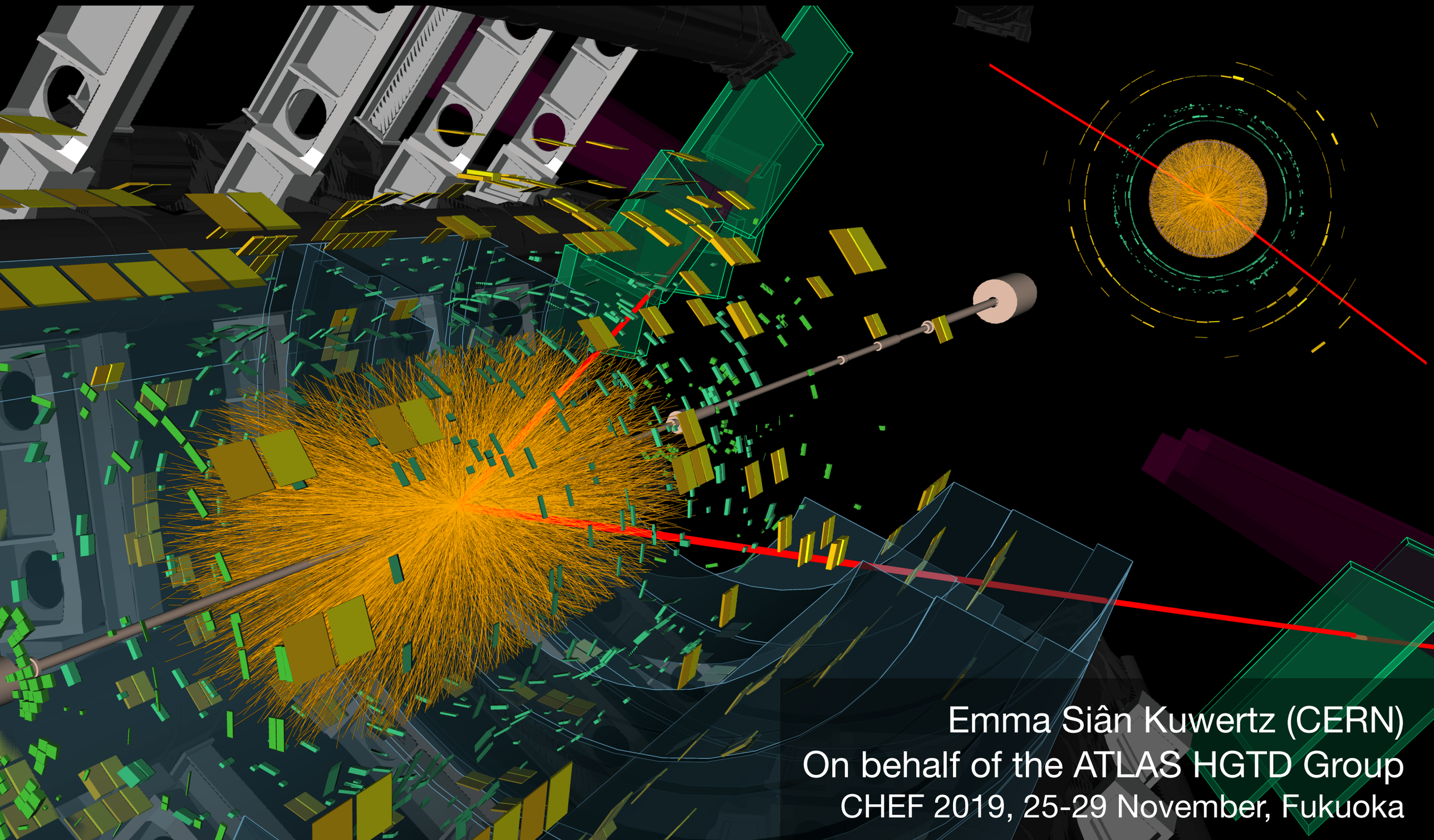
A High-Granularity Timing Detector (HGTD) for the ATLAS Phase-II upgrade:

detector concept, description and R&D and beam test results



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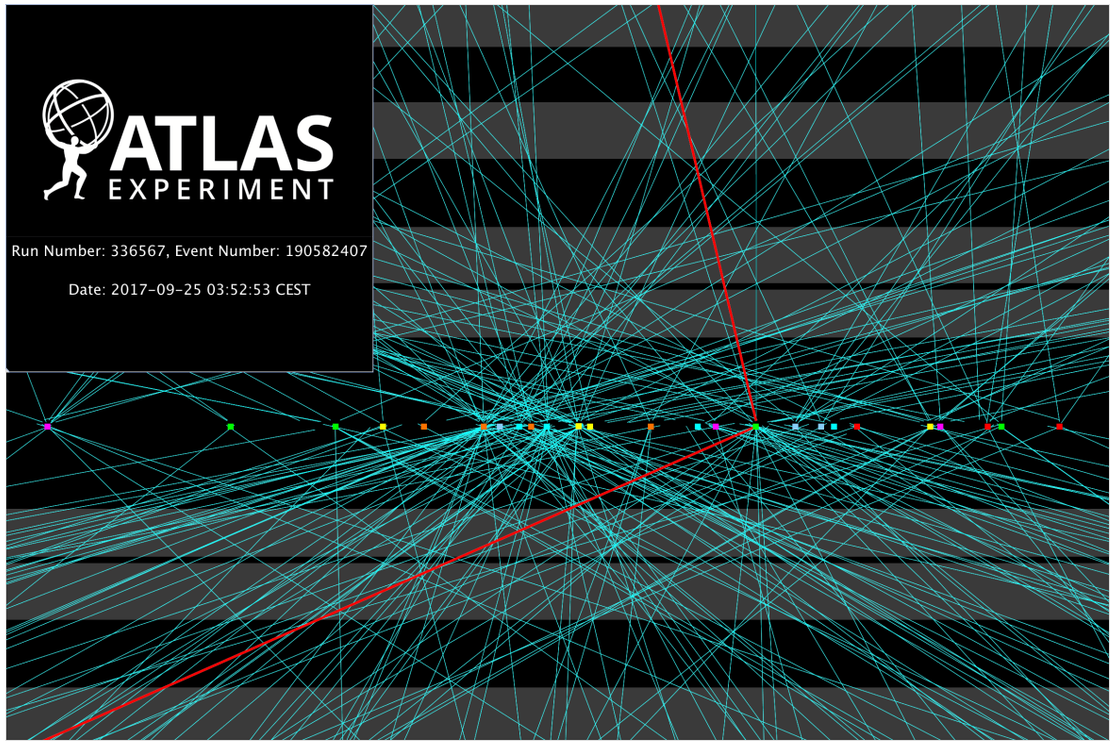
On behalf of the ATLAS HGTD Group
CHEF 2019, 25-29 November, Fukuoka

Pileup challenges at high luminosity

Z→μμ candidate event

bunch crossing with 24 additional reconstructed vertices from minimum bias interactions

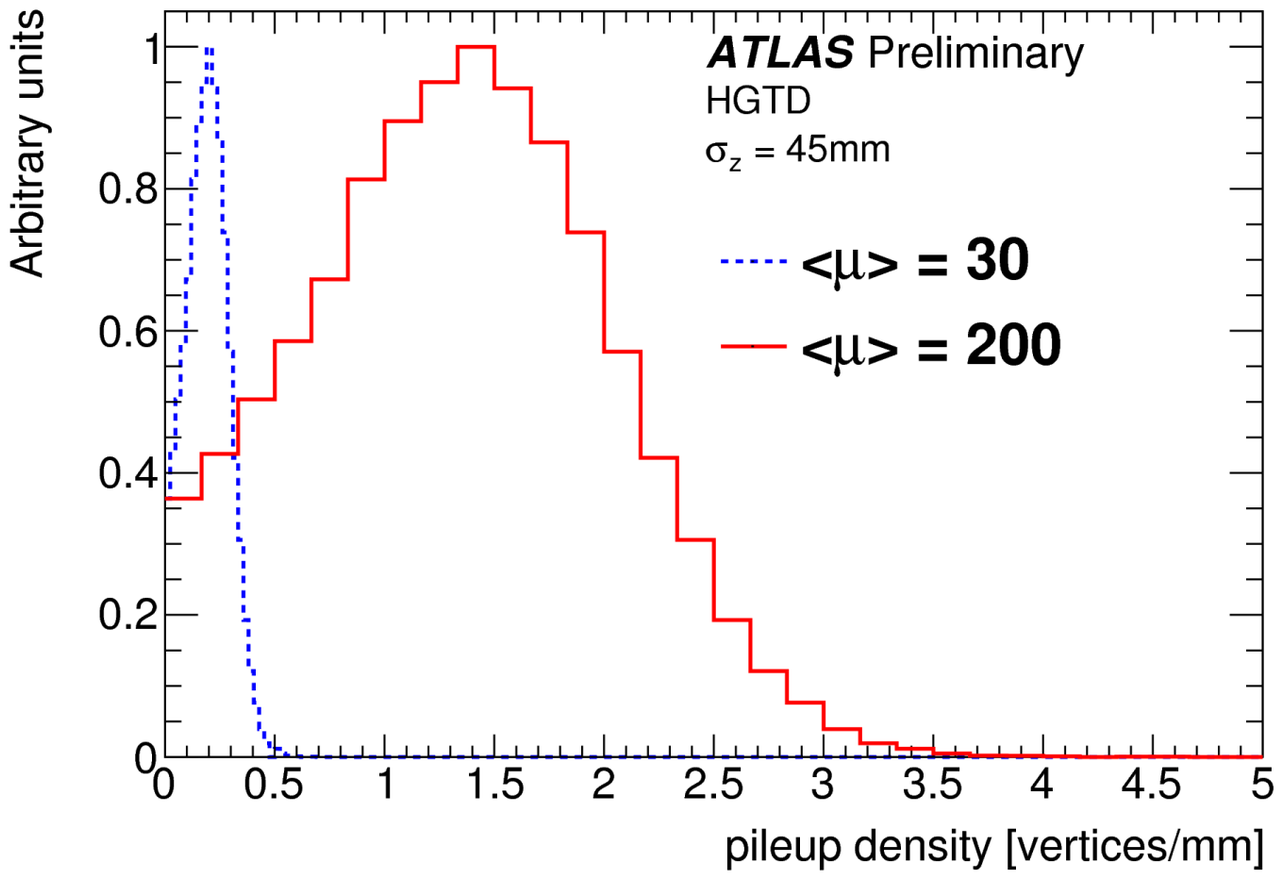


Average number of interactions per bunch crossing <μ>

- End of LHC Run 2: ~ 36
- HL-LHC: ~ 200

HL-LHC will bring increased particle densities (~1.8 collisions/mm)

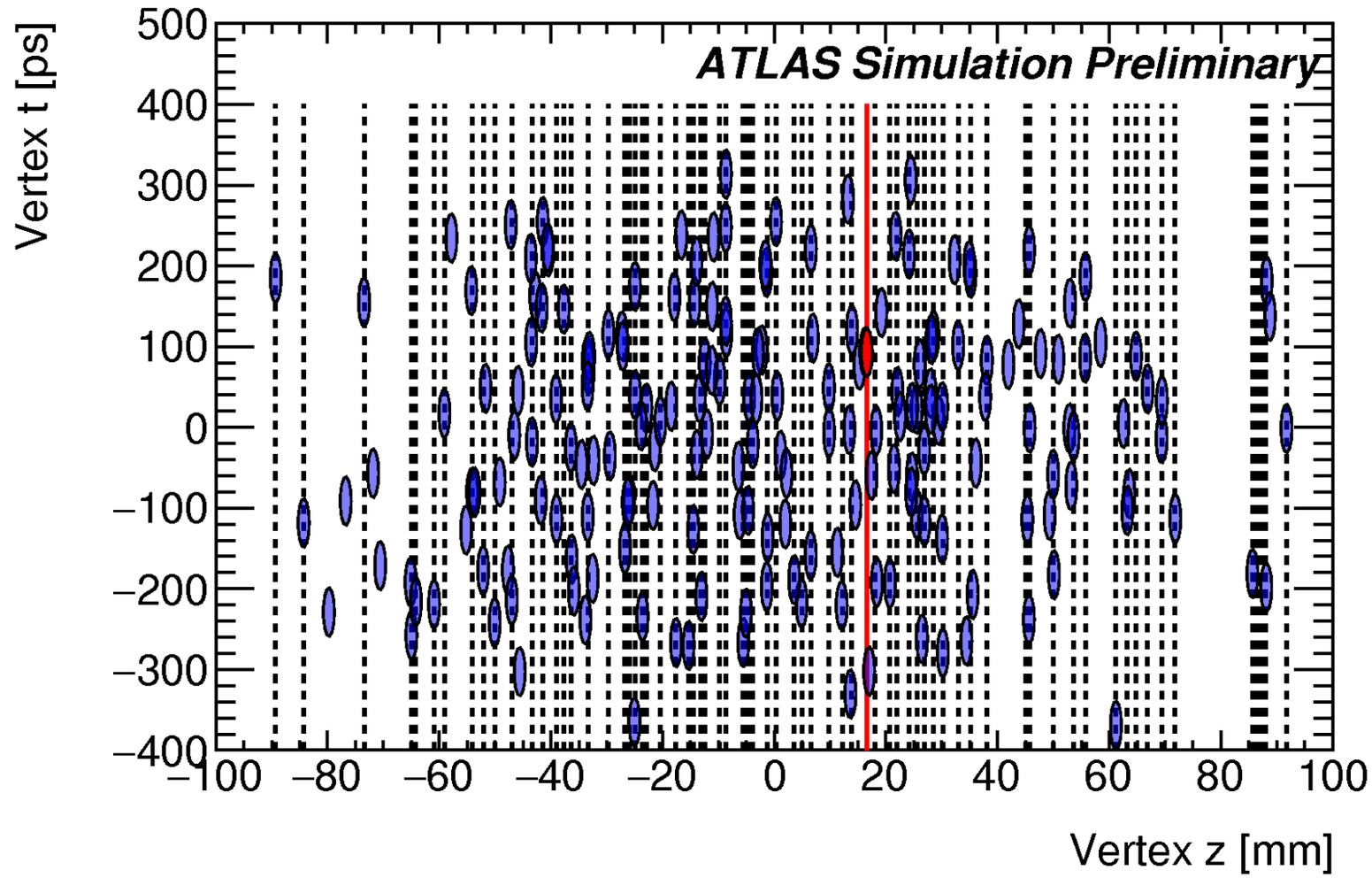
- Requires excellent longitudinal (z) resolution for reliable track-to-vertex association
- Silicon inner tracker (ITk) upgrade provides coverage up to |η|=4.0
- z resolution degrades even more severely in ***forward region***



