# A High Granularity Timing Detector for the Phase-2 Upgrade of the ATLAS Calorimeter

***S. Grinstein*** on behalf of the **ATLAS** LAr-HGTD group

***The 11th International Conference on Position Sensitive Detectors (PSD11)***

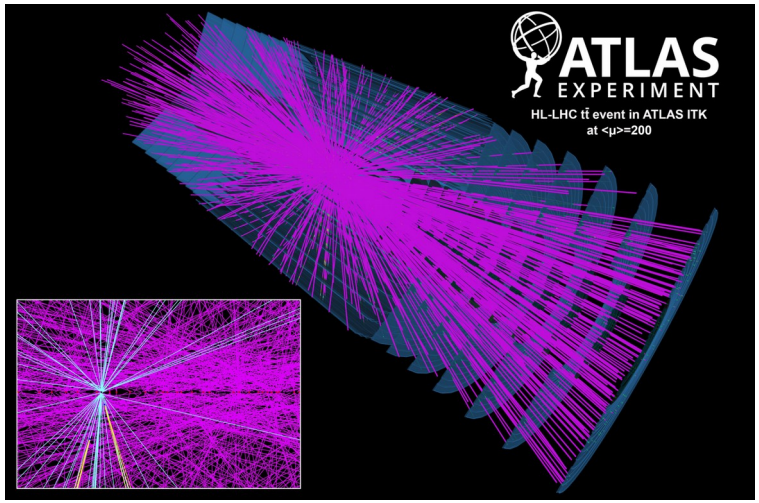
***3rd - 8th September 2017***

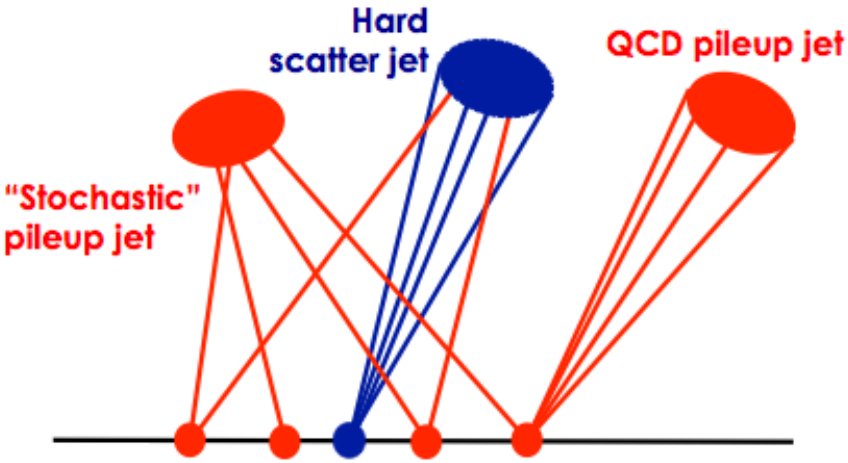
*The Open University*
*Milton Keynes (UK)*

# High Luminosity LHC

- LHC accelerator at CERN performing very well
- ATLAS very successful scientific output since first collisions in 2010
- To improve physics reach, the **LHC accelerator machine will be upgraded**
  - Foreseen for 2026, increase by 7-8 peak luminosity
- To maintain/improve physics performance, ATLAS detector will be upgraded
  - One of the main challenges of **HL-LHC** period will be **pile-up**

***Phase-2, High-Luminosity LHC:***
*14 TeV beams*
*Peak luminosity: 7.5E34 $cm^{-2}s^{-1}$ (x7)*
*Average pile-up: $<\mu> \sim 200$ (x8)*
*Integrated luminosity: 4000/fb (x13)*



