Overview of CNM LGADs results with B, Ga and C diffused Si-on-Si and epitaxial wafers

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POSITION SENSITIVE
DETECTORS

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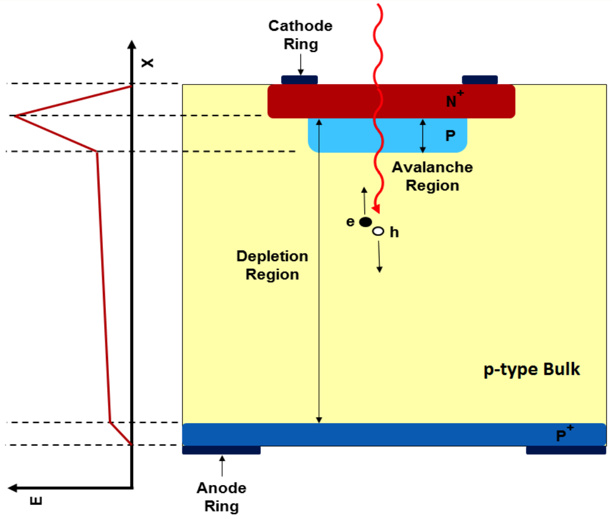
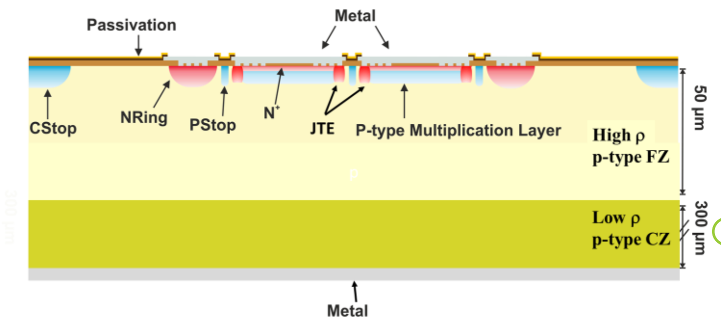
Motivation and outline



Single pad sensor



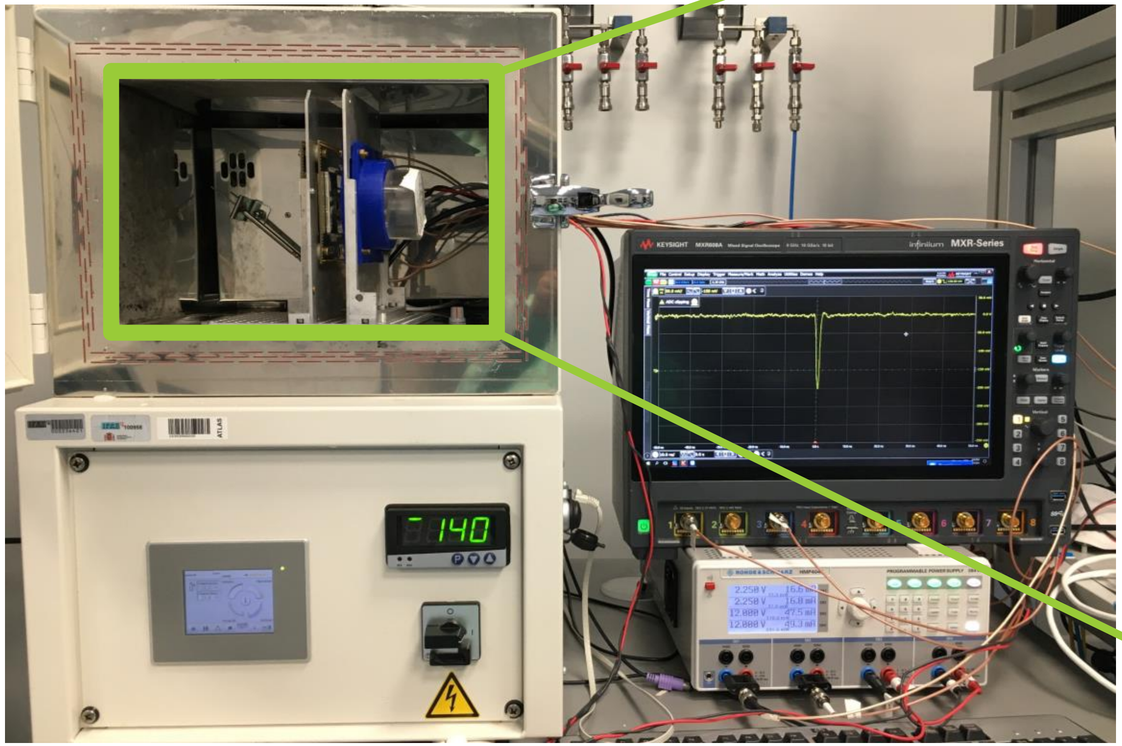
2×2 LGADs array

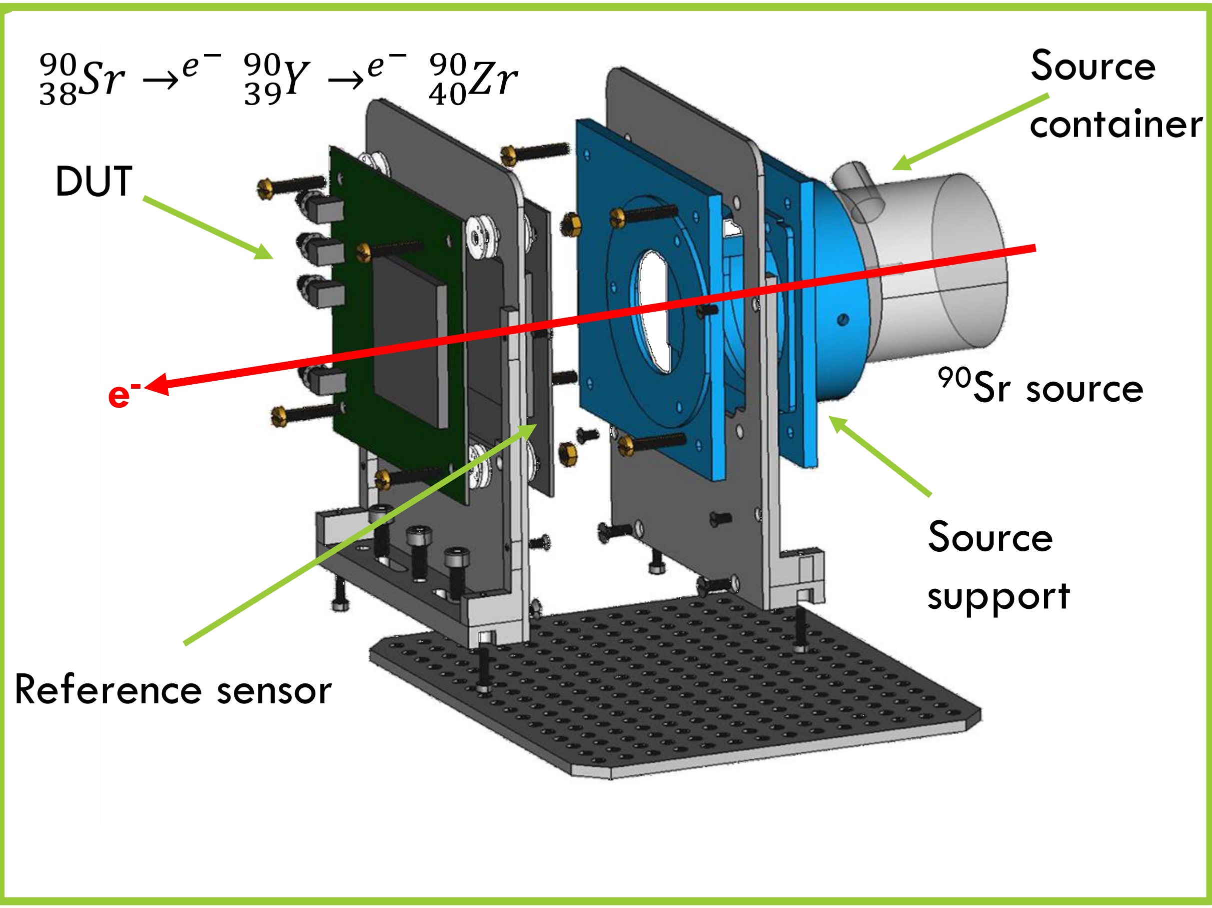
- Low **G**ain **A**valanche **D**iodes (**LGAD**s) sensors
  - Developed at CNM to explore improvements towards radiation hardness
  - Proposed for timing applications (30ps achieved before irradiation)
- Interest to study LGAD performances at high fluences beyond $10^{15}\ n_{eq}/cm^2$
  - Performances remain challenging due to degradation of gain layer
  - Different doping material investigated: ***B***, ***B+C***, ***Ga***
- ATLAS and CMS experiments have chosen the LGAD technology for their **H**igh **G**ranularity **T**iming **D**etector (**HGTD**) and for the **E**nd-**C**ap **T**iming **L**ayer (**ETL**) **See more about HGTD on S. Mazza talk later today!**
  - Requirements: at least $4fC$ and $50ps$/track time resolution for fluences from $1{,}5 \times 10^{15} n_{eq}/cm^2$ (at maximum 600V)
- Results will be presented for different technologies of CNM LGADs: Si-on-Si and low resistivity epitaxial wafers
  - Beta source measurements
  - Transient current tecnique (TCT) measurements

Beta source measurements: Setup

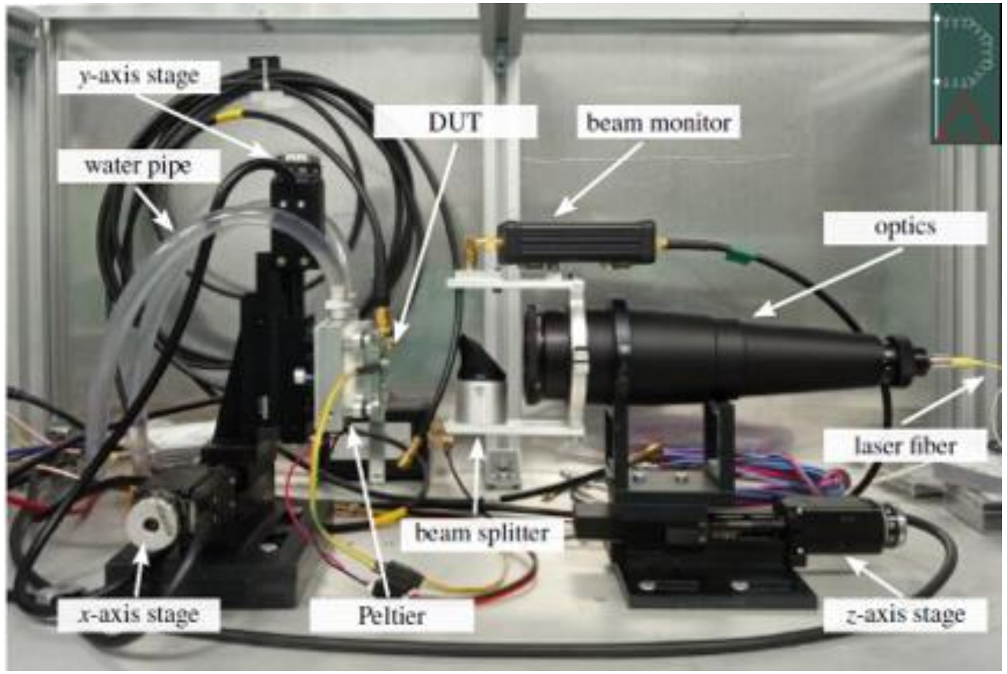
- Climate chamber for temperature control down to -30 C
- Use of dry air to avoiding condensation
- Different oscilloscope for waveform capture
- Reference and DUT mounted back-to-back
- DAQ system can be run remotely

More info about setup and DAQ system in the backup!





Transient Current Tecnique



- **Setup**
  - Red ($\lambda = 640nm$) and InfraRed ($\lambda = 1064nm$) lasers
  - Room temperature and cold measurements (till -20°C)
  - Cooling system with Peltier + Chiller
  - Sensor mounted in metal box on a movable stage
  - Setup can be controlled remotely (HV on the sensors, stage movements)
- **Measurements with IR laser**
  - Only LGADs sensors with opening in the metalization layer
  - Gain measurements vs irradiation for single pads
  - IP gap vs irradiation for 2x2 arrays

CNM Run 10478 B, B+C doping

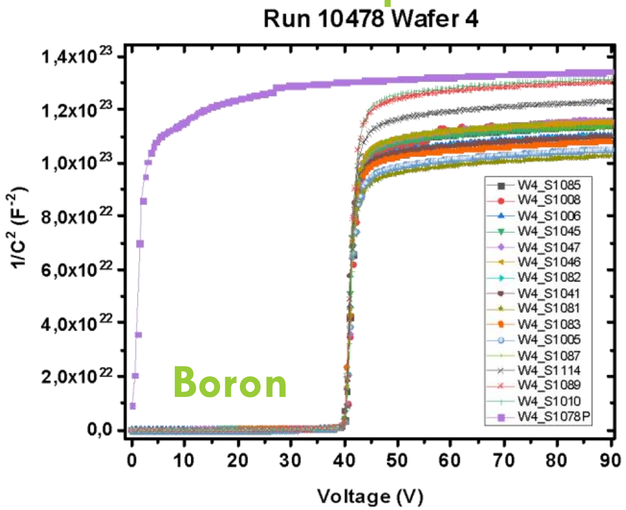
More infos here

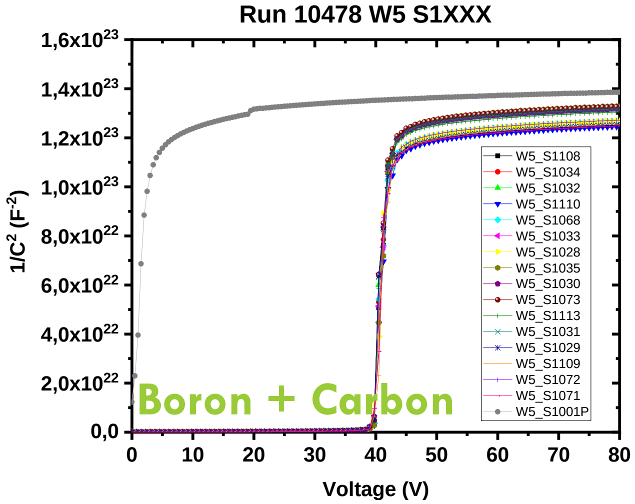
- 50 µm active layer, **Si-on-Si** wafer
- W4 B: $V_{gl}\sim38V, V_{fd}\sim42V, V_{bd}\sim130V$
- W5 B+C: $V_{gl}\sim38V, V_{fd}\sim42V, V_{bd}\sim110-140V$
- Expected gain higher than 20

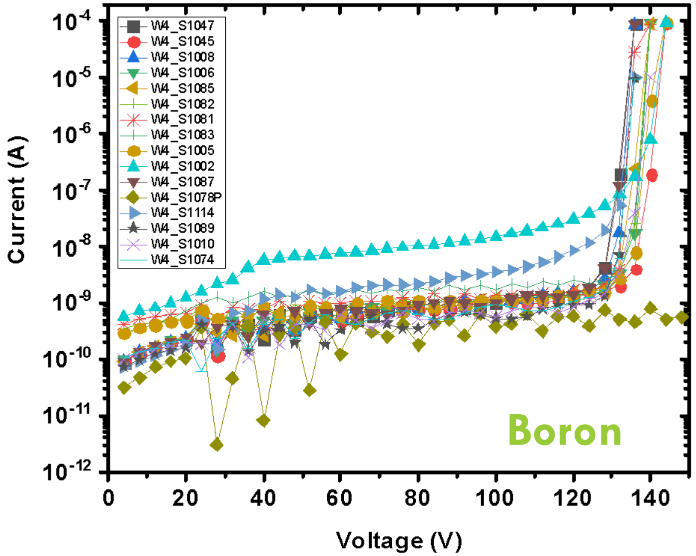
Wafer	Thickness (µm)	Dose (at/cm²)	Energy (keV)	Doping
4	50	1,5E13	100	B
5	50	1,5E13	100	B + C