"4-D tracking" in the forward region

Time spread of vertices ~175 ps

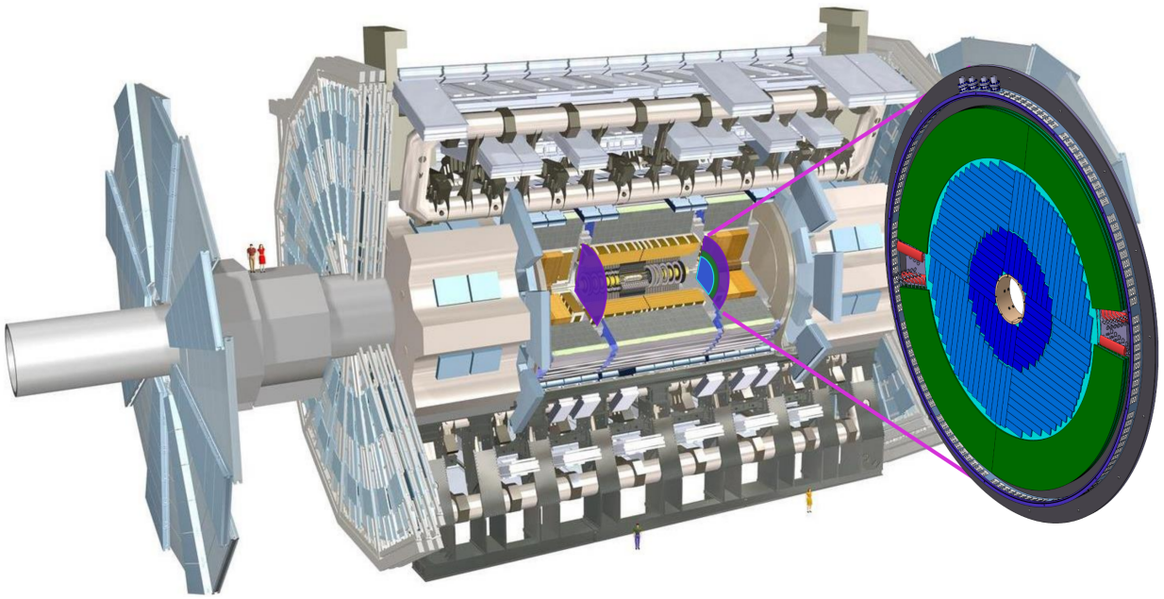
- Exploit time information in addition to space spread of tracks
- Extend pileup rejection capabilities in the forward region (2.4<|η|<4.0)
- Use track time to improve track-to-vertex association



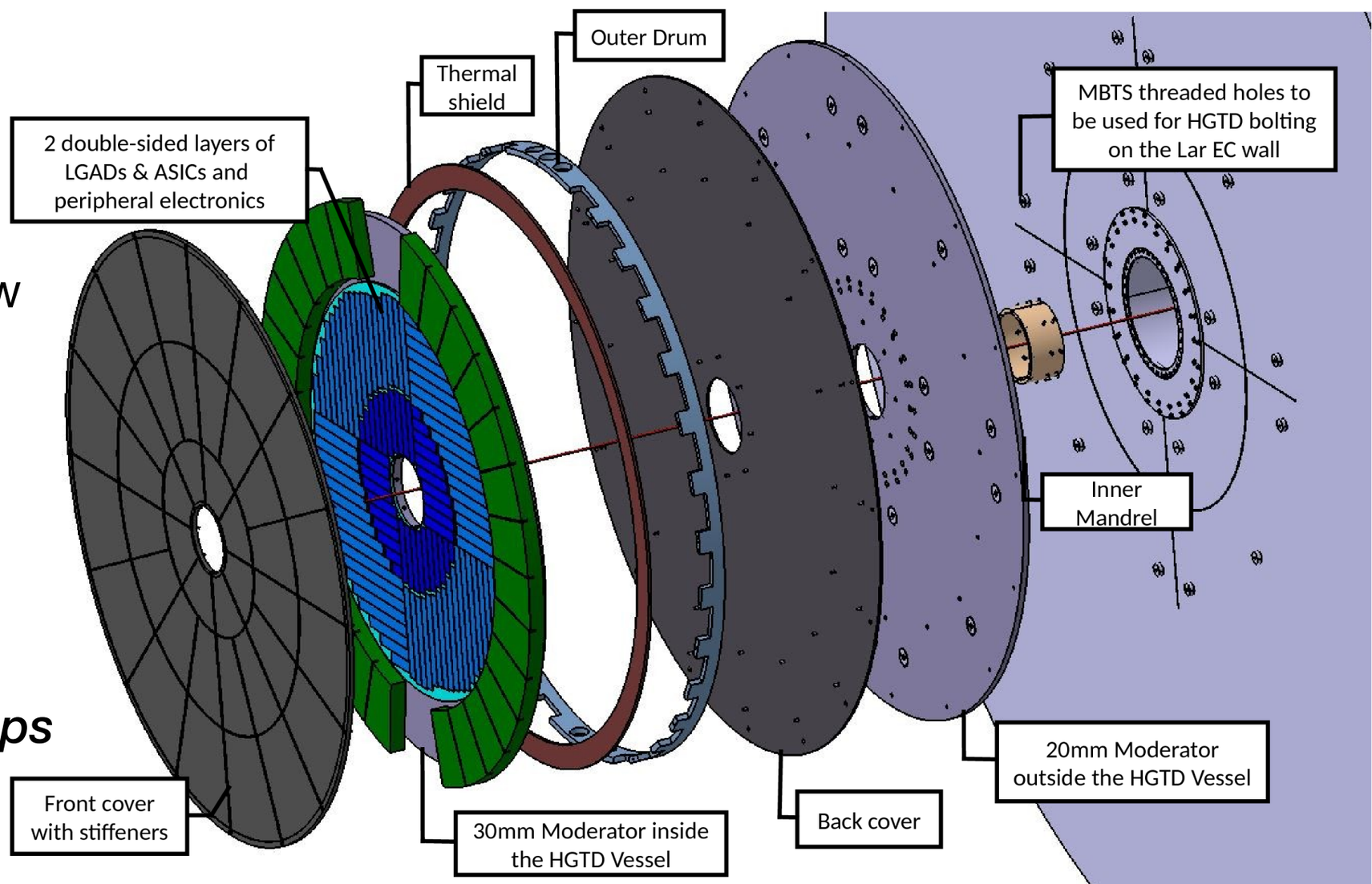
With a time resolution of 30 ps → ~6× more pileup rejection

- Improve physics and object reconstruction performance
- Reduce jets from pileup vertices
- Reduce tracks from pileup vertices being associated with hard-scatter jets

A High-Granularity Timing Detector (HGTD)



- Inserted within unoccupied region in each endcap (Δz=75mm)
- Two double-sided layers mounted on cooling disks in each endcap

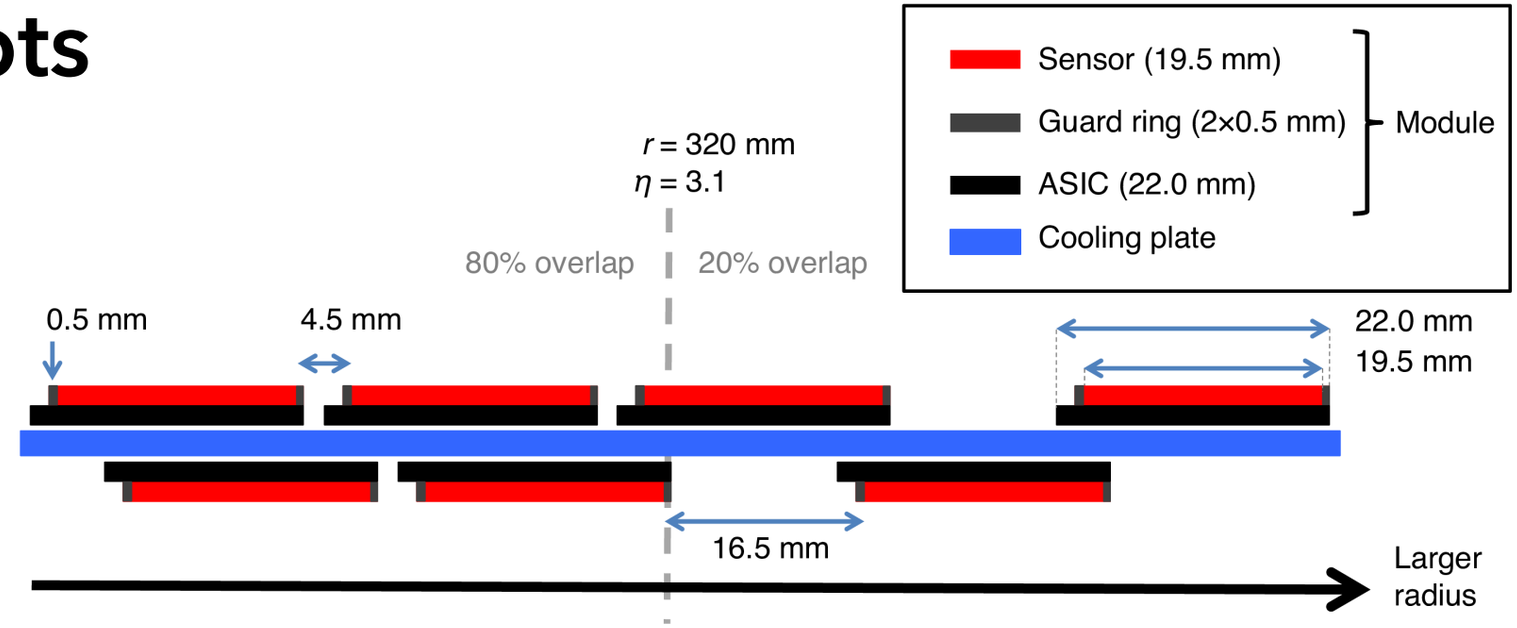


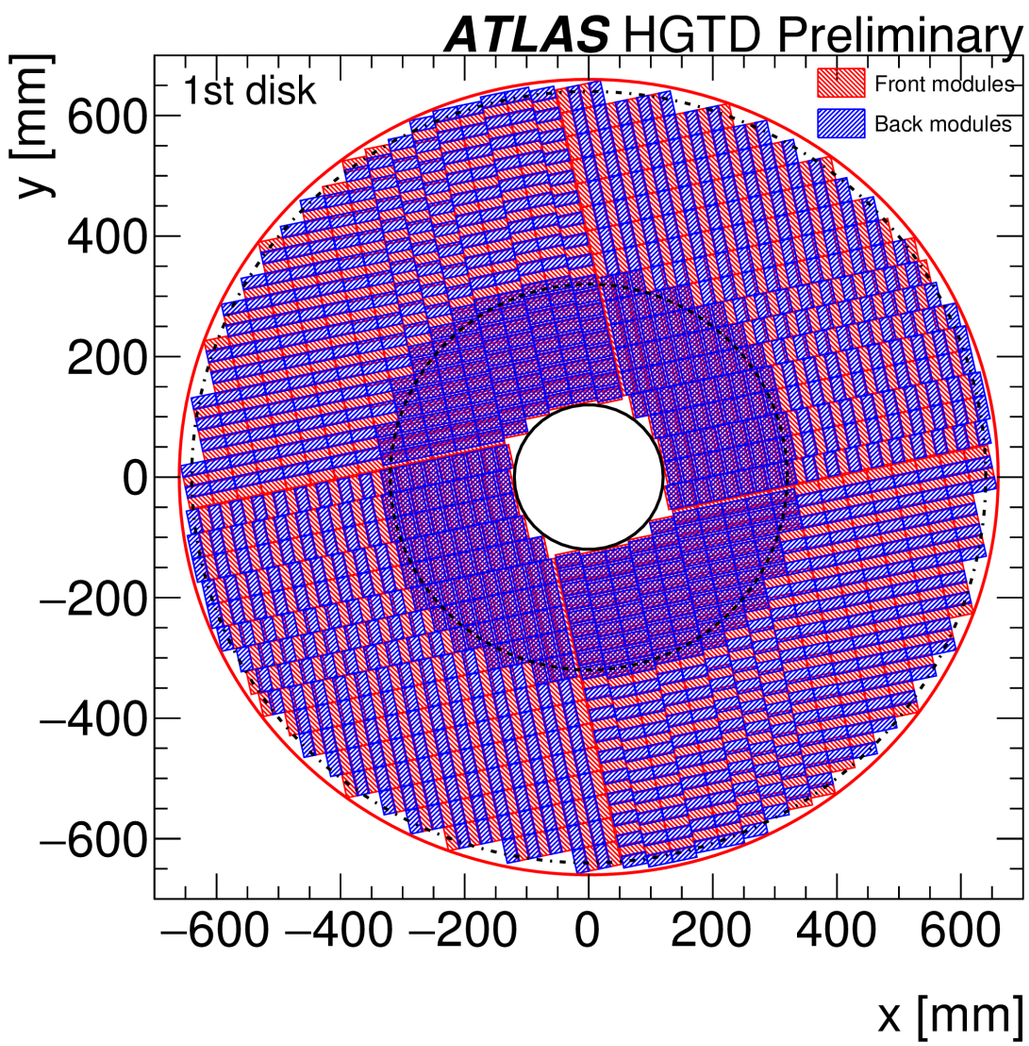
- Instrumented with silicon **L**ow **G**ain **A**valanche **D**etectors (LGADs)
- Specially designed ASIC ATLIROC front-end
- Total ***active area*** = 6.4 m²
- ***Time resolution/track 25-50 ps***

