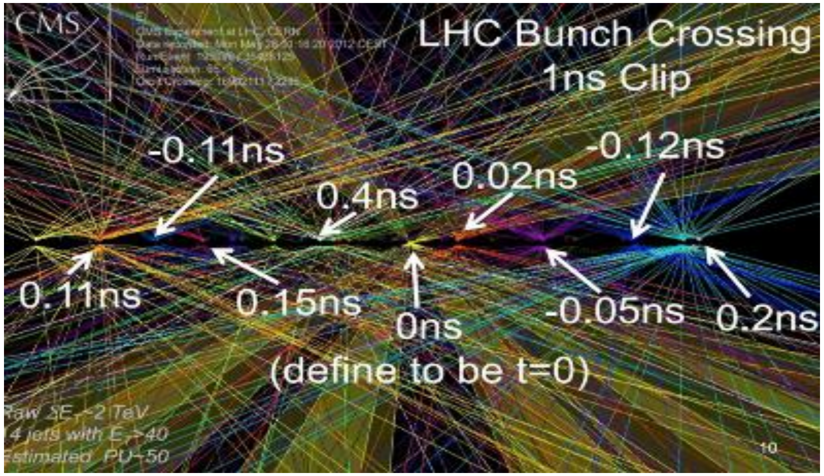
PPD R&D activities

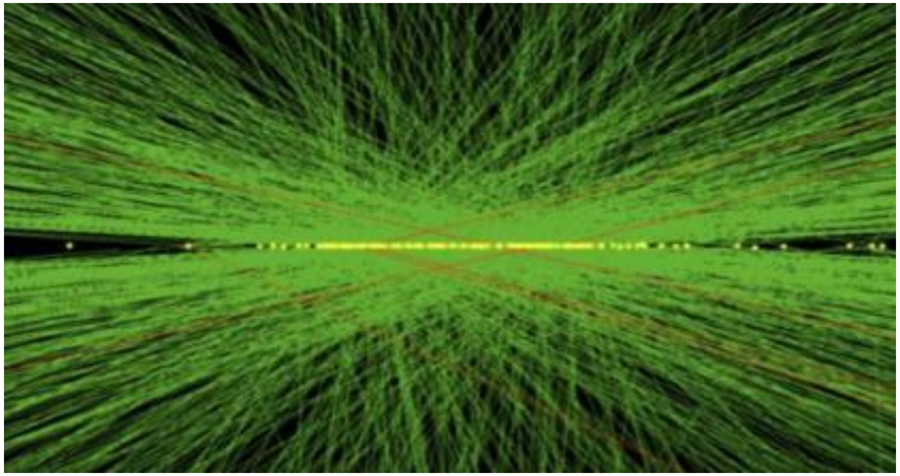
- Ultra Fast detectors
- Wide bandgap semiconductor detectors
- Lab activities

Ultra Fast Silicon Detectors

Ultra-fast Silicon detectors: high granularity detectors with added high resolution time measurements (‘4D’ tracking)

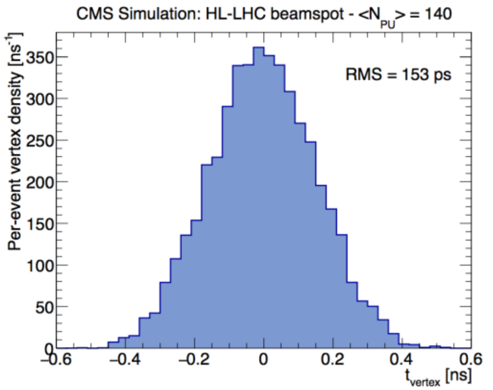


LHC: events well separated in space - standard 3D reconstruction is adequate

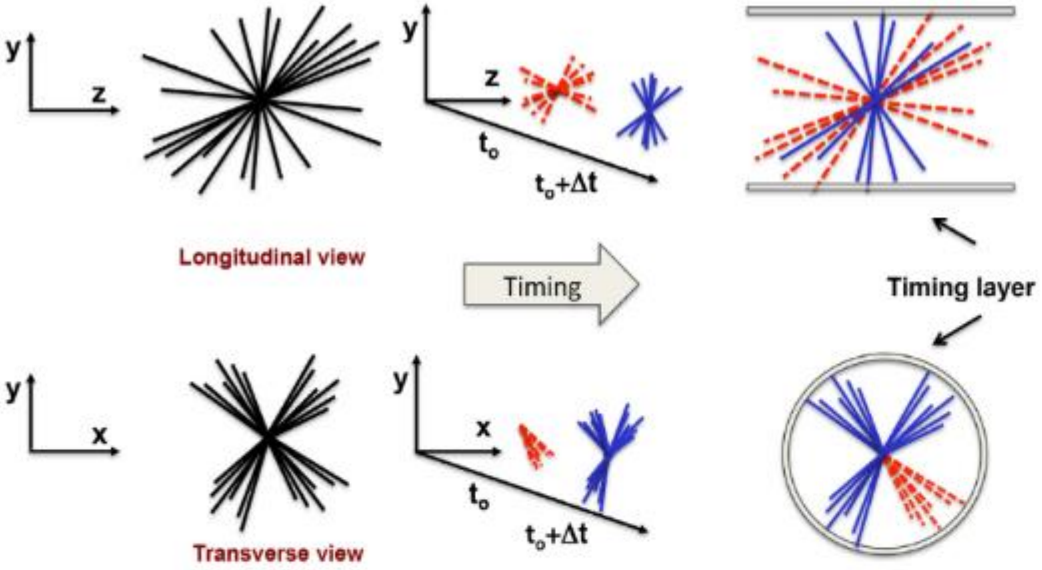


HL-LHC (2026): Pile-up issue – high density of events along beam axis will cause them to overlap in space