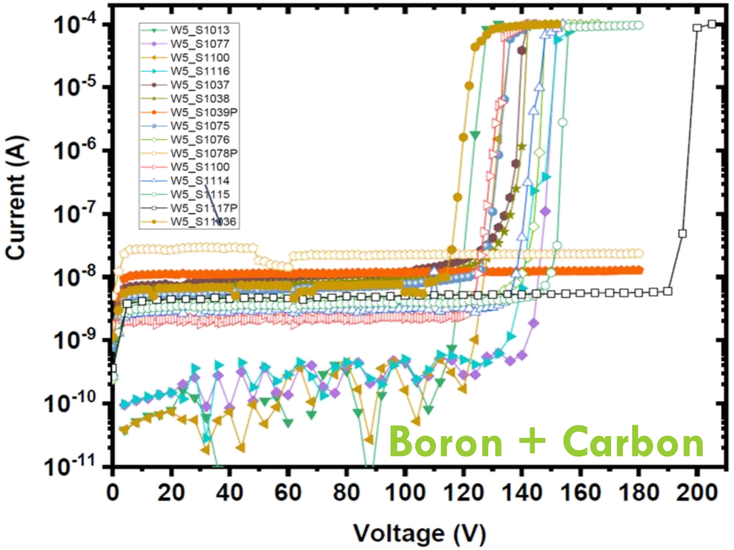
Unirradiated devices

Room temperature







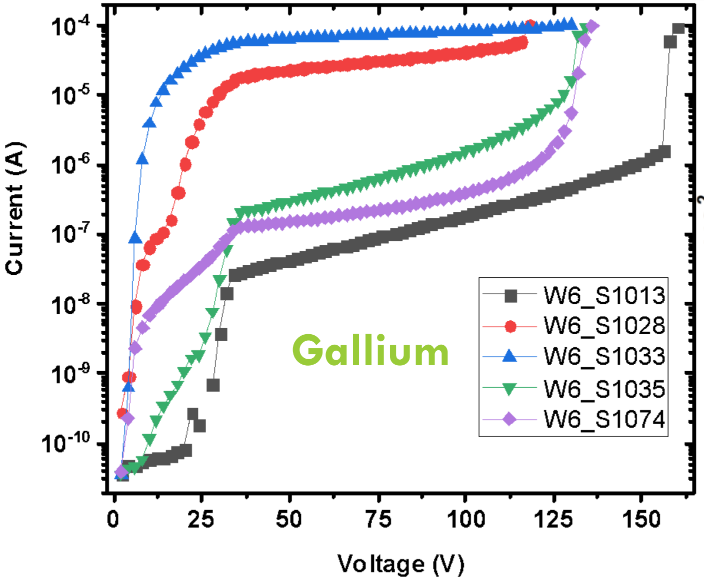


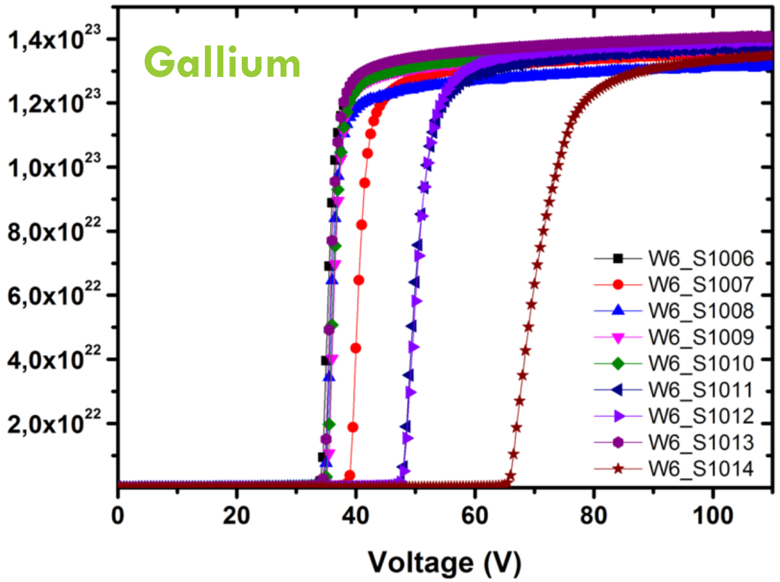
CNM Run 10924 Ga Doping

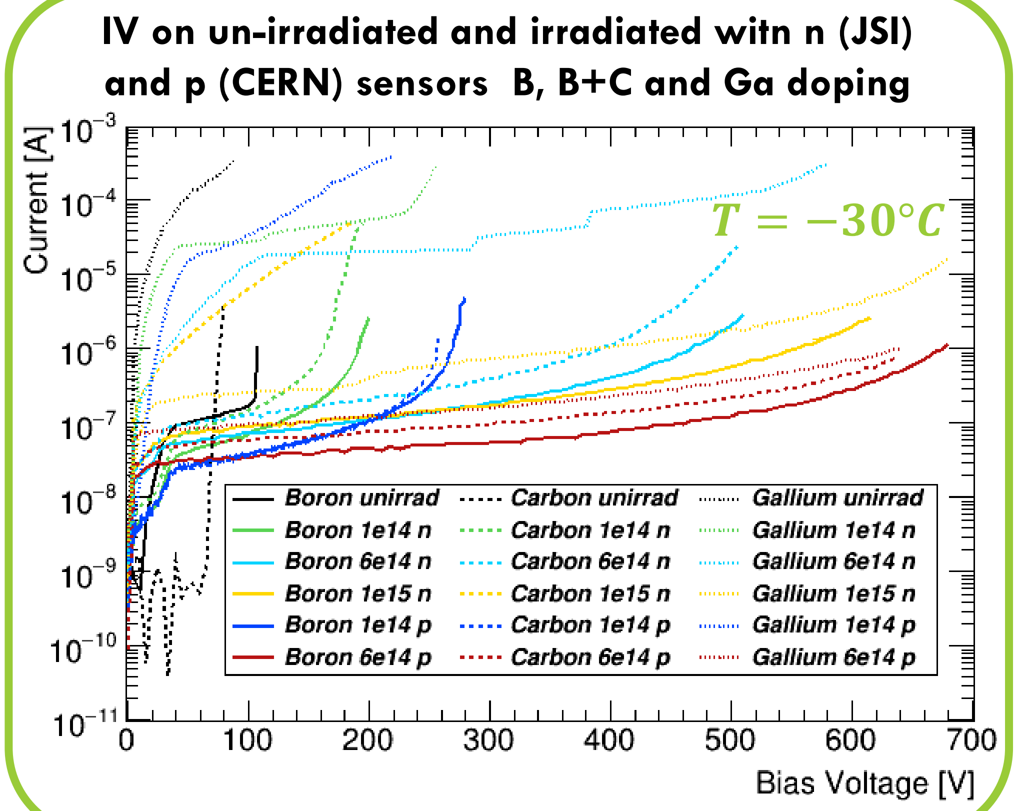
More infos here

- 50 µm active layer, **Si-on-Si** wafer
- Gallium doping
- Dose 6e13 at/cm2

Wafer	Thickness (µm)	Dose (at/cm²)	Energy (keV)
6	50	6E13	195



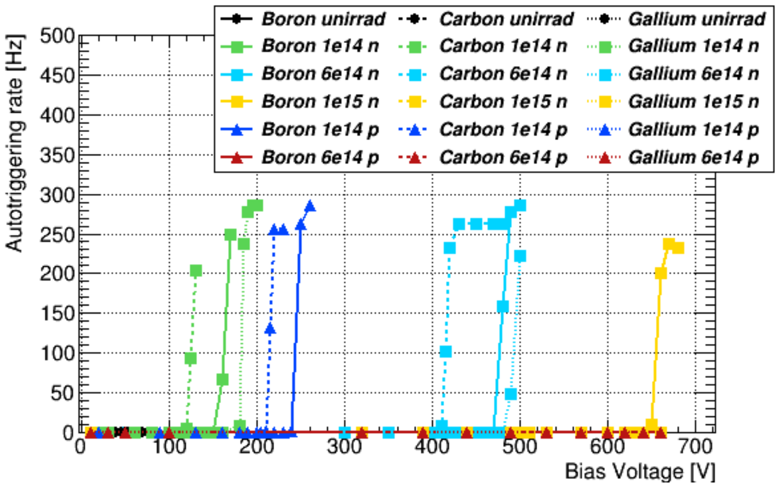




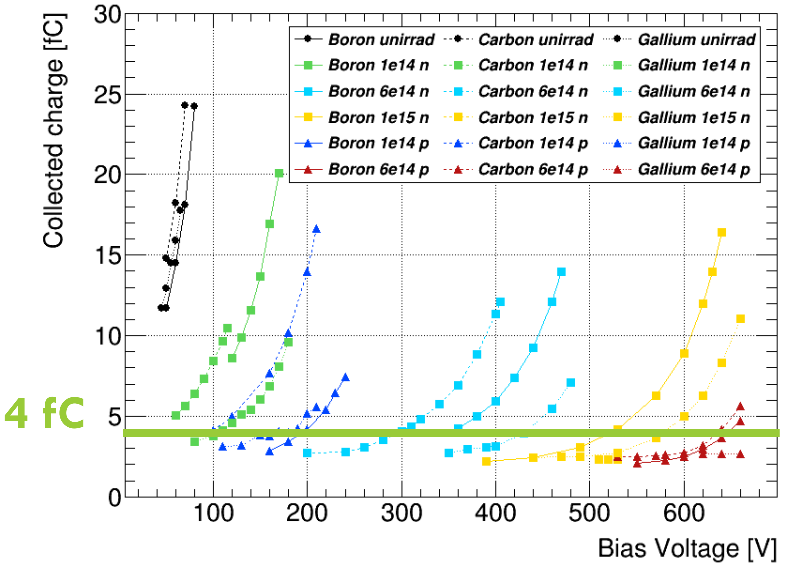
- V_{gl} varies a lot
  - Caused by little penetration of Ga (wrt B) in Si and its fast diffusion
  - No real control of gain layer characteristics
  - Simulation models not reliable
- High current on un-irradiated devices due to a huge charge multiplication

B, B+C and Ga results: Performances with ^{90}Sr

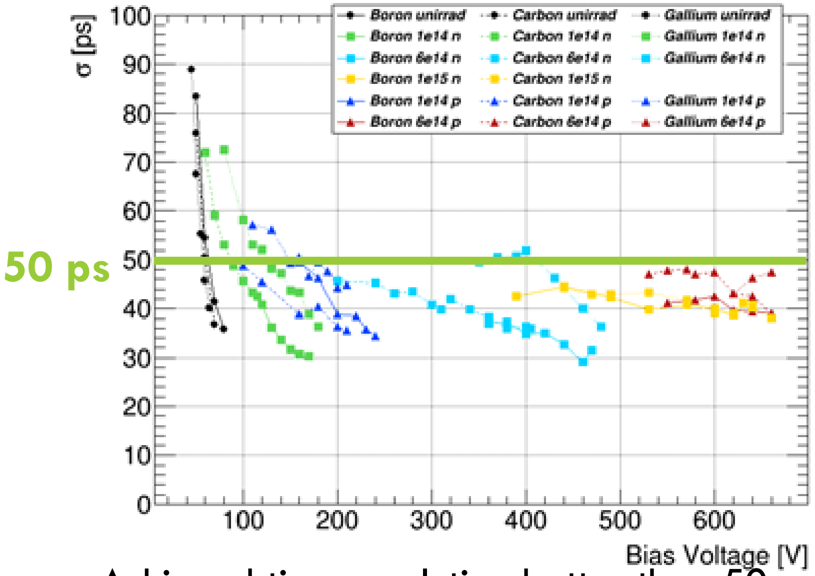
Auto triggering $T = -30°C$



Collected charge



Time resolution



- Rate of self pulses is studied without external source, this limits the operability of the sensors and is fundamental to define optimal operational points for data taking
- B+C sensors seems to start auto-triggering before than B and Ga sensors
- Neutron iradiaton damages the gain layer less than proton one

- C sensors have larger charge collection than B ad Ga at same bias voltage
- C helps to reduce the effect of gain reduction with irradiation
- Although B+C sensors start autotriggering earlier in voltage than other doping
  - This make them not operable at higher voltages

- Achieved time resolution better than 50 ps
- B and B+C are similar in time performances
- Ga achieves a worse time resolution due to the high leakage current

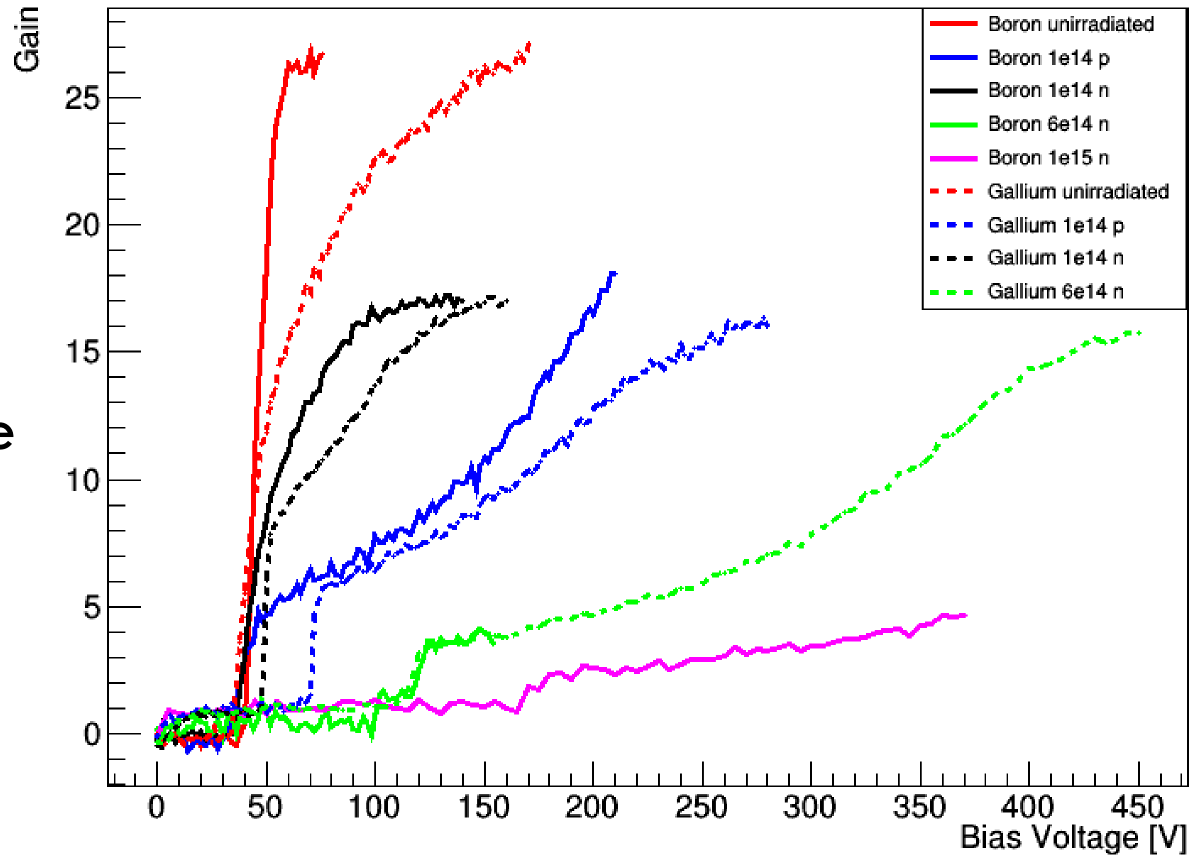
More studies on B, B+C and Ga in these slides

