+ LGAD +flex cable): 5×5 results in lab and bump bonding R&D
  - Peripheral electronics and BE electronics: design/concept and components tests
  - Services layout and mock-up in surface
  - Develop path for construction/tests of a demonstrator (cooling plate+stave+ flex+peripheral elect.)
  - Strategy for installation and maintenance
  - Update CORE and manpower evaluation for construction


ATLAS EXPERIMENT

Technical Design Report:
A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade

The ATLAS Collaboration

Draft version: 0.0
Created: 26th September 2018 – 18:24
Prepared by: The ATLAS Collaboration

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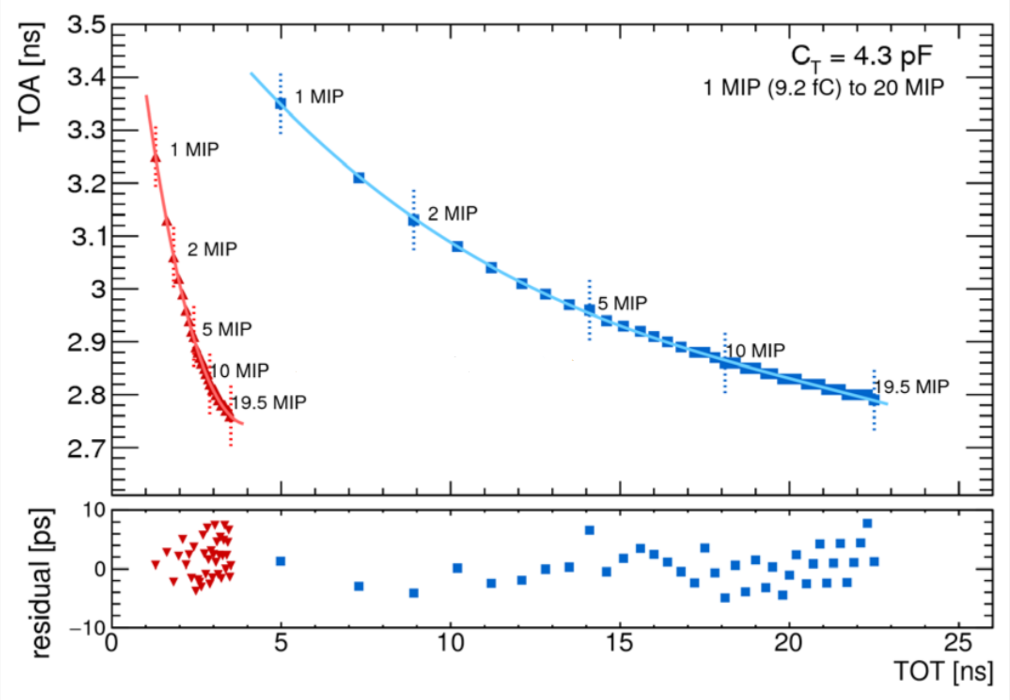
Time walk correction

- ALTIROC ASIC will provide **T**ime **O**f **A**rrival (TOA) and **T**ime **O**ver **T**hreshold (TOT) measurements