Needs for Ultra Fast Silicon Detectors



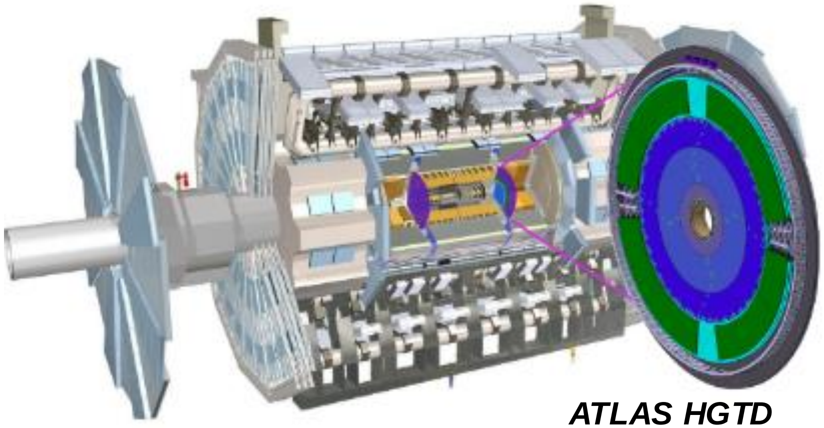
Events timing distribution at HL-LHC: a resolution of ~ 30 ps will divide events in 5 groups, each sufficiently separated to avoid overlap



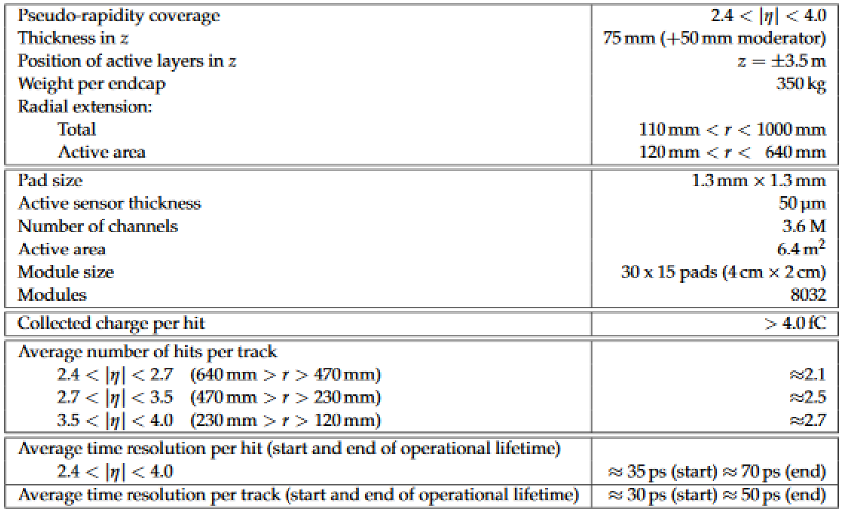
Example of disentangling of two overlapping events using timing information: tracks can be separated.

- Inclusion of timing information in a recorded event improves the reconstruction process : ‘4D tracking’
- Current approach: **timing measurement implemented at track level**

Needs for Ultra Fast Silicon Detectors



ATLAS HGTD



Pseudo-rapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	$z = \pm 3.5$ m
Weight per endcap	350 kg
Radial extension:	
Total	$110\,\text{mm} < r < 1000\,\text{mm}$
Active area	$120\,\text{mm} < r < 640\,\text{mm}$
Pad size	1.3 mm × 1.3 mm
Active sensor thickness	50 µm
Number of channels	3.6 M
Active area	$6.4\,\text{m}^2$
Module size	30 x 15 pads (4 cm × 2 cm)
Modules	8032
Collected charge per hit	> 4.0 fC
Average number of hits per track	
$2.4 < \|\eta\| < 2.7$ ($640\,\text{mm} > r > 470\,\text{mm}$)	≈2.1
$2.7 < \|\eta\| < 3.5$ ($470\,\text{mm} > r > 230\,\text{mm}$)	≈2.5
$3.5 < \|\eta\| < 4.0$ ($230\,\text{mm} > r > 120\,\text{mm}$)	≈2.7
Average time resolution per hit (start and end of operational lifetime)	
$2.4 < \|\eta\| < 4.0$	≈ 35 ps (start) ≈ 70 ps (end)
Average time resolution per track (start and end of operational lifetime)	≈ 30 ps (start) ≈ 50 ps (end)

https://cds.cern.ch/record/2706573/files/ATL-COM-UPGRADE-2020-002.pdf?version=2

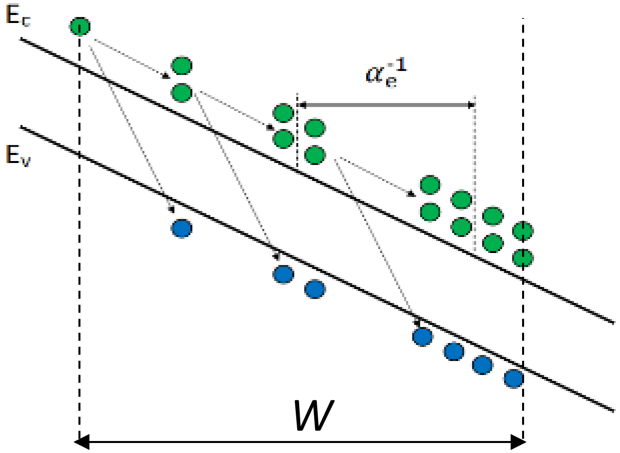
- **ATLAS High-Granularity Timing Detector (HGTD)**

Placed outside the ITk in front of end-cap calorimeter, at ±3.5 m from IP

- ATLAS HGTD aimed at suppressing pile up effects in ITK

- The HGTD sensors will consist of **LGAD** (**Low Gain Avalanche Detectors)** .

