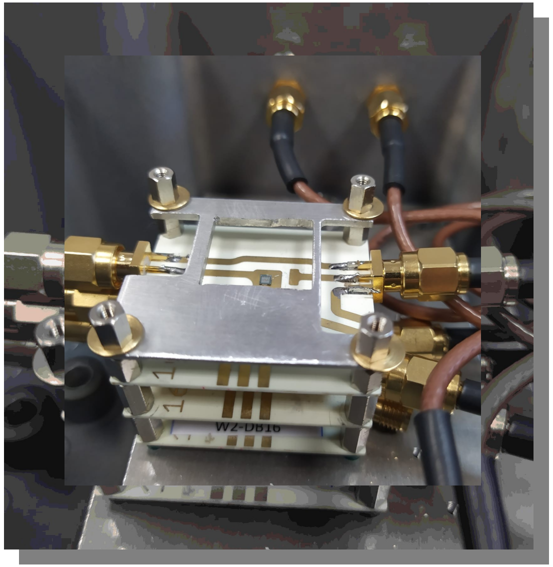
Radiation tolerance study of LGADs for the CMS Endcap Timing Layer detector.



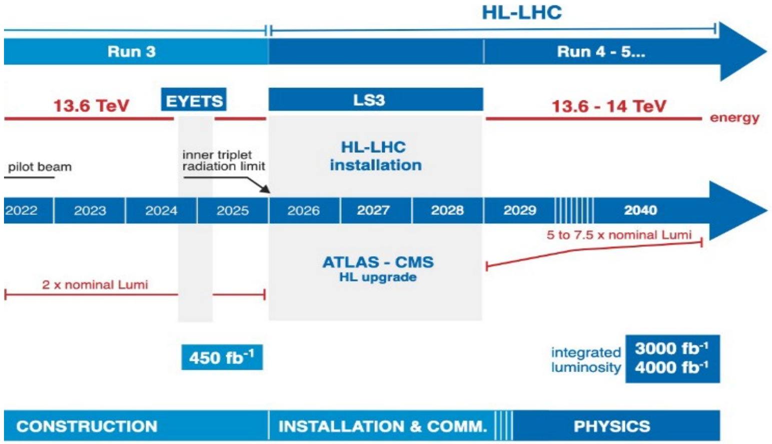
18th "Trento" Workshop on Advanced Silicon Radiation Detectors

Efrén Navarrete Ramos.
On behalf of the CMS Collaboration

Contents

- **Motivation**
- **Samples Description**
- **Determination of the Acceptor Removal Constant**
- **Radioactive Source Characterization**
  - Charge Collection
  - Time Resolution
- **Conclusions**

Motivation



The new HL-LHC upgrade environment:

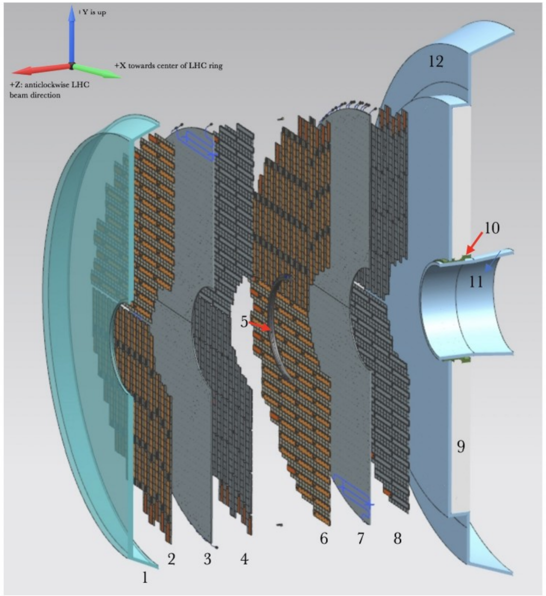
- CMS and ATLAS detectors will be upgraded (Phase II - HL upgrade)
- Integrated luminosity ≥ 3000 fb^{-1} (~10x times more than Phase 1)
- Pile-up = 200 (4x times more than Phase 1)
- **Timing will help resolve all collisions**

Timing with silicon detectors:

- Track timing, with the new Endcap Timing Layer (ETL): Assign the "time stamp" to the track.
- Disentangling Primary vertex reconstruction will lead to higher effective luminosity

Endcap Timing Layer (ETL): $1.6<|\eta|<3.0$

- Silicon sensors with internal gain (**LGAD**)
- Surface: ~14 m^2
- Radiation tolerance up to **$1.5x10^{15}$** n_{eq}/cm^2 at $|\eta|=3.0$
- Fluence is less than **$1x10^{15}$ n_{eq} /cm^2** for **80%** of the ETL area



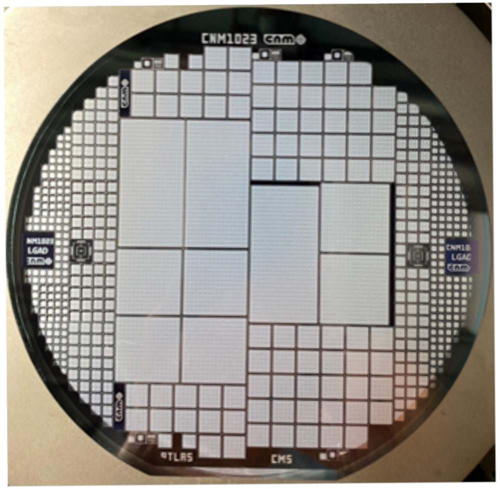
1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

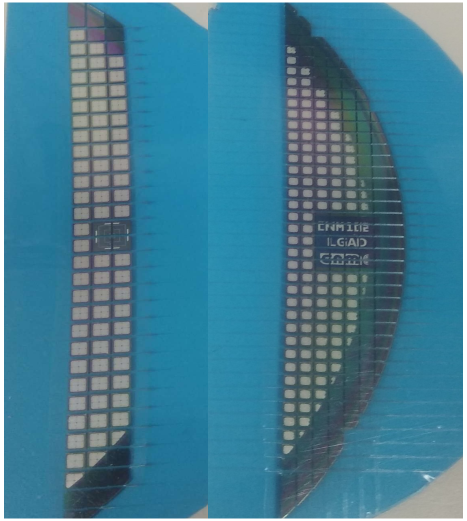
Scheme of one of the two parts of the ETL

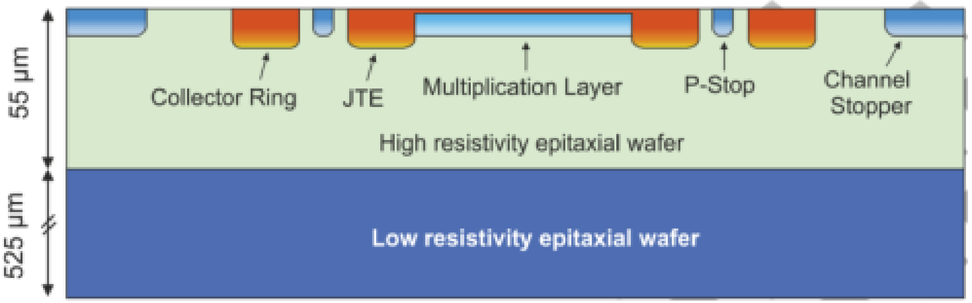
Samples Description CNM

CNM-IMB Run 15246: 6” ATLAS-CMS.

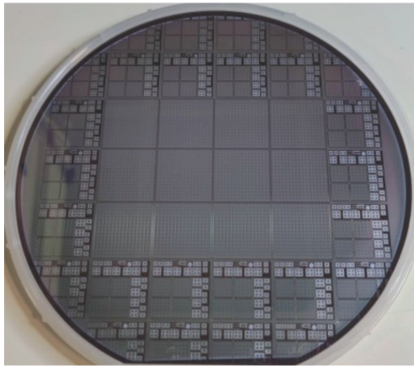
- **Epitaxial** Wafers, **shallow** junction, some with **carbonated** gain layer**,** 55µm active thickness and 525µm handling wafer.
- Sensor sizes: **1x1,** 2x2, 5x5, 16x16 & 16x32 of 1.3x1.3mm^2
- CNM fresh detectors measured before and after neutron irradiation (**0.6E15, 1E15 & 1.5E15 [n_{eq}/cm^2]** @ **Ljubljana).**







Samples Description FBK



Wafer Group	Wafer #	DI	Gain Layer Dose	Carbon	Diffusion
1	1	Shallow	0.96	0.8	CH-BL
2	2	Shallow	1.00	1	CH-BL
3	3	Shallow	0.98	1	CH-BL
3	4	Shallow	0.98	1	CH-BL
4	5	Shallow	0.98	0.8	CH-BL
4	6	Shallow	0.98	0.8	CH-BL
4	7	Shallow	0.98	0.8	CH-BL
4	8	Shallow	0.98	0.8	CH-BL
4	9	Shallow	0.98	0.8	CH-BL
5	10	Shallow	0.98	0.8 + CS0.6	CH-BL
5	11	Shallow	0.98	0.8 + CS0.6	CH-BL
6	12	Deep	0.75	0.6	CL-BL
7	13	Deep	0.77	0.6	CL-BL
8	14	Deep	0.77	0.6	CL-BL
8	15	Deep	0.77	0.6	CL-BL
9	16	Deep	0.79	0.6	CL-BL
9	17	Deep	0.79	0.6	CL-BL
9	18	Deep	0.79	0.6	CL-BL

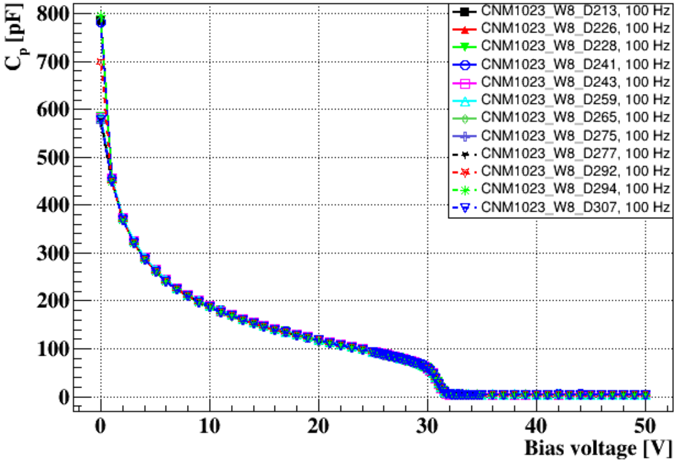
FBK UFSD4 Production.

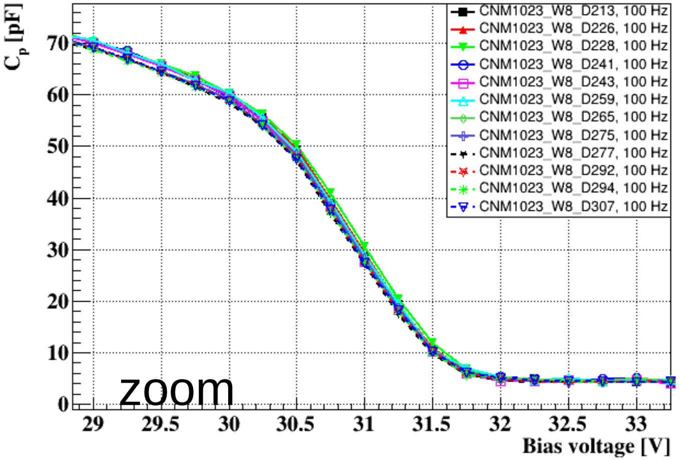
- Consisting on carbonated and standard gain layer wafers, 2 layouts for interpad regions: Type 9 (Double p-stop) and Type 10 (GuardRing-Grid), Shallow and Deep Drive-In configurations. **55 µm** active thickness.
- UFSD includes single pad, **1x2**, **2x2**, 5x5 & 16x16 array.
- This study focused on Wafers for **Carbonated** and **Shallow** Drive-In Gain layer.

