A High-Granularity Timing Detector for the Phase-II upgrade of ATLAS

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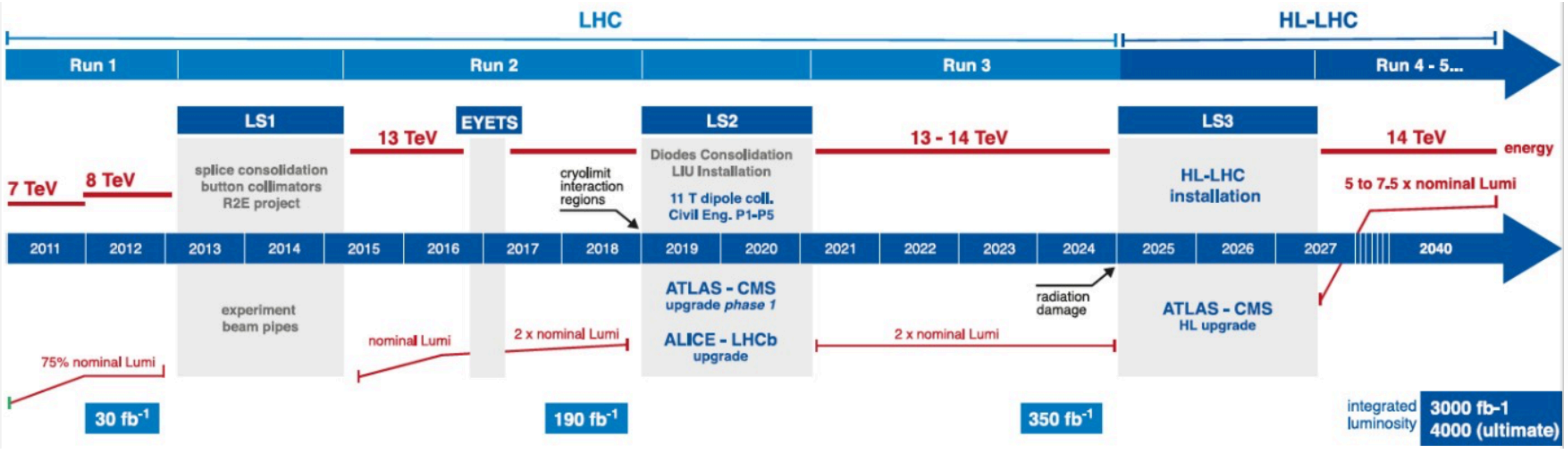
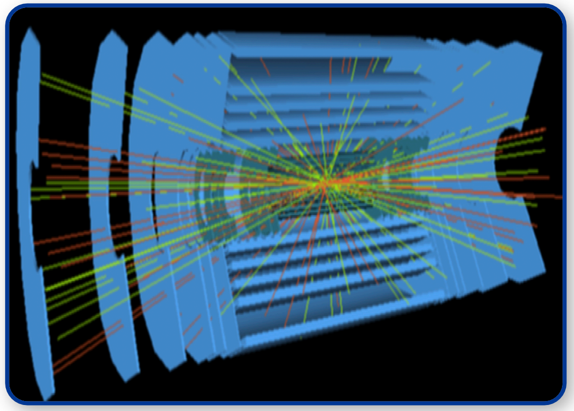
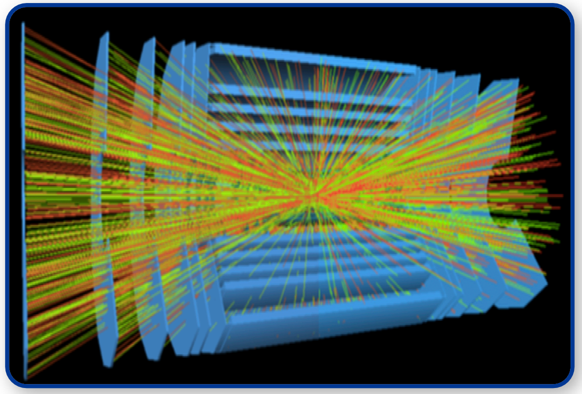
On behalf of the ATLAS High Granularity Timing Detector Group

Challenge for High Luminosity LHC



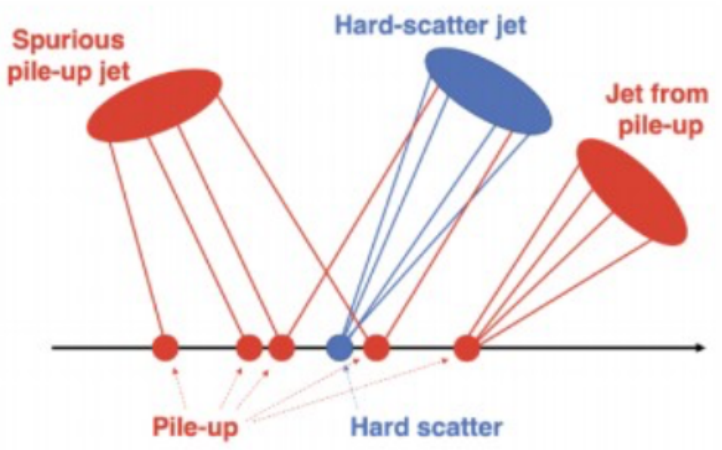


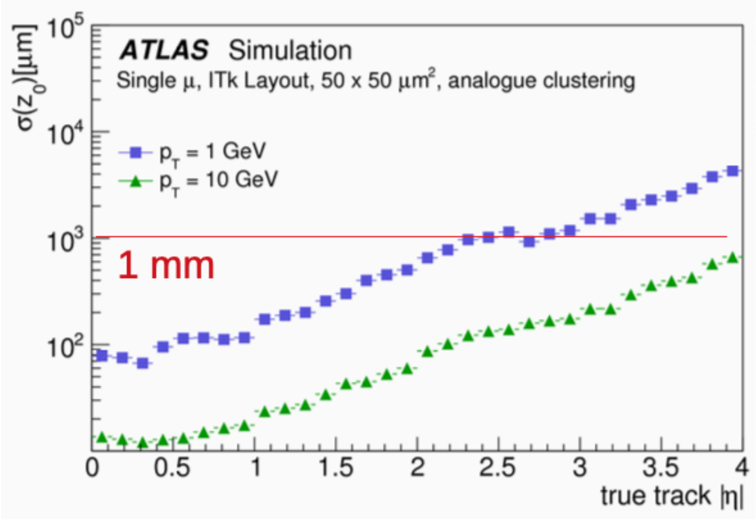


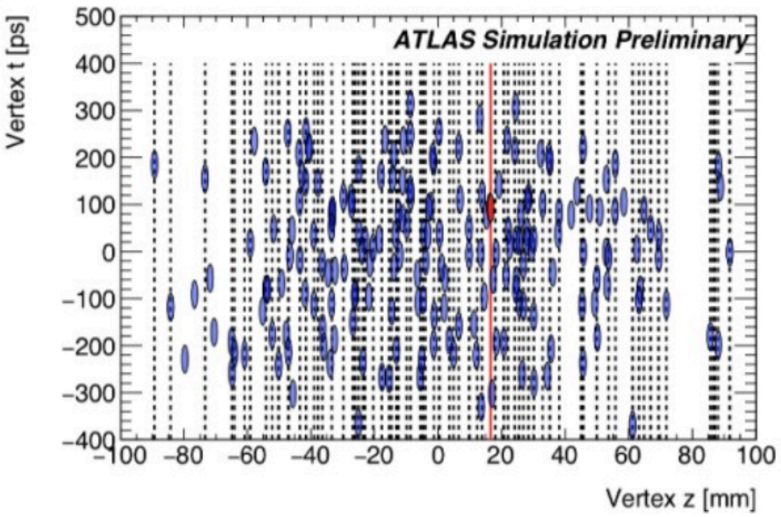
- HL-LHC will start in ~ 2027
- Instantaneous luminosity 7.5×10^{34} $cm^{-2}s^{-1}$, 5~7.5x increase
- Average number of interactions per bunch crossing (pile-up events) reach 200

The High Luminosity LHC

- Average 1.6 collisions/mm.
- Pile-up can add jets, create spurious jets, alter the properties of hard scattered jets, degrading physics performance
- The Inner Tracker (ITk) mostly migigates the effect of pile-up, but still challenging in the forward region
- Timing information (σ_t~30 ps) can be used to mitigate the effect of pile-up.