LGAD as UFSD



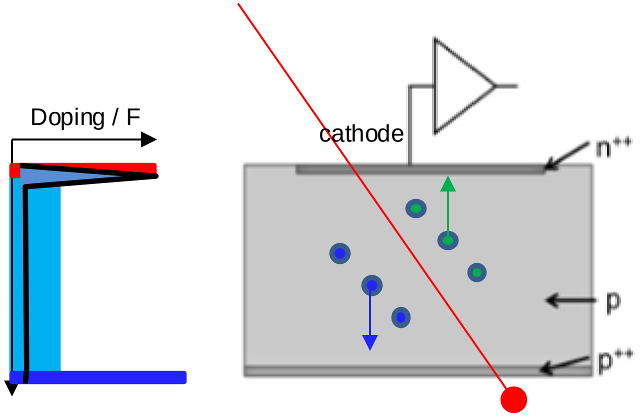
If $\alpha_e >> \alpha_h$

$$M_e = e^{\int_0^W \alpha_e dx}$$

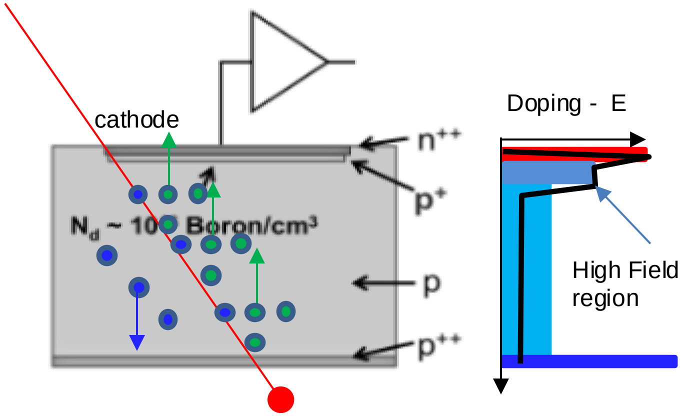
- Electron impact ionisation process. The electron, accelerated along an average distance $\alpha_e{}^{-1}$, undergoes a collision and its excess energy produces a new e-h pair. Consecutive collisions might ignite an avalanche

- **An LGAD is a detector which provides an increased signal gain by exploiting impact ionisation**

LGAD structure



Traditional silicon detector



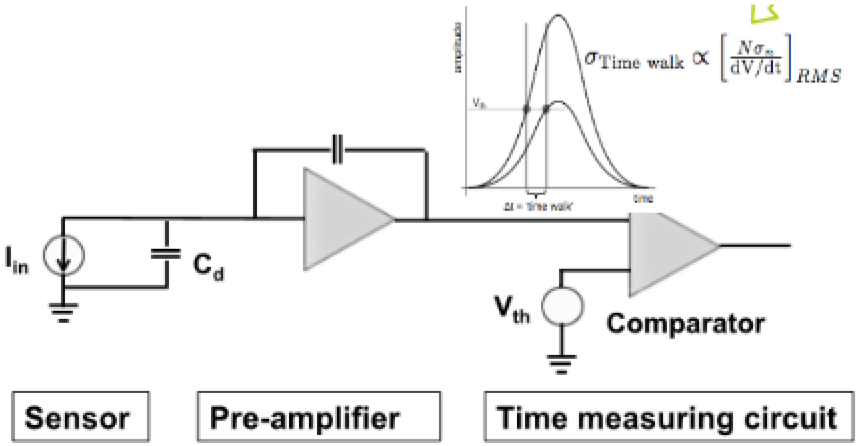
Low gain avalanche detectors

$Q_{coll} <= Q_{gen}$

$Q_{coll} > Q_{gen}$

- An additional layer of moderately high doping is added under the collecting well of a diode
- The effect of the electric field due to the additional layer is to increase the energy of electrons drifting towards the cathode
- If the energy acquired is high enough, additional charge is created by ***impact ionization***. In this case $\mathbf{Q_{coll} > Q_{gen}}$, leading to ***signal amplification, which allows to obtain high timing resolution***