- FBK_2022v1_1x2_W7 → Non-irradiated
- FBK_2022v1_1x2_W7 → Non-irradiated
- FBK_2022v1_1x2_W7 → Non-irradiated
- FBK_2022v1_2x2_W7-8 → Irr 1E15
- FBK_2022v1_2x2_W7-8 → Irr 1.5E15
- FBK_2022v1_2x2_W9 → Irr 1E15

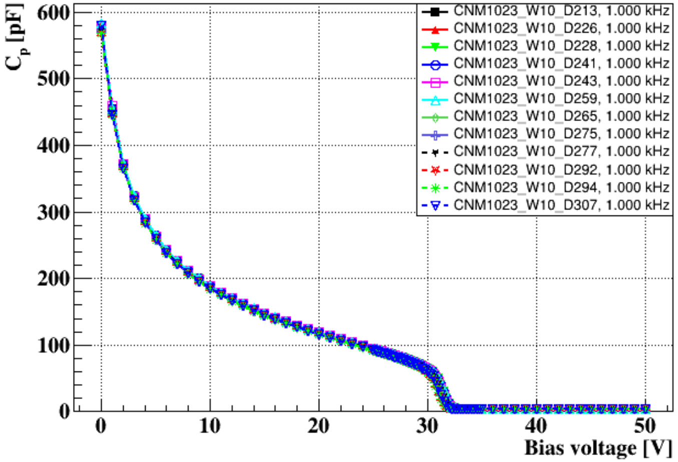
Electric Characterization, CV (Fresh)

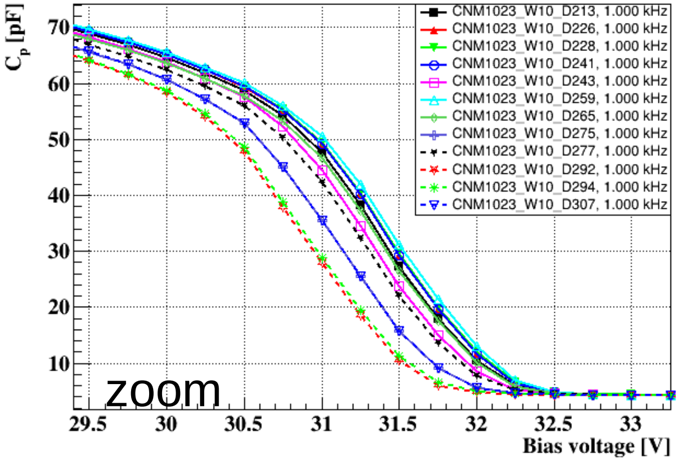
Carbonated, CNM, RT





Standard, CNM, RT

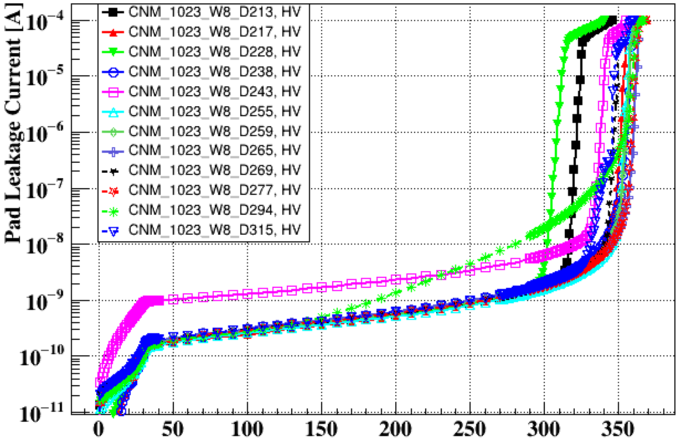


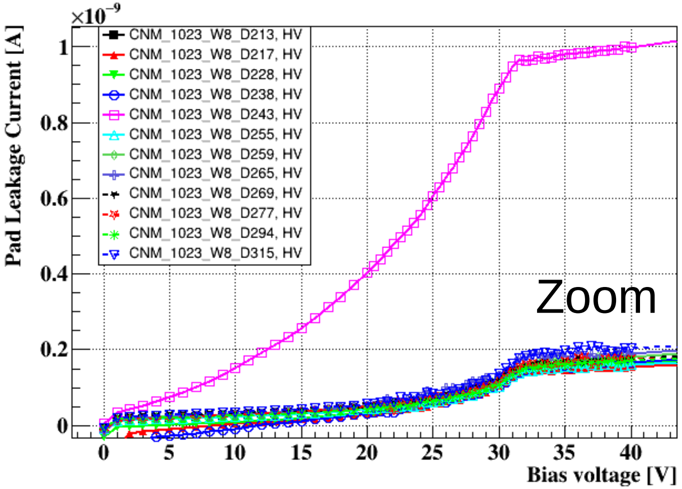


Main Diode: HV
GR: biased HV
BackSide: Ground
Temperature: RT
Frequency: 1000 Hz

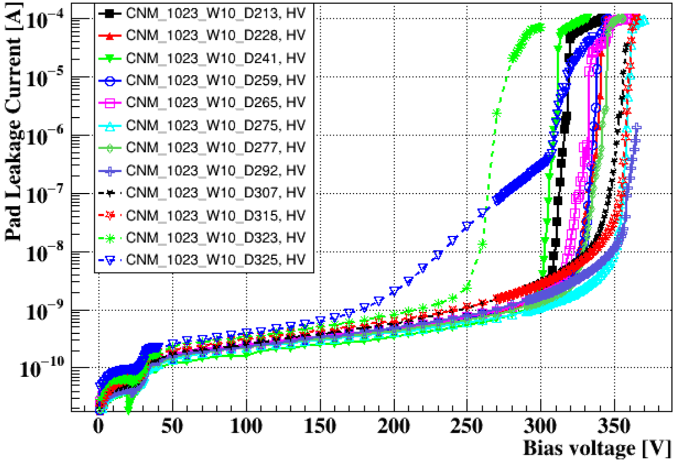
Electric Characterization, IV (Fresh)

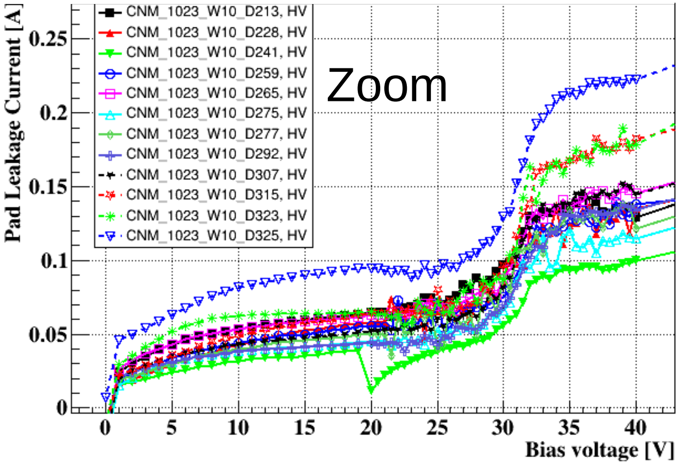
Carbonated, CNM, RT





Standard, CNM, RT

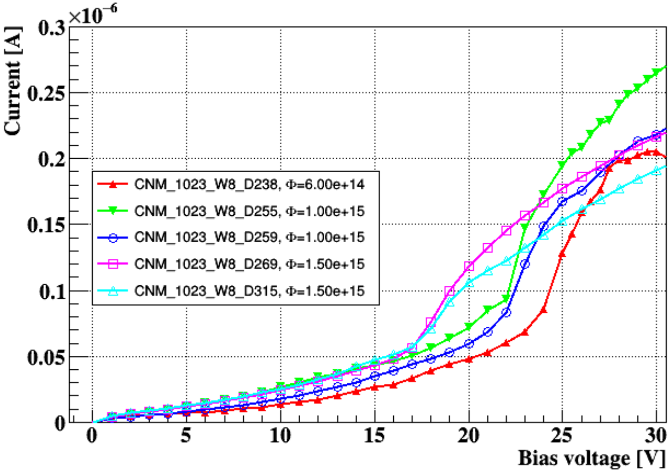


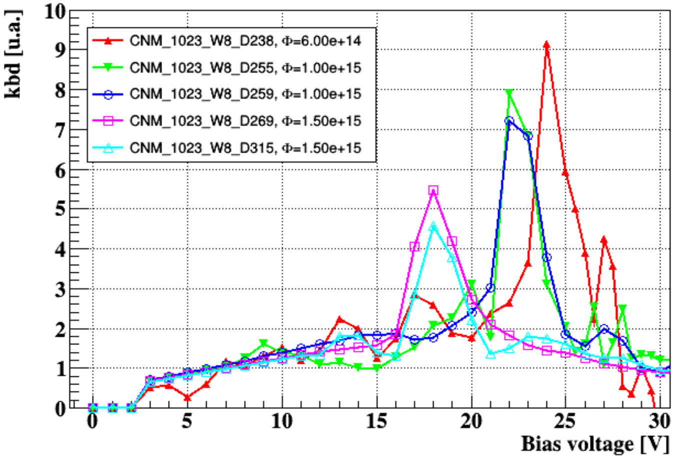


Main Diode: HV
GR: biased HV
BackSide: Ground
Temperature: RT
Compliance: 100 uA

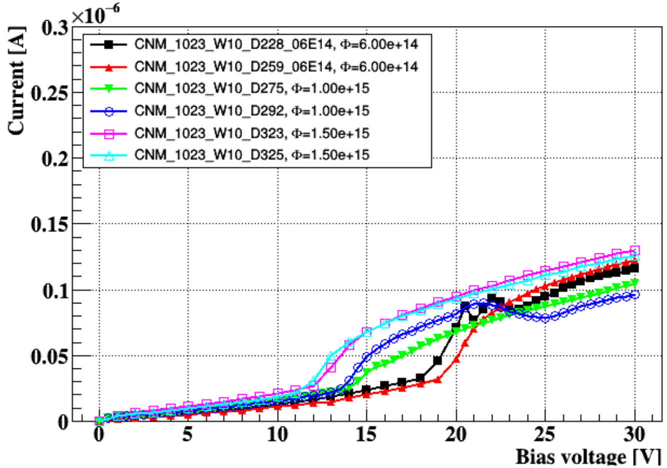
Acceptor Removal: IV

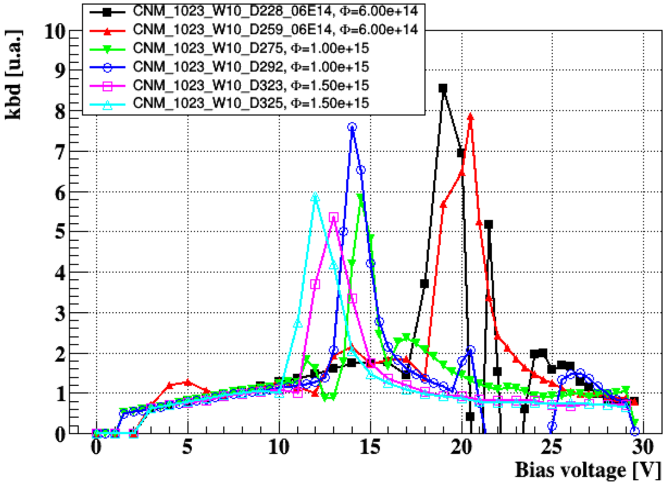
Carbonated, CNM, -25º C





Standard, CNM, -25º C





V_{gl} calculation

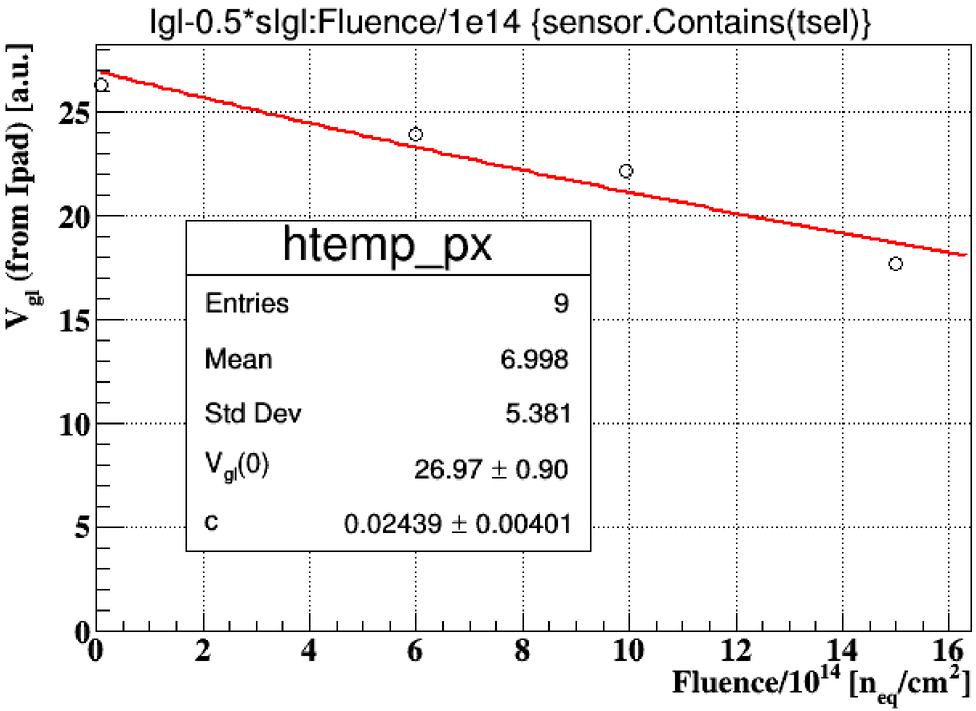
Using "automatic" variable **kbd**[1], based on the derivative of current[2], to identify depletion transition from gain layer to bulk. (See BackUp).

$$K(I,V)=\frac{dI}{dV}\frac{V}{I}$$

[1] Marcos Fernandez 16th Trento Workshop on Advanced Silicon Radiation Detectors, 17th Feb 2021
[2] N. Bachetta et al. *https://doi.org/10.1016/S0168-9002(00)01207-9*
Other methods to calculate Vgl, see: V. Gkougkousis, 35th RD50 workshop, 2019.

