Barcelona Institute of Science and Technology

Performance studies of CNM LGADs on Si-Si and epitaxial wafers irradiated to extreme fluences up to 1e16 neq/cm2

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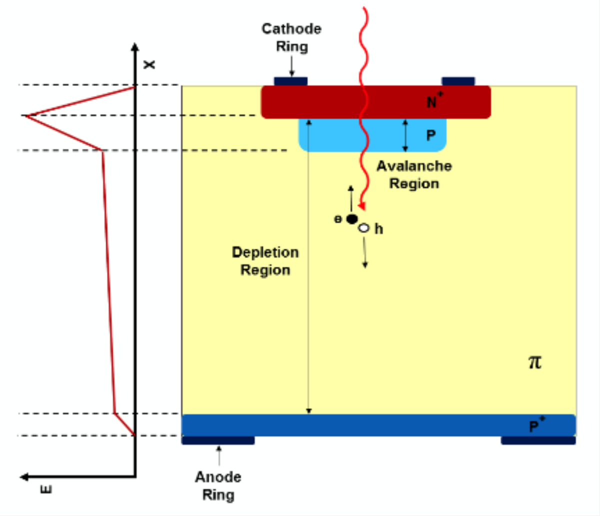
The 39th RD50 Workshop (Valencia)

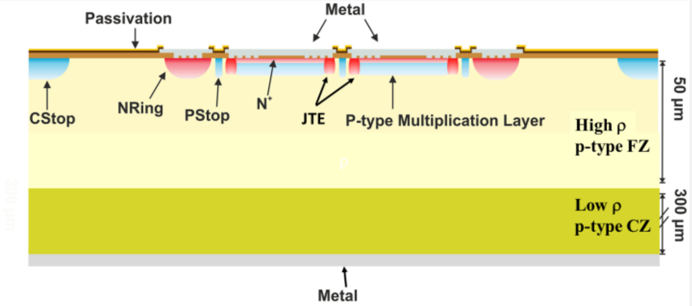
Outline

- Motivation
- Radiation damage
- CNM LGAD technologies (Si-on-Si and low resistivity epitaxial wafers)
- LGAD performance
  - Electrical characterization (IV/CV)
  - Auto-triggering measurements → define operating voltages
  - Beta source measurements for single pad sensor
    - Collected charge
    - Time resolution
  - Transient Current Technique (TCT) measurements
    - Inter-pad (IP) gap on 2×2 LGAD arrays
- Summary and outlook

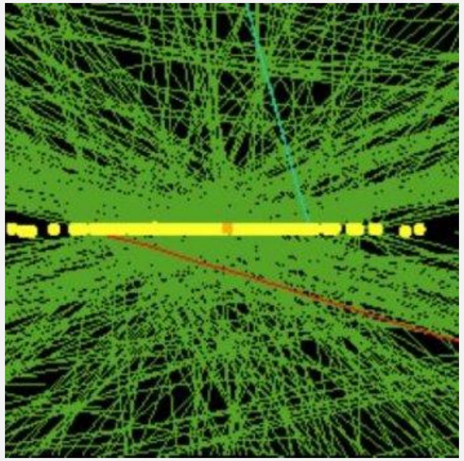
Motivation

- **L**ow **G**ain **A**valanche **D**iode (LGADs) sensors
  - Originally developed by CNM to explore the possible improvement towards radiation hardness (through charge multiplication)
  - Later proposed for timing applications
    - Achieving a time resolution of about 30 ps before irradiation
- Interest to study LGADs and their performance at **high fluences beyond 10^{15} n_{eq}/cm^2**
  - Performance remains challenging due to degradation of the gain layer
  - Investigate new doping materials (B+C, Ga), substrates and new geometries
  - Deliver thin sensors providing good time resolution, fine segmentation, radiation hardness
- ATLAS and CMS experiments have chosen the LGAD technology for the **H**igh **G**ranularity **T**iming **D**etector (HGTD) and for the **E**nd-Cap **T**iming **L**ayer (ETL)
  - ATLAS : 4 fC at 2.5×10^{15} n_{eq}/cm^2 at (max) 600 V, 50 ps time resolution (talk)
  - CMS : 10 fC at 1.5×10^{15} n_{eq}/cm^2 at (max) 600 V, 50 ps time resolution (talk)





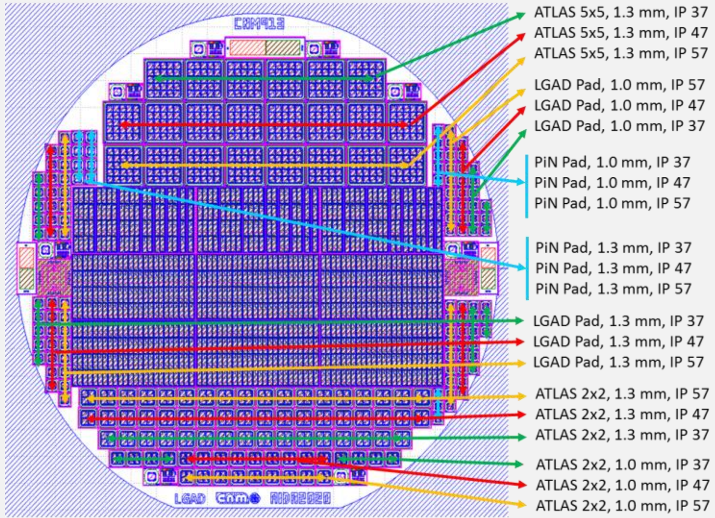
Radiation damage



- Silicon pixel detectors are especially important for the precise determination of tracks and vertices, enabling the selection of interesting events through the identification of b-jets (b-tagging)
- Particle accelerators are improved to further probe the energy frontier delivering higher energies and **increasing the number of collisions per unit time**
- At High Luminosity LHC (HL-LHC):
  - The number of collisions per bunch crossing will be increased
  - The instantaneous luminosity will be approximately a factor of ~5 higher than the LHC nominal values
  - Several LHC experiment sub-systems will require an upgrade in order to **cope with the high rate, hit occupancy and radiation environment**
- Two main types of radiation damage:
  - **Bulk damage** due to Non Ionizing Energy Loss (NIEL)
    - Effective doping concentration, acceptor removal, leakage current, trapping
  - **Surface damage** due to Ionizing Energy Loss (IEL)
    - Accumulation of positive charge
- **New solutions have to be found** for the silicon sensors and the associated front-end electronics

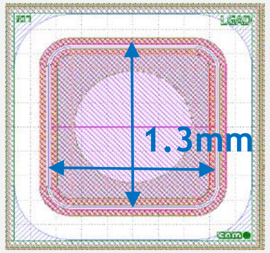
CNM LGAD technologies

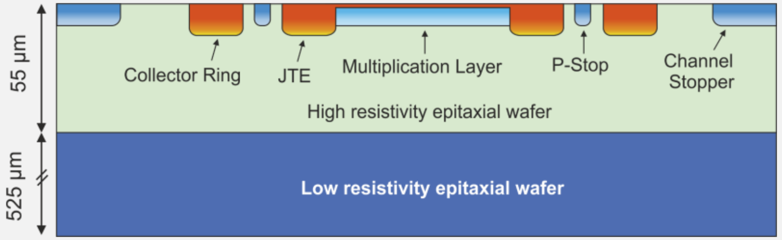
- **CNM Run 12916 AIDA2020**
  - ○ 50 µm active thickness
  - ○ Si-on-Si wafers
  - ○ $V_{gl}{\sim}38V, V_{fd}{\sim}42V, V_{bd}{\sim}85V$ at room temperature
  - ○ B dose: 1.8×10^{13} atoms/cm^2



talk@37th RD50 Workshop

- **CNM Run 13002 EPI (2021)**
  - ○ 6” epitaxial wafers
  - ○ 55/525 µm
  - ○ Substrate resistivity = 0.001-1 Ωcm
  - ○ Epi-layer resistivity ~ 200 Ωcm
  - ○ $V_{gl}{\sim}30V, V_{fd}{\sim}35V, V_{bd}{\sim}400V$ at room temperature
  - ○ B dose: 2×10^{13} atoms/cm^2

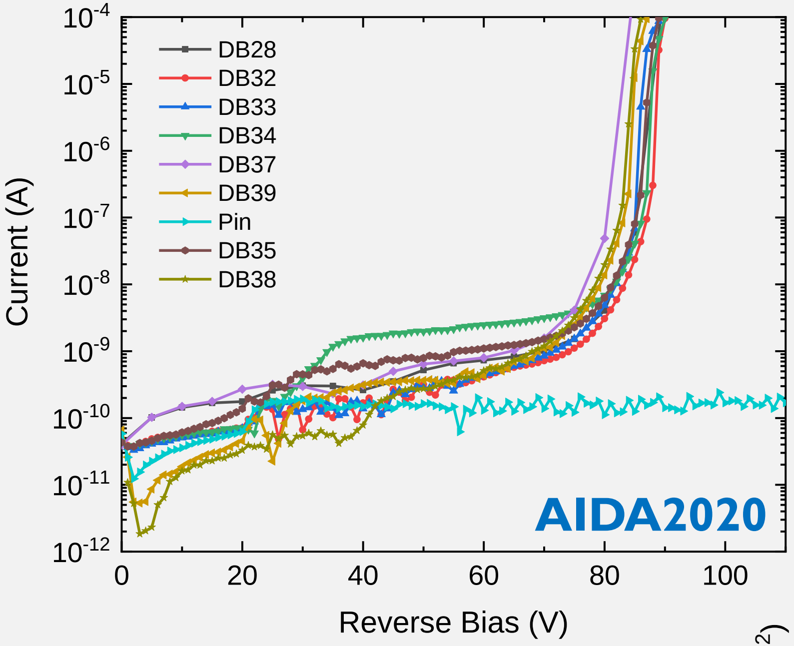


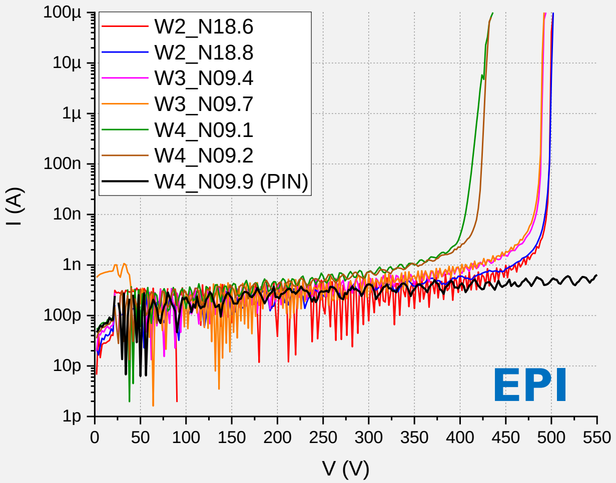


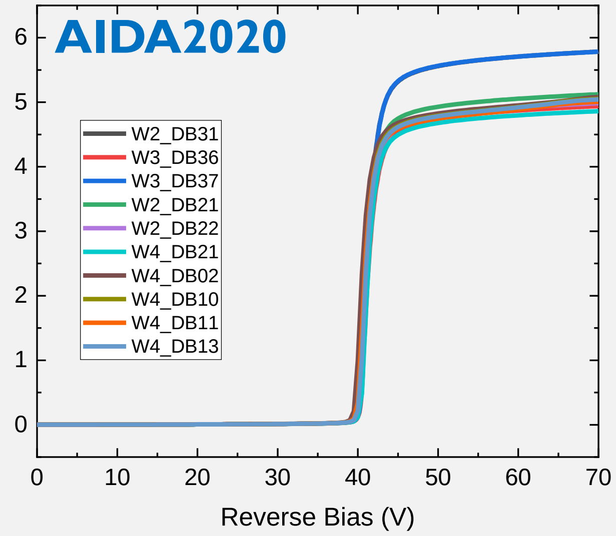
talk@RD50 Workshop

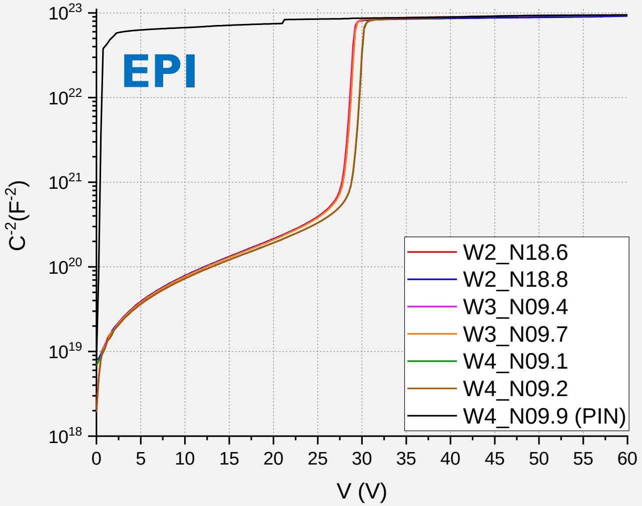
Electrical characterization
(I-V and C-V room temperature at CNM)