LGAD timing



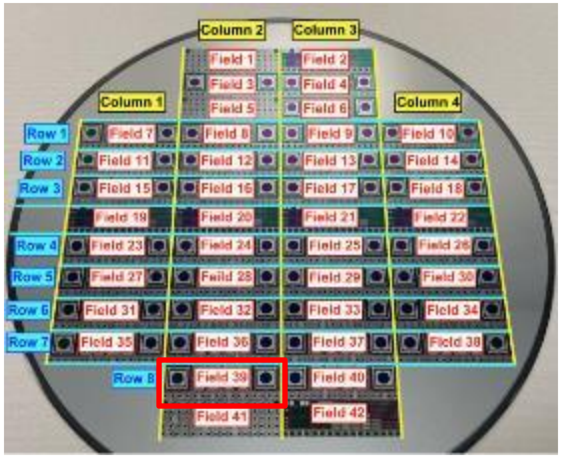
- Time-tagging: sensor signal output is shaped (filtered) and compared to a threshold to determine time of arrival of a particle
- Time resolution can by expressed as:

$$\sigma_t^2 = \sigma_{\text{Time walk}}^2 + \sigma_{\text{Landau noise}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TDC}}^2$$

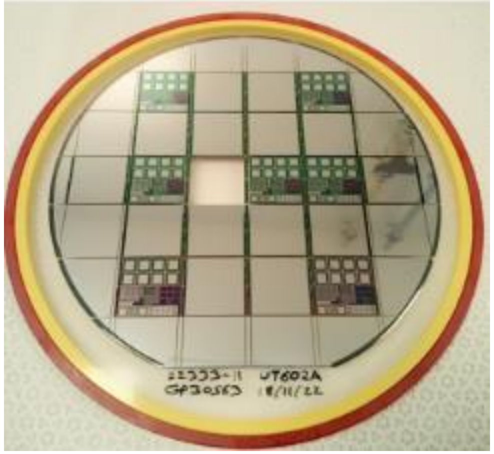
- **Time resolution *benefits from high Slew Rate (S/tr) AND low noise N:***

$$\sigma_{jit} \propto \frac{t_r}{\frac{S}{N}} = \frac{e_n C_s}{Q_{inj}} \sqrt{\frac{t_{ri}^2 + t_{dr}^2}{2t_{ri}}}$$

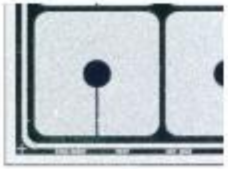
Te2v LGAD project



1st Te2v LGAD 6'' wafer



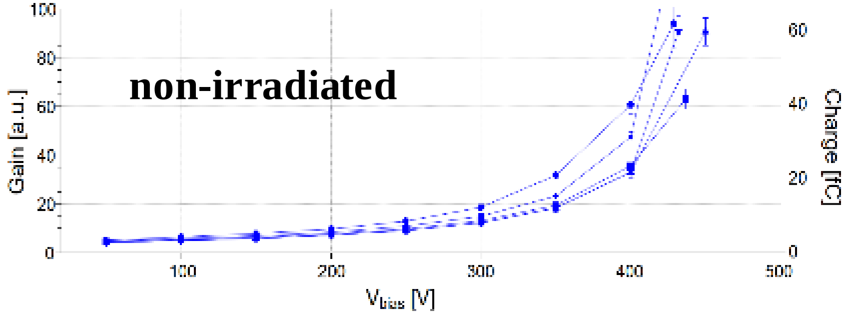
2nd Te2v LGAD 6'' wafer

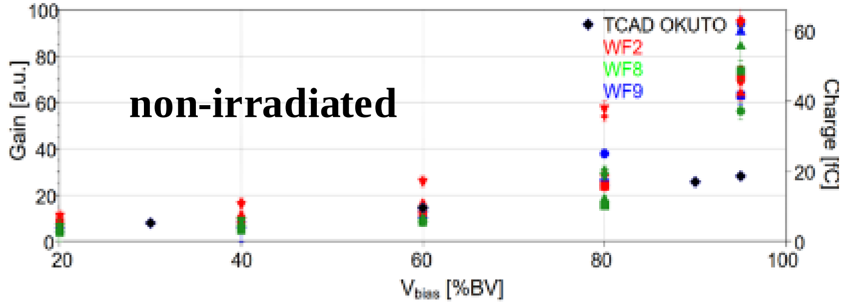


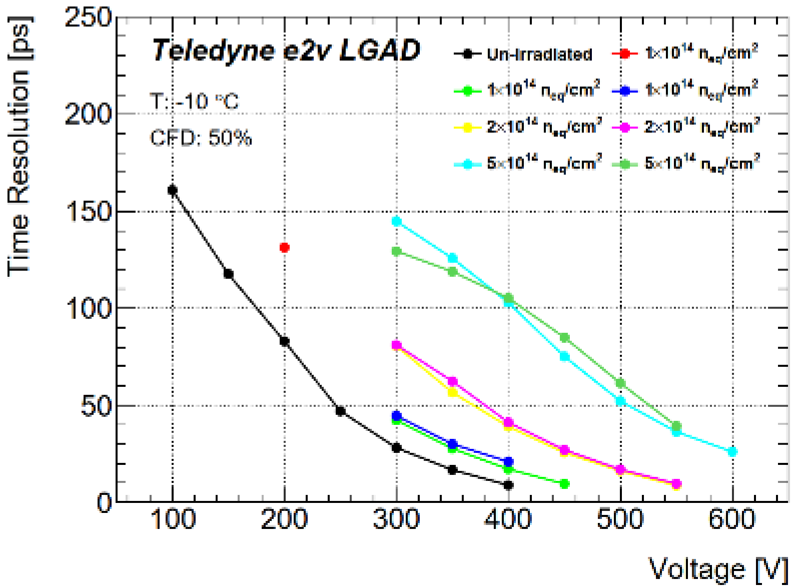
A RAL, Oxford, Birmingham and Open University project in collaboration with Teledyne e2v foundry for LGAD production

