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

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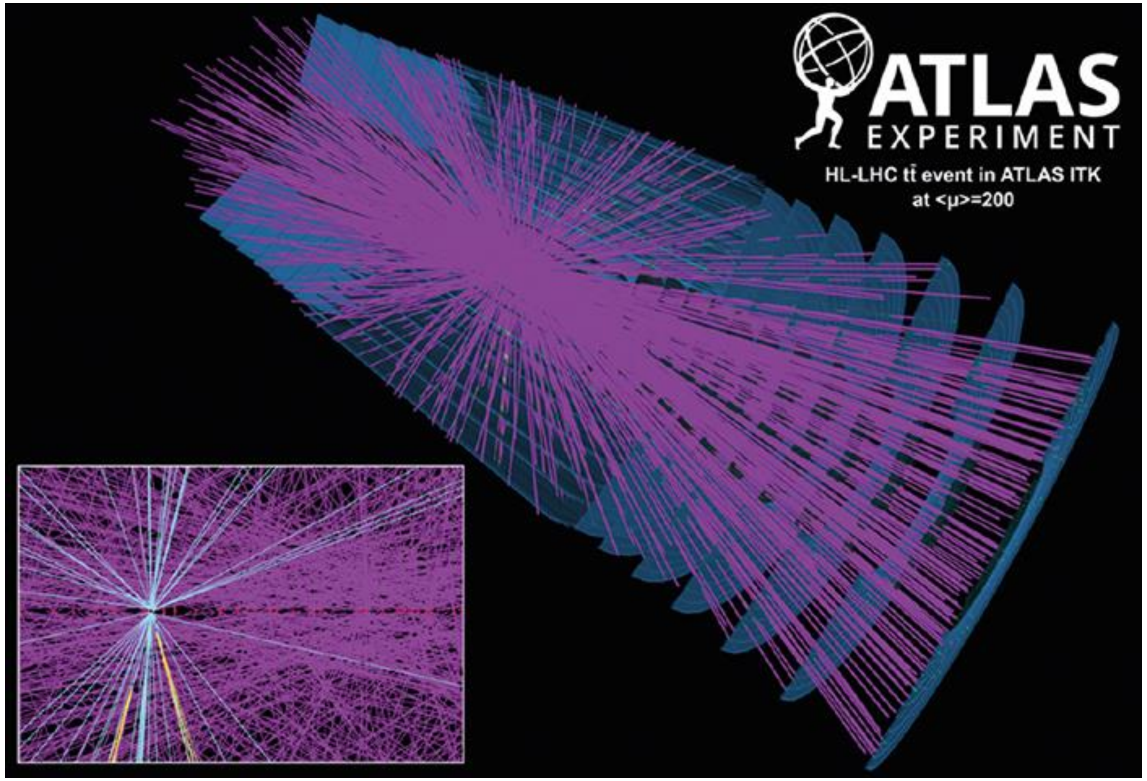
Outline

- **The High Luminosity LHC**
- **Motivation for a High Granularity Timing Detector**
- **Detector Overview**
- **Sensor Technology and Testing**
- **Electronics**
- **Conclusions**

The High Luminosity LHC

- increase in **instantaneous** luminosity from 10^{34} to **7.5×10^{34} cm^{-2} s^{-1}**
- Increasing the integrated luminosity from 100 to 4000 fb^{-1}
- Scheduled to start at 2026
- Main challenge of HL-LHC will be **pile-up** interactions

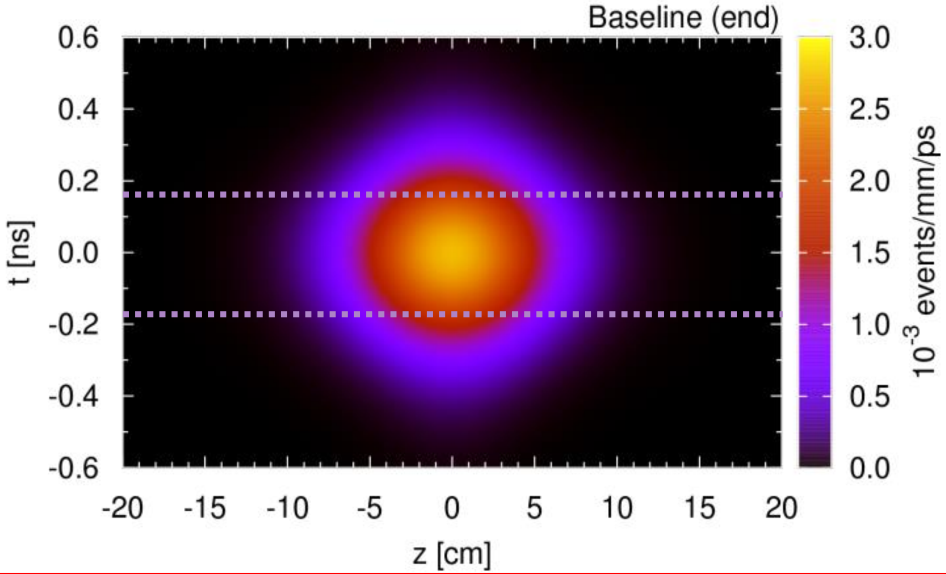


- **Pile-up:** all interactions happening around the interaction of interest
  - Run 2 (now) : 30 PU/event
  - HL-LHC:<μ>=200!

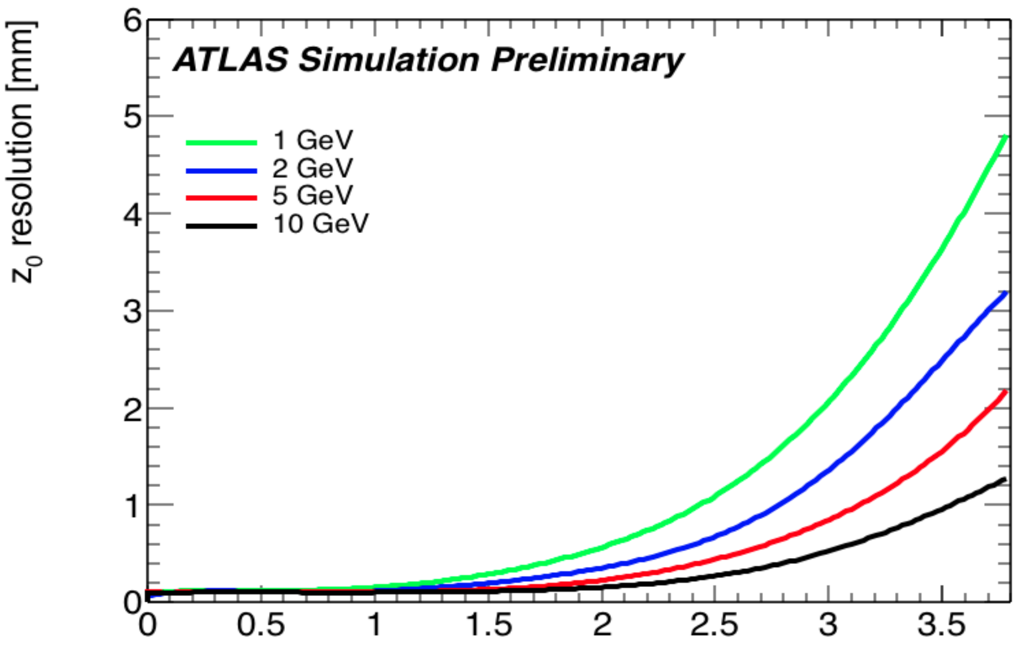
Pile-up particles contaminate all physics objects, degrading the performance of the current detectors…

Motivation for a High Granularity Timing Detector

- Time information is completely orthogonal to space information
  - **Pile-up mitigation** by rejecting out-of-time tracks
  - Improvements in: jet reconstruction, electron isolation, b-tagging and MET, Primary Vertex ID and track-to-vertex association
  - HGTD can also be used as a **luminometer**:
    - High granularity→ good linearity between n. of hits and n. of interactions



At HL-LHC: vertex spread in time ~ 180ps
Time resolution of 30 ps can greatly help disentangle merged-in-space vertices



Z0 resolution of ITk as a function of η: for |η|>2.5 resolution increasing above the average vertex density (1.6vertex/mm).

*Tracks matched to vertices by comparing their **z positions**:*

$$\frac{z_0 - z_{vertex}}{\sigma_{z_0}} < 2$$

Detector Overview

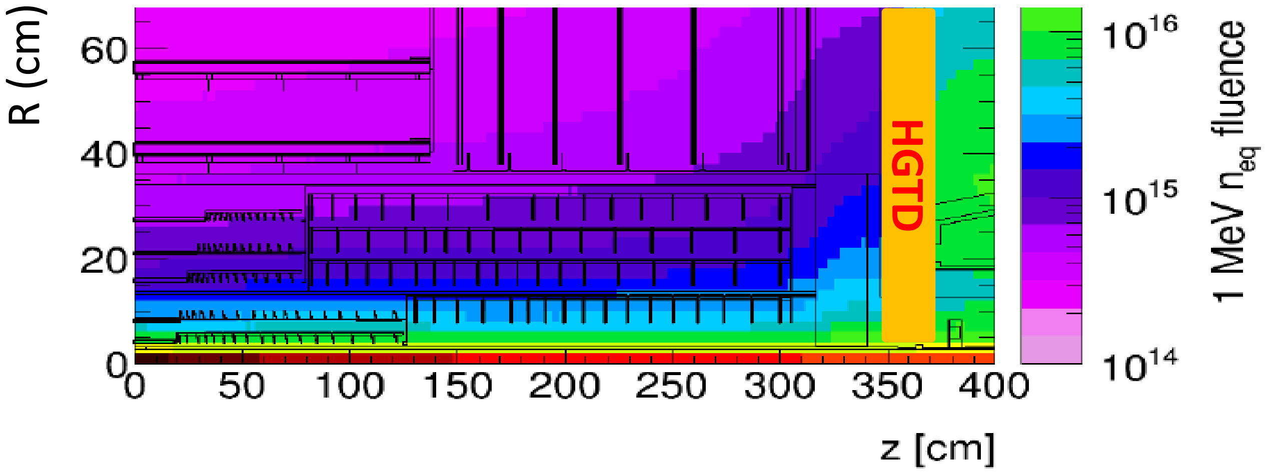
HGTD will be placed in the **forward region**, between the **Inner Tracker** and the end-cap **EM Calorimeter** and will include 4 Layers per side:

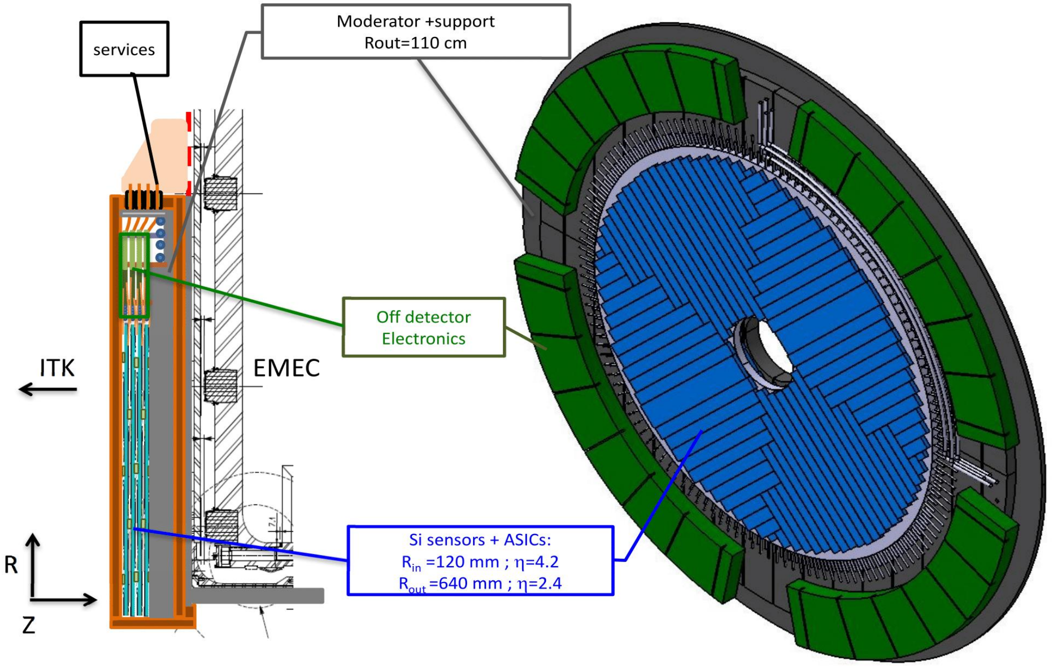
- **Time resolution: 30ps/mip** (60ps/mip/layer)
- **Granularity (<10% Occu)**: 1.3x1.3mm^2