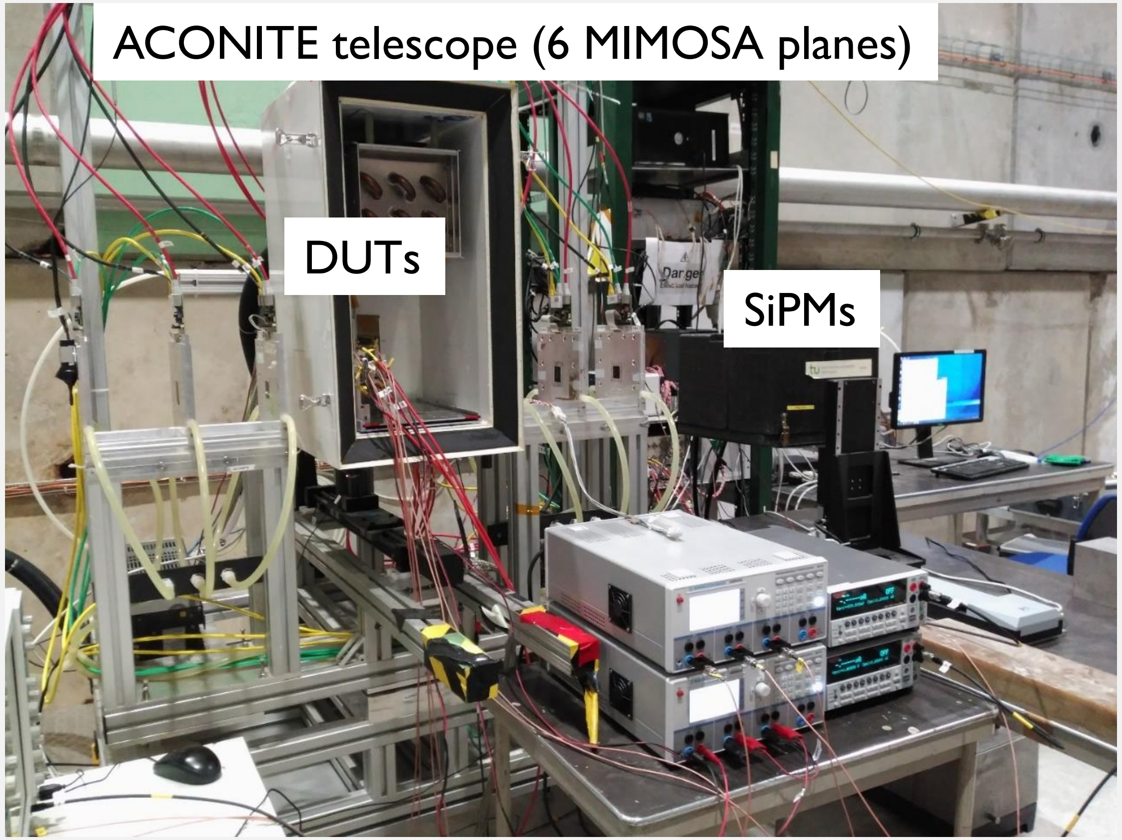
- TOA of signal corrected for time walk effects using TOT technique
  - Charge injection tests with an estimated input capacitance of 4.3 pF
  - Two different pre-amplifiers
    - Voltage
    - Trans-impedance (shorter TOT)
  - After correction <10 ps contribution



- Other techniques as the **C**onstant **F**raction **D**iscriminator (CFD) can be used to correct for time walk

Beam test campaigns in 2018

- CERN North Area SPS H6A & B beamlines (120 GeV pion beam)
  - ACONITE telescope in H6A and AIDA telescope in H6B
  - April – May 2018
    - Neutron vs Proton irradiated Boron implanted CNM sensors
  - June – July 2018
    - Proton irradiated Carbon diffused CNM sensors
    - Un-irradiated Gallium implanted HPK sensors
    - 2×2 array sensors with ALTIROC0_v2
  - September 2018
    - Neutron irradiated Carbon diffused CNM sensors
    - Proton irradiated Gallium sensors
  - October 2018
    - Neutron irradiated Gallium sensors
    - Arrays with different inter pad gaps
    - ALTIROC
- SLAC beam tests → See talk "[HGTD testbeam at the SLAC beamline]" by S. Mazza