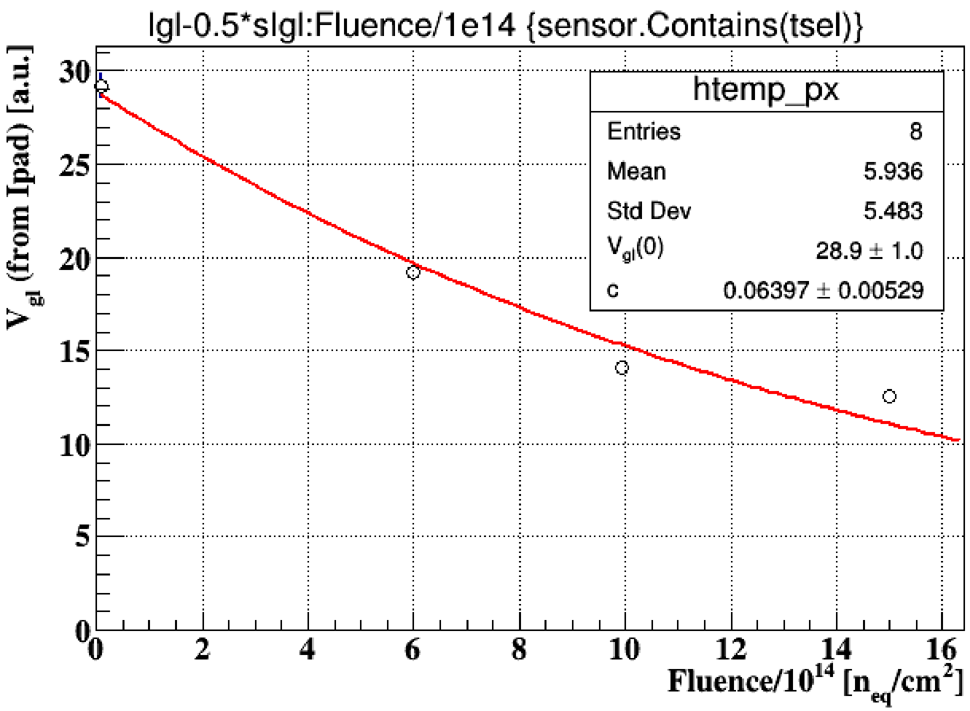
Acceptor Removal Constant

Carbonated, CNM, -25º C



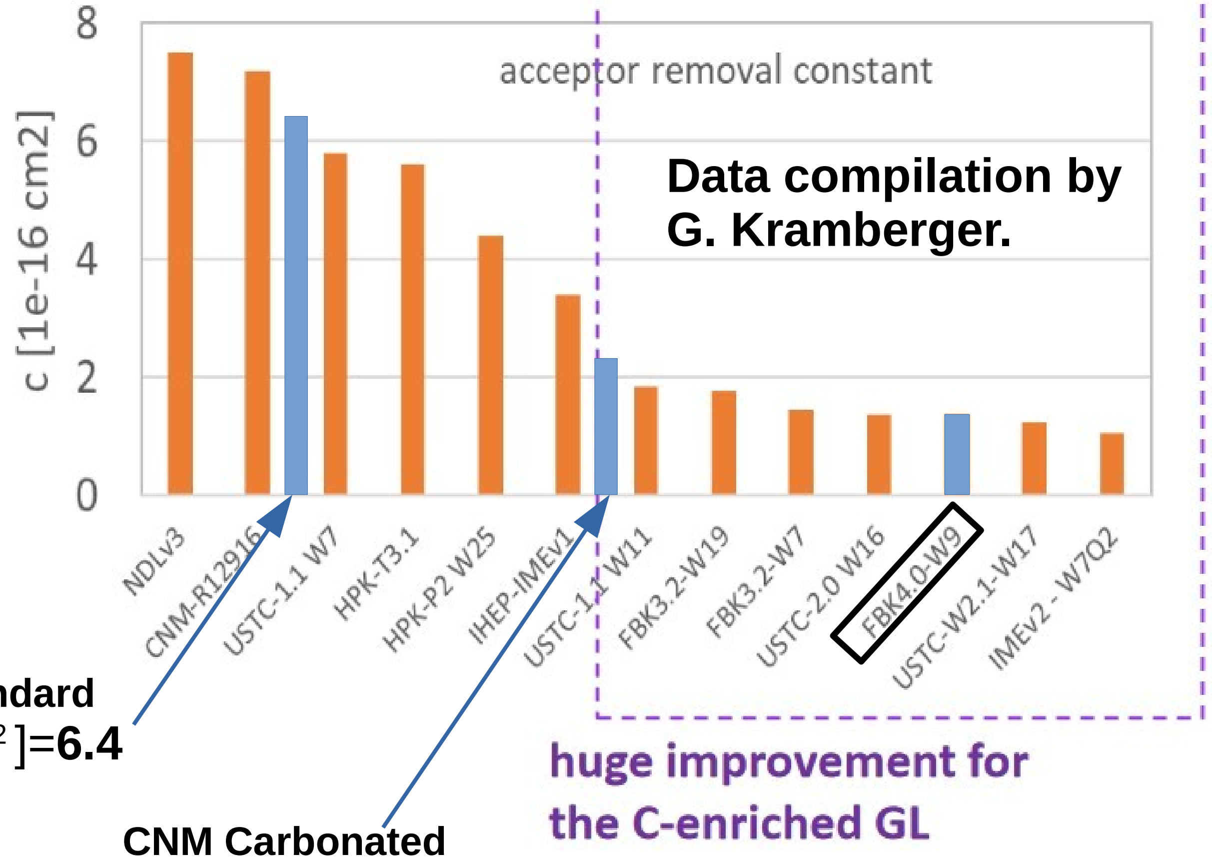
c [10^{-16} cm^2]=**2.4**

Standard, CNM, -25º C



c [10^{-16} cm^2]=**6.4**

Acceptor Removal Constant



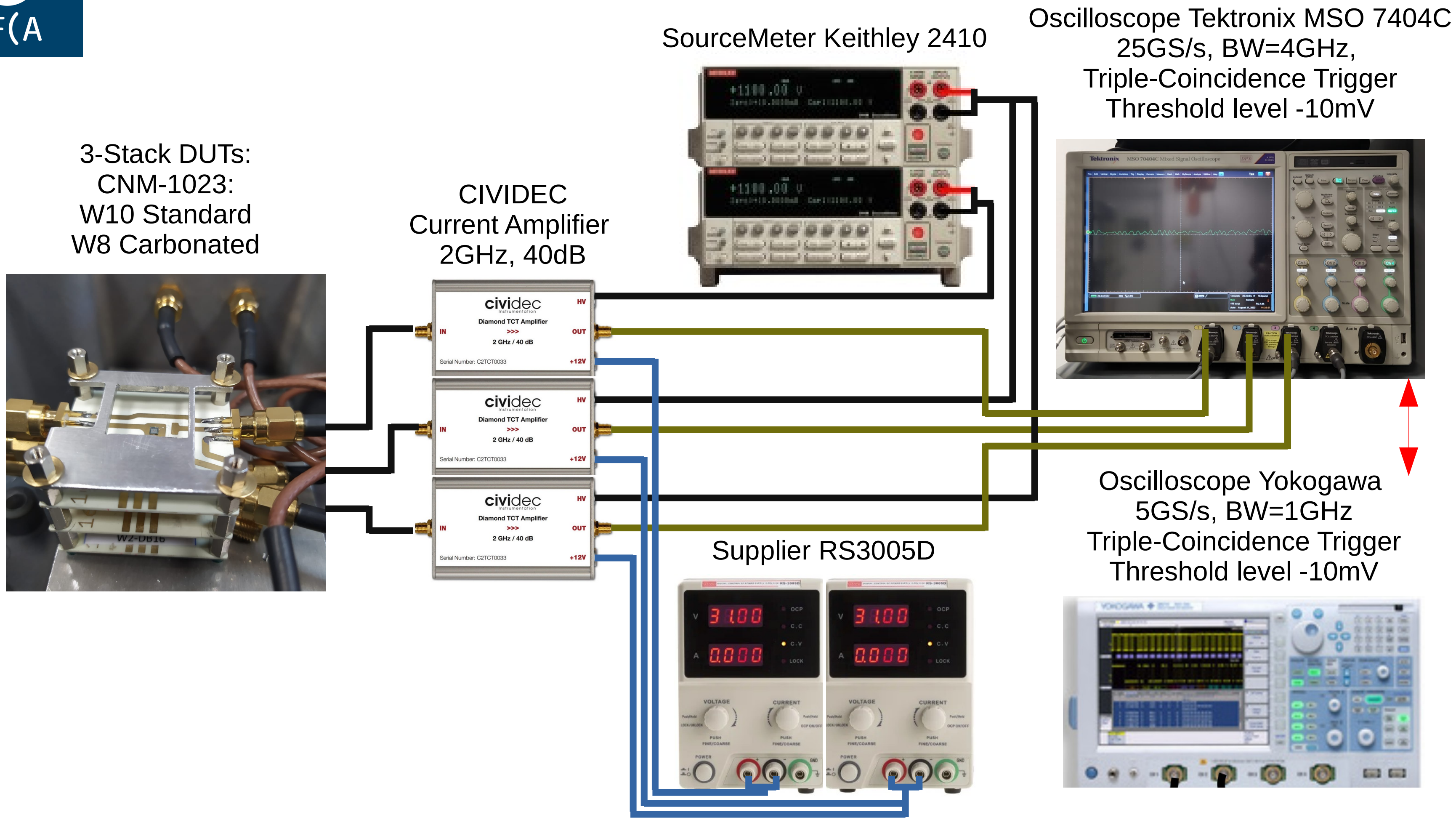
Data compilation by G. Kramberger.

CNM Standard
c [10^{-16} cm^2]=**6.4**

CNM Carbonated
c [10^{-16} cm^2]=**2.4**

Caveat:
Not all C-constants were calculated with the same method

Radioactive Source Setup



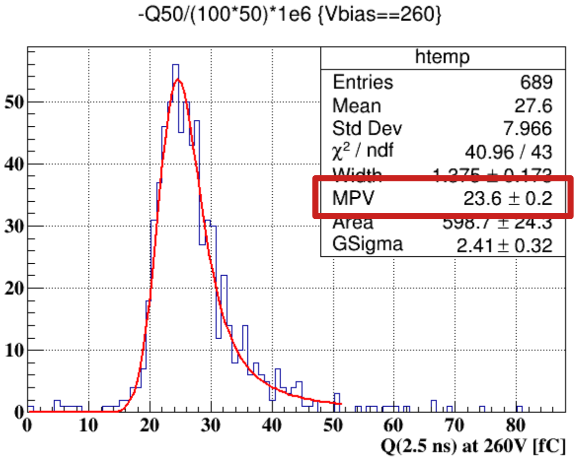
Devices Under Test, CNM samples

Manufacturer	CNM		FBK
Irradiation [n_{eq}/cm^2]	**W8 Carbonated (Single diodes)**	**W10 Standard (Single diodes)**	**Carbonated**
Non-Irradiated	**2**	**3**	**3**
0.6e15	**2**	**2**	**-**
1.0e15	**2**	**2**	**2**
1.5e15	**2**	**-**	**1**