Unirradiated devices





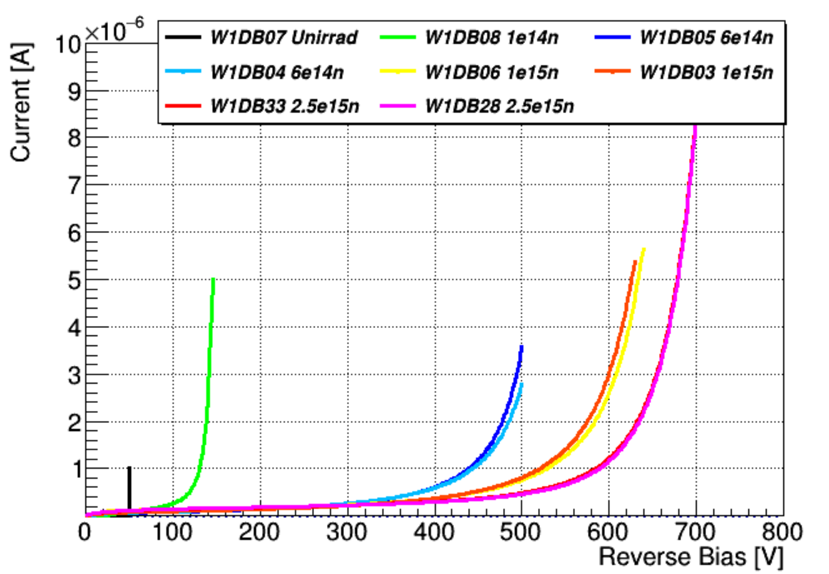




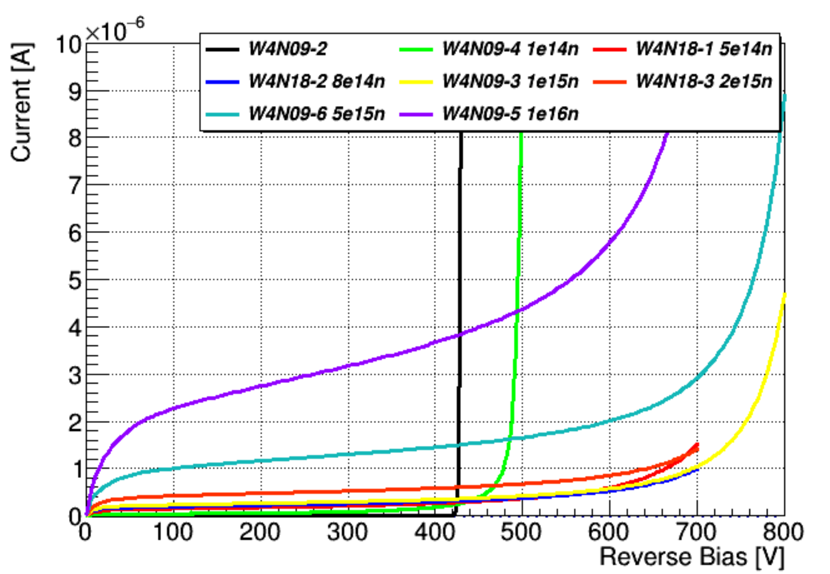
Electrical characterization
(I-V -30 °C)

Irradiated devices

AIDA2020 $T = -30°C$



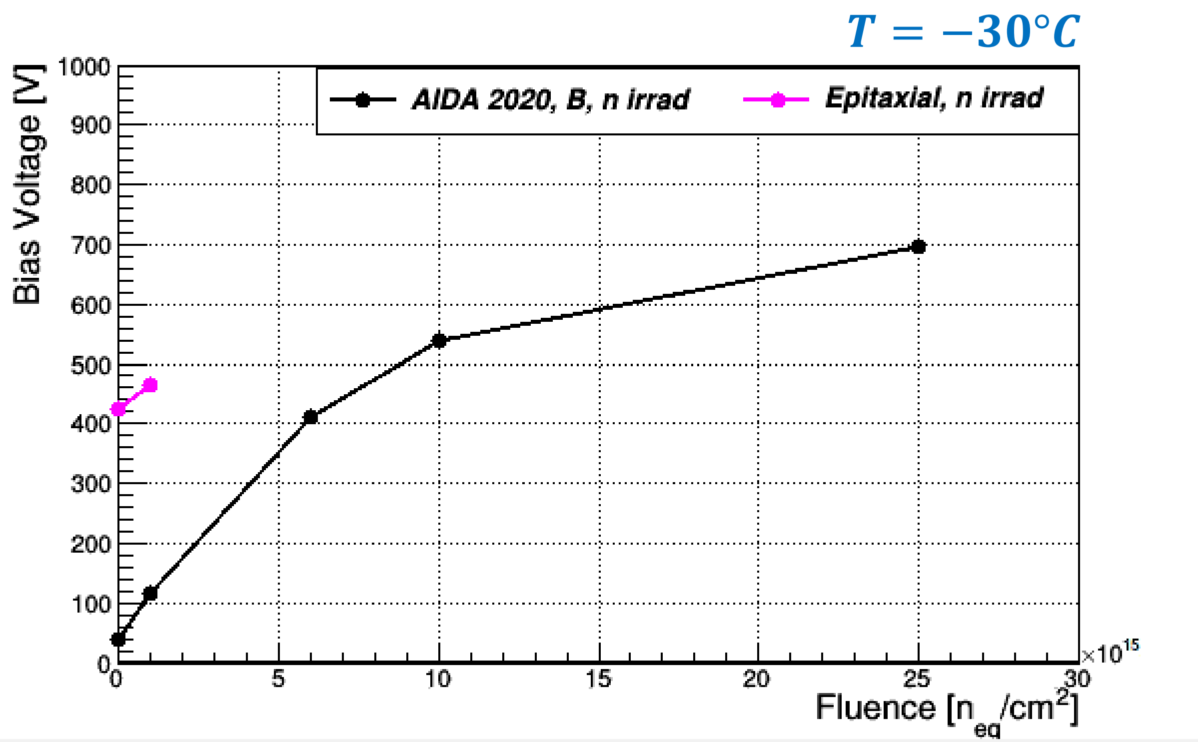
EPI $T = -20°C$



- Early breakdown due to higher dose of wafer implant wrt old B run
- Breakdown is happening at higher voltages

Operational voltage

- The limitation on operating voltages is given by auto-triggering studies
- LGADs at high bias voltages present self pulses (w/o external source)
- We need to make sure that a coincidence event from both tested sensors is a real one, not a fake → need to ensure sensor is not auto-triggering
- Auto-triggering events have waveforms that are identical to real events
- Estimate the frequency of these events
- Trigger on different threshold values for different bias voltages (here only showing 10 mV~5σ_{noise})
- Maximum voltage with an acceptable auto-triggering rate of 1 kHz

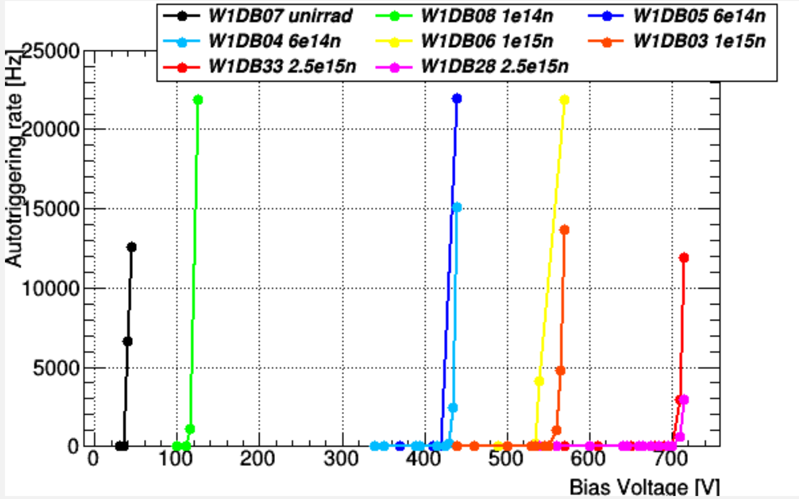


- Subsequent measurements are taken up to bias voltage without auto-triggering

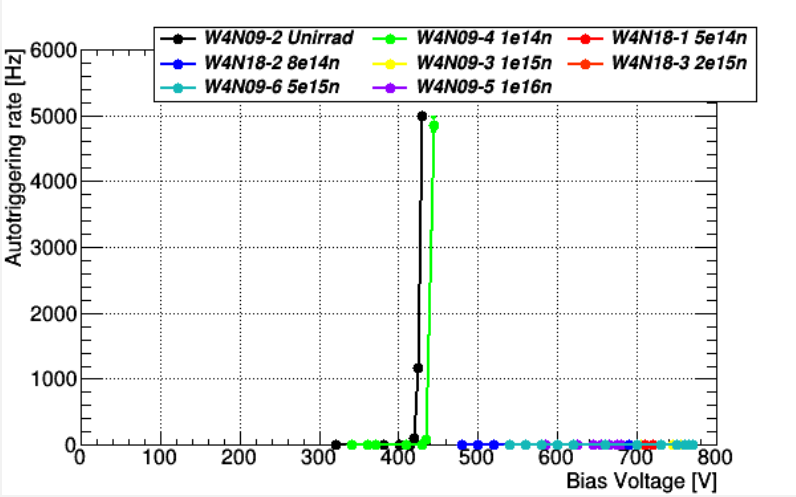
Auto-triggering studies

$T = -30°C$

CNM Run 12916 AIDA2020



CNM Run 13002 EPI

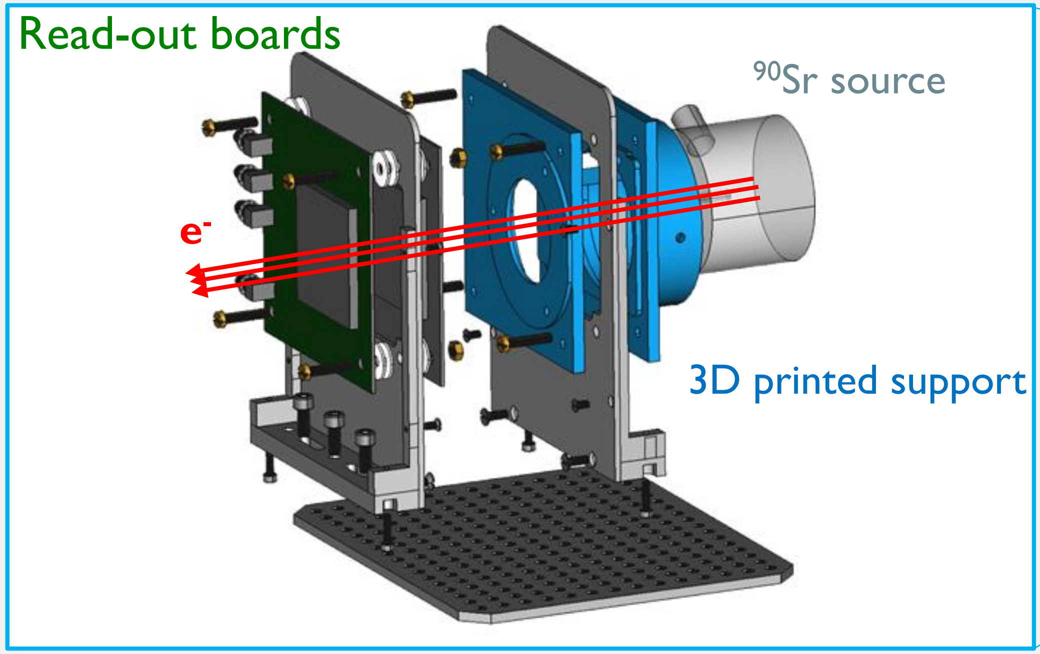


- Unirradiated sensor present a high auto-triggering rate at low voltage which hinders operating it at cold temperature
- Only marginal performances can be achieved before irradiation

- All the fluences present enough room to operate between V_{gl} and V_{bd}
- No detectable auto-triggering up to 770 V for 10^{15} n_{eq}/cm^2 and up to 720 V for 10^{16} n_{eq}/cm^2 but high current, not possible to go higher in voltage

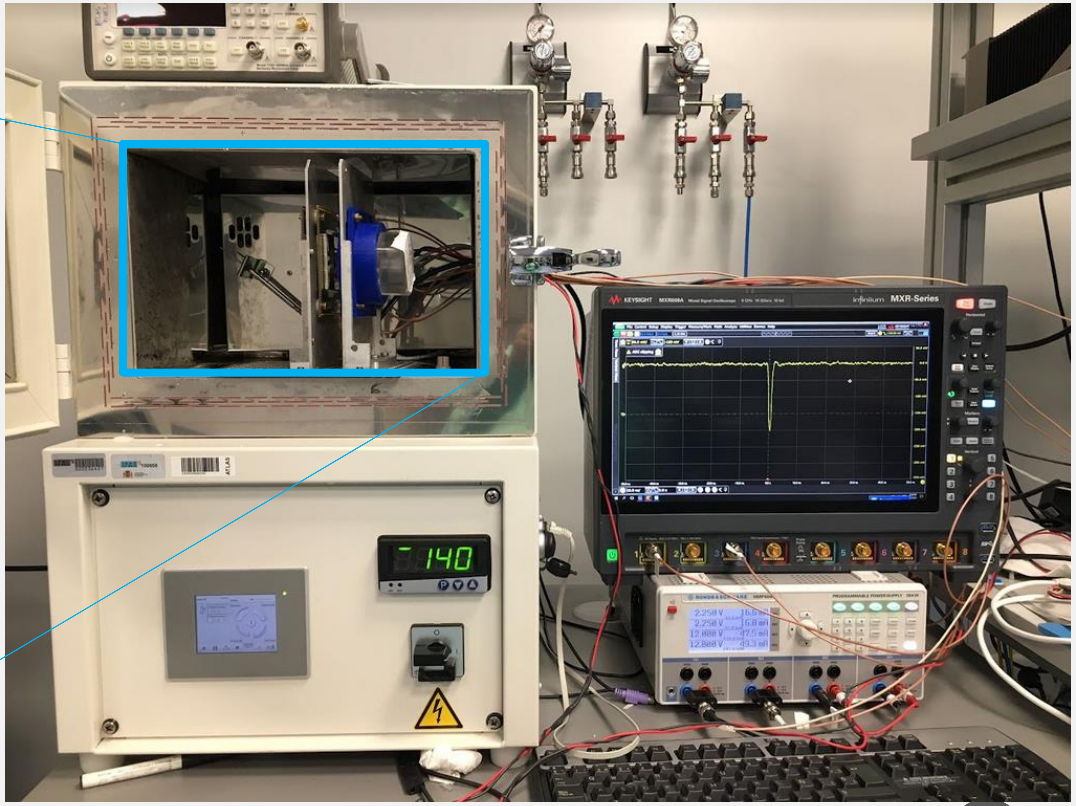
Charged particle measurements

- **Set-up**
  - ^{90}Sr source, custom read-out boards, oscilloscope
  - Temperature control down to -30 °C with climate chamber
  - Avoid condensation by providing dry air