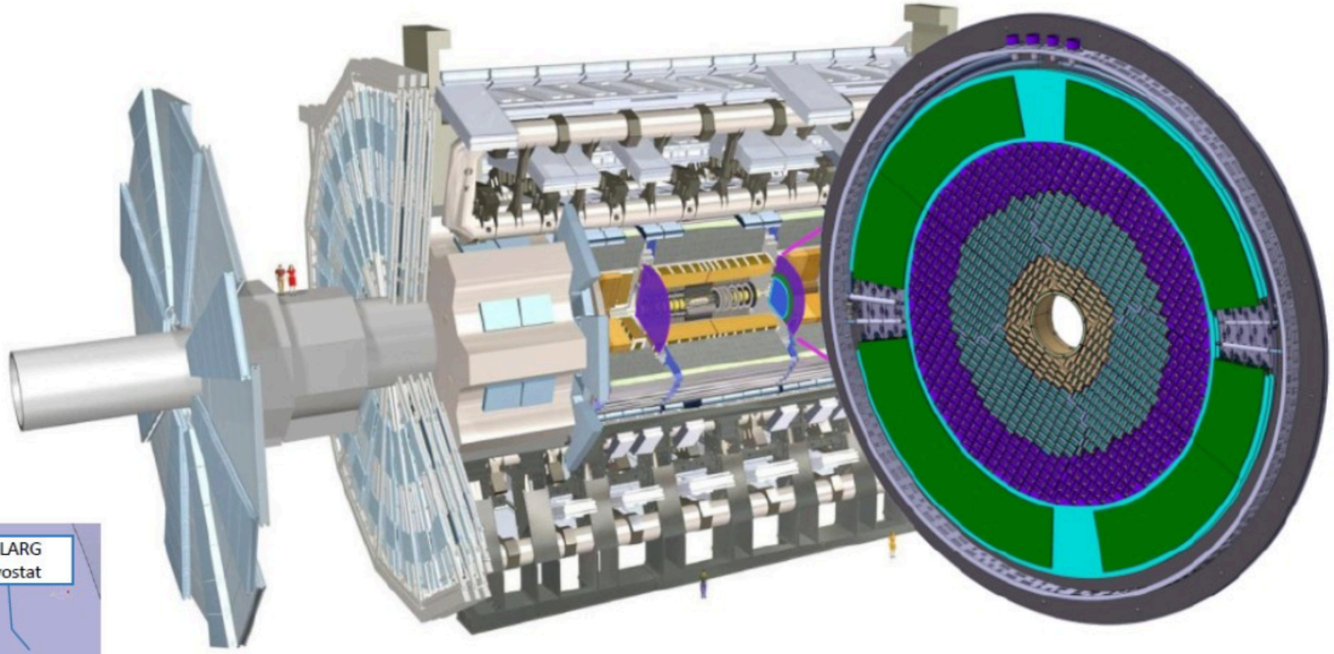


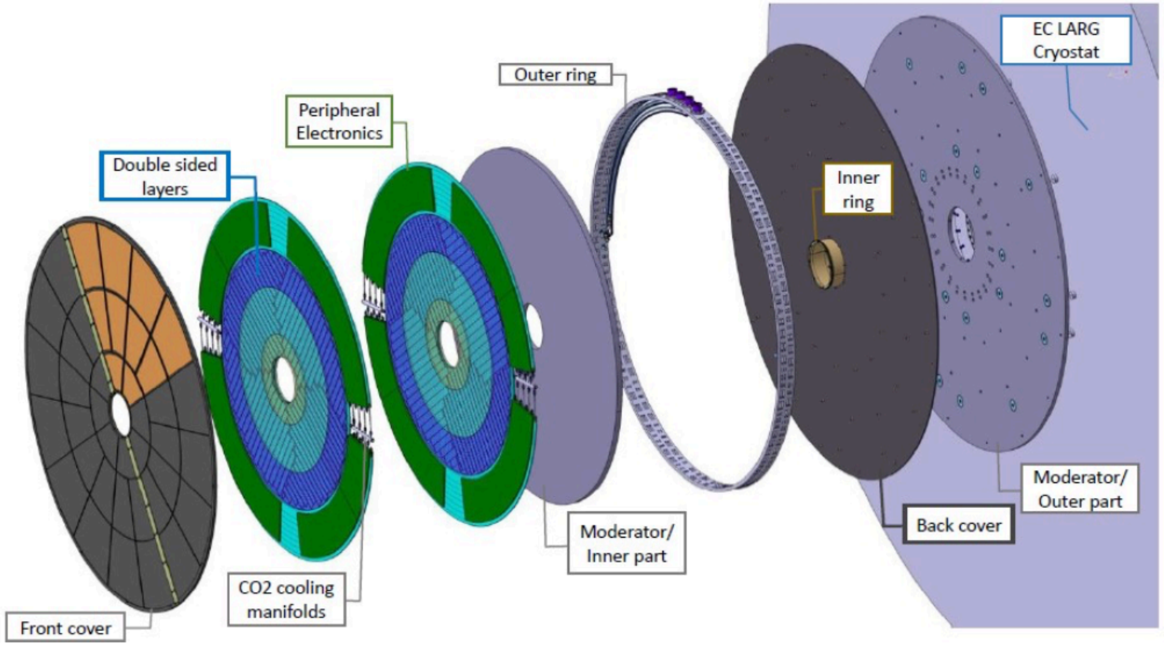




High Granularity Timing Detector (HGTD)

- HGTD designed to improve the forward region in view of increased pile-up
- Target time resolution: 30~50 ps/track up to 4000/fb

