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

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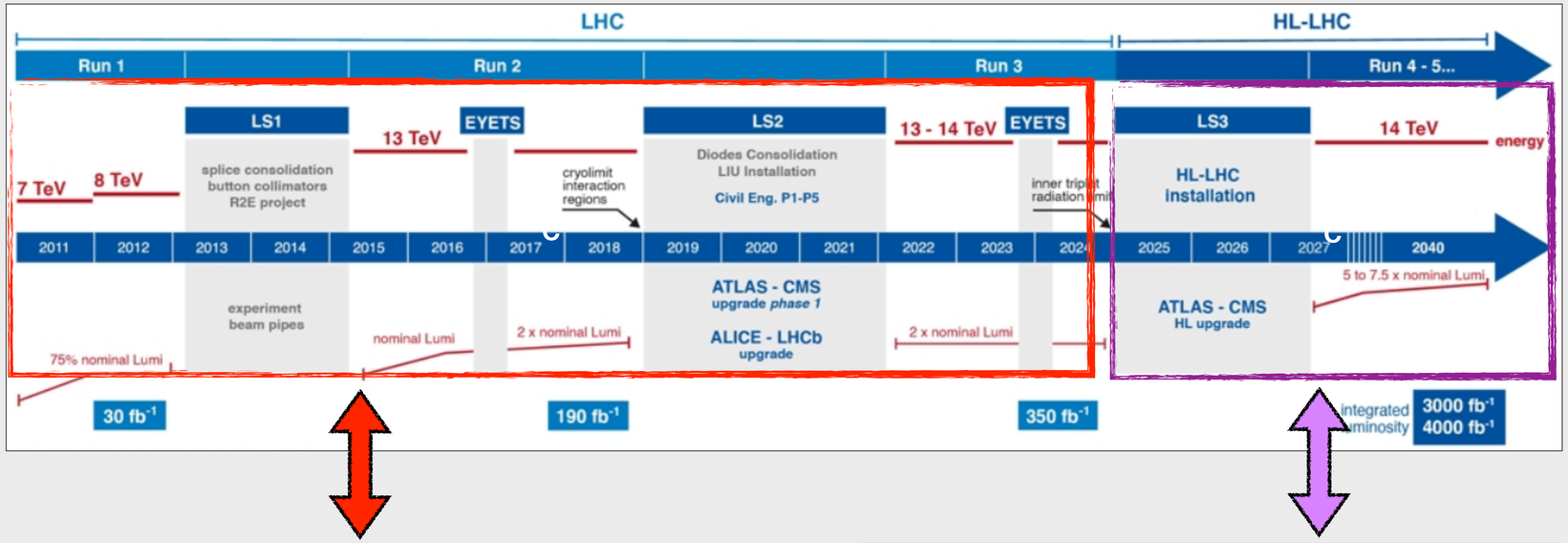
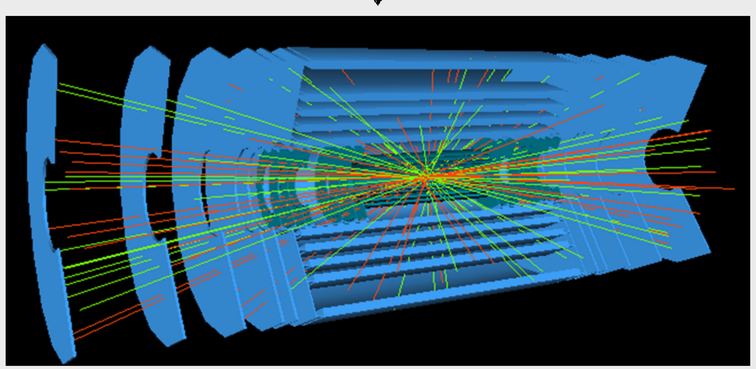
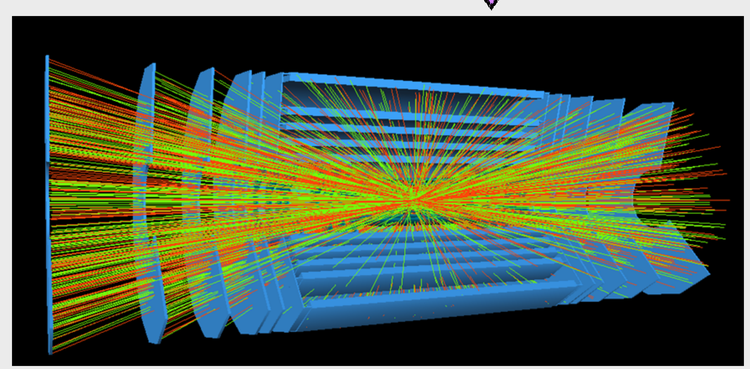
High Luminosity LHC : Schedule and challenges

- The High Luminosity LHC will start in 2027 with instantaneous luminosity $7.5 \times 10^{34} cm^{-2} s^{-1}$, $5 \sim 7.5 \times$ increase.
- In order to further increase the discovery potential, the ATLAS experiment will need an upgrade.





<μ>~30 in Run 2

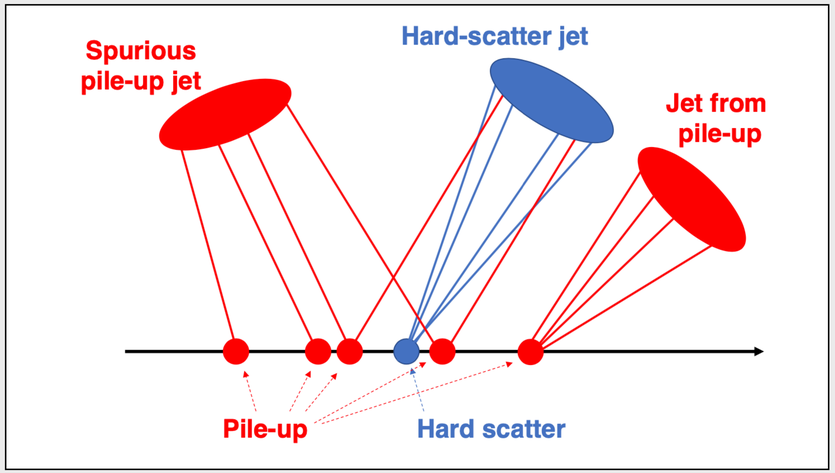


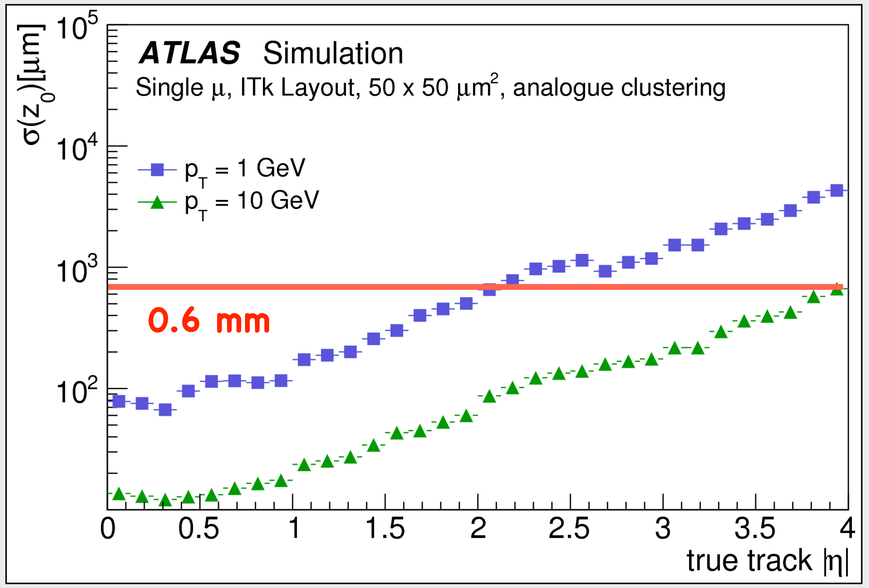
<μ>~200 in HL-LHC

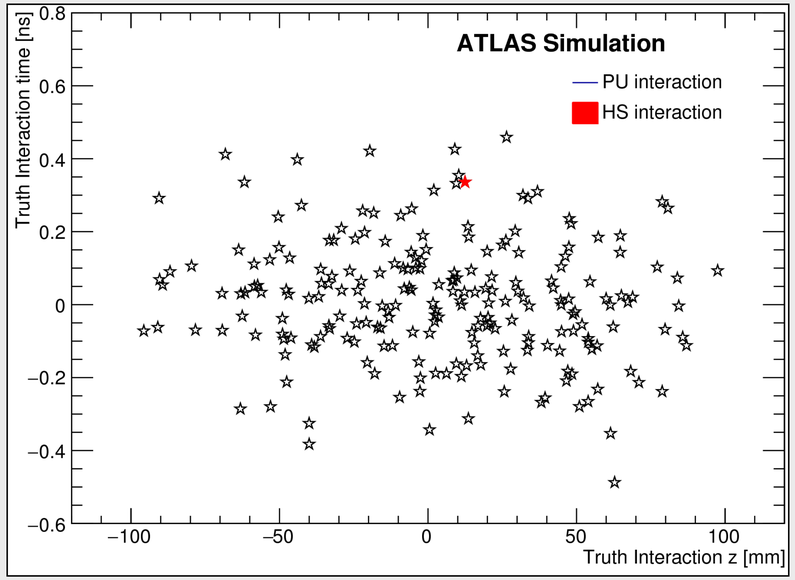
The main HL-LHC challenges :

- ☑ Pile-up challenge : from <μ>~30 to 200
- ☑ Radiation hardness

Pile-up challenge at HL-LHC





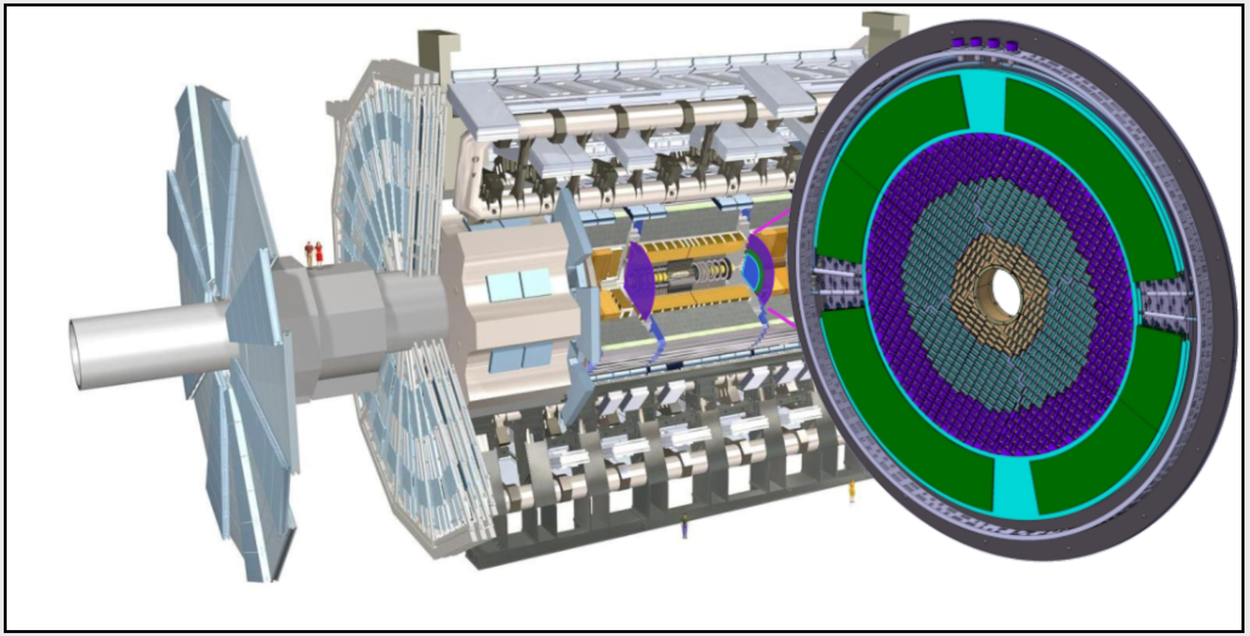


- At HL-LHC, pile-up can :
  - ☑ Add jets.
  - ☑ Create spurious jets.
  - ☑ Alter the properties of hard scattered jets.
  - ☑ Degrading physics performance.