- RAL PPD design and simulation on 6" wafers 50 um HR epitaxial thickness
- Two fabrication runs:
    - First run of eight LGAD flavors (GL) and PiN diodes of same layouts
    - Second run for ATLAS HGTD

Te2v LGAD project



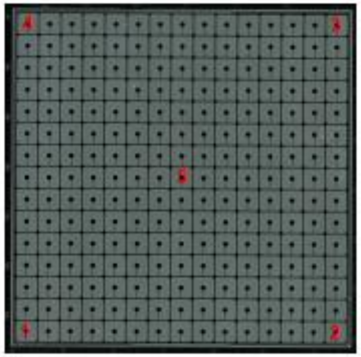




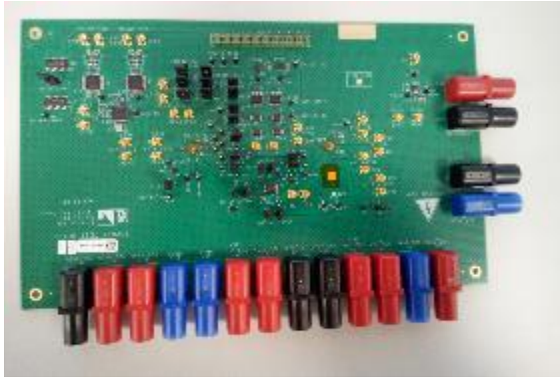
- Example of LGAD Gain and Timing: good TCAD prediction up to 80% of breakdown voltage
- Best jitter performances around 10 ps for non-irradiated devices
- Time resolution degrades with radiation, best around 20 ps @ 5 x 10^{14} n-fluence. Max operating fluence between 0.5 and 1 x 10^{15}

LGAD summary – wish list

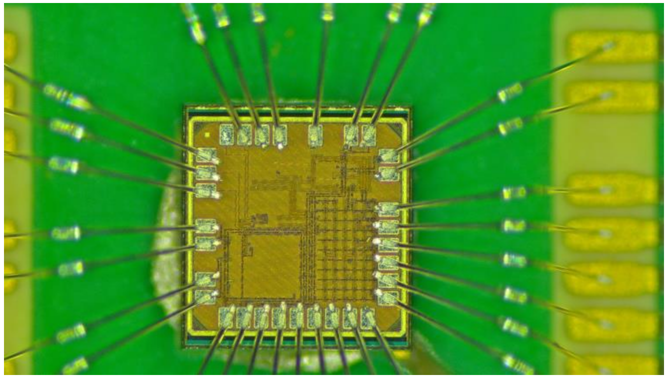
- **Designed LGAD successfully work:**
  - Timing resolution 10 ps (IR) 35 ps (MIP)
  - Operational up to 10^{15} n-fluence
  - Presentation at conferences and workshop (Vertex, IPRD, RD50, DRD
  - Papers published (JINST, NIM-A, TNS)
  - Material for 4 PhD thesis
- **Next – wish list**
  - Test the full LGAD array
  - Evaluation of 28 nm fast front-end ASIC, designed to Te2V LGAD specifications



Te2v LGAD array – 15 x 15 cells

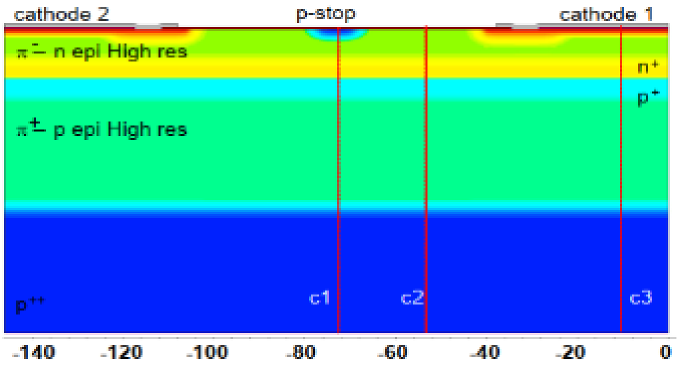


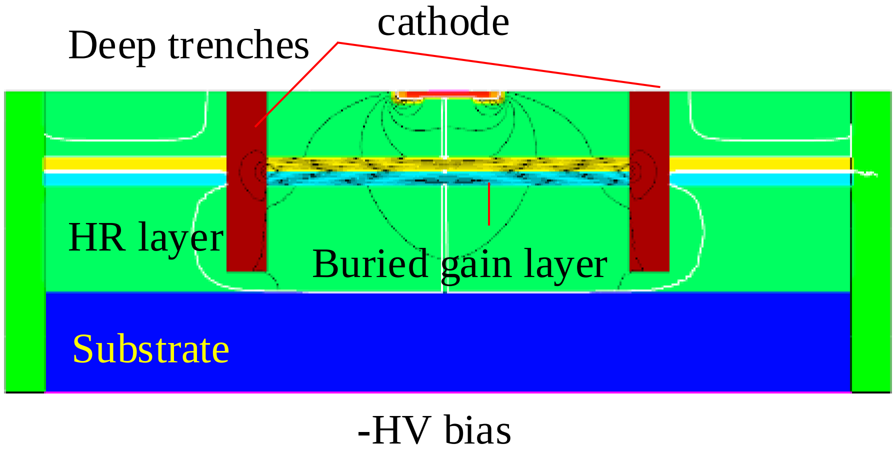
28 nm TSMC test board



the new 28 nm ASIC which includes 2 channel front-end LGAD. The size is 1 x 1 mm^2