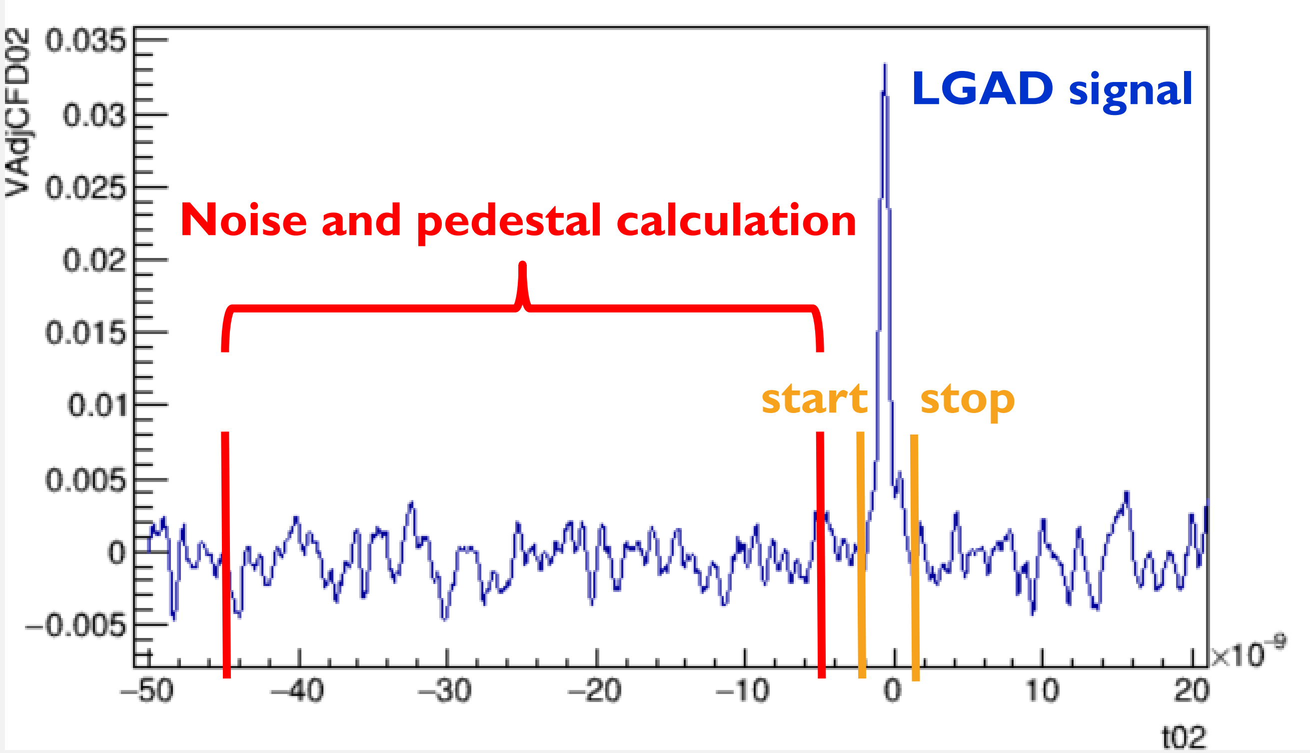
More info: @37th RD50 workshop talk

- **Measurements:**
  - Collected charge
  - Time resolution



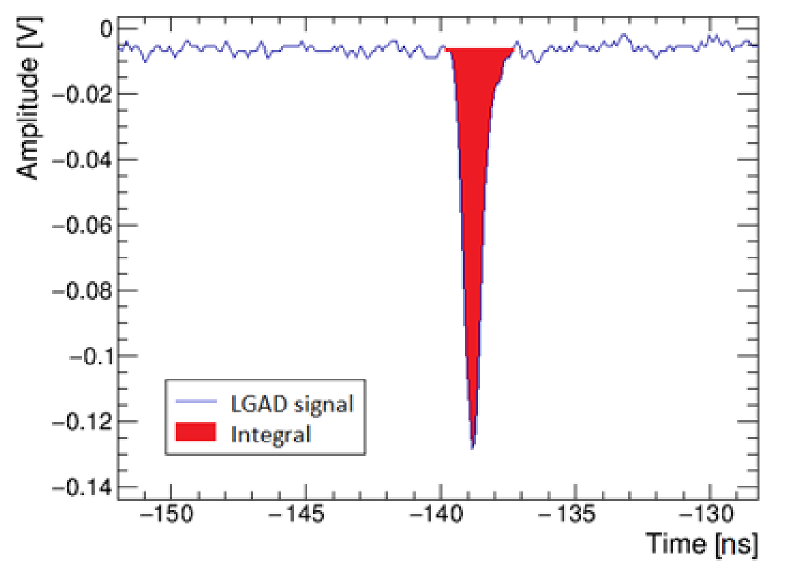
LGAD analysis framework

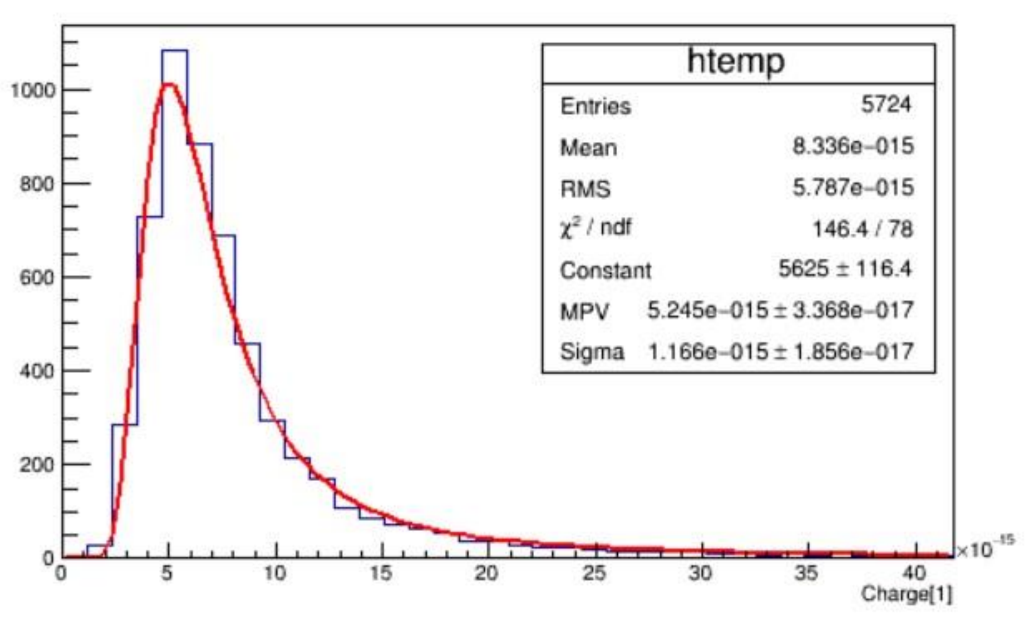
- Waveform processing performed with **LGADUtils framework v1.4 (C++ based)** developed at IFAE by E. L. Gkougkousis (documentation, gitlab)
- Steps:
  - Conversion oscilloscope ASCII/binary data to Root ntuple with raw waveform information
  - Merging with track ntuple from EUTelescope (in test beam)
  - Waveform analysis
    - Determination of pulse polarity, signal start and stop, determine if the pulse is noise or signal
    - Calculate noise level and pedestal using Gaussian fit, pedestal subtraction, re-calculation of start and stop of the signal
    - Compute charge, rise time, time at different CFD fractions, ...
  - User analysis
    - Efficiency
    - Timing



LGAD collected charge

- At each bias voltage point:
  - For each recorded waveform (event), after pedestal substraction, the charge is calculated as the integral of the LGAD signal area
  - A charge distribution is built
  - The collected charge is defined as the MPV value of the Landau-Gauss fit

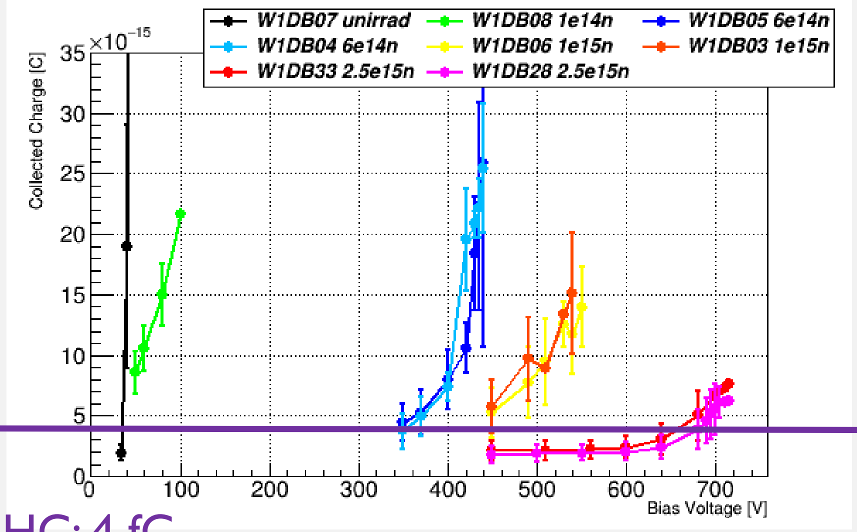




Collected charge

$T = -30^{\circ}C$

CNM Run 12916 AIDA2020



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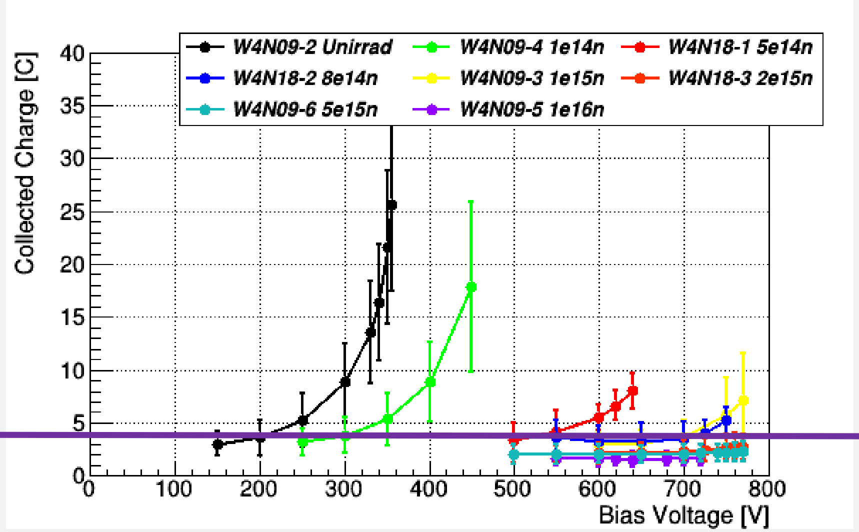
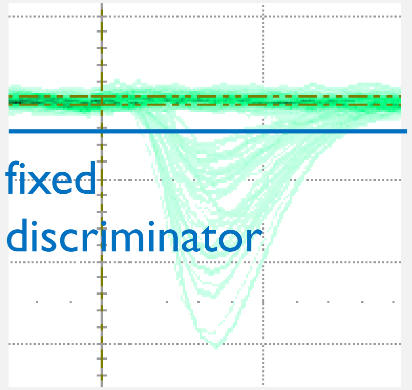


Limit @ HL-LHC: 4 fC

- Unirradiated sensor results are biased by the high auto-triggering rate
  - Not enough room to operate the sensor at -30°C
- 2.5×10^{15} n_{eq}/cm^2 irradiated sensors reach 4 fC for bias voltage higher than 680 V

- Up to 10^{14} n_{eq}/cm^2 irradiated sensors a high collected charge (>10 fC) is achieved
- For 10^{15} n_{eq}/cm^2 irradiated sensor 4 fC is reached at BV>700 V
- No detectable gain for 1e16 n up to 720 V
- Tests of intermediate fluences (5×10^{14}, 8×10^{14}, 2×10^{15}, and 5×10^{15} n_{eq}/cm^2) show that fluences above 10^{15} do not have gain

LGAD time resolution (ref. LGAD)