S/N, charge and gain from 2016

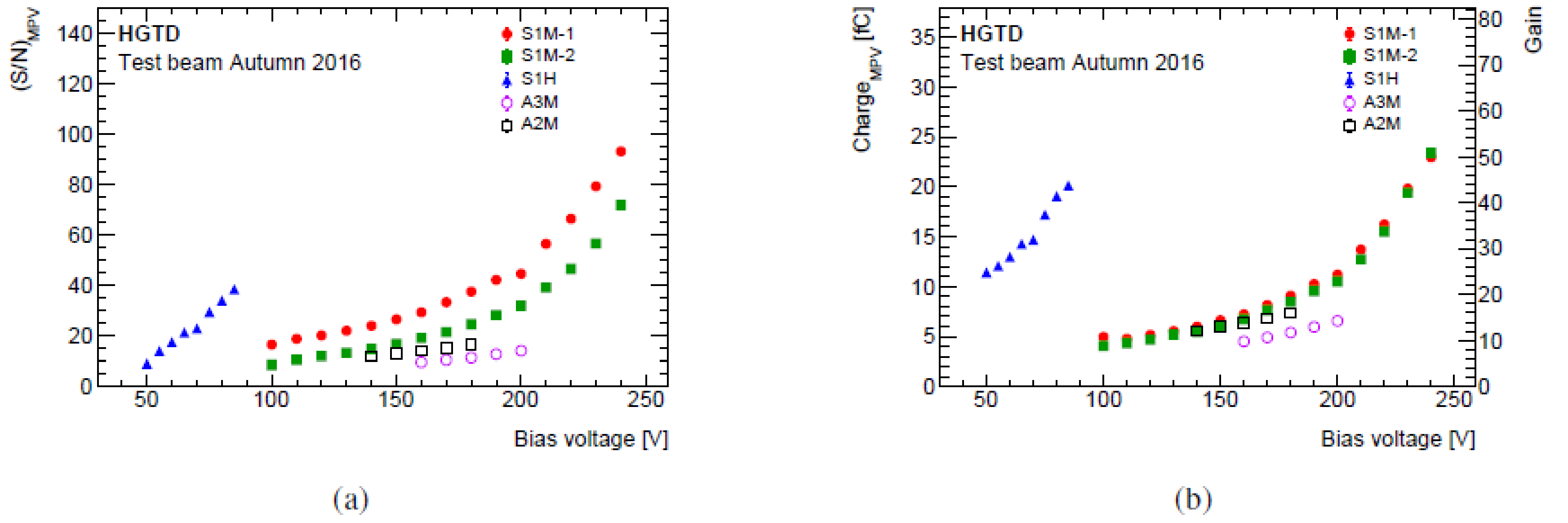
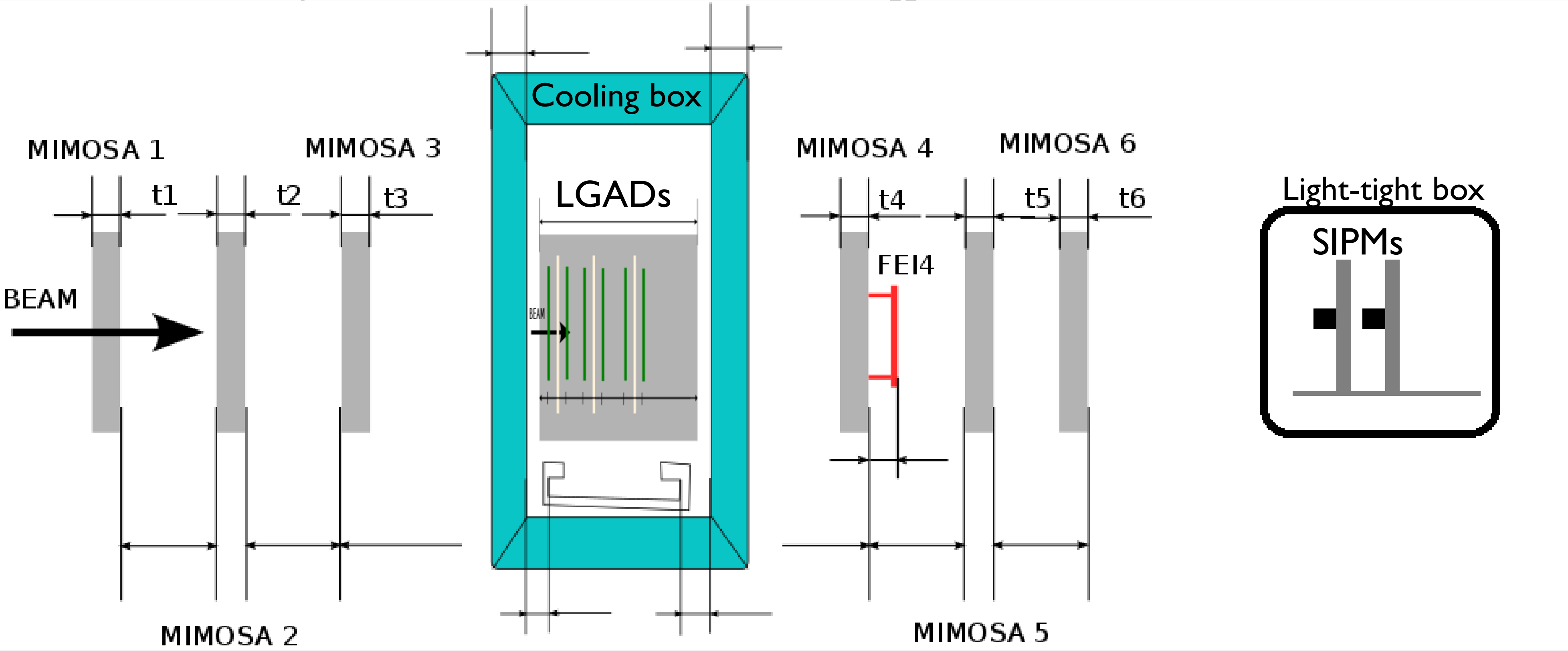