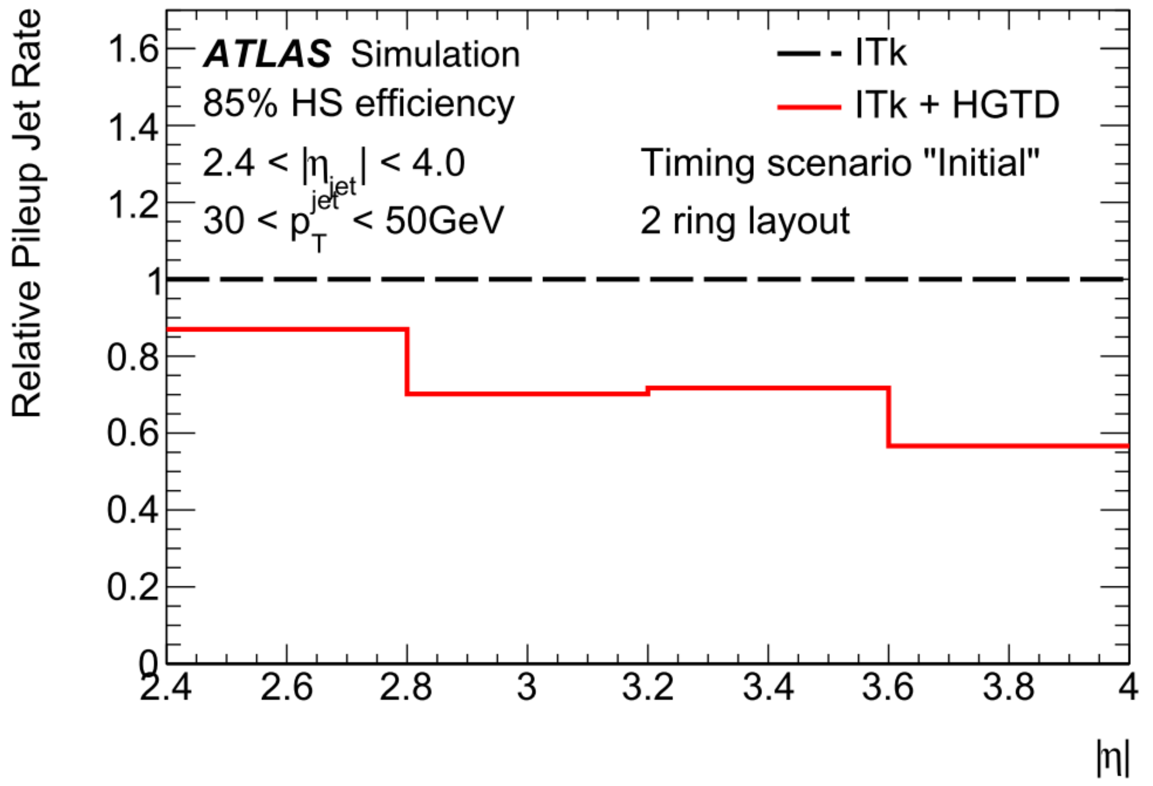




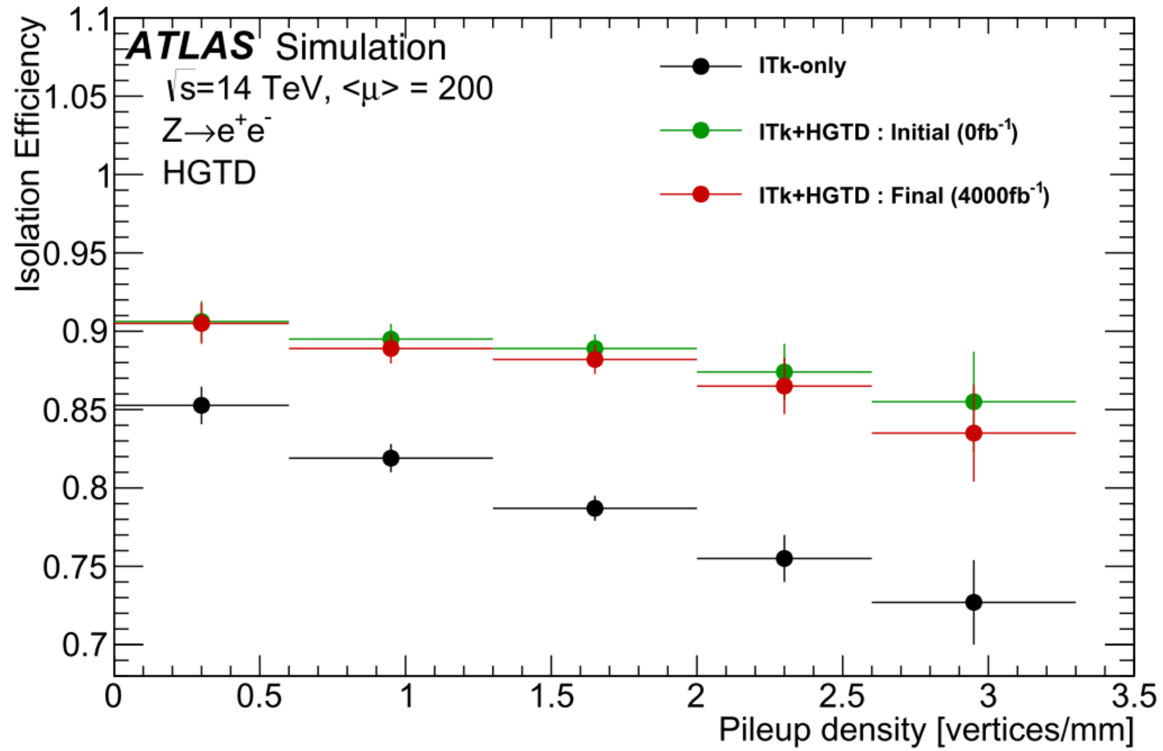
- Located between barrel and endcap calorimeters ($|z| = 3.5$ m)
- Silicon detector modules mounted on disks
- Two sensor layers/disk
- Two disks/side
- Active area: 12 cm < r < 64 cm
- Coverage: $2.4 < |\eta| < 4.0$

Impact of HGTD with two examples

- Pile-up rejection especially at large η

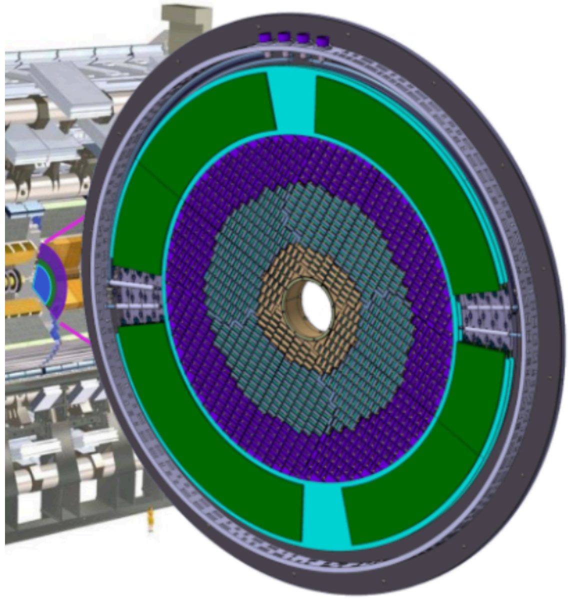


- Maintain high electron isolation efficiency

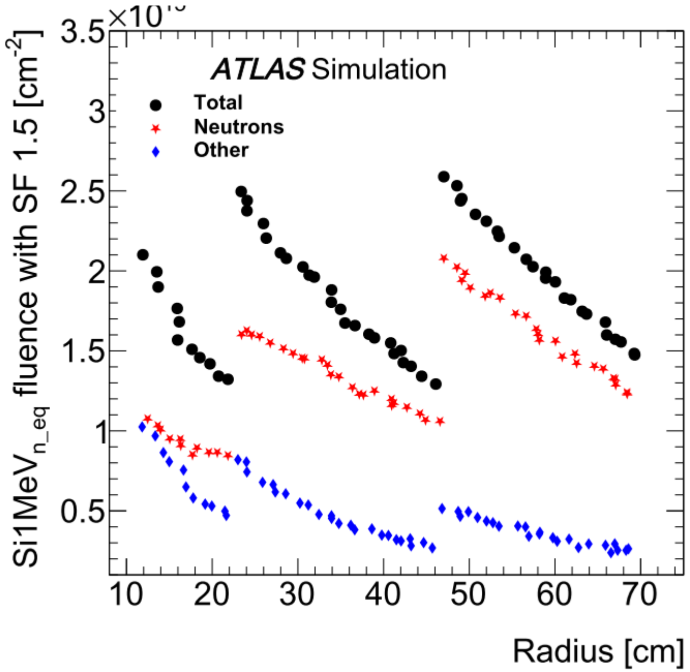


Radiation Hardness

- Maximum fluence: 2.5E15 1MeV n_{eq}/cm^2 and 2 MGy at the end of HL-LHC (4000/fb)