Ga direction looks like to be not worth due to poor performances, B+C seems more stable but require better diffusion tecniques

B and Ga results: TCT measurements

- Measurements for B and Ga doped LGADs up to $1 \times 10^{15} n_{eq}/cm^2$
  - p and n irradiation
  - B+C sensors metalized on the back
- Gain is computed as: $G = \frac{Q_{DUT}}{<Q_{pin}>}$ for each bias voltage
  - Q_{DUT} is the collected charge obtained by the integration of waveform signal on the DUT
  - $< Q_{pin} >$ is the PIN averaged collected charge (device with no multiplication)
- Boron sensors show more gain than Gallium ones at same bias voltages, in agreement with beta source results

$T = -20°C$

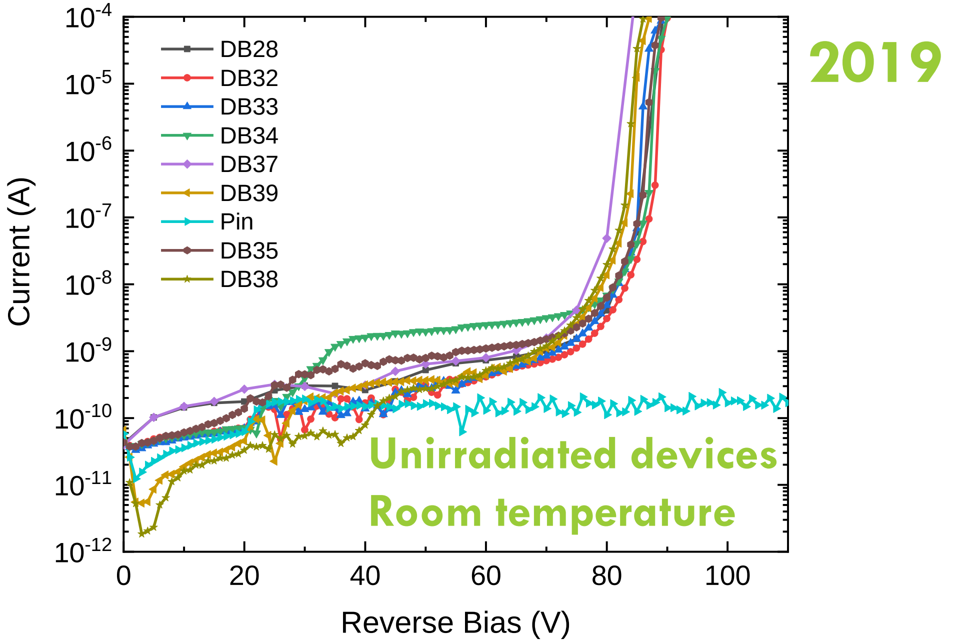


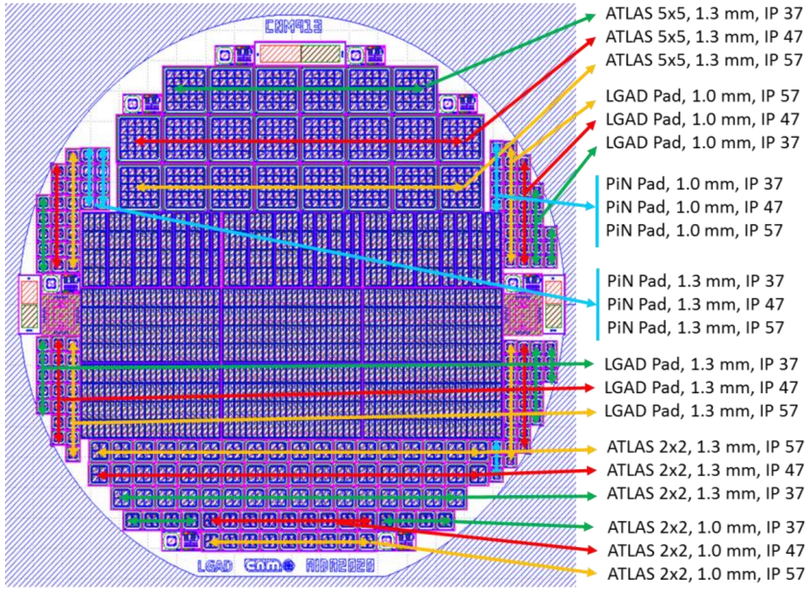
More infos here

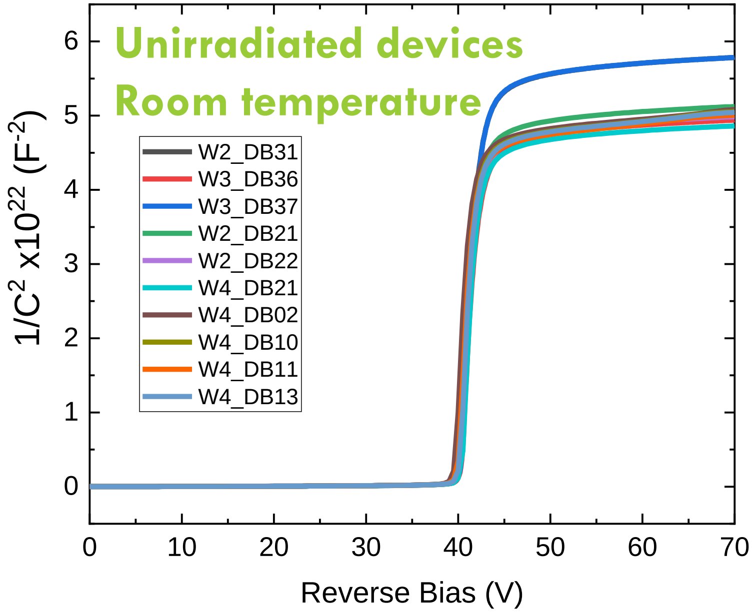
CNM AIDA 2020 Run 12916

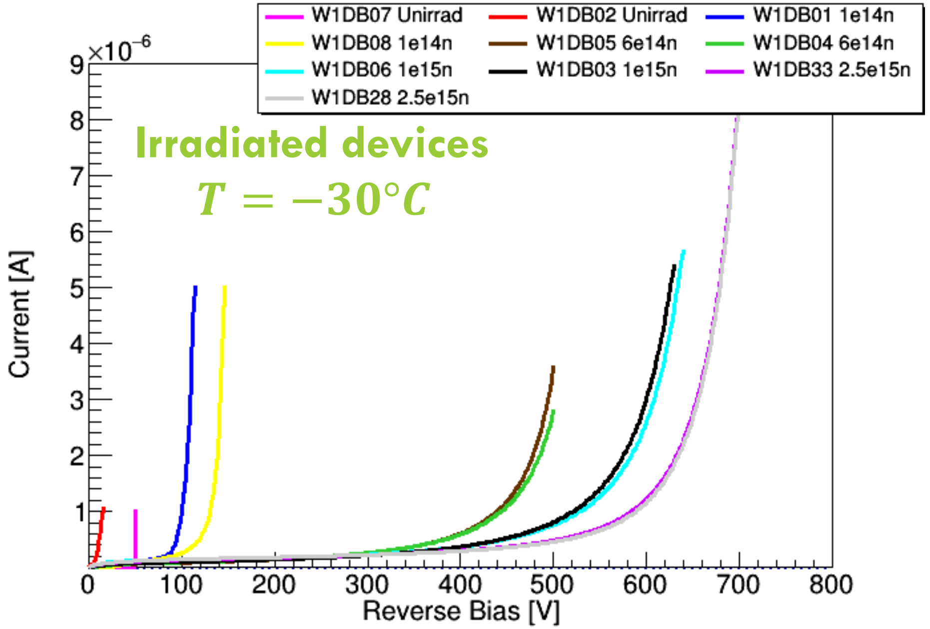
- 4 wafers
- 50 µm active layer, **Si-on-Si** wafers
- $V_{gl}{\sim}38V, V_{fd}{\sim}42V, V_{bd}{\sim}85V$ at room temperature

Wafer	Thickness (µm)	Dose (at/cm²)	Energy (keV)
1-4	50	1,8E13	100





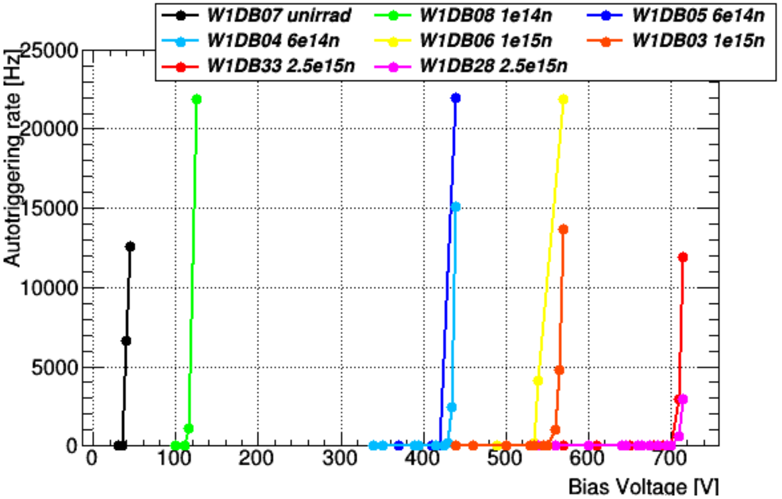




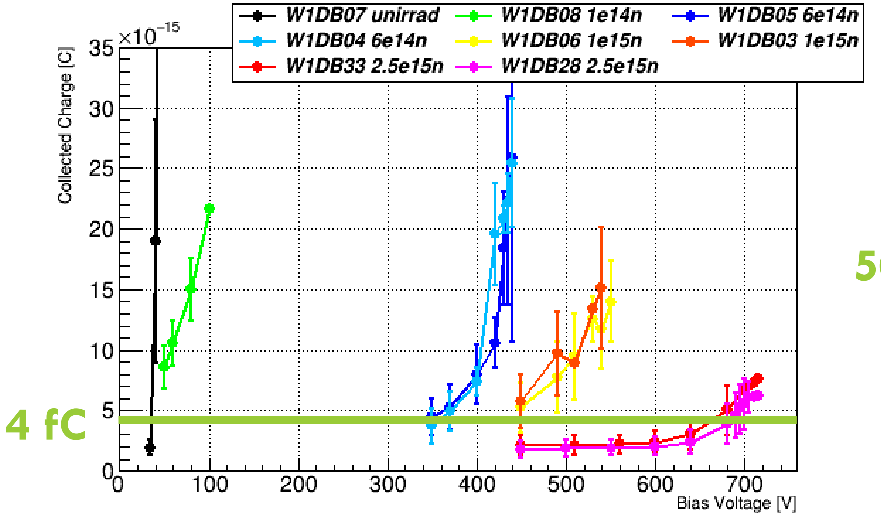
AIDA 2020 results: Performances with ^{90}Sr

$T = -30°C$

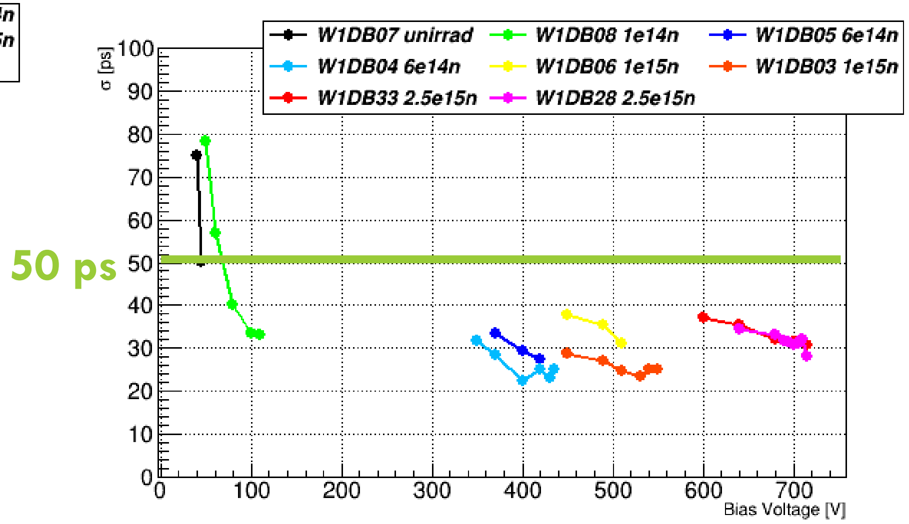
Auto triggering



Collected charge



Time resolution



- Unirradiated sensor present a high autotriggering rate at low voltage which brings difficulty in operating it at cold temperature
- Only marginal performances can be achieved before irradiation

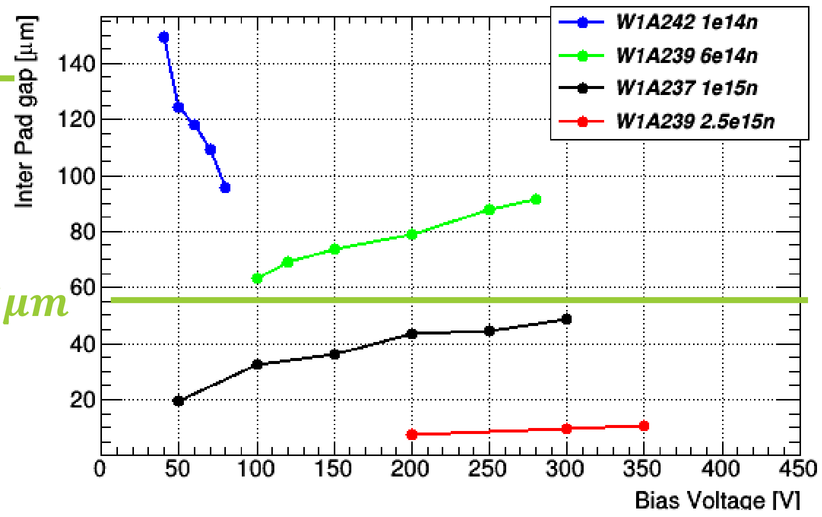
- Unirradiated sensor results are biased by the high auto-triggering rate
  - Not enough room to operate the sensor at -30°C
- 2,5e15 n irradiated sensors provide 4fC for bias voltage higher than 680V

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

Unirradiated devices do not have enough room to operate at cold temperature due to early breakdown