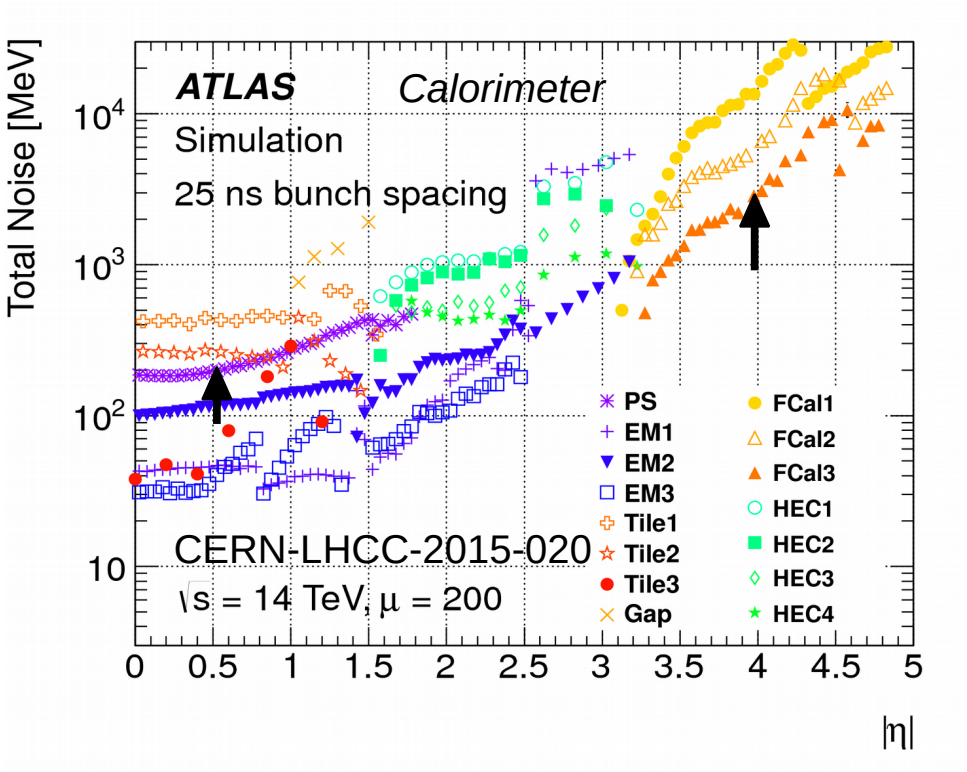



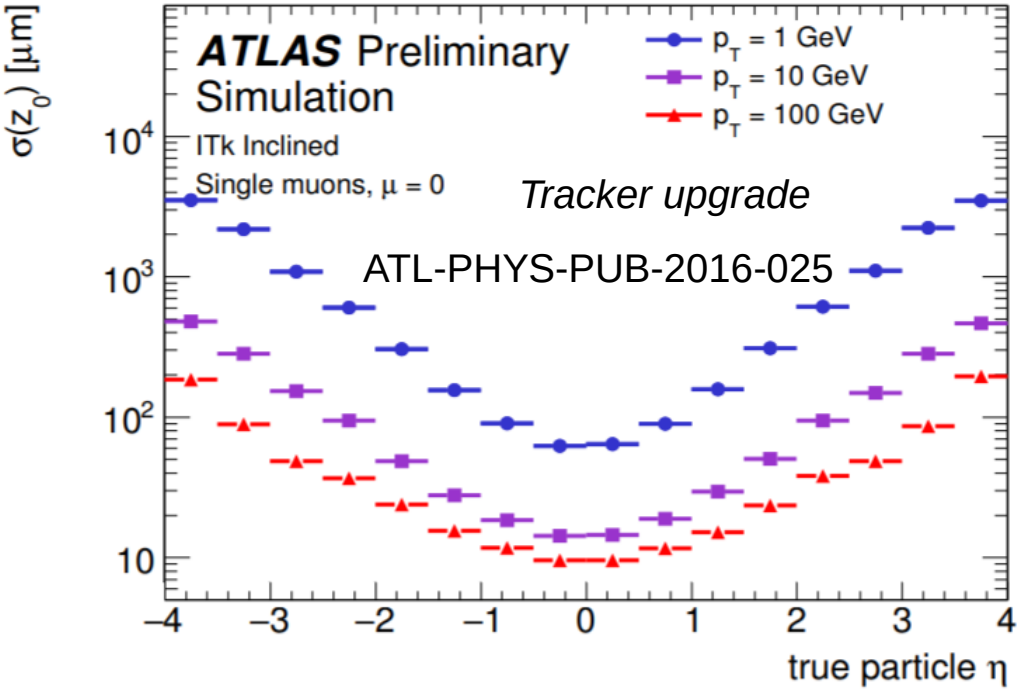

**Pile-up**: other pp collisions in addition to the one of interest

- Adds energy to reconstructed hard-scatter jets
- Produces pile-up jets

# ATLAS and High Luminosity LHC

Current ATLAS baseline upgrade plan not optimized for pile-up mitigation at high η



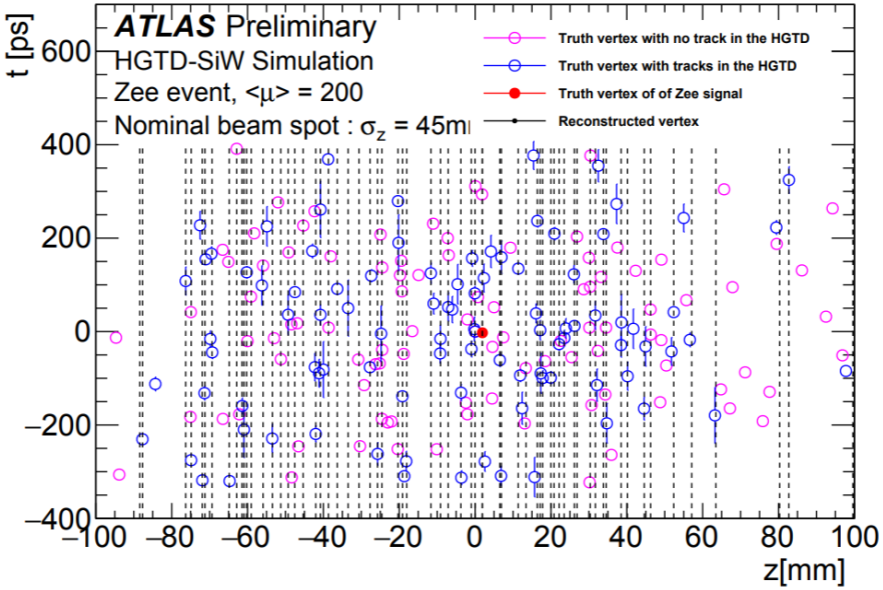

- **Calorimeter** noise will increase significantly in HL-LHC, impairing pile-up rejection specially at high η
- **Tracking detector** (ITk) upgrade will provide excellent position resolution, but in the very forward region, resolution only reaches a few mm

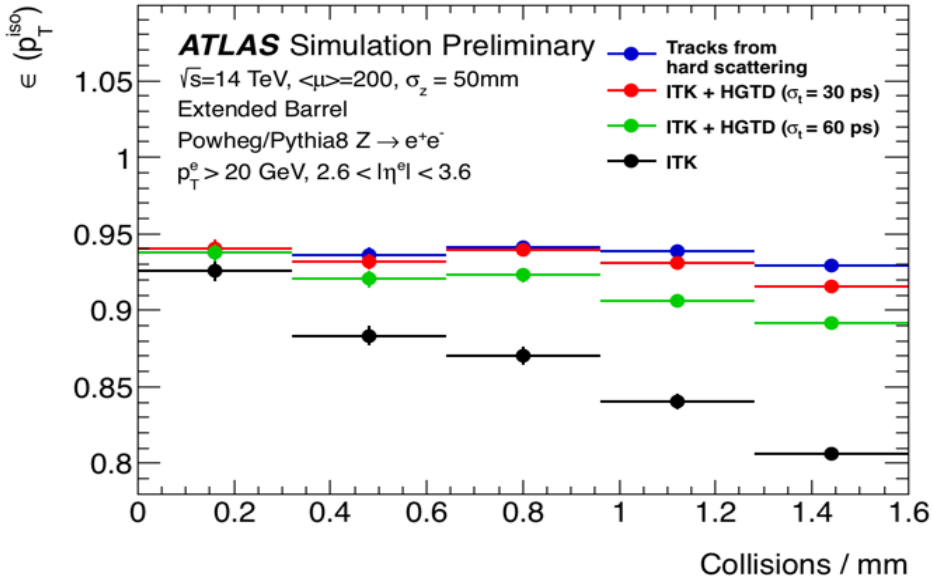
Explore improvements on pile-up rejection at high η

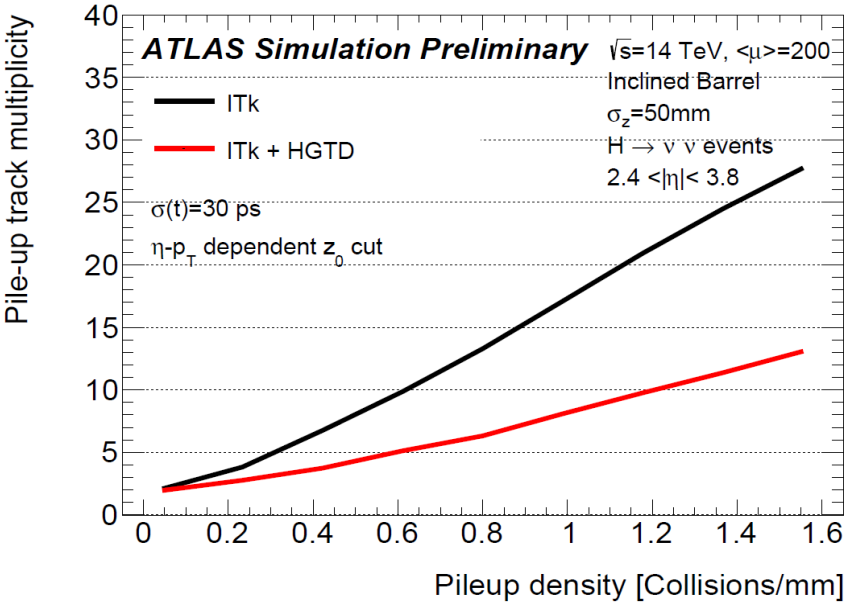
# HGTD Motivation

- **HL-LHC** interaction region at ATLAS will have a spread with RMS of 50 mm (nominal LHC mode)
- Corresponds to ~1.6 collisions/mm for μ=200 (x6 current LHC density)
- Collisions also spread in time with RMS of 180 ps