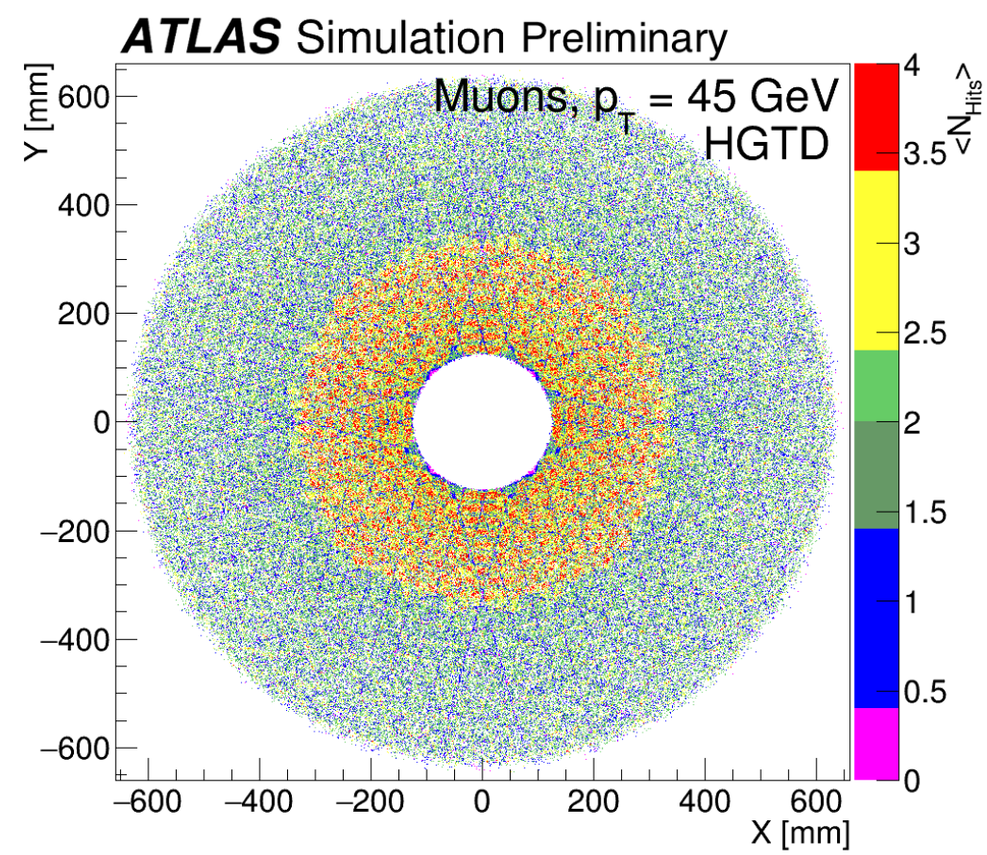
HGTD design concepts

Coverage

- Module overlap optimised for uniformity
- 15° rotation of each disk in opposite directions to avoid gaps







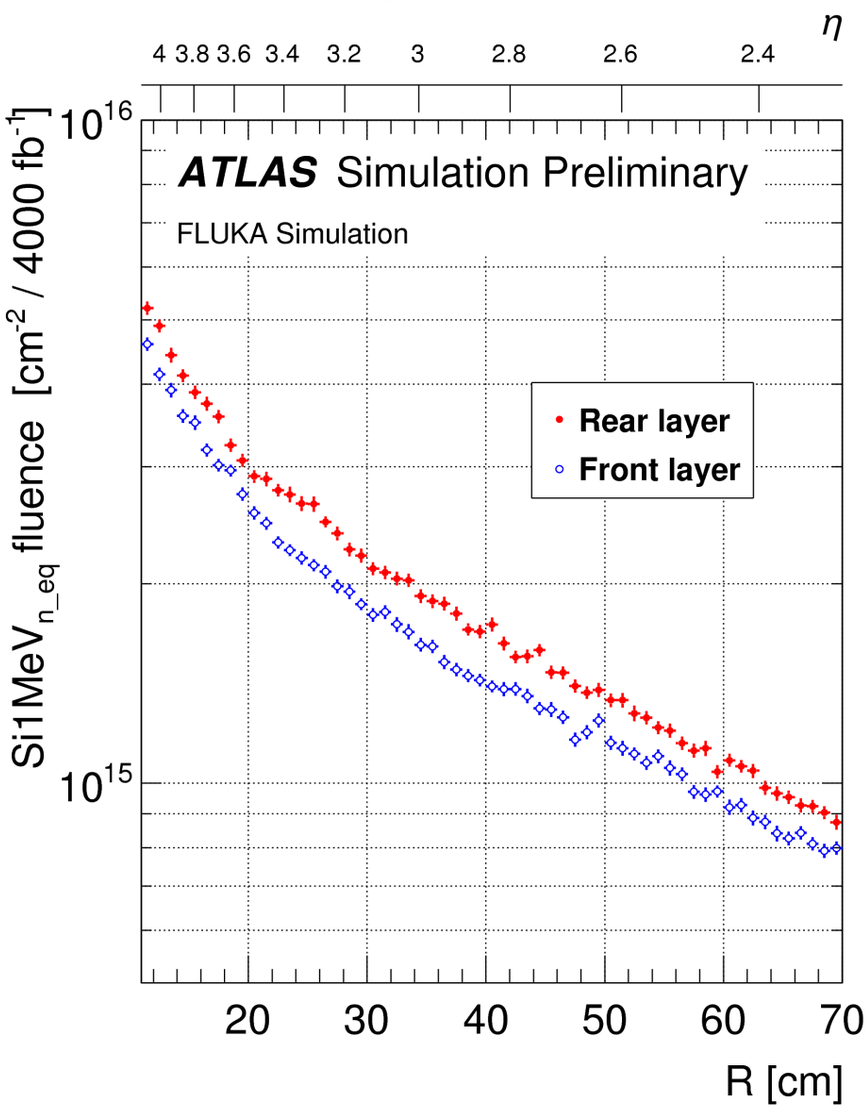
Number of hits/track: 2 for 2.4<|η|<3.1
3 for 3.1<|η|<4.0

HGTD design concepts

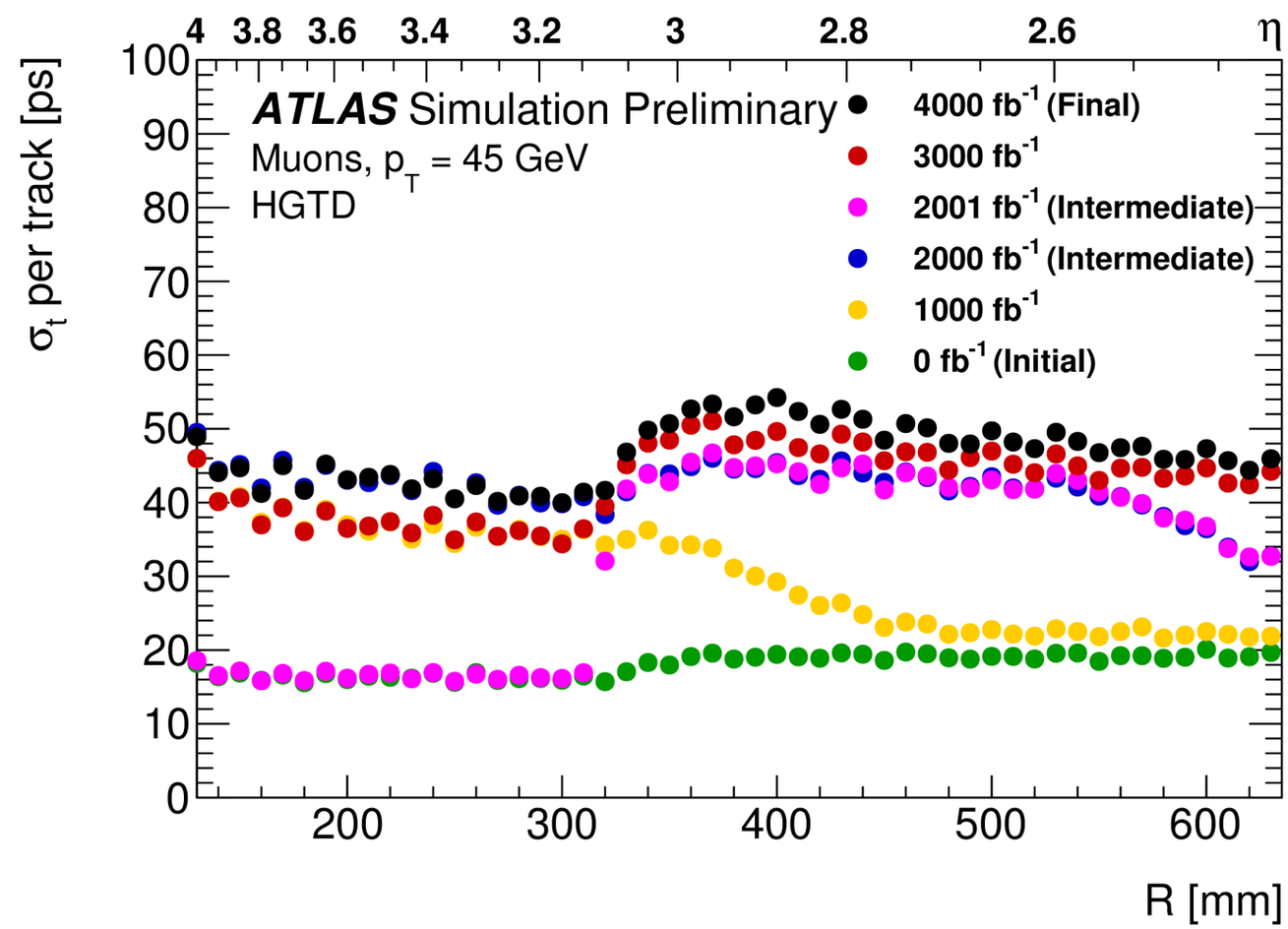
Radiation effects

In HL-LHC lifetime:

- Integrated luminosity ~ 4000 fb^{-1}
- Total ionising dose (TID) ~ 3.6 MGy (with safety factor of 2.25)
- Fluence ~ 3.7×10^{15} n_{eq} cm^{-2} (with 1.5 safety factor)



- CO_2 cooling for sensor operation at -30°C.
- LGAD thickness 50 μm - faster rise time lower impact from radiation.
- Replace innermost parts of detector to maintain good performance.



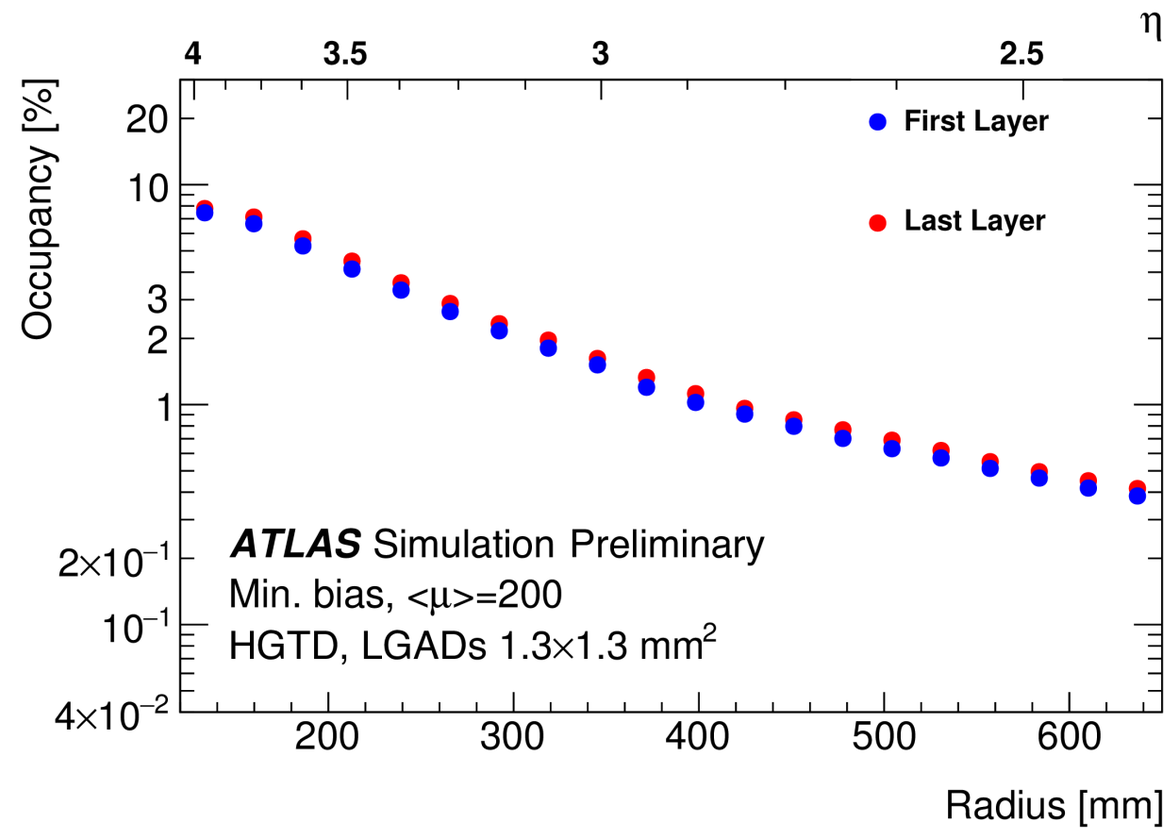
To withstand high radiation levels at low radius replace inner ring at 2000 fb^{-1}

HGTD design concepts

Low occupancy

- Small size to reduce multiple hit probability
- Minimise noise from electronics

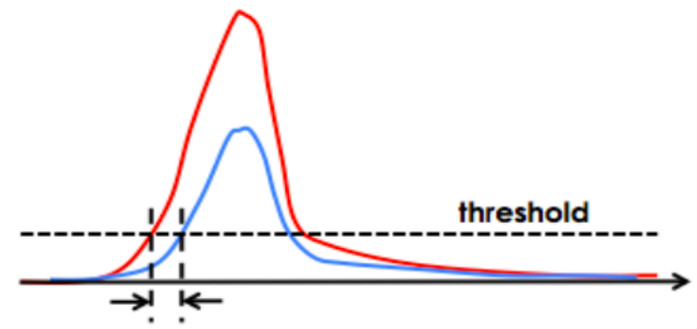
$$\sigma_t^2 = \sigma_{LandauNoise}^2 + \sigma_{TimeWalk}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$