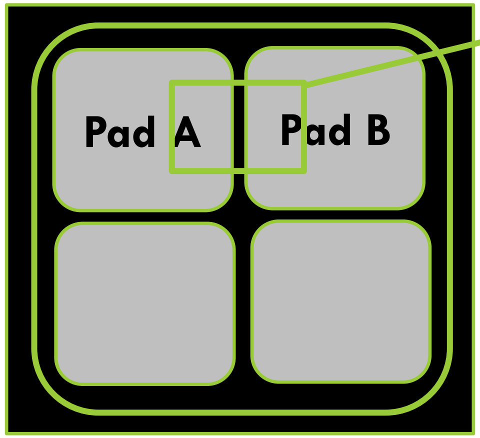
AIDA 2020 results: IP gap

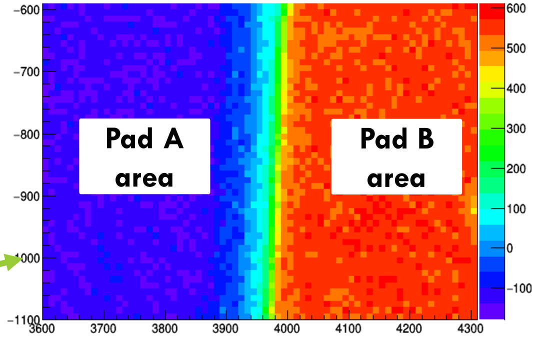
- IP gap defined as distances between multiplication layers
- Measurements:
  - X-Y scan in the middle of two pads (1000wfm per point)
  - Pad A and B read through two different readout lines
  - 2D map drawn for each of the pads, charge on colour axis
  - Projection fit with (reverse) error function
  - X position corresponding at half of the height taken for IP gap calculation

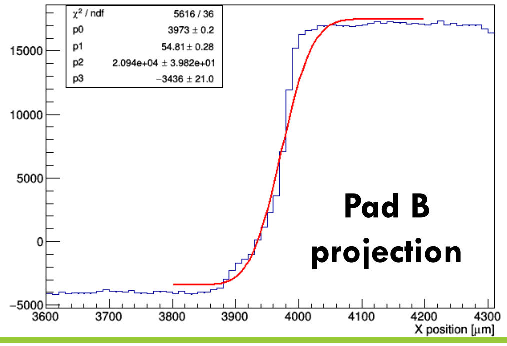


$T = -20°C$

Scanned area for IP measurements





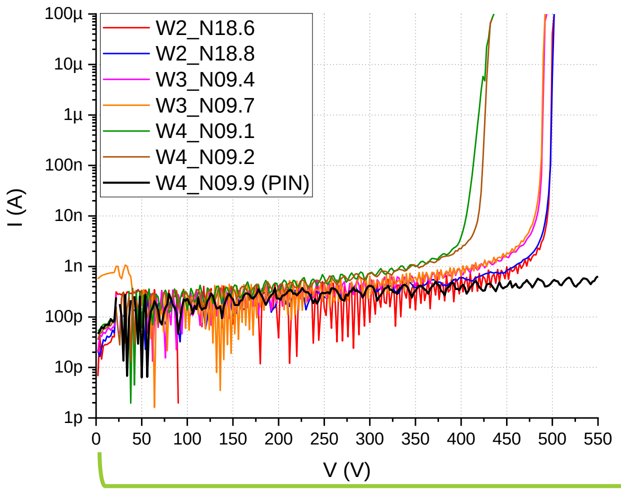


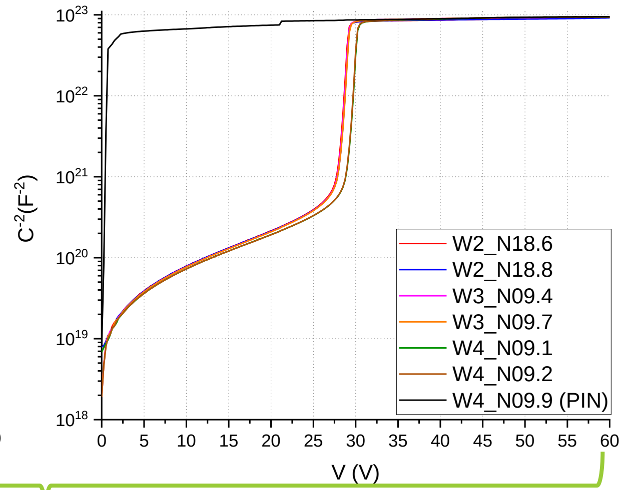
- $IP_{gap} = |x_{A50\%} - x_{B50\%}|$
- Unirradiated sensor not operable
  - High current and early beakdown
- At low fluences:
  - Carries generated underneath the gain layer, drift on JTE and don't have multiplication
- At high fluences (higher than 6e14n):
  - Some gain from carries drifting to the JTE, a smaller IP has been measured at low bias voltages
  - The gap is larger at higer bias voltages
- Results are compatible with previous ones and confirmed by simulation

More infos here

Run 13002: 6-inch LGAD in Epitaxial Wafers

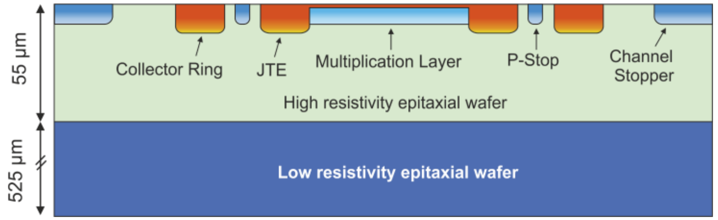
- **4 wafers (3 LGAD + 1 PiN)**
- 6-inch 55/525 µm **epitaxial** wafers.
  - Substrate resistivity = 0.001-1 Ohm-cm
  - Epilayer resistivity ~ 200 Ohm-cm
- $V_{gl} \sim 30V, V_{fd} \sim 35V, V_{bd} \sim 400V$ at room temperature



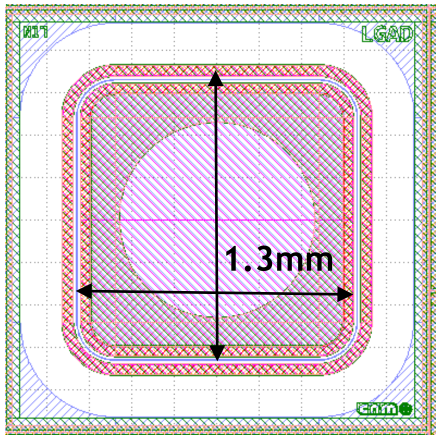


Unirradiated devices, Room temperature

2020



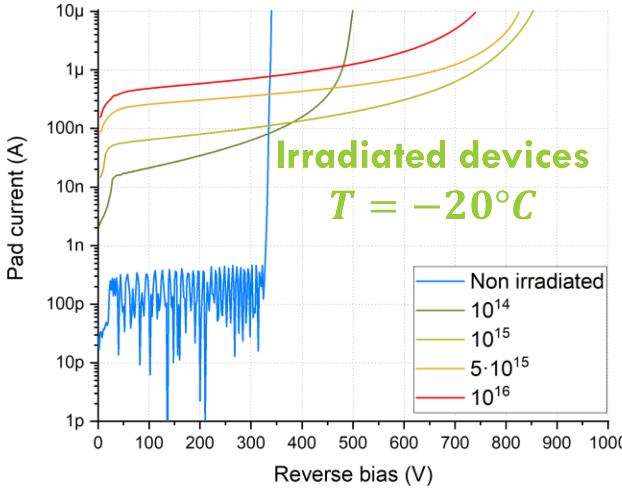
Pad diodes



Results aftr irradiation shown for W4

Wafer	Dose (at/cm²)	Energy (keV)
1	-	-
2	$1{,}9 \cdot 10^{13}$	100
3	$1{,}95 \cdot 10^{13}$	100
4	$2{,}0 \cdot 10^{13}$	100

Diode	Φ_{eq} (1/cm²)
W4_N18.6	-
W4_N09.4	10^{14}
W4_N09.3	10^{15}
W4_N09.6	$5 \cdot 10^{15}$
W4_N09.6	10^{16}



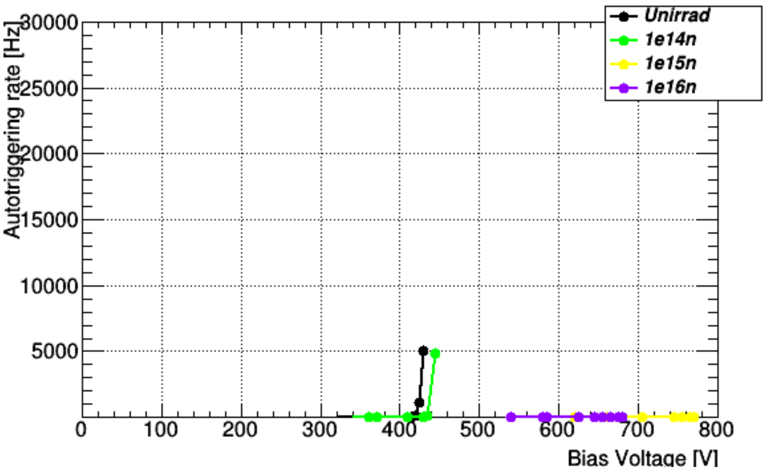
Irradiated devices

$T = -20°C$

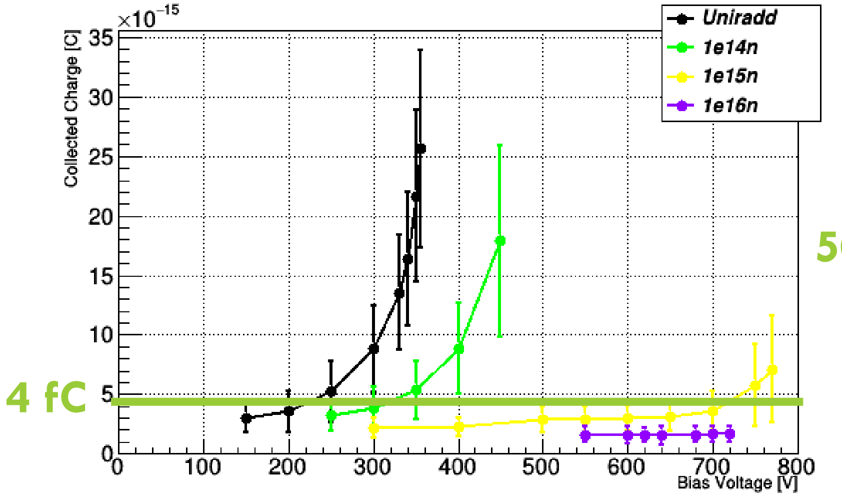
Epitaxial run results: Performance with ^{90}Sr

$T = -30°C$

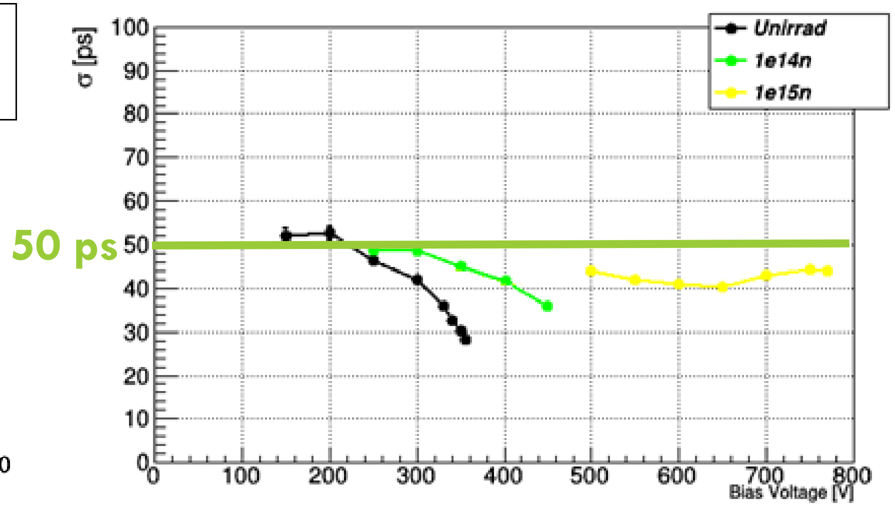
Auto triggering



Collected charge



Time resolution



- All the fluences present enough room to operate between V_{gl} and V_{bd}
- Not detectable auto triggering up to 770V for fluence of 1e15n and up to 720V for fluence of1e16n but high current, no possible to go higher in voltage

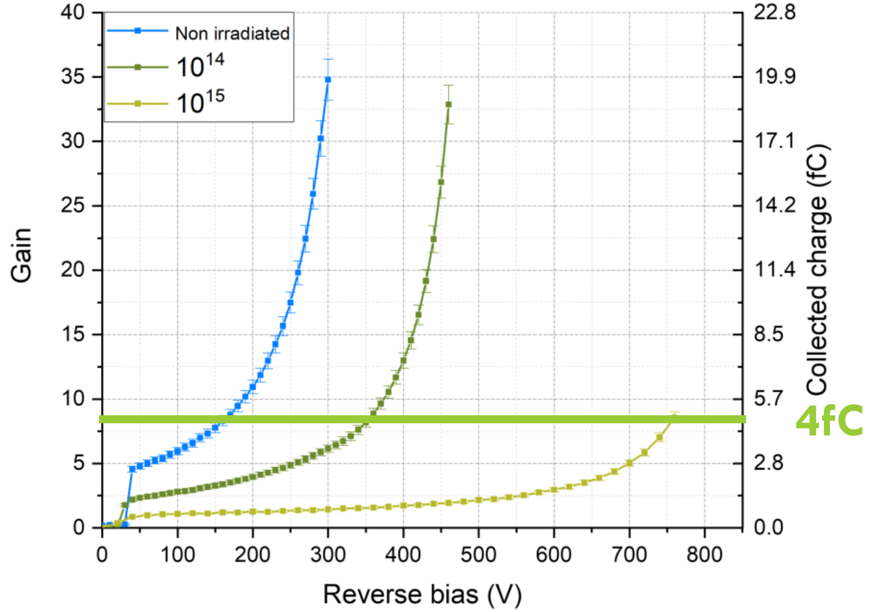
- Up to 1e14 n irradiated sensors a high collected charge (>10 fC) is achieved
- For 1e15 n irradiated sensor 4 fC are reached at HV>700V
- No detectable gain for 1e16n up to 720V
- Foreseen tests of intermediate fluences (5e14n, 8e14n, 2e15n, 3e15n and 5e15n)

- A time resolution < 50 ps is achieved for sensor irradiated up to 1e15n
  - A plateau-like around 43ps is reached for this fluence
- For 1e14n the measured time resolution is below 40 ps

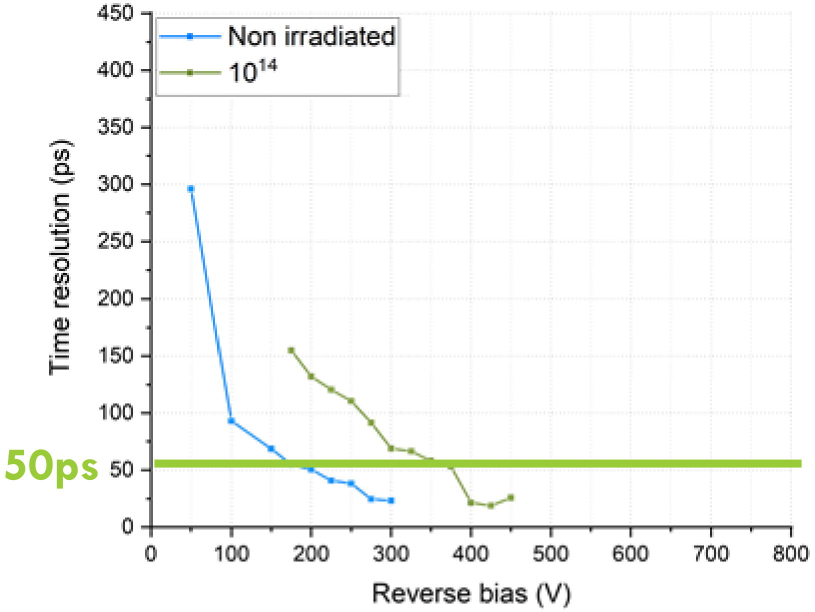
Unirradiated devices have enough room to operate, but irradiated ones works at relative high bias