- **Pseudorapidity** coverage: $2.4<|\eta|<4$
- **Radial extension:** R=110-1100mm (120-640mm active area)
- **Position in z**: 3420<z<3545mm (50mm of moderator + Δz=75mm HGTD)

After ½HL-LHC, fluence @ inner-radius region about **4×10^{15} n_{eq}/cm^2** and TID of **4MGy**

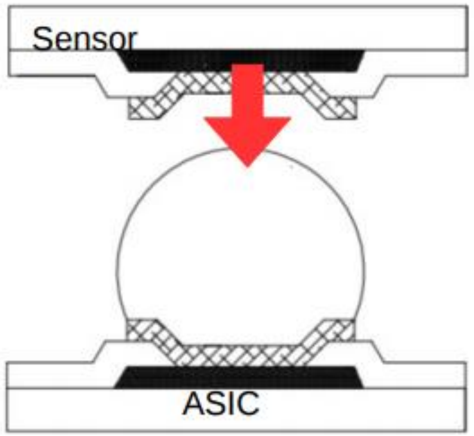
→ Replacement of pads planned for R<300mm





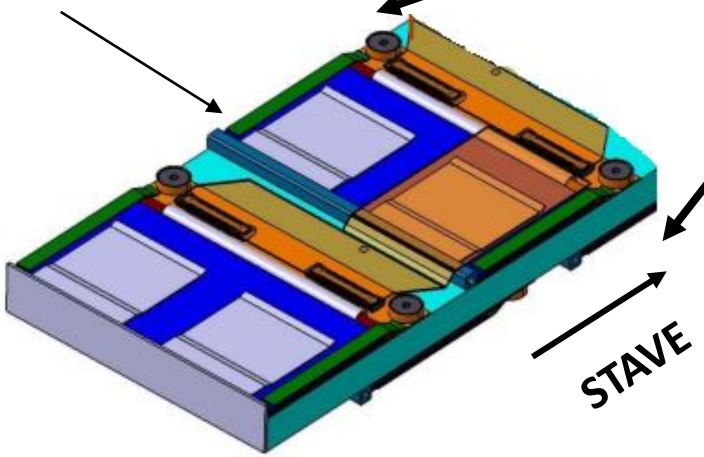
Detector Overview

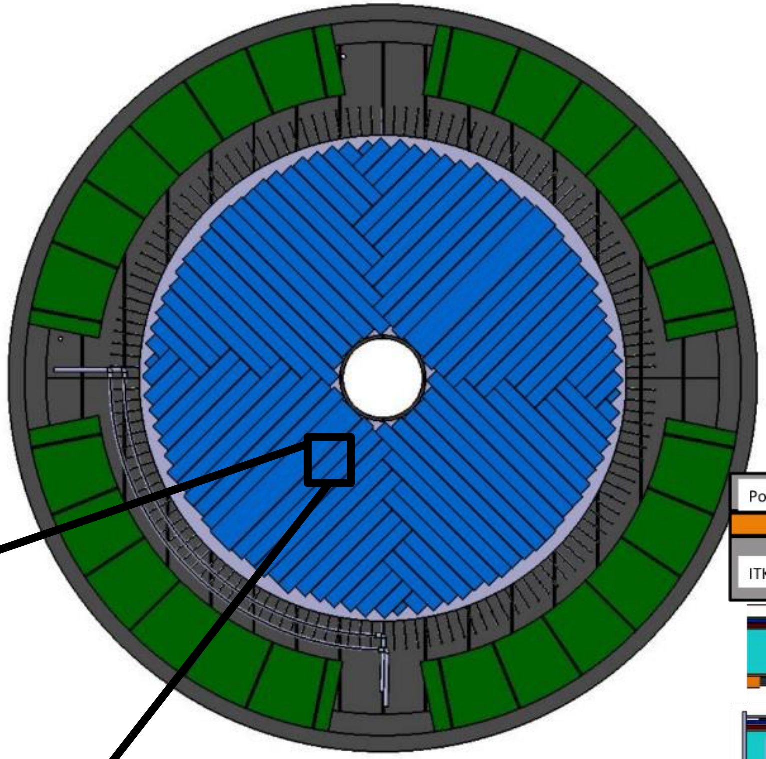
Sensor Material: **Si** - radiation hard, compact, sufficient time resolution, 1.3x1.3mm^2 granularity achievable



Sensors **bump-bonded** to 225 channel ASICs (1x1cm^2)

Modules: 2x4cm^2 (2 ASICs)



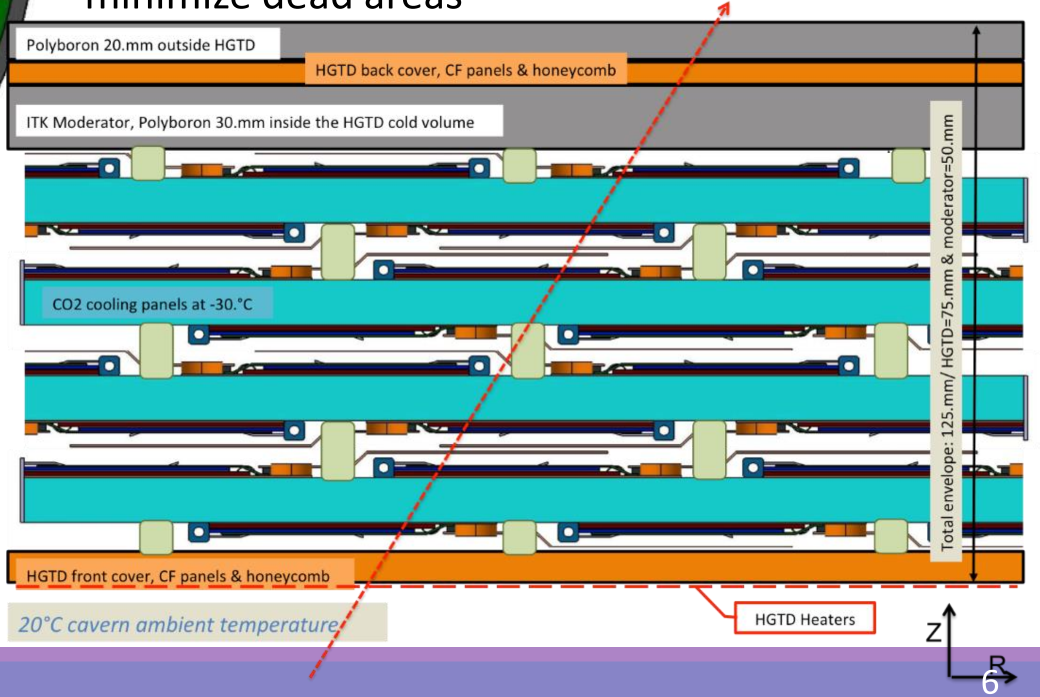


Blue: Active Area (120-640mm)

Green: Off-detector electronics

Gray: Moderator + support

Modules placed on top of kapton flex staves in both sides of cooling plate with small overlap to minimize dead areas



Sensor Technology: Low Gain Avalanche Detectors

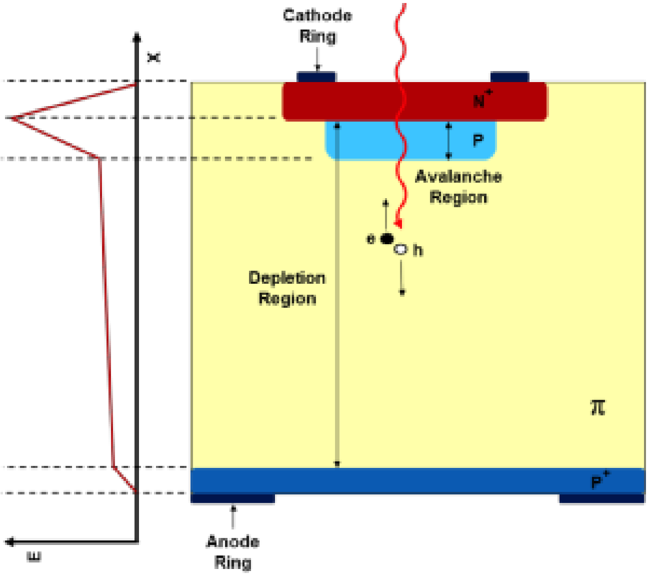
LGAD: n-on-p Si detector with extra doped p-layer:

- The doped layer causes internal amplification → x20 gain
- Increases S/N w.r.t external amplifiers

$$\sigma_{det}^2 = \sigma_{Landau}^2 + \sigma_{Elec}^2$$

Sensor dimensions that optimize the time resolution:

- **Thin sensors** (50µm) → higher slew rate and minimum Landau contributions
- **Small area** → minimizes the detector capacitance



Manufacturers: CNM , FBK and HPK

Sensors produced in single pads and arrays

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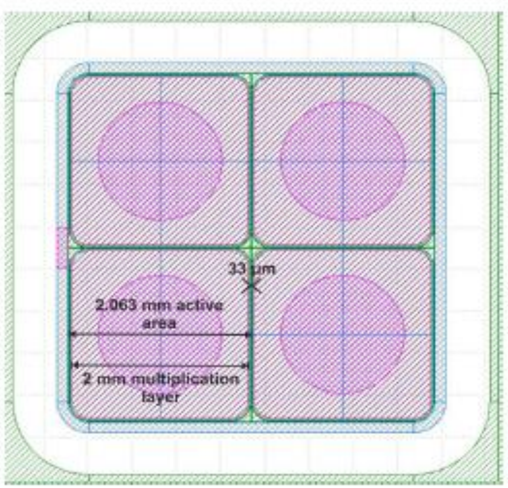
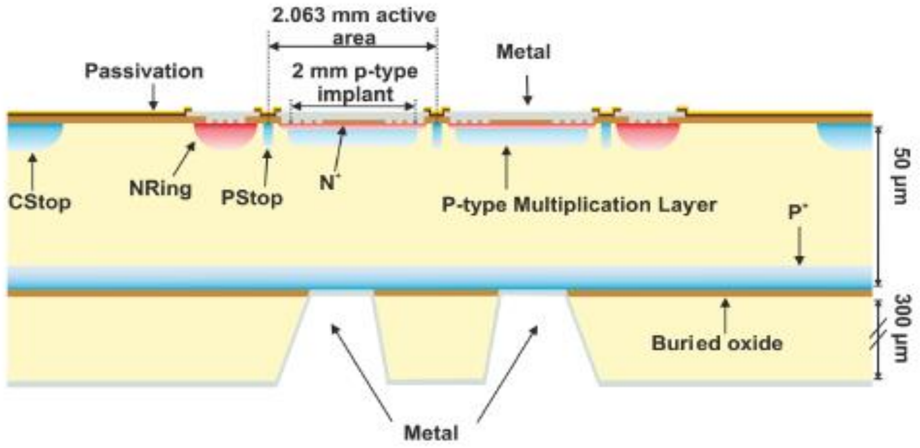
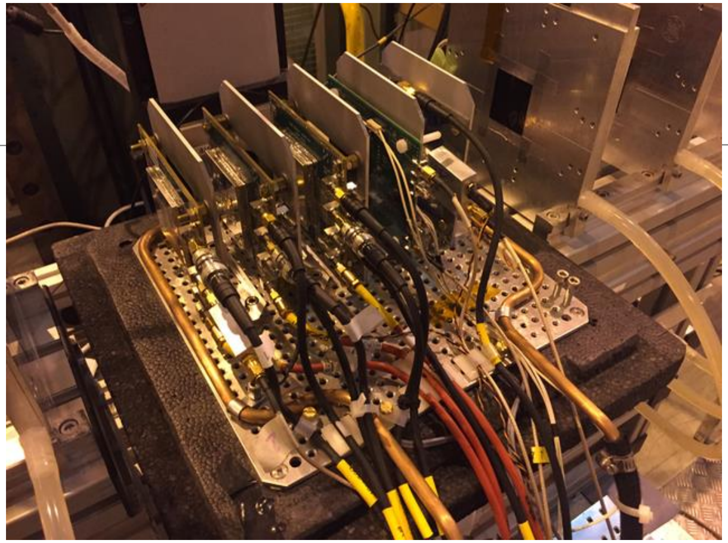
2x2 Array