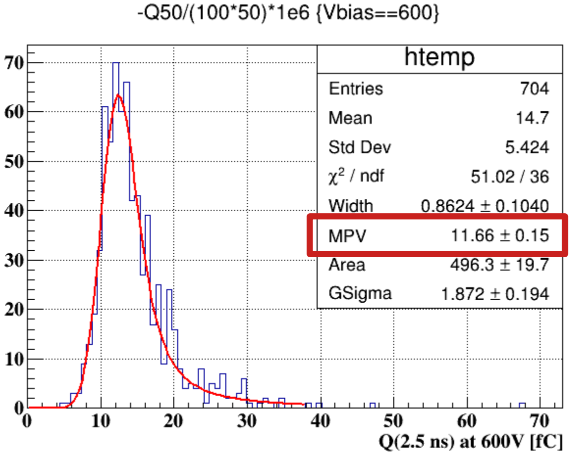
Charge Collection

Carbonated, CNM, -25º C

Non-irradiated

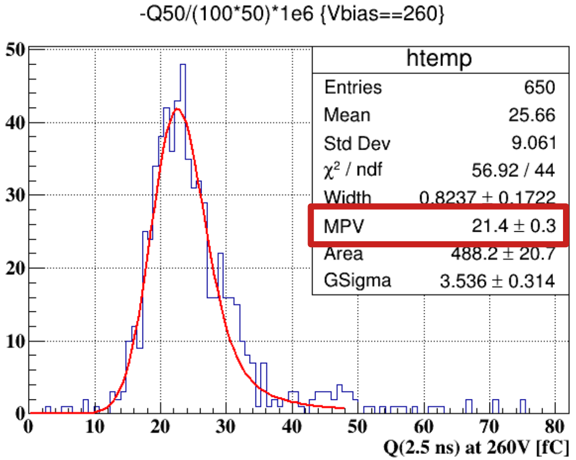


Irradiated 1E15

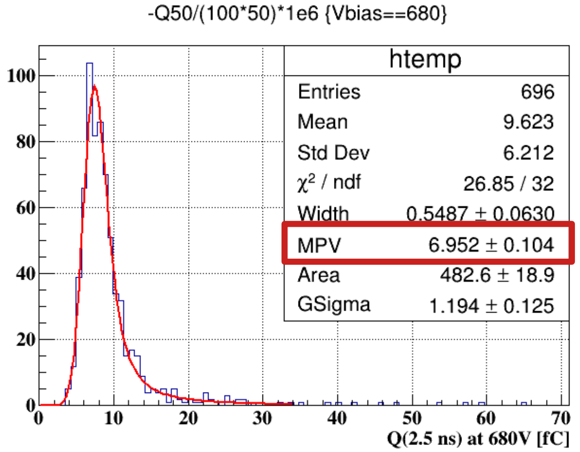


Standard, CNM, -25º C

Non-irradiated



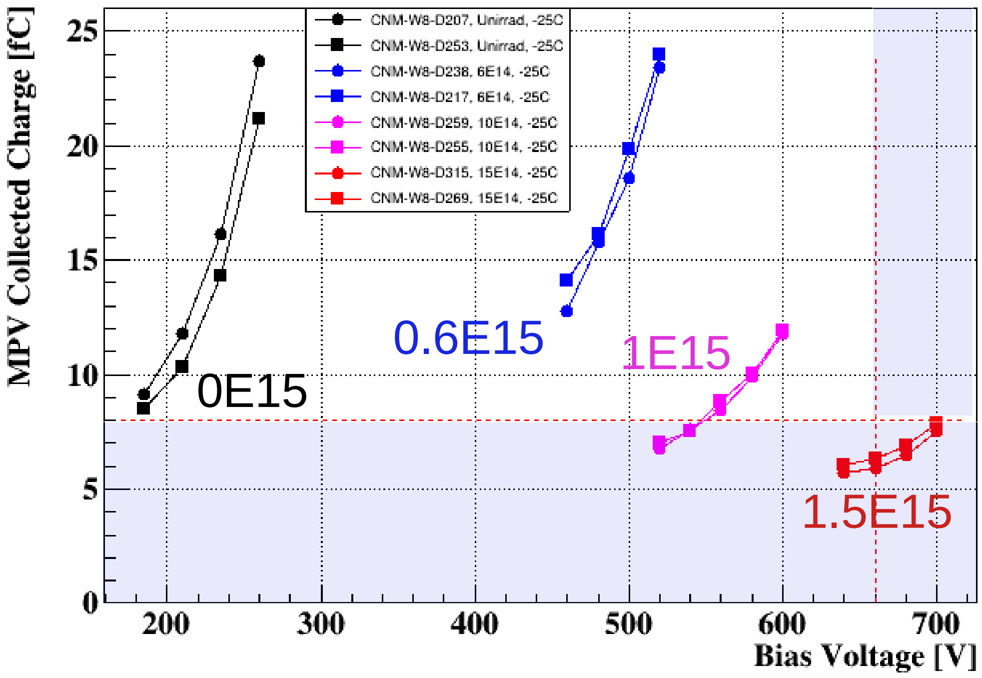
Irradiated 1E15



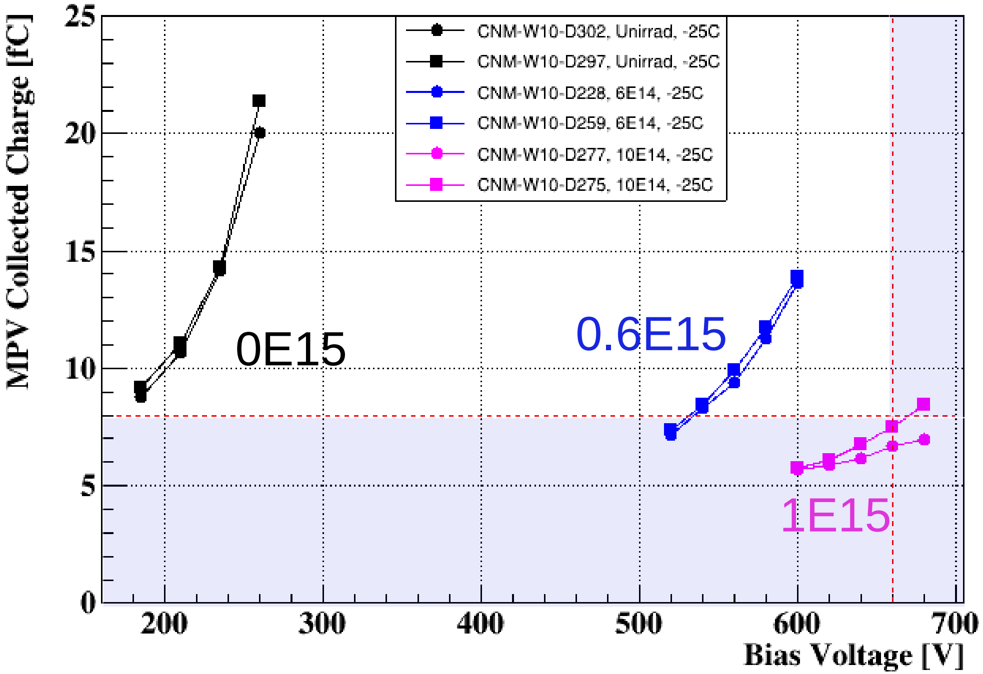
Collected charge: Integral of the Waveforms.
Most Probable Value Of **Landau+Gaus** Fit.

