A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS: detector concept description and first beam test results

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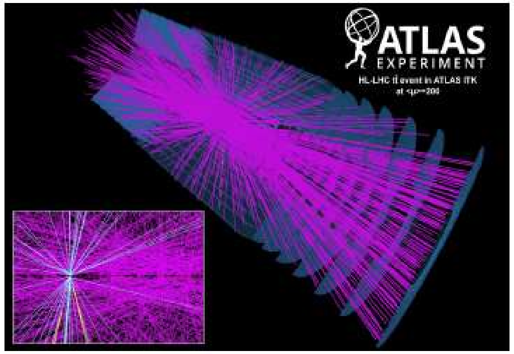
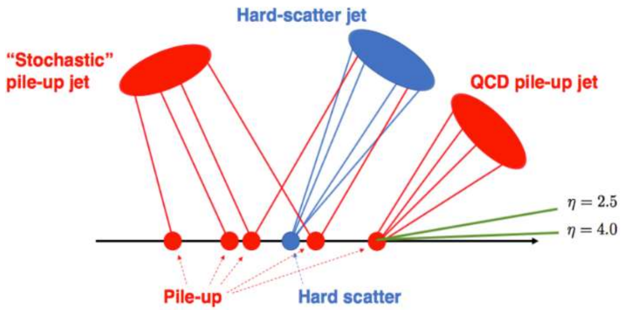
High Luminosity LHC

- 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: <μ> ~ 200 (x8)
Integrated luminosity: 4000/fb (x13)

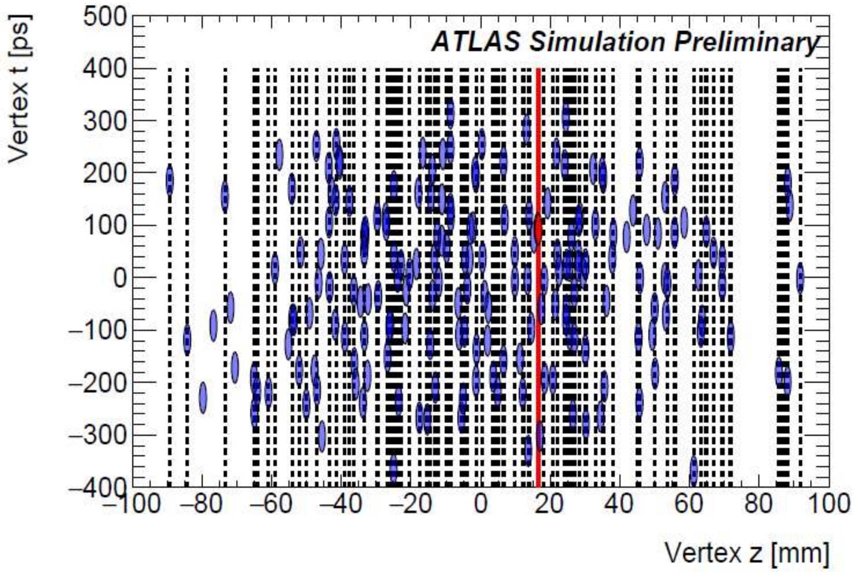




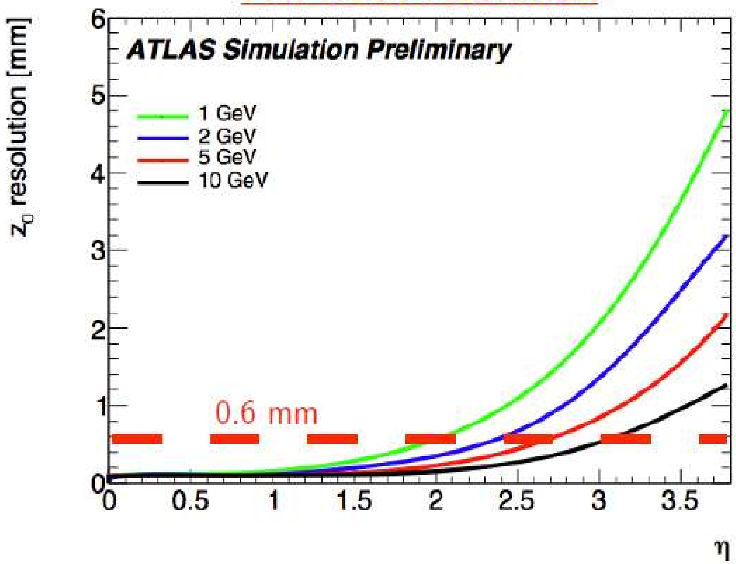
Pile-up: other pp collisions in addition to the one of interest
- Adds energy to reconstructed hard-scatter jets
- Produces pile-up jets

HGTD motivations

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



ITk track resolution



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

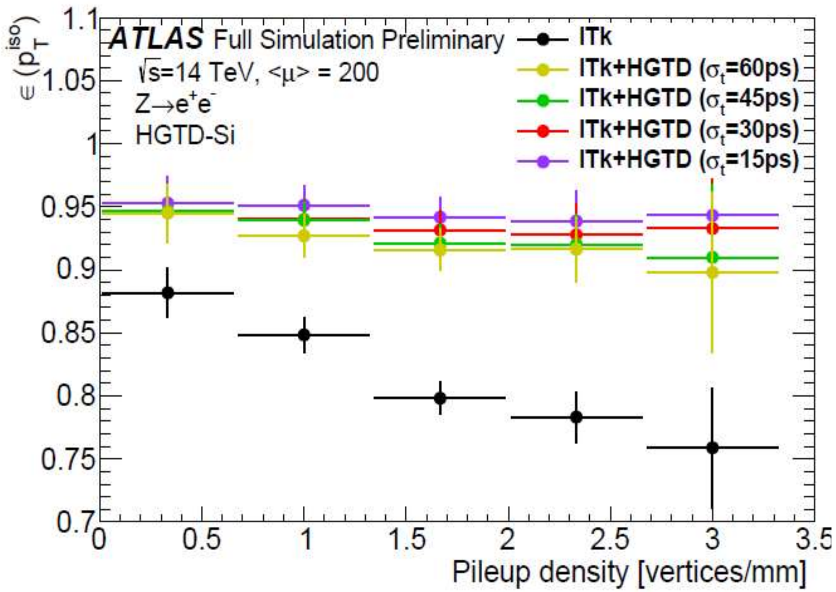
Tracking detector (ITk) upgrade will provide excellent position resolution, but in the very forward region, resolution only reaches a few mm.