A **High Granularity Timing Detector (HGTD)** being considered to improve the assignment of tracks to vertices in the forward region, which impacts: electron ID, jet reconstruction, missing transverse energy and b-tagging



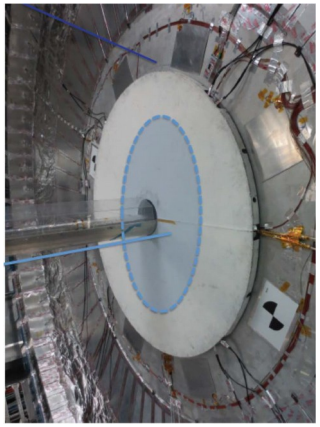



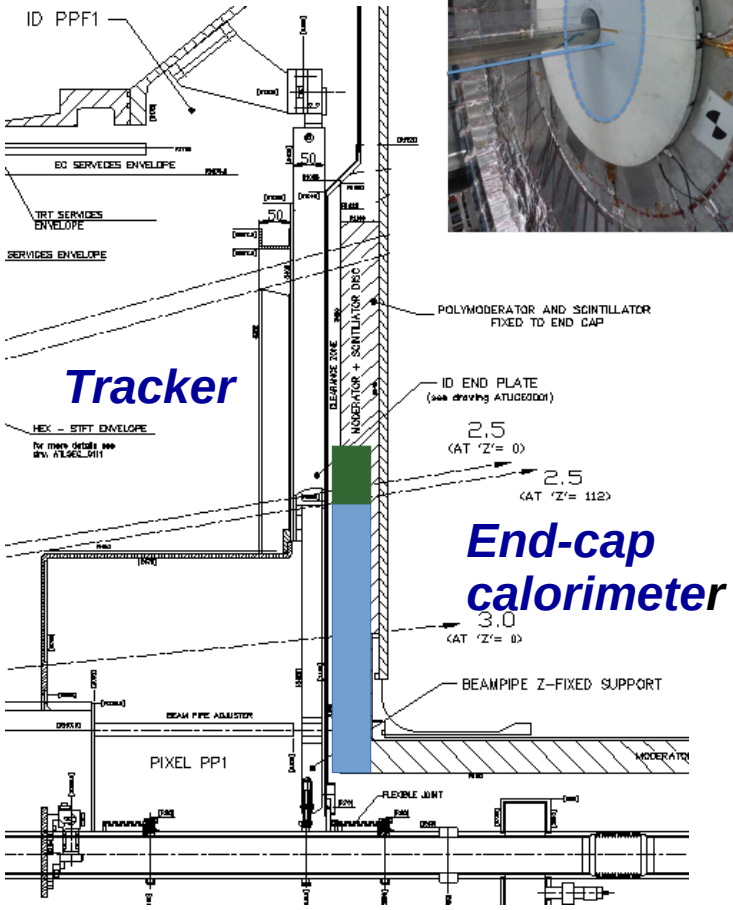

HGTD targets a time resolution of **30 ps** to recover current LHC pile-up conditions

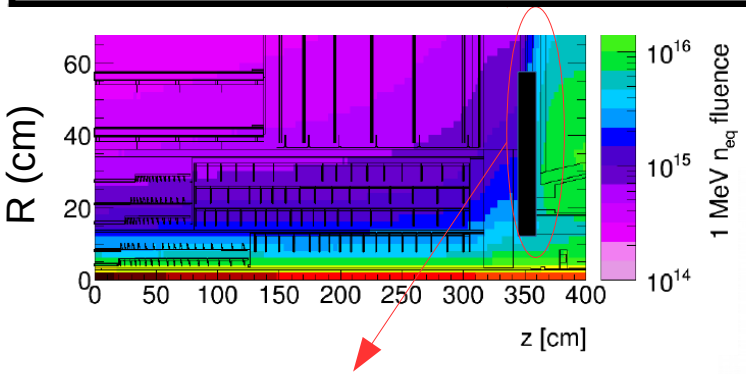
# HGTD Detector

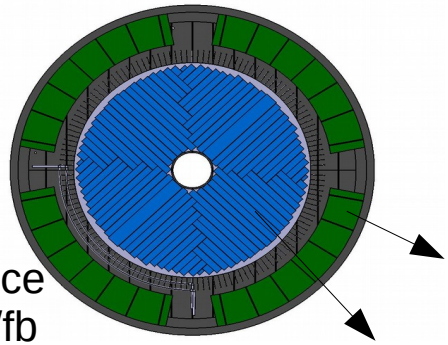
- **HGTD** would be **placed** in the forward region **between** the **tracker** and the **end-cap calorimeter**
- Tight z space: **Δz = 65 mm**

| | |
|---|---|
| **Pseudo-rapidity coverage** | 2.4 < \|eta\| < 4.2 @ z = 3.5 m |
| **Radial extension (active area)** | 110-1000 mm (120-640 mm) |
| **Time resolution** **(4 layers)** | 30 ps / mip (< 60 ps/mip/layer) |
| **Granularity (Occ < 10%)** | 1.3 mm x 1.3 mm |
| **Number of channels** | 6.3 M |
| **Total active area (Si)** | 11.16 m2 |