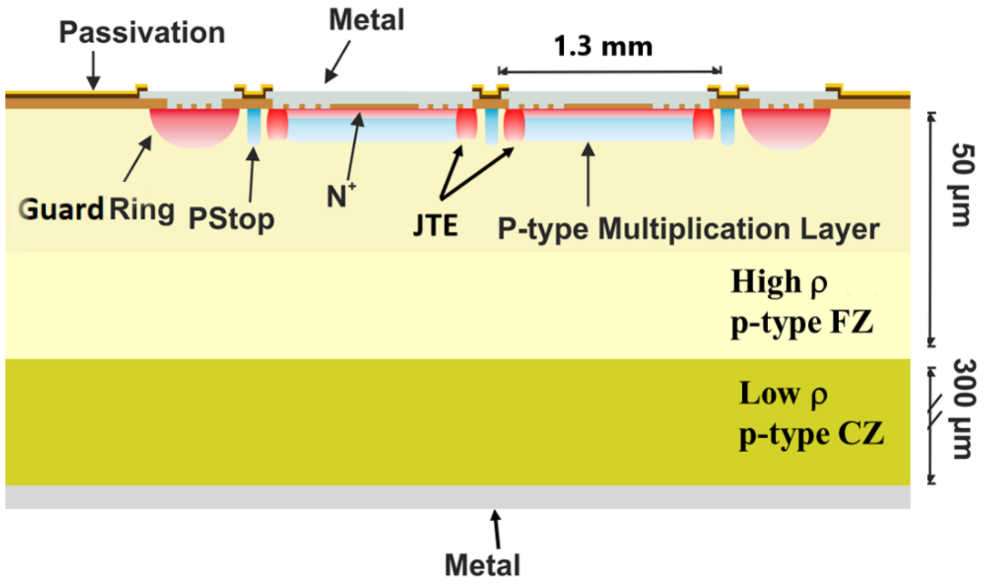


- Inner ring (12-23 cm) replaced every 1000/fb
- Middle ring (23-47 cm) replaced every 2000/fb
- Outer ring (47-64 cm) never replaced



Sensor - Low Gain Avalanche Detector (LGAD)

- n on p sensor with p-type multiplication layer
- Low gain (G~10): to improve signal slope but control noise



HGTD requirements after 2.5E15 n_{eq}/cm^2

- Good and uniform electrical behavior (IV)
- 4fC collected charge (for front-end functionality)
- Time resolution better than 70ps (~50 ps/track)
- Hit efficiency better than 95%

$$\sigma^2_{\text{det}} = \sigma^2_{\text{Landau}} + \sigma^2_{\text{elec}}$$

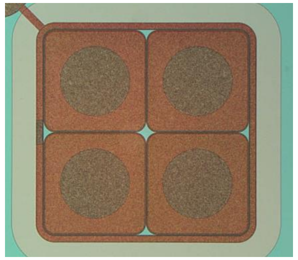
$$\sigma^2_{elec} = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$

Jitter   Time walk

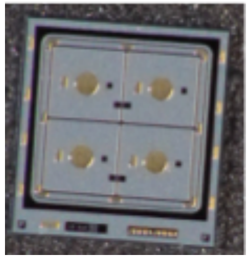
Sensor Lab Measurements

- Single diodes (CNM, FBK, HPK, NDL, IME ...) extensively studied
- Need to understand the electrical performance of large sensors (15x15)
  - Probe-card developed to study IV of pads
  - Preliminary measurements indicate a reasonable yield is achievable