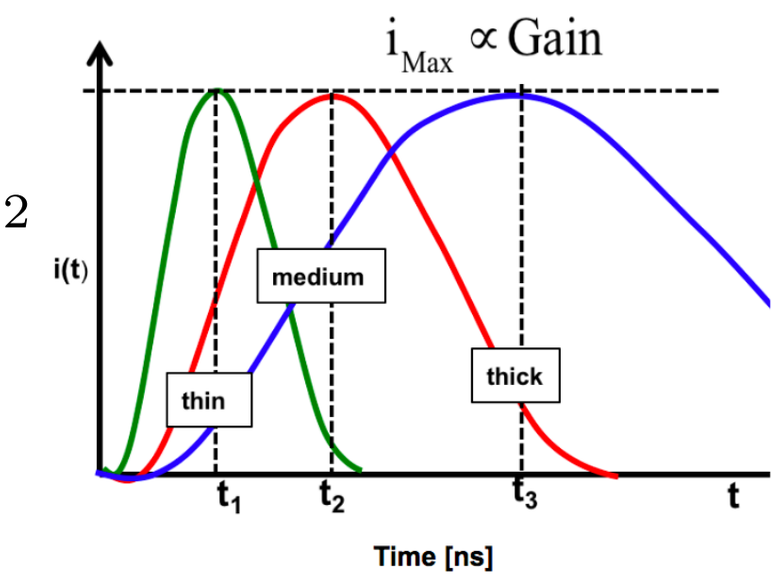
Excellent time resolution

- Time walk correction for time over threshold
- Digitisation granularity < 5 ps
- Thin LGAD sensors (50 μm) for faster rise time; moderate gain to increase S/N
- Small Landau fluctuations with

$\sigma_{LandauNoise}$ < 25 ps (pre-irradiation)



$$\sigma_{Jitter}^2 = \left(\frac{t_{rise}}{S/N}\right)^2$$

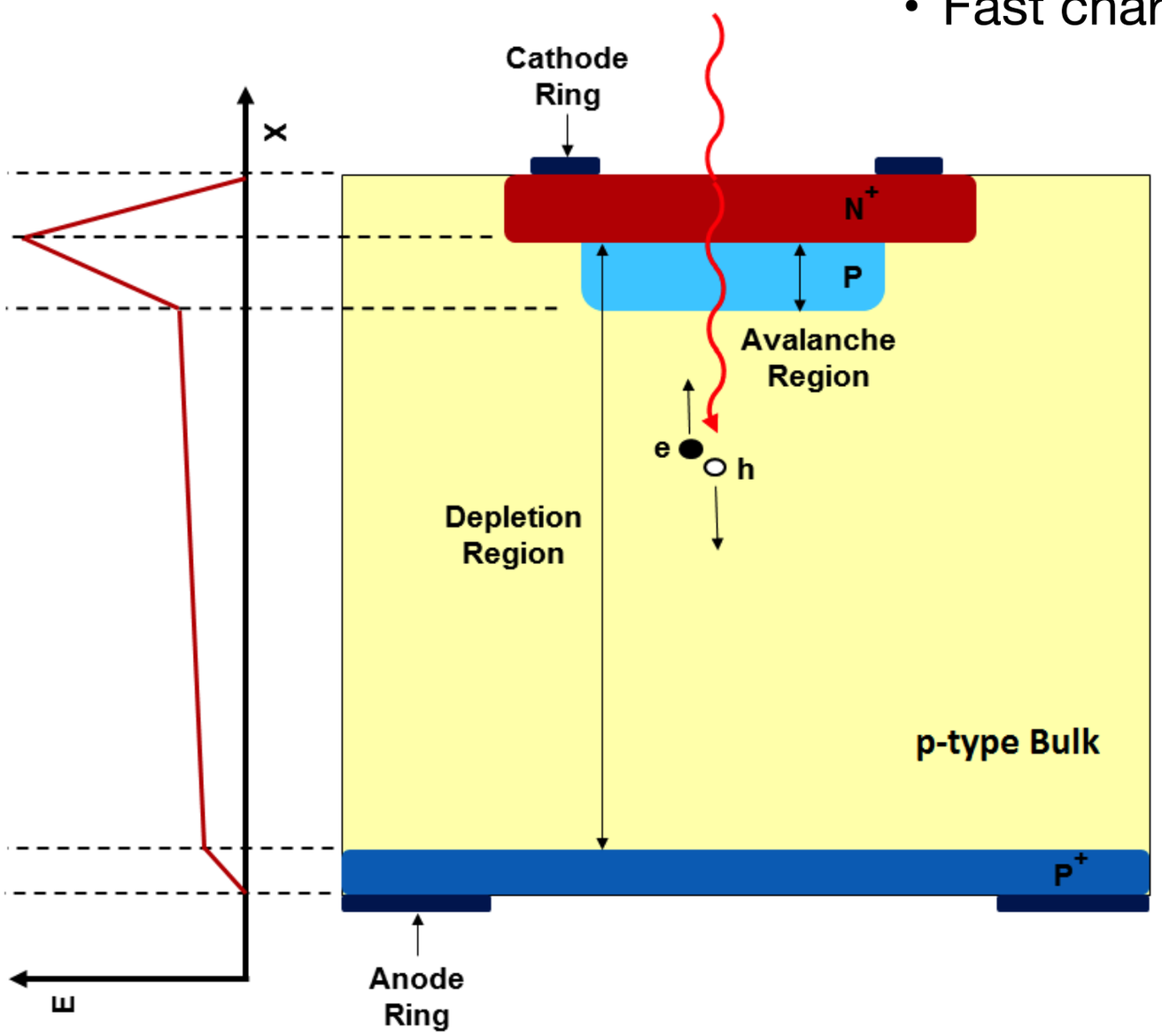


Low Gain Avalanche Detectors (LGADs)

- Developed by Barcelona CNM and CERN RD50 Collaboration
- **Manufacturers:** CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), IHEP-NDL (China)

LGAD: n-p silicon detector with highly-doped p-layer

- High E-field → internal gain (~10 - 50)
- Low rise time (~400 ps)
- Fast charge collection (~1 ns)




CNM LGAD for HGTD

Past and ongoing sensor studies

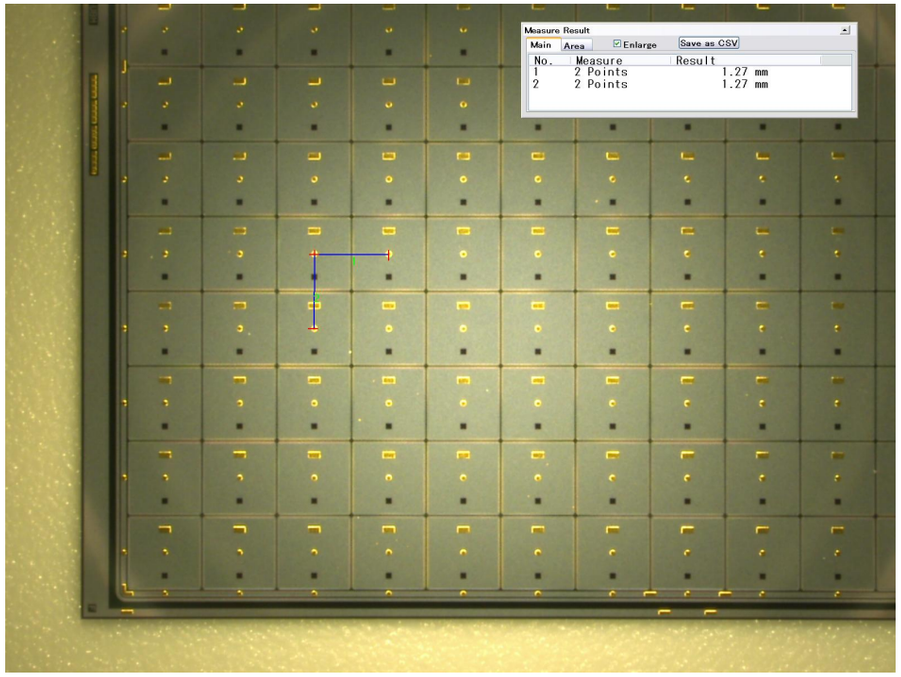
- Laboratory measurements (IV, CV)
- Laboratory β tests (collected charge, gain, time resolution)
- Beam tests (timing, time resolution, collected charge, uniformity, hit efficiency)

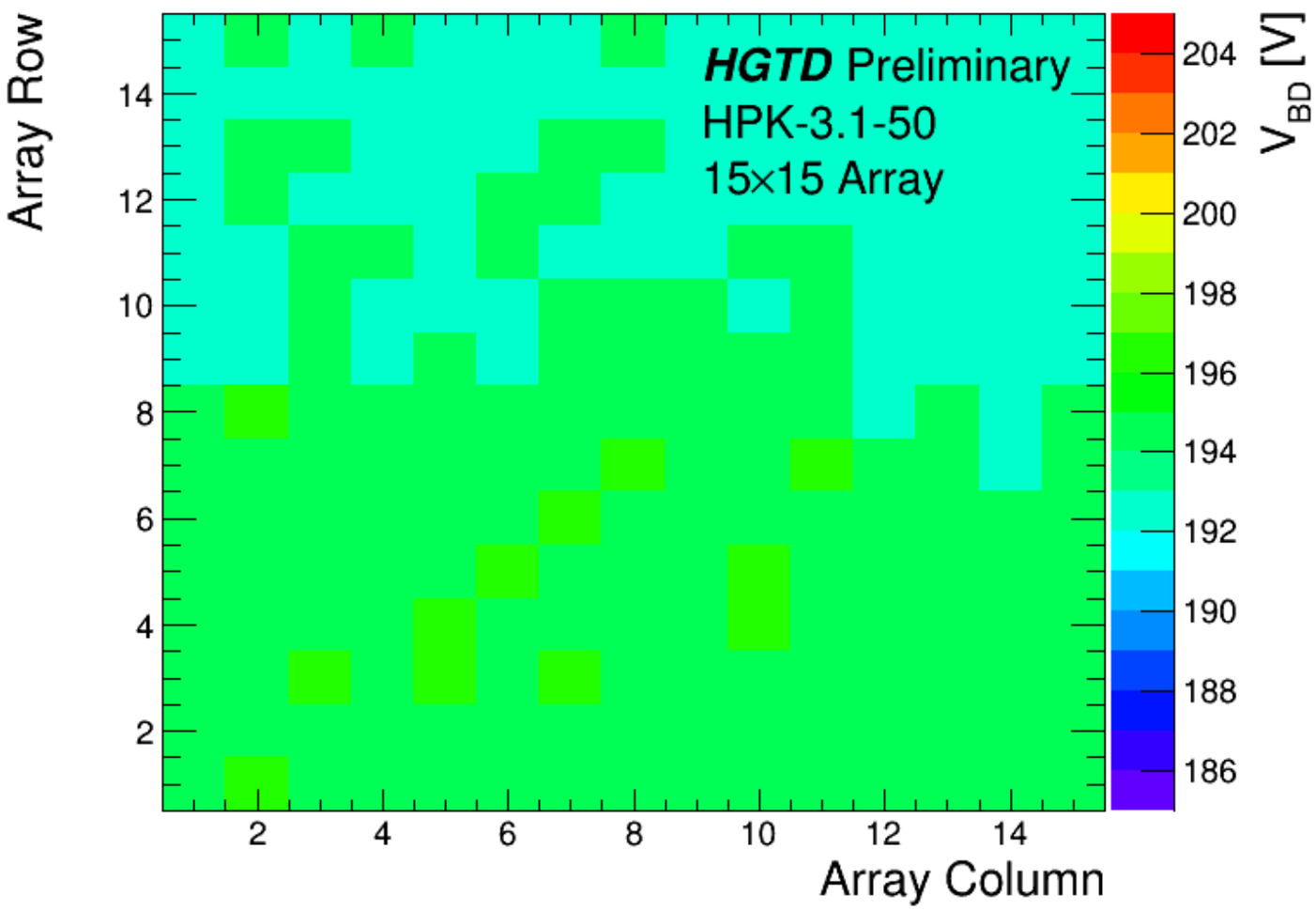
Full scale LGAD arrays

Full size LGAD sensors for HGTD module:

- 15 × 30 pixels (each pixel 1.3 × 13 mm²)
- Studies of 15 × 15 arrays ongoing
- Demonstrate feasibility of large-size LGAD arrays

HPK 3.1 15 × 15 array under a microscope (partial view)