Epitaxial run results: Gain and Time resolution

$T = -20°C$



- Gain is computed as: $G = \frac{Q_{DUT}}{<Q_{pin}>}$ for each bias voltage point
  - Q_{DUT} is the collected charge obtained by the integration of waveform signal on the DUT
  - $< Q_{pin} >$ is the averaged collected charge obtained for the device with no multiplication (PIN)
- $G = 1 = 0.569fC$ $(MIP \rightarrow 67\ e/h\ pairs$ per μm in silicon low doped $\times\ 53\mu m)$



- Same signal delayed of 50 ns
- Time resolution of the sensor coputed as $\sigma_{DUT} = \frac{\sigma_{fit}}{\sqrt{2}}$
- Time difference is calculated at all CFD fractions
- 1000 waveforms for each voltage point
- Minimum time resolution plotted here

Results aready presented to RD50 community

Conclusions and outlook

Boron, Boron + Carbon and Gallium dopings (Run 10478 W4 & W5, Run 10924 W6)

- **Carbon** seems to help more to maintain gain after irradiation
  - However in this first run with Carbon it was diffused in all substrate and benefits are not clear (as from results from other)
  - Even though need a god control of the C implant in the gain layer
- **Gallium** presents 20% less gain and acceptor removal wrt Boron, but requires better diffusion techniques
  - Direction not worth since the poorer radiation hardness and timing performances
- Sensors have been also tested in test beams (2018-2019) and a paper with results is in preparation

AIDA 2020 Boron (Run 12916)

- Un-irradiated sensor 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 2,5e15 n

Epitaxial Boron (Run 13002)

- Un-irradiated sensors show enough room to operate between V_{gl}, V_{fd} and V_{bd} voltages and low auto-triggering rate
- 1e15 n irradiated sensors work but at relative high bias (700V), this is due to too low resistivity

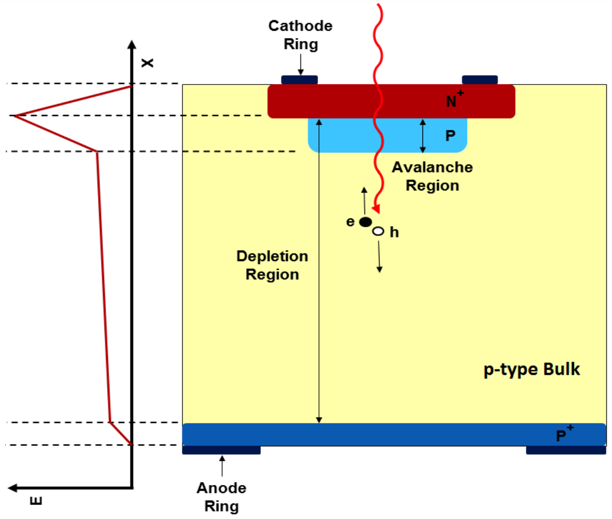
Next

- A new common ATLAS/CMS run will be ready by the end of this year
  - Epitaxial run with C infusion on some wafers

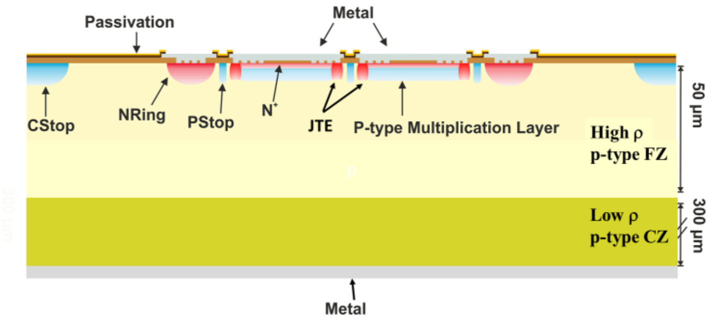
Thanks for listening!

BACKUP

Low Gain Avalanche Detectors (LGADs)



Single pad sensor



2×2 LGADs array

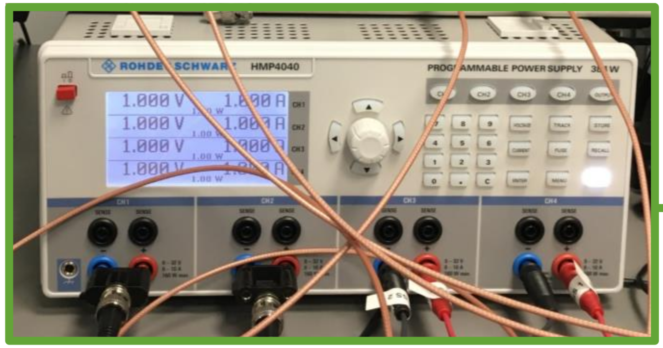
Pioneered by Centro Nacional de Microelectrónica (CNM)

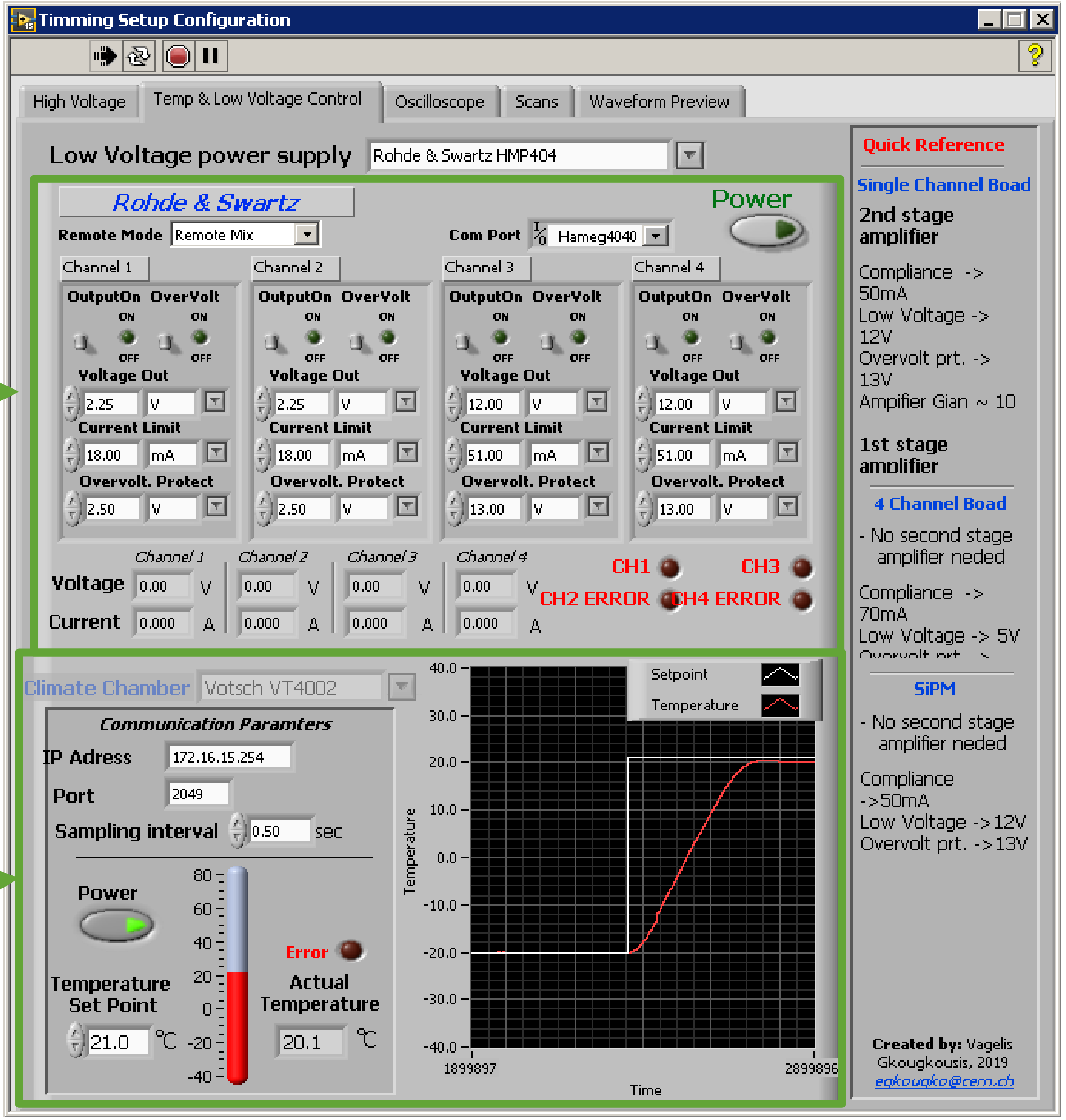
- n-on-p silicon detector with extra doped p-layer beow the n-p junction which provides signal amplification
  - High E field
  - Internal gain: ~ 10-50 (large S/N ratio)
  - Typical rise time: ~ 0,5 – 0,8 ns
  - Time resolution before irradiation < 30 ps
  - 50 μm thick sensors → faster rise time and lower impact from radiation
- Different doping material investigated: *B, B+C, Ga*
- Different manufacturers: CNM, HPK, FBK, BNL and IHEP-NDL
- Interest to study LGAD performance at high fluences beyond $10^{15}\ n_{eq}/cm^2$
- ATLAS and CMS experiments have chosen the LGAD technology for their High Granularity Timing Detector (HGTD) and for the End-Cap Timing Layer (ETL)
  - CMS : 10fC at 1.5·1015 /cm² at (max) 600V
  - ATLAS : 4fC at 2.5·1015 /cm² at (max) 600V
- Results will be presented for different technologies of CNM LGADs both Si-on-Si and low resistivity epitaxial wafer
  - Beta source measurements for single pad sensor
  - Interpad gap distances on 2x2 LGAD arrays with transient current tecnique and gain for single pad sensors

Beta source setup

Low voltage power supply control panel

- Different type of power supplies implemented
- Connected through Ethernet
- LV power of boards
- LV power on second stage amplifiers



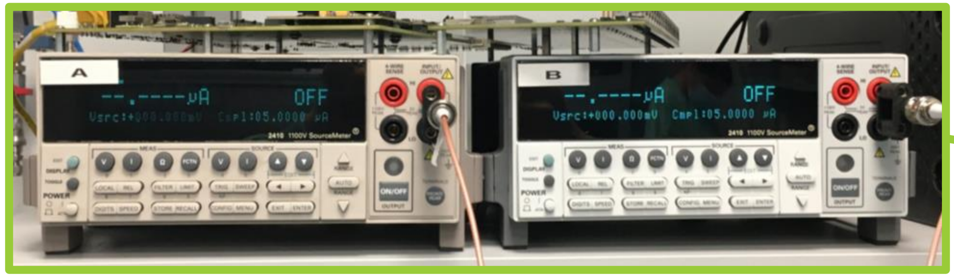


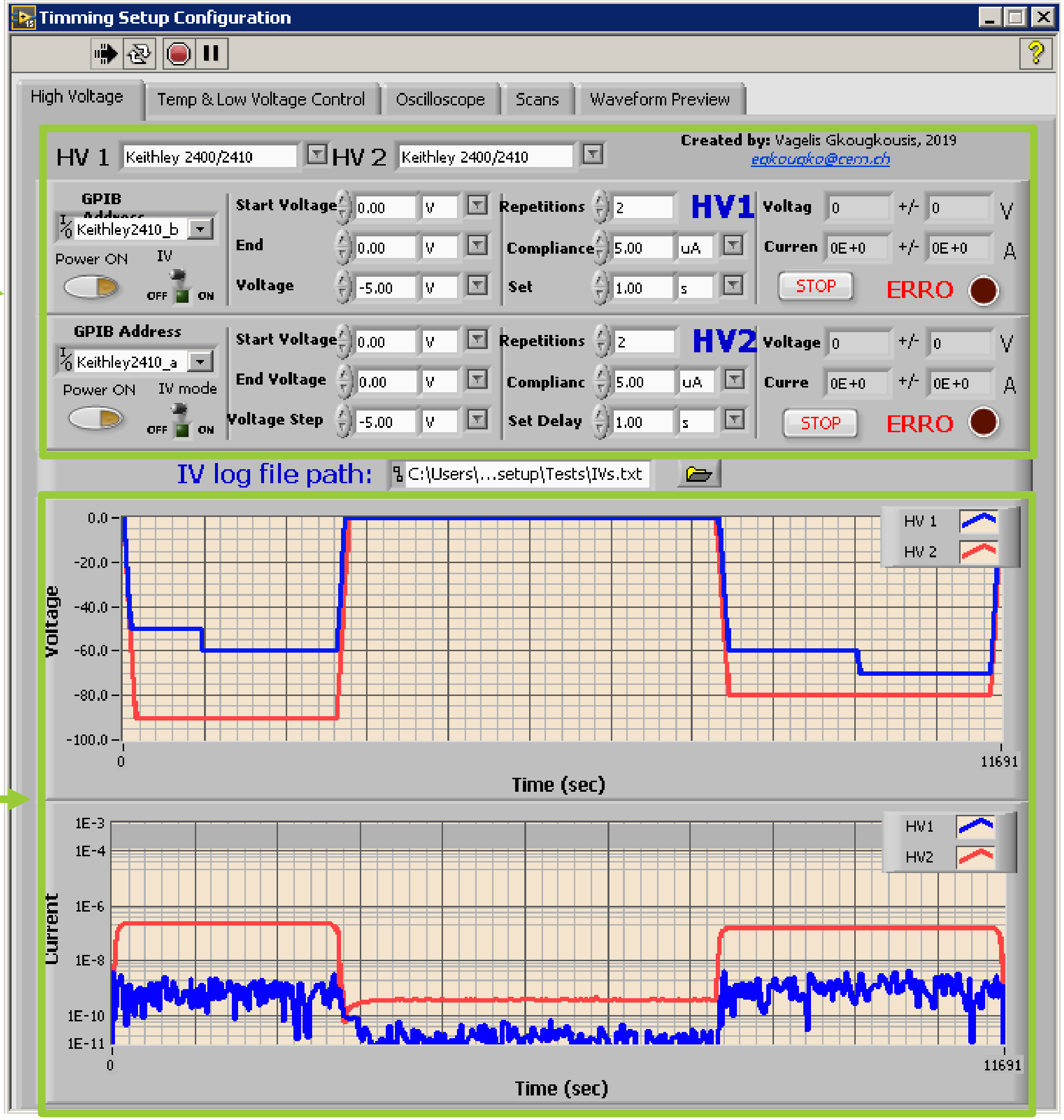
Climate chamber control panel

- Connected through Ethernet
- Remote setting of temperature

Dry air needed to be put ‘by hand’