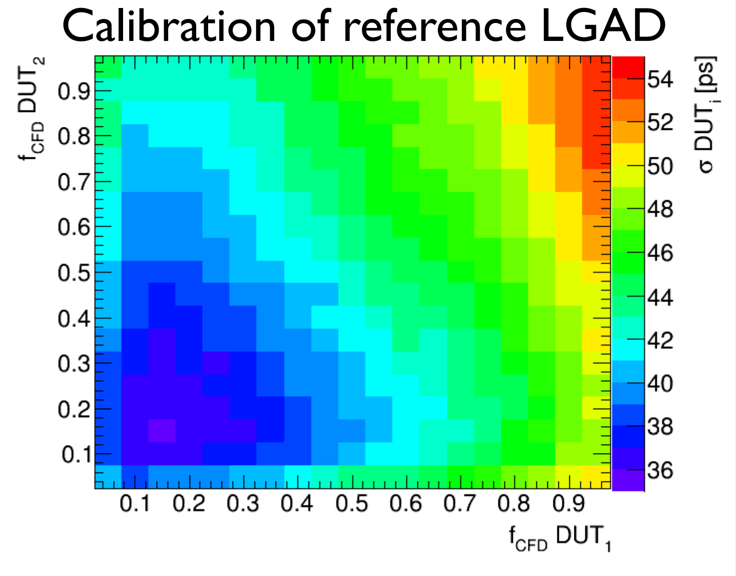
- Time walk effect due to signals with different amplitude reaching a single discriminator threshold is corrected using Constant Fraction Discrimination (CFD) method

- Find optimal CFD fraction achieving the minimum time resolution for the reference LGAD
  - Build a 2D map of time resolution as a function of the CFD fractions (${f_{CFD}}_{DUT1}$, ${f_{CFD}}_{DUT2}$)
    - Time difference distribution calculated as:

$$\Delta t = t_{DUT1({f_{CFD}}_i)} - t_{DUT2({f_{CFD}}_j)}$$

    - Time resolution is defined as $1/\sqrt{2}$ the standard deviation of the Gaussian fit

- Reference LGAD calibrated in the lab at -30 °C
  - Best time resolution achieved is 35.7 ps for ${f_{CFD}}_{ref}$=15%



LGAD time resolution (DUT)

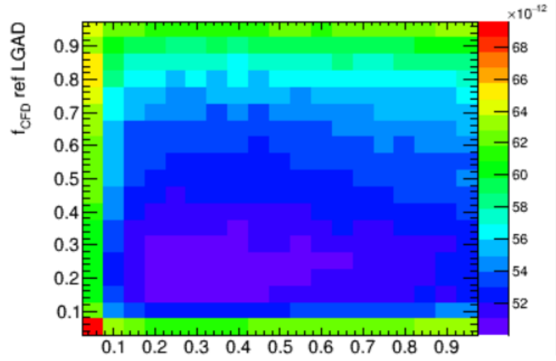
- Find optimal CFD fraction achieving the minimum time resolution for the DUT
  - Build a 2D map of time resolution as a function of the CFD fractions ($f_{CFD_{DUT}}, f_{CFD_{ref\ LGAD}}$)
    - Time difference distribution calculated as:

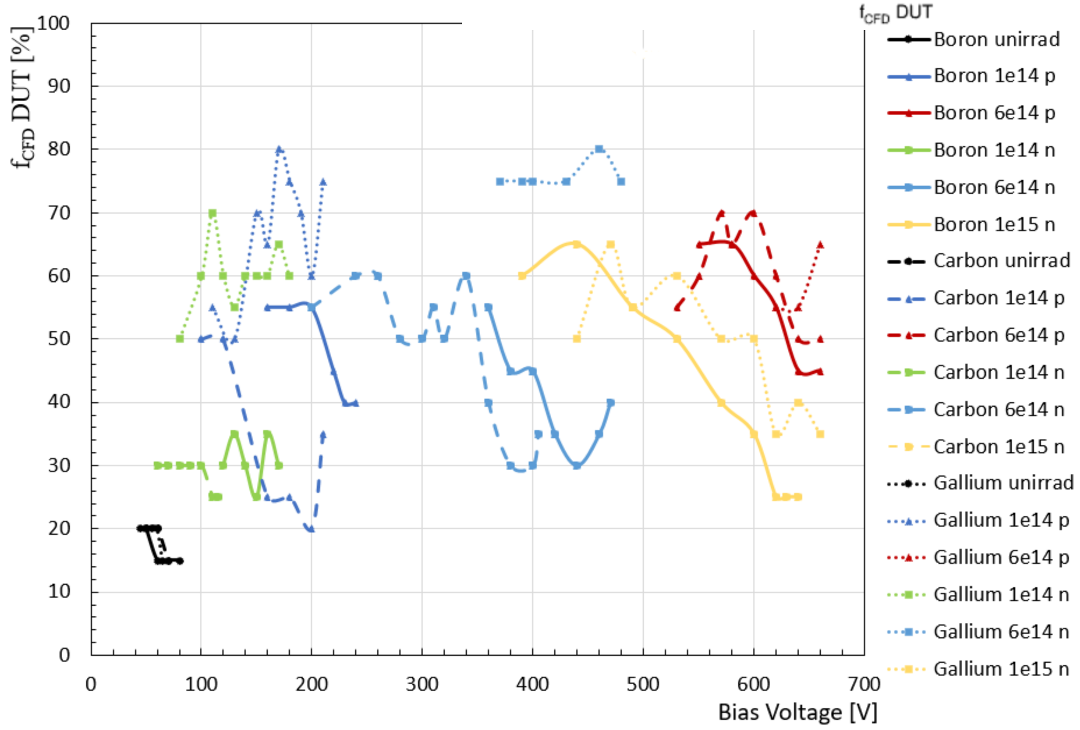
$$\Delta t = t_{DUT(f_{CFD_i})} - t_{ref\ LGAD(f_{CFD_j})}$$

    - Time resolution is defined as:

$$\sigma_{DUT} = \sqrt{\sigma_{fit}^2 - \sigma_{ref\ LGAD}^2}$$

  - Fraction defined by the dominant contribution
    - Unirradiated sensor → Landau fluctuations of charge deposition
    - Irradiated sensor → jitter (higher threshold)

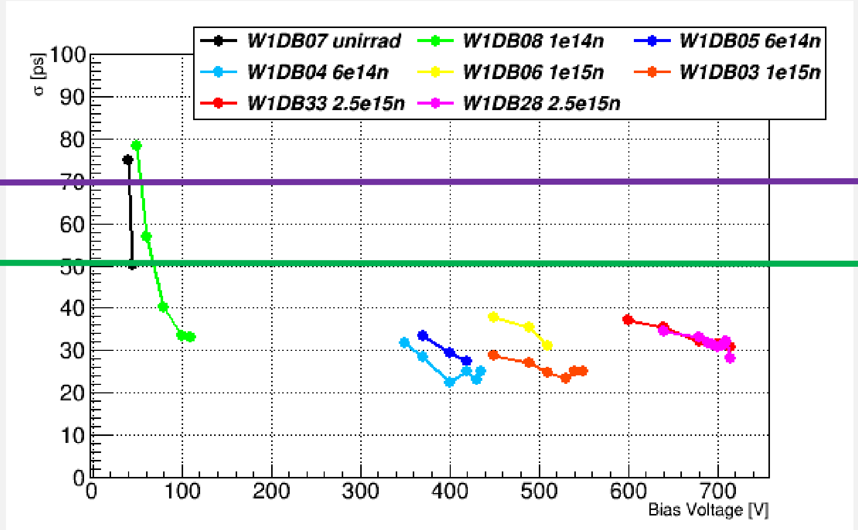




Time resolution

$T = -30°C$

CNM Run 12916 AIDA2020



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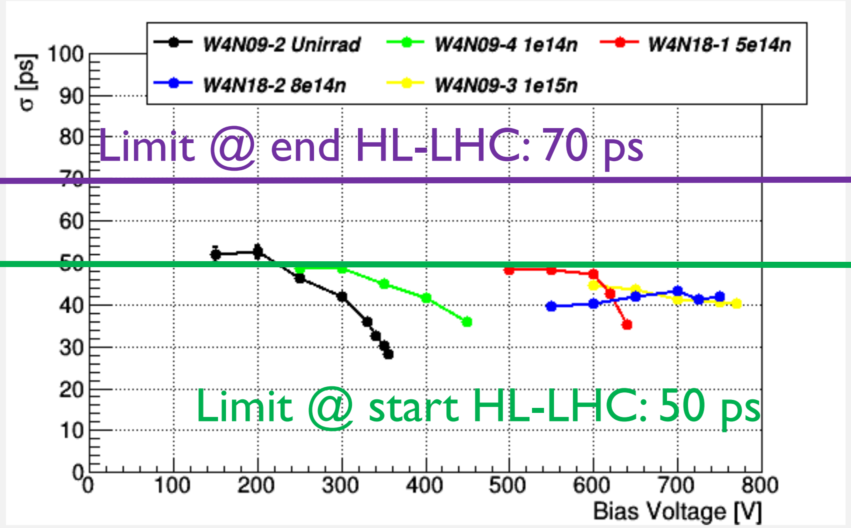


Limit @ end HL-LHC: 70 ps

Limit @ start HL-LHC: 50 ps

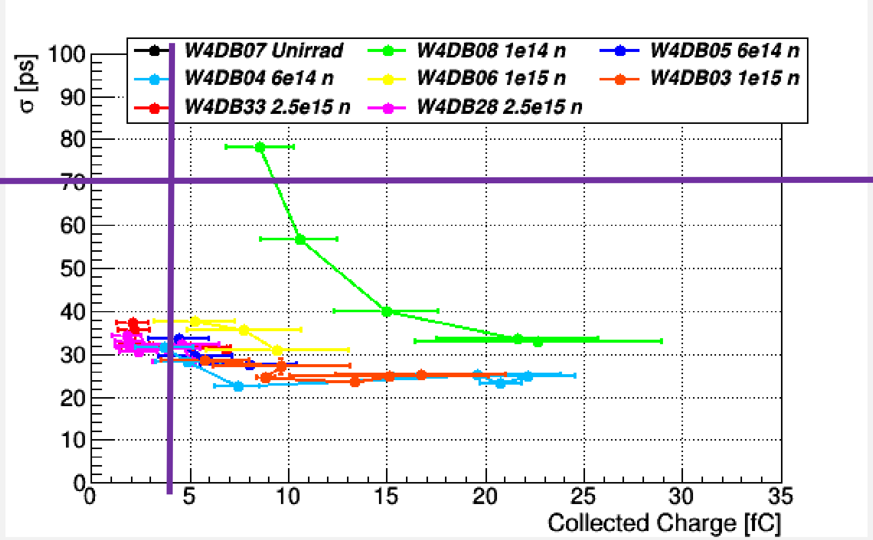
- Unirradiated sensor cannot be operate at higher voltage due to auto-triggering, marginal performances in timing
- Irradiated sensors achieve a time resolution lower than 40 ps at all level of neutron irradiation

- A time resolution < 50 ps is achieved for sensor irradiated up to 10^{15} n_{eq}/cm^2
- For fluences lower than 8×10^{14} n_{eq}/cm^2 the sensors achieve a time resolution below 40 ps for the higher voltages

Time resolution vs Collected charge

$T = -30^{\circ}C$

CNM Run 12916 AIDA2020



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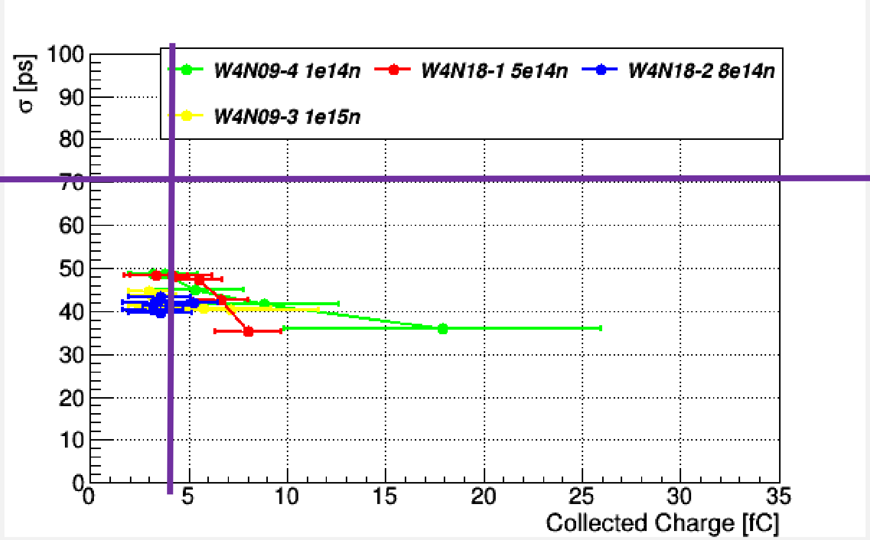
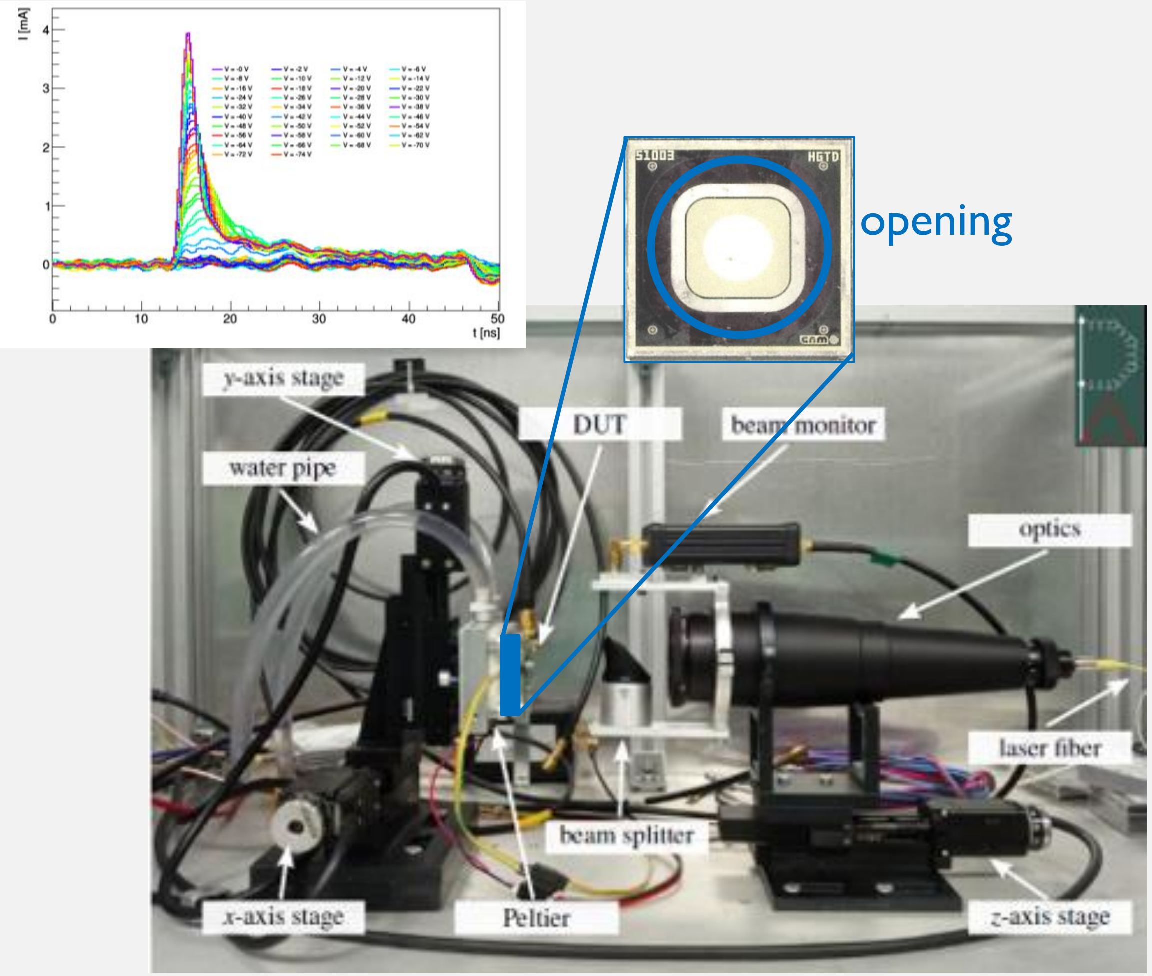