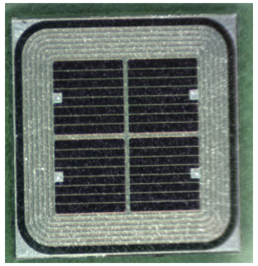
CNM



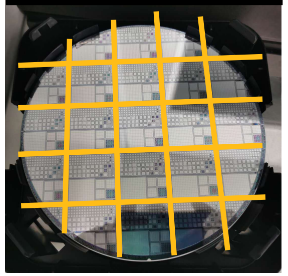
FBK



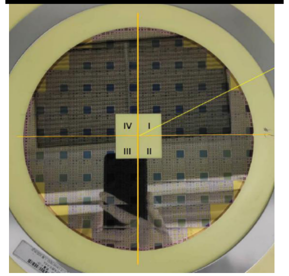
NDL



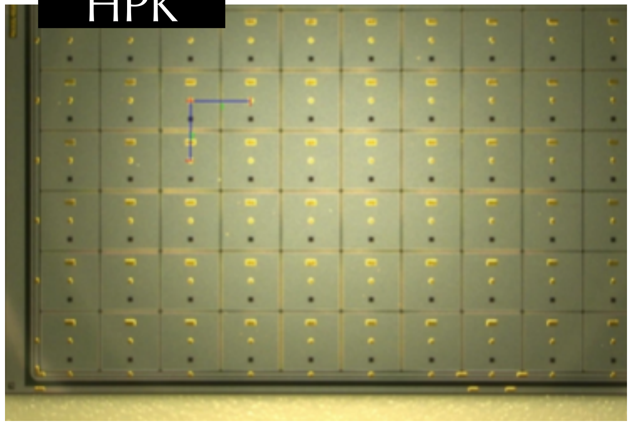
USTC-IME

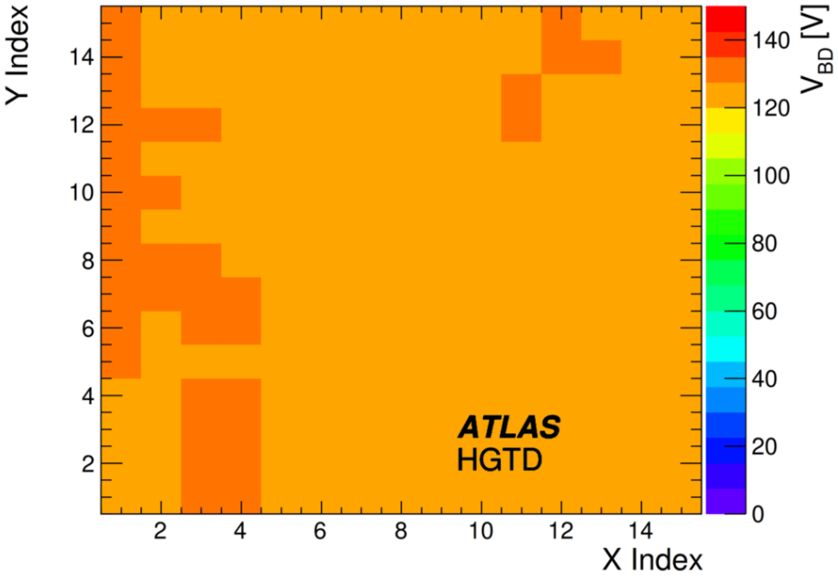


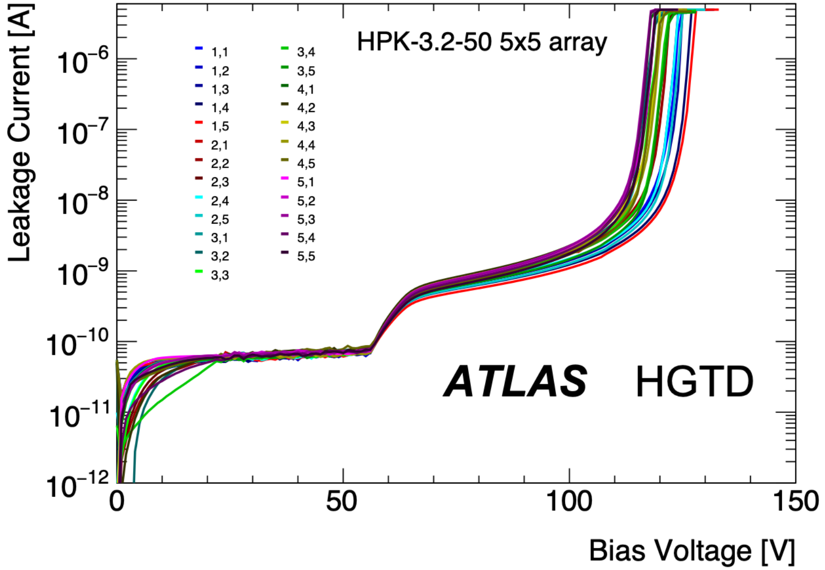
IHEP-IME



HPK

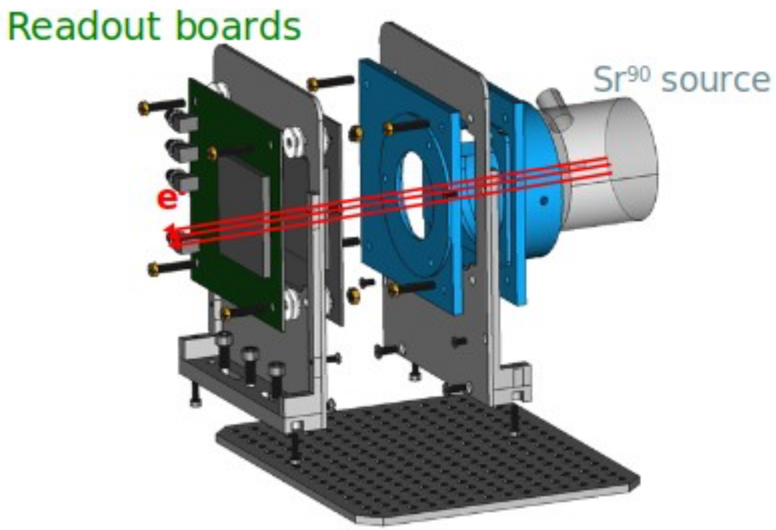


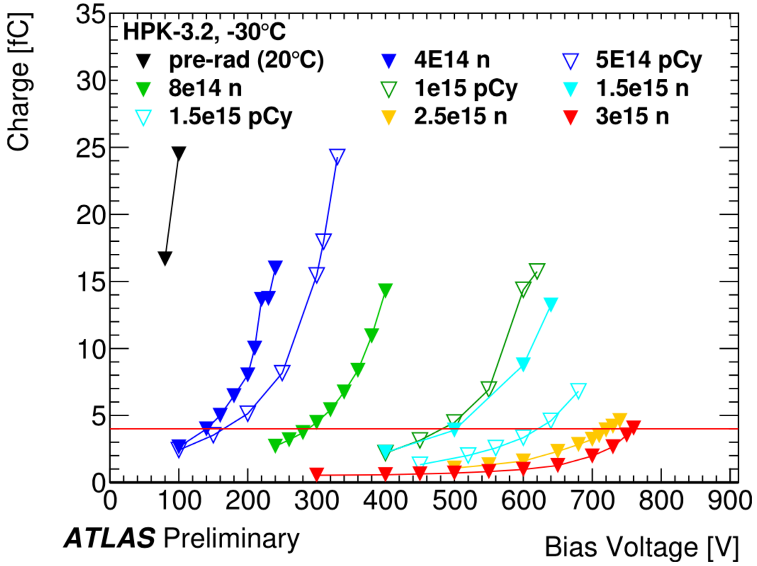


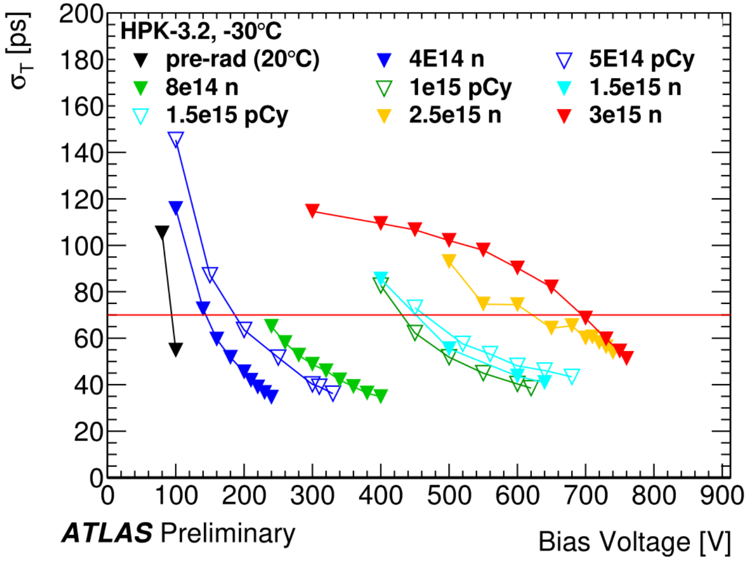


Charge collection and time resolution

- Use electrons from Sr-90 source in well controlled climate chamber