Sensor Testing

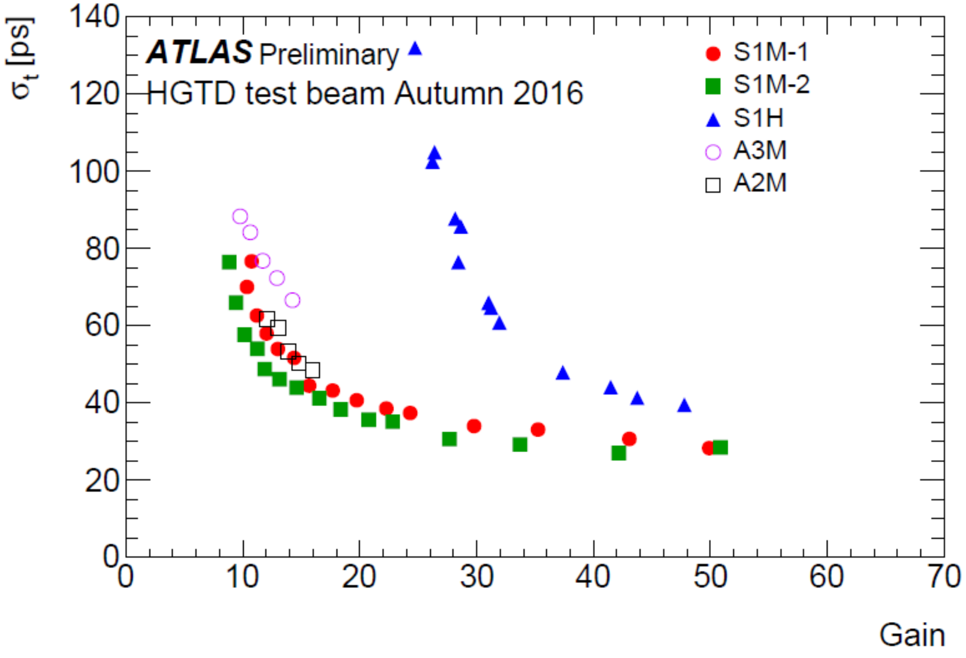
- Sensor characterization in lab probe stations (laser, β-source measurements)
- **Testbeam** measurements to estimate performance in more realistic conditions
  - August/October/November 2016 and June/July/August/September 2017 @ Cern, lines H6A and H6B of SPS with **120GeV pions**

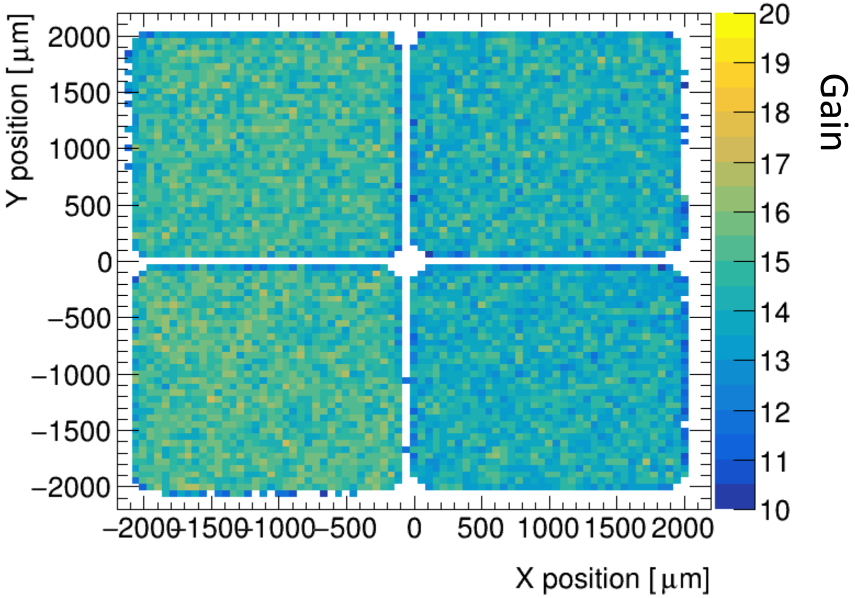


Testbeam setup at Cern, line H6A, November 2016

Results Before Irradiation:

- **Gain** = Charge in LGAD / Charge in p-n diode without amplification layer
  - increases as a function of Vbias and for lower T
- **Time resolution** reaches a 25ps plateau for gain>20
  - Operation at **g=20** meets the timing requirements





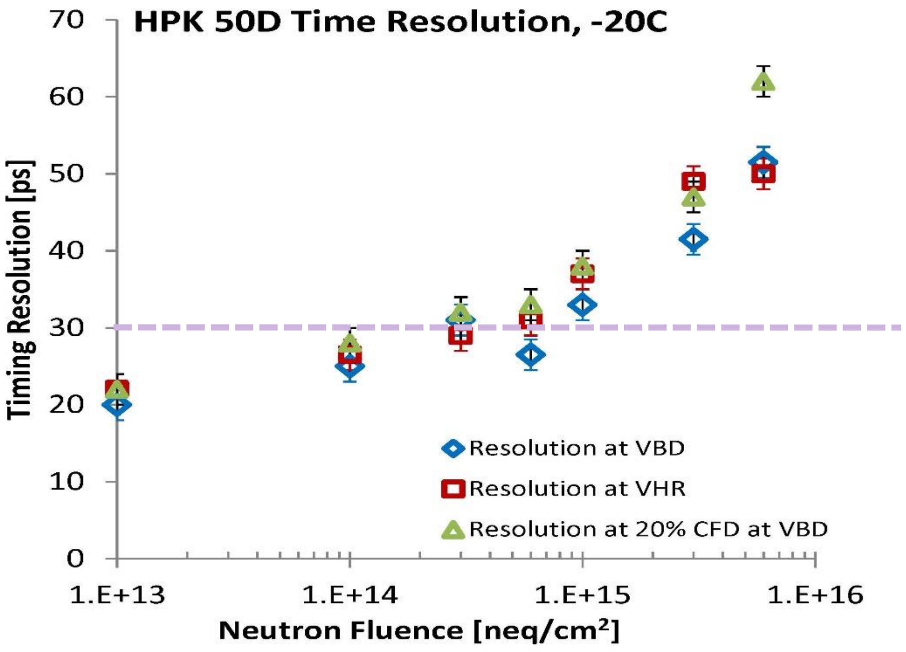
Position specific testbeam measurements show gain **fairly uniform**!

Sensor Performance After Irradiation

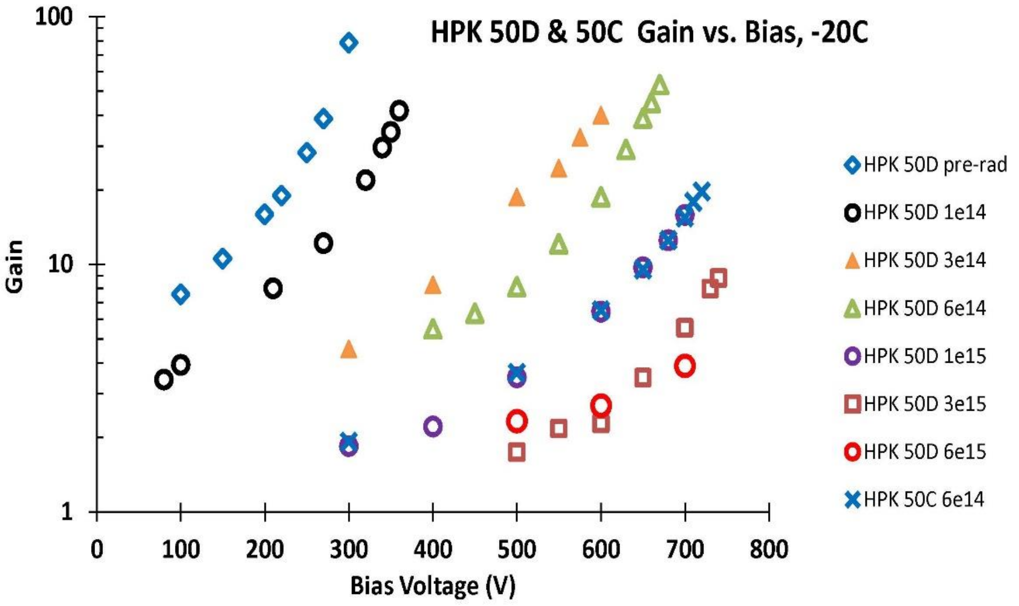
Sensors were irradiated by neutrons at the JSI research reactor in Ljubljana up to $6x10^{15}$ n_{eq} /cm^2 fluence

- **Reduction of gain** because dopants are removed → need to **operate at higher V_{bias}**
- Increase of **leakage current** → need to operate at T=-20-30 C
- electrically active defects in the bulk → high fields in the bulk

Time resolution worsened due to the loss of gain



Sensors irradiated up to various fluences –higher V_{bias} needed



HGTD Front End Electronics

Convert the LGAD **signal** into a **time measurement** integrated into the 225 channel - 1x1cm[2] ALTIROC ASIC.