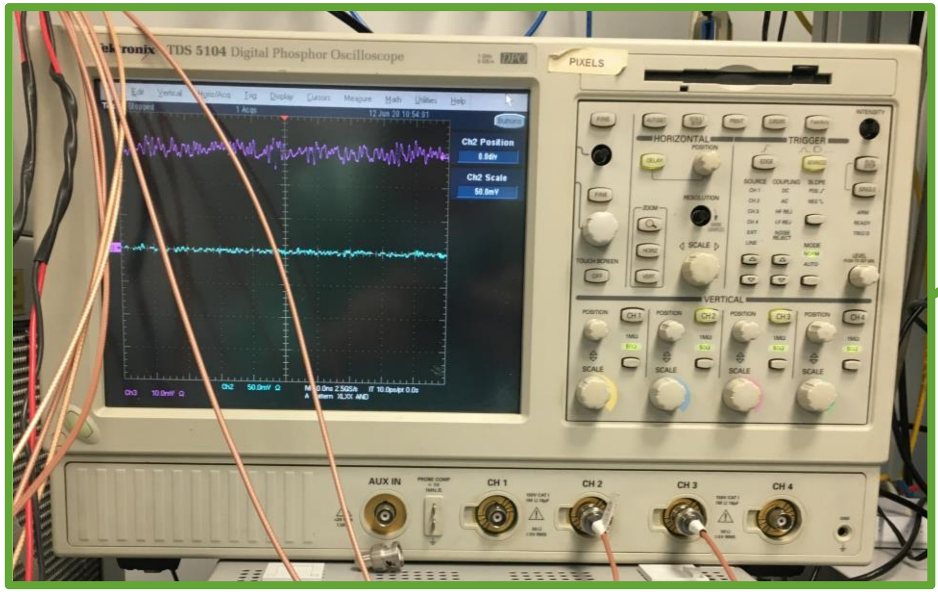
Beta source setup



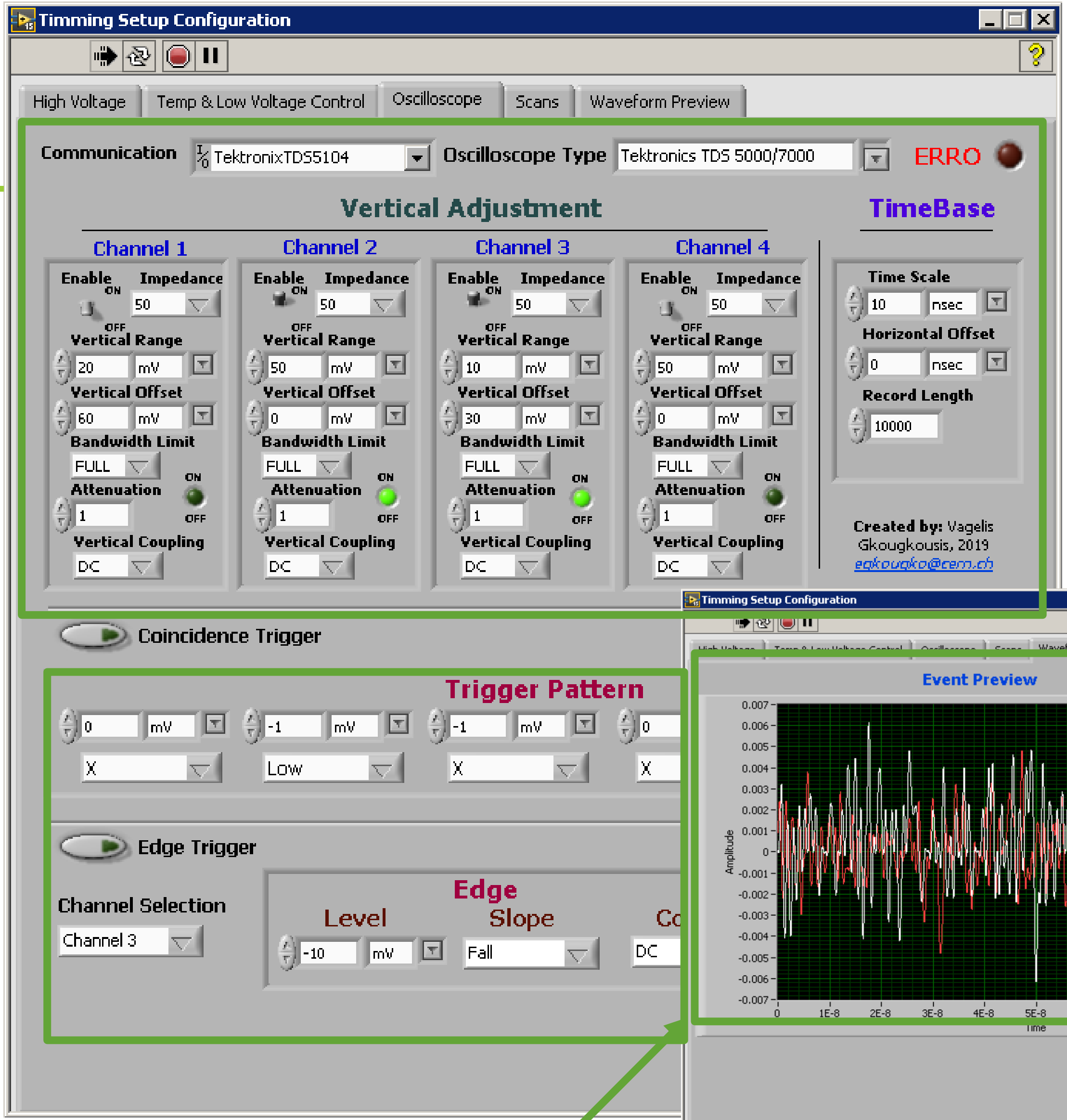


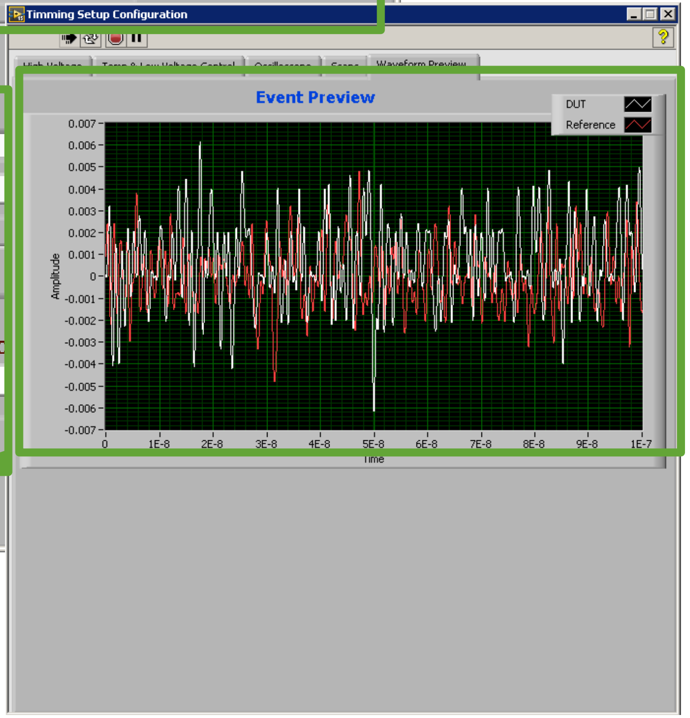
- High voltage power supply panel
- High voltage for sensors
- GPIB connection through USB to PC
- Several instruments implemented
- Voltage and current monitoring
- IV will be saved in txt file

Beta source setup



Oscilloscope control panel
- Several instruments implemented
- Connected through Ethernet
- Possibility to act on all the scope functions (trigger pattern, edge etc…)





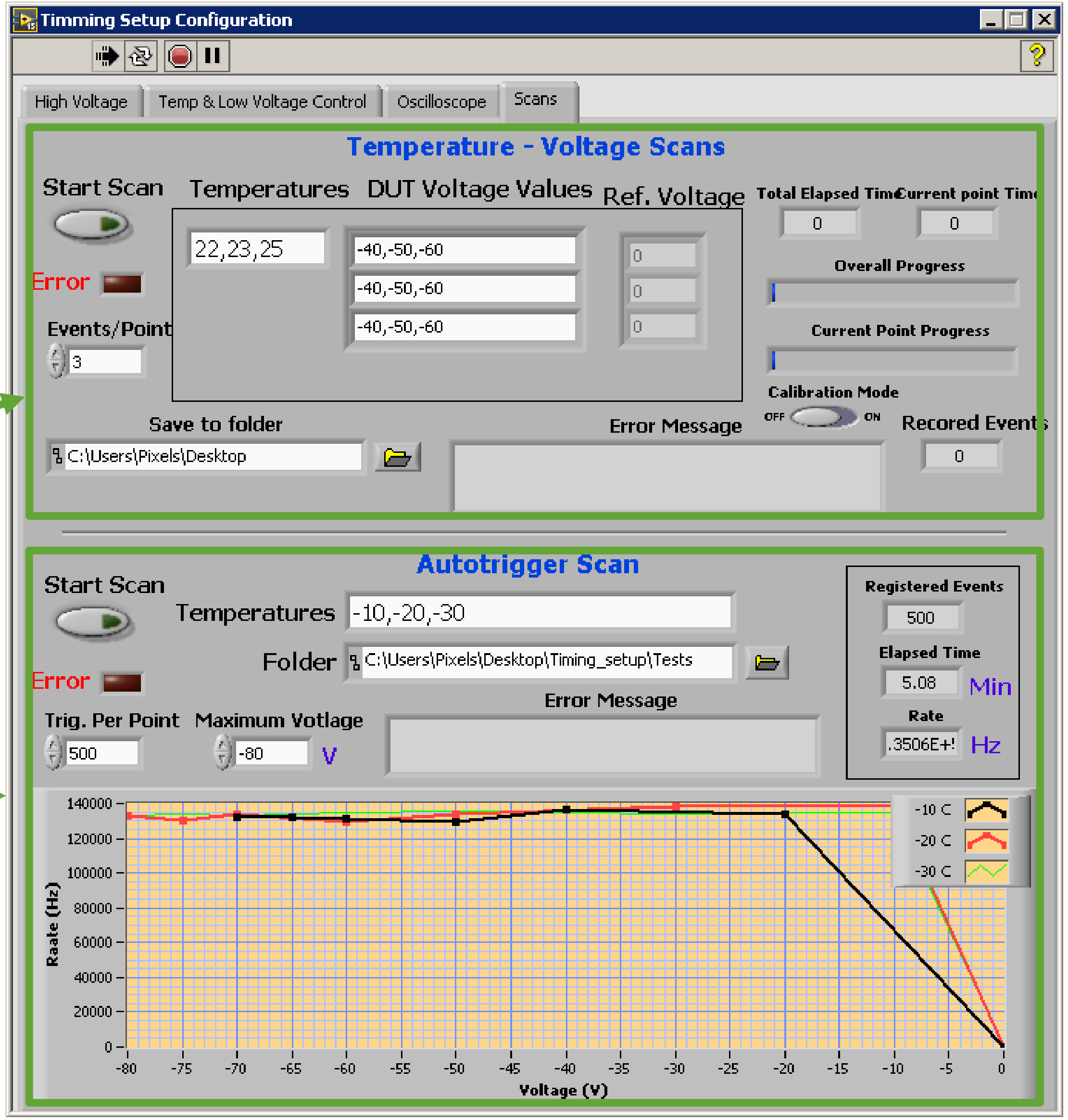
Event preview for remote control

Beta source setup

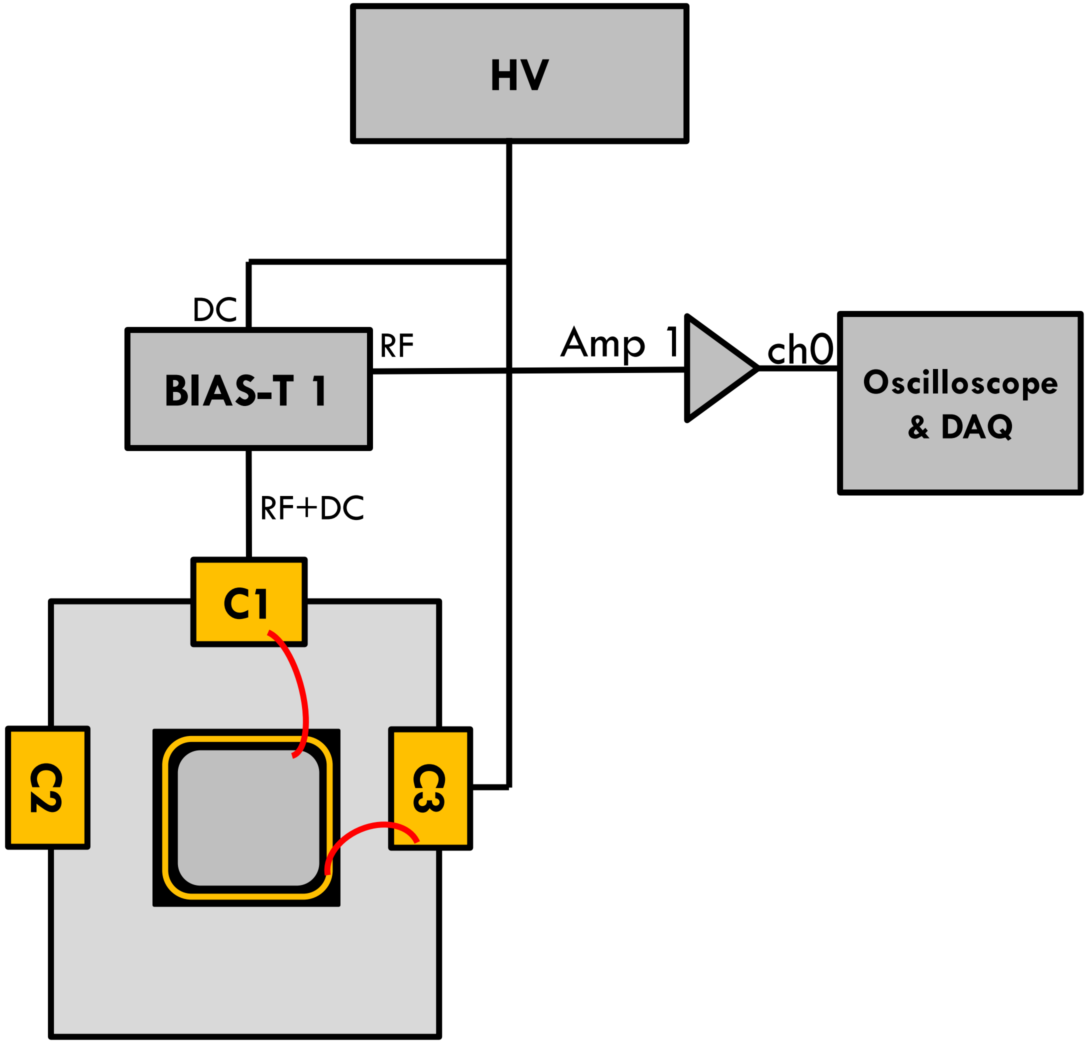
Automated data taking

- Scans panel: Voltage scans
- Setting desired temperature points for data taking
- Setting voltage points per each temperature
- Setting number of events per point
- Saving box for datafile

- Scans panel: Autotriggering
- Setting desired temperature points
- Saving box for datafile
- Number of trigger for each voltage point
- Monitoring for rate vs HV