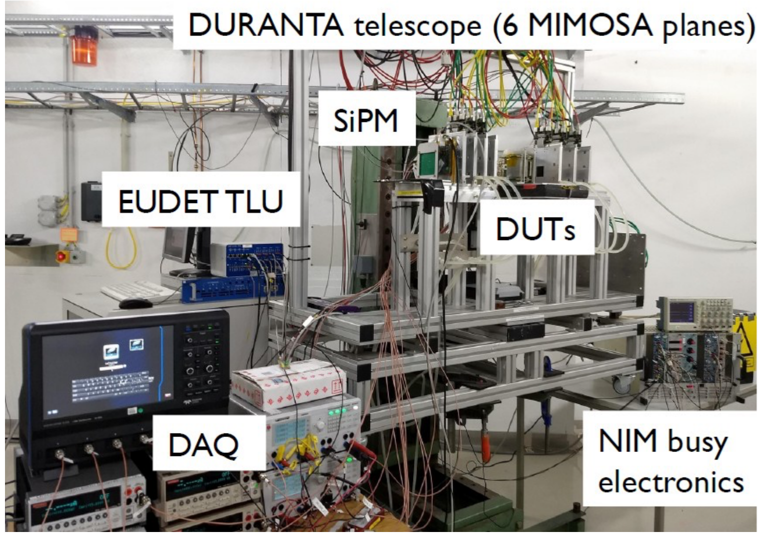


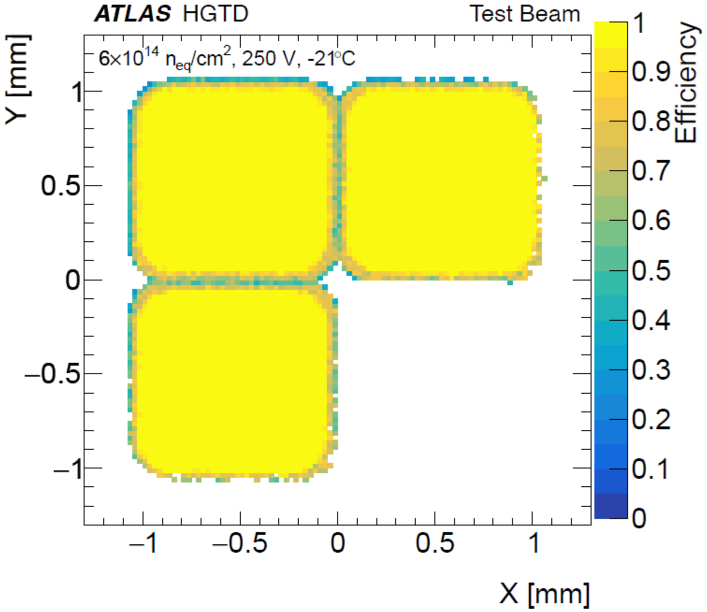


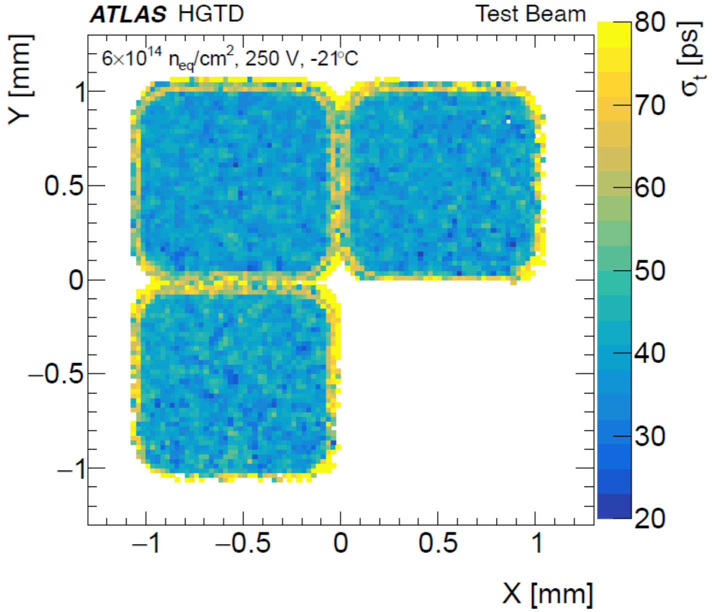
- After irradiation gain layer degradation
- LGAD sensors from a variety of vendors satisfy collected charge requirement after irradiation to 2.5e15 n_{eq}/cm^2

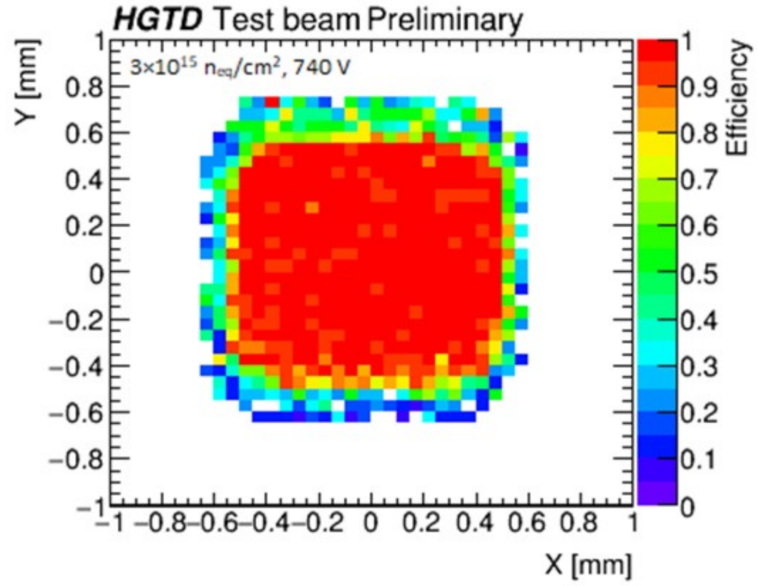
Sensor Testbeam Measurements

- Test beam with pion/electron beams (CERN/DESY)
- Telescope planes to provide track reconstruction
- Record wave-forms to perform analysis
- Tested single diodes and 2x2 arrays