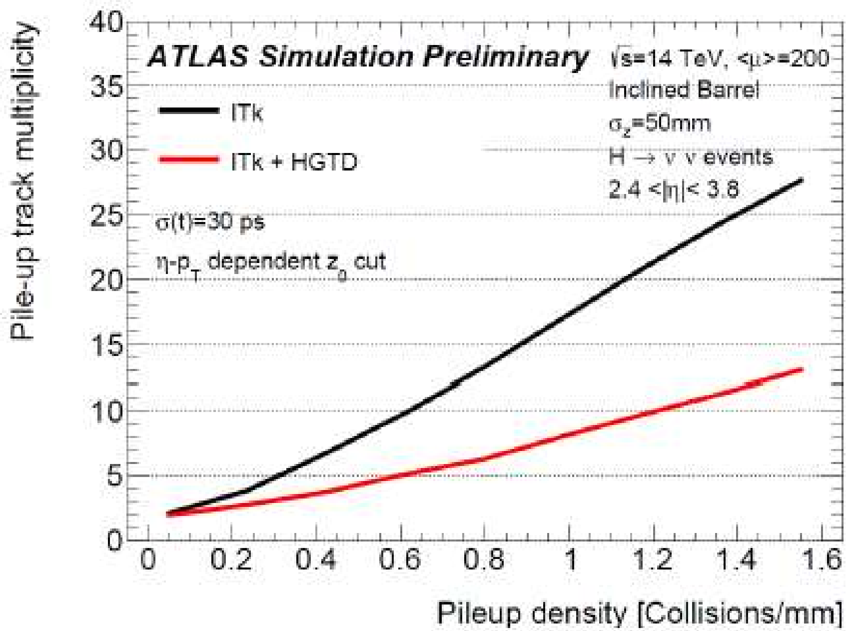
In order to reconstruct primary vertices, the resolution of the longitudinal track impact parameter (z0), provided by ITk, to be much smaller than the inverse of the average pileup density (0.6 mm).

=> Explore improvements on pile-up rejection at high η

HGTD performance improvements

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

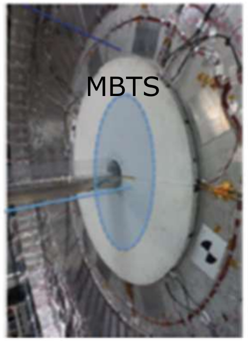


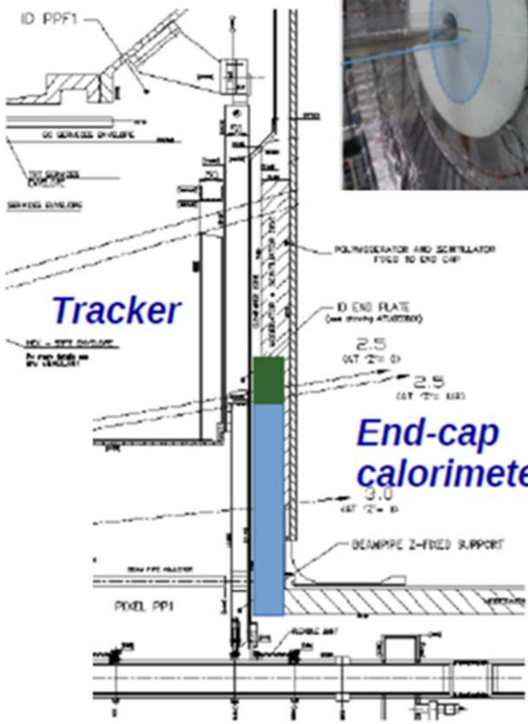


HGTD targets a time resolution of **30 ps** to recover current LHC pile-up conditions

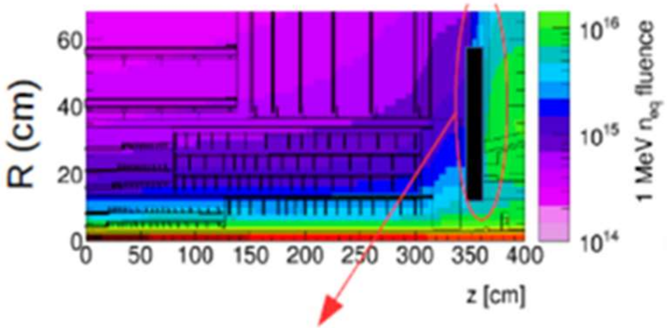
HGTD Detector

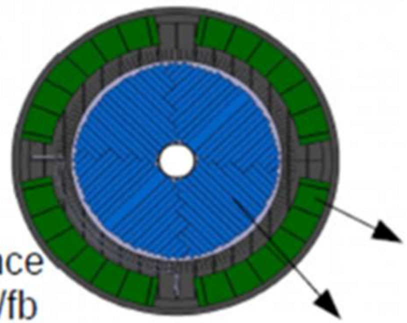
- **HGTD** would be placed in the **forward** region between the tracker and the end-cap calorimeter
- Tight z space: **Δz = 65 mm**