- The Inner Tracker ITk resolution on track impact parameter is good to mitigate the effect of pile-up but this resolution degrades in the forward region. (especially that in HL-LHC $\langle\mu\rangle$ = 200, average of 1.6 vertices/mm is expected.)

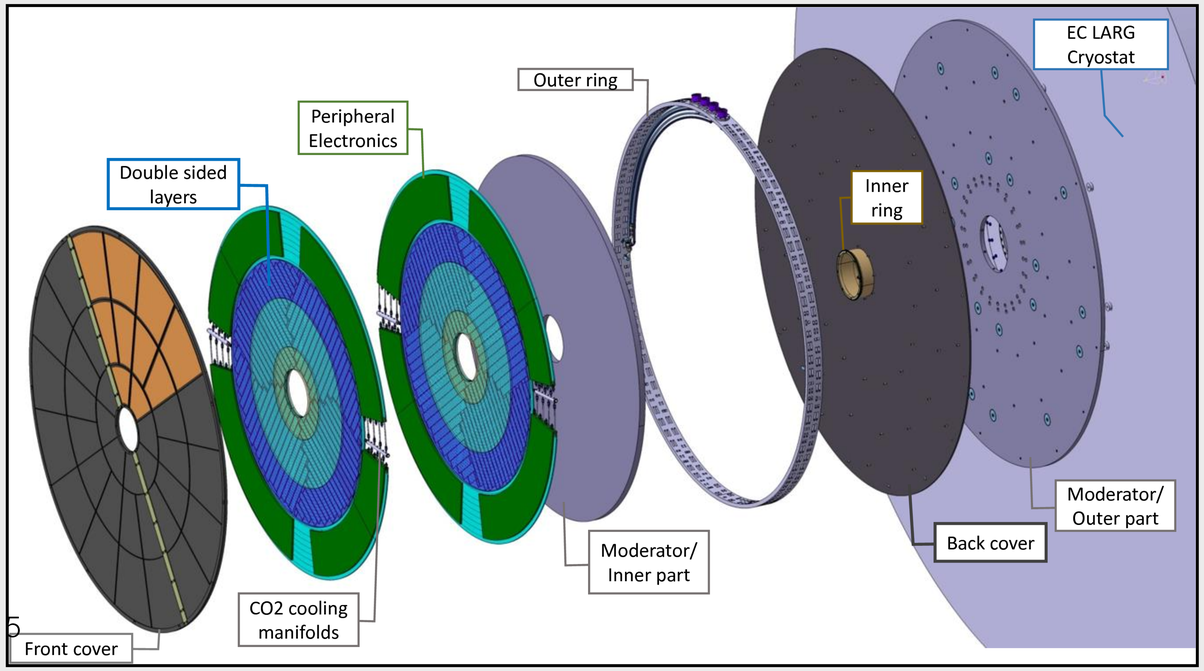
- Adding HGTD in the forward region will add timing information to mitigate the effect of pile-up
- At a given z position, timing information helps to discriminate between pile-up and hard scattering interaction

High Granularity Timing Detector (HGTD)

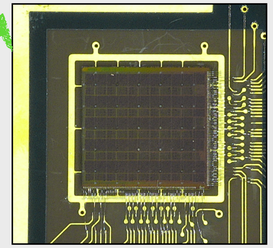


- Located between barrel and endcap calorimeters (z±3.5).
- Active area : 12 cm < R < 64 cm (2.4 < η < 4.0)
- Two disks on each side of the ATLAS interaction point.

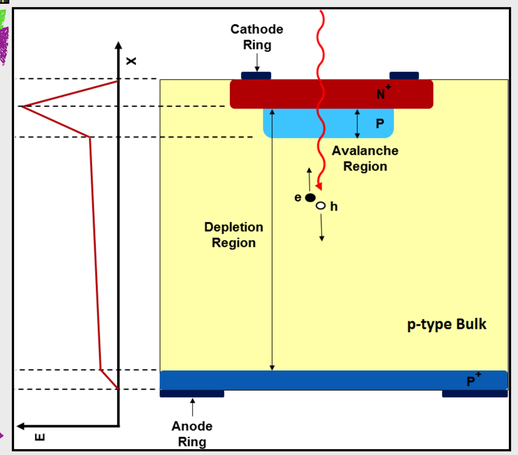
- **Goal:** improve performance in the forward region in view of increased pile-up.
- Target time resolution :30-50 ps per track



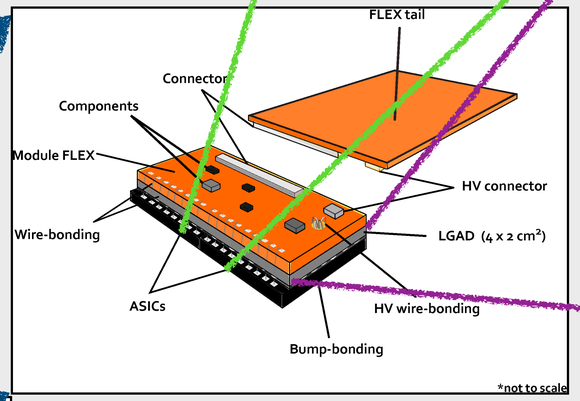
Detector principle



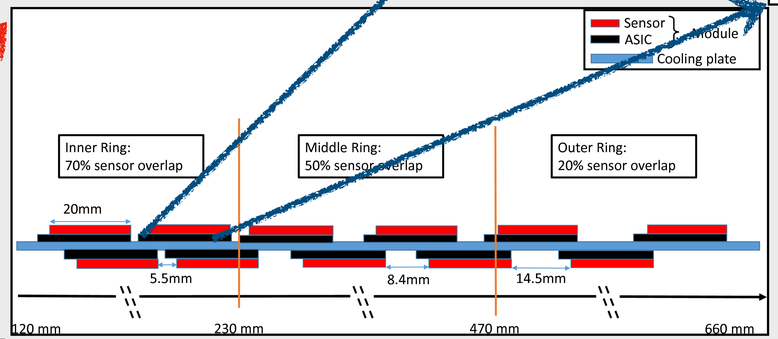
ASIC: ALTIROC



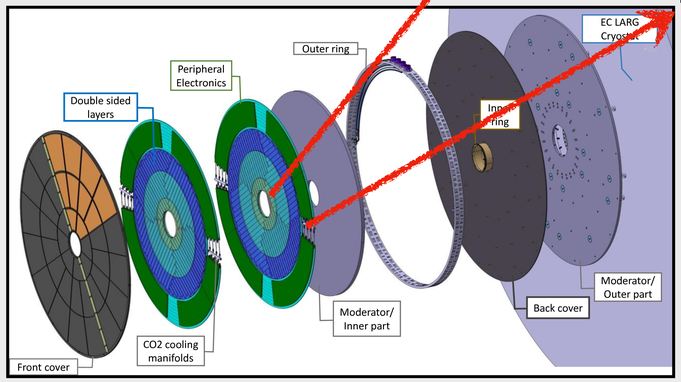
LGAD sensor



Bare module: two LGAD sensors and two ASICs

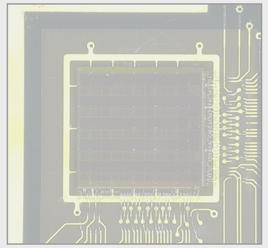


Row of modules



Detector principle

- ☑ The modules on the two sides of a disk are arranged to overlap
- ☑ The overlap increases with 1/R to achieve the targeted track resolution.
- ☑ The hit density is much higher at low radius.



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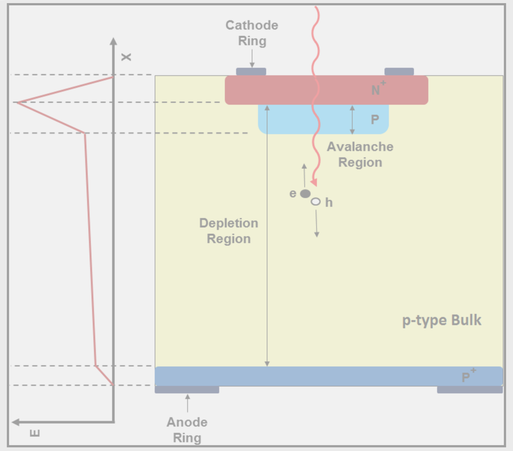
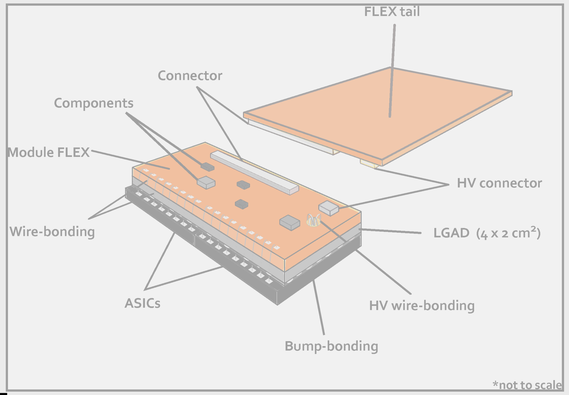
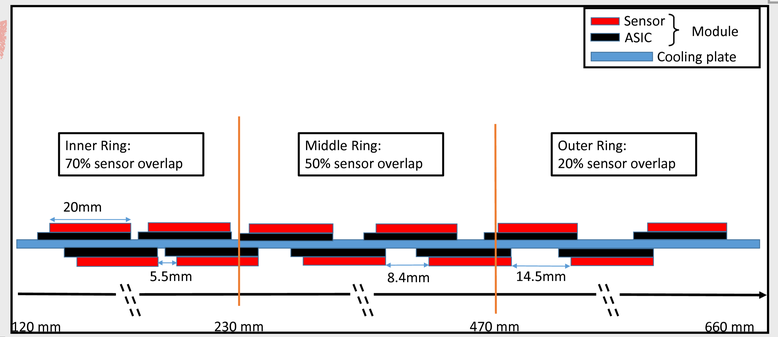


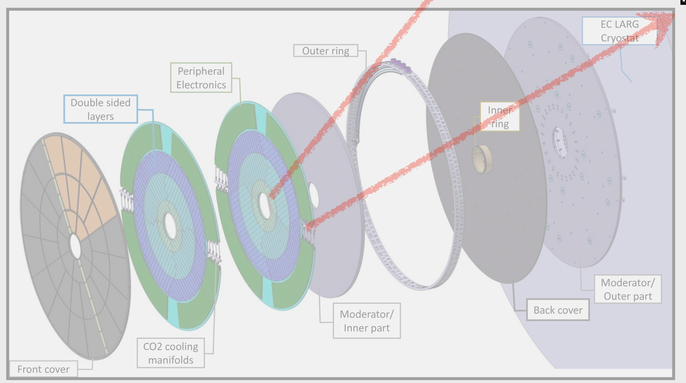
LGAD sensor



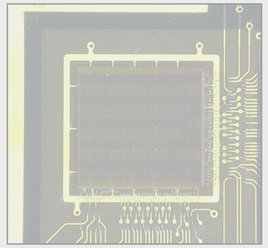
Bare module: two LGAD sensors and two ASICs