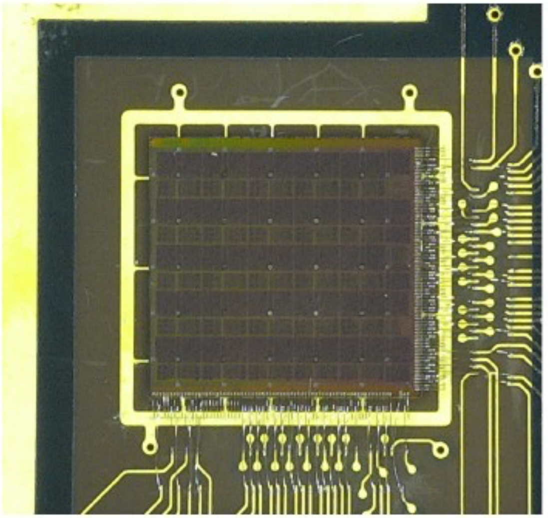


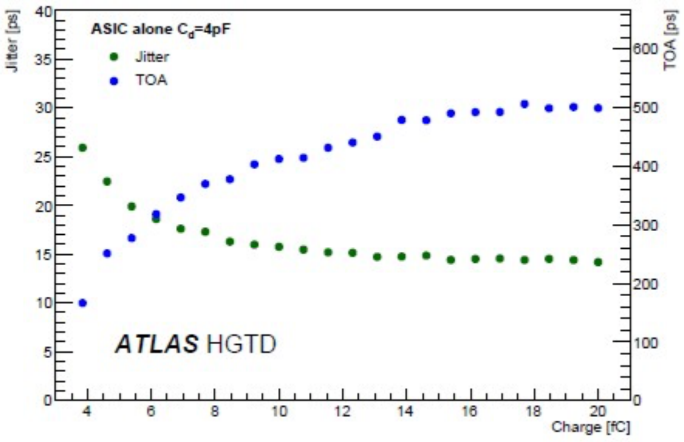


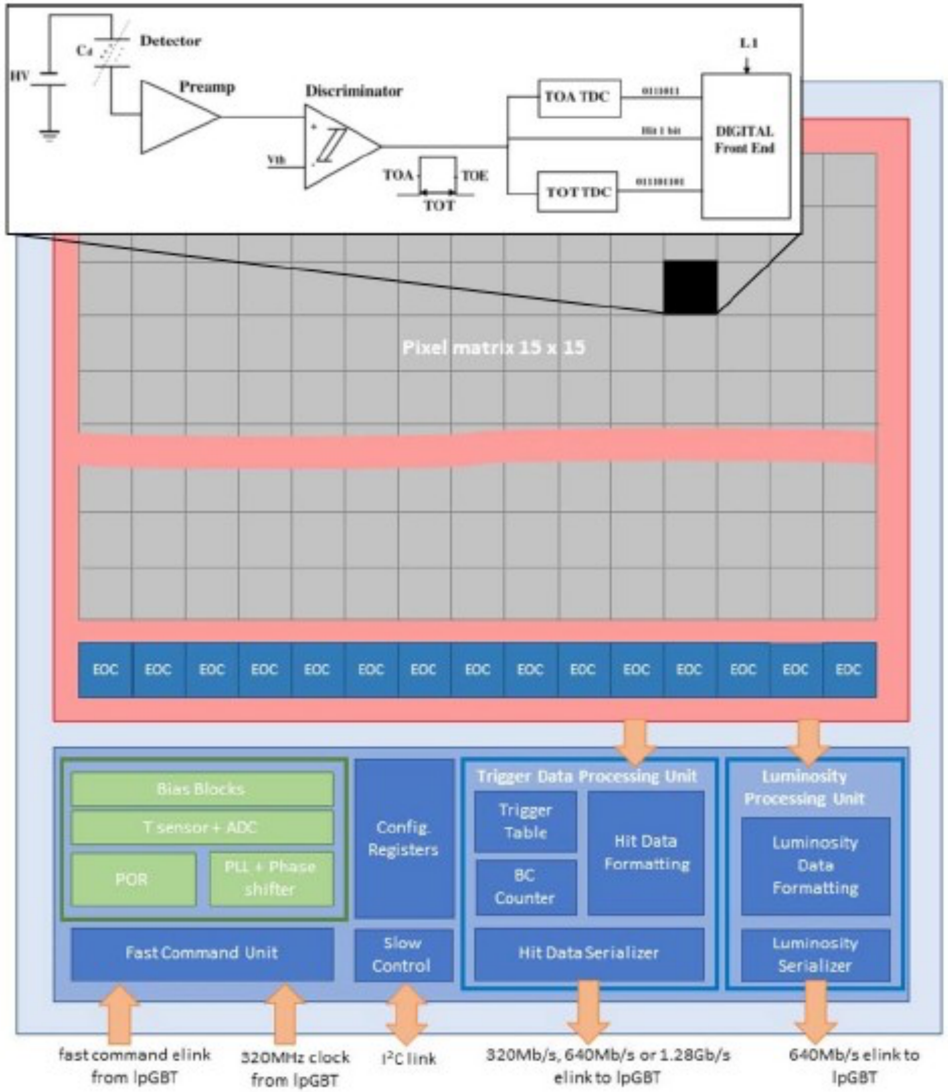


HGTD Frond End Chip: ALTIROC

- TSMC CMOS 130nm technology
- 15x15 readout channels
- Pre-amplifier followed by TOA and TOT (for time-walk correction)
- Prototypes produced and tested: 2x2 (ALTIROC0) and 5x5 (ALTIROC1)
- ALTIROC1 with 4pF input capacitance can achieve ~25ps jitter at 4fC input charge

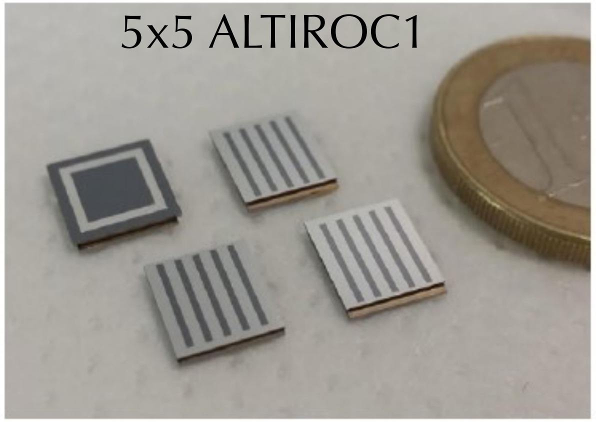


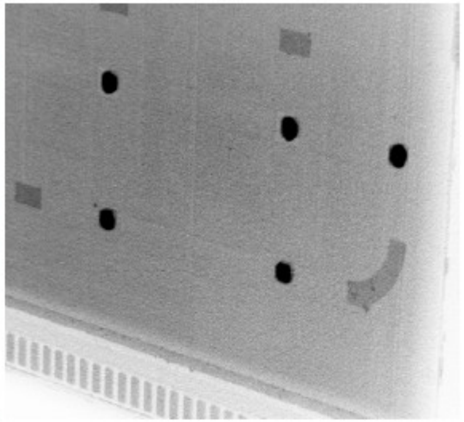




Hybridization Process

- LGAD sensor and ALTIROC hybridization through bump-bonding
- Simpler than “pixel detector” process due to larger pads