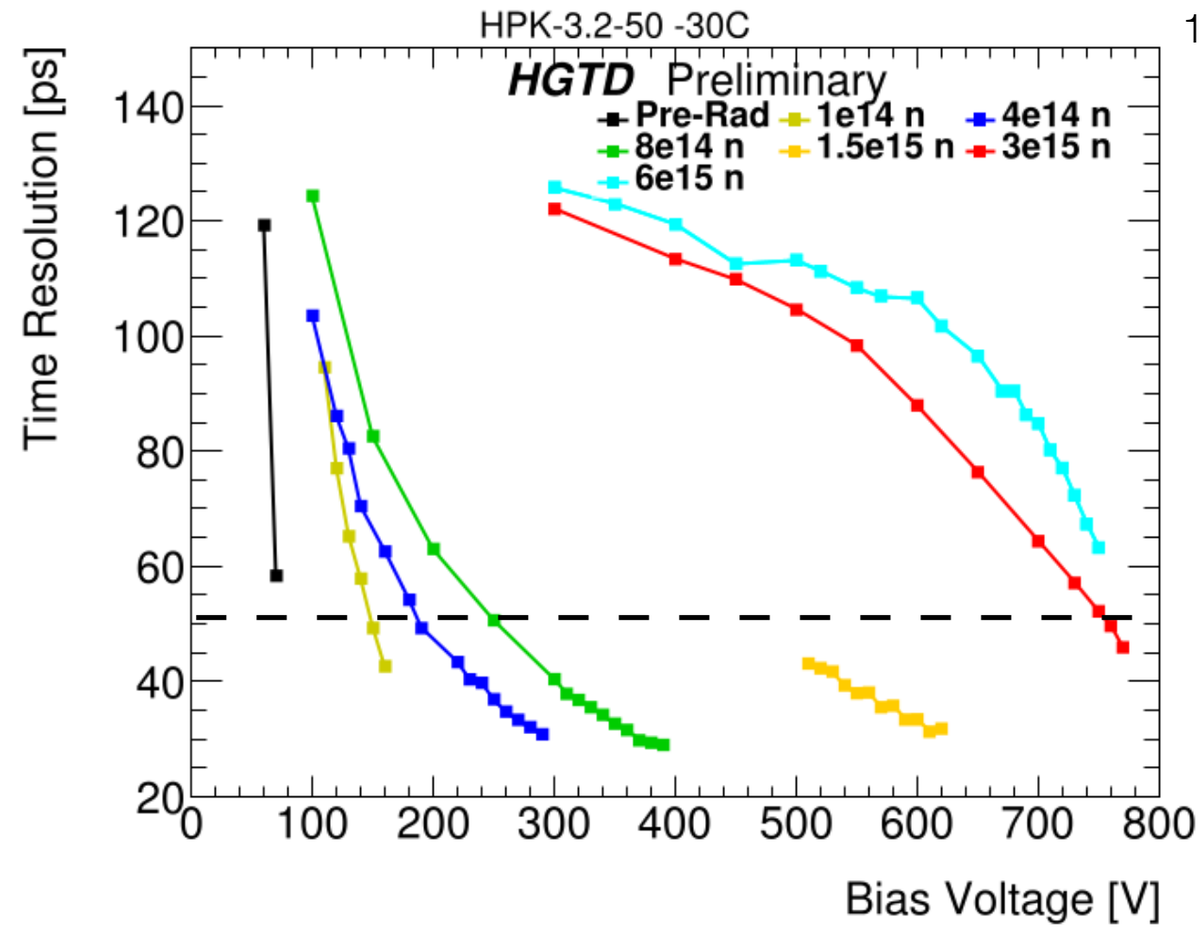
Uniformity measurements

- Measured using automatic probe station
- Excellent uniformity (leakage current, gain, breakdown voltage)

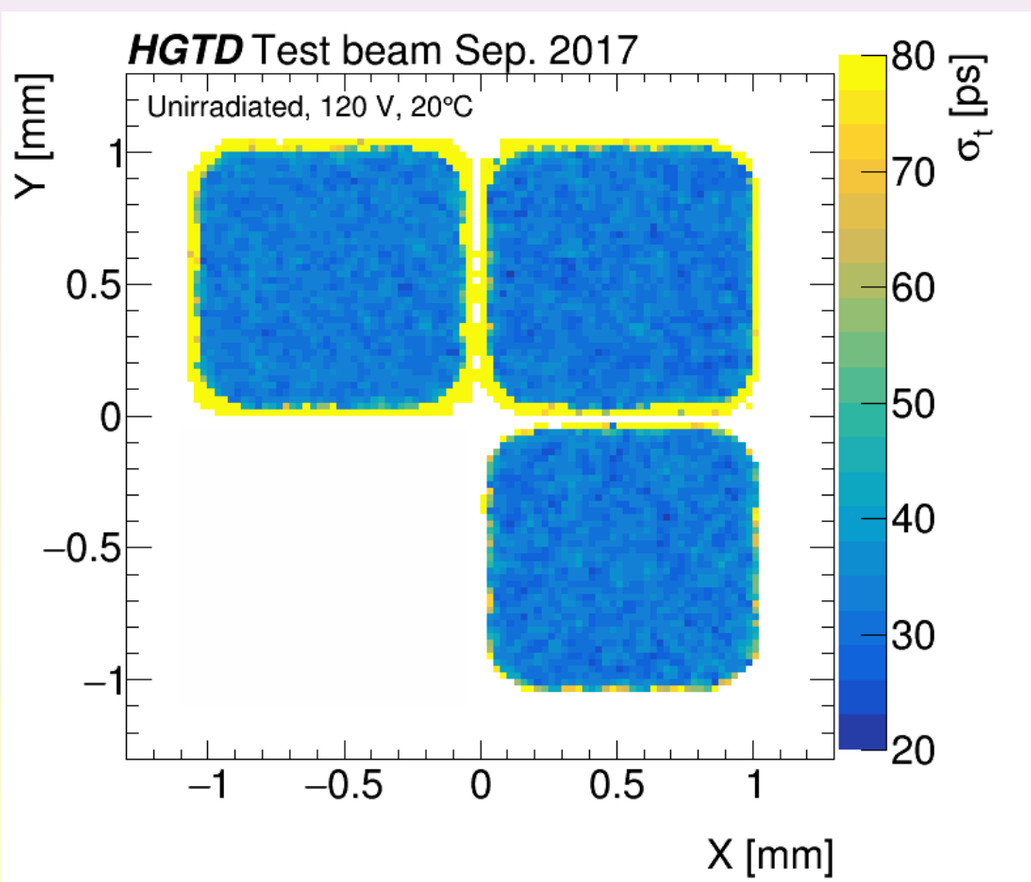
LGAD time resolution

Require $\sigma_t < 50$ ps at full lifetime.

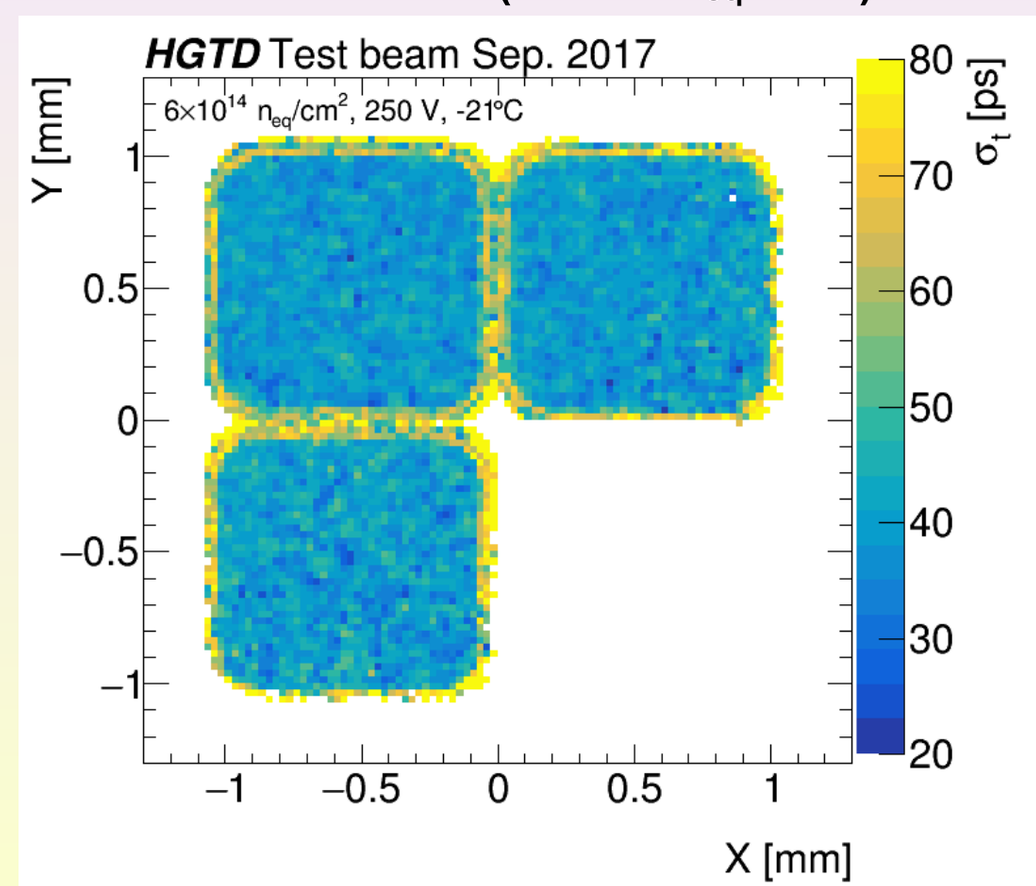
- Sensor irradiation campaigns at CERN (PS-IRRAD) & Ljubljana (IJS).
- CERN pion test beam results using 2x2 CNM array.
- Slight radiation impact visible.



Before irradiation



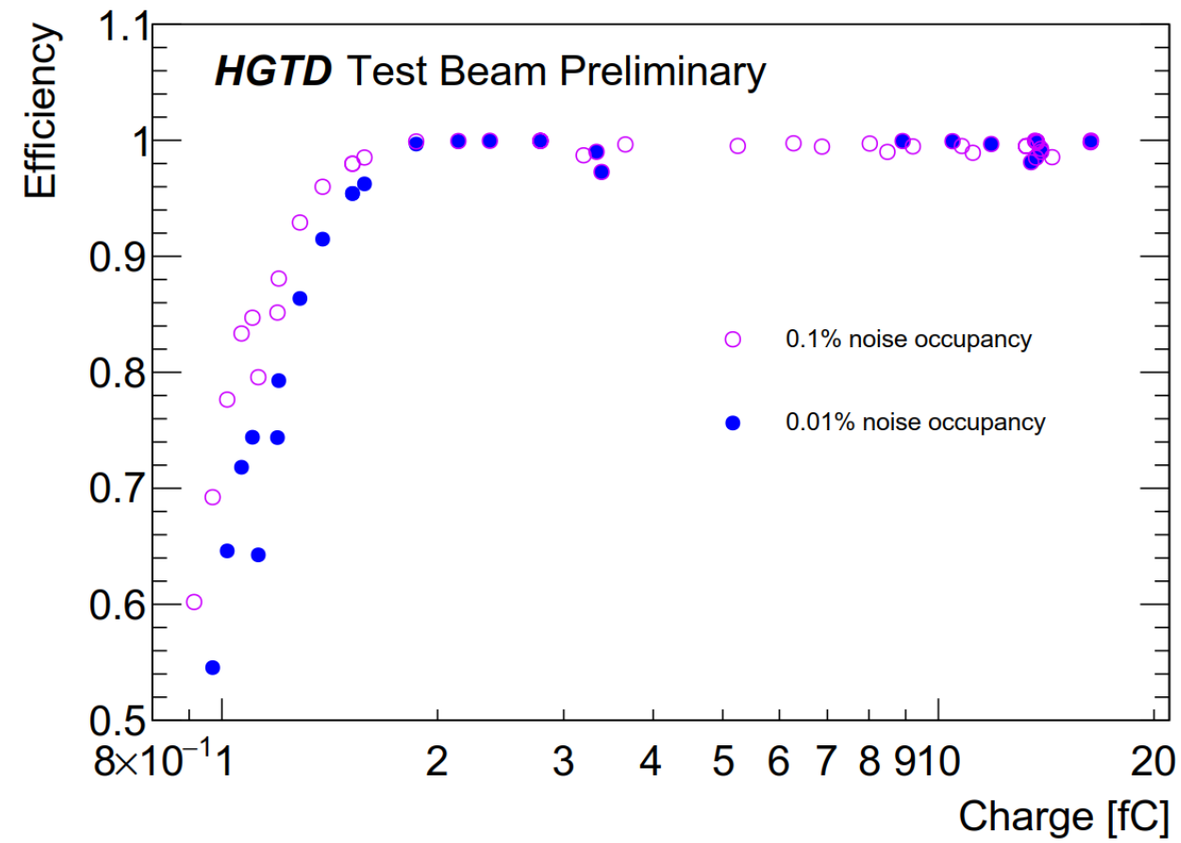
After irradiation (6×10^{14} n_{eq} cm^{-2})



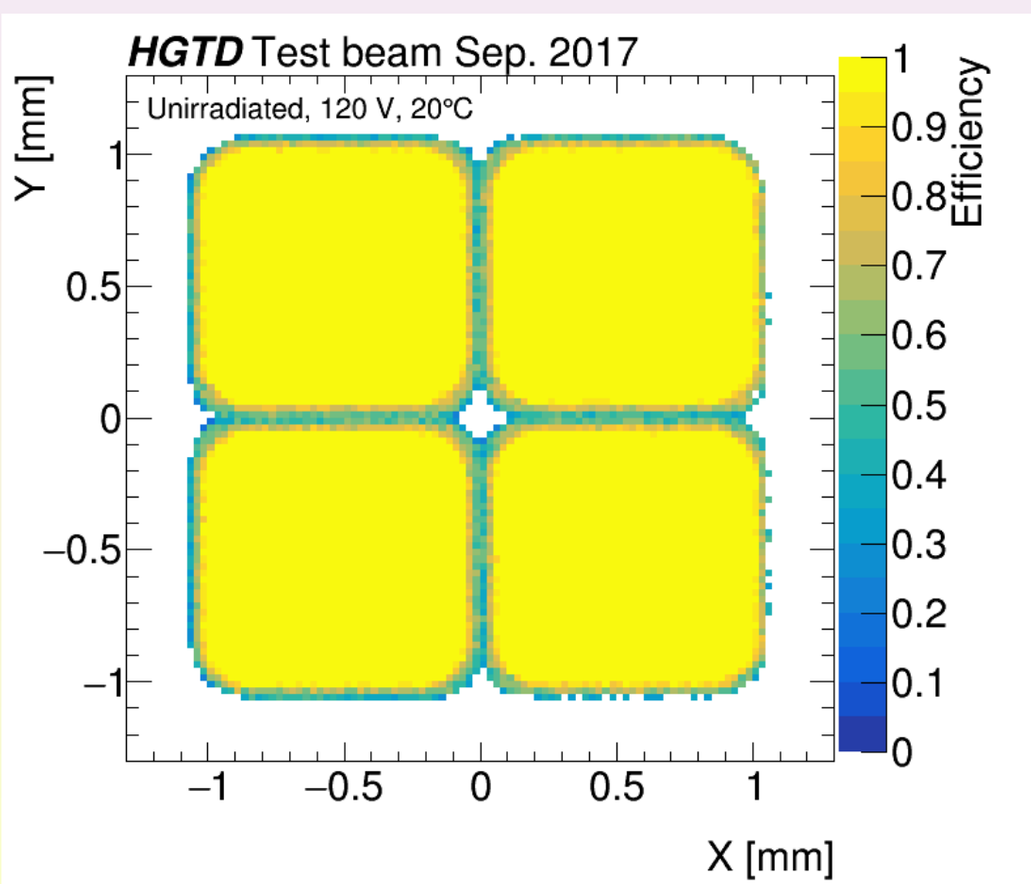
LGAD efficiencies

Hit efficiency above 99% for collected charge > 2 fC.