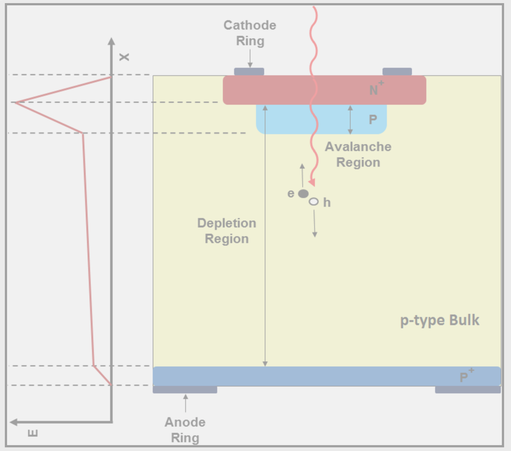
Row of modules



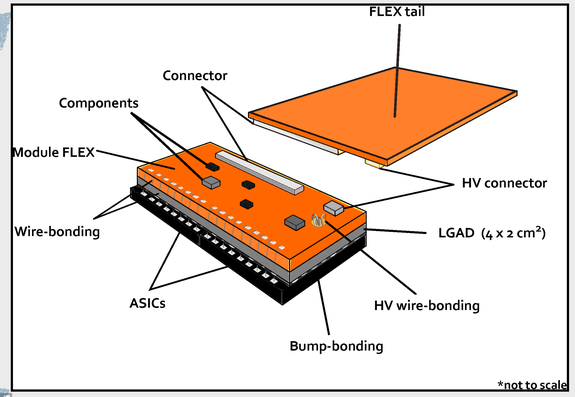
Detector principle



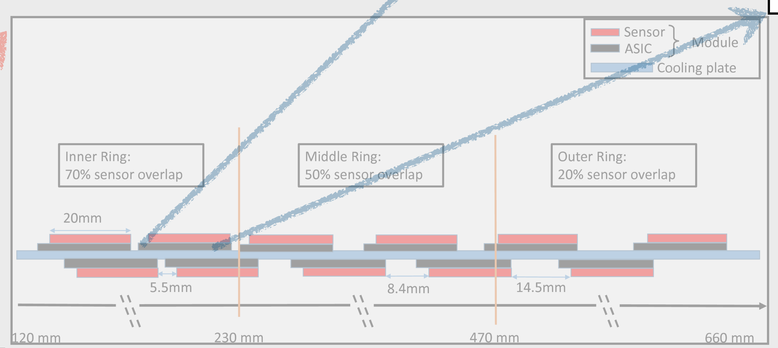
ASIC: ALTIROC



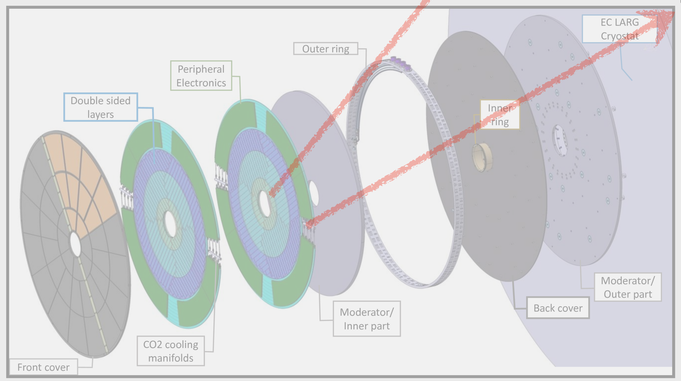
LGAD sensor



Bare module: two LGAD sensors and two ASICs



Row of modules



HGTD

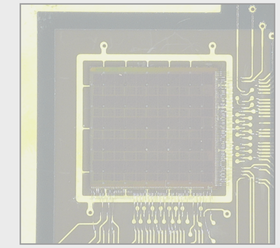
- ☑ LGAD sensor: 15×15 pads.
- ☑ Each LGAD sensor is bump bonded to one ASIC for form a bare module.
  - ➡ When glued to the mother flex, two hybrids make one module.
- ☑ Total number of bare module is 8032

Detector principle

- ☑ Sensor - Low Gain Avalanche Detector (LGAD)
- ☑ n on p sensors with a p-type multiple layer thickness of 50μm

- ☑ HGTD requirements:
  - ✓ **Large S/N ratio** (larger than 7)
  - ✓ **Excellent time resolution** (< 30 ps before irradiation)
  - ✓ **Lower impact from radiation**

- ☑ Sensors will be operated at -30° C (CO2 cooling)



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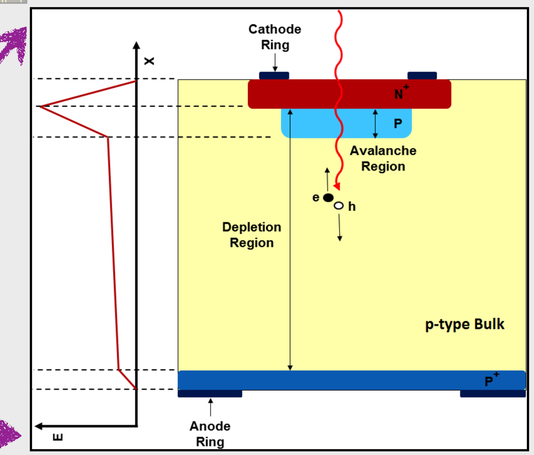
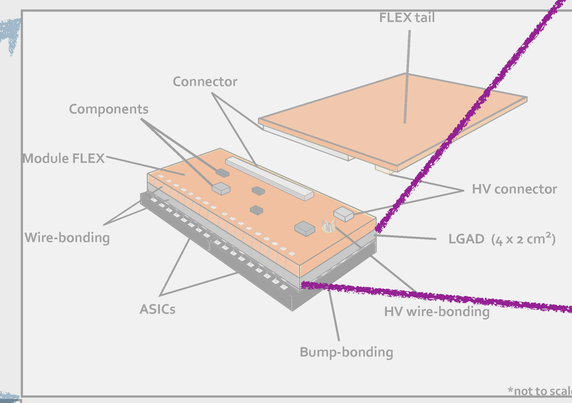
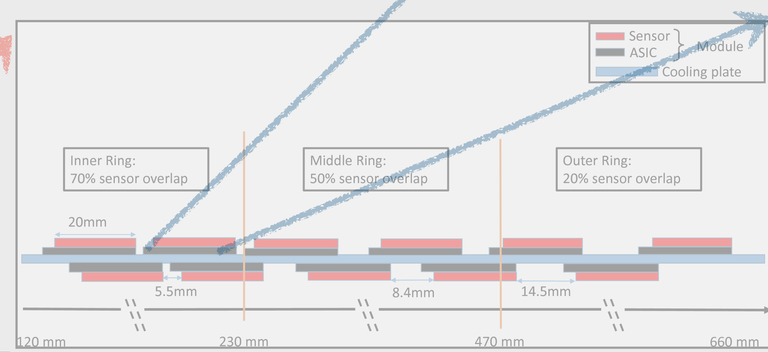


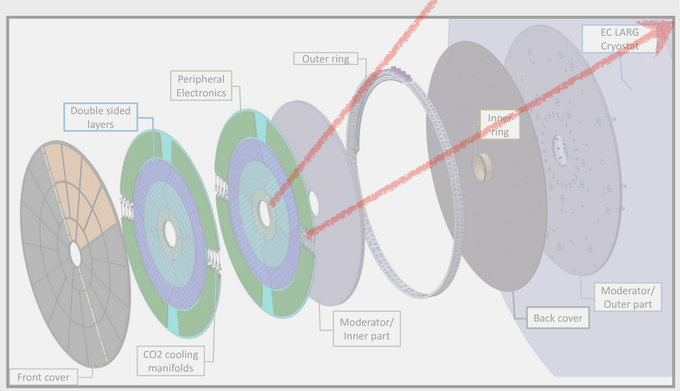
LGAD sensor



Bare module: two LGAD sensors and two ASICs

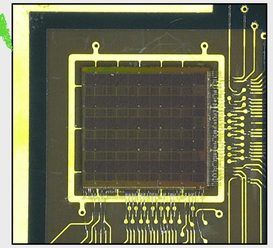


Row of modules

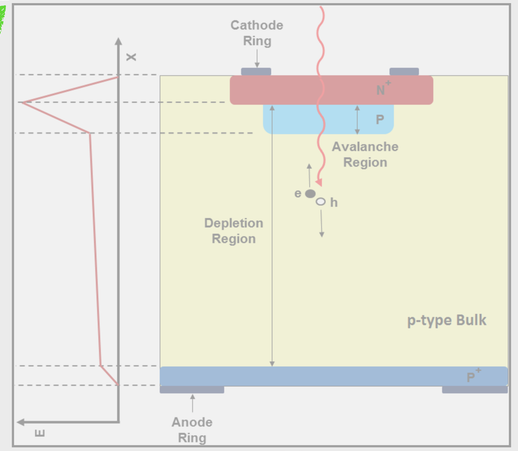


Detector principle

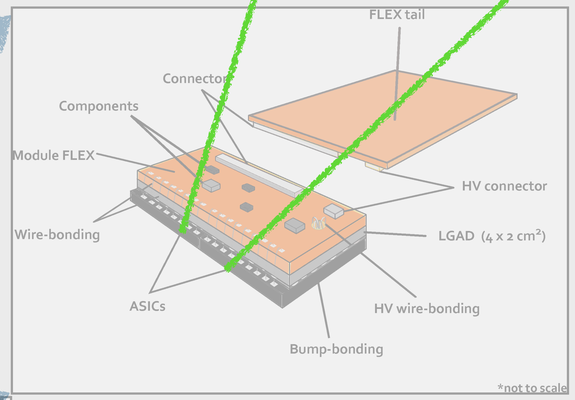
- ☑ The ASIC provides :
  - ➡ Digitised measurement of the Time Of Arrival (TOA) as well as the Time Over Threshold (TOT)
  - ➡ Hit counting for luminosity measurements
  - ➡ Monitoring informations
- ☑ Each ASIC reading a matrix of 225 (15 × 15) channels.
  - ➡ HGTD has in total 3.6M channels (225 × (8032 × 2)).