Each channel of the ASIC contains:

- **Preamplifier** that shapes the LGAD signal
- **Discriminator** for a **TOT** (=**T**ime **O**ver **T**hreshold - pulse width above threshold)
- **Time-to-Digital Converter (TDC):** digitization of the TOA and TOT measurement
- **Local FIFO memory :** stores information until trigger signal

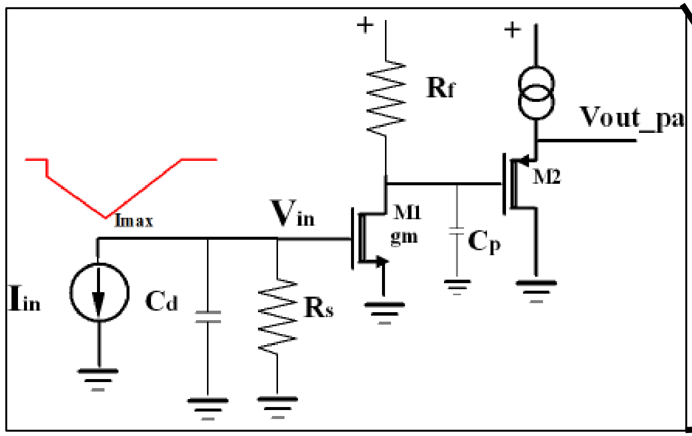
Contributions of the electronics to the time resolution:

$$\sigma^2_{elec} = \sigma^2_{TimeWalk} + \sigma^2_{jitter} + \sigma^2_{TDC}$$

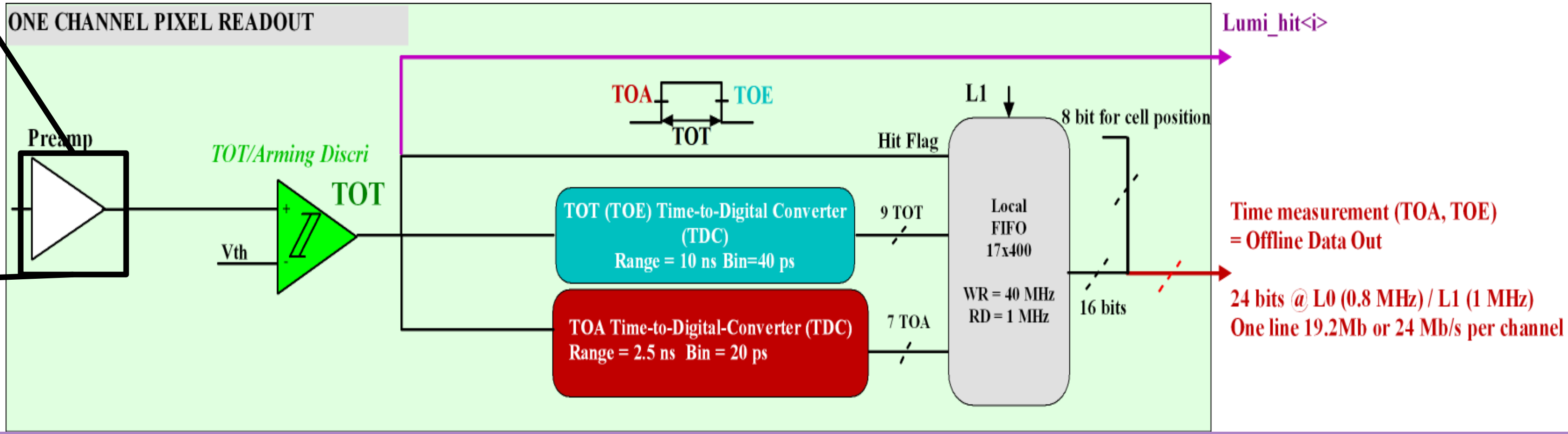
•**TimeWalk:** large signals cross threshold faster than small ones biasing the time measurement → can be corrected with a TOT measurement (offline) Expecting **<10ps** contribution.

•**Jitter:** Noise contribution to the signal – $\sigma_{jitter} = N/(\frac{dV}{dt})$. Minimized for high slew rate and small detector capacitance.

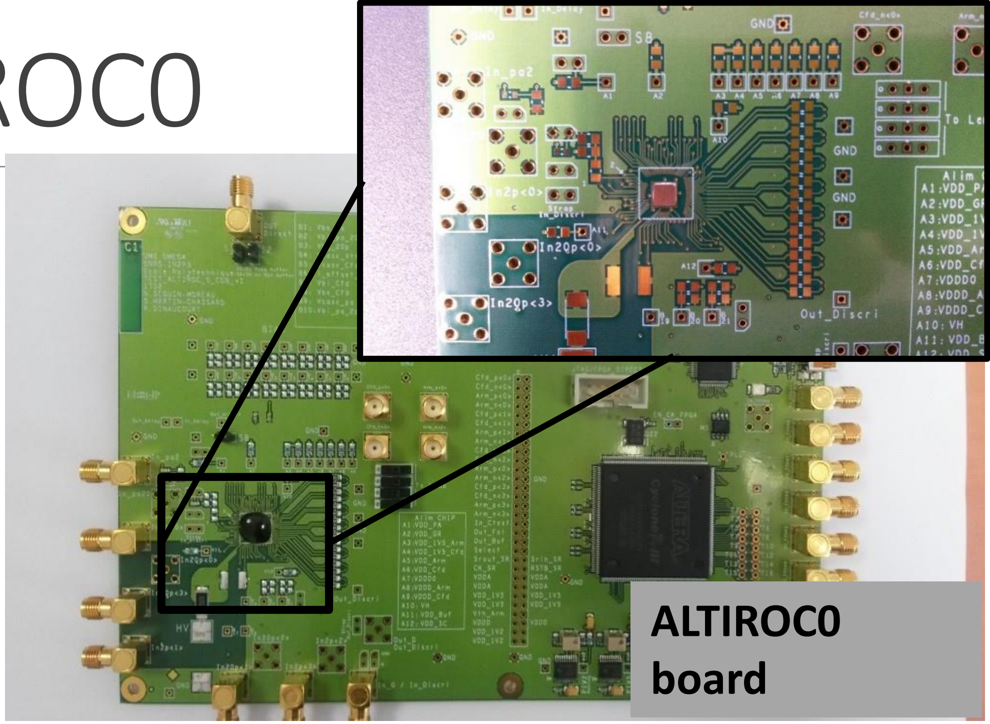
• **TDC** error due to the TDC binning = 20ps . $\sigma_{TDC} = 20ps/\sqrt{12}$



Preamplifier scheme. The sensor can be viewed as a current source with a parallel capacitance (Cd=3.4pF for 50µm 1.3x1.3 LGADs)



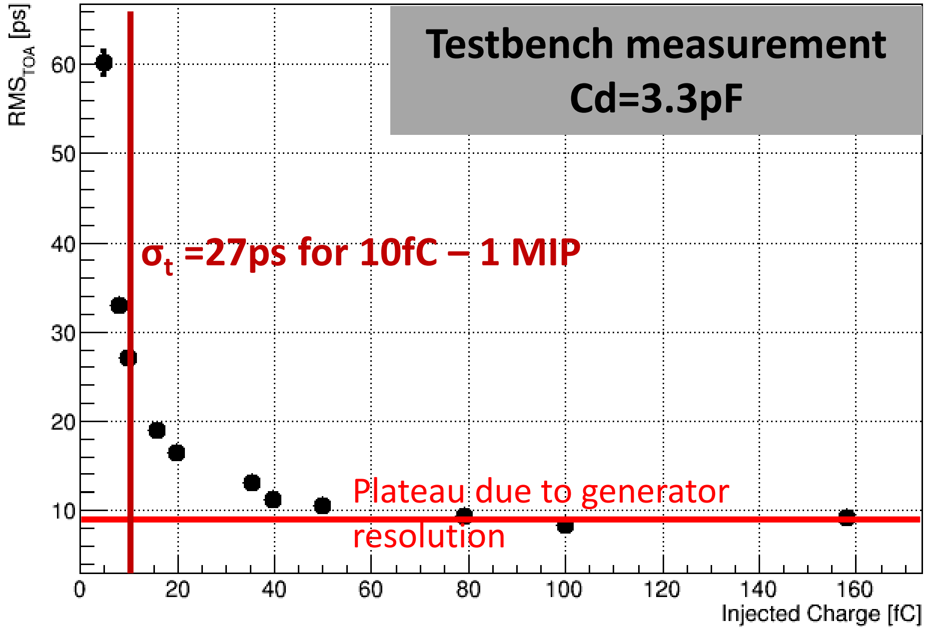
First Measurements with the ALTIROC0

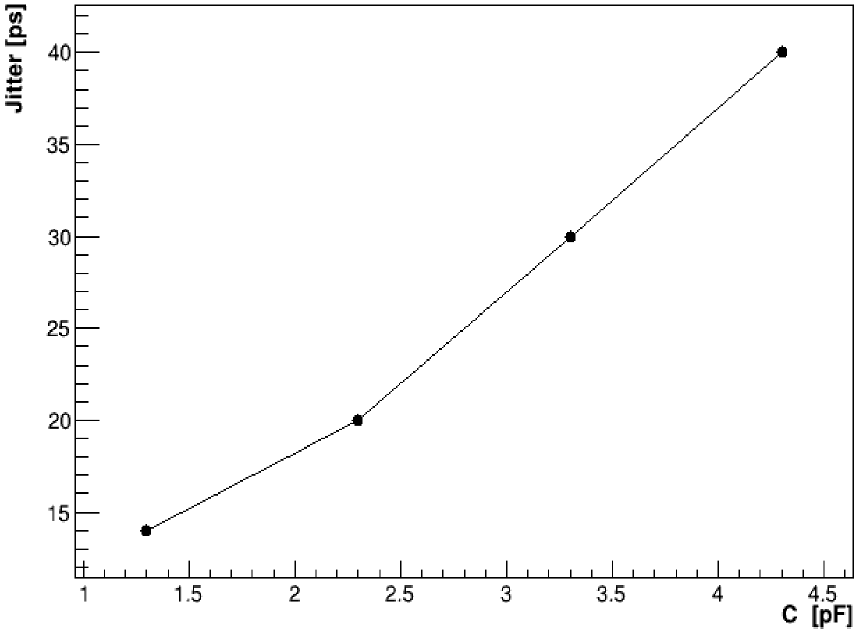


ALTIROC-0 prototype was designed by Omega – 7 boards received in March 2017

- 8 Channel chip with preamplifier + TOT
- No TDC → test analog characteristics

Prototype tested ***@Omega Testbench*** using a ps generator, without sensors





Time resolution increases as a function of the detector capacitance:

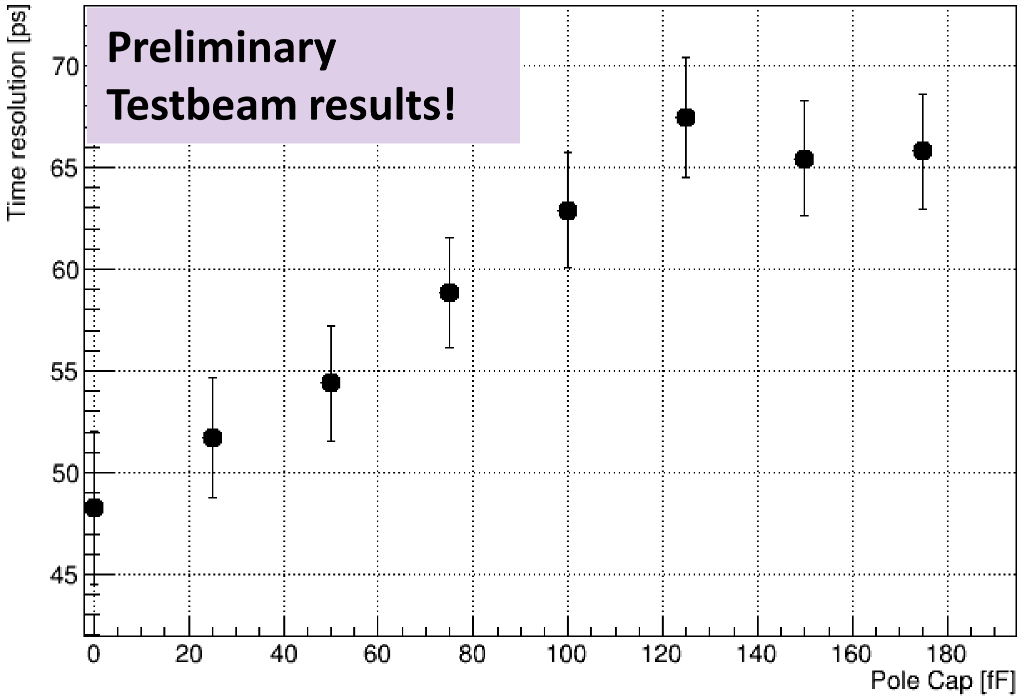
- Small area LGADs favored ($1x1mm^2$ → 2pF capacitance)
- Capacitance in measurement = C_{det} + **1.3pF parasitic capacitance** (due to the board)