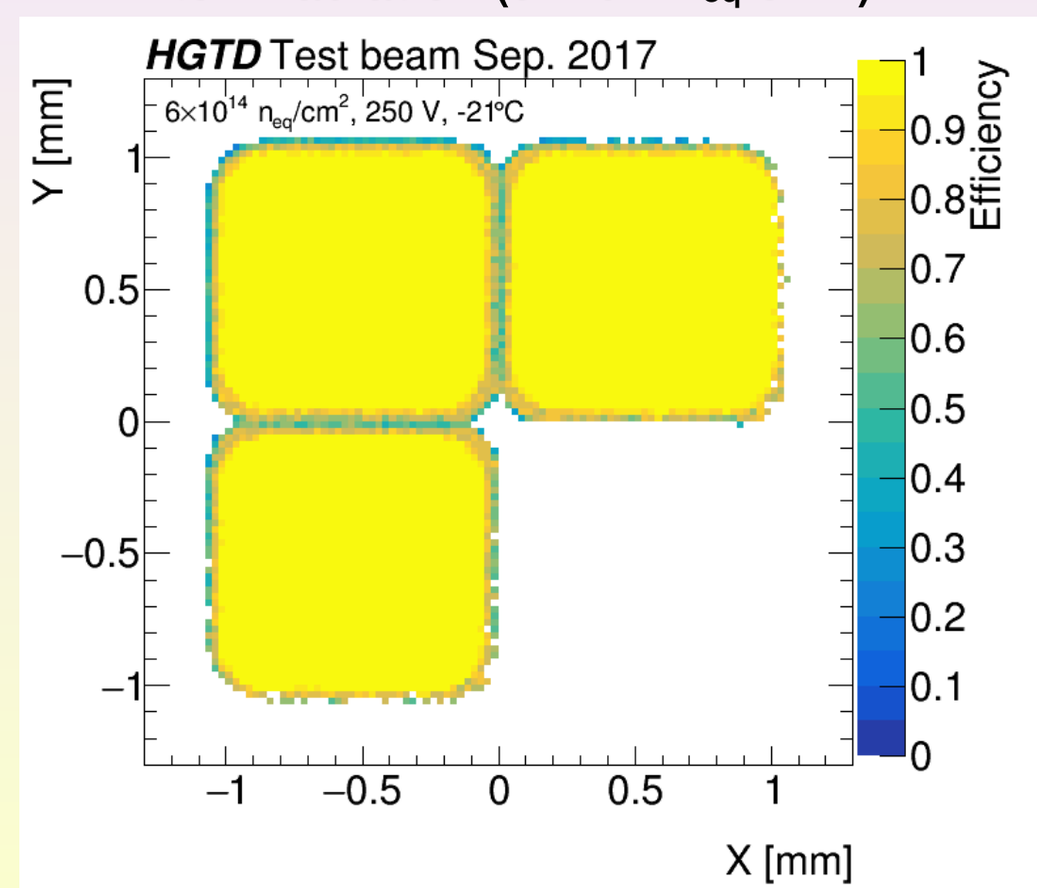
- CERN pion test beam results using 2x2 CNM array.
- Inter-pad gap region slightly more efficient after irradiation.



Before irradiation



After irradiation (6×10^{14} n_{eq} cm^{-2})

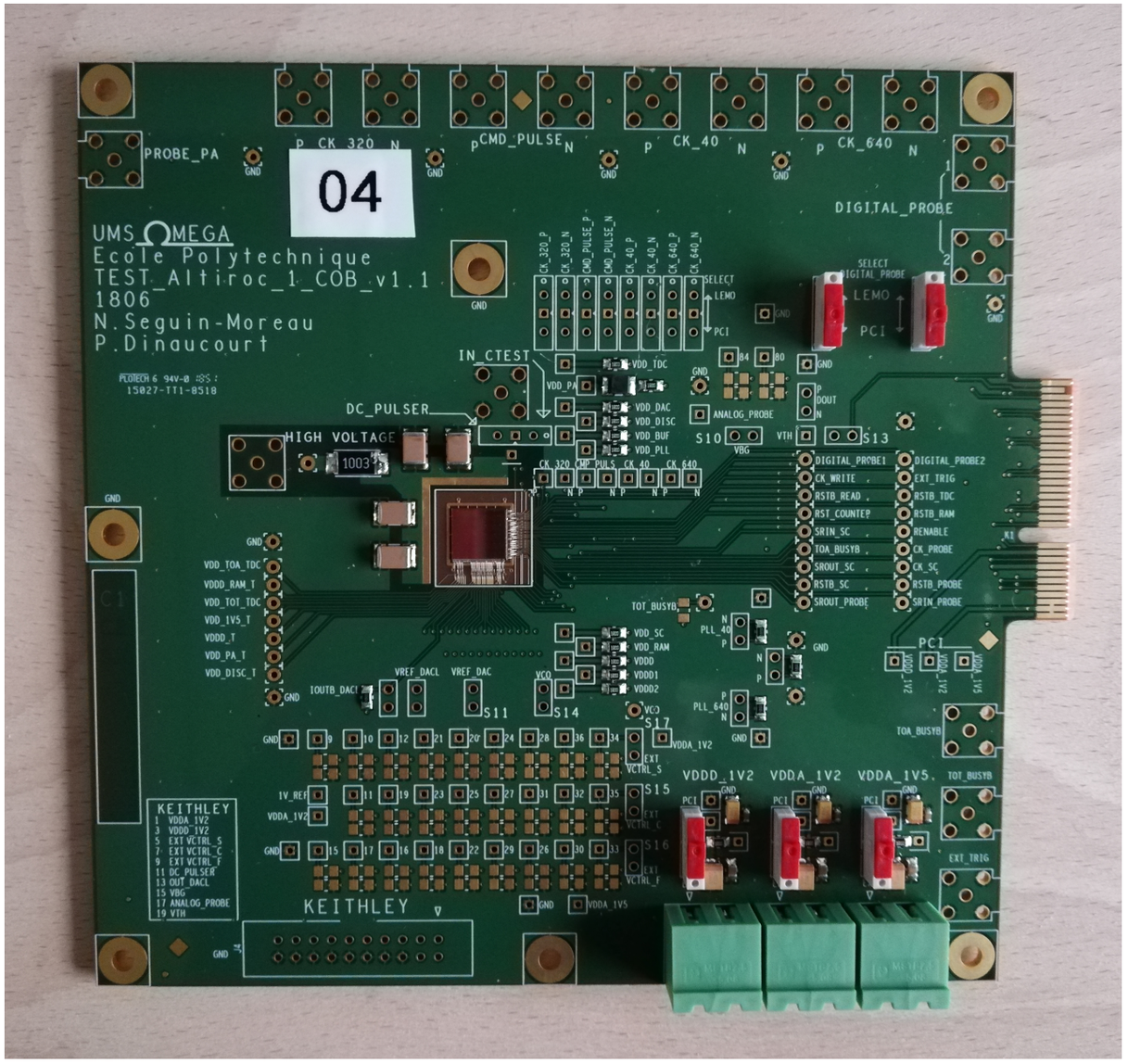


ATLIROC ASIC

ATLAS **L**GAD **T**iming **I**ntegrated **R**ead**O**ut **C**hip

- Bump-bonded to LGAD
- Single pad readout (225 channels/ASIC)
- Provide time over threshold (TOT) and time of arrival (TOA)
- 300 ps pre-amp rise time to minimise jitter
- Reads out number of hits for each ASIC at 40 MHz
    - *Per bunch luminosity measurement capabilities*

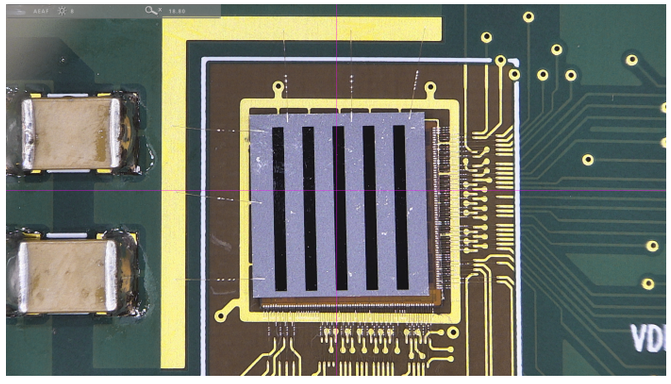
ALTIROC1 (5×5 channels)



ALTIROC0: single pixel analogue readout for 2 × 2 sensors (done)

ALTIROC1: 5 × 5 channel readout bump-bonded to sensors (already tested in test beam)

ALTIROC2: full scale version with 15 × 15 channel readout (available Spring 2020)