Figure 9: Signal-to-noise ratio (a) and charge and gain (b) as a function of the bias voltage for single-pad sensors and arrays. Statistical uncertainties are negligible and smaller than the marker size. [link to HGTD beam test paper]

HGTD beam test layout

- North Area SPS H6A line
- Telescope with 6 MIMOSA planes
- FE-I4 used as reference plane
- HGTD DUTs: 6 LGADs
- Time reference system: quartz bars + SIPMs
- Trigger: FE-I4 + scintillator after MIMOSA 6



Tracking using EUTelescope software

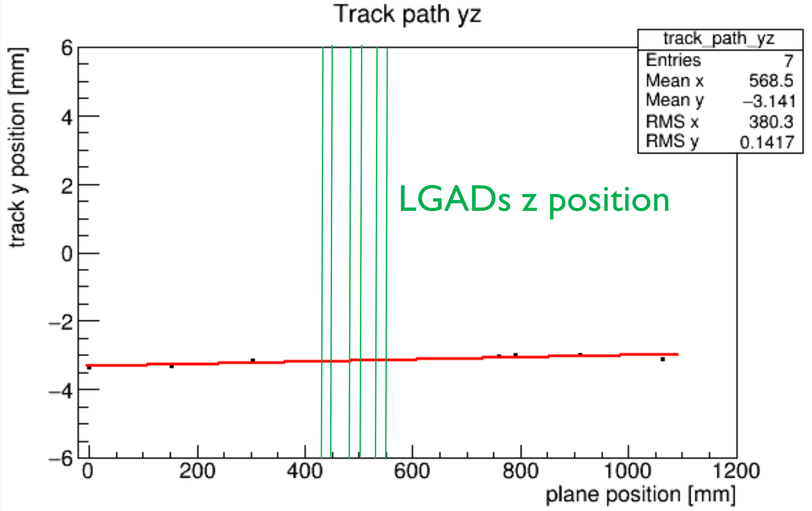
- Using iLCsoftware v01-19-02, EUTelescope version master, EUDAQ version branch/1.x-dev
- Start point: native data from telescope (September 2018)
- Steps:
  - Implement test beam geometry (6 MIMOSA planes + 1 FE-I4 plane) in gear file
  - Fill run list in a .csv file
  - Prepare steering and configuration files including required processors, parameters and variables
  - Submit EUTelescope jobtasks: converter, clustering, hitmaker, align, fitter
  - Resulting ntuple contains track information on FE-I4 plane / MIMOSA planes
  - Develop analysis to combine data from oscilloscope and telescope files (same number of events)

Efficiency using EUTelescope tracking software

- Reconstruction procedure
  - Using iLCsoftware v01-19-02, EUTelescope version master, EUDAQ version branch/1.x-dev

Native data from telescope → Geometry in gear file: 6 MIMOSA + 1 FE-I4 → EUTelescope jobtasks: converter, clustering, hitmaker, align, fitter → Ntuple containing track info at MIMOSA and FE-I4 planes

  - Match event information between oscilloscope and telescope ntuples (same number of events)
  - Fit track x-z and y-z points on all MIMOSA planes and extrapolate to LGADs z position



- Conditions to calculate the efficiency:
  - Select tracks passing through FE-I4 within the defined ROI mask
  - Have a hit on LGAD (waveform is recorded in oscilloscope)
  - LGAD signal amplitude > threshold

MIMOSA and FE-I4 hit maps

- FE-I4 plane is rotated 90 degrees
- ROI mask containing LGADs and SIPMs is clearly seen
- Z in log scale to see FE-I4 mask on MIMOSA planes