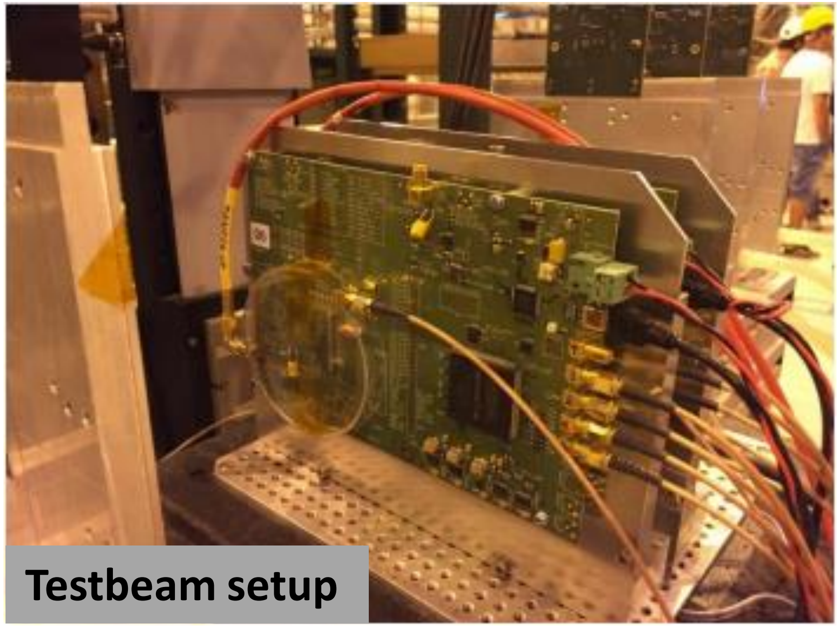
First Measurements with the ALTIROC0

Prototype also tested ***@Cern Testbeam line H6B – September 2017*** with a 2x2 un-irradiated bump-bonded sensor array.

Time resolution as a function of the preamplifier pole capacitance:

- Pole capacitance=adjusts the preamplifier rise time
- Best time resolution achieved for C_p =0 → **48ps**
- Testbeam results show ***preamplifier slower than expected***





Testbeam setup

Conclusions

- The HGTD is a timing detector that can significantly improve the reconstruction of all physics objects and the selection of events of interest by **mitigating pile-up interactions**

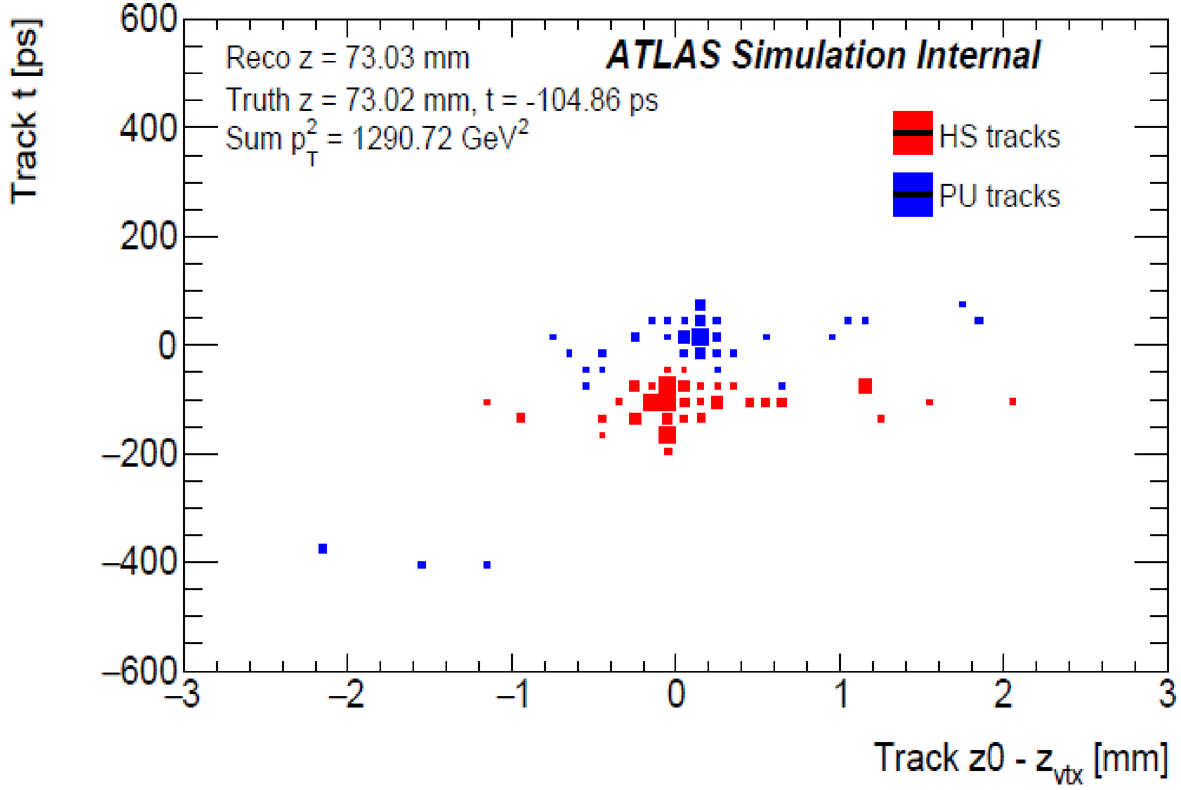
- Its requirements to be radiation hard, compact and highly granular are well met with **Si sensors**, while the **LGAD technology** meets the time resolution requirements
  - Sensor tests have proven that **a <30ps time resolution** can be achieved **pre-radiation**

- First prototype of the electronics ASIC, **ALTIROC0** has been fabricated, integrating only 8 channels with the analog parts of the electronic design:
  - So far, tests of the preamplifier and TOT, with pulse generator @ testbench and bump-bonded sensors @ testbeam
  - Next iteration: improved preamplifier, include TDC and local FIFO memory

Results preliminary but very promising – 30ps time resolution achievable!

Backup Slides

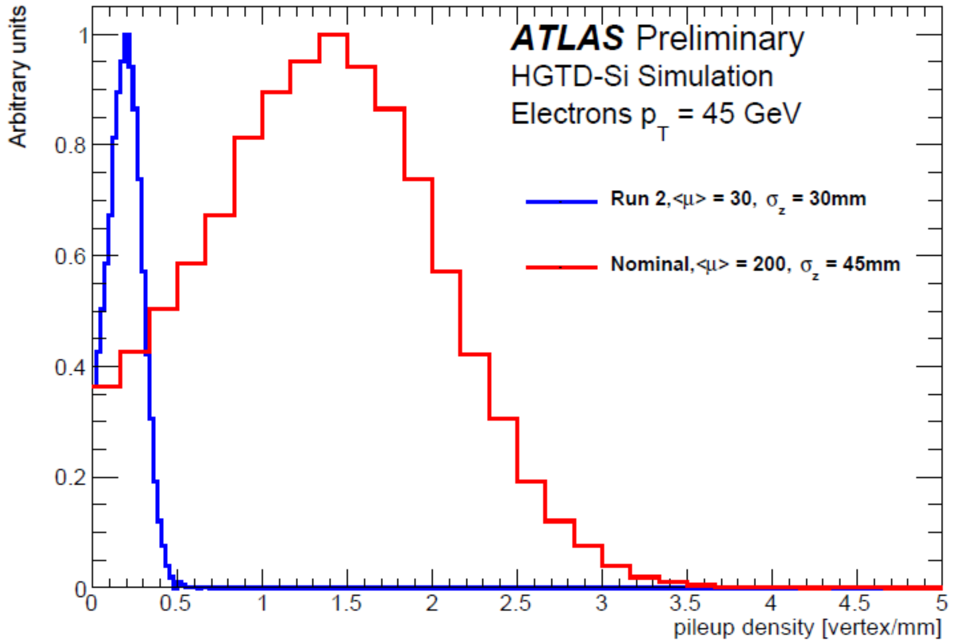
Motivation for a High Granularity Timing Detector



p_T weighted 2D distribution of the time and z position of tracks from a VBF Higgs to invisible event with on average additional 200 pileup interactions

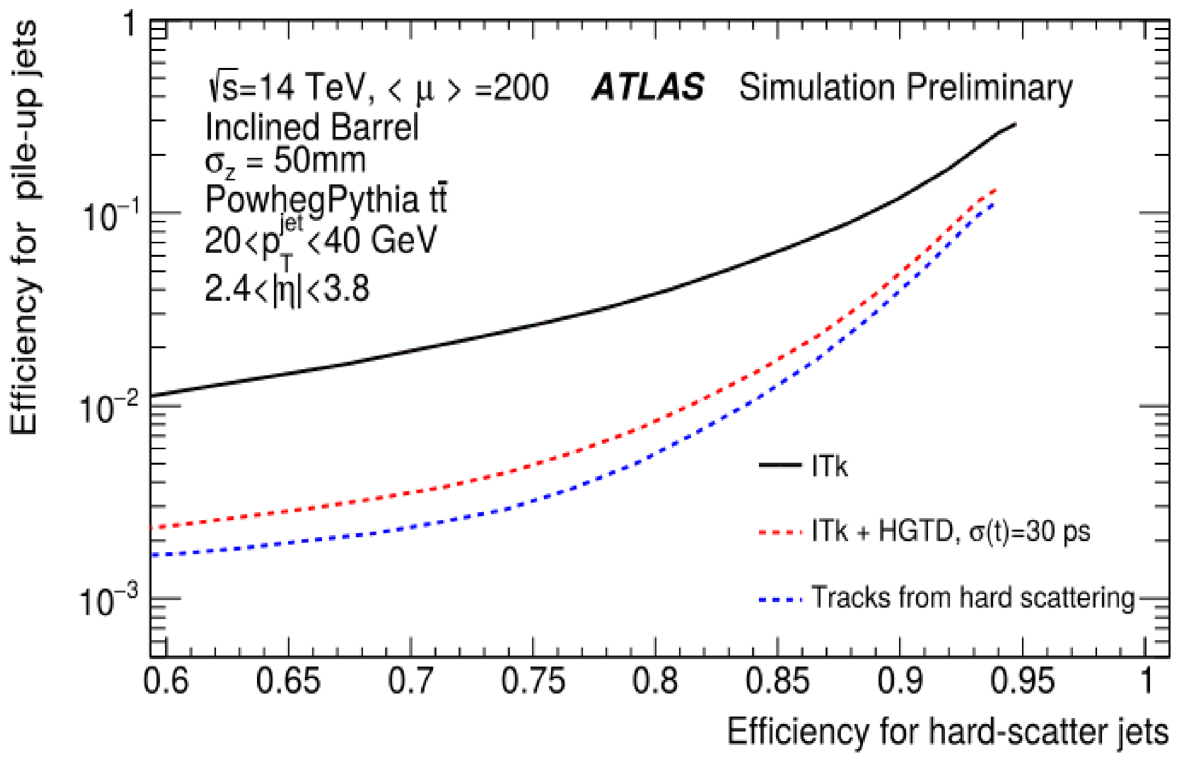
Merged tracks in z can be disentangled using time information!

HL-LHC: Average density =1.6 vertices/mm BUT long tails → density can reach up to 3.5 vertices/mm



Local pile-up vertex density comparison between Run 2 and HL-LHC. The density is calculated as the number of truth vertices in a +- 3mm range around the signal vertex.