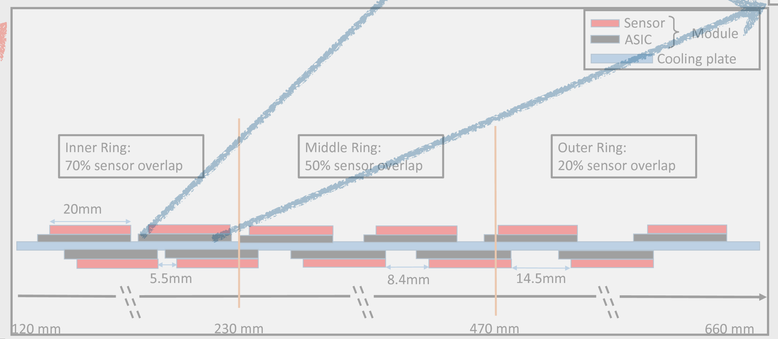
ASIC: ALTIROC



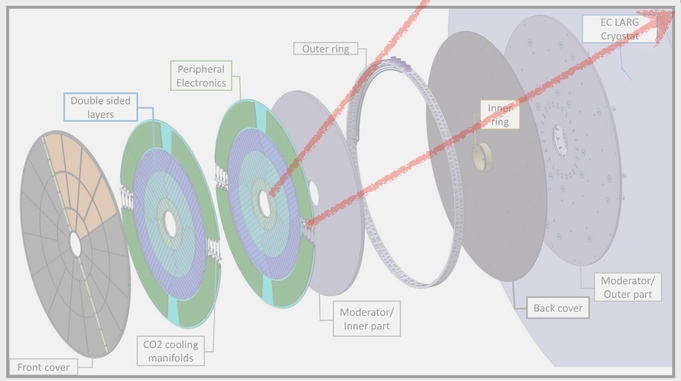
LGAD sensor



Bare module: two LGAD sensors and two ASICs



Row of modules



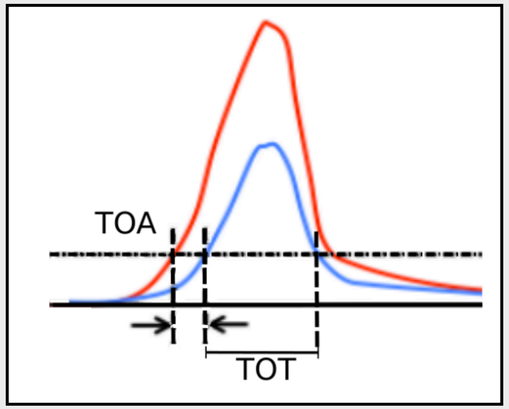
HGTD

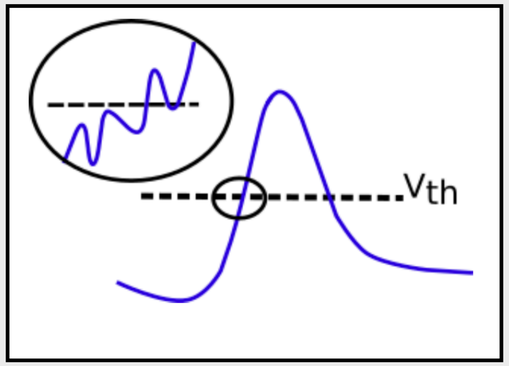
Time resolution

- Time resolution of a detector is defined as the dispersion of time measurement :

$$\sigma_T^2 = \sigma_{Landau}^2 + \sigma_{TW}^2 + \sigma_{jitter}^2 + \sigma_{clock}^2$$

- σ_{Landau}^2
- $\sigma_{TW}^2 = ([\frac{V_{th}}{S/t_{rise}}]_{RMS})^2$
- $\sigma_{jitter}^2 = (\frac{t_{rise}}{S/N})^2$
- $\sigma_{clock}^2 < 15ps$

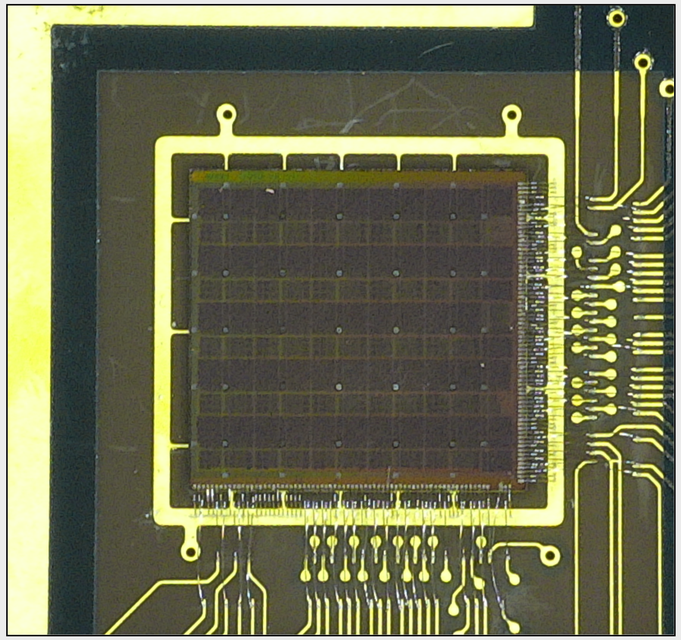


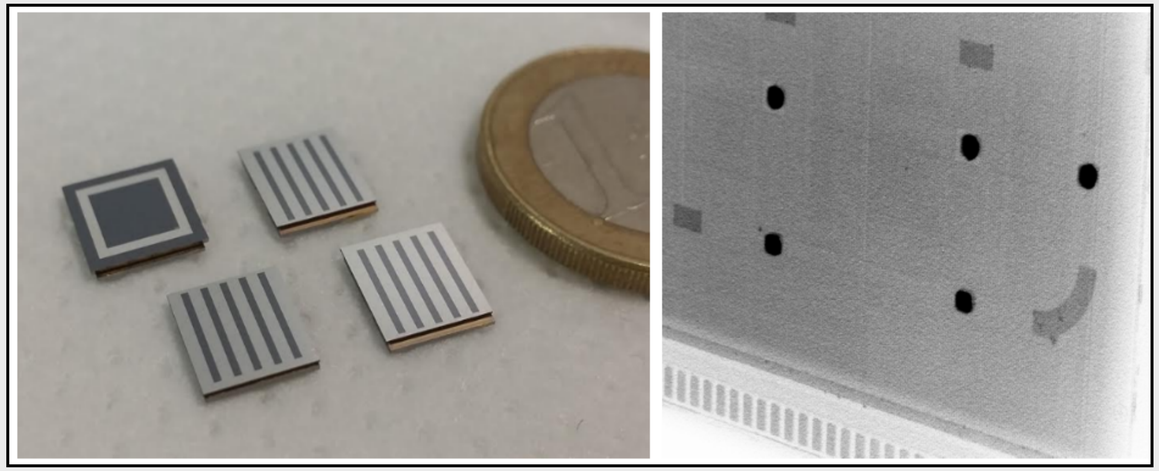


ALTIROC1 ASIC prototype

- ☑ The ALTIROC1 ASIC devices have been assembled for different types of tests (total of 20 bare modules were produced):
  - ➡ Mechanical and electronic
- ☑ Prototypes are being developed and tested:
  - ➡ ALTIROC0: bump-bonded to a sensor of 2×2 pads.
  - ➡ ALTIROC1: bump-bonded to a sensor of 5×5 pads.
  - ➡ ALTIROC2: full size (15x15 channels)
- ☑ Given the HGTD coverage, withstand high radiation levels (~ 2.0 MGy)
- ☑ Able to sustain a shear force of 1000 gf, between the ASIC and sensor
- ☑ Good alignment was observed as well as good connectivity in all the bumps.

Picture of a ALTIROC1 with 5×5 channels wire-bonded on the test board.



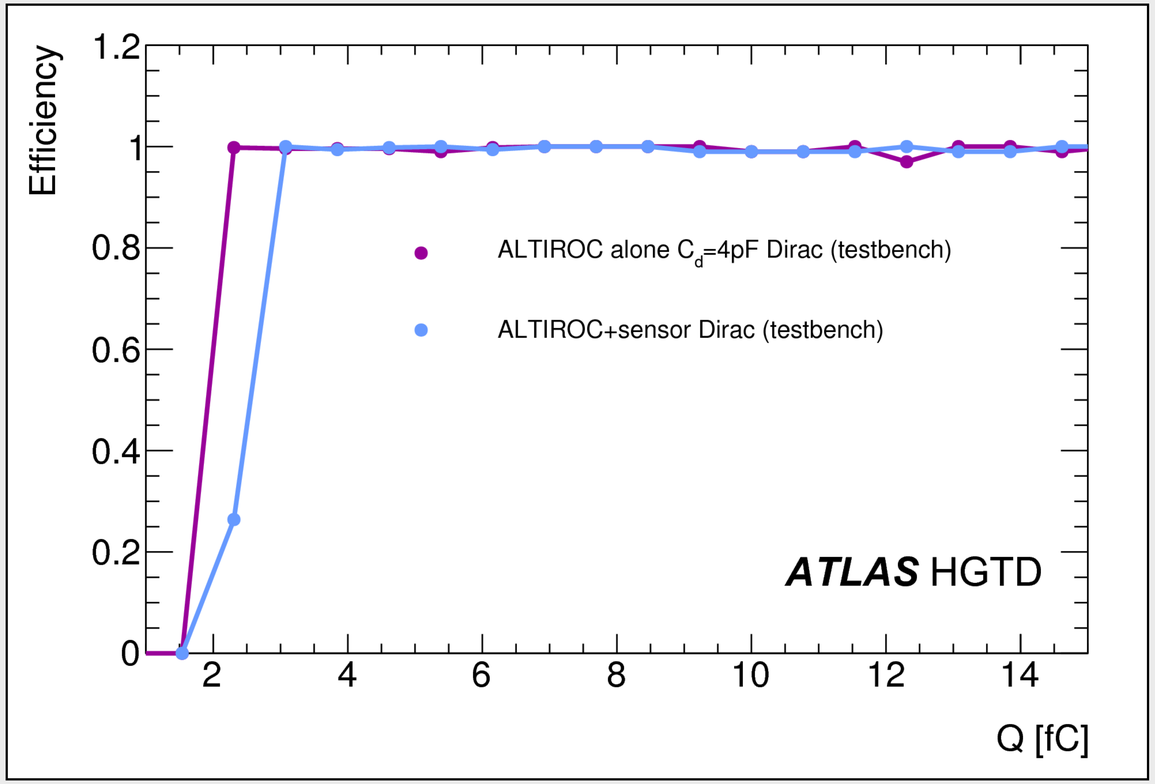


5x5 ALTIROC1 devices, with CNM and HPK sensors

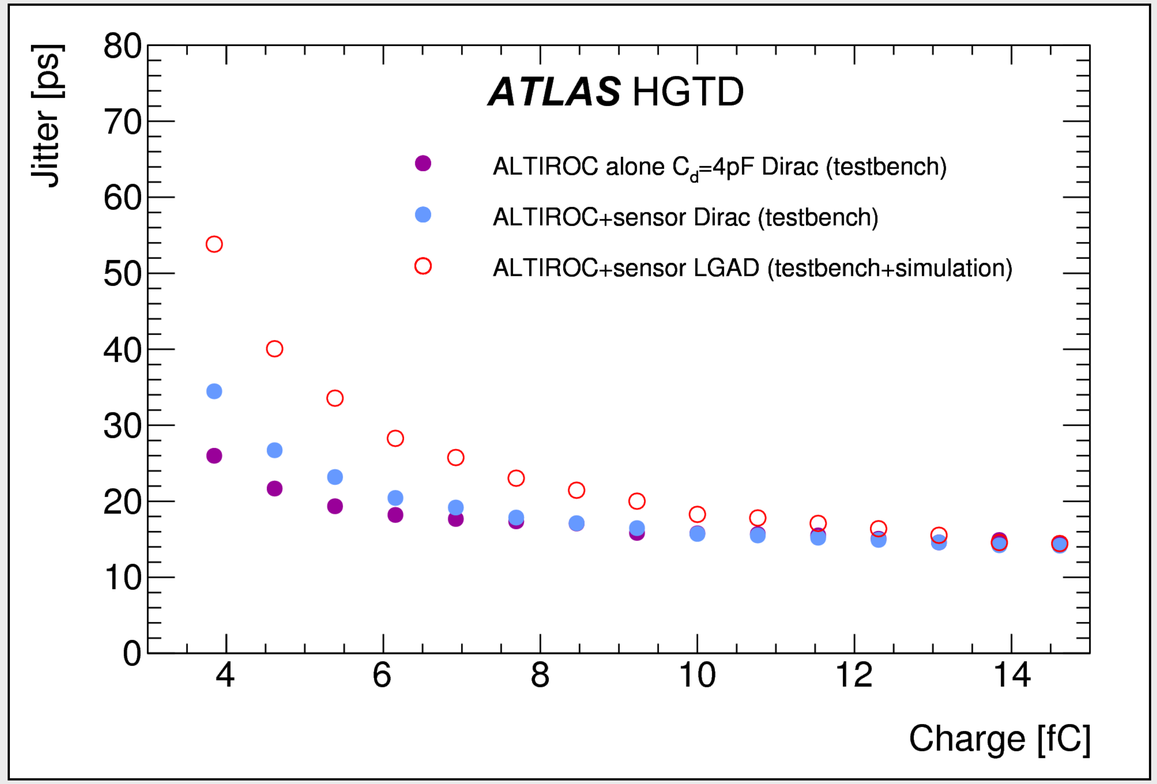
X-ray inspection

ALTIROC measurements on test benches

- Efficiency as a function of injected charge.