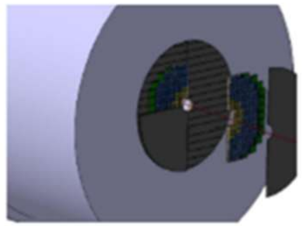
Pseudorapidity coverage	$2.4 < \|\eta\| < 4.0$
Position in z	$3420 < z < 3545$ mm including 50 mm of moderator
Position of active layers	$3435 < z < 3485$ mm
Radial extension (active area)	110–1100 mm (120 mm–640 mm)
Time resolution	30 ps per track





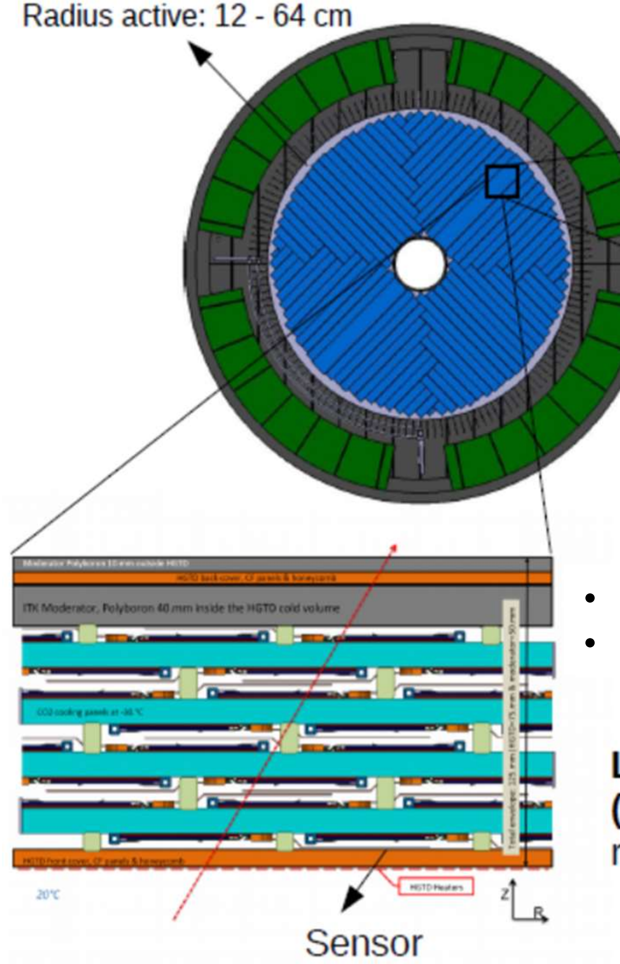
Radiation requirements:

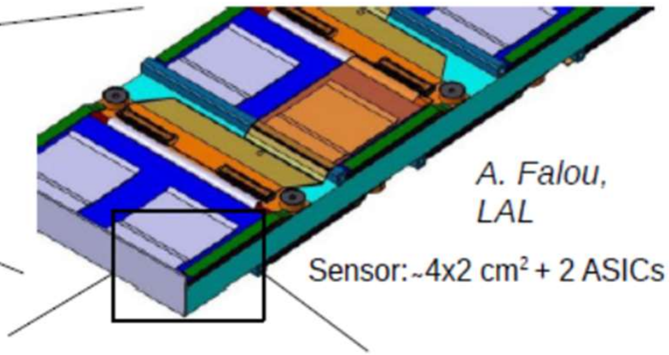
- For innermost sensors, expect a fluence of ~**4.5E15 n_{eq}/cm^2** at 10 cm for 2000/fb
- Replacement of inner layer(s) at R<300 mm foreseen at the half time of the HL-HLC



HGTD Detector

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

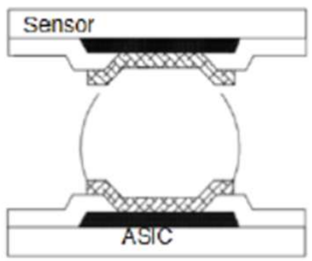




Core of HGTD: hybrid silicon sensors with 1.3 x 1.3 mm² pixels

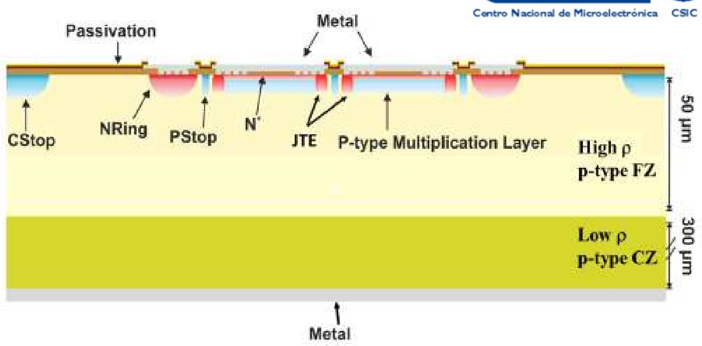
- 2 to 4 layers in about 7cm
- 30 ps/mip resolution

Low gain avalanche detectors (LGAD) to achieve target resolution



HGTD Sensor Technology

HGTD needs to achieve about 30 ps/mip **resolution**: technology beyond standard silicon devices



Time resolution:

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

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

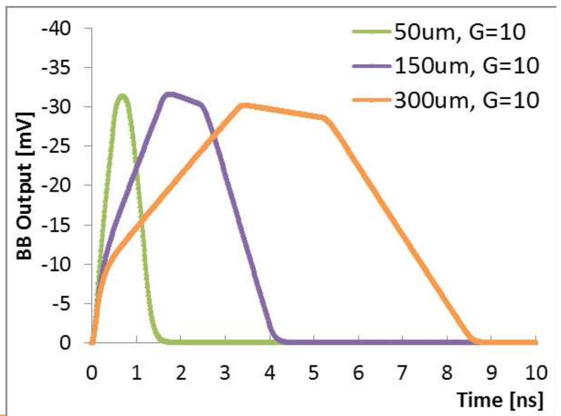
Jitter *Timewalk*

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]

- Need fast and excellent **S/N**
  - A multiplication layer increases signal slope
  - Timewalk contribution can be corrected (TOT)
- Thin sensors (50 µm) to reduce intrinsic Landau contribution to resolution and steeper slope.