Motivation for a High Granularity Timing Detector



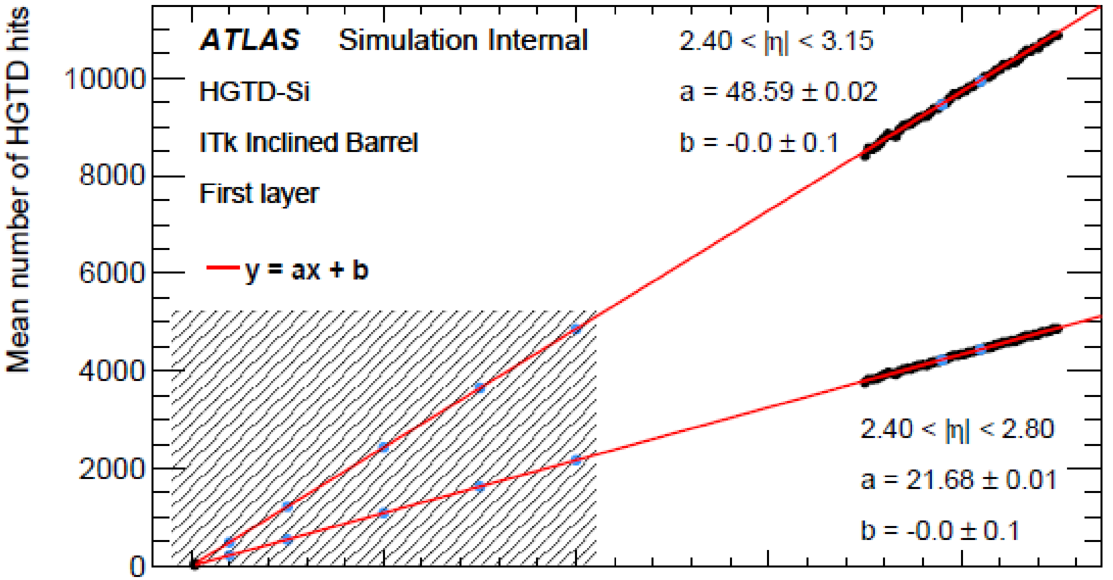
Efficiency for PU jets as a function of HS jet efficiency for HS jets with $20<p_T^{jet}<40$GeV. R_{pT} jet variable to distinguish between PU and HS jets.

The selection efficiency for jets improves by using track time selection provided by a 30ps resolution HGTD!

$$R_{pT} = \frac{\sum_k p_T^{trck}(PV_0)}{p_T^{jet}}$$ ~ 0.5 for HS jets ,~0 for PU

Motivation for a High Granularity Timing Detector

- Time information is completely orthogonal to space information
  - Pile-up mitigation by rejecting out-of-time tracks
  - Improvements in: jet reconstruction, electron isolation, b-tagging and MET
  - Also in: Primary Vertex ID and track-to-vertex association!
  - HGTD can also be used as a **luminometer**:
    - Sampling n.of hits before triggers
    - High granularity→ good linearity between n. of hits and n. of interactions
    - Time information before and after nominal interaction can help study ***afterglow***



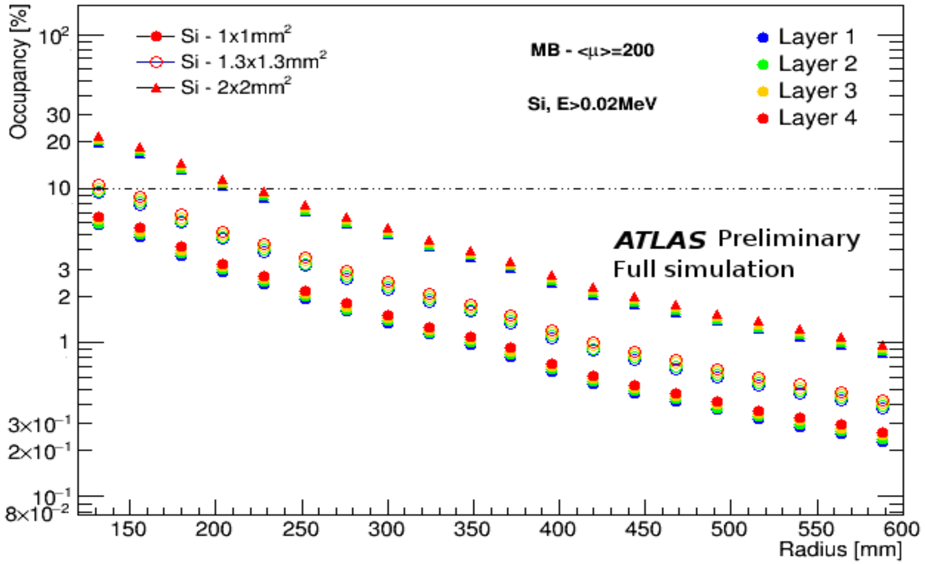
N. of interactions

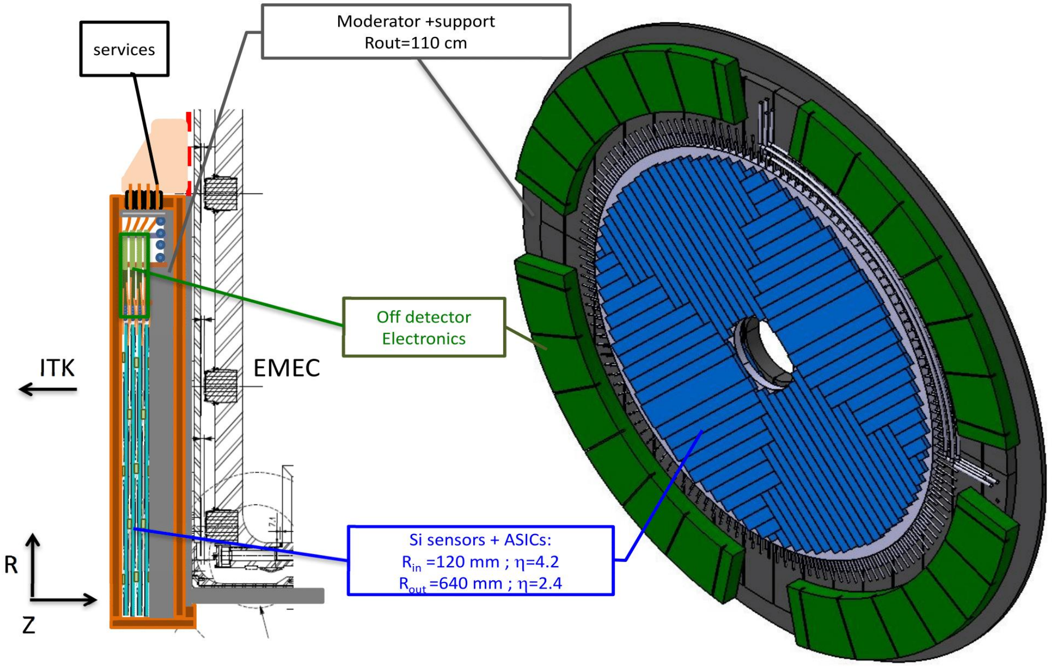
Detector Overview

HGTD will be placed in the **forward region**, between the **Inner Tracker** and the end-cap **EM Calorimeter** and will include 4 Layers per side

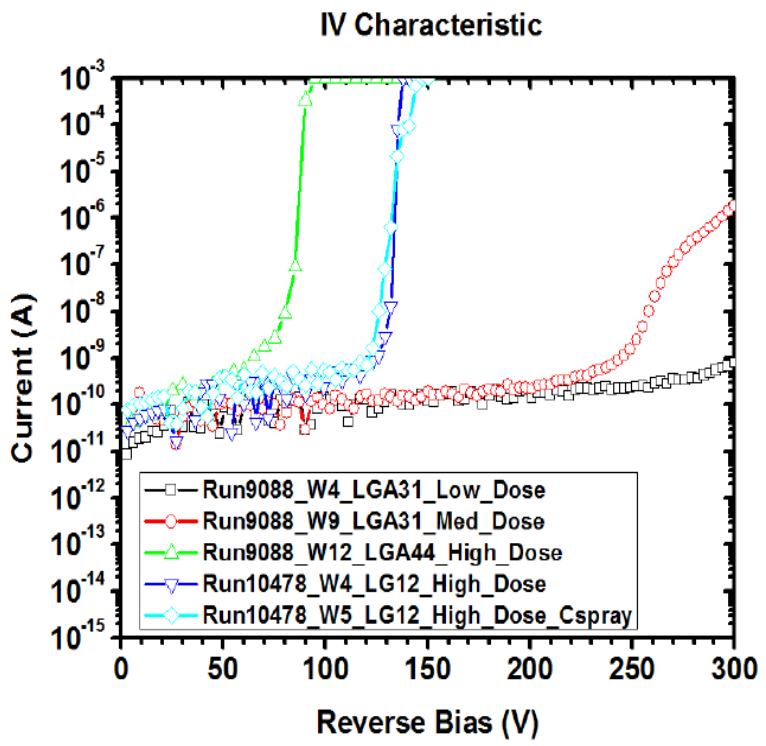
- Pseudorapidity coverage: $2.4<|\eta|<4.2$
- Radial extension: R=110-1100mm (120-640mm active area)
- Position in z: 3420<z<3545mm (50mm of moderator + Δz=75mm HGTD)
- Time resolution: **30ps/mip (60ps/mip/layer)**
- Granularity (<10% Occu): 1.3x1.3mm^2

Occupancy as a function of the radius for 1x1, 1.3x1.3 and 2x2mm^2 sensors – inner radius with the highest particle rate