Charge Collection vs Fluence, CNM

Carbonated CNM, -25º C

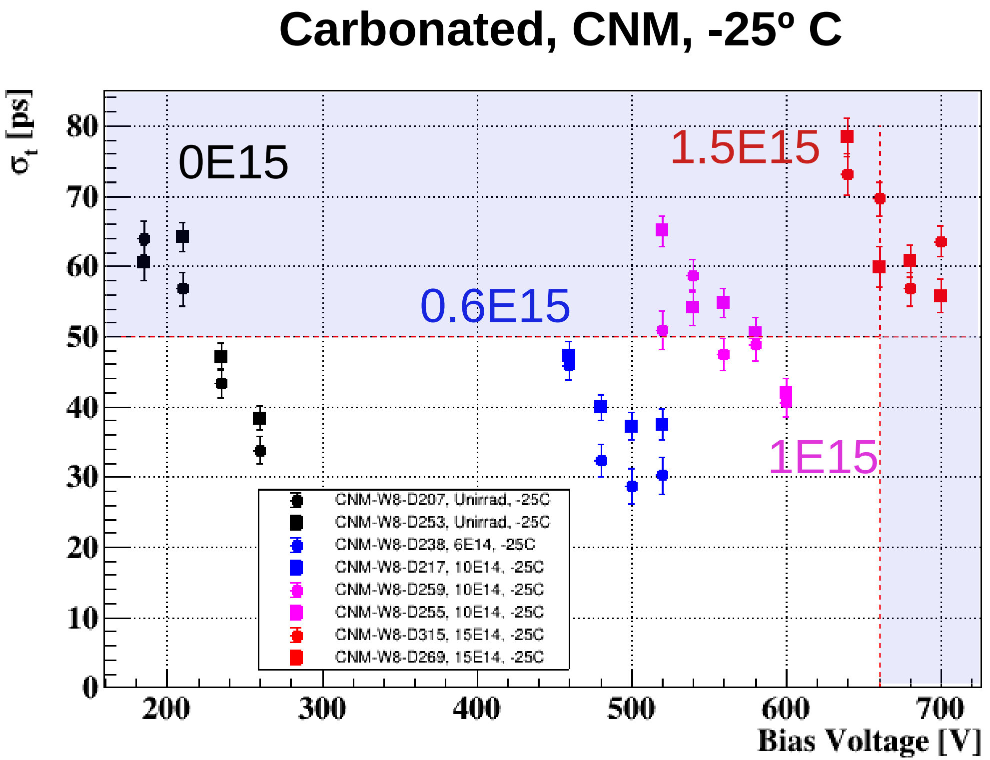


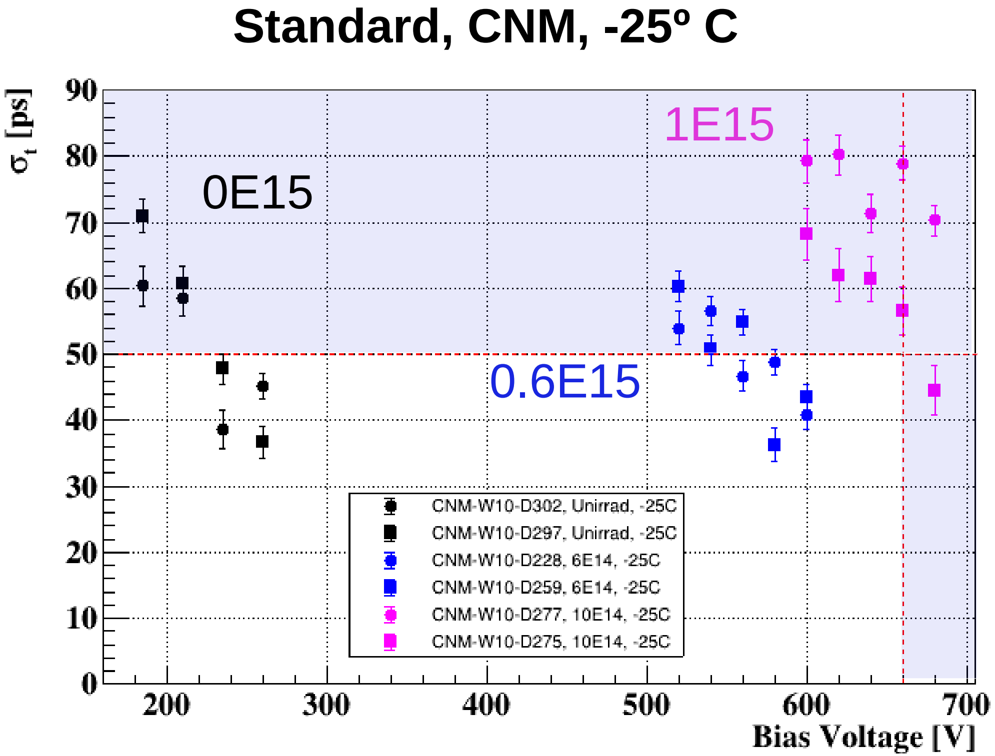
Standard CNM, -25º C



Carbonated CNM samples comply with the low fluence requirement up to 1E15

Time Resolution vs Fluence, CNM

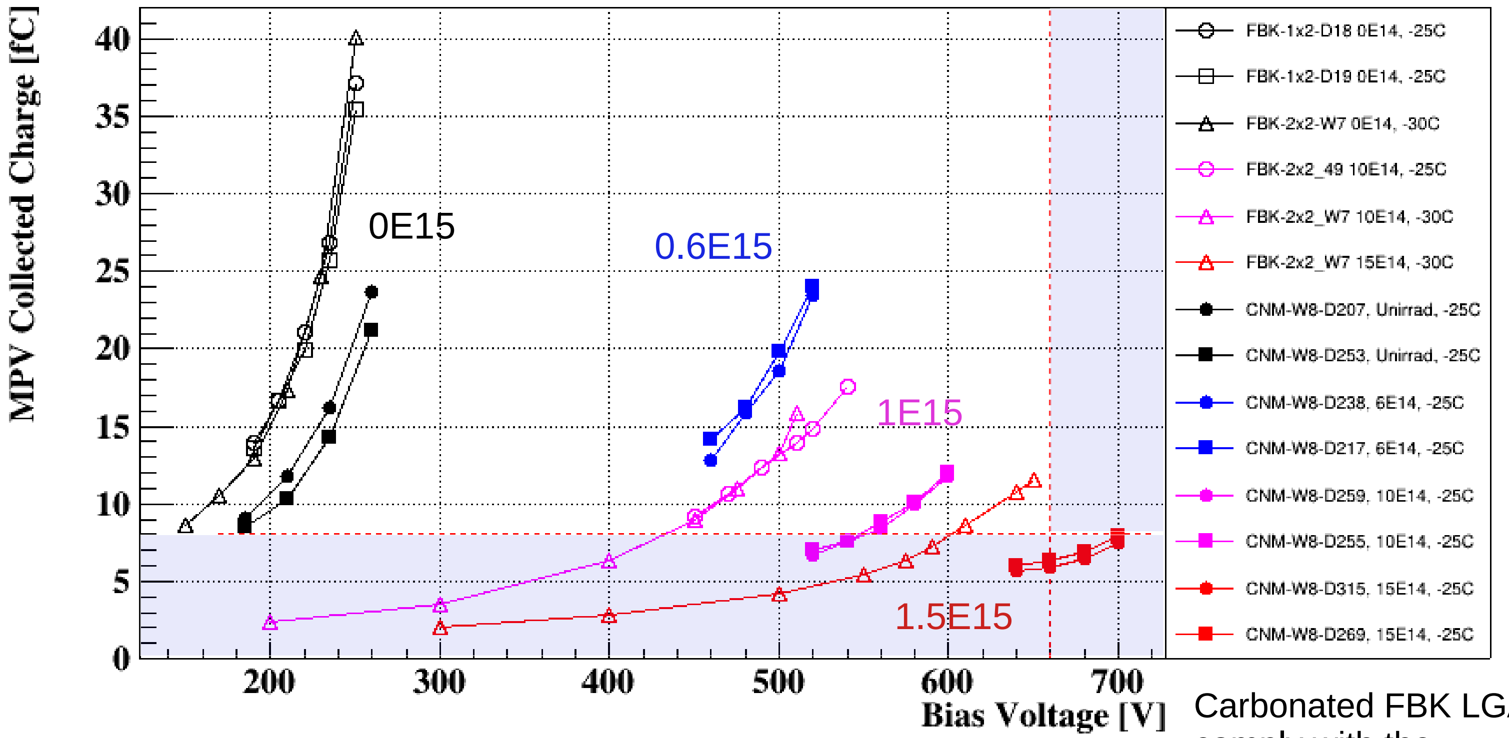




Time resolution of the carbonated CNM samples complies with the low fluence requirement up to 1E15.

Charge collection comparison

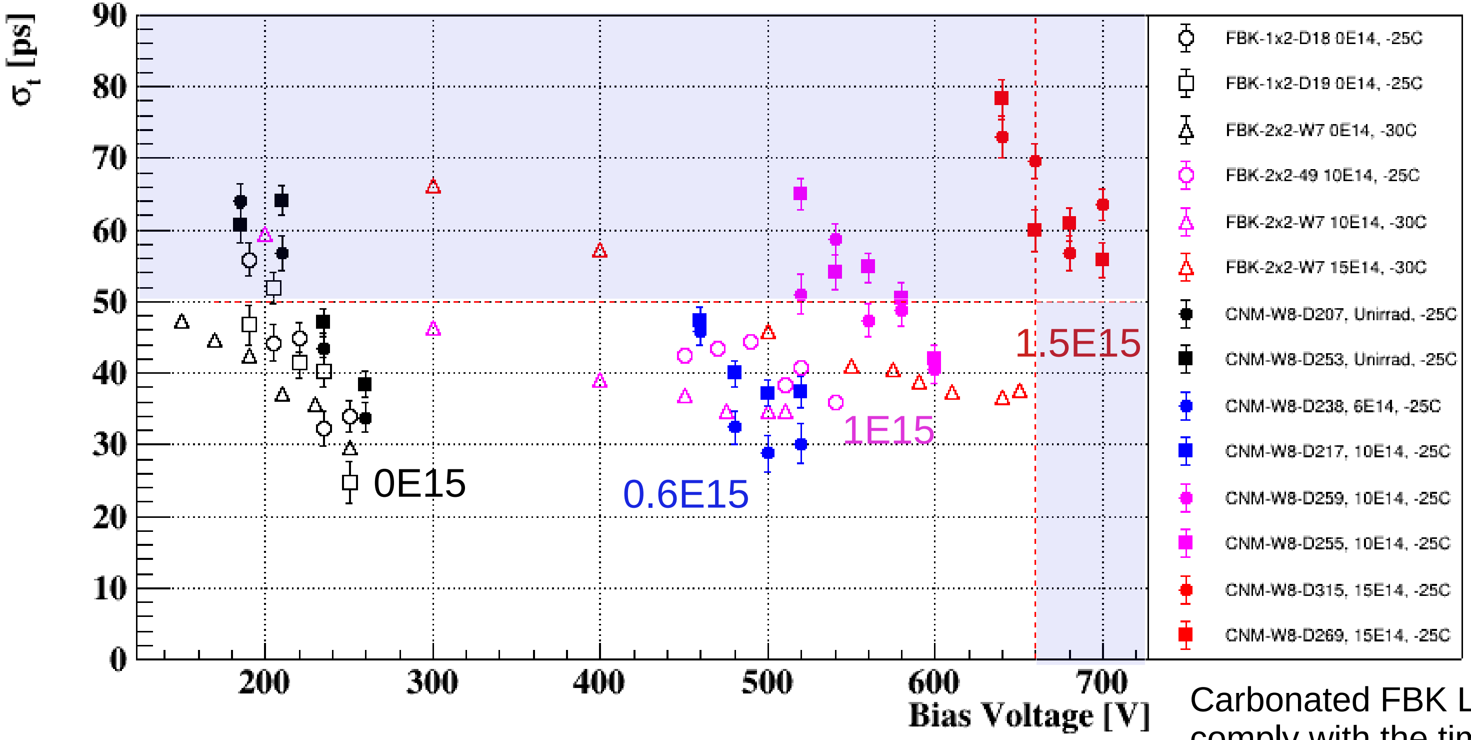
Carbonated CNM vs Carbonated FBK



Carbonated FBK LGADs comply with the requirements at the highest fluence

Time Resolution comparison

Carbonated CNM vs Carbonated FBK



Carbonated FBK LGADs comply with the time resolution requirements

Conclusions

- Radiation tolerance study completed for **CNM** and **FBK LGADs** productions.
- **Acceptor Removal Constant** of **Carbonated samples** with respect to the Standard samples was **reduced** by more than a factor of two, on **CNM LGADs**.
- **CNM Carbonated LGADs comply** with **CMS** radiation tolerance requirement up to a fluence of **1E15 [n_{eq}/cm^2].** This is the first CNM production in achieving these specifications.
- **FBK Carbonated LGADs comply** with CMS requirements at all irradiation fluences.

THANK YOU

BackUp

Electric Characterization (Fresh)

IV Mapping Single pad diodes

Carbonated

D326					
D325					
D323	D324P				
D321	D322P				
D318	D319P	D320			
D315	D316P	D317			
D311	D312P	D313	D314		
D307	D308P	D309	D310		
D302	D303P	D304	D305	D306	
D297	D298P	D299	D300	D301	
D292	D293P	D294	D295	D296	
D287	D288P	D289	D290	D291	
D281	D282P	D283	D284	D285	D286
D275	D276P	D277	D278	D279	D280
D269	D270P	D271	D272	D273	D274
D267	D268P				
D265	D266P				
D263	D364P				
D261	D262P				
D259	D260P				
D253	D254P	D255	D256	D257	D258
D247	D248P	**D249**	D250	D251	D252
D241	D242P	D243	D244	D245	D246
D236	D237P	D238	D239	D240	
D231	D232P	**D233**	D234	D235	
D226	D227P	D228	D229	D230	
D221	D222P	D223	D224	D225	
D217	D218P	D219	D220		
D213	D214P	D215	D216		
D210	D211P	D212			
D207	D208P	D209			
D205	D206P				
D203	D204P				
D202					
D201					

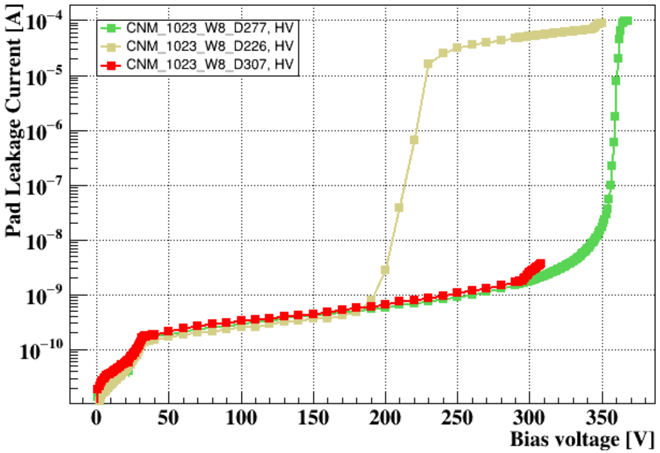
27 measured

Standard

D326					
D325					
D323	D324P				
D321	D322P				
D318	D319P	D320			
D315	D316P	D317			
D311	D312P	D313	D314		
D307	D308P	D309	D310		
D302	D303P	D304	D305	D306	
D297	D298P	D299	D300	D301	
D292	D293P	D294	D295	D296	
D287	D288P	D289	D290	D291	
D281	D282P	D283	D284	D285	D286
D275	D276P	D277	D278	D279	D280
D269	D270P	D271	D272	D273	D274
D267	D268P				
D265	D266P				
D263	D364P				
D261	D262P				
D259	D260P				
D253	D254P	D255	D256	D257	D258
D247	D248P	D249	D250	D251	D252
D241	D242P	D243	D244	D245	D246
D236	D237P	D238	D239	D240	
D231	D232P	D233	D234	D235	
D226	D227P	D228	D229	D230	
D221	D222P	D223	D224	D225	
D217	D218P	D219	D220		
D213	D214P	D215	D216		
D210	D211P	D212			
D207	D208P	D209			
D205	D206P				
D203	D204P				
D202					
D201					

22 measured

GOOD	33/49
OK but step on IV before breakdown	15/49
Early breakdown in GR	1/49



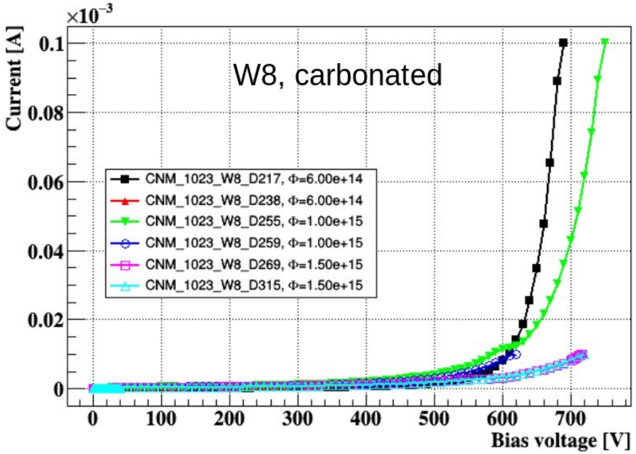
Electric Characterization

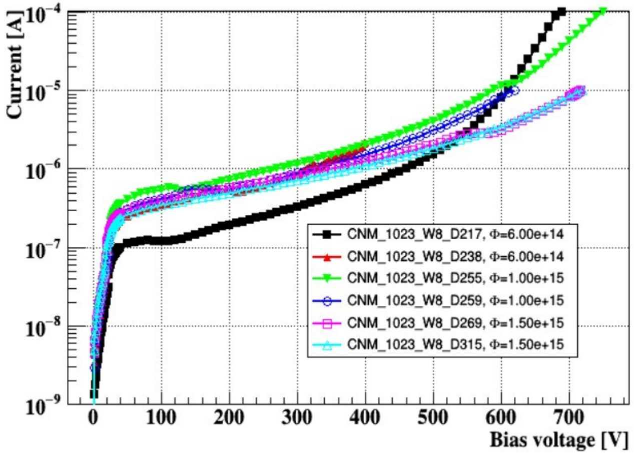
Characterization summary (88 sensors measured fresh)