- LGADs exposed to neutron fluence up to 2.5×10^{15} n$_{eq}$/cm^2
- A charge of 4 fC can be reach up to a fluence of 2.5×10^{15} n$_{eq}$/cm^2, providing a time resolution better than 70 ps per hit
- The performance of LGADs from the two technologies is similar, AIDA2020 run achieve better time resolution
- The time resolution for the largest fluence is fully dominated by the electronics jitter

Transient Current Technique (TCT)

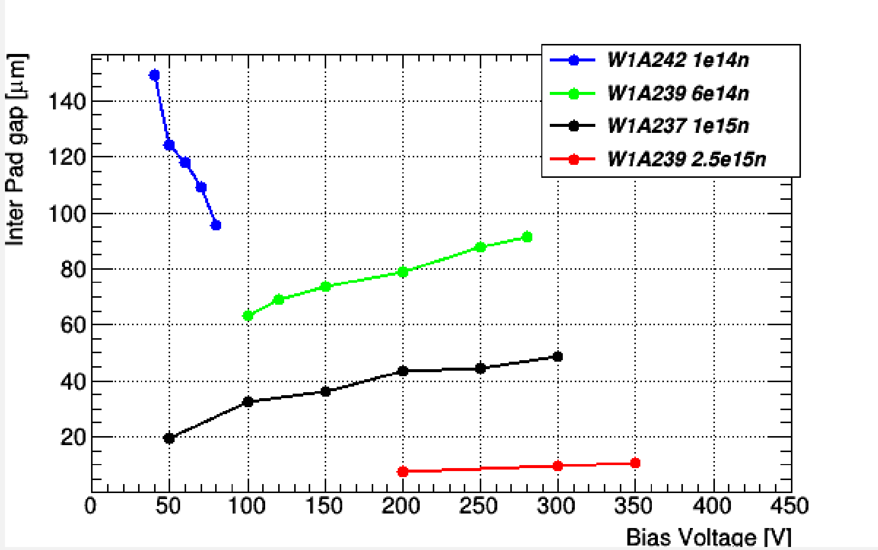
- **Set-up:**
  - Time-resolved current waveforms introduced by drift charge inside a sensor
  - Current proportional to the number of charges, drift velocity and weighting field of the readout electrode
  - Pulsed laser source (spot size = 10 μm) mimics the behavior of a charged particle
    - Red ($\lambda_1 = 640\ nm$) and Infra-Red ($\lambda_2 = 1040\ nm$)
  - Possibility to perform room temperature and cold measurements (till -20 °C)
    - Cooling system with Peltier + Chiller
    - Dry environment
  - LGAD assembled in a metal box mounted on the movable X-Y stage
  - Set-up is remotely controlled
  - Detector illuminated from the back with IR laser
    - To perform TCT LGADs need to have an opening in the metallization layer
- **Aim of measurements:**
  - Compare behaviour before and after irradiation
    - Gain for single pad devices
    - IP gap for 2×2 arrays



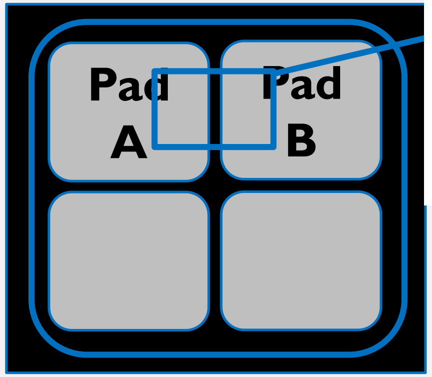
AIDA2020 results: IP gap

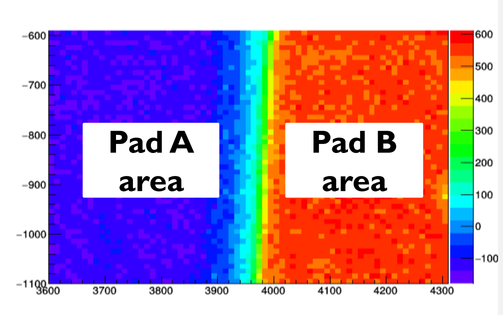
$T = -20°C$

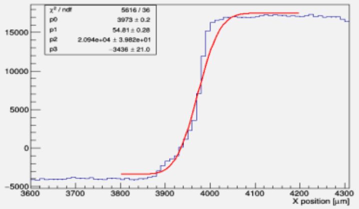
- Measure IP gap by scanning the area between two pads
  - Record 1k waveforms for each X-Y position
  - Pad A and B are readout through two different lines
  - Build a 2D map of collected charge as a function of the laser position
  - Make projection for each pad and fit it with an S-curve
  - IP is defined as: $IP\ gap = |x_{A\ 50\%} - x_{B\ 50\%}|$



Scanned area for IP gap





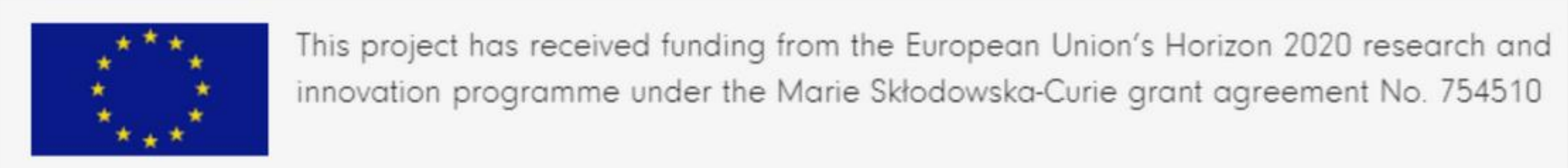


- Unirradiated sensor not operable →high current and early breakdown
- Low fluences
  - Carriers generated underneath the gain layer end their drift on JTE and don't undergo multiplication
- High fluences (>6×10^{14} n$_{eq}$/cm^{2}):
  - Some gain from carriers drifting to the JTE, a smaller IP has been measured
  - The IP gap is larger at higher bias voltages
- Results are compatible with previous results on LGADs from other vendors (slides@38th RD50 Workshop) and in agreement with their simulation

Summary and outlook

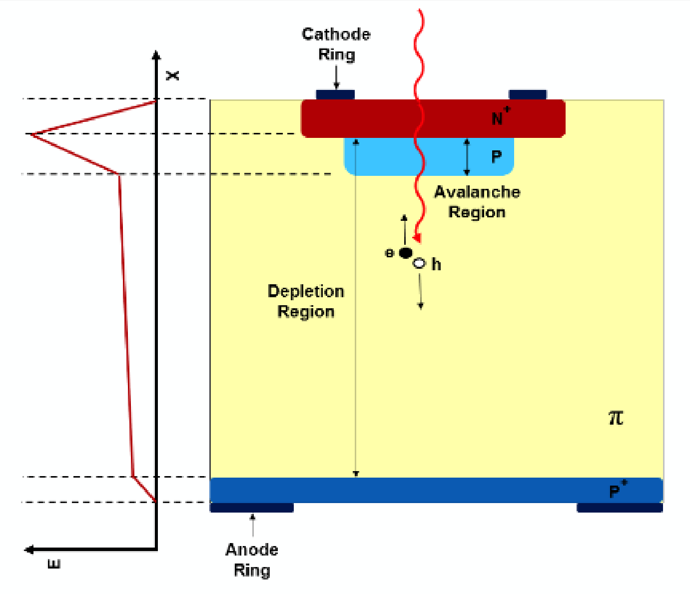
- **AIDA 2020 Boron (Run 12916)**
  - Unirradiated LGAD does not show enough room to operate between V_{gl}, V_{fd} and V_{bd} voltages and early breakdown
  - Good performances in collected charge and time resolution achieved for fluences up to 2.5×10^{15} n_{eq}/cm^2
- **Epitaxial Boron (Run 13002)**
  - Unirradiated LGADs show enough room to operate between V_{gl}, V_{fd} and V_{bd} voltages and low auto-triggering rate
  - LGADs irradiated to a fluence of 10^{15} n_{eq}/cm^2 work but at relative high bias (700 V), due to low gain and low resistivity of wafer
- **Next steps**
  - A new common ATLAS/CMS run will be ready by the end of this year
    - Epitaxial run with C implanted in the gain layer on some wafers

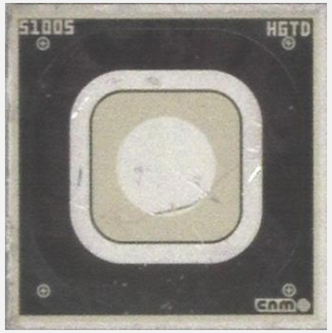
THANK YOU FOR YOUR ATTENTION


This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 754510

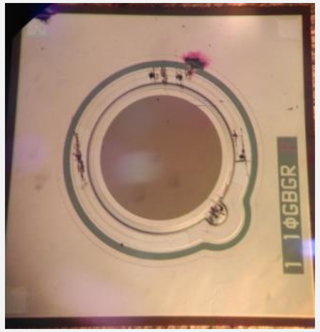
Detection technology: LGAD

- **L**ow **G**ain **A**valanche **D**etectors (LGADs) originally developed by CNM
  - n-p silicon planar detector + multiplication layer that amplifies the signal
  - High E field
  - Moderate internal gain (10-50)
  - Typical rise time 0.5 ns
  - Excellent time resolution <30 ps before irradiation
- R&D programme to deliver thin sensors to provide the required time resolution (30 ps per track), fine segmentation, radiation hardness
  - New doping materials, substrates and new geometries
  - Prototypes tested from CNM, HPK, BNL, FBK





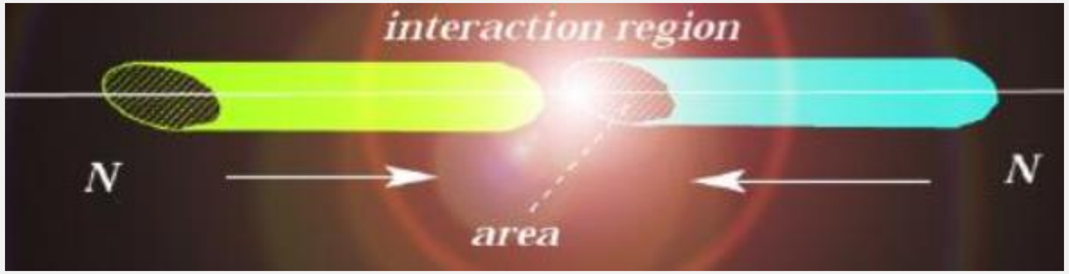
CNM LGAD for HGTD

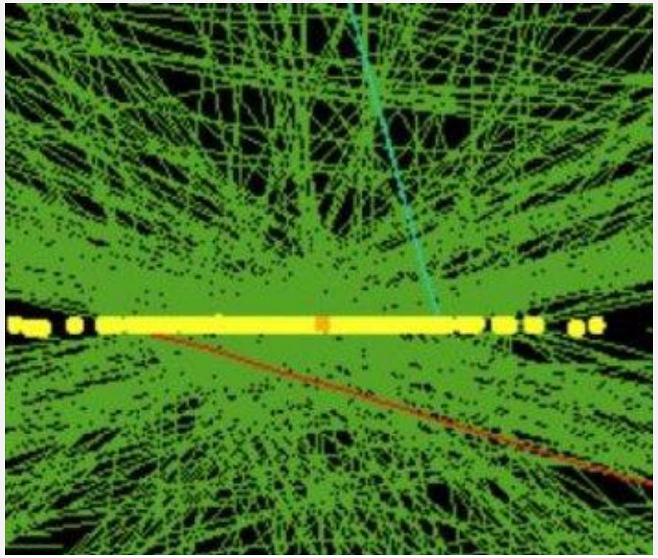


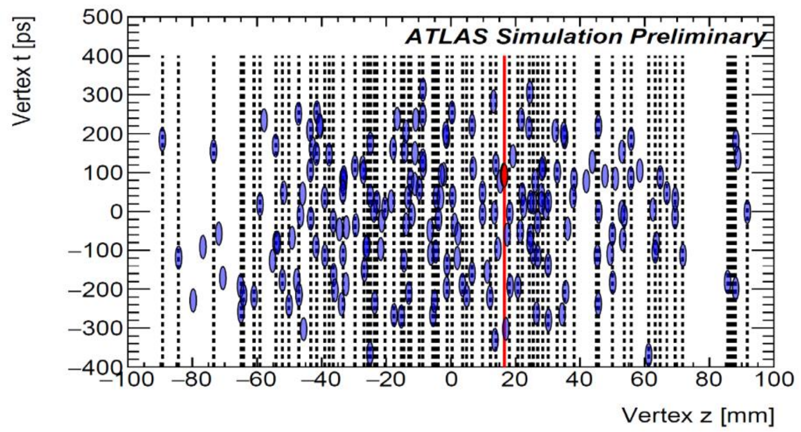
HPK LGAD for HGTD

Why timing is so important?