- Jitter as a function of injected charge

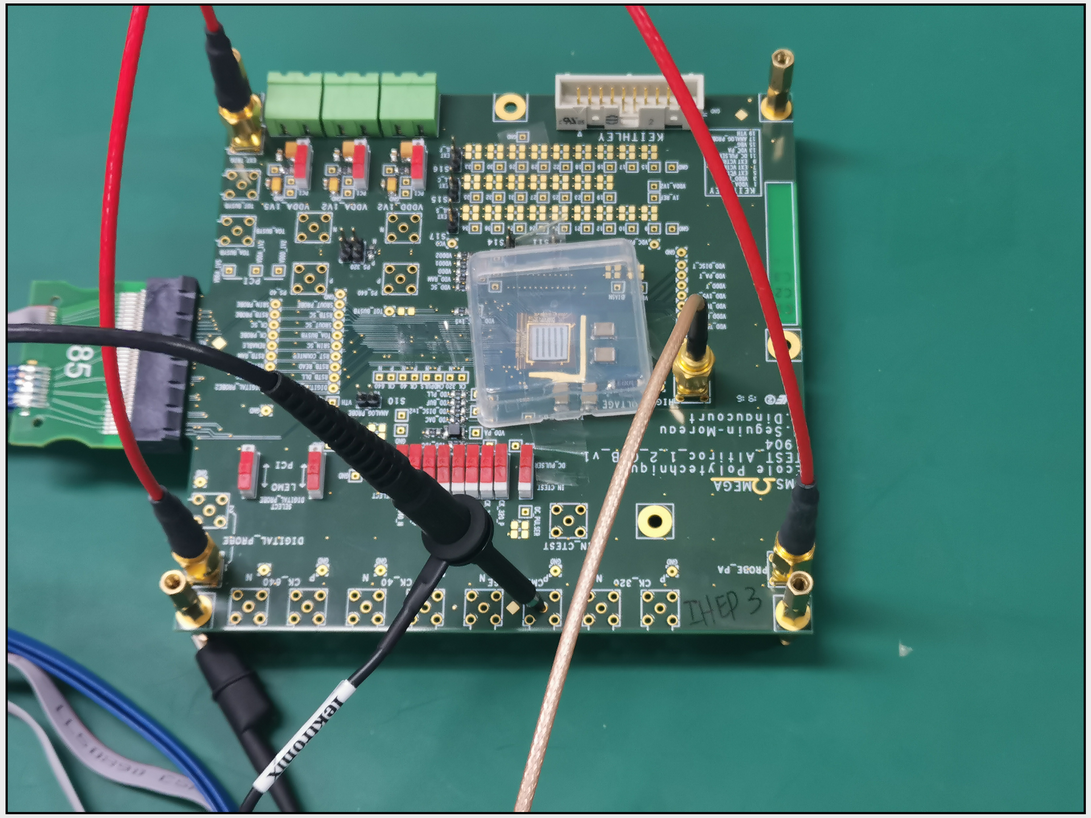


- The difference between the two curves is attributed to noise which is about 30% larger for the sensor case.

- The larger jitter with sensor is attributed to larger noise measured in the sensor case and also to a larger detector capacitance

ALTIROC Measurements at Test Beams

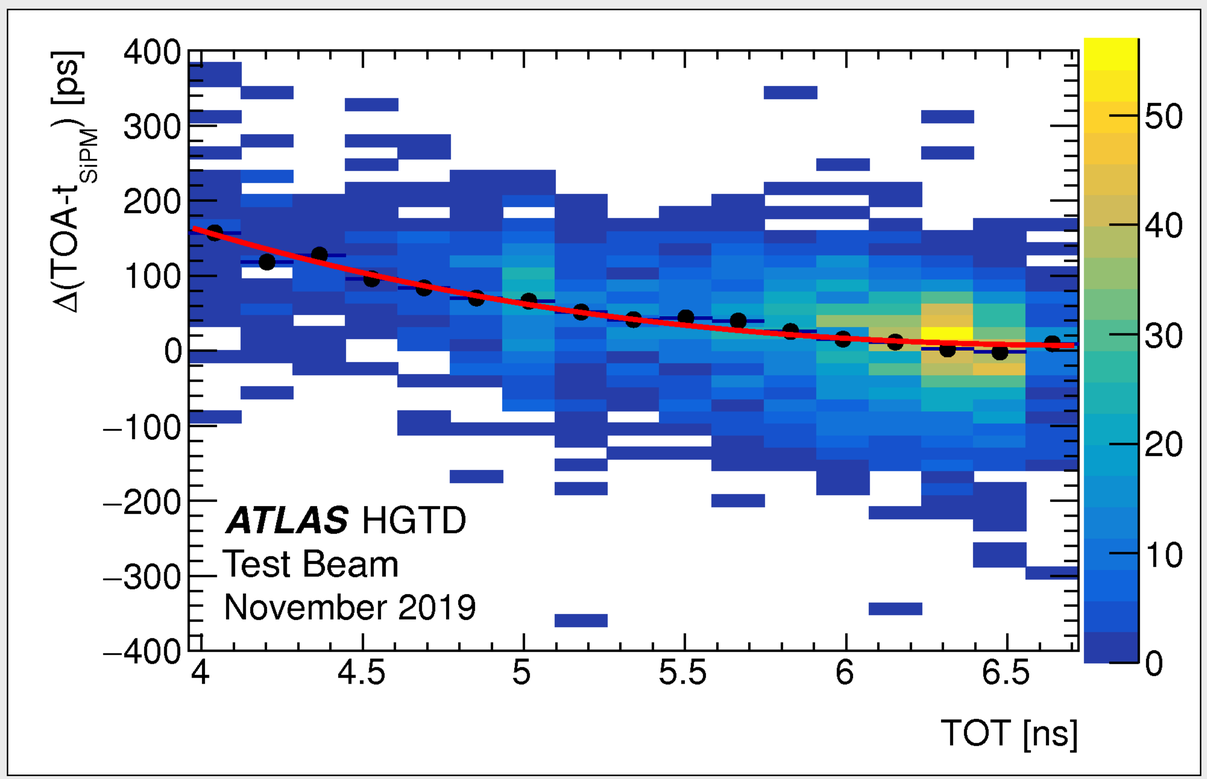
- ☑ The electron beam test setup for bare module prototypes at DESY in autumn 2019.
- ☑ Goal : Measurement of collected charge, time resolution, efficiency, uniformity

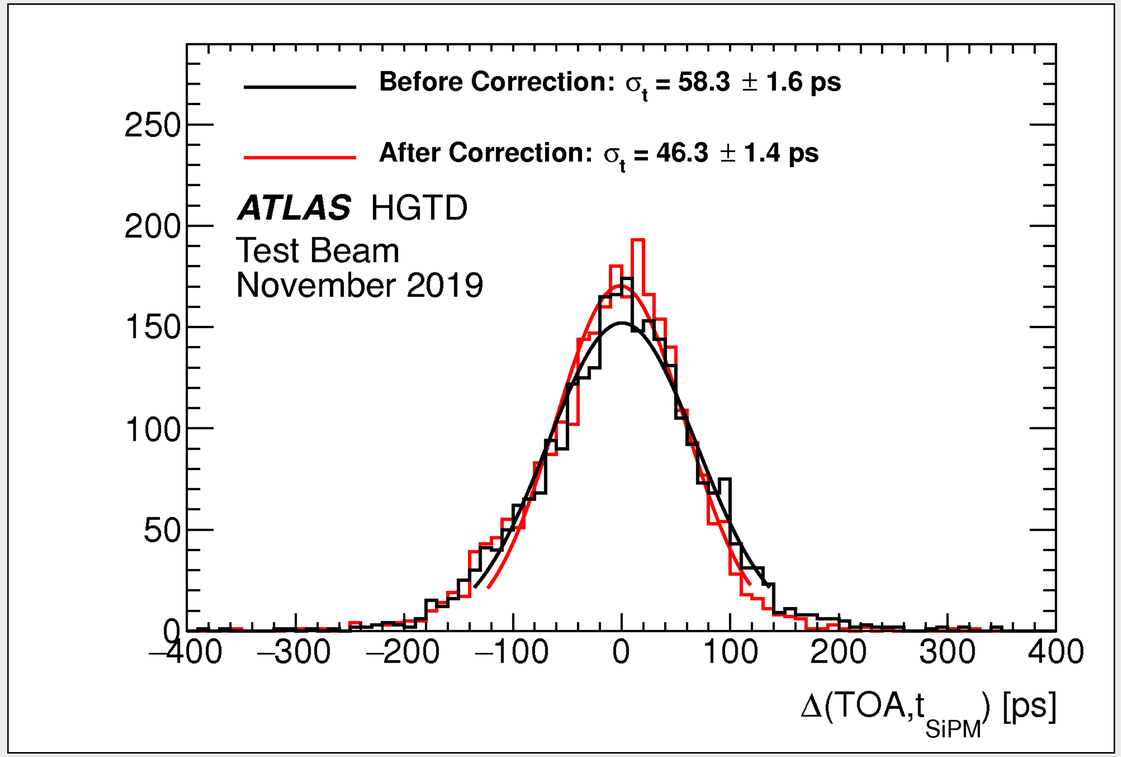


- ☑ Setup of test-bench measurements for bare module prototypes.
- ☑ Bare module prototypes are glued on a printed circuit board (test board).

ALTIROC Measurements at Test Beams

- ☑ Estimated resolution about 46 ps (after subtracting time-walk contribution)
  - ➡ Including Landau contribution (~25ps)
- ☑ Estimated jitter contribution about 39ps