	CV		IV	
	W8	**W10**	**W8**	**W10**
Single sensors	12	12	27	22
2X2 sensors	12	13	**9+7+1**	**16+3+3**
Total:	24	25	44	44

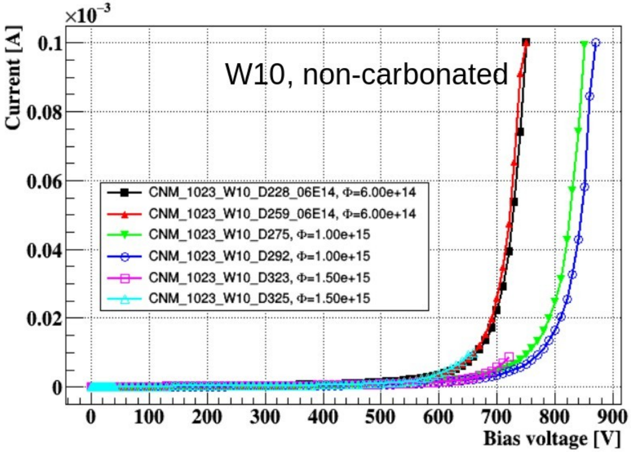
Electric Characterization, IV Irradiated

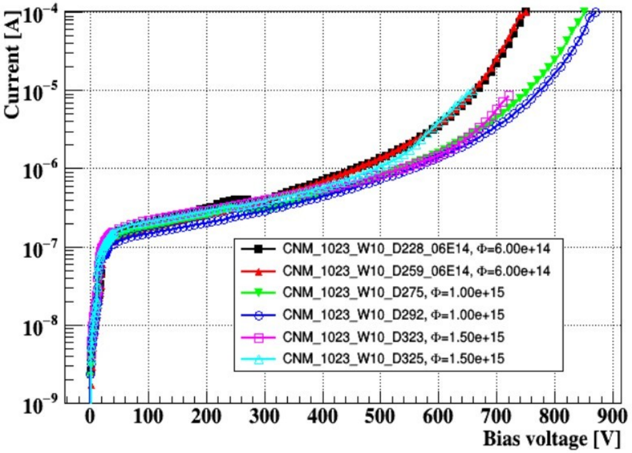
Carbonated, CNM, -25º C



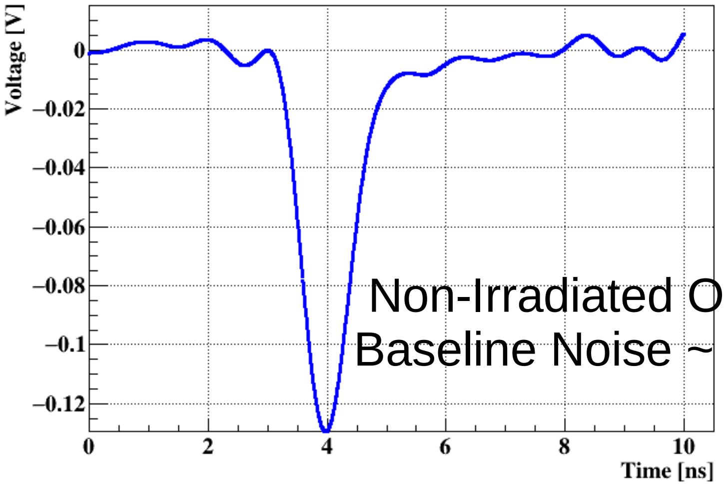


Standard, CNM, -25º C

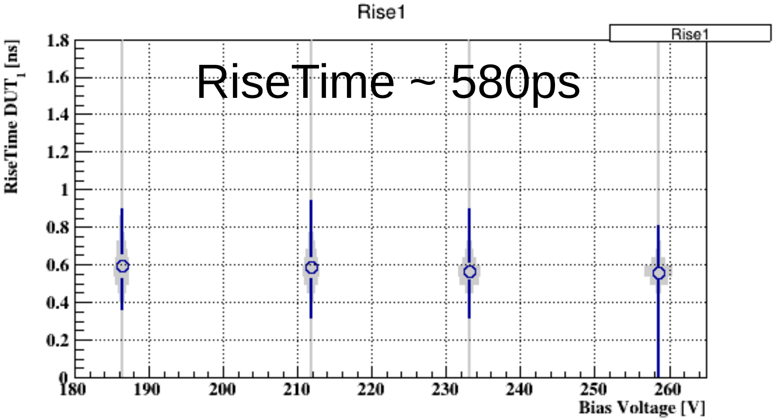




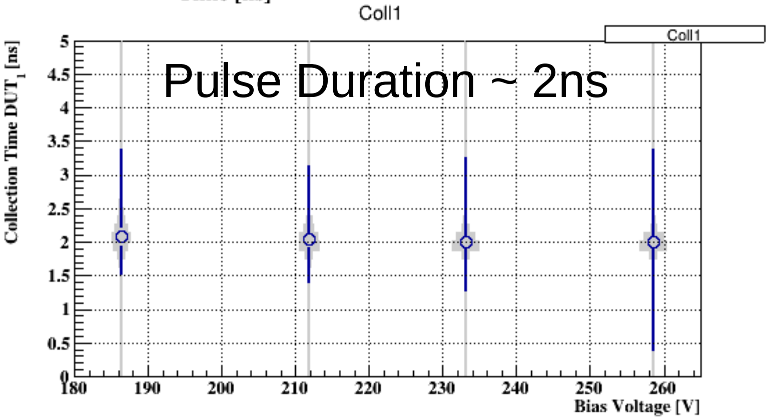
Typical Waveform



Non-Irradiated One-Shot
Baseline Noise ~ 3mV

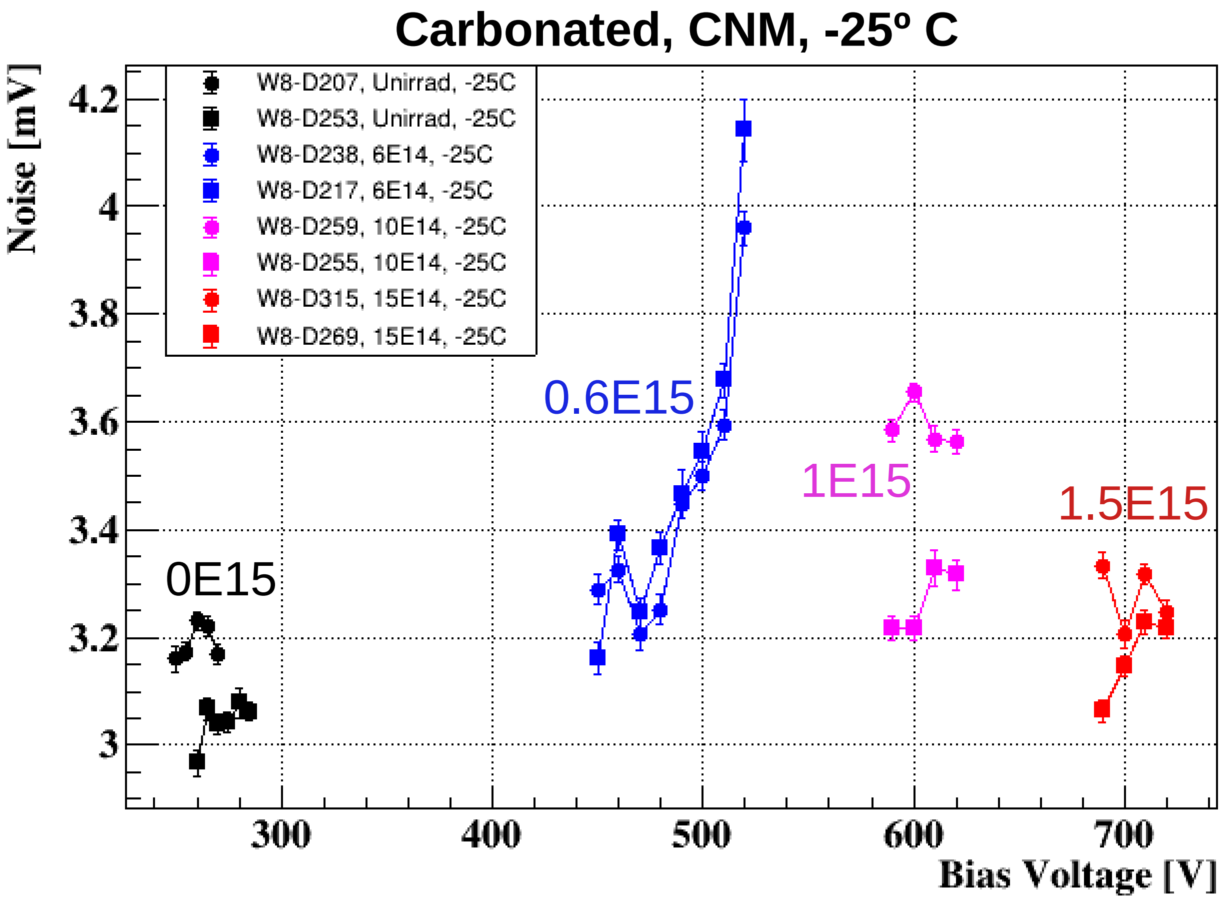


RiseTime ~ 580ps



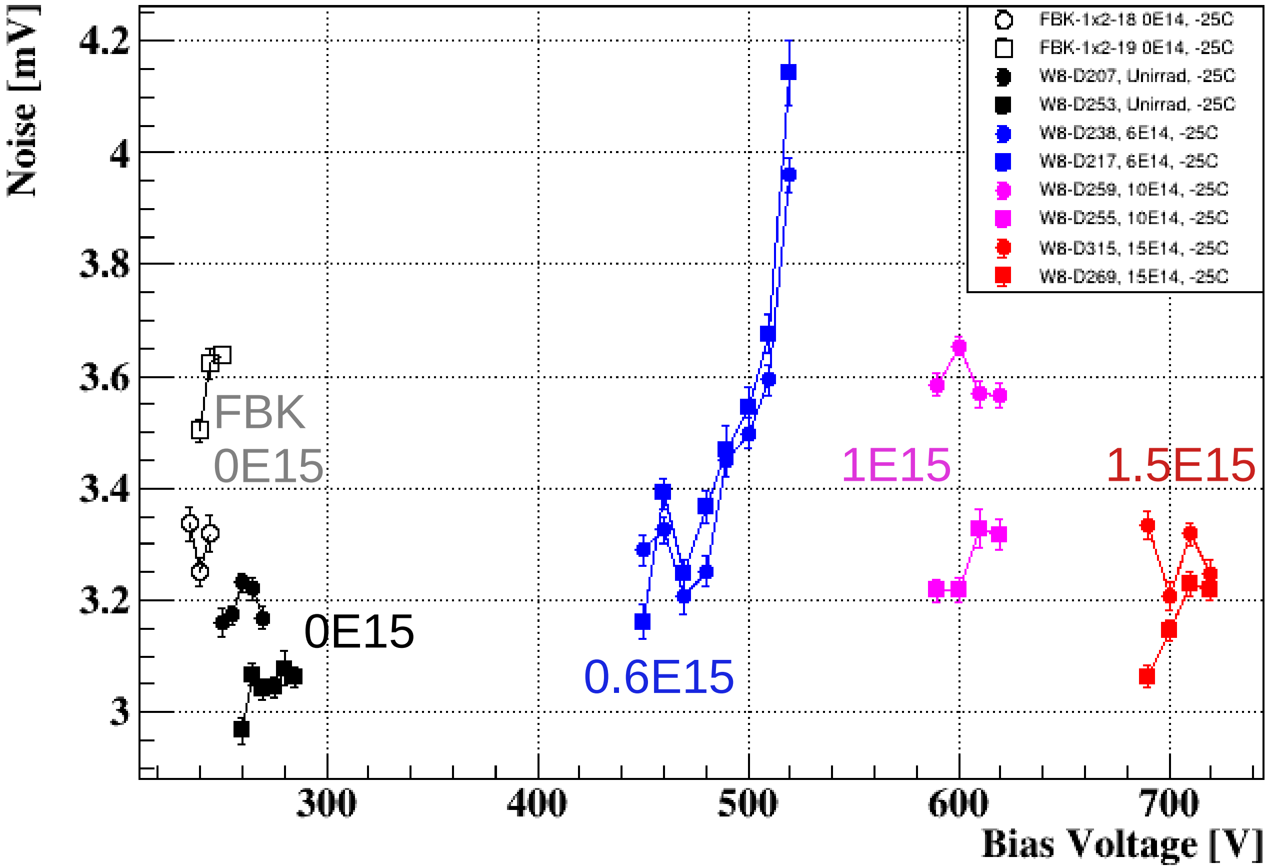
Pulse Duration ~ 2ns

BaseLine Noise Bias Dependence