HGTD sensors based on thin LGAD technology

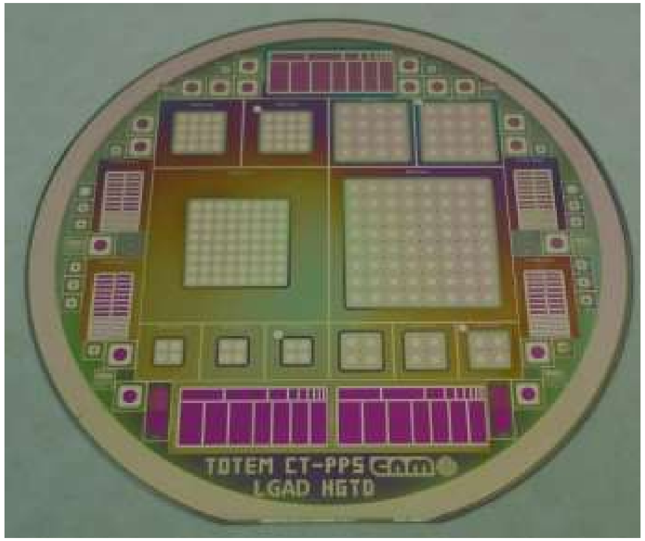


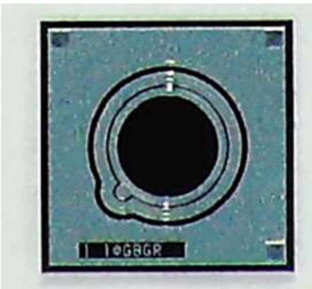
[1] G. Pellegrini et al., NIM A765 (2014) 12
[2] H.-W. Sadrozinski et al., arXiv: 1704.08666
[3] F. Cenna et al, NIM A796 (2015) 149-153

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





HPK 50um LGAD 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

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

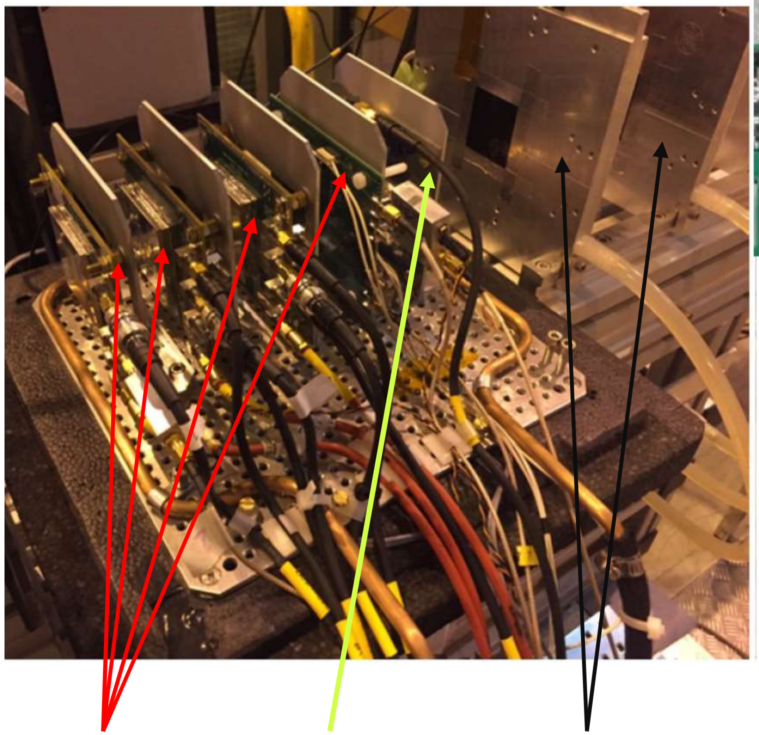
HGTD Sensor Testing

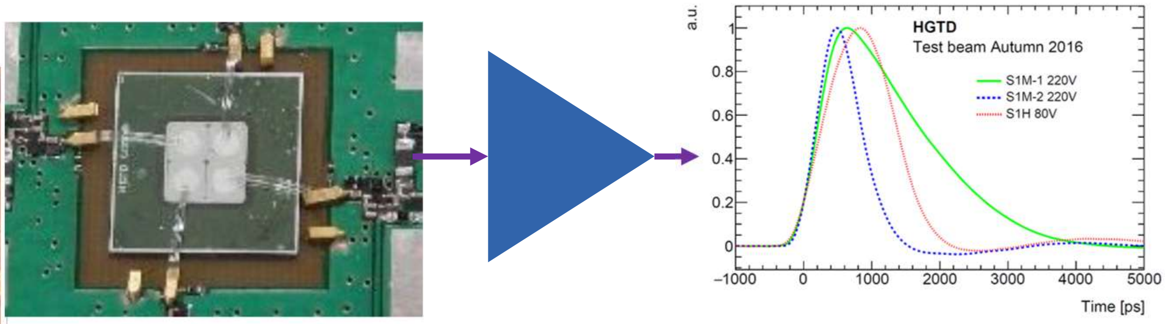
Laboratory measurements are carried out to characterize sensor performance

- *See, for example: G. Kramberger et al., JINST 10 (2015) P07006, J. Lange et al., JINST 12 (2017) 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**