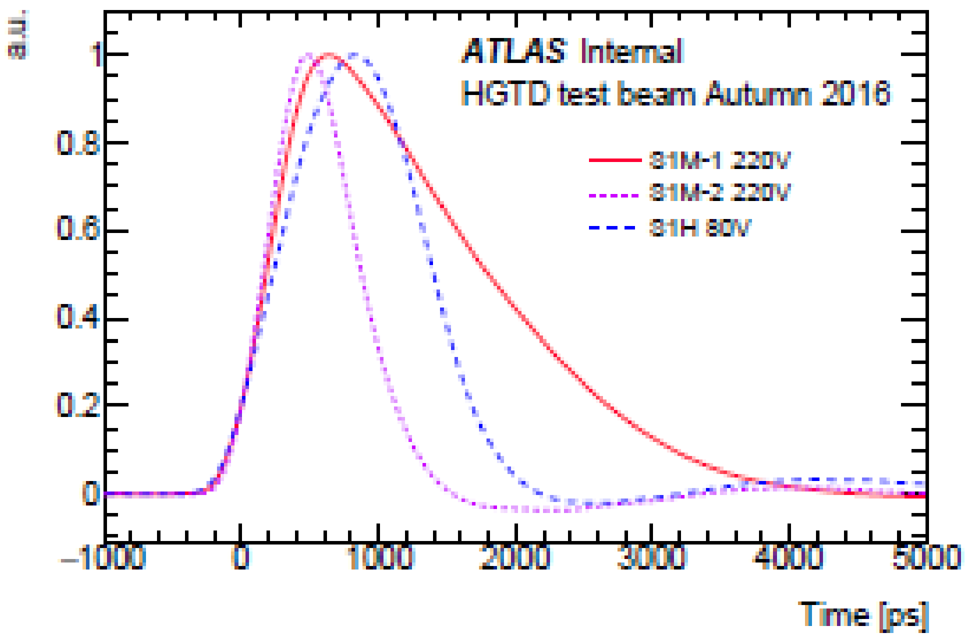




Sensor Testing

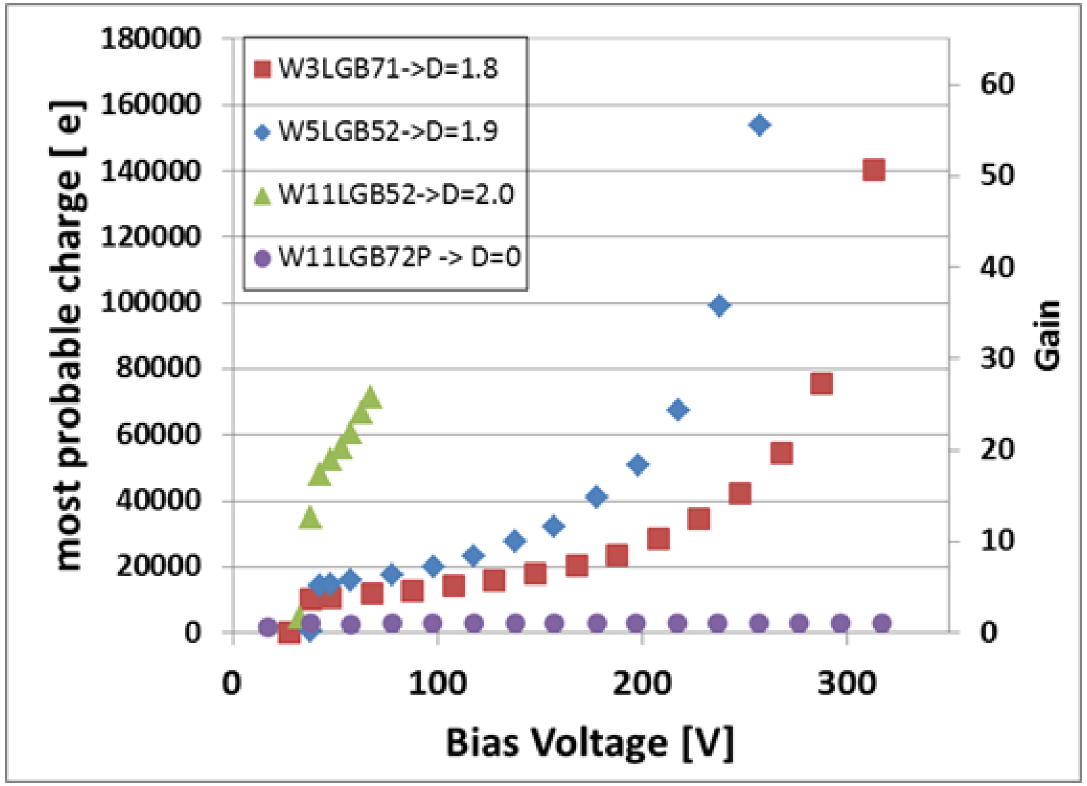


I-V curves of un-irradiated sensors with different doping dose. Sensors with high dose exhibit lower breakdown Voltage due to higher internal field

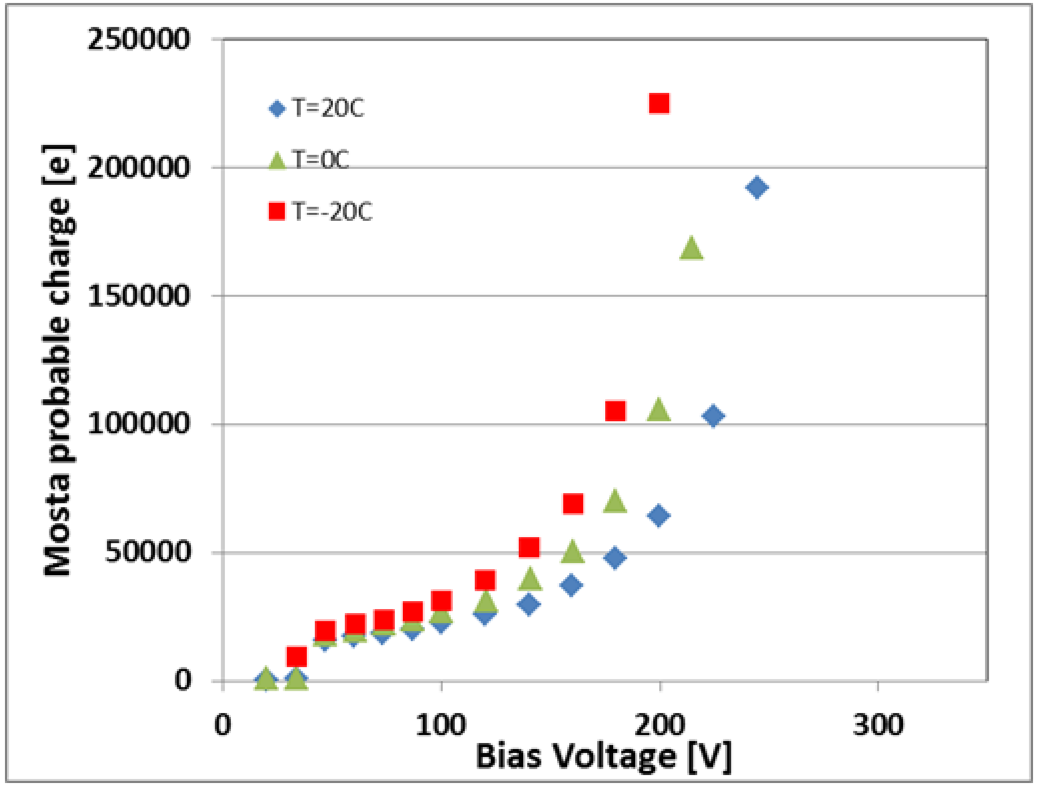


Average single-pad un-irradiated sensors with different doping doses and preamplifiers

Sensor Testing

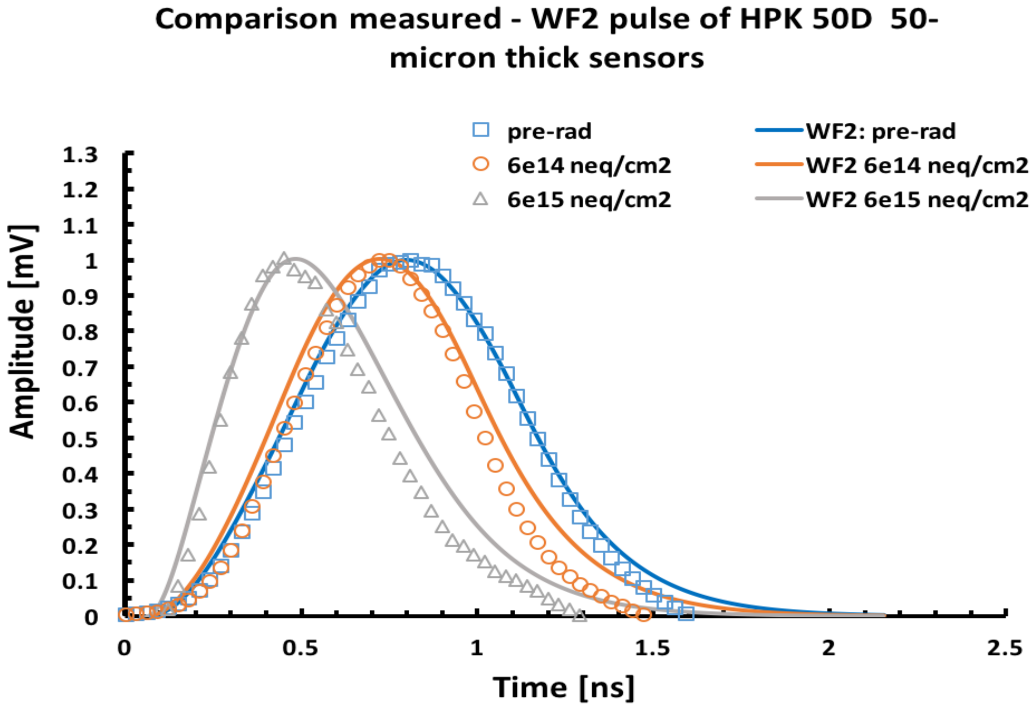


Gain increases as a function of V_{bias} and doping concentration.



Gain increases for lower temperatures due to higher impact ionisation

Sensors After Irradiation



At high fluence, part of multiplication happens at the bulk of the LGAD, due to high fields induced by defects → **rise time decreases**

Electronics for the HGTD

Front End Electronics: convert the LGAD signal into a time measurement integrated into the 225 channel - 1x1cm^2 ALTIROC ASIC. Each channel of the ASIC contains:

- **2 Time-to-Digital Converters (TDC):** digitization of the TOT and CFD measurements. The TDC has 2 Vernier Lines, one 'slow' with a 135ps delay that receives the TOA and a 'fast' one with 115ps delay that receives the end of measurement window. The time needed for the fast signal to surpass the slow one corresponds to the time measurement with a bin of **135-115=20ps.**

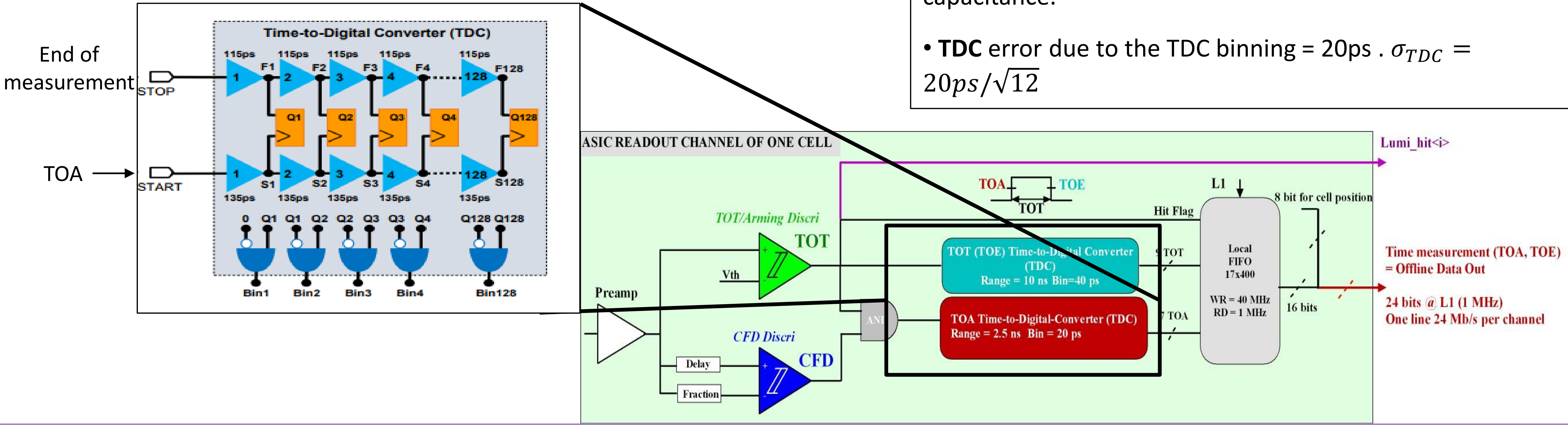
Contributions of the electronics to the time resolution:

$$\sigma_{elec}^2 = \sigma_{TimeWalk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2$$

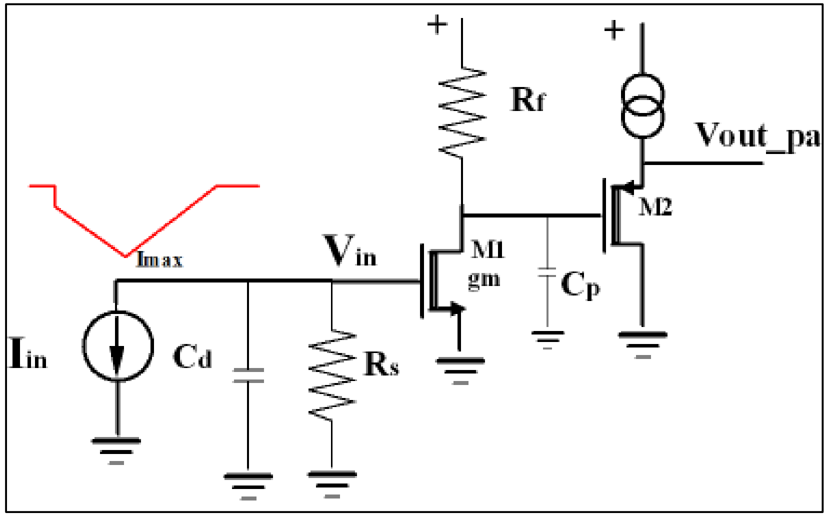
•**TimeWalk:** large signals cross threshold faster than small ones biasing the time measurement → can be corrected with (1) a TOT measurement (offline) or (2) a CFD (online) measurement. Expecting **<10ps** contribution.