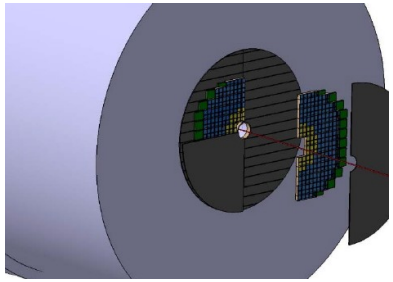


Off-detector electronics

Sensor area



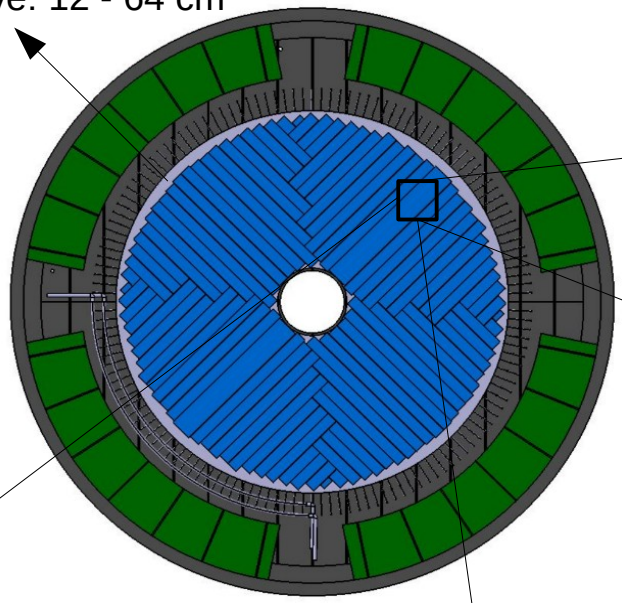
**Radiation requirements:**

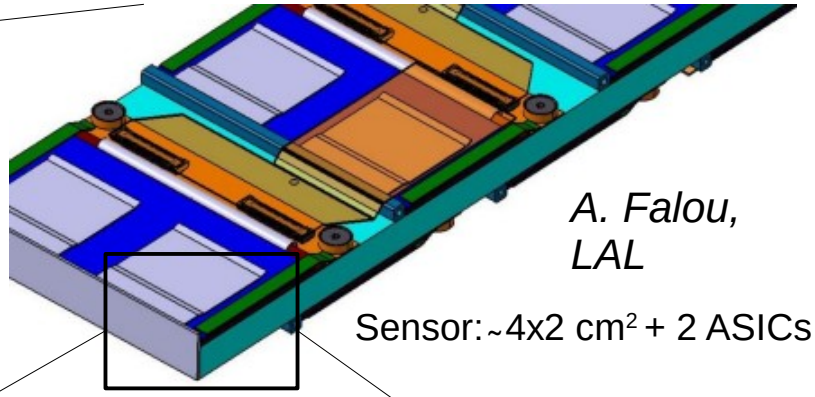
- For innermost sensors, expect a fluence of ~**4.5E15 $n_{eq}$/cm²** at 10 cm for 2000/fb
- Replacement of inner layer(s) at R<300 mm foreseen at the half time of the HL-HLC

# HGTD Detector

- HGTD requirements of **radiation hardness** and **compactness** well met with **silicon sensors**

Radius active: 12 - 64 cm

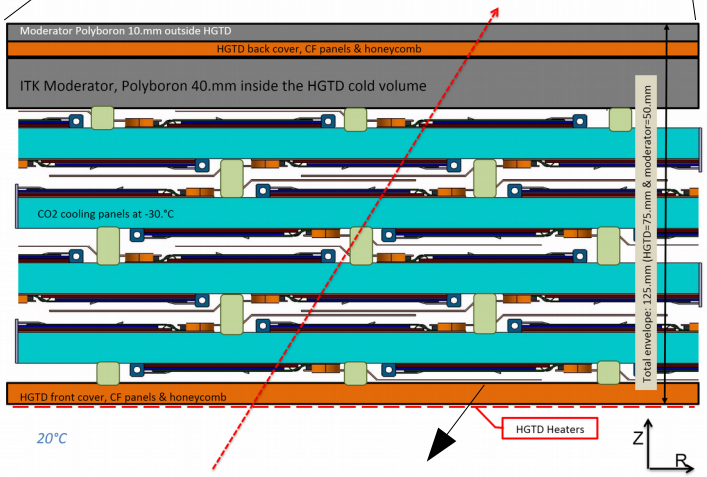




*A. Falou, LAL*

Sensor: ~4x2 cm$^2$ + 2 ASICs

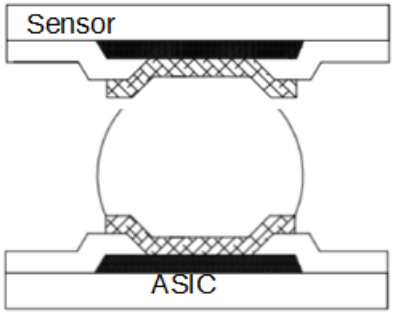
**Core of HGTD**: hybrid silicon sensors with 1.3 x 1.3 mm$^2$ pixels




Sensor

- 4 layers in about 7 cm
- 60 ps/mip/layer resolution

**Low gain avalanche detectors (LGAD)** to achieve target resolution



# HGTD Sensor Technology

- HGTD needs to achieve about 60 ps/mip/layer resolution: technology **beyond standard silicon** devices

Time resolution:

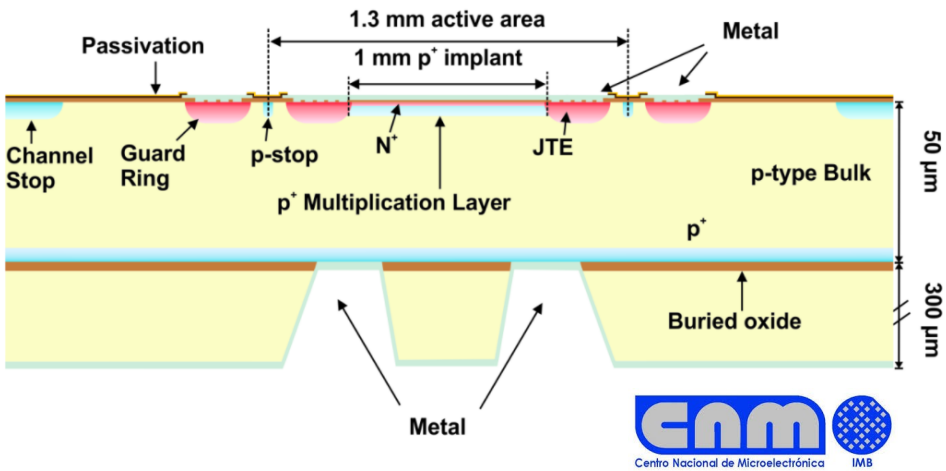
$$\sigma^2_{\text{det}} = \sigma^2_{\text{Landau}} + \sigma^2_{\text{elec}}$$