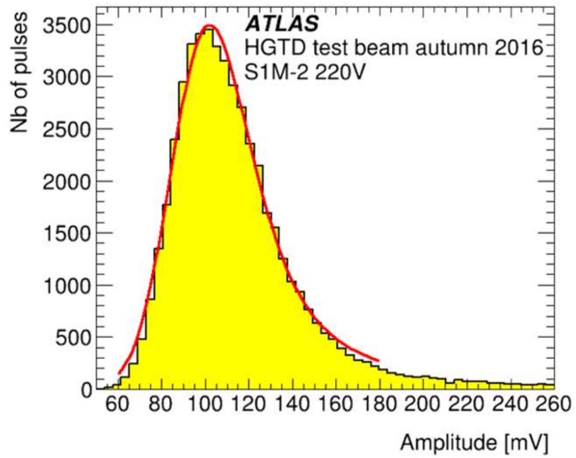
- Test-beam campaigns carried out at CERN SPS 120 GeV pion line





Sensor Amplification Oscilloscope

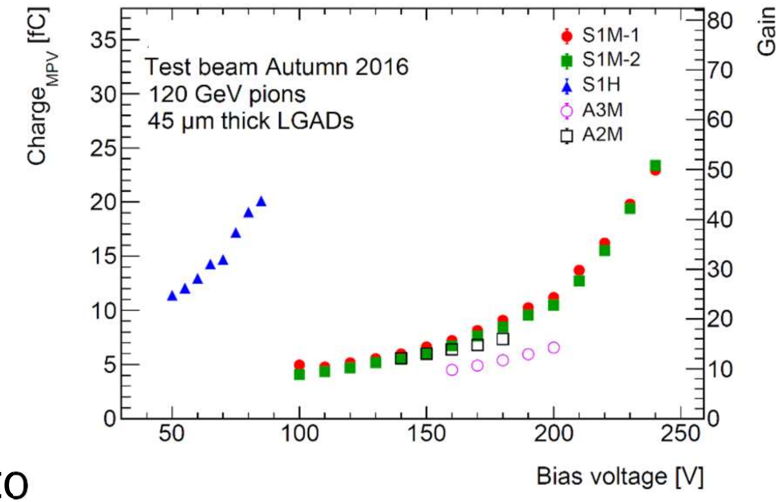
- Multiple LGAD sensors mounted on beam
- Also SiPM (~ 16 ps) used as timing reference
- Particle tracking available
- Waveforms stored and analysed offline (CFD)
- Extract measurements from convoluted Landau + Gauss fits

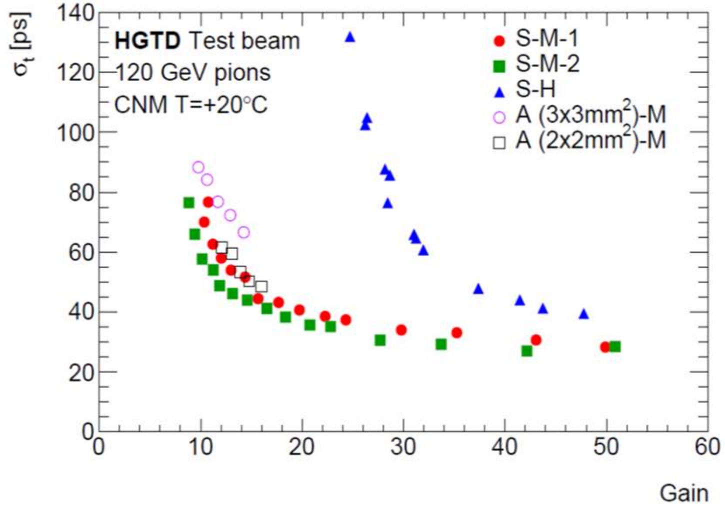


HGTD Sensor Performance

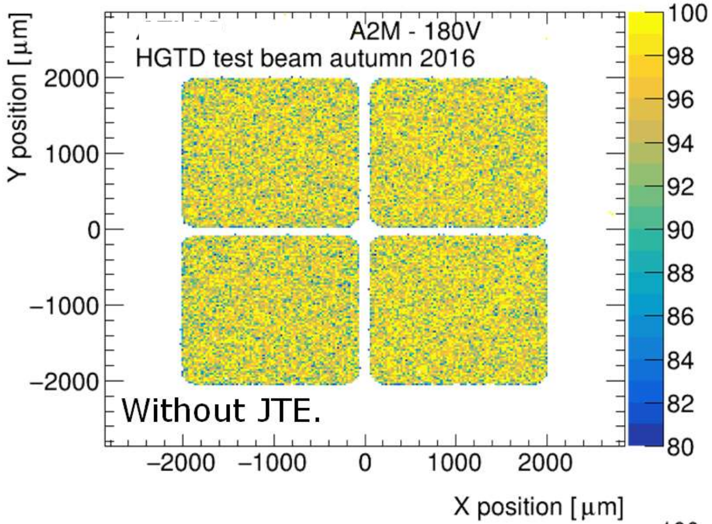
Results for **non-irradiated** LGAD sensors

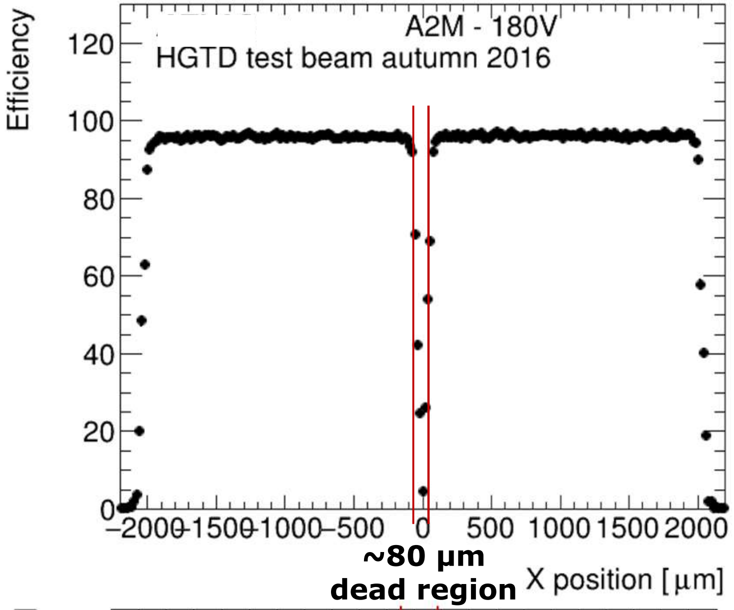
- Gain determined from ratio of charge in LGAD to non-gain LGAD
- Time resolution reaches **25 ps/layer** at highest gain
    - Noise mostly flat, rise time improves with voltage
    - Well within requirements, do not need to operate at very high gain
    - In agreement with other measurements
        - N. Cartiglia et al., NIM A850 (2017) 83,
        - J. Lange et al., JINST 12 (2017) P05003