•**Jitter:** Noise contribution to the signal – $\sigma_{jitter} = N/(\frac{dV}{dt})$. Minimized for high slew rate and small detector capacitance.

• **TDC** error due to the TDC binning = 20ps . $\sigma_{TDC} = 20ps/\sqrt{12}$



Preamplifier Speed



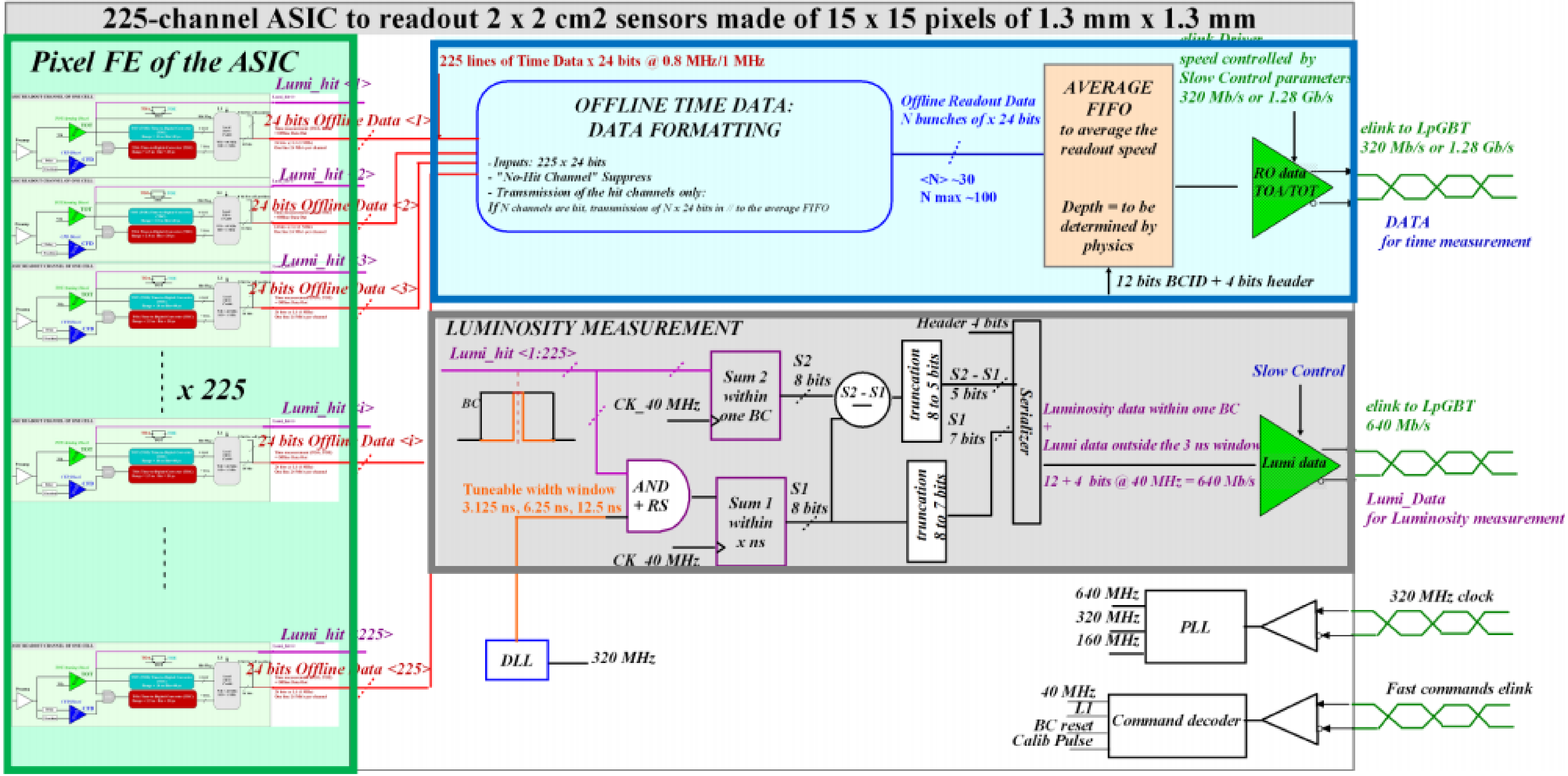
Jitter optimized when preamplifier rise time = LGAD drift time

$$\sigma_t^J = \frac{N}{\frac{dV}{dt}} = \frac{N}{\frac{S}{\sqrt{t_{r\_a}^2 + t_d^2}}} = \frac{\sqrt{t_{r\_a}^2 + t_d^2}}{\frac{S}{N}} = \alpha \frac{\sqrt{t_{r\_a}^2 + t_d^2}}{\sqrt{\frac{g_m}{4kT\Gamma}}\frac{Q_{in}}{C_d}\sqrt{t_{r\_a}}} = \alpha \frac{C_d}{Q_{in}}\sqrt{\frac{4kT\Gamma}{g_m}}\frac{\sqrt{t_{r\_a}^2 + t_d^2}}{\sqrt{t_{r\_a}}}$$

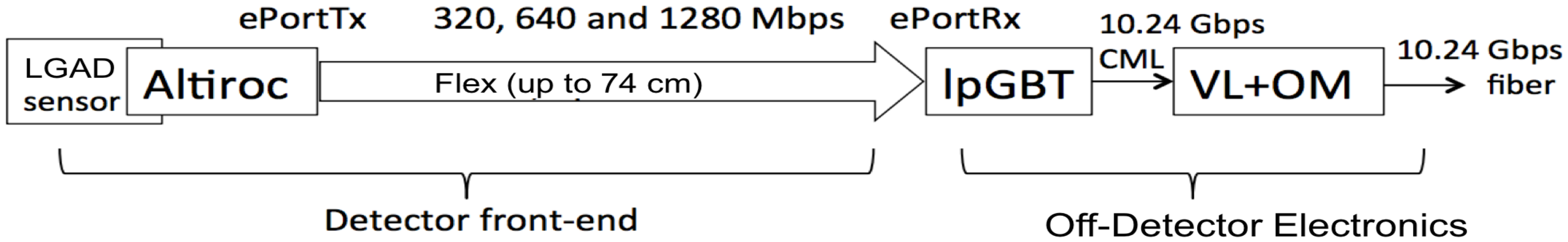
Optimum value: $t_{r\_a} = t_d$

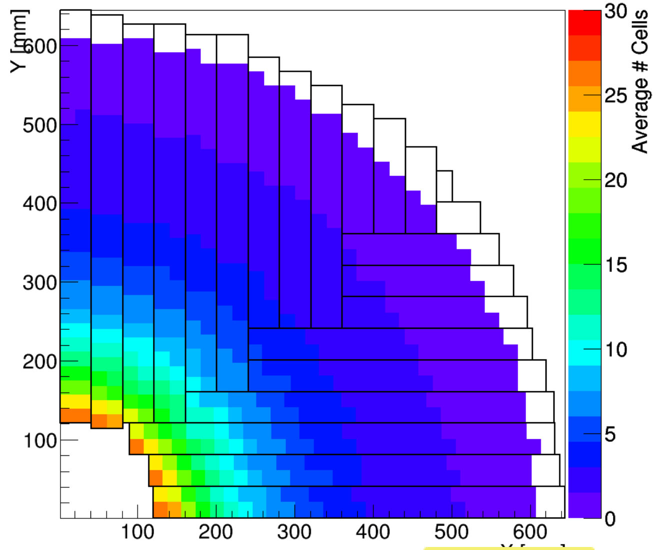
$$\sigma_t^J \approx \alpha \frac{C_d}{Q_{in}}\sqrt{\frac{4kT\Gamma}{g_m}}\sqrt{t_d}$$

225-Channel ASIC conceptual design

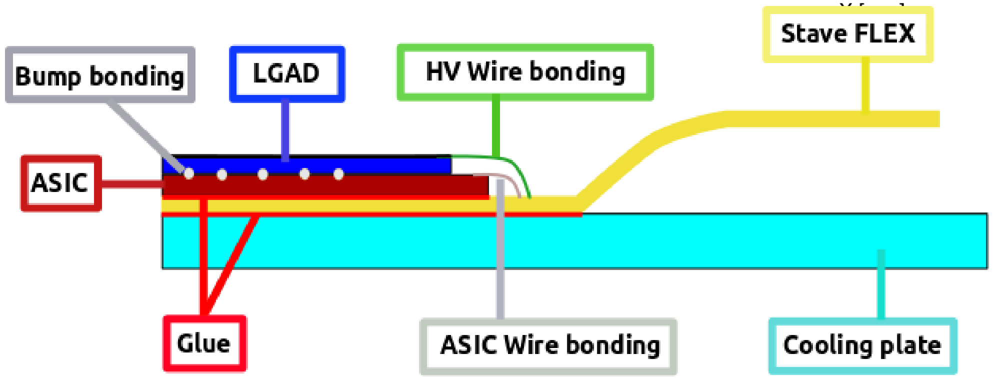


Data Transfer to Offline Electronics

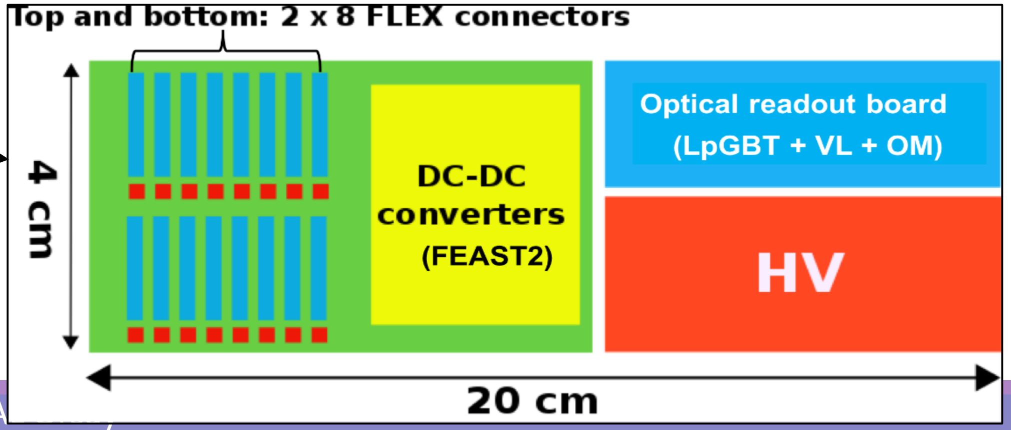




- Data is transferred from the Altiroc ASIC through a **Kapton Flex** along each stave:
  - Transfer with 320/640/1280Mbps e-links (depending on ASIC position)
  - Only channels with hits are transmitted to minimize the readout amount (and power consumption?)
    - Average n. of readout cells radius dependent ~**30 hits** for inner radius.
  - <Hitchannels> x 24 bits (7bits TOA, 9bits TOT, 8 bits pixel position)
  - FIFO memory averages the rates to "fit" in the LpGBT entries



- <u>**Off-detector Electronics**</u>: at the periphery of the detector containing
  - DC/DC converters
  - HV
  - LpGBTs that serialize the data in preparation for optical transmission
  - optical link transceivers/transmitters
  - *Research for the best design is starting*



Off-detector electronics possible design