LGAD next – wish list

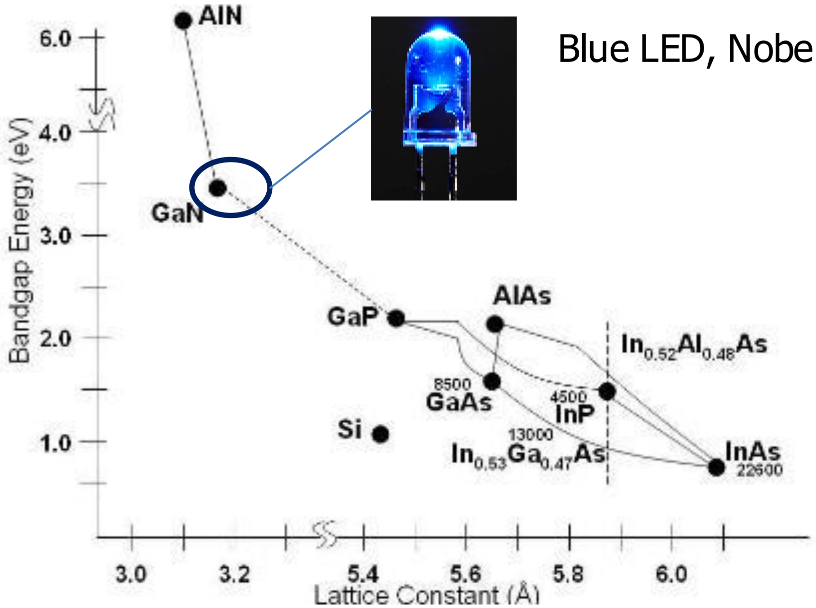




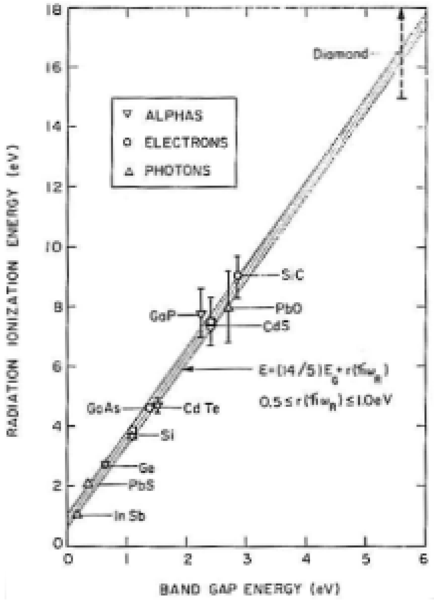
- High granularity LGAD using a deep trench isolation and gain layer formed by epitaxial growth – **no implantation required**
- Feasibility check confirms the process is possible: wafer quotation already obtained
- Application to STFC Early Research and development scheme, 3 years approx. 600k£

Wide bandgap semiconductor Gallium Nitride (GaN)

Design and fabrication of epitaxial gallium nitride (GaN) based devices, and their full characterization after irradiation to HL-LHC fluences and beyond.