- **High-Luminosity phase of LHC** (HL-LHC)
  - Instantaneous luminosities up to L $\simeq 7.5\times10^{34}$ cm^{-2} s^{-1} (×5 current L_{inst})
    - Luminosity = number of collisions in a detector per cm^2 and per second



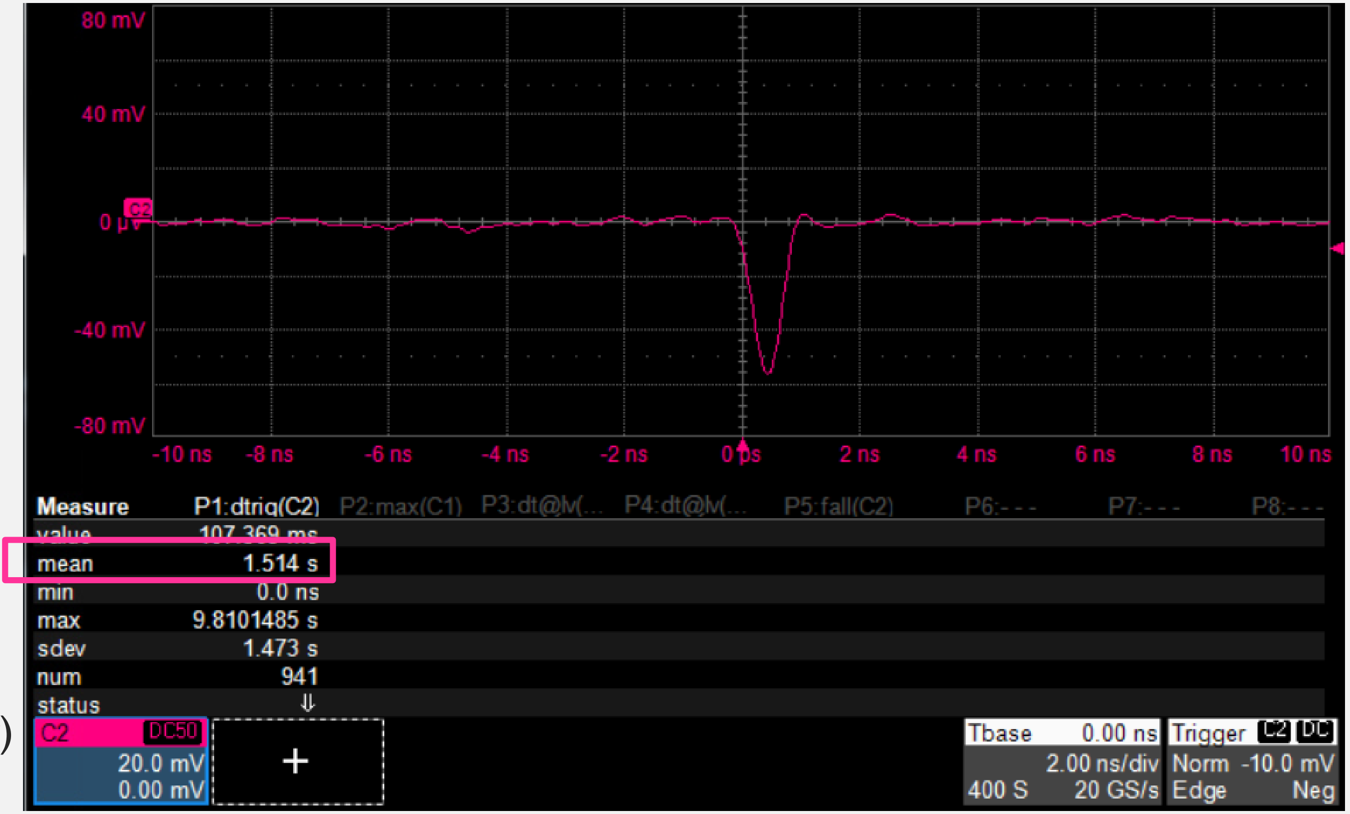




  - Pile-up: $<\mu>$ = 200 interactions per bunch crossing → 1.5 vertex/mm on average
  - Vertex reconstruction and physics objects performance will be significantly degraded
  - Push to higher luminosity → timing is more and more important
    - Using timing information easier to reconstruct vertices

Basic principles

- Study on proton and neutron irradiated CNM LGADs
    - Boron implanted (R10478 W4)
    - Boron implanted + Carbon enriched (R10478 W5)
    - Gallium implanted (R10924 W6)
- We need to make sure that a coincidence event from both tested sensors is a real one, not a fake → need to ensure sensor is not auto-triggering
- Trigger on different threshold values for different bias Voltages (here only showing 10mV)
- No radioactive source or other source of events
- Collect at least 1k events and estimate period (frequency)
- Noise events have waveforms that are identical to real events

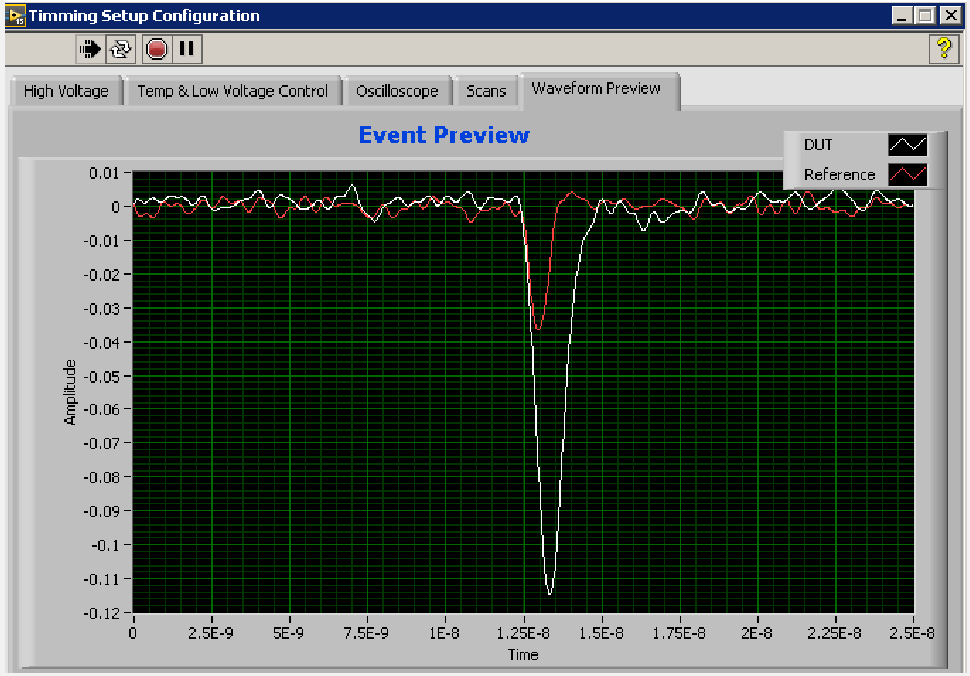


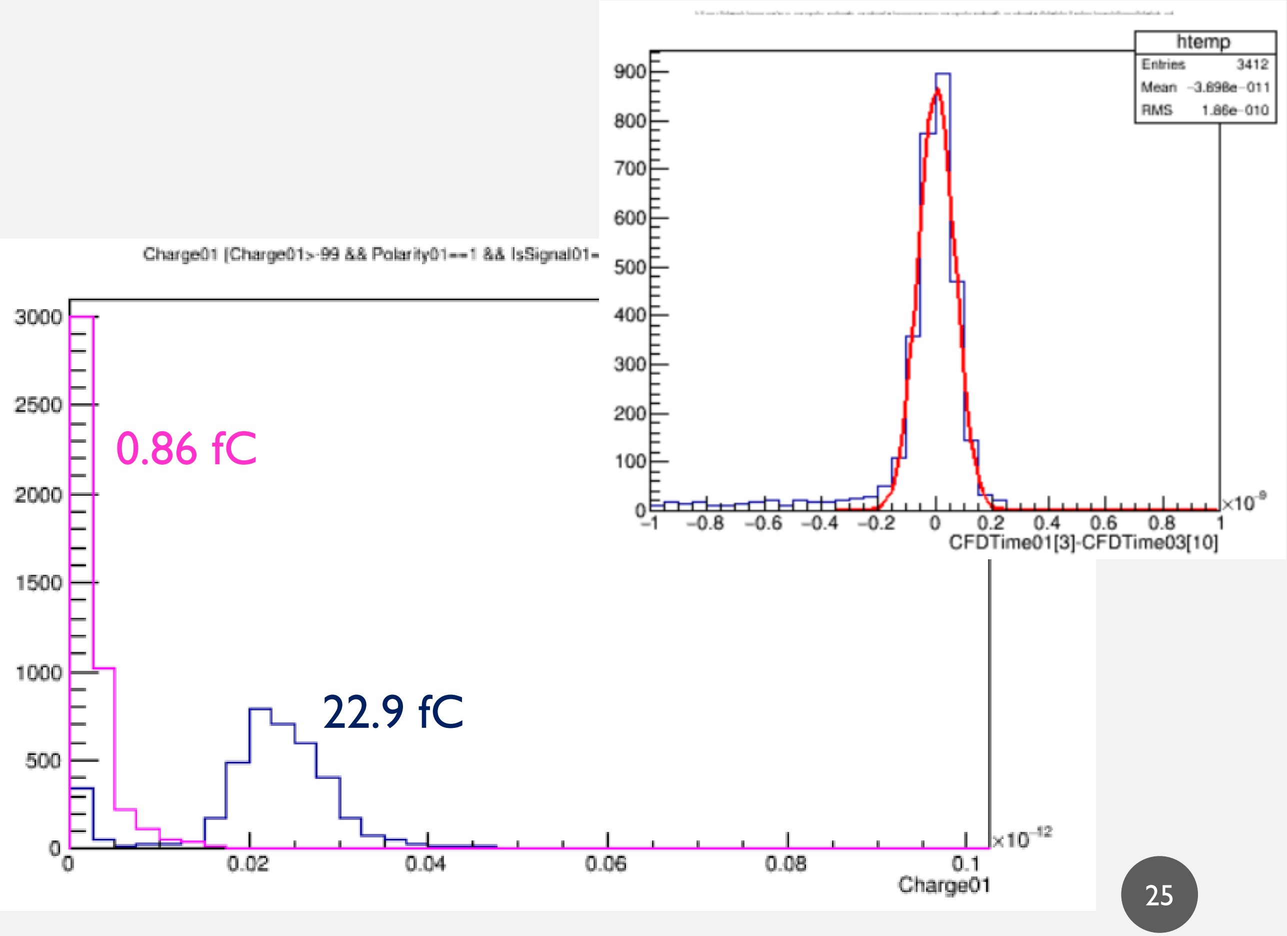
Measure	P1:dtrig(C2)	P2:max(C1)	P3:dt@lv(...	P4:dt@lv(...	P5:fall(C2)	P6:- - -	P7:- - -	P8:- - -
value	107.369 ms							
mean	1.514 s							
min	0.0 ns							
max	9.8101485 s							
sdev	1.473 s							
num	941							
status	⇓							

Preliminary results

- Beta source set-up
  - DUT: W6S1080 6e14 p @-560 V (-30 C) → data taking until -700 V
  - Ref: W4S1022 unirradiated @-80 V (-30 C)

σ_{DUT} =64.8 ps (σ_{ref} =35.7 ps) → 54.1 ps

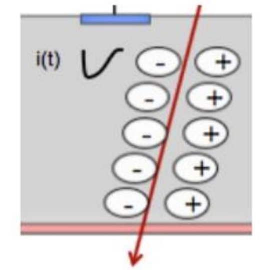


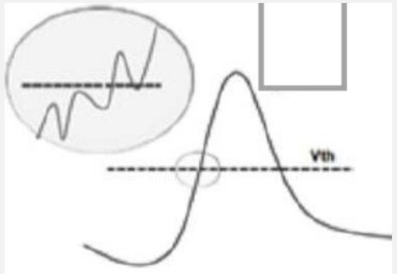


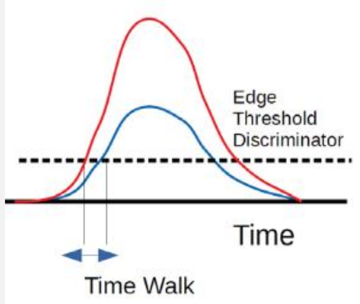
Contributions to timing

- **Time resolution:**
  - Landau term <25 ps
    - Reduce for thin sensors: 35-50 μm
  - Jitter term <15 ps and time walk term <10 ps
    - Low noise and fast signals
  - Digitization granularity ~5 ps
  - Clock distribution <15 ps