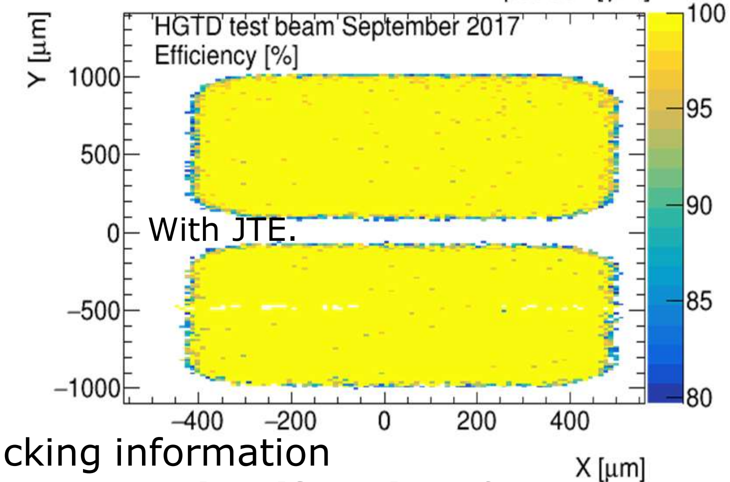


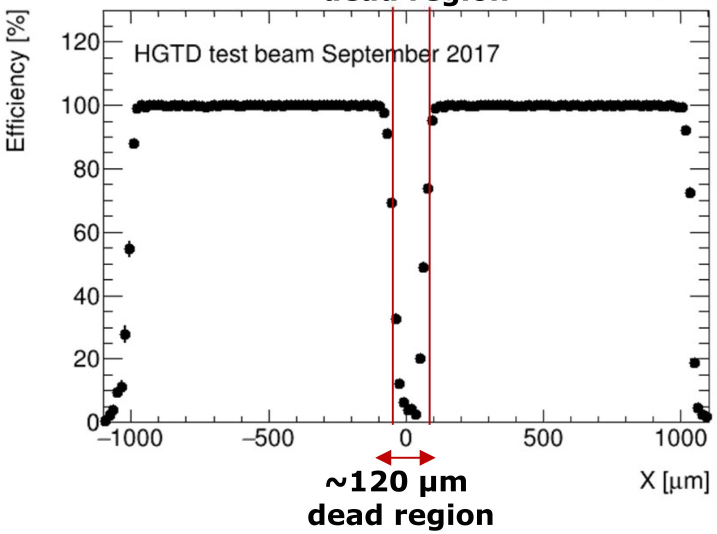


HGTD Sensor Performance









Tracking information

- **Good uniformity** of signal over the pads (1%)
- Inter pad regions remain to be optimized
- Different interpad gap distances studied

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

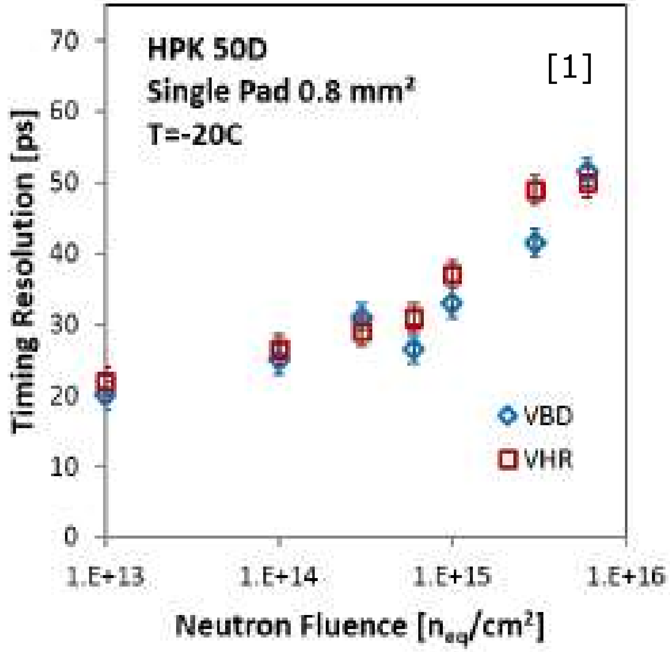
Laboratory measurements with **HPK** irradiated samples:

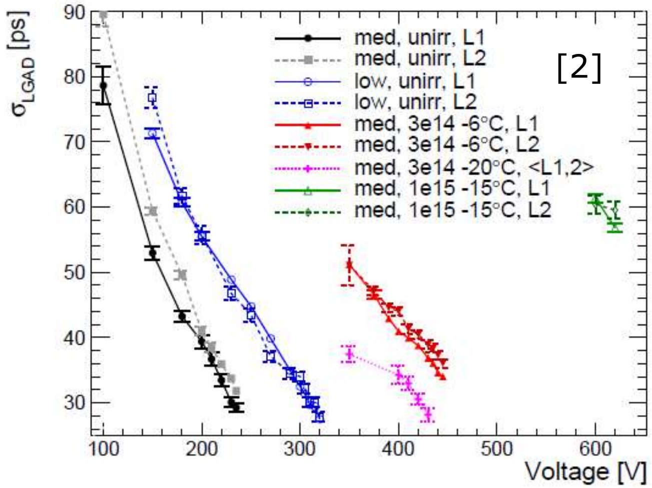
- Results with Sr 90 setup
- Similar results than CNM at low fluencies
- Significant improvement at larger fluencies
  - **50ps** after 6E15 n_{eq}/cm^2