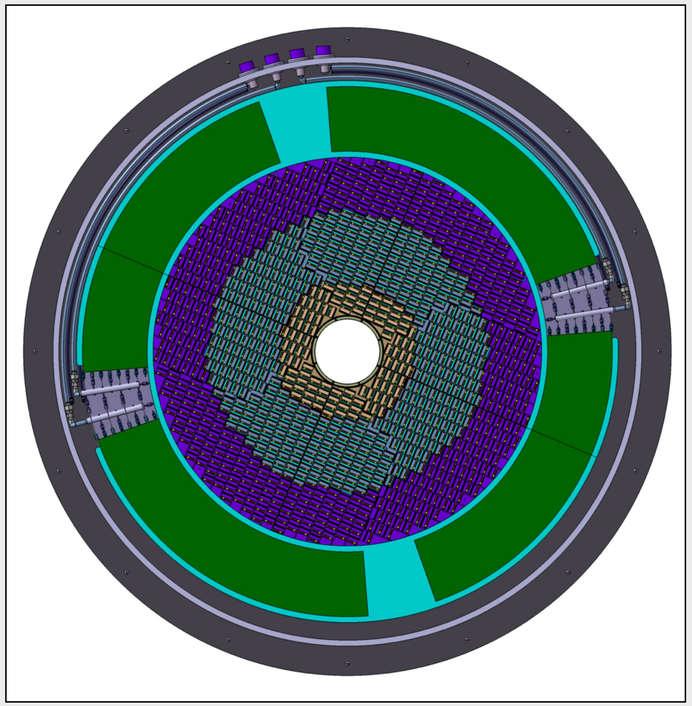




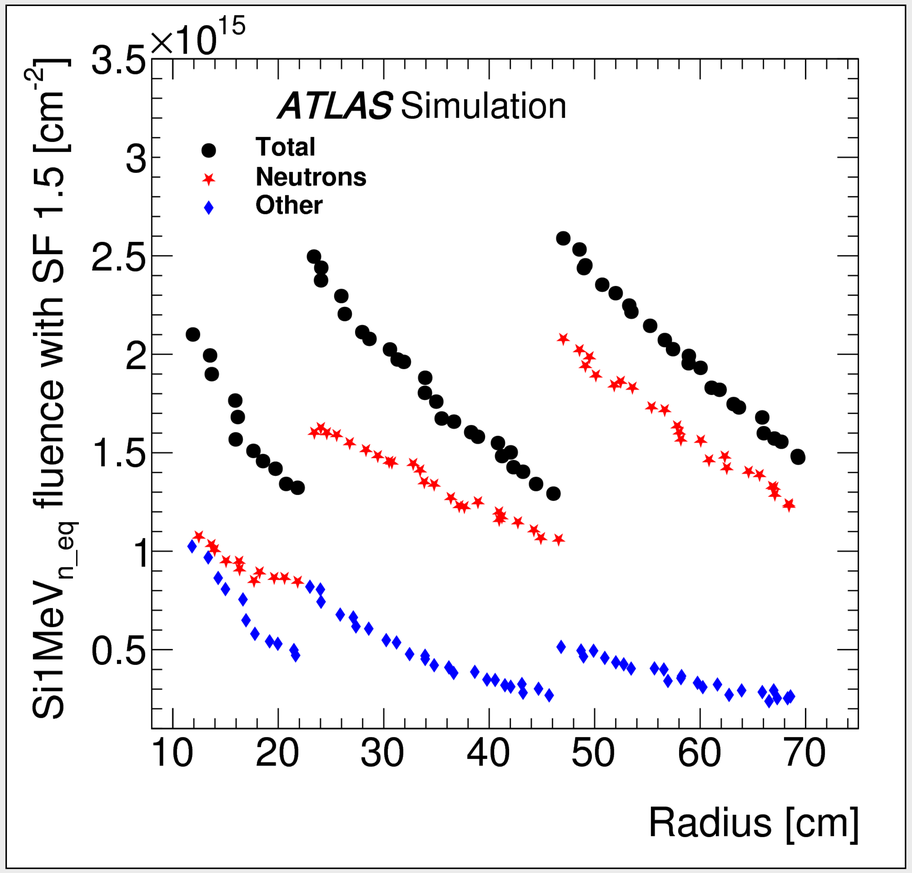
- ☑ Un-irradiated ALTIROC1 modules
- ☑ TOA corrected for time-walk
  - ➡ Achieving ~25ps target.

Radiation hardness

- Given the HGTD converge, withstand the radiation levels throughout the HL-LHC operations is very crucial.

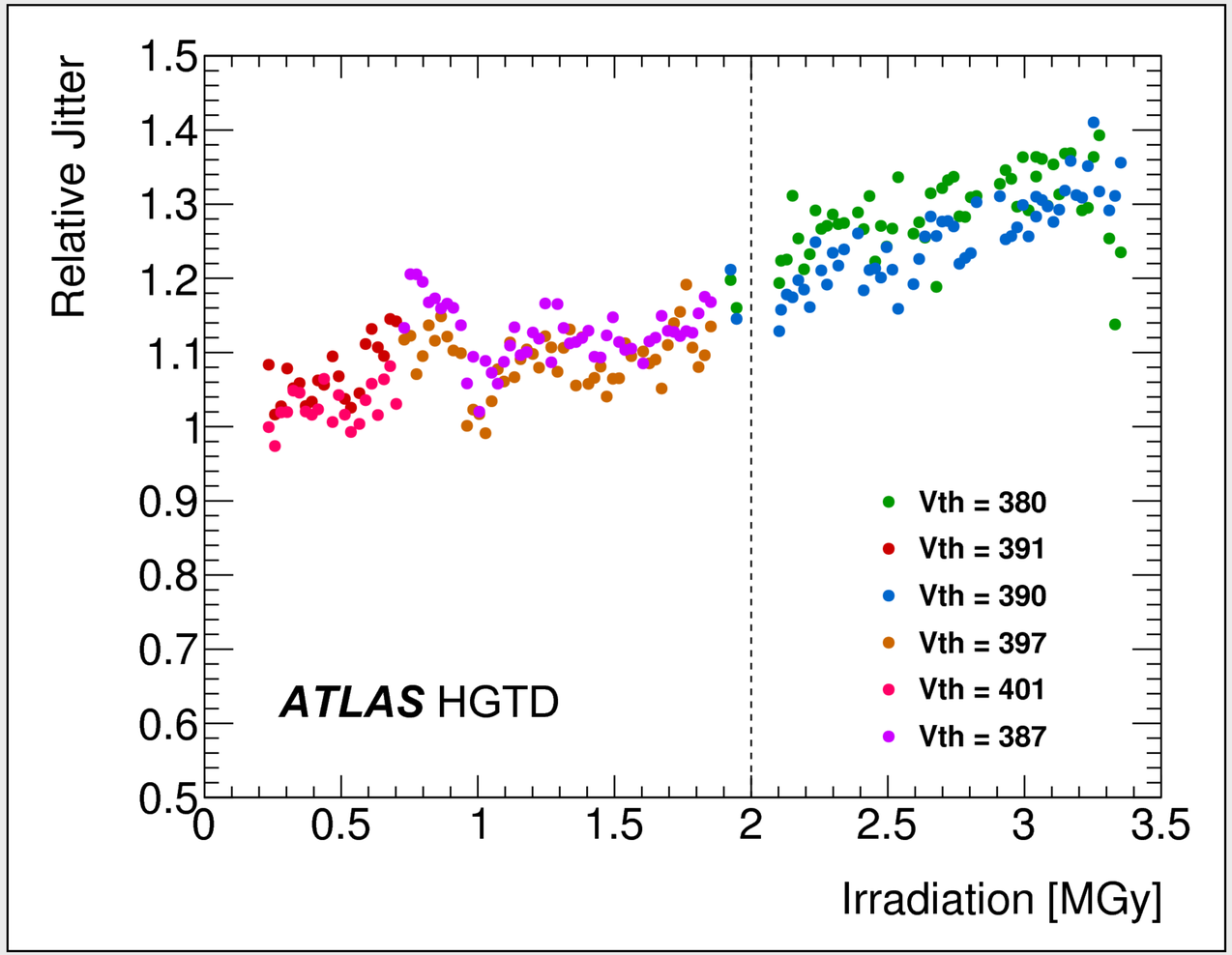


- The maximum fluence $2.5 \times 10^{15} n_{eq}/cm^2$
- The maximum TID 2 MGy



- Ring structure that allows for an easy replacement of sensors that suffer high radiation damage :
  - Inner ring (R < 230 mm) replaced each 1000 fb^{-1}
  - Middle ring (230 mm < R < 470 mm) replaced each 2000 fb^{-1}
  - Outer ring (470-640 mm) never replaced

ALTIROC Irradiation tests



- ☑ Relative jitter as a function of irradiation.
- ☑ The dashed vertical line represents the maximal the total ionising dose (TID) for HGTD.
- ☑ Relative increase in the jitter level between 10 and 15% after 2 MGy.

Conclusion

- ☑ The HL-LHC challenging environment are unprecedented, timing information expected to play a key role to mitigate the impact of pile-up.

- ☑ The HGTD technology and layout are optimised to reach time resolution of about 30-50 ps up to the end of the lifetime of the detector

- ☑ Sensors (see Irena Nikolic's talk) and ASICs are being tested, and have shown to be able to reach the required performance

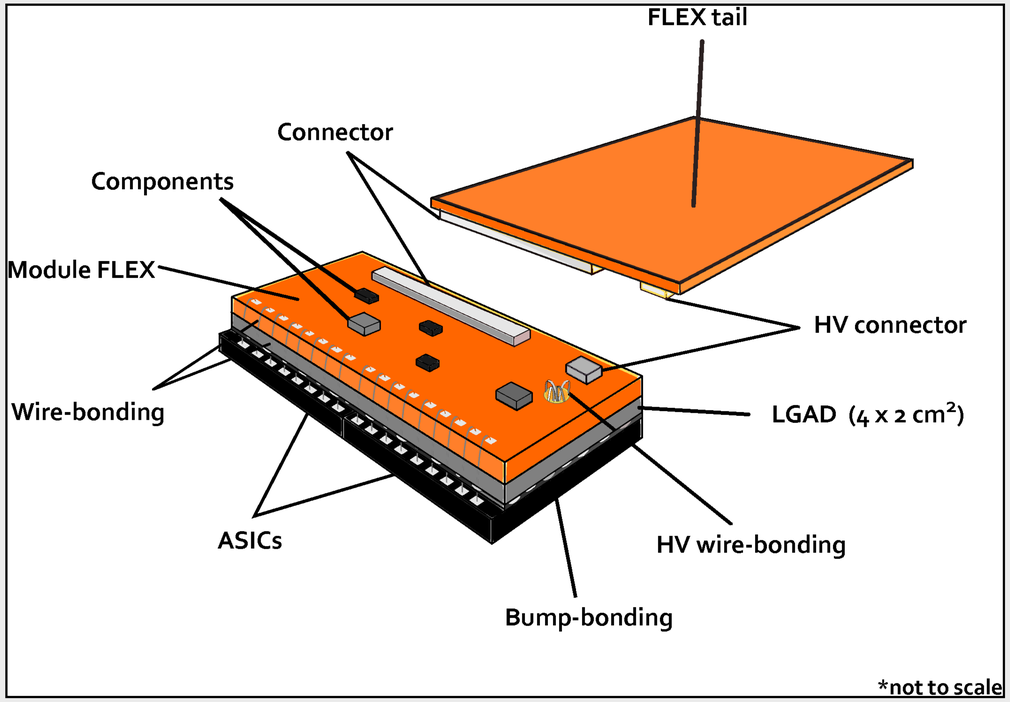
- ☑ The HGTD Technical Design Report has been approved in Sept 2020 CERN-LHCC-2020-007; ATLAS-TDR-031