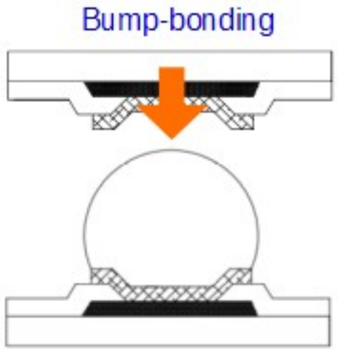




QC with X-ray inspection

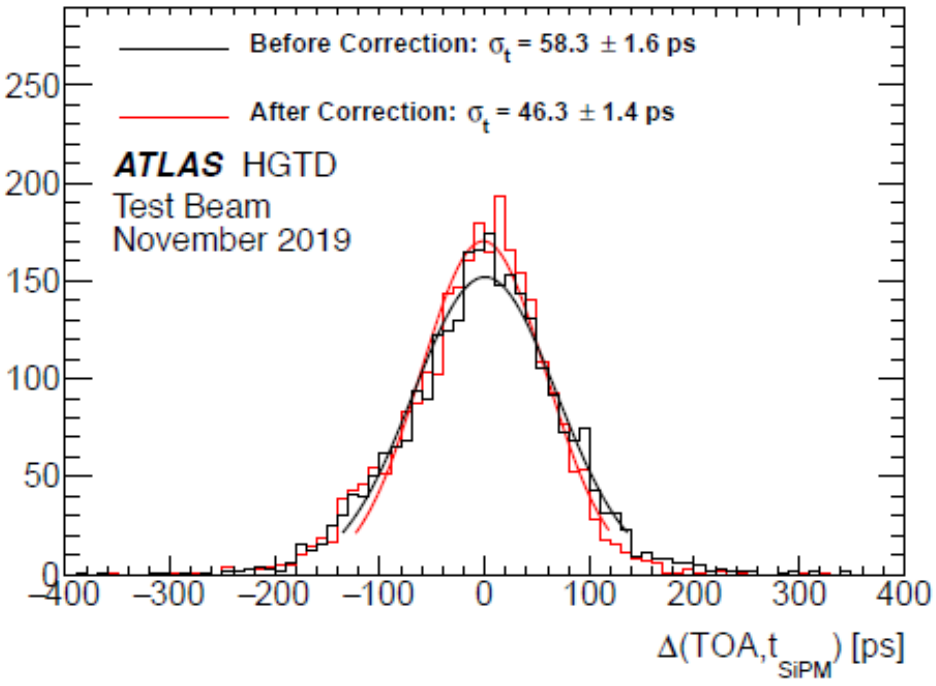
80 um Ø dump connection

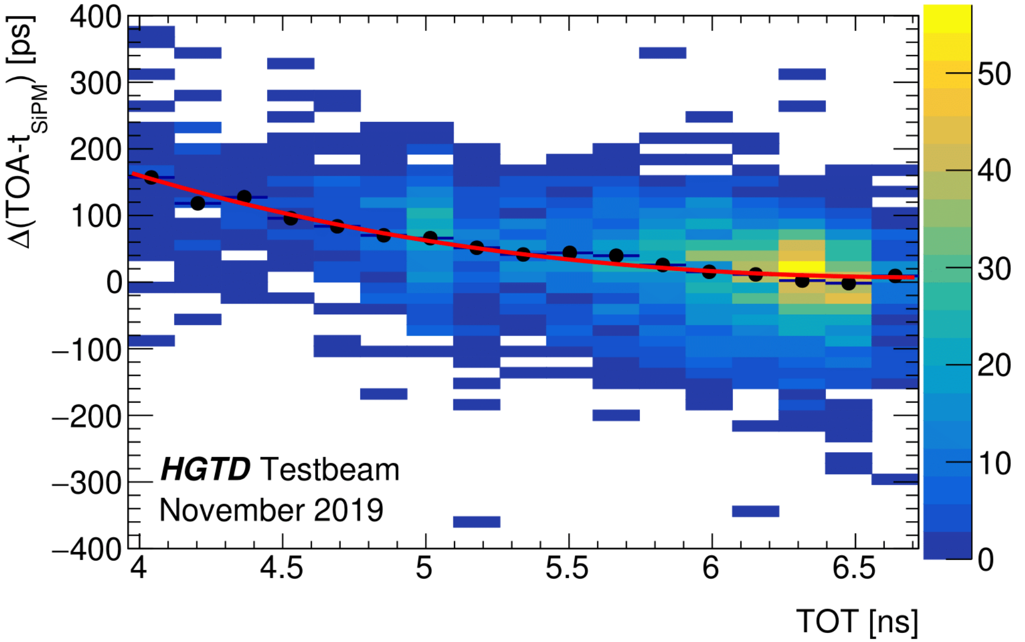
- Produced 5x5 ALTIROC1samples and 15x15 dummies
- Shear and pull forces: > 1kgf, > 100gf
- Reliable baseline hybridization process



First ALTIROC1 Module Testing

- Test beam measurements with electrons at DESY
- Unirradiated ALTIROC1 modules
- TOA corrected for time-walk

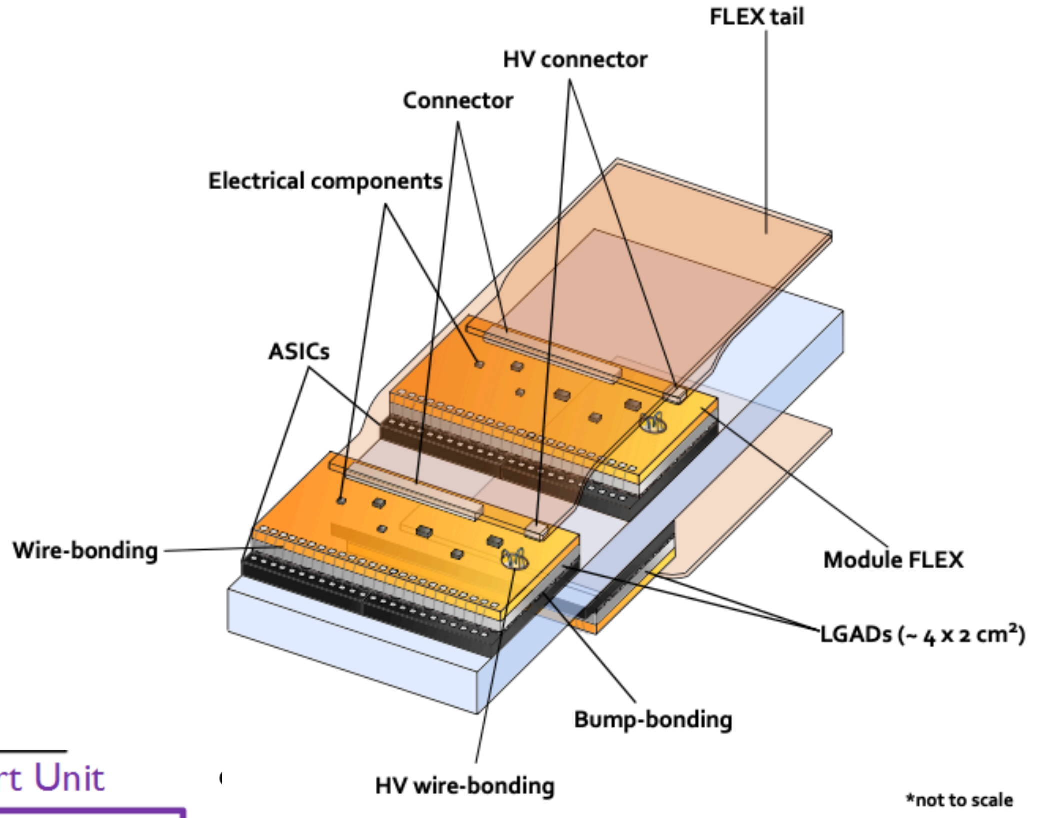


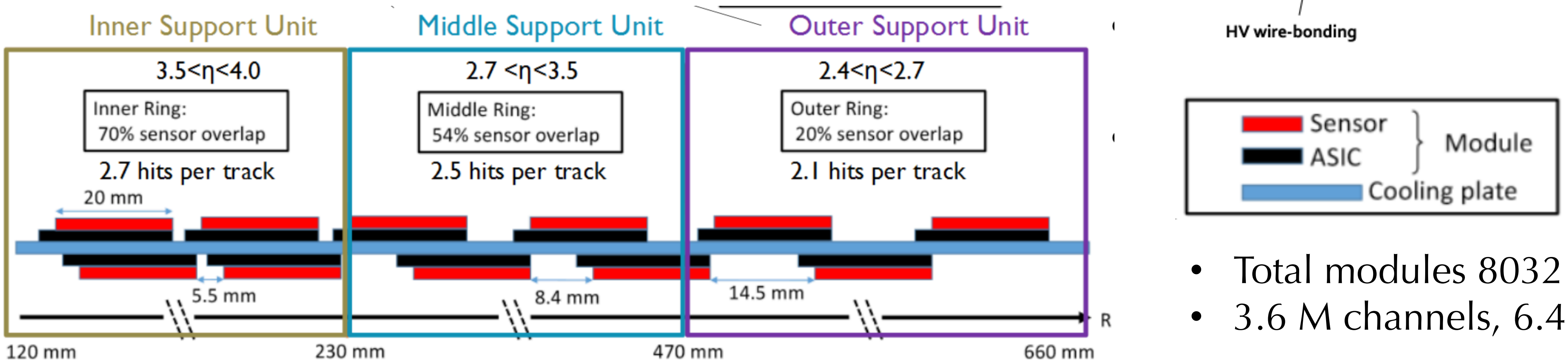


- Estimated resolution about 46 ps (subtracting time-walk contribution)
- Including Landau contribution (~25ps)
- Estimated jitter contribution about 39ps
  - Improved DAQ (FPGA) reduced contribution by 35%
  - achieving ~25ps target

HGTD Module

- Sensor: 15x30 pads of 1.3x1.3 mm^2
- Bump-bonded to two readout ASICs
- Flex-PCB glued on top
- Flexible tail to outer radius electronics





- Total modules 8032
- 3.6 M channels, 6.4 m^2

Summary

- The HL-LHC presents unprecedented challenges, timing information expected to play a key role to mitigate the impact of pile-up
- ATLAS High Granularity Timing Detector will use the LGAD technology to improve the ATLAS performance in the forward region
- The HGTD is optimized to reach a per-track resolution of about 30-50 ps up to the end of the lifetime of the detector
- Sensors and ASICs are being tested, and have shown to be able to reach the required performance
- The HGTD Technical Design Report has been approved in Sept 2020
  CERN-LHCC-2020-007; ATLAS-TDR-031
- The overall design and construction works are progressing in all directions (mechanics, cooling, demonstrator, etc.)