Blue LED, Nobel prize 2014

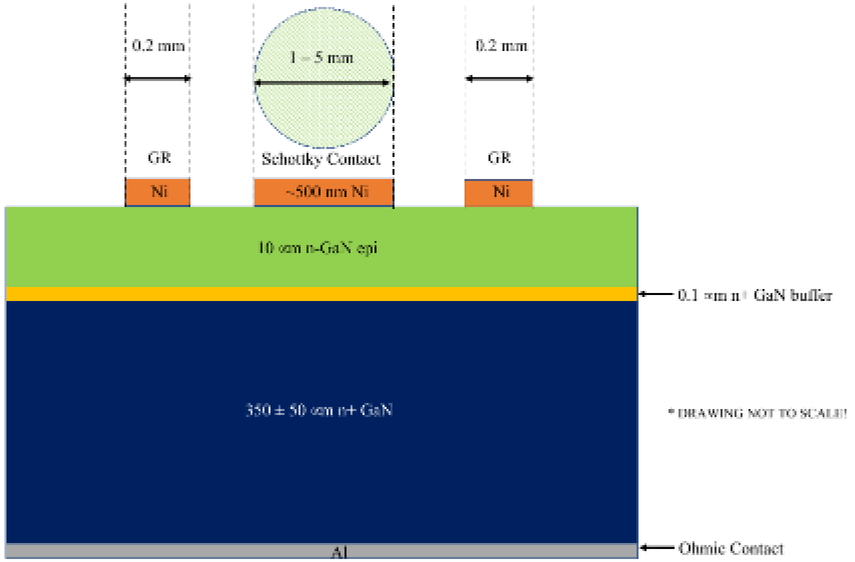


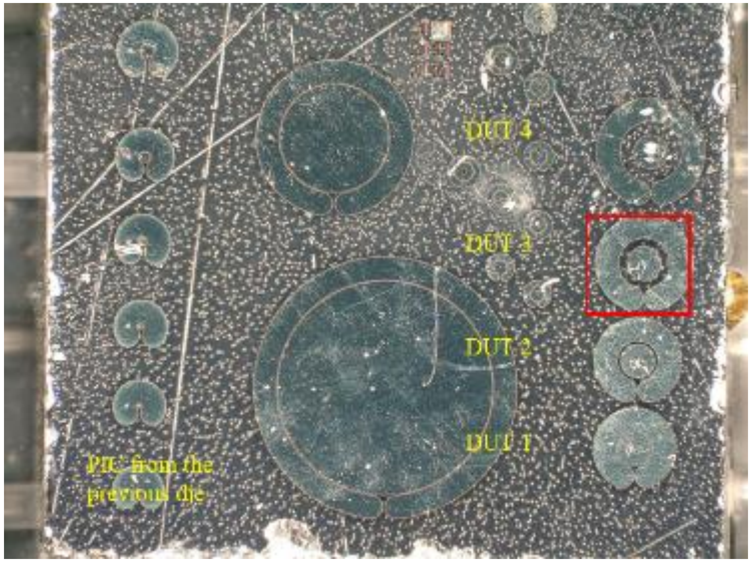
Motivation and Goal

Detection of high energy particles and fast read-out electronics.

The very high Ga–N bond strength and a relatively large room temperature bandgap of 3.4 eV implies higher radiation tolerance and lower leakage (low noise).

Wide bandgap semiconductor Gallium Nitride (GaN)

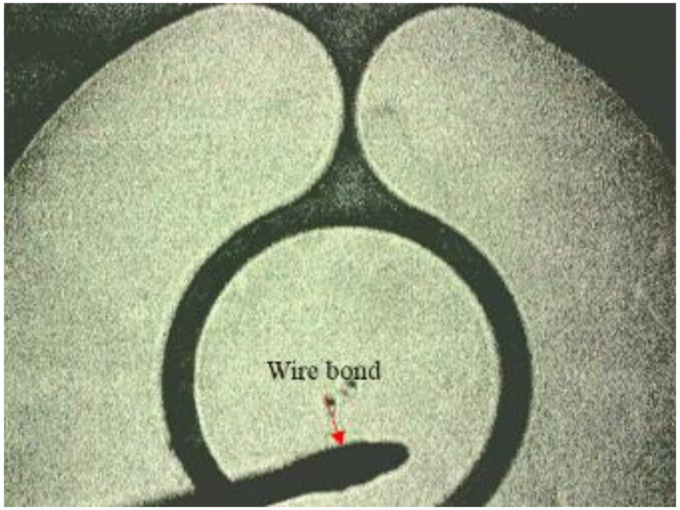


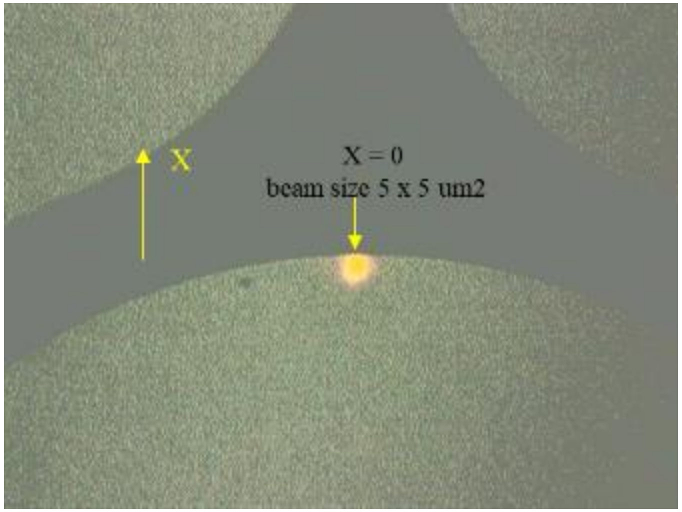


A **RAL PPD**, **University of Oxford**, **Carleton University** (Canada), **CNM** (Spain)
Epitaxial thickness of up to 10 μm, grown on an n$^+$-GaN substrate buffered by a 0.1 μm n$^+$ (Si doped) layer.

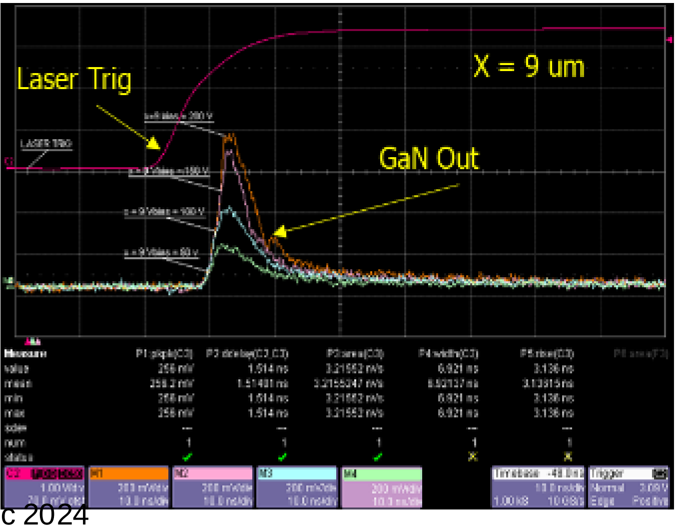
Funding received from RD50 (CERN)

Wide bandgap semiconductor Gallium Nitride (GaN)