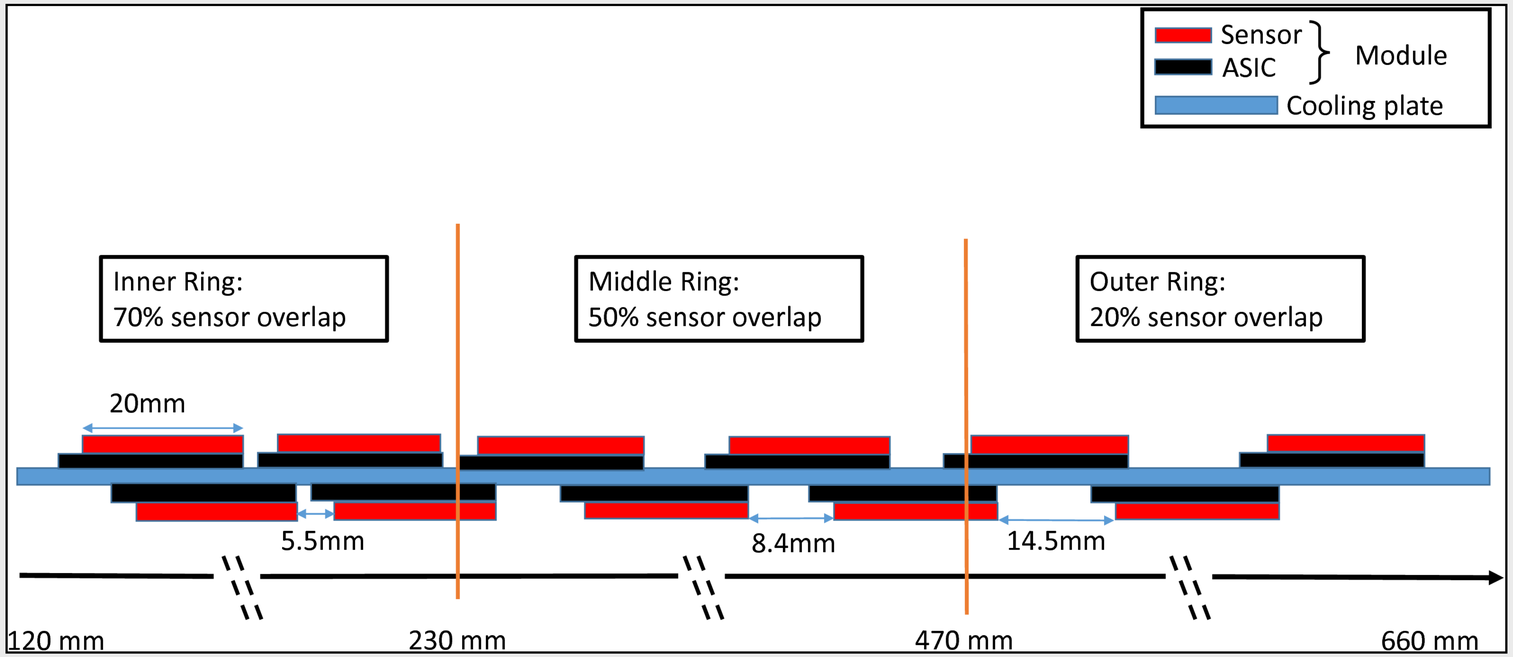
- ☑ Test beam campaigns : ALTIROC beam tests done at DESY. Tests with CERN SPS beam foreseen in Octobre.

Backup

HGTD Modules

- ☑ The modules on the two sides of a disk are arranged to overlap
- ☑ The maximal overlap is decreases with R to achieve the required timing resolution



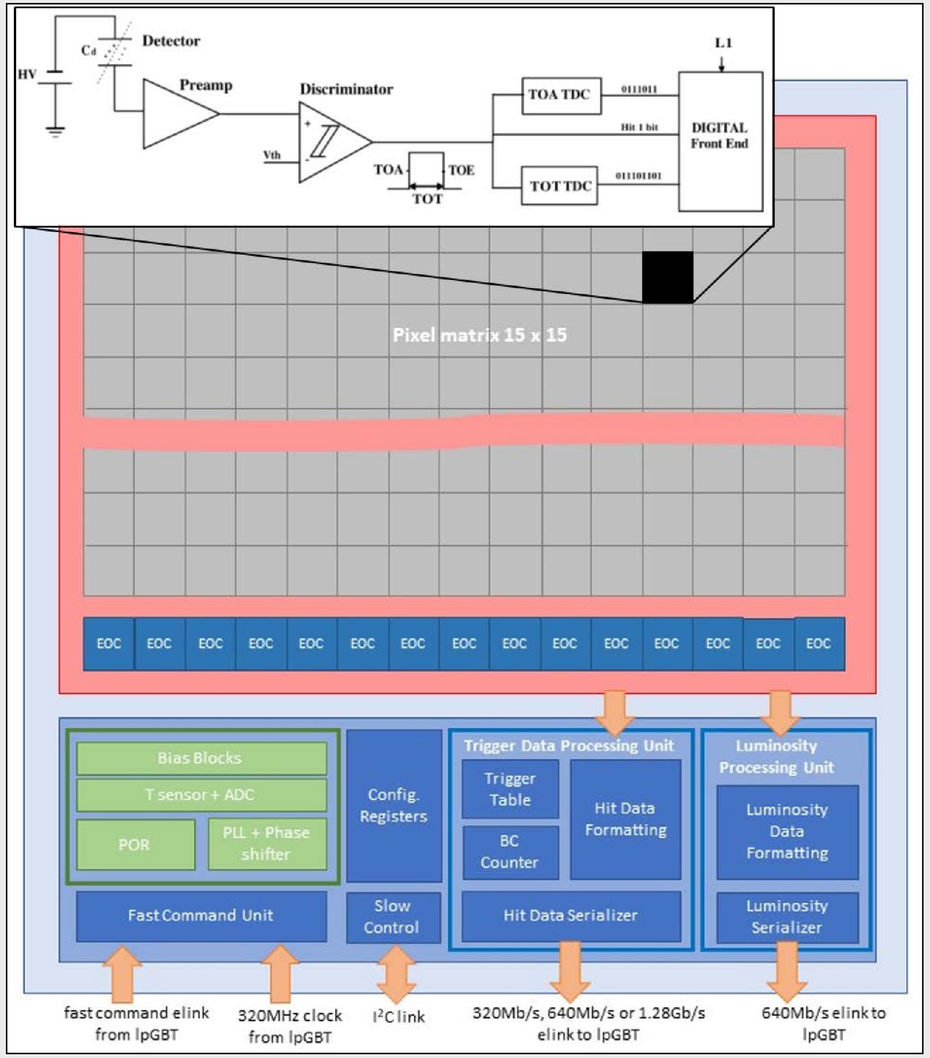


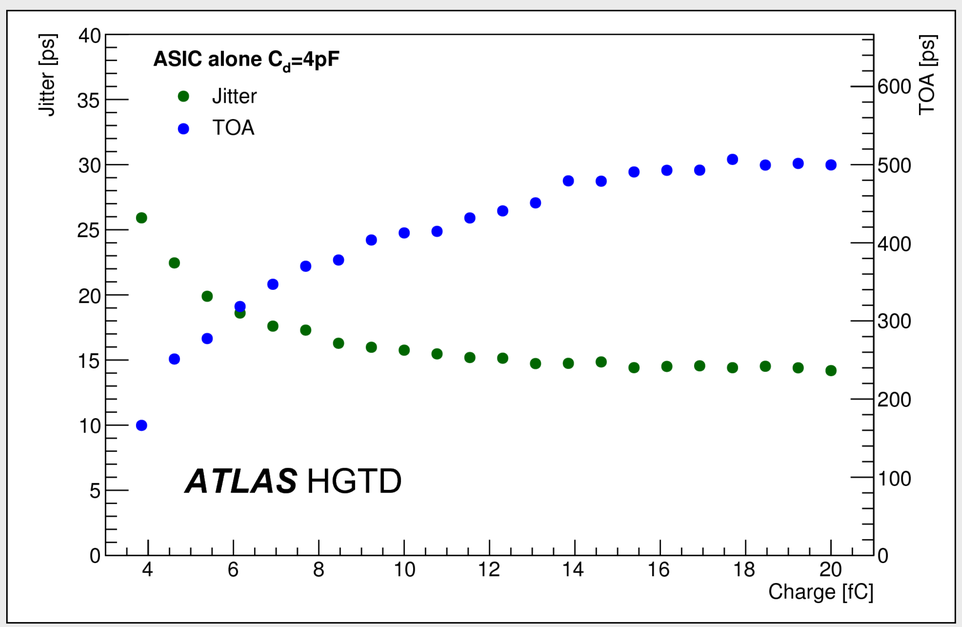
- ☑ Bare module : two LGAD sensors and two ASICs
  - ☆ LGAD sensor: 15×15 pads
  - ☆ Total number of bare module is 8032, 3.6M channels, 6.4 m^2

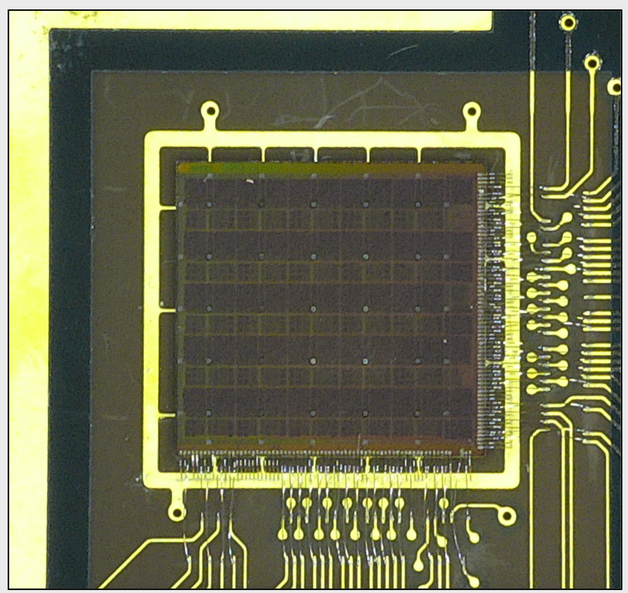
HGTD Frond End Chip: ALTIROC

- HGTD AISC chip is connected to the LGAD sensor: 15x15 readout channels.
- Have to withstand high radiation levels: 2.0 MGy at the edge of non-replacing ring.
- Pre-amplifier followed by TOA and TOT (for time-walk correction).
- Prototypes are being developed and tested:
  - ALTIROC0: bump-bonded to a sensor of 2×2 pads.
  - ALTIROC1: bump-bonded to a sensor of 5×5 pads.
  - ALTIROC2: full size (15x15 channels)
- ALTIROC1 with 4pF input capacitance can achieve ~15ps jitter at 10fC input charge