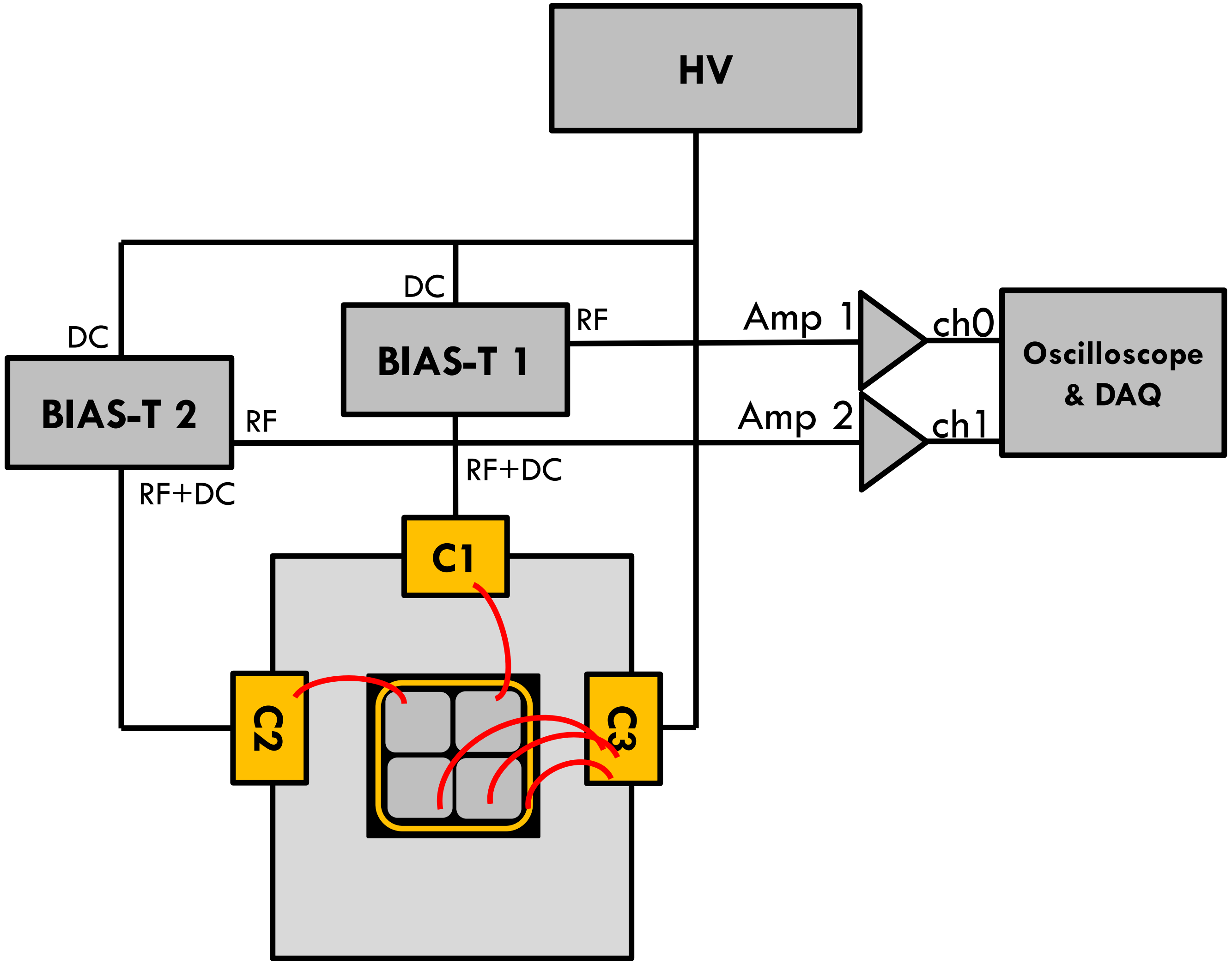


TCT setup schematic and readout: Single Pad



- 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

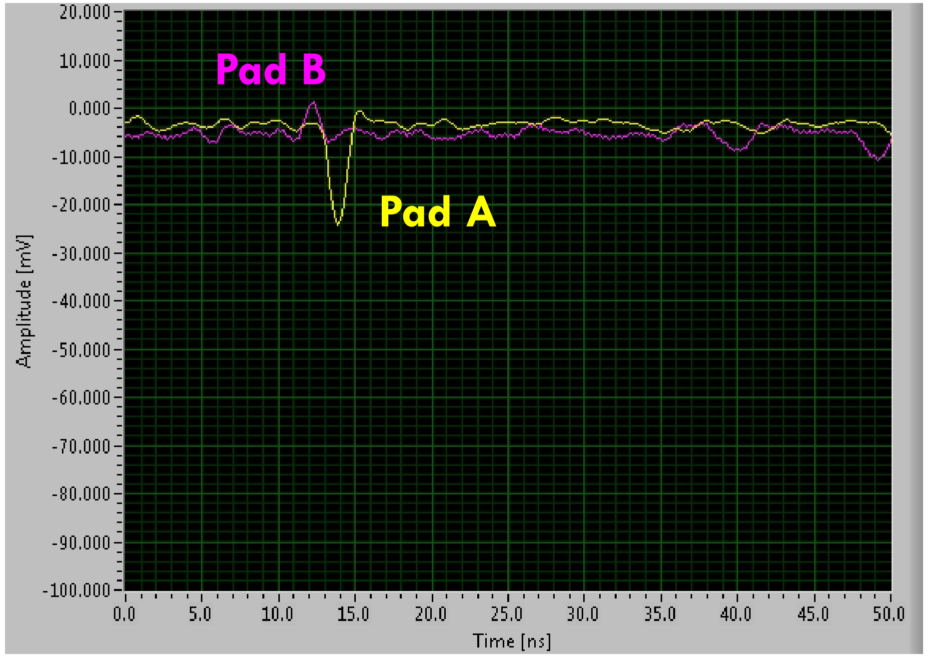
TCT setup schematic and readout: 2x2 arrays



- 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

2x2 arrays TCT measurements

- Laser light is hitting Pad A area
- Pad B presents a positive signal due to the discarging of the capacitor
  - This will give a negative charge value once waveform is integrated
- More info in this study: https://www.sciencedirect.com/science/article/pii/S0168900220308913



Electrical characterization at -30 C AIDA 12916

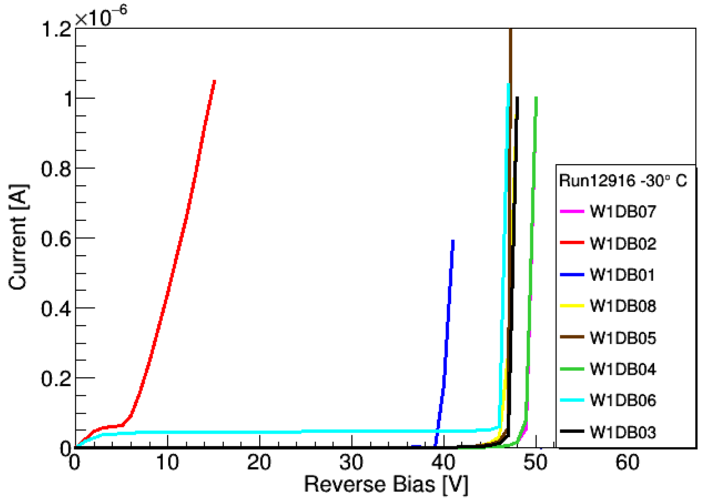
- Tests performed on a set of single pads ($1.3x1.3\ mm^2$) from W1
- IV measurements at $T = -30°C$ before and after neutron irradiation in JSI
- Applied positive Bias Voltage to Pad and GR, back of the sensor grounded
- Compliance set at $5\mu A$ for both Pad and GR
- The plot shows total current

$$I_{tot} = I_{GR} + I_{PAD}$$

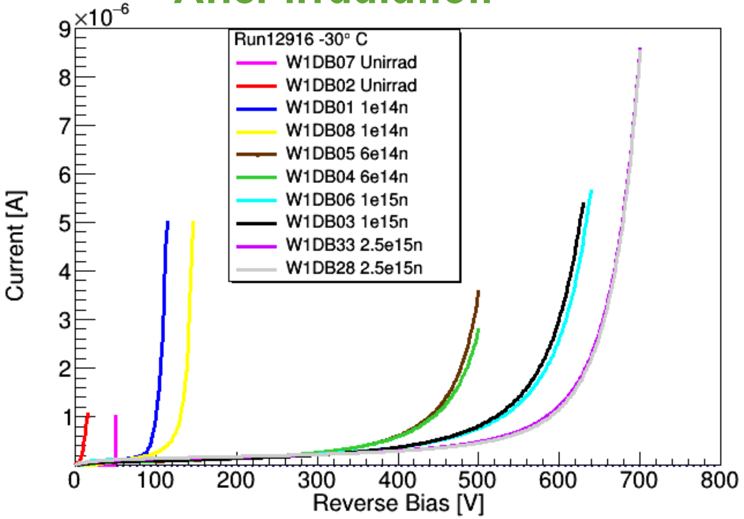
- All the sensors are working after irradiation

Name	Fluence
DB02	Unirrad
DB07	Unirrad
DB01	1e14 n
DB08	1e14 n
DB04	6e14 n
DB05	6e14 n
DB06	1e15 n
DB03	1e15 n
DB28	2,5e15 n
DB33	2,5e15 n

Before irradiation



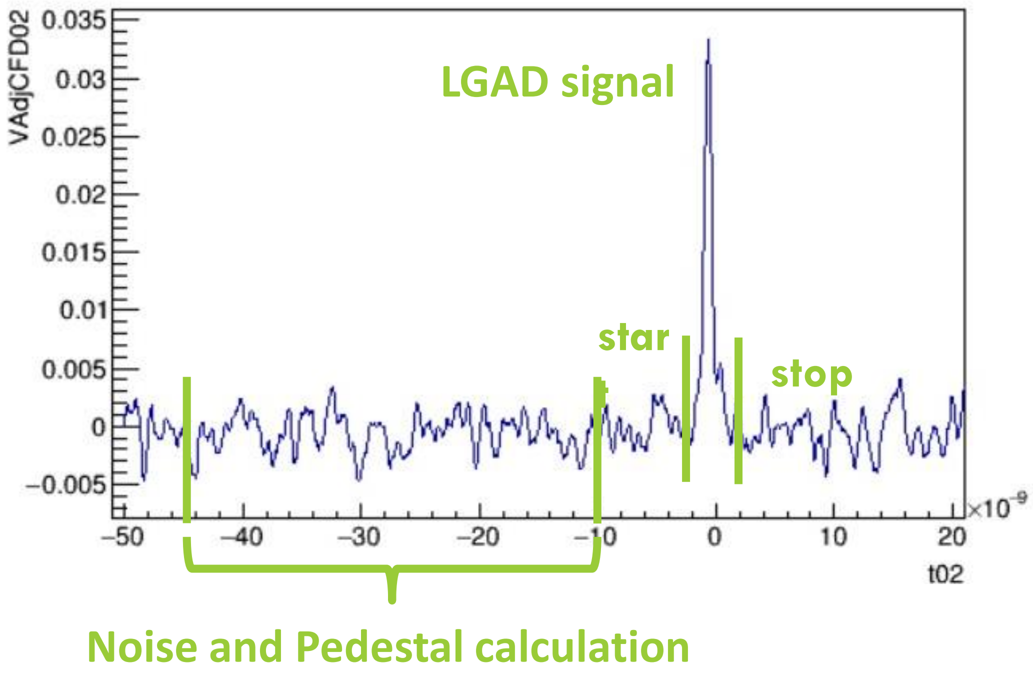
After irradiation



Note the different x-axis scale

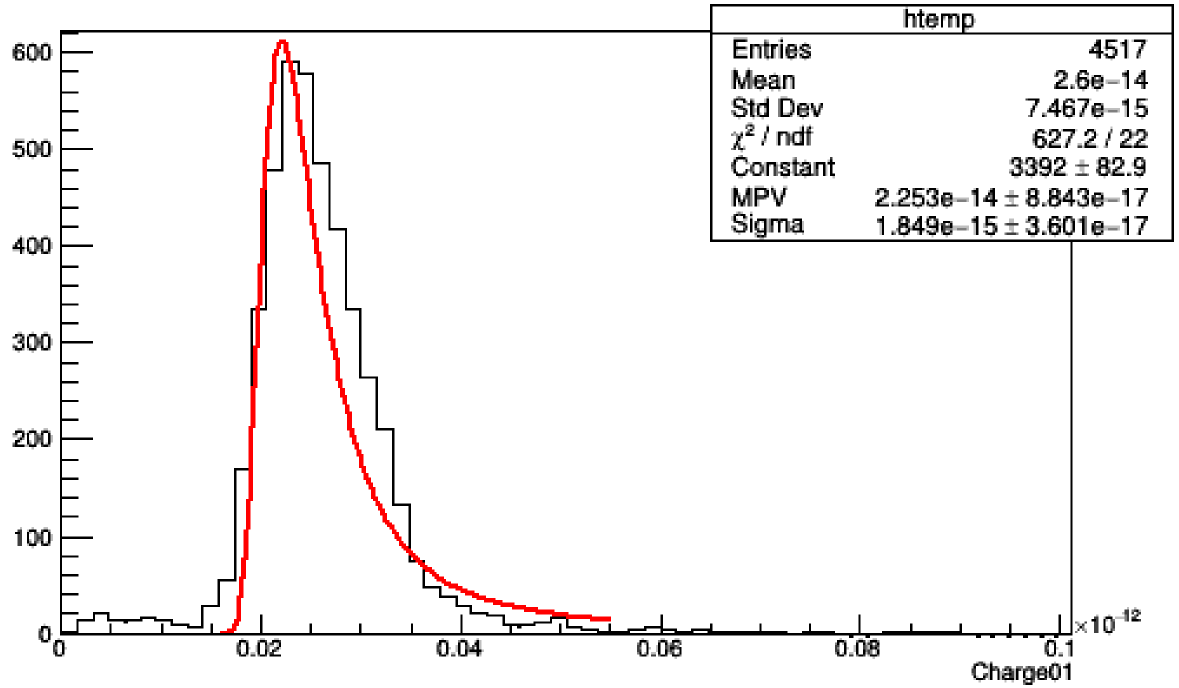
Waveform analysis: LGADUtils framework

- Waveform processing performed with LGADUtils framework (C++ based) developed at IFAE by V. Gkougkousis (documentation, gitlab)
- Working with Root v5-v6, different operating system
- Steps
  - Conversion oscilloscope binary data to Root ntuple with raw waveform information
  - Merging with track ntuple from EUTelescope
  - Waveform analysis
    - Determination of pulse polarity, signal start and stop, determine if the pulse is noise or signal
    - Calculate noise level and pedestal using Gauss fit, pedestal substraction, recalculation of start and stop of the signal
    - Compute charge, rise time, time at different CFD fractions…
    - Perform CFD Time Walk correction
  - User analysis
    - Efficiency
    - Timing



Waveform analysis: collected charge

- Charge of the signal is obtained from waveform integration between start and stop
- Values from integral fill charge distribution (plot on the right)
- Each distribution is fitted with a convolution of Landau with Gauss function
- Charge for HV value is the MPV of the fit, sigma is its error