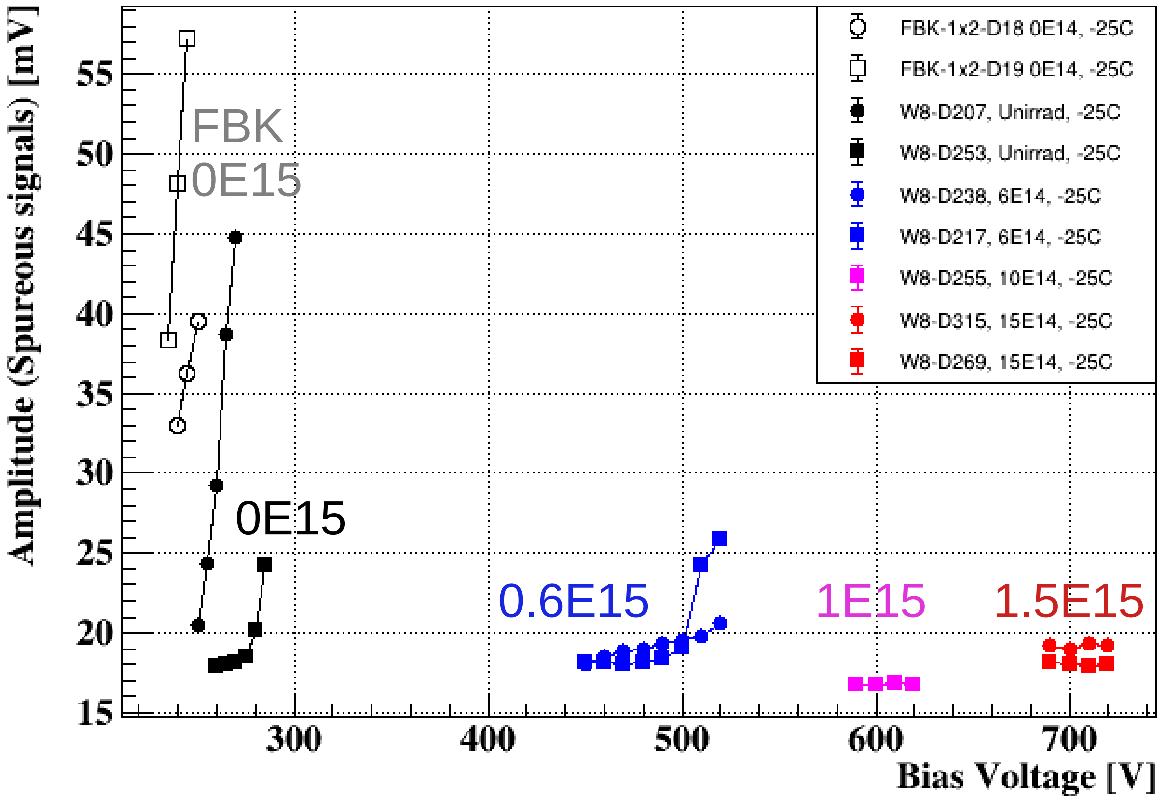
BaseLine Noise Bias Dependence

Carbonated CNM & FBK, -25º C



Spurious Pulses Amplitude vs Vbias

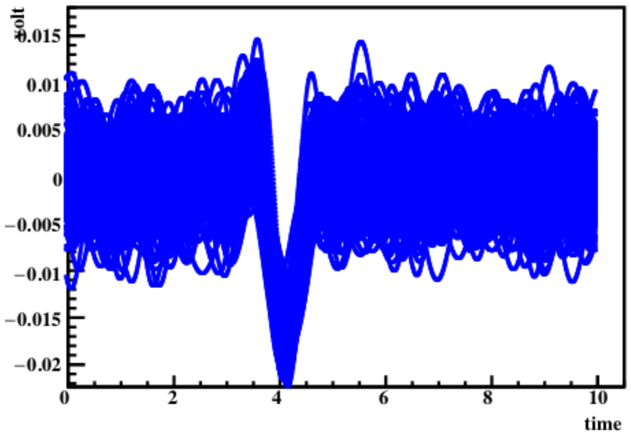
Carbonated CNM vs FBK, -25º C



Spurious Pulse Rate at Operating Vbias

Carbonated CNM, -25º C

Example of waveforms of thermally triggered Spurious pulses:

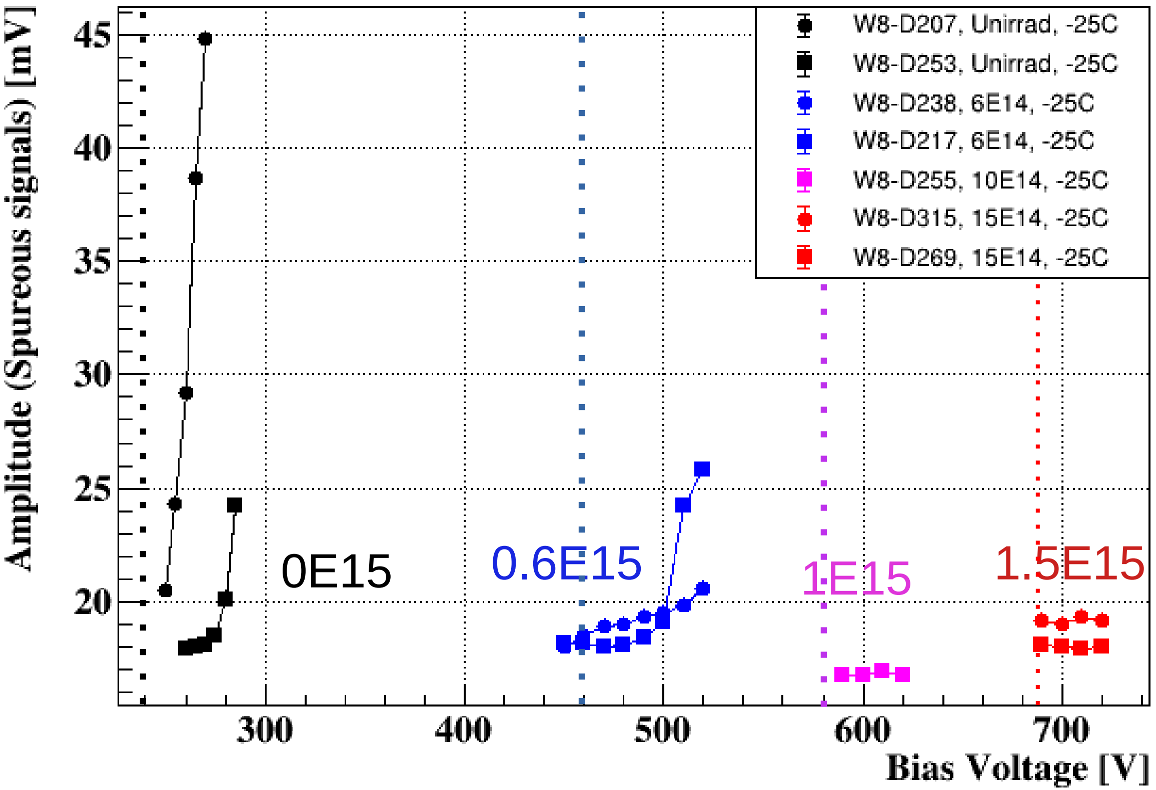


Due to the Aggressive Interpad Distance (IP47)

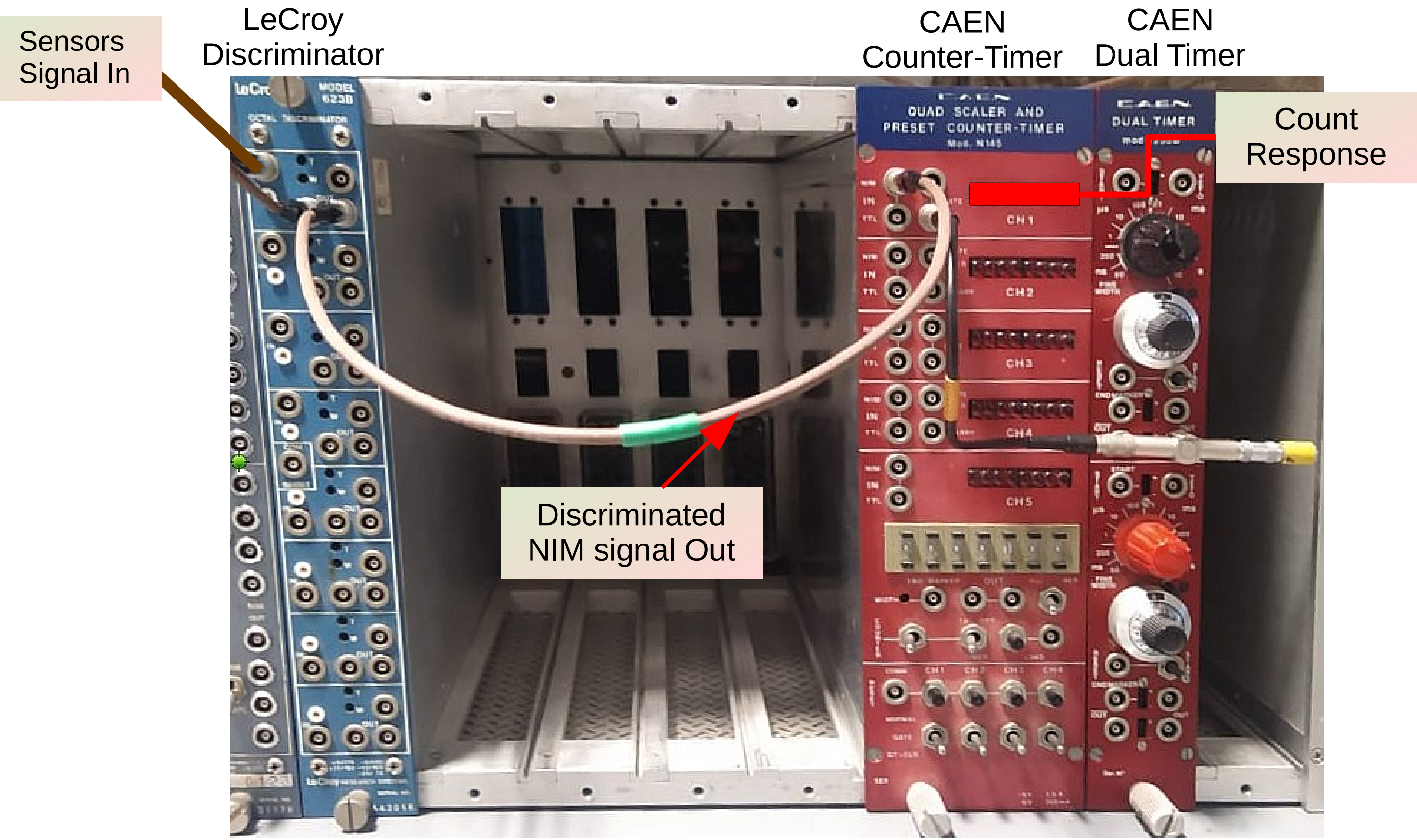
Fluence	Operating voltage (50ps)	Spurious pulse rate (-15mV th)
0E15	240Vbias	2Hz
		7Hz
0.6E15	460Vbias	7Hz
		40Hz
1E15	580Vbias	1Hz
		59Hz

Caveat: Pulse rate may be limited by the digital Scope BandWidth.