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

*Jitter* *Timewalk*

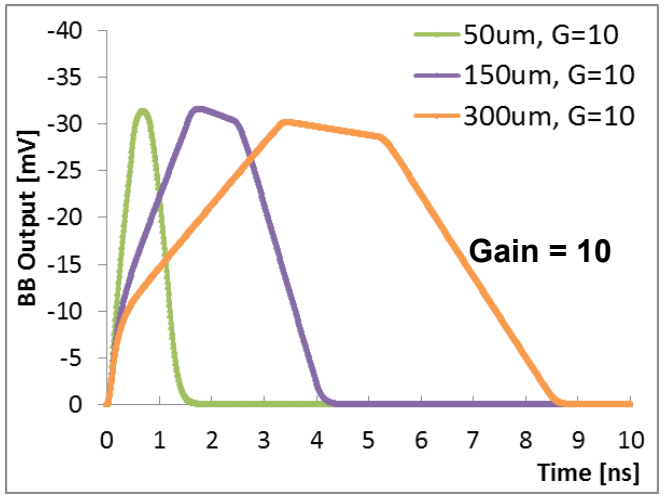
- Need fast and excellent S/N
  - A multiplication layer increases signal slope
  - Timewalk contribution negligible with CFD
- Thin sensors (50 µm) to reduce intrinsic Landau contribution to resolution

HGTD sensors based on thin LGAD technology




Low Gain Avalanche Detector (LGAD)

- Low gain (G=10-20): improve signal slope but control noise
- Developed at CNM (Barcelona) [1]
- Proposed for timing by UCSC/Torino [2]

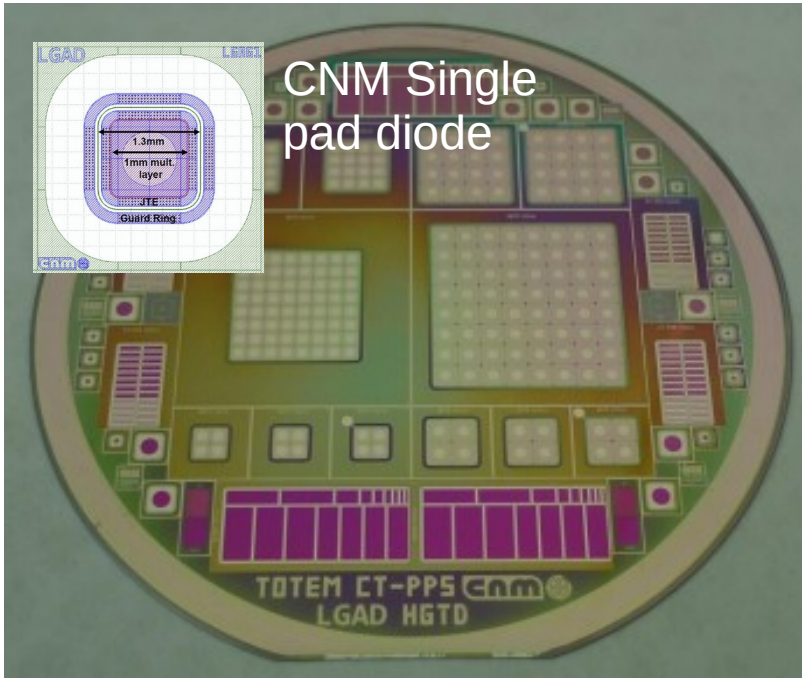



*Weightfield 2 Simulation [3]*


*[1] G. Pellegrini et al., NIM A765 (2014) 12*
*[2] H.-W. Sadrozinski et al., arXiv: 1704.08666*
*[3] F. Cenna et al, NIM A796 (2015) 149-153*

# HGTD Sensor Productions

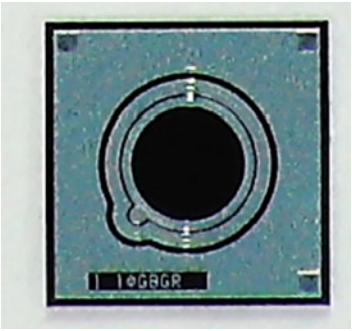
- Technology development and initial productions for R&D done at CNM (Barcelona)
  - Productions in collaboration with Totem (CMS) and RD50
- Now FBK (Italy) and HPK (Japan) also producing LGAD sensors




CNM Single pad diode

**First* CNM production**

- 4” SOI wafers
- 50 µm thickness on 300 µm support wafer
- Different implantation doses
- Various structures including:
  - Pad diodes of 1.3x1.3 $mm^2$
  - 2x2 arrays of 2x2 and 3x3 $mm^2$ pads
  - Larger structures for different applications



HPK 50um LGAD diode

**First HPK production**

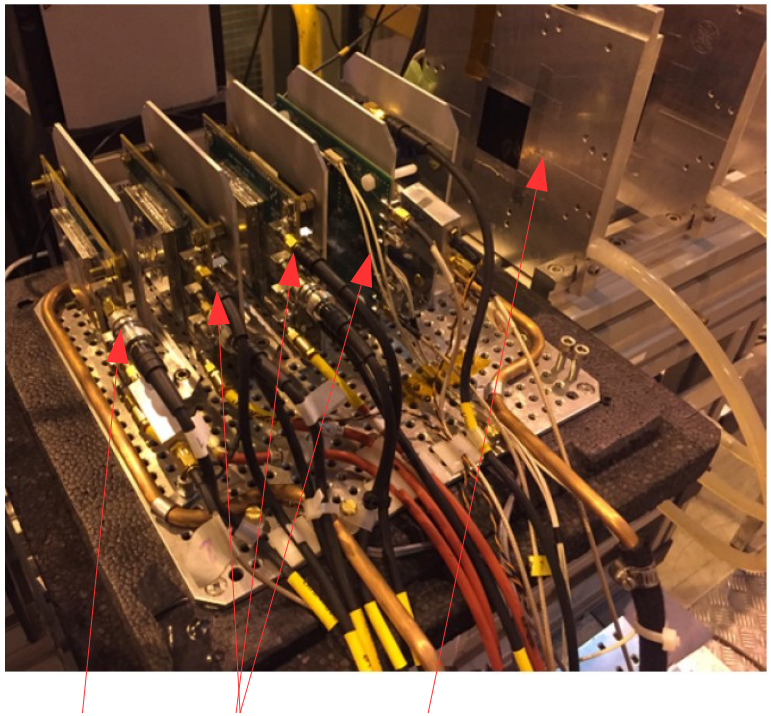
- 6” Si-on-Si wafers
- 50 µm thickness on 150 µm support wafer
- Different implantation doses
- Various structures including:
  - Pad diodes of 0.9x0.9 $mm^2$
  - 2x2 arrays of 3x3 $mm^2$ pads



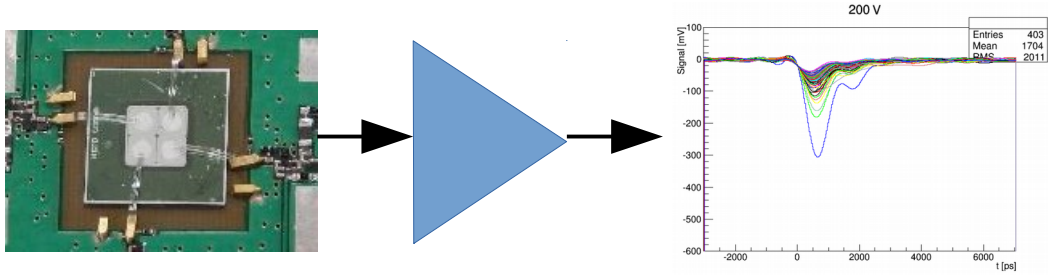
* More recent production being studied now