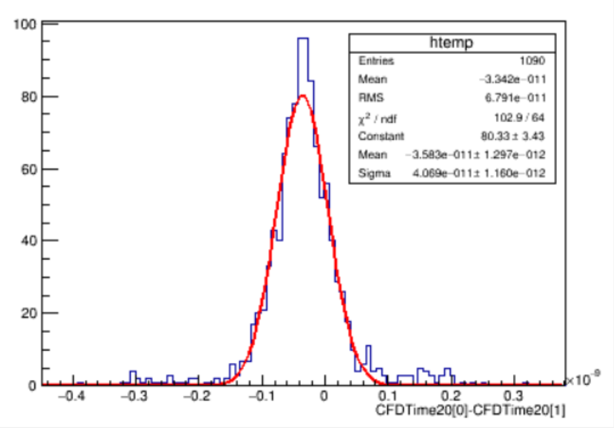
$$\sigma_{tot}^2 = \sigma_{Landau}^2 + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{\mathrm{TDC}_{bin}}{\sqrt{12}}\right)^2 + \sigma_{clock}^2$$

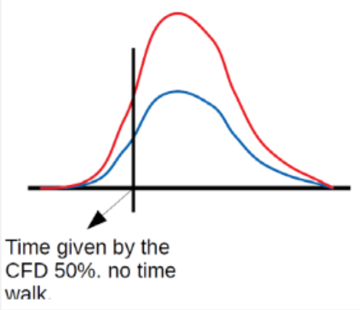






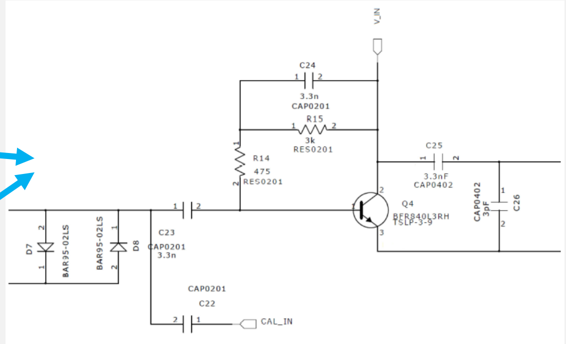
- Time walk corrections on beam test data using the **C**onstant **F**raction **D**iscriminator (CFD) technique
  - Considering the time at a fraction of 50% of the amplitude (typical fraction is 20%)

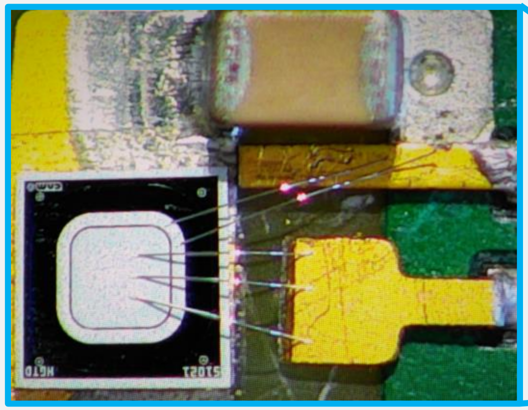


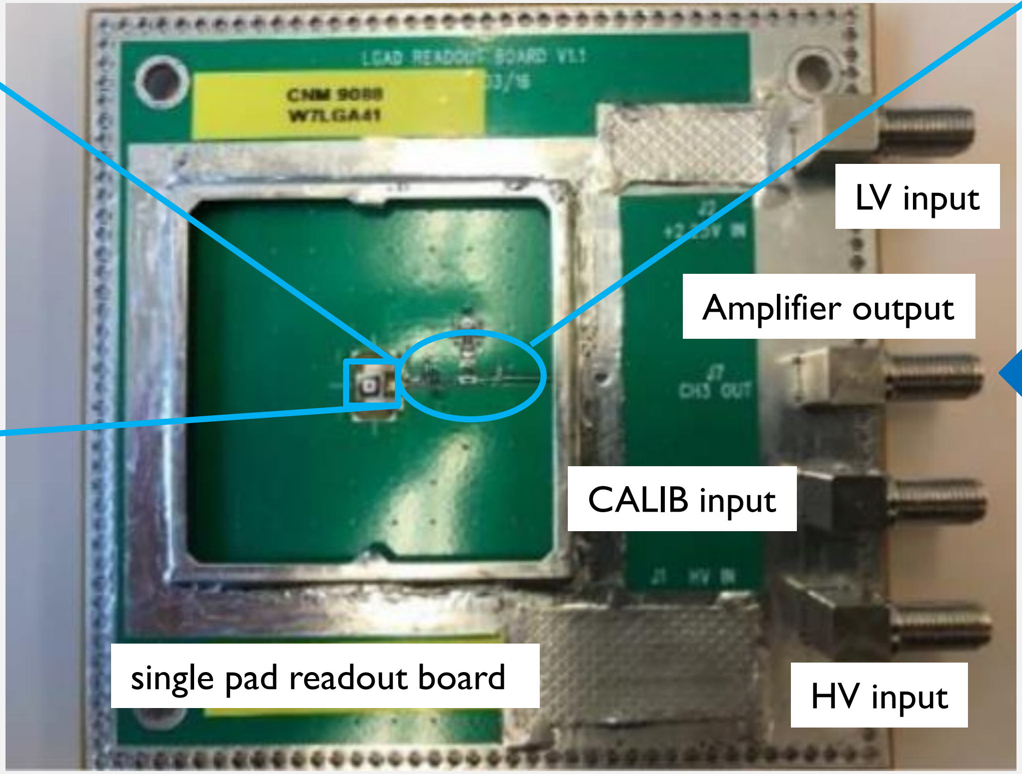


Assembly Sensor + Readout board

- 50 sensors (unirradiated, p- and n-irradiated) tested so far
- LGAD readout boards with trans-impedance first stage amplifier
- Voltage second stage amplifiers with hermetic E/B cover design





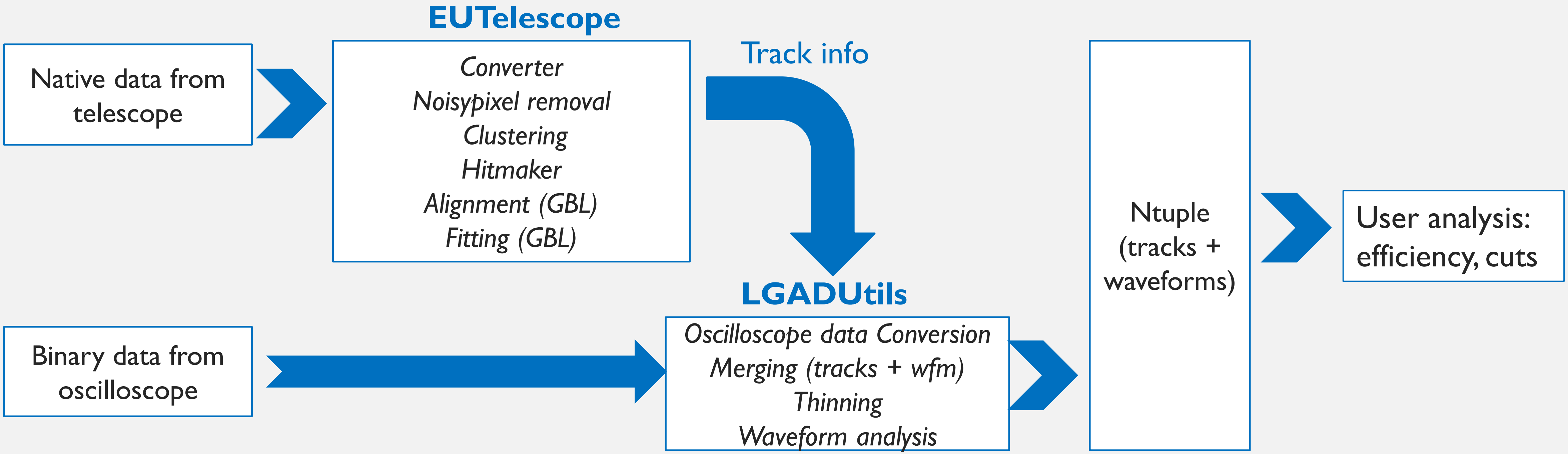


- Sensor attached to board using double-sided conductive tape
- Amplifier input coupled to metallization layer via wire bonds
- Guard ring grounded

Second stage amplifier output to oscilloscope

- Gain of ~10
- 2 GHz Bandwidth

Data analysis tools



EUTelescope

Native data from telescope

Converter
Noisypixel removal
Clustering
Hitmaker
Alignment (GBL)
Fitting (GBL)

Track info

LGADUtils

Binary data from oscilloscope

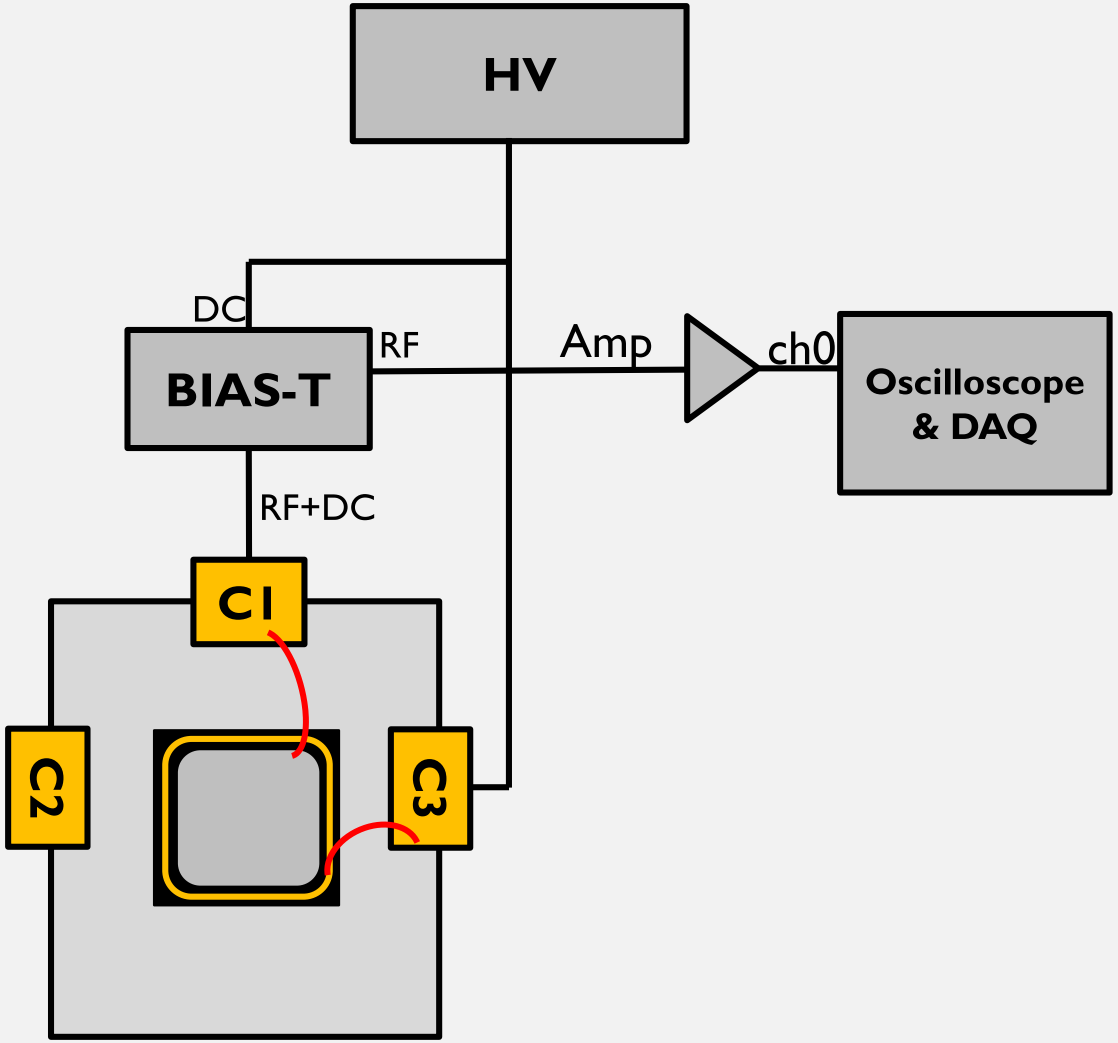
Oscilloscope data Conversion
Merging (tracks + wfm)
Thinning
Waveform analysis

Ntuple (tracks + waveforms)