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

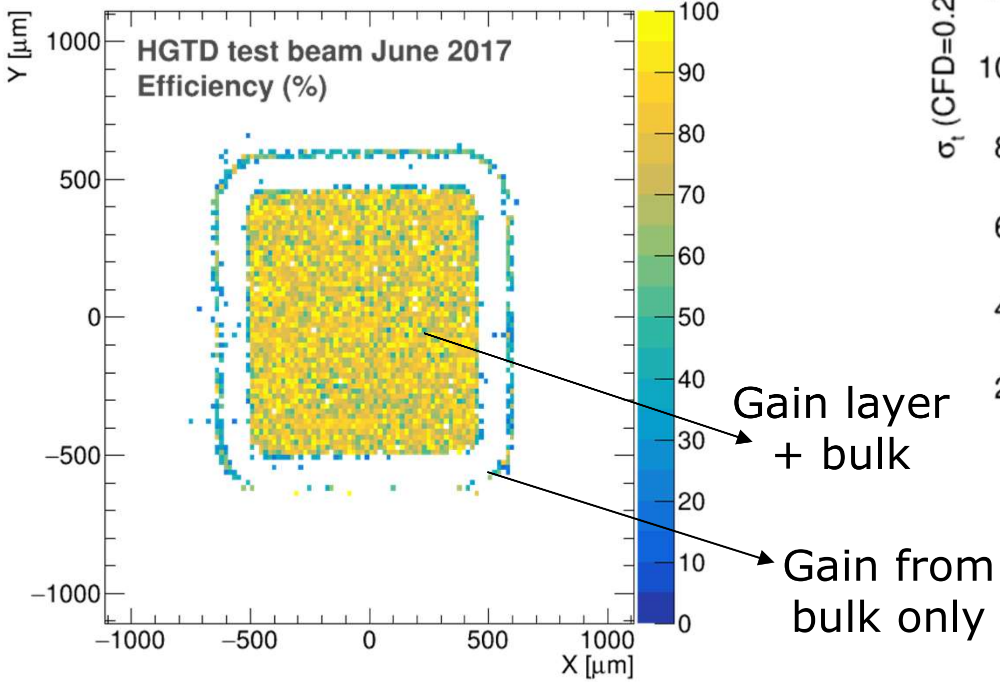


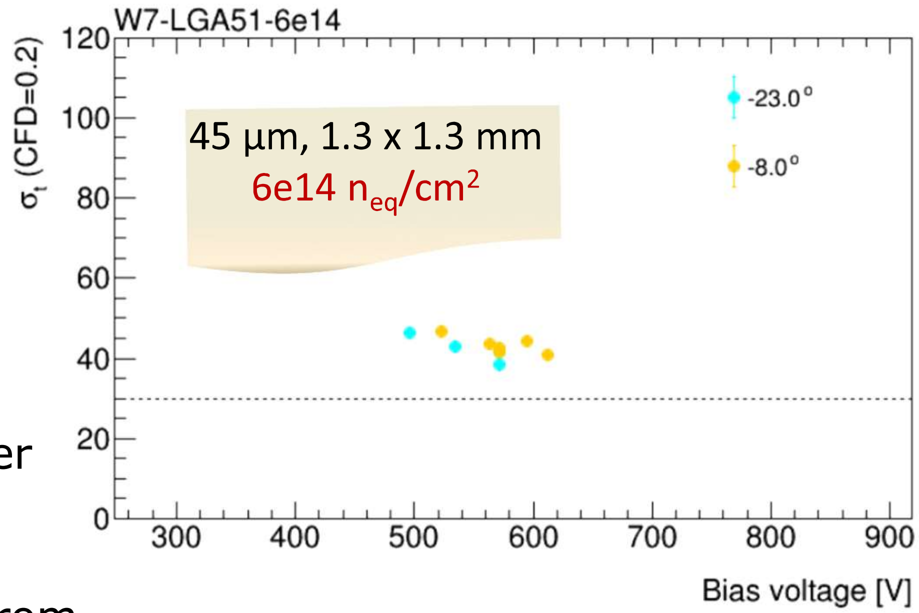


1. *Z. Galloway et al., arXiv:1707.04961,*
2. *J. Lange et al., JINST 12 (2017) P05003,*

HGTD Sensor Performance

Irradiated Single Pads





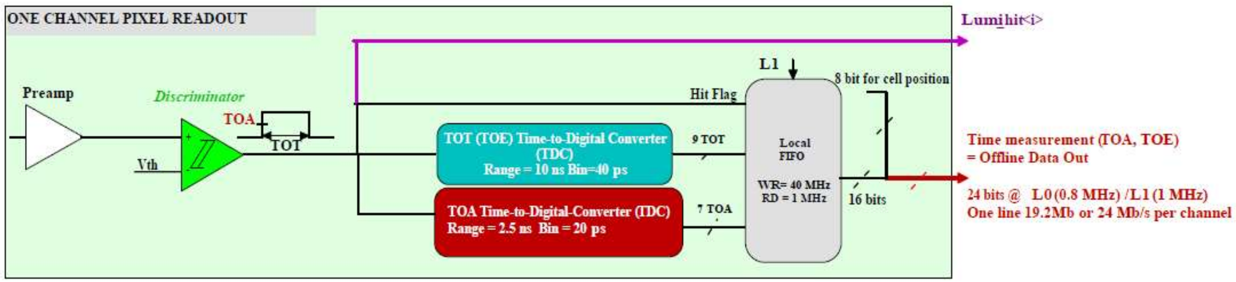
- 45um thick sensors, irradiated with neutrons.
- Good **uniformity** of response within pad diode observed after irradiation
- 35ps time resolution after 6E14 n_{eq}/cm^2