# HGTD Sensor Testing

- Laboratory measurements are carried out to characterize sensor performance
  - *See, for example: G. Kramberger et al., JINST 10 (2015) P07006, J. Lange et al., JINST 12 (2917) P05003, Z. Galloway et al., arXiv:1707.04961, N. Cartiglia et al., NIM A850 (2017) 83*
- But tests with particle beam provide ultimate timing measurements
  - Test-beam campaigns carried out at **CERN SPS** 120 GeV pion line

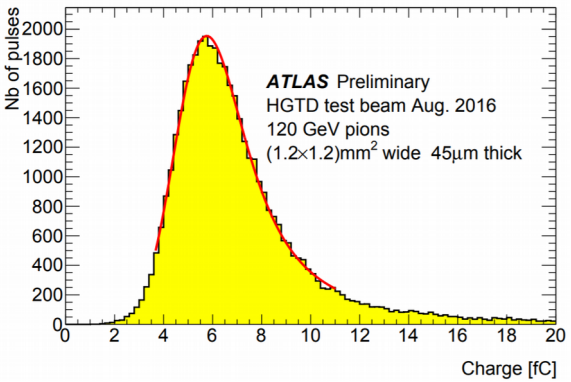


SiPM, LGADs, Tracking




Sensor Amplification Oscilloscope

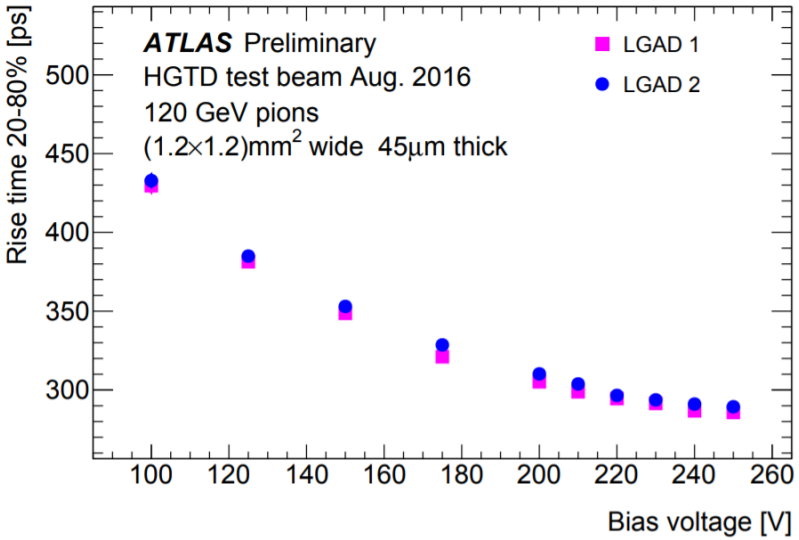
- Multiple LGAD sensors mounted on beam
- Also SiPM (10 ps) used for timing reference
- Particle tracking available
- Waveforms stored and analyzed offline (CFD)
- Extract measurements from Landau+Gauss fits

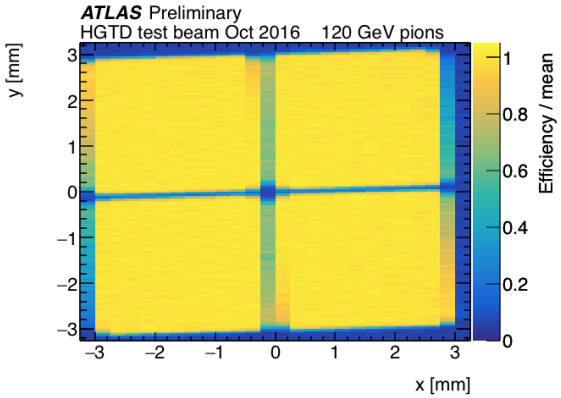


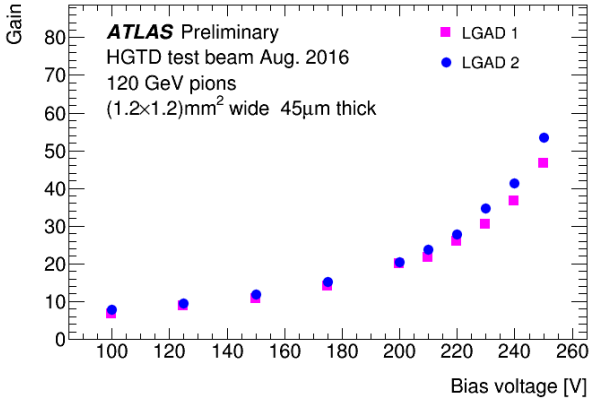
# HGTD Sensor Performance

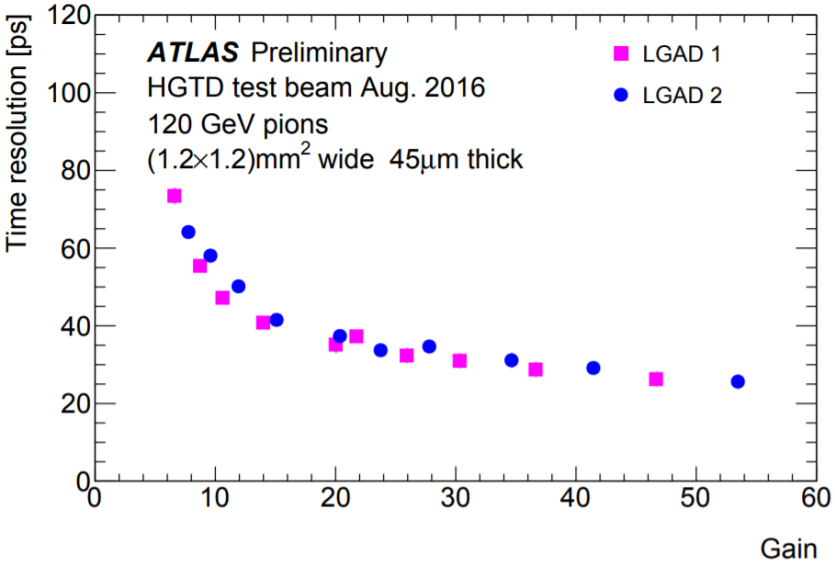
Results for **non-irradiated** LGAD sensors