Global architecture of the ALTIROC ASIC



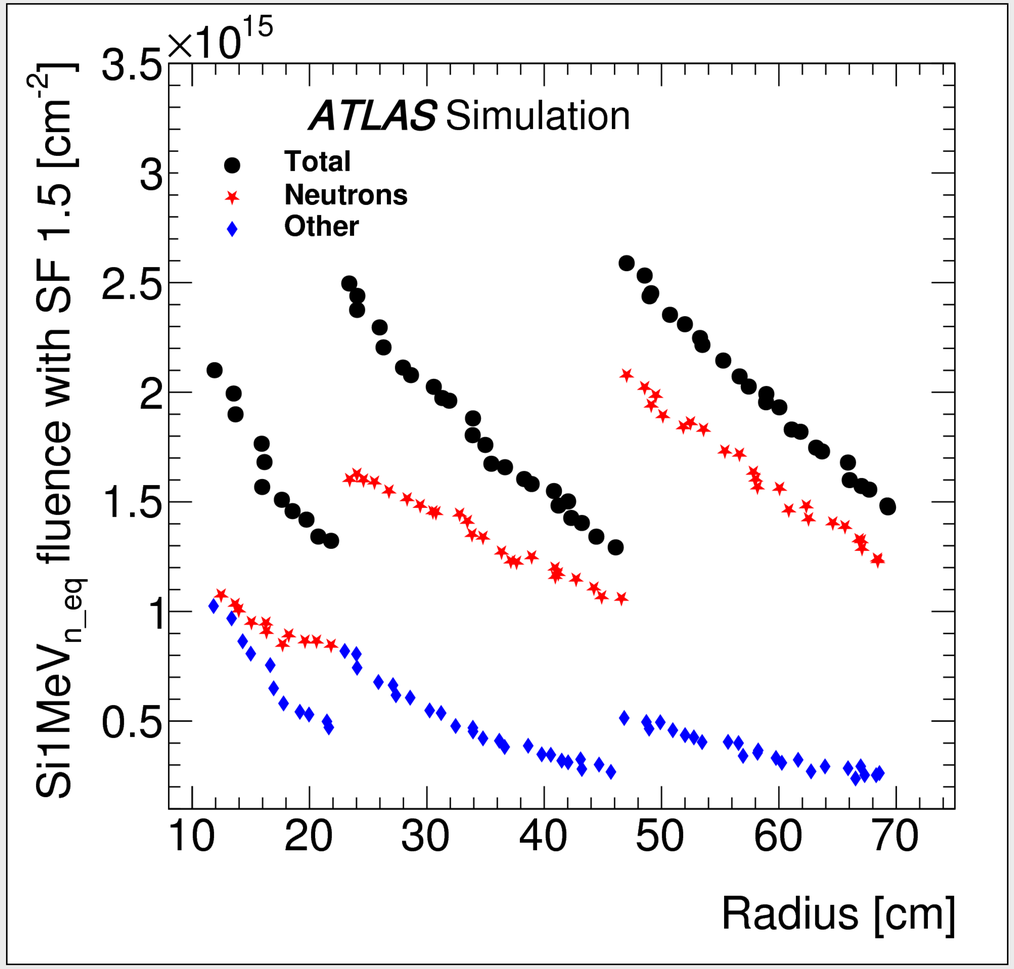




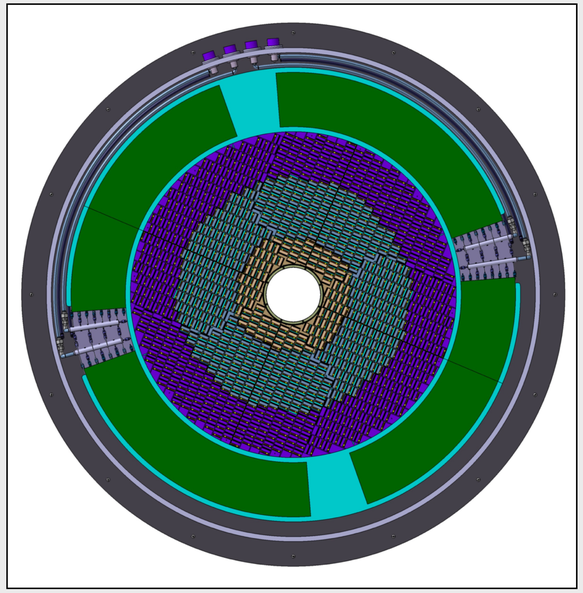
ALTIROC1

Radiation hardness

- Given the HGTD converge, withstand the radiation levels throughout the HL-LHC operations is very crucial.



- As a results:
  - Sensors will be operated at -30°C using a common CO_2 cooling system with ITk.
  - Ring structure that allows for an easy replacement of sensors that suffer high radiation damage:
    - Inner ring (R < 230 mm) replaced each 1000 fb^{-1}
    - Middle ring (230 mm < R < 470 mm) replaced each 2000 fb^{-1}
    - Outer ring (470-640 mm) never replaced



- To achieve good time resolution with HGTD, the maximum fluence (using the Fluka estimations) should not exceed $2.5 \times 10^{15} n_{eq}/cm^2$ and the total ionising dose (TID) about 2MGy

Time resolution

- Time resolution of a detector is defined as the accuracy of measuring the time at which particles are detected

$$\sigma_T^2 = \sigma_{Landau}^2 + \sigma_{TW}^2 + \sigma_{jitter}^2 + \sigma_{clock}^2$$

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- σ_{Landu}^2 :
  - ➡ Landau fluctuations in the energy deposits of the particles
  - ➡ non-uniformity of the energy deposit along the particle path. (depends on the sensor thickness)
  - ➡ σ_{Landu}^2 < 25 ps (reduced for thin sensors 35-50 μm)

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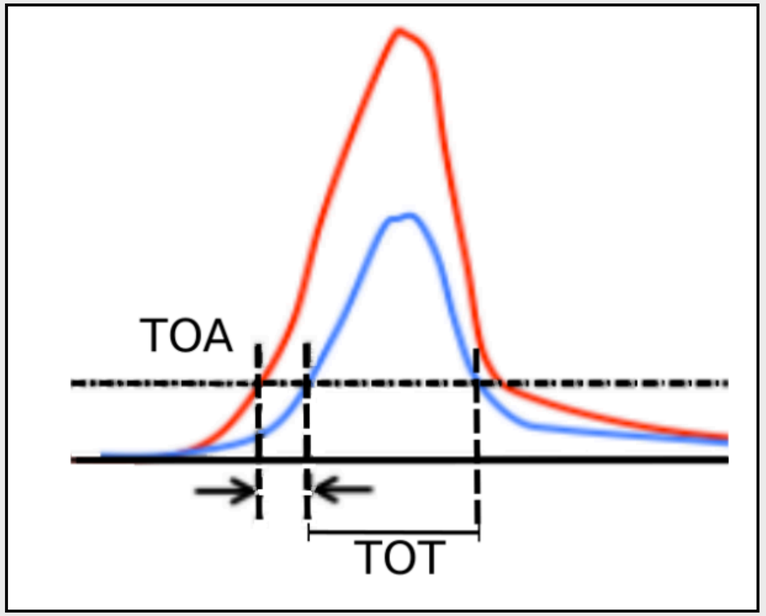
- $\sigma_{TW}^2 = ([\frac{V_{th}}{S/t_{rise}}]_{RMS})^2$:
  - ➡ Variations due to differences in the amplitude of the signal.
  - ➡ Expected to be negligible after applying an offline correction based on measuring the TOT.



Time resolution

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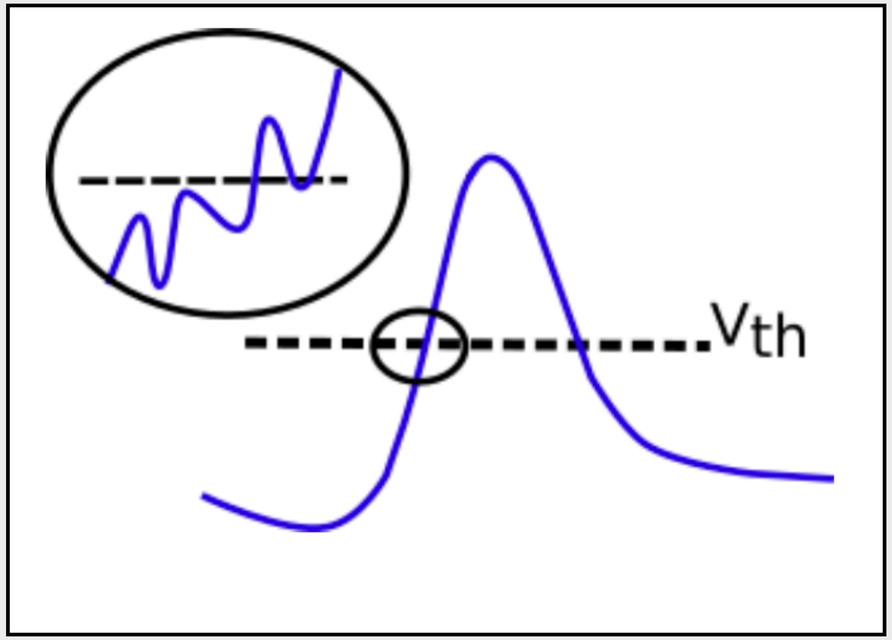
- $\sigma_{jitter}^2 = (\frac{t_{rise}}{S/N})^2$:
  - ➡ Variations due to noise in the signal
  - ➡ $\sqrt{\sigma_{jitter}^2 + \sigma_{TW}^2}$ < 25 ps (70 ps at 4000 fb^{-1}) -> need **fast signal and excellent S/N**



Time resolution

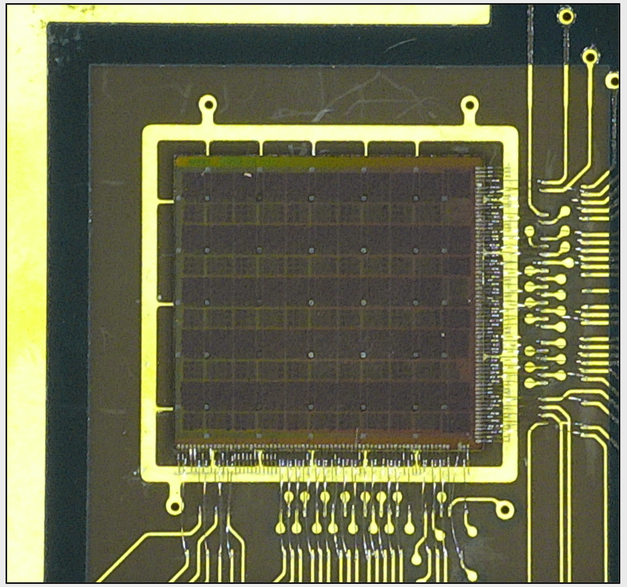
- Time resolution of a detector is defined as the accuracy of measuring the time at which particles are detected

$$\sigma_T^2 = \sigma_{Landau}^2 + \sigma_{TW}^2 + \sigma_{jitter}^2 + \sigma_{clock}^2$$

- σ_{clock}^2 = contribution from the clock distribution :
  - ➡ High Frequency: bunch to neighbouring bunch 'jitter'
  - ➡ Low frequency: drift over longer periods (~ 1 ms), can be corrected offline with calibration
  - ➡ σ_{clock}^2 < 15 ps

HGTD Frond End Chip: ALTIROC

ALTIROC1



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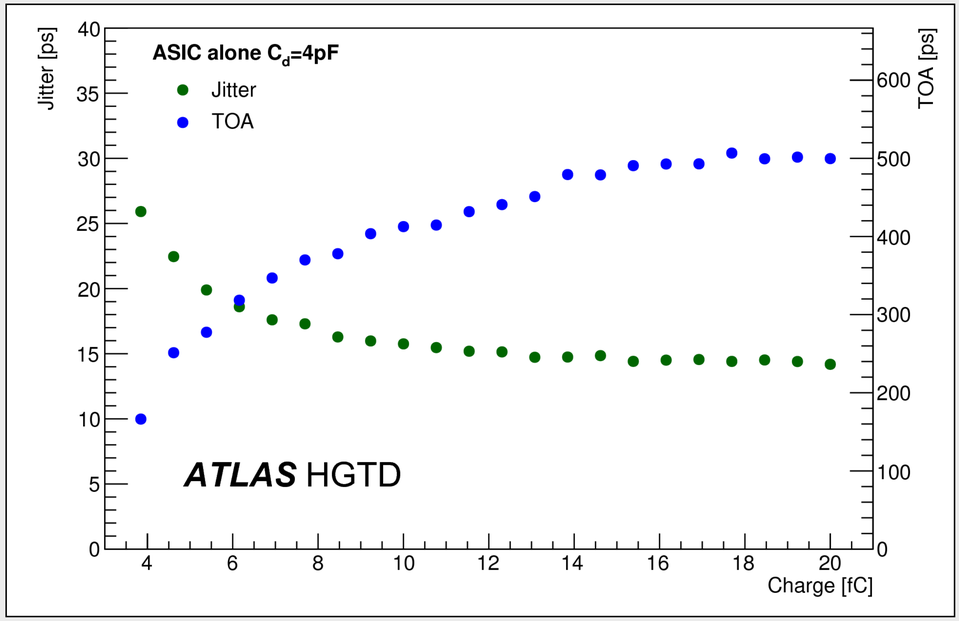

Sensor - Low Gain Avalanche Detector (LGAD)

- ☑ n on p sensors with a p-type multiple layer thickness of 50μm

- ☑ HGTD requirements:
  - ✓ Moderate internal **gain (8 - 50)**
  - ✓ **Large S/N ratio** (larger than 7)
  - ✓ **Fast rise time (t_{rise})** (0.5-0.8 ns)
  - ✓ **Excellent time resolution** (< 30 ps before irradiation)
  - ✓ **Lower impact from radiation**

- ☑ **Sensors will be operated at -30° C**
  ➡ **CO2 cooling**