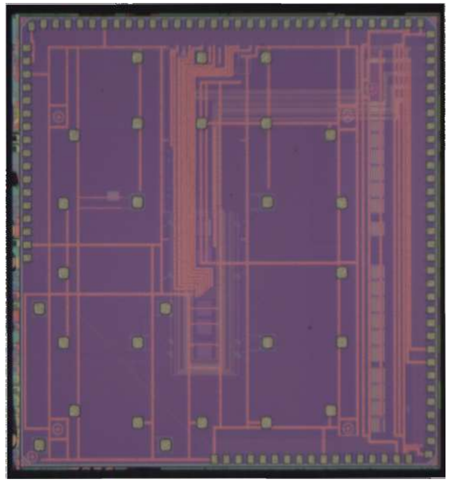
HGTD Electronics

- 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**

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

C. de la Taille
TWEPP 2017




ALTIROC chip prototype

Final chip:
➔ Digital output ToT + TDC
➔ 225 channels
➔ ~400 Mrad

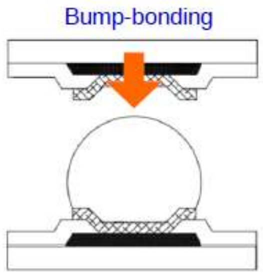
Altiroc0 (2017)
- 1x1mm^2 pads
- 2x2 matrix

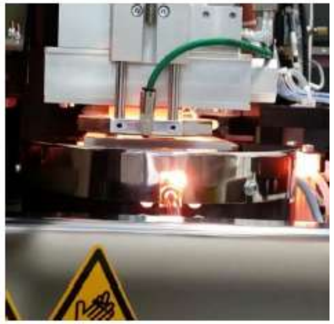
Altiroc1 (2018)
- 1.3x1.3 mm^2 pads
- 5x5 matrix

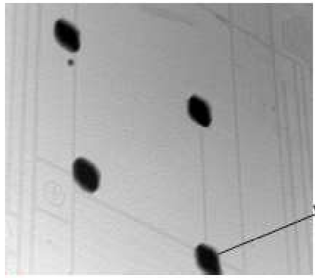
HGTD Module

Sensor and Altrioc hybridization through bump-bonding:

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

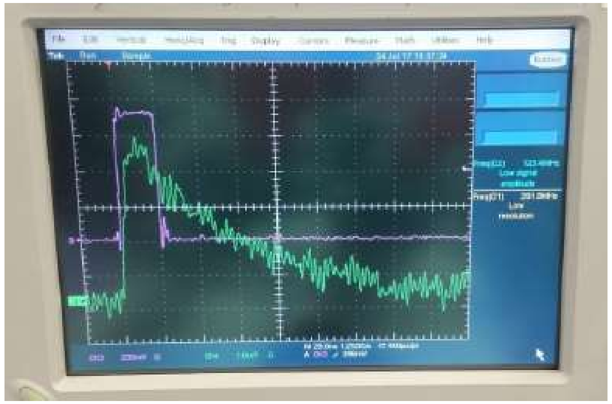


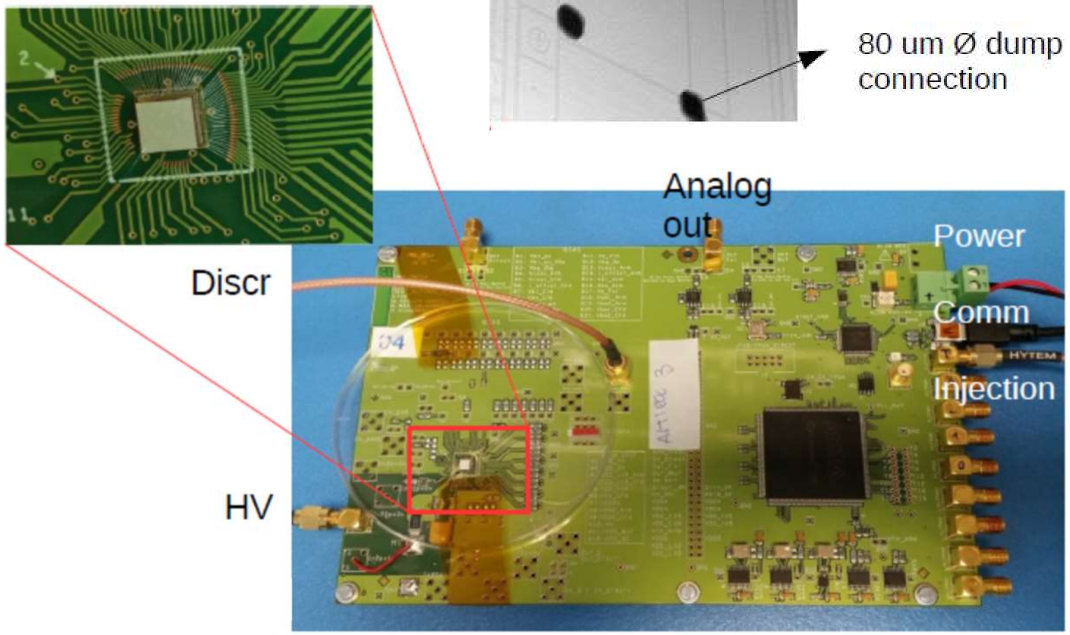




QC with X-ray inspection

80 um Ø dump connection





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**


11th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking detectors - HSTD11
in conjunction with
2nd Workshop on SOI Pixel Detector - SOIPIX2017
OIST, Okinawa, Japan, Dec. 11-15, 2017
KEY DATES:
Abstract submission: 10 July - 28 Aug.
Registration: 10 July – 20 Nov.
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