- Gain determined from ratio of charge in LGAD to non-gain LGAD
- Time resolution reaches **25 ps/layer** at highest gain
  - Noise mostly flat, rise time improves with voltage
  - Well within requirements, do not need to operate at very high gain
  - In agreement with other measurements
    - N. Cartiglia et al., NIM A850 (2017) 83, *J. Lange et al., JINST 12 (2017) P05003*
- Tracking information
  - **Good uniformity** of signal over the pads (1%)
  - Inter pad regions remain to be optimized



# HGTD Sensor Performance

Results for **irradiated** LGAD sensors

- Irradiated to different fluencies with neutrons (*Ljubljana*)
- Testbeam and laboratory measurements performed with cooling system (-6, -15, -20 °C)
- Different multiplication layer dose implants studied

Laboratory measurements with HPK irradiated samples:

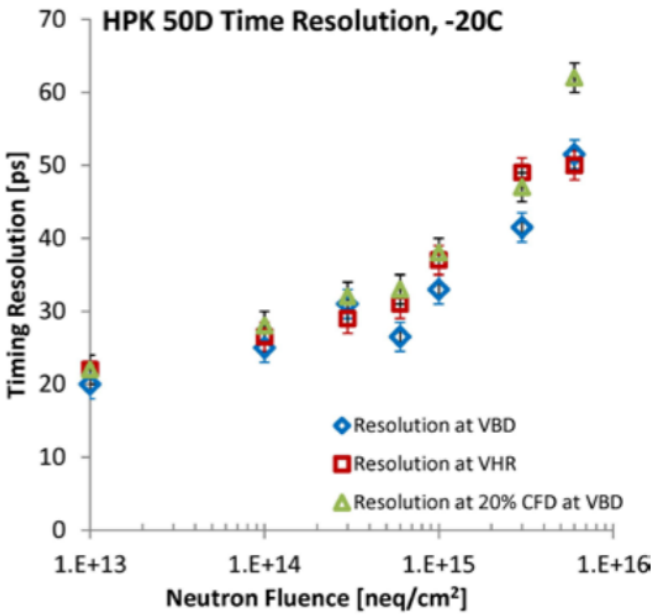
- Results with Sr 90 setup
- Similar results than CNM at low fluencies
- Significant improvement at larger fluencies
  - 50ps after 6E15 $n_{eq}/cm^2$

Testbeam results with CNM irradiated samples:

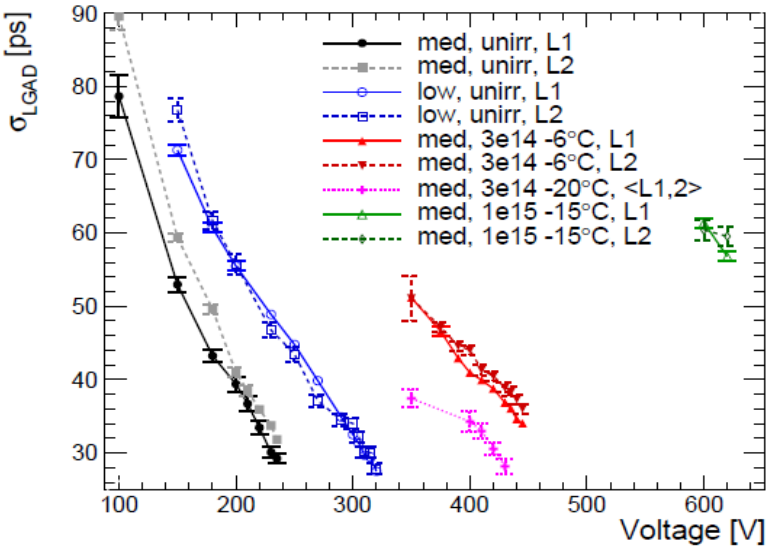
- At 3E14 $n_{eq}/cm^2$, can recover performance of unirradiated sensors (at higher V)
- At **1E15 $n_{eq}/cm^2$** about **60 ps** resolution achieved
- Possible differences with HPK results being investigated (metalization, setup...)

**LGAD sensors satisfy the timing resolution requirements of HGTD after irradiation**

*Z. Galloway et al., arXiv:1707.04961*




*J. Lange et al., JINST 12 (2017) P05003*



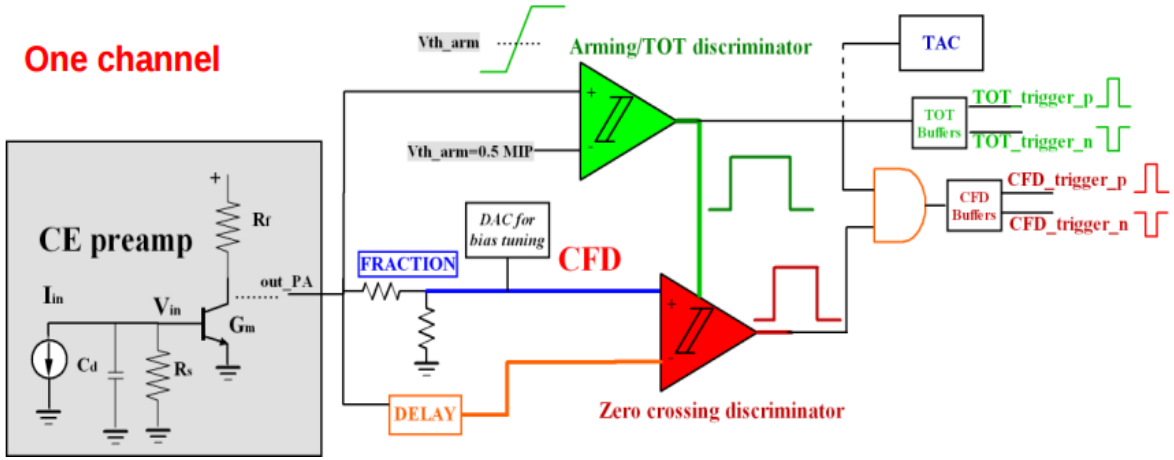
# HGTD Electronics

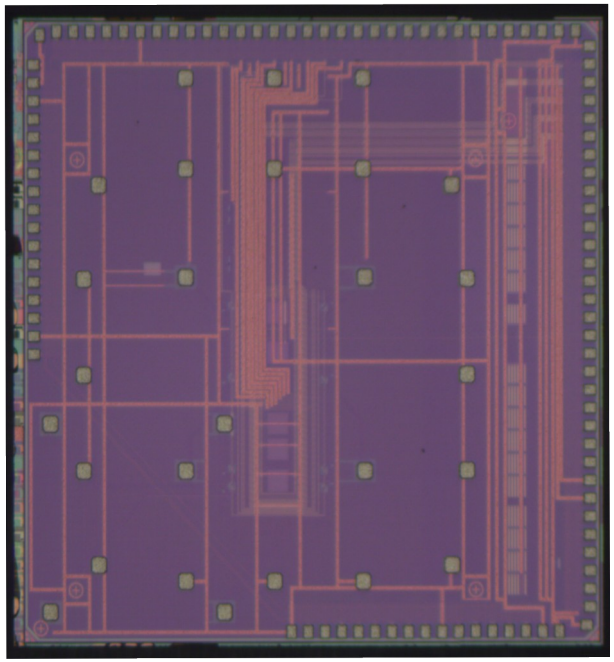
- Front end electronics 1st prototype designed by **Omega** (France)
- **Altiroc**: Atlas Lgad Timing Integrated ReadOut Chip
- Fabricated on TSMC **130 nm** technology, delivered in April 2017
- **Four channels** dedicated for **2pF** pads (~1x1 mm$^2$ sensors)
- Also option for larger pads (10 pF and 20 pF)
- Each channel (200 µm x 100 µm) = **Preamplifiers** + **TOT** and **CFD**