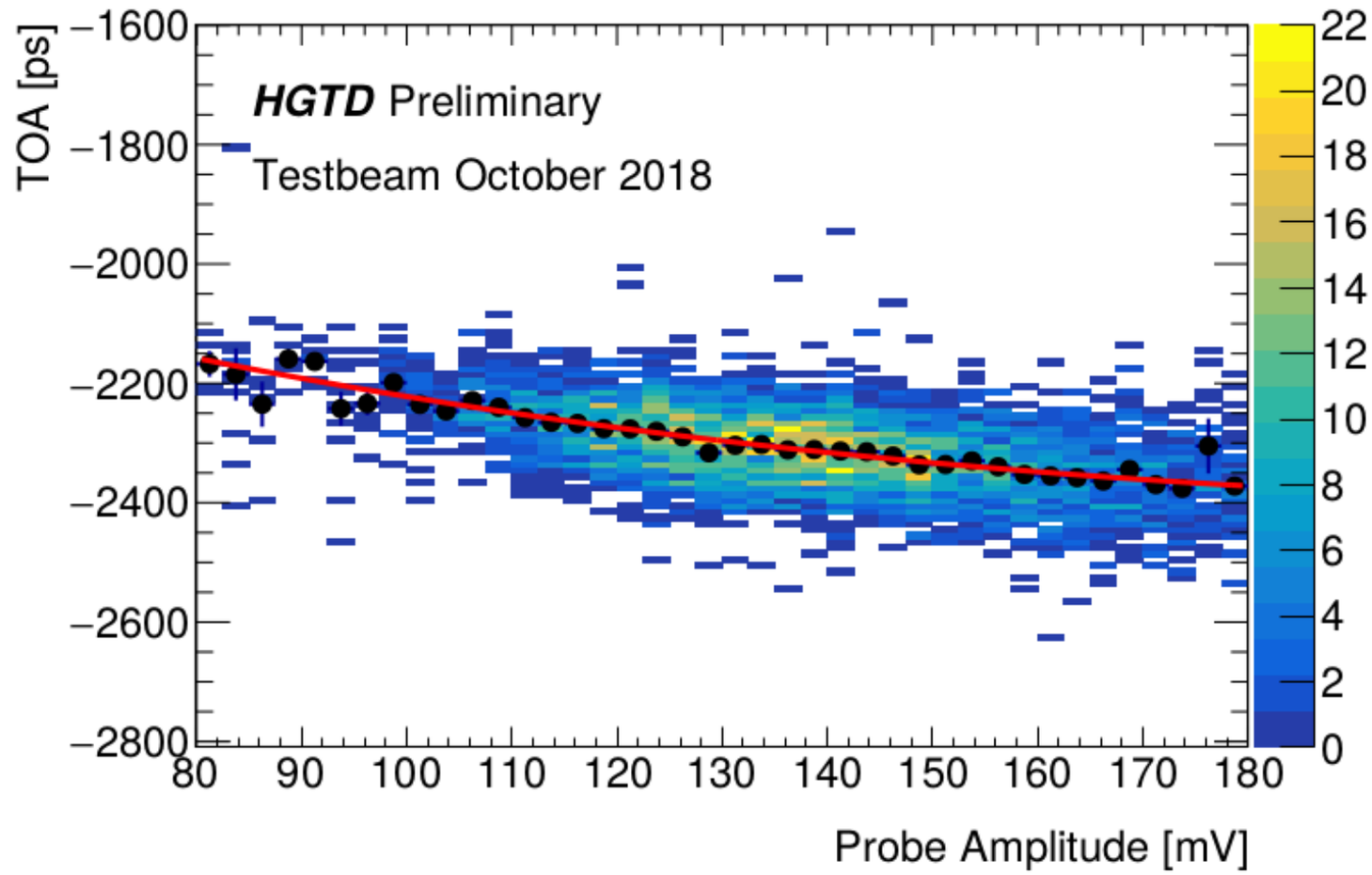


LGAD bump-bonded to ALTIROC

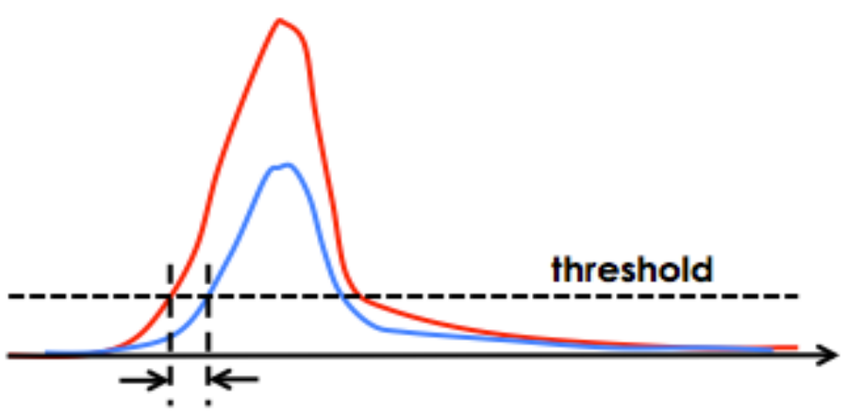
ATLIROC ASIC

ALTIROC0 (bump-bonded to 2 x 2 array) test beam results

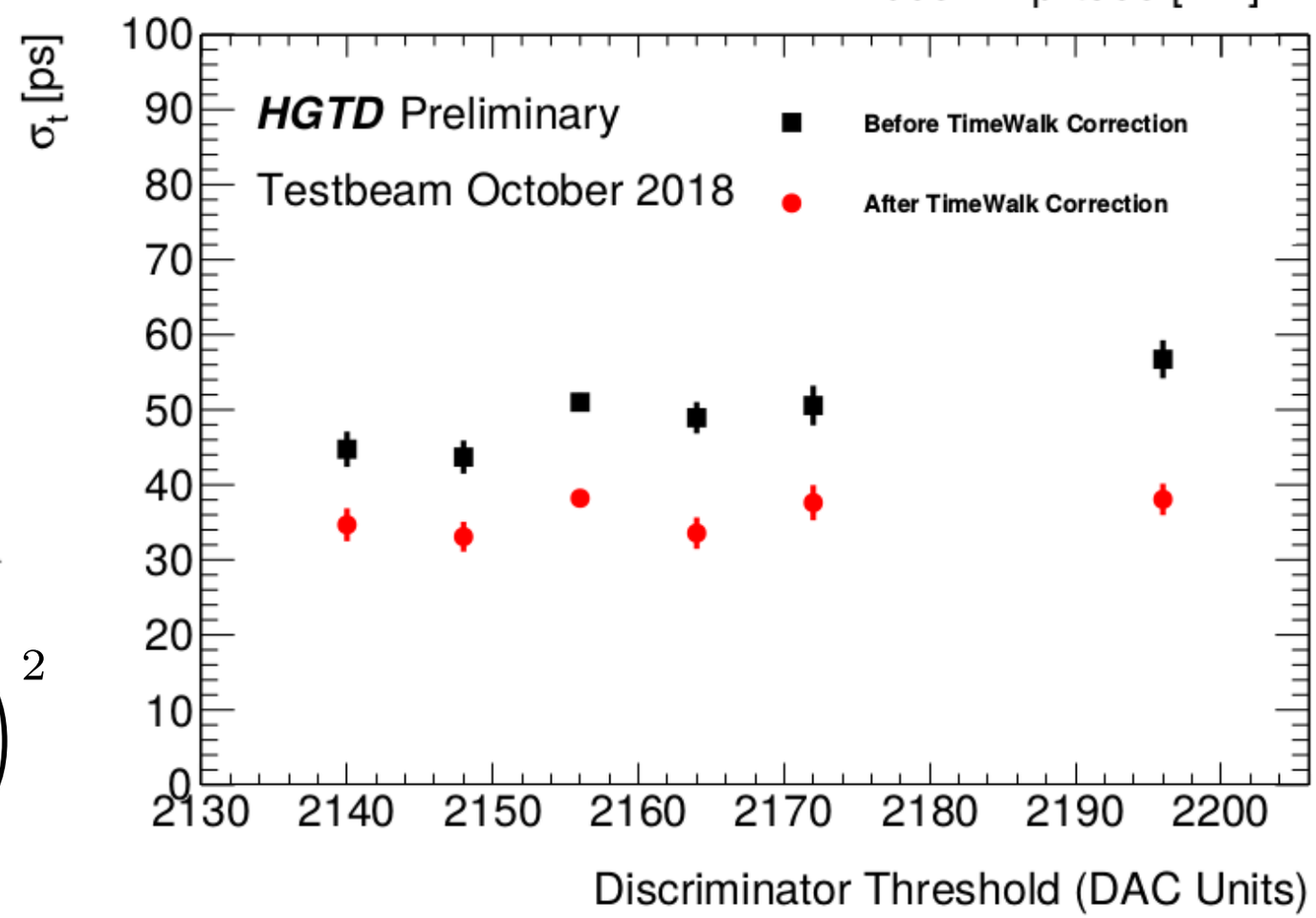
- Time of arrival as a function of preamplifier probe amplitude - polynomial fit used to correct for time walk effect.



- Time resolution of ***35 ps*** achievable after time walk correction (sensor+jitter).



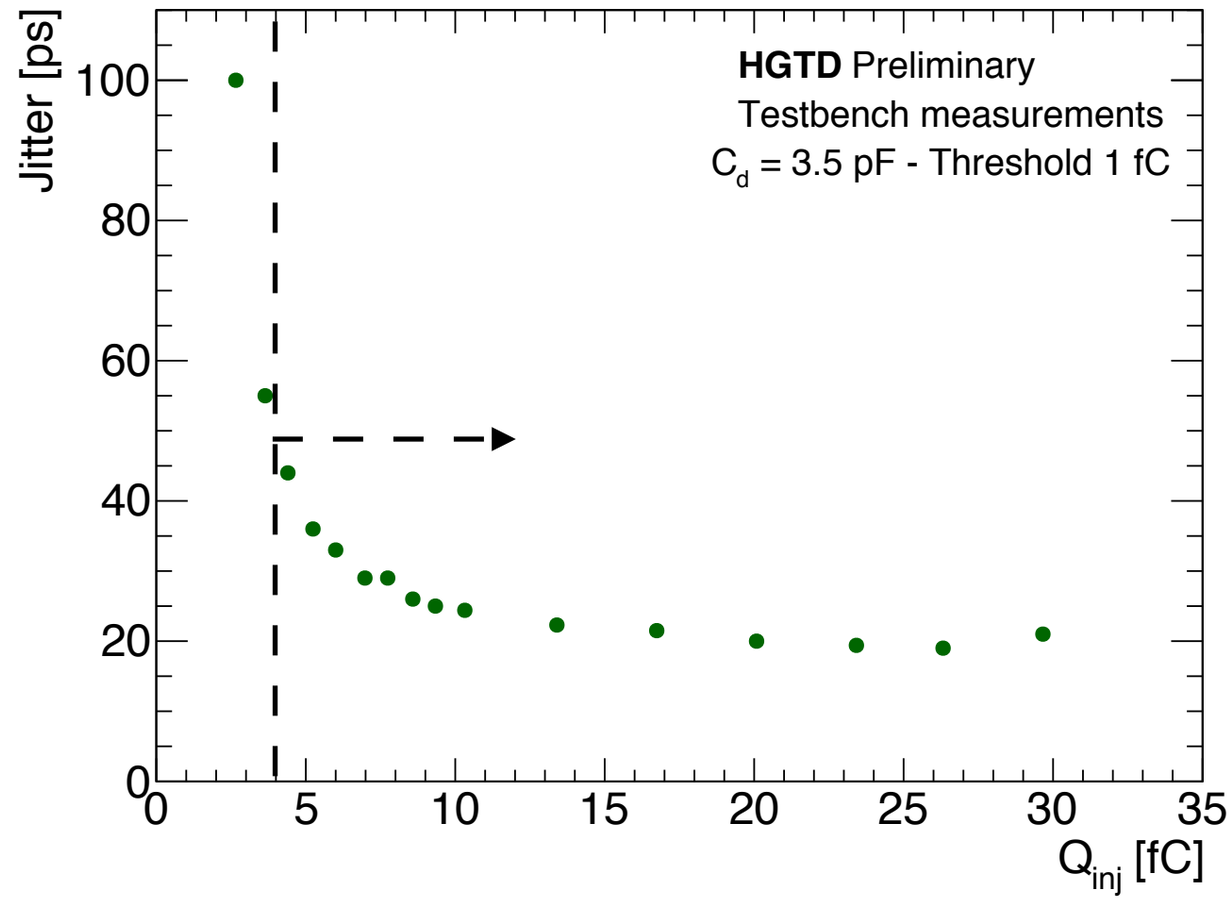
$$\sigma^2_{TimeWalk} = \left(\left[\frac{V_{threshold}}{S/t_{rise}} \right]_{RMS} \right)^2$$

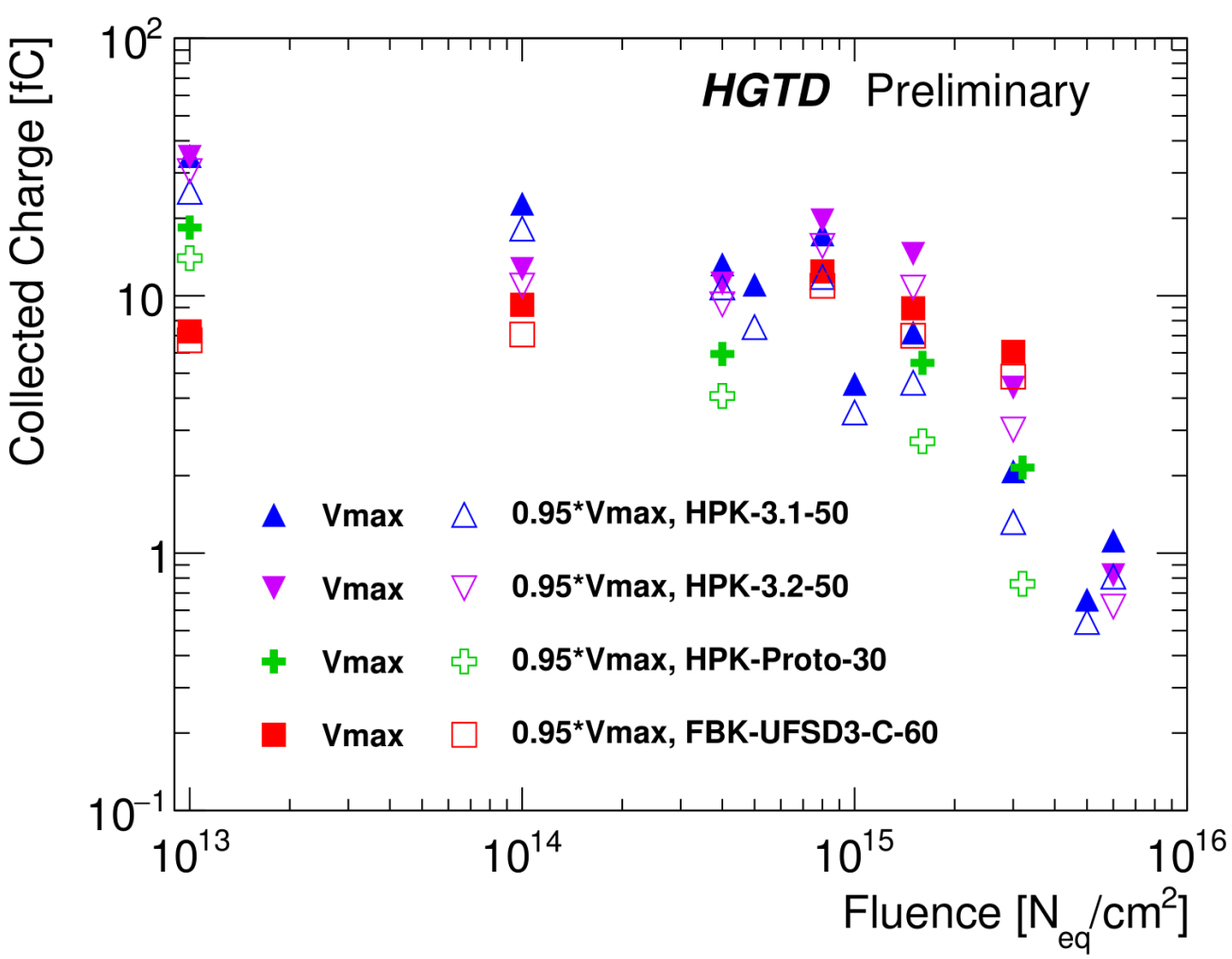


Collected charge and jitter

Test bench measurements of jitter vs injected charge

- Optimisation of sensor+ASIC
- Large increase in jitter at < 4 fC
- Important to collect sufficient charge over full lifetime
  - ***Require collected charge > 4 fC at 2.5×10^{15} n_{eq} cm^{-2}***