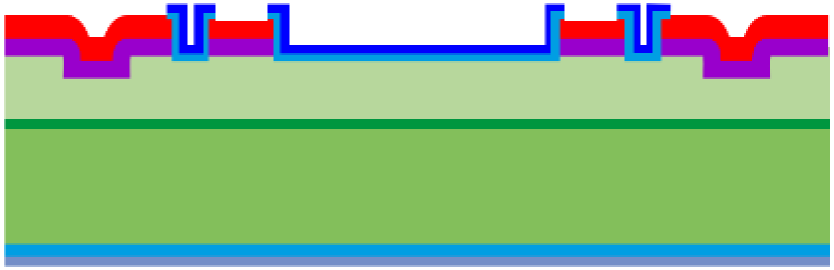




- Tests done at RAL using UV laser
- **The signal increases ≃ linearly in magnitude with bias voltage**
- Being investigated



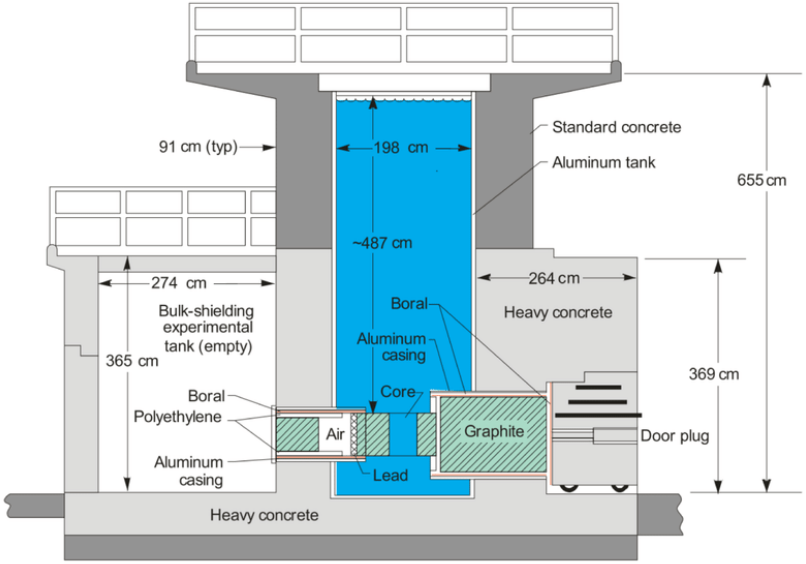
GaN next – wish list



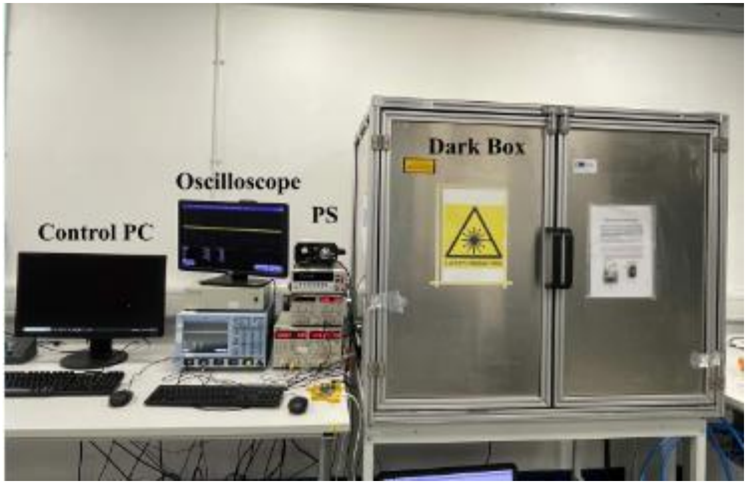
- 2nd run of fabrication of GaN devices, at Carleton/NRC and CNM, to address the issue of top layer fragility (difficult to bond)

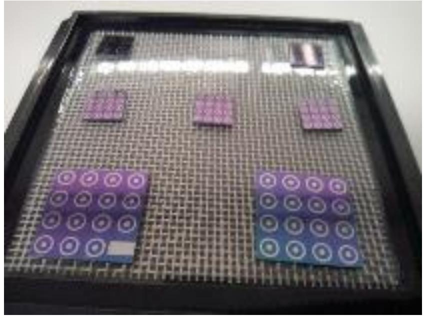
- Neutron / proton Irradiation campaign to HL LHC fluence

- RAL - Oxford PhD studentship on the development of GaN devices for HEP applications



Lab activities

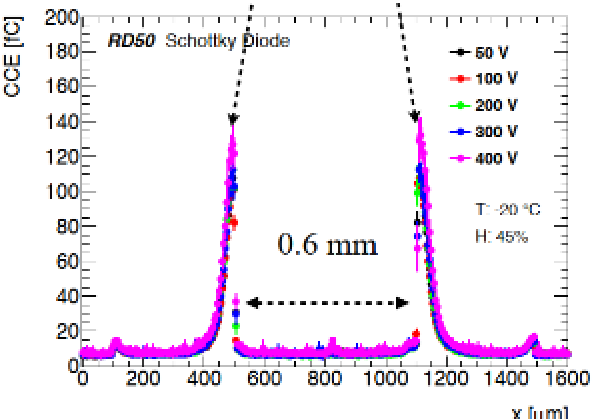




Proposed, designed, fabricated and tested silicon Schottky devices at RAL PPD using I-TAC facility.

Sadly I-TAC closed down due to HS reason

Unclear exactly when it will re-open at RAL (> 5 years)



LabWish

- Proposed relocation (partial / full) of I-TAC to Oxford
- Currently being discussed among parties
- It would lead to the creation of an international centre for advanced HEP detectors fabrication