OMEGA Microelectronics

*C. de la Taille*
*TWEPP 2017*

*Measured jitter ~20 ps (9.2 fC charge for 1 mip and gain=20)*



*Altiroc0*

- Area= 3.4 x 3.4 mm$^2$
- Thickness = 300 µm

**Final chip:**

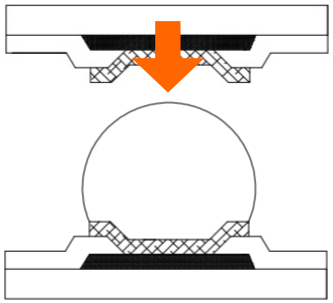
➔ Digital output
ToT or CFD + TDC
➔ 225 channels
➔ ~400 Mrad

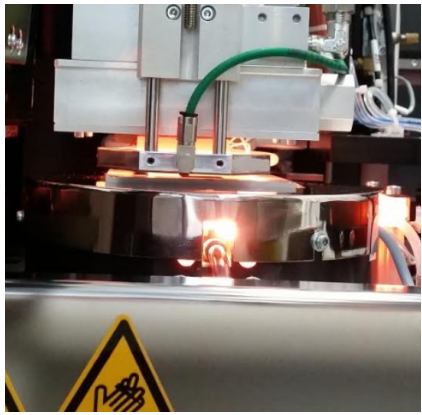
# HGTD Module

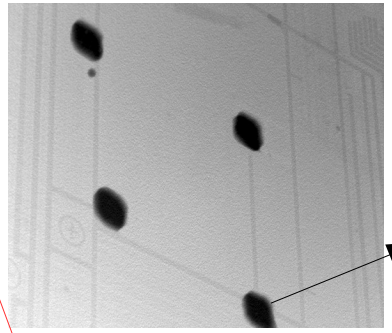
Sensor and Altrioc hybridization through bump-bonding:

- Under bump metalization of both ASIC and sensor (CNM)
  - Solder can not bond directly to aluminum
- Solder bump deposition on ASIC
  - Ball placement
- Flip-chip
  - Connection step through thermal cycle
- Reflow
- Quality control
- Module assembly
  - Gluing and wire-bonding

Bump-bonding

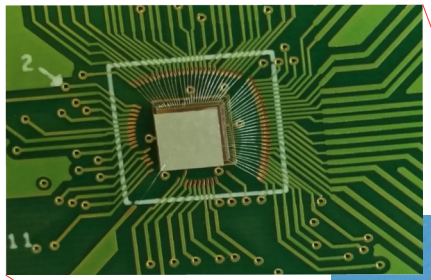


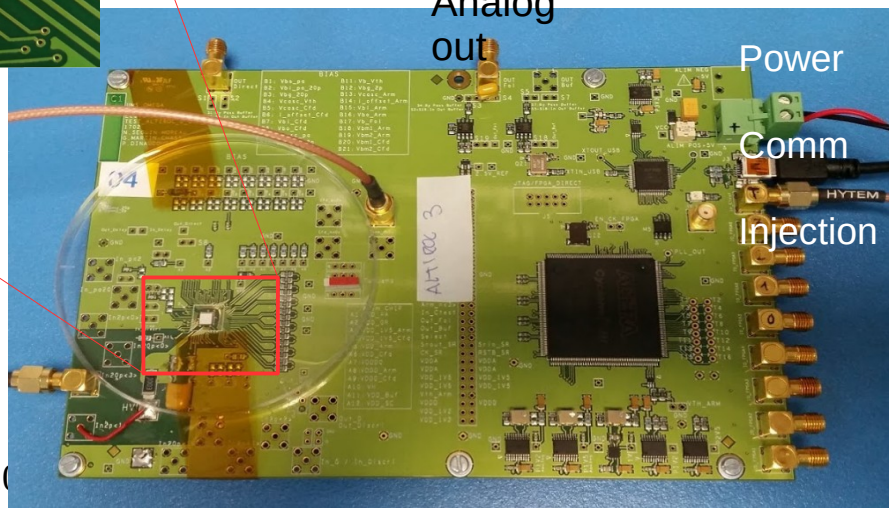


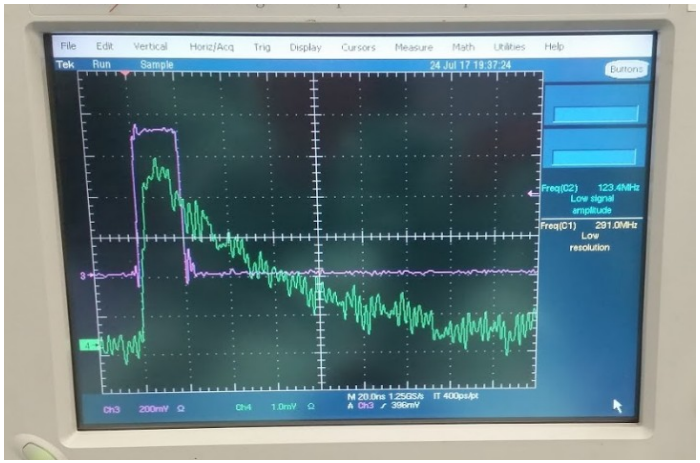


*QC with X-ray inspection*

80 um Ø dump connection





Signal of Sr90 source verified
Will be tested with beam in Sept.

# Conclusions

- **HGTD** detector promises to improve **pile-up rejection** for HL-LHC
  - Significant improvements on reconstruction performance at high-η
- Proposed **LGAD sensor technology**
  - Well suited to meet HGTD requirements
    - Timing, occupancy, physical space and radiation hardness
  - Challenging **<30 ps** resolution obtained for diodes **before irradiation**
  - Good **uniformity** of response within pad diode observed (<1%)
  - Irradiated LGAD sensors satisfy HGTD radiation hardness requirement
- First version of dedicated **ASIC** fabricated
  - Initial module prototypes assembled, **preliminary tests successful**

# Backup Slides