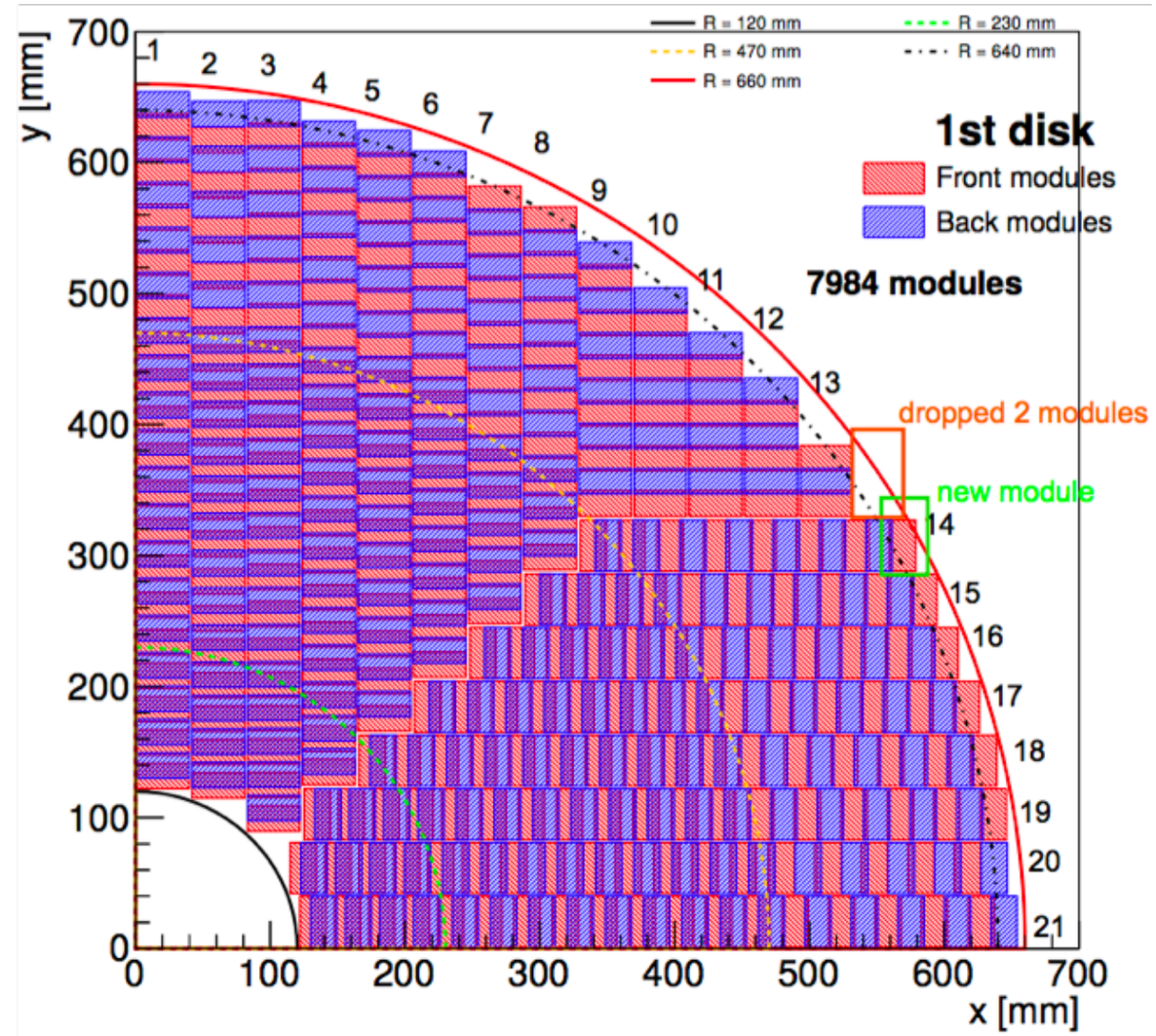


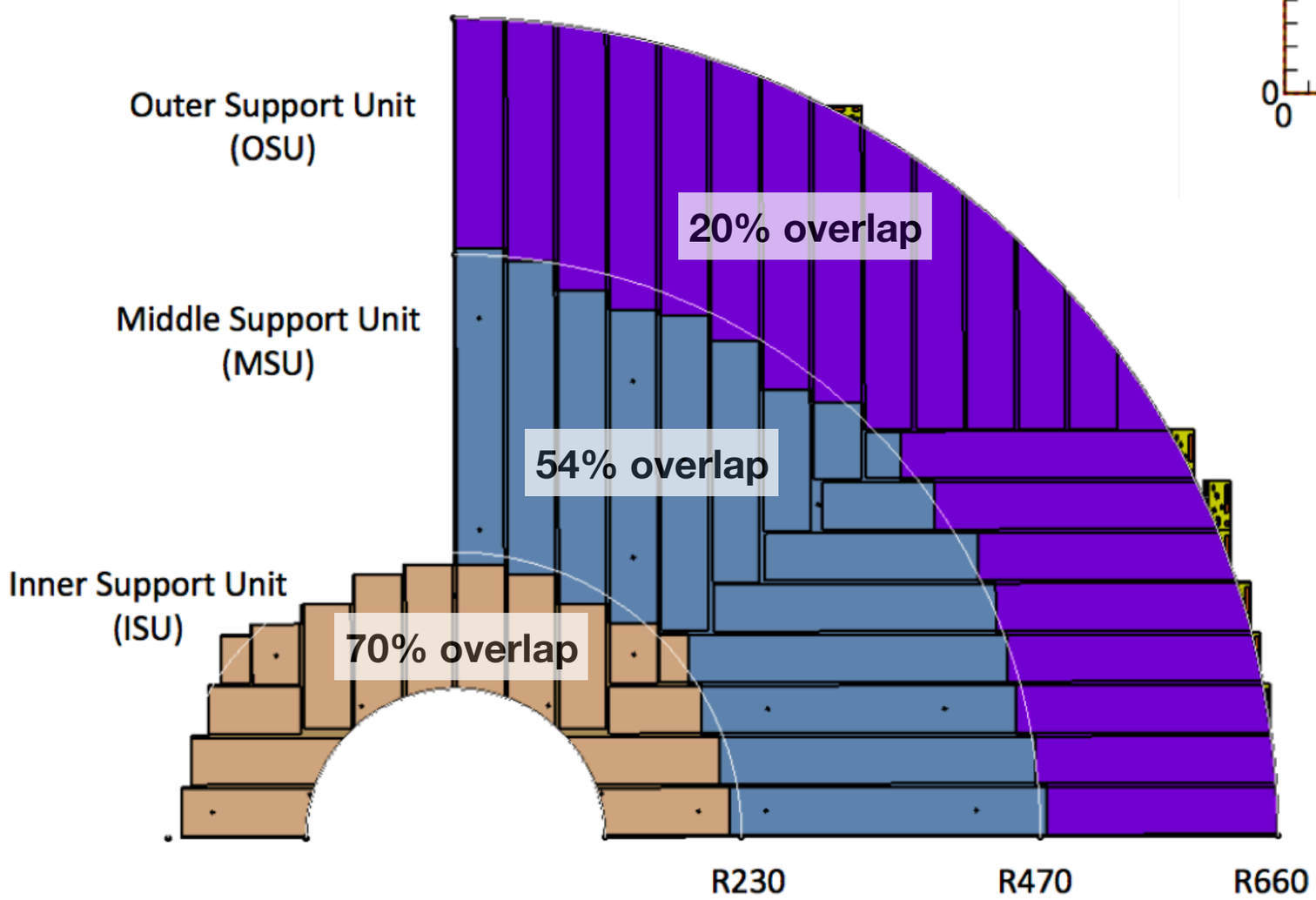
Sensor collected charge measured for fluences up to 6×10^{15} n_{eq} cm^{-2}

- Collected charge decreases at fluences above 10^{15} n_{eq} cm^{-2}
- HPK 3.2 & FBK can achieve 4 fC at 3×10^{15} n_{eq} cm^{-2}

New three-ring layout

- R&D suggests we can't maintain > 4 fC at 2.5×10^{15} n_{eq} cm^{-2} with two-ring layout
- New three-ring proposal for Technical Design Report
- Number of hits/track ≥ 2 for new layout

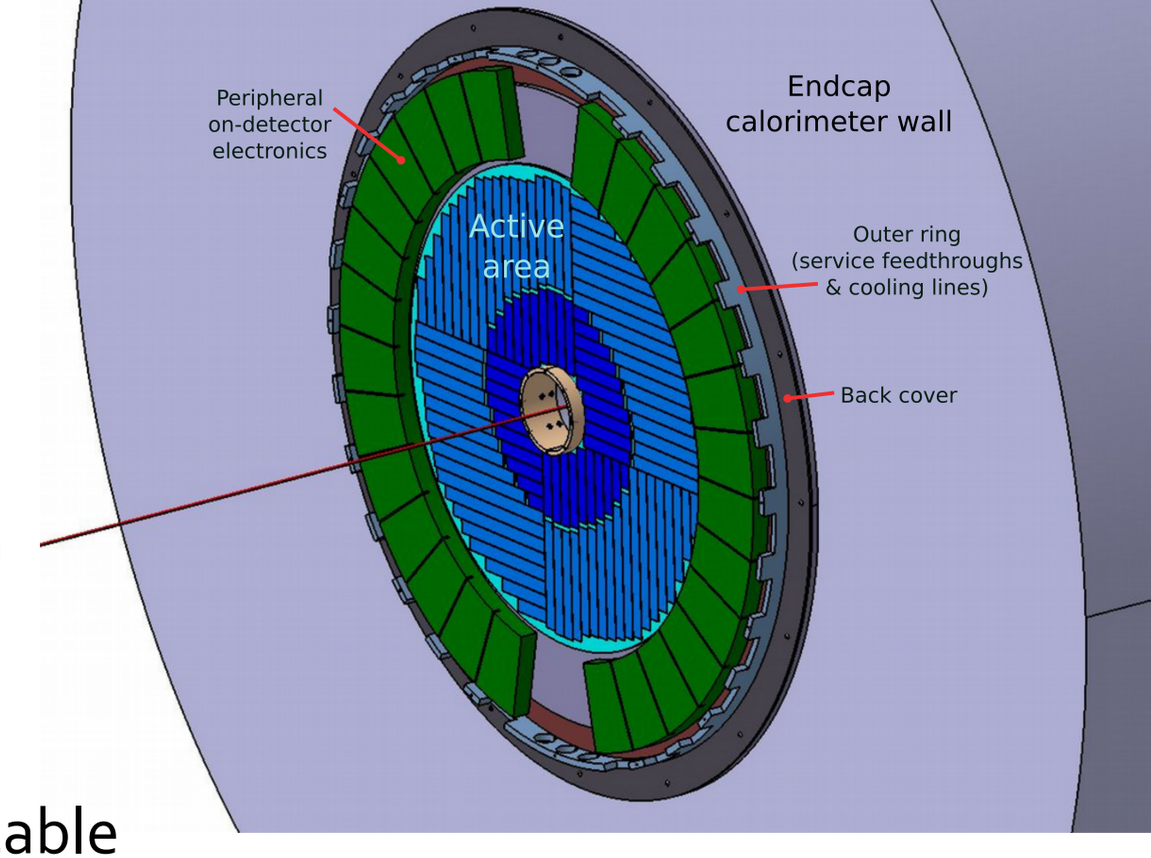


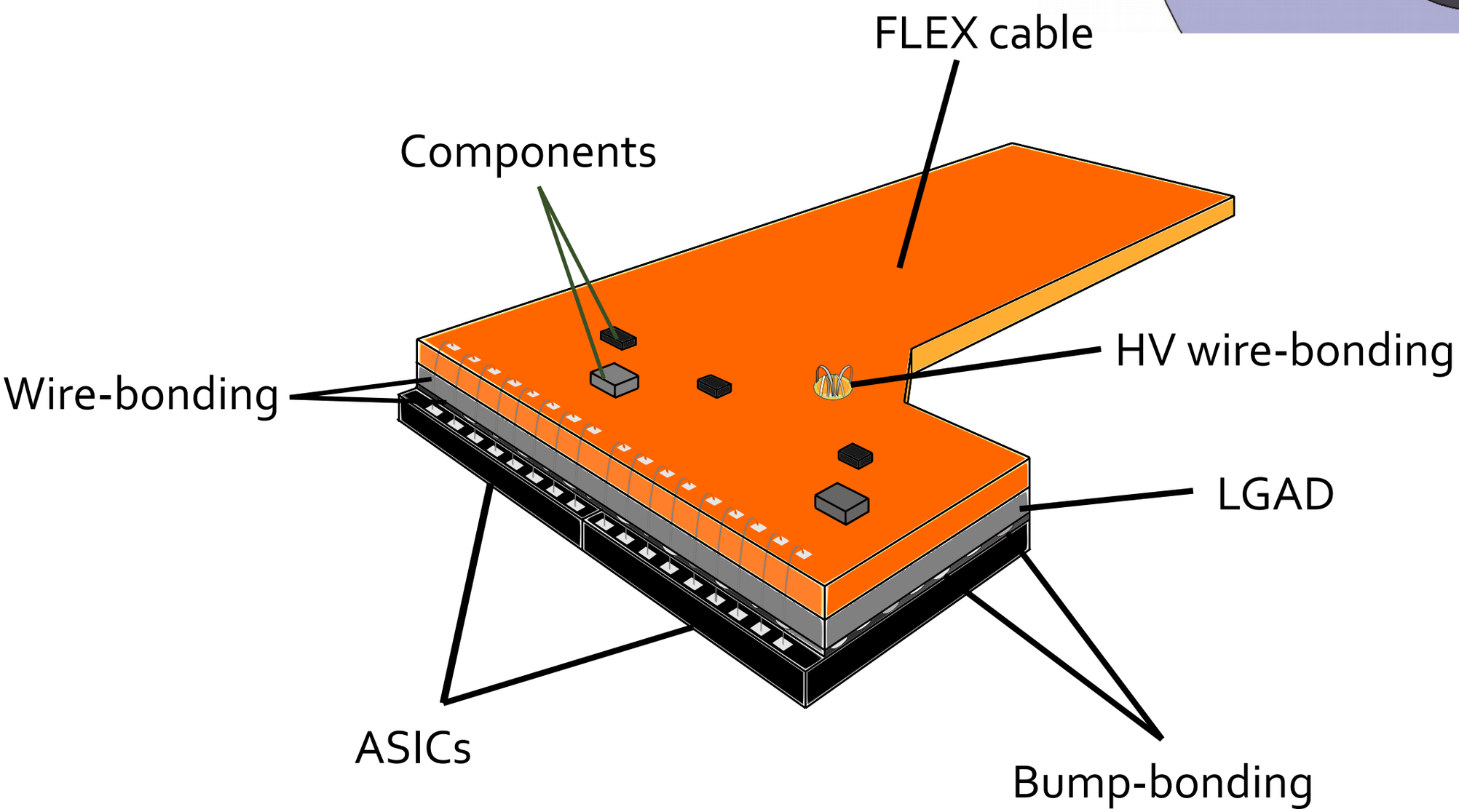


- Replace inner ring after each 1000 fb^{-1}
- Replace middle ring after 2000 fb^{-1}
- Ensures operation with > 4 fC at 2.5×10^{15} n_{eq} cm^{-2} over full lifetime

HGTD module: Sensor+ASIC

- Module size 2 × 4 cm²
- Sensor (15 × 30 pixels) bump-bonded to 2 ALTIROC readout chips (225 channels / ALTIROC)





Conclusions and outlook

- The HL-LHC will provide challenging conditions in which to perform track-to-vertex association.
- The HGTD project will make use of time information to mitigate the effects of increased pileup in the forward region.
  - Intense R&D program
  - Lab and beam tests performed with single pads and arrays
  - Time resolution of < 50 ps achievable up to 2.5×10^{15} n_{eq} cm^{-2} with 50 μm LGADs
  - Expect full-size 15 × 30 arrays to become available mid 2020
- Technical Proposal approved by LHCC
- Technical Design Report target April 2020

Back up