User analysis: efficiency, cuts

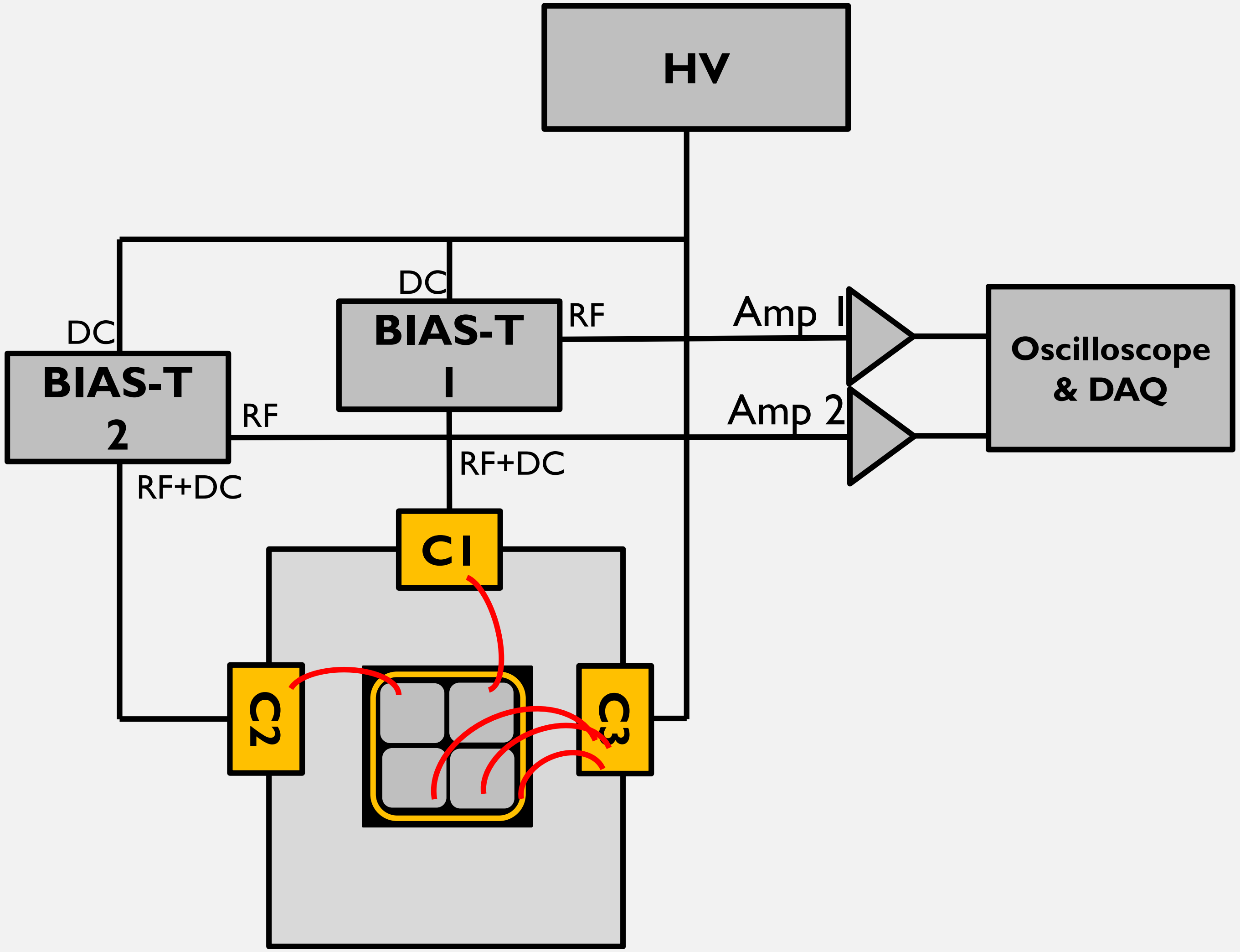
- Track reconstruction performed with **EUTelescope software v01-19-02 using GBL algorithm**
    - Requiring one hit in FE-I4 plane → resulting in ~30% of total events with an average FE-I4 efficiency of 99.6%
- Waveform processing performed with **LGADUtils framework v1.0 (C++ based)** developed at IFAE by V. Gkougkousis (https://indico.cern.ch/event/782573/#preview:2889703)
    - Match event information between telescope and oscilloscope discarding events without FE-I4 hits

Schematic and read-out: single pad



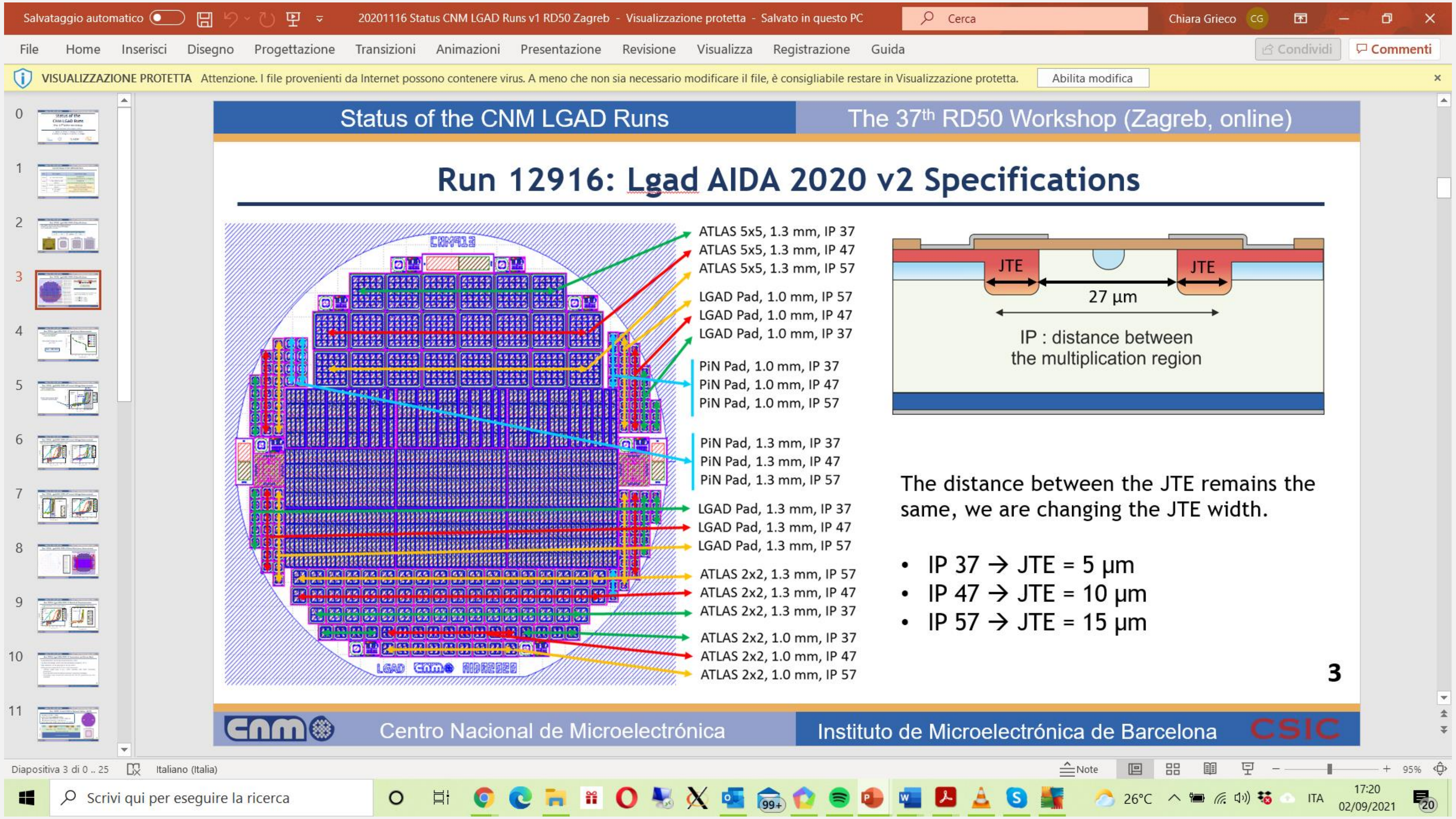
- Sensor is biased from the top side with POSITIVE voltage, this is possible due to the presence of the BIAS-T element
    - DC input is used for bias voltage
    - RF output is sent to amplifier and then to the scope
    - RF+DC in/out is used for the connection with the sensor
- Illuminated with IR lased on the backside
- CIVIDEC amplifiers present a gain of 100
- Average of 1000 waveforms are collected from DRS oscilloscope

Schematic and read-out: 2x2 arrays



- Sensor is biased from the top side with POSITIVE voltage, this is possible due to the presence of the BIAS-T element
    - DC input is used for bias voltage
    - RF output is sent to amplifier and then to the scope
    - RF+DC in/out is used for the connection with the sensor
- Illuminated with IR lased on the backside
- CIVIDEC amplifiers present a gain of 100
- Average of 1000 waveforms are collected from DRS oscilloscope

AIDA2020 IP gap



VISUALIZZAZIONE PROTETTA Attenzione. I file provenienti da Internet possono contenere virus. A meno che non sia necessario modificare il file, è consigliabile restare in Visualizzazione protetta.

Status of the CNM LGAD Runs | The 37th RD50 Workshop (Zagreb, online)

Run 12916: Lgad AIDA 2020 v2 Specifications

ATLAS 5x5, 1.3 mm, IP 37
ATLAS 5x5, 1.3 mm, IP 47
ATLAS 5x5, 1.3 mm, IP 57

LGAD Pad, 1.0 mm, IP 57
LGAD Pad, 1.0 mm, IP 47
LGAD Pad, 1.0 mm, IP 37

PiN Pad, 1.0 mm, IP 37
PiN Pad, 1.0 mm, IP 47
PiN Pad, 1.0 mm, IP 57

PiN Pad, 1.3 mm, IP 37
PiN Pad, 1.3 mm, IP 47
PiN Pad, 1.3 mm, IP 57

LGAD Pad, 1.3 mm, IP 37
LGAD Pad, 1.3 mm, IP 47
LGAD Pad, 1.3 mm, IP 57

ATLAS 2x2, 1.3 mm, IP 57
ATLAS 2x2, 1.3 mm, IP 47
ATLAS 2x2, 1.3 mm, IP 37

ATLAS 2x2, 1.0 mm, IP 37
ATLAS 2x2, 1.0 mm, IP 47
ATLAS 2x2, 1.0 mm, IP 57

IP : distance between the multiplication region

The distance between the JTE remains the same, we are changing the JTE width.

- IP 37 → JTE = 5 µm
- IP 47 → JTE = 10 µm
- IP 57 → JTE = 15 µm

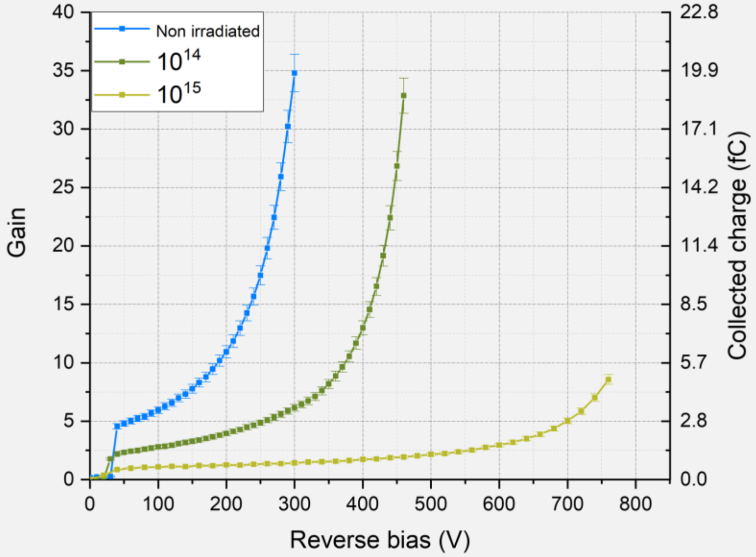
3

Centro Nacional de Microelectrónica | Instituto de Microelectrónica de Barcelona CSIC

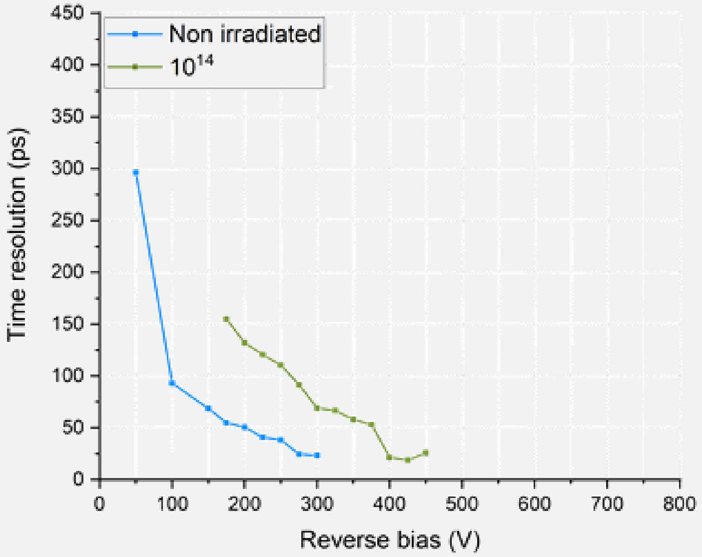
Epi results: Gain and time resolution

$T = -20°C$

Gain



Time resolution



- Gain is computed as: $G = \frac{Q_{DUT}}{<Q_{pin}>}$ for each bias voltage point
  - Q_{DUT} is the collected charge obtained by the integral of the signal from the DUT
  - $< Q_{pin} >$ is the average collected charge obtained for the device with no multiplication (PIN)
- Gain 1 = 0.569 fC
  - MIP → 67 e/h pairs/µm in silicon low doped x 53 µm

- Laser signal is split, one is delayed by 50 ns and then both are combined
- Time difference is calculated at different CFD fractions for 1000 events for each voltage point
- Intrinsic time resolution of the LGAD is $\sigma_{DUT} = \frac{\sigma_{fit}}{\sqrt{2}}$
- Minimum time resolution as a function of the reverse bias
- Results aready presented to RD50 community: slides@38th RD50 Workshop