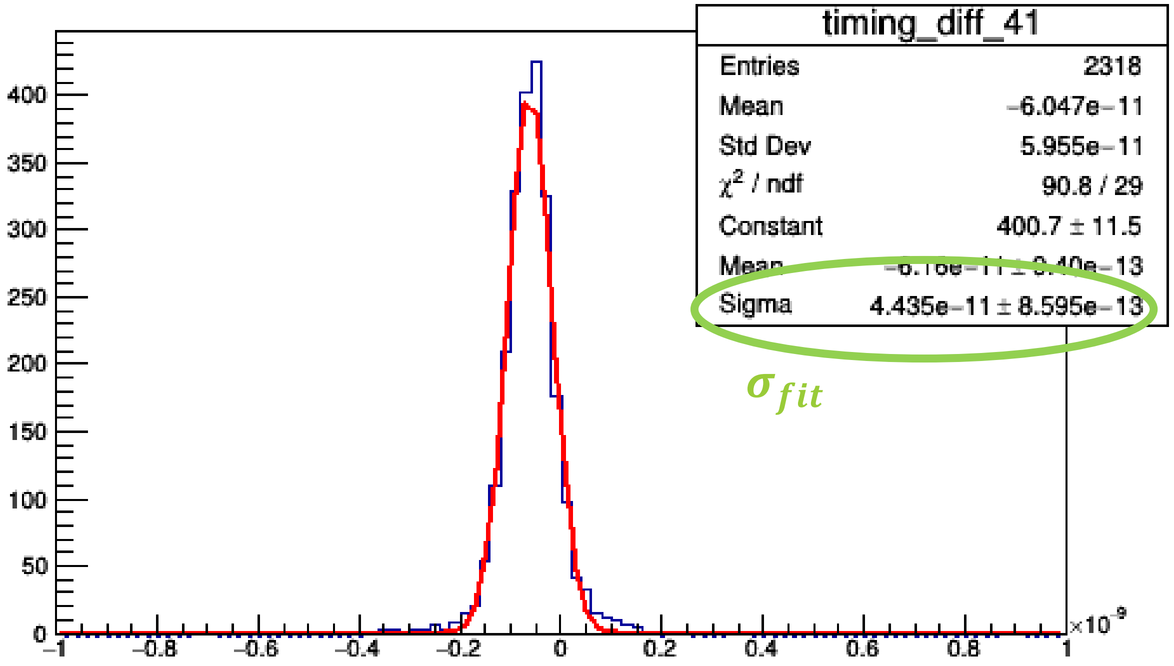


Waveform analysis: collected charge

- Time differences is computed for each CFD fraction combination between DUT and reference sensors
  $$\Delta t = t(DUT(f_{CFD})) - t(REF(f_{CFD}))$$
- The time difference distribution is fitted with a Gaussian with the time resolution of the system defined as the σ of the Gaussian
- Time resolution of the DUT is obtained by subtracting the contribution of the reference sensor

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

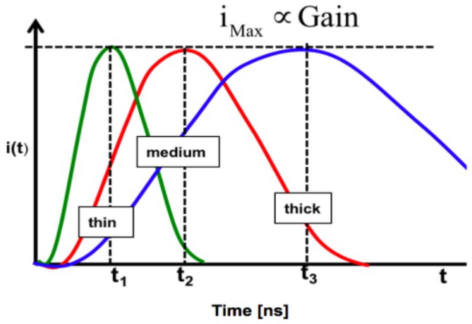
- Where $\sigma_{REF} \sim 35ps$ is known from previous calibration measurements

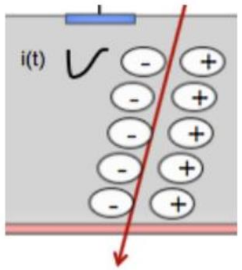


Timing contributions

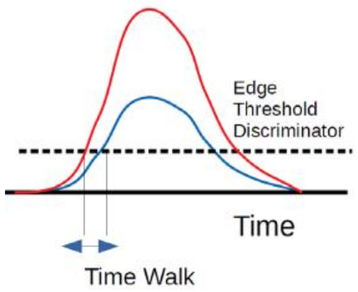
$$\sigma_{tot}^2 = \sigma_{Landau}^2 + \underbrace{\left(\frac{t_{rise}}{S/N}\right)^2}_{\sigma_{jitter}^2} + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + \sigma_{clock}^2$$

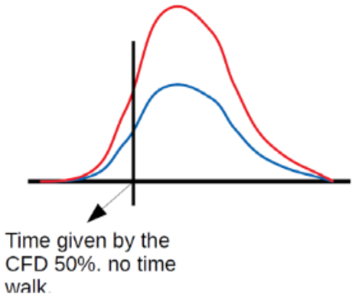
- Landau term $< 25\ ps$
  - Reduce for thin sensors $35 - 50\mu m$
- Jitter term $< 15\ ps$ and time walk correction $< 10\ ps$
  - Low noise and fast signals
- Digitization granularity $\sim 5\ ps$
- Clock distribution $< 10\ ps$





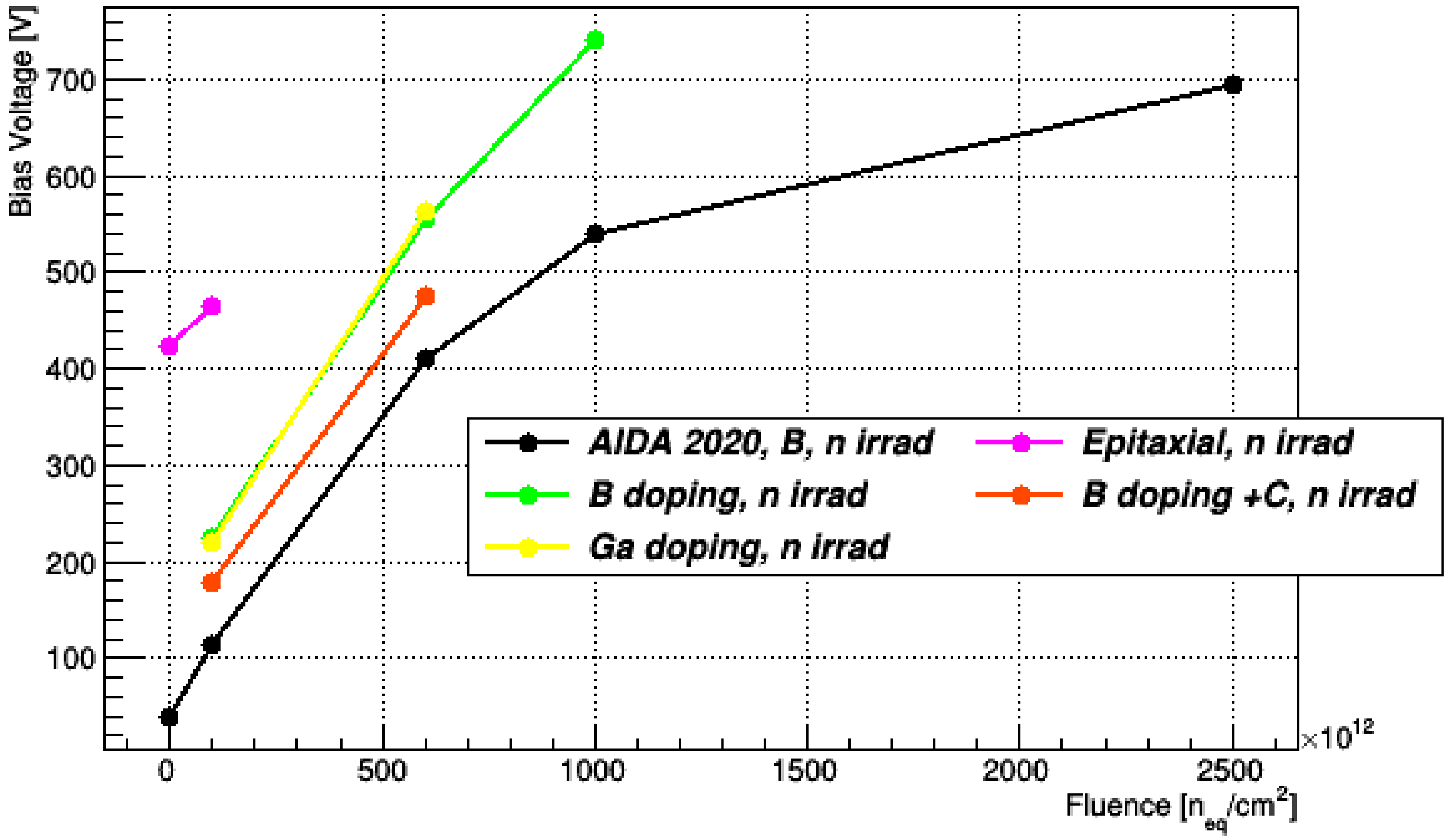
- Time walk correction for test beam data using the **C**ostant **F**raction **D**iscriminator (**CFD**) technique
  - Time at a fraction of 50% of amplitude





Auto-triggering voltage vs fluence

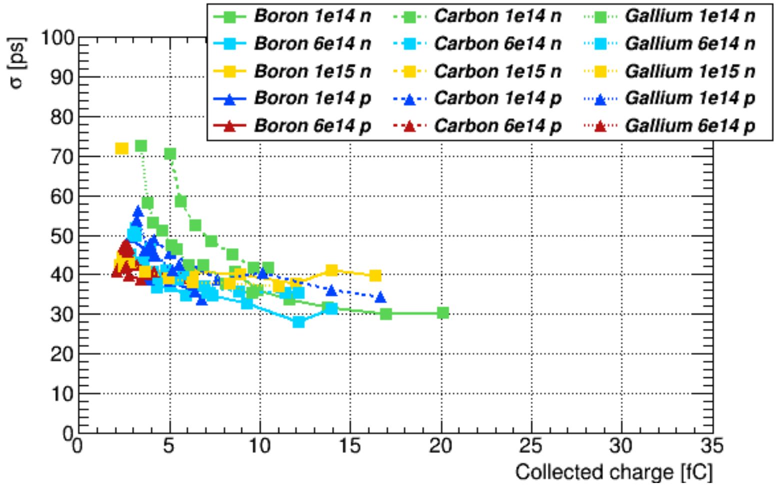
Bias voltage at which auto-triggering rate goes over 1kHz wrt fluence



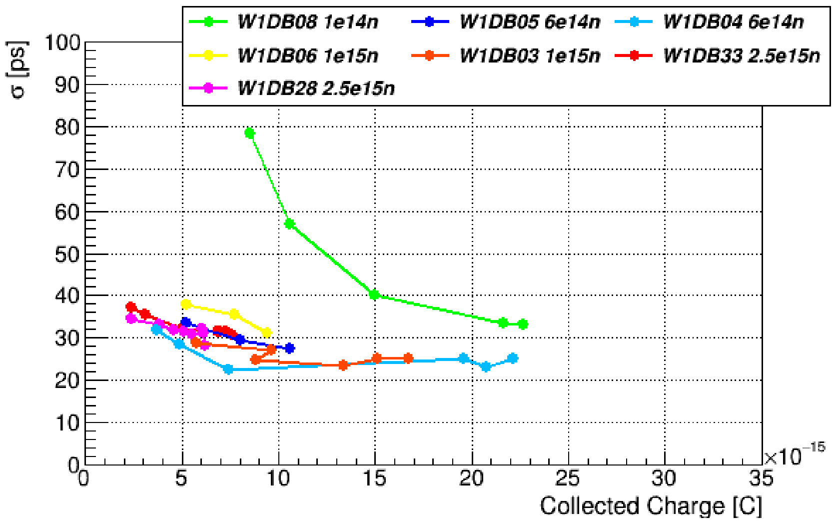
Time resolution Vs collected charge

$T = -30°C$

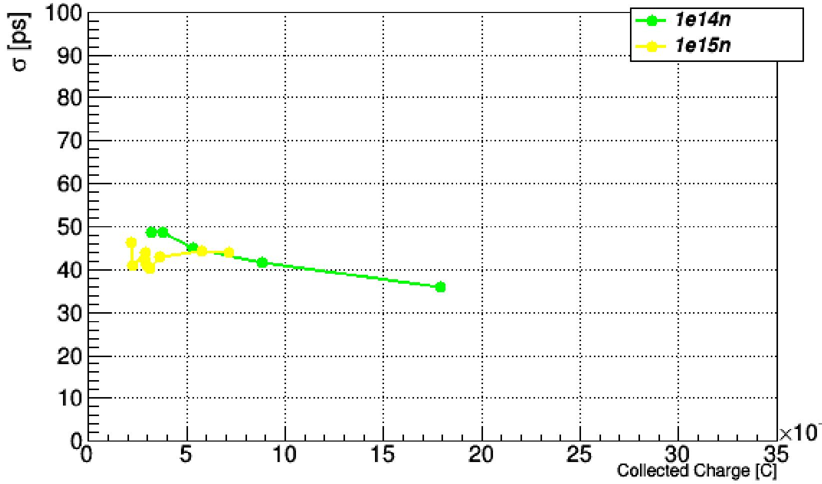
B, B+C and Ga



AIDA



EPI



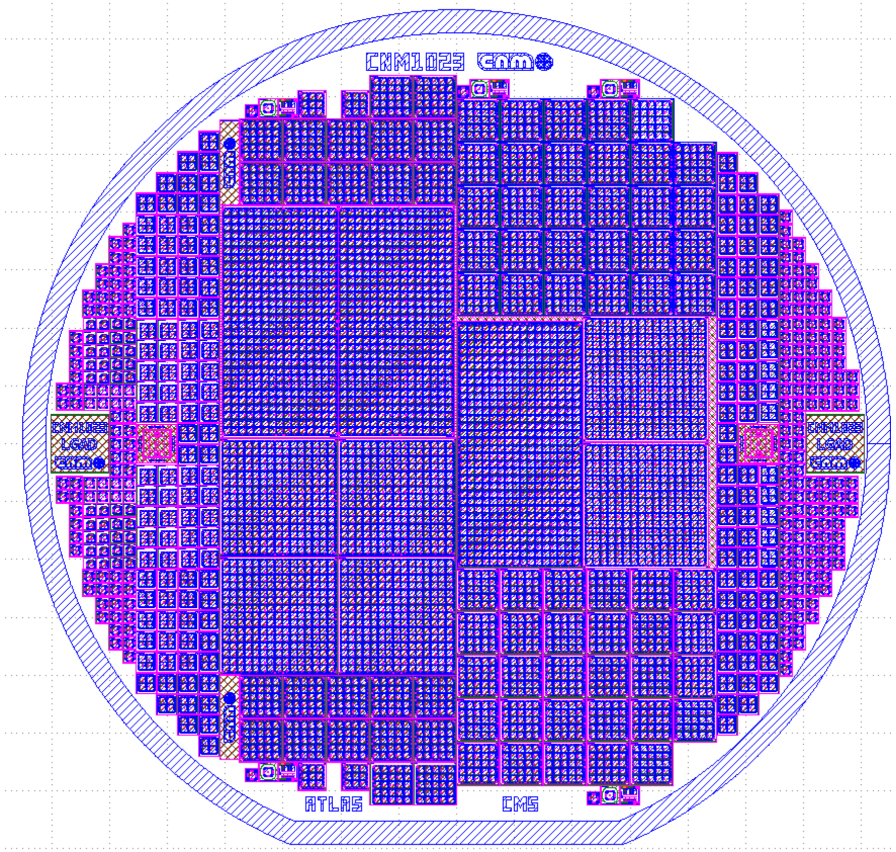
- All the fluences present enough room to operate between V_{gl} and V_{bd}
- Not detectabòe auto triggering up to 770V for fluence of 1e15n and up to 720V for fluence of1e16n but high current, no possible to go higher in voltage

- Up to 1e14 n irradiated sensors a high collected charge (>10 fC) is achieved
- For 1e15 n irradiated sensor 4 fC are reached at HV>700V
- No detectable gain for 1e16n up to 720V
- Foreseen tests of intermediate fluences (5e14n, 8e14n, 2e15n, 3e15n and 5e15n)

- A time resolution < 50 ps is achieved for sensor irradiated up to 1e15n
  - A plateau-like around 43ps is reached for this fluence
- For 1e14n the measured time resolution is below 40 ps

Unirradiated devices have enough room to operate, but irradiated ones works at relative high bias

Run 13840: 6” ATLAS-CMS Common Run (6LG3)



1x1, 2x2, 5x5 & 16x16 mm² devices

- 9 LGAD + 1 PiN wafers.
- Some of them carbonated
- 6-inch 55/525 µm **epitaxial** wafers.
  - ➢ Handle wafer resistivity = 0.001-1 Ohm-cm
  - ➢ Substrate resistivity > 200 Ohm-cm
- Same technological process as Run 13002 : 6LG3
- New diffusion furnace → Higher diffusion processes quality and uniformity
- It will be terminated by : forth quarter of 2021
- Waiting to define optimal dose and implantation E