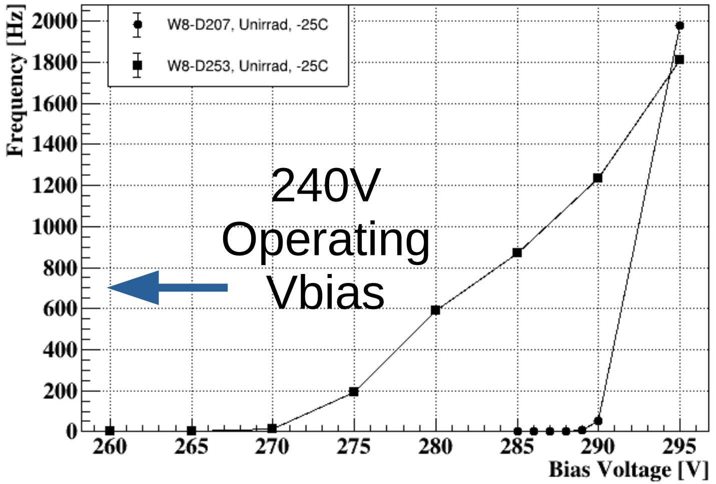
Spurious Pulses Amplitude vs Vbias

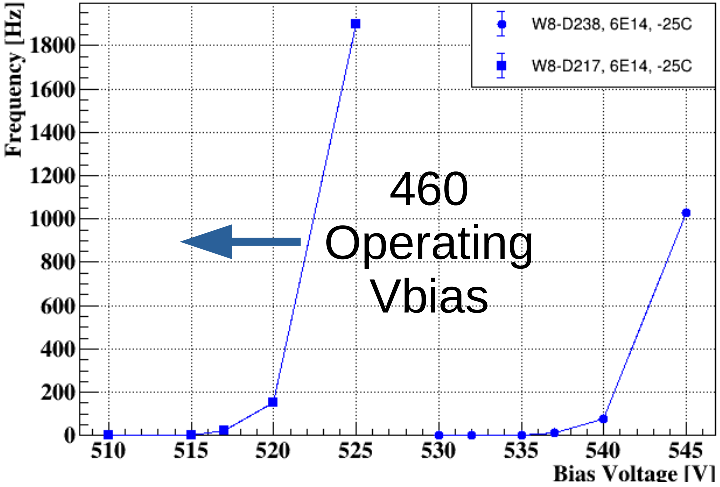


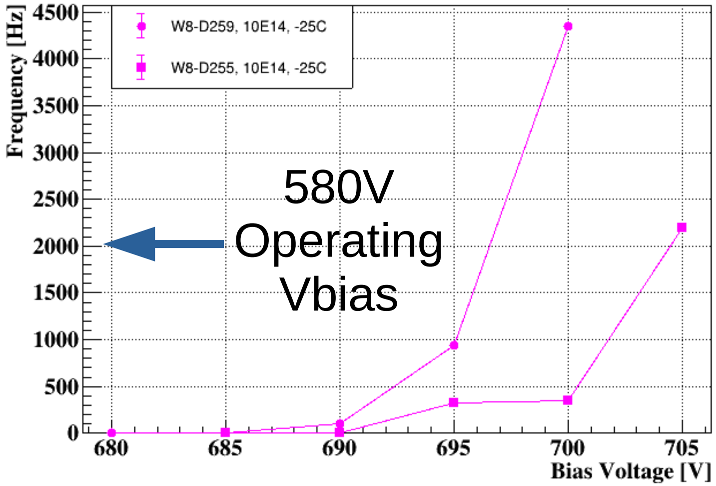
NIM-electronics Setup

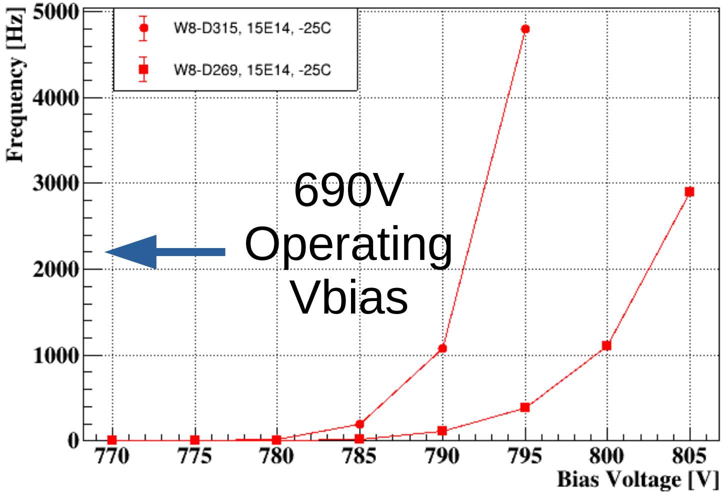


Spurious Pulse Rate (th=-25mV)



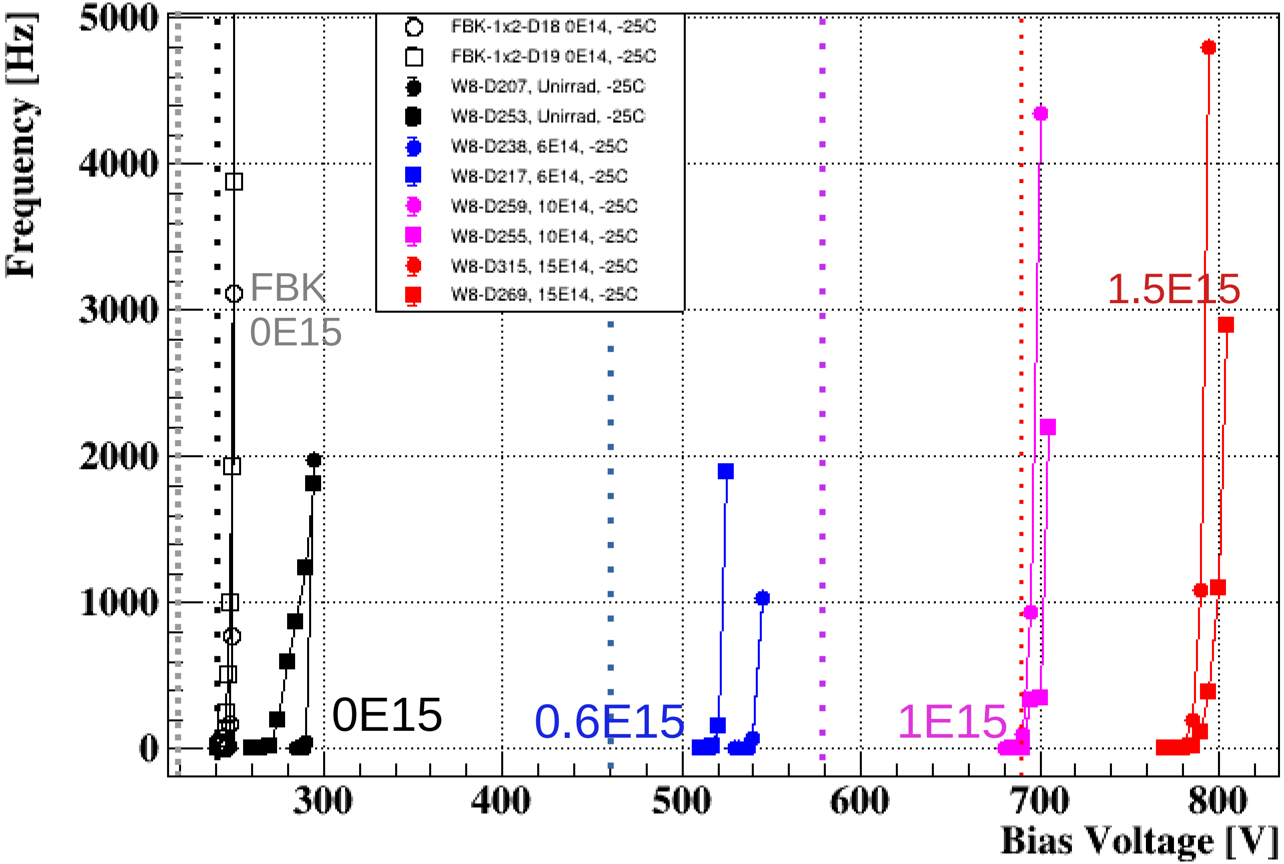






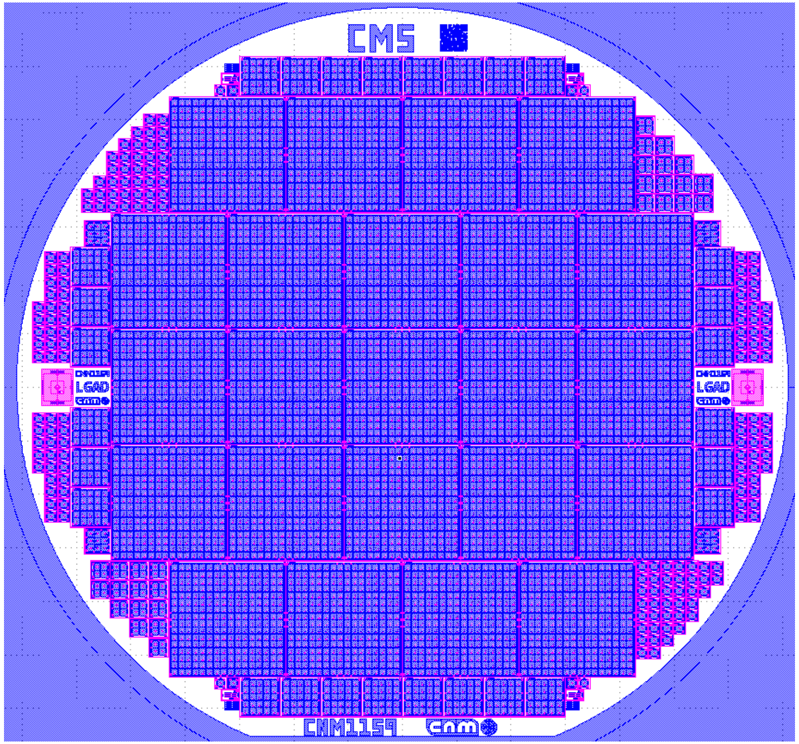
Spurious Rate (NIM) th=-25mV

Carbonated CNM vs FBK, -25º C



New CMS Run (6LG2)

To estimate the production yield there will be a dedicated Run



Devices (**CMS**) : 1x1, 2x2, 5x5 & 16x16 pixels of 1.3x1.3 mm²

- **10 LGAD wafers**
- 150 mm, 55/525 µm, **Si-Si** wafers (**6LG2**)
- Some of them carbonated
- **Interpad IP60 - IP80**
- Gain layer design
  - CNM standard multiplication layer, as in MS run.
  - Deep P-layer

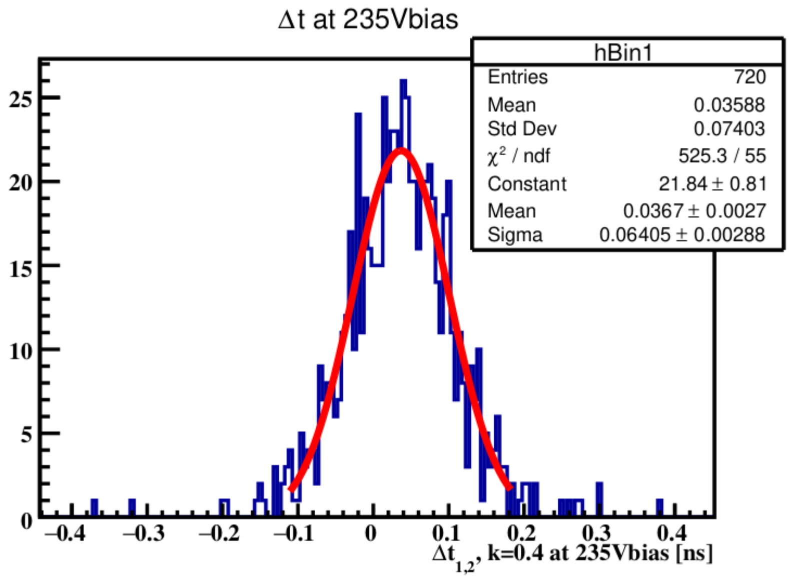
- **CMS 16x16**: **23** devices
  - **ETLROC** chip compatible (waiting for final layout)
  - **SE3**, 300 µm (500 µm at wire bonding area)
  - **No TCT opening window**
  - Reduced dead area in corners to **improve fill factor**

Time Resolution

Constant Fraction Discrimination (40%).

Compute the Time of arrival difference between the three sensors: **$\Delta t_{1,2}$, $\Delta t_{1,3}$ & $\Delta t_{2,3}$**

Fit the Width of the difference distributions: **$\sigma_{1,2}$, $\sigma_{1,3}$ & $\sigma_{2,3}$**



The time resolution and its errors[2] are determined by:

$$\sigma_1 = \left(\frac{1}{2}\left(\sigma_{21}^2 + \sigma_{13}^2 - \sigma_{32}^2\right)\right)^{\frac{1}{2}}, \quad \sigma_2 = \left(\frac{1}{2}\left(\sigma_{21}^2 - \sigma_{13}^2 + \sigma_{32}^2\right)\right)^{\frac{1}{2}}, \quad \sigma_3 = \left(\frac{1}{2}\left(-\sigma_{21}^2 + \sigma_{13}^2 + \sigma_{32}^2\right)\right)^{\frac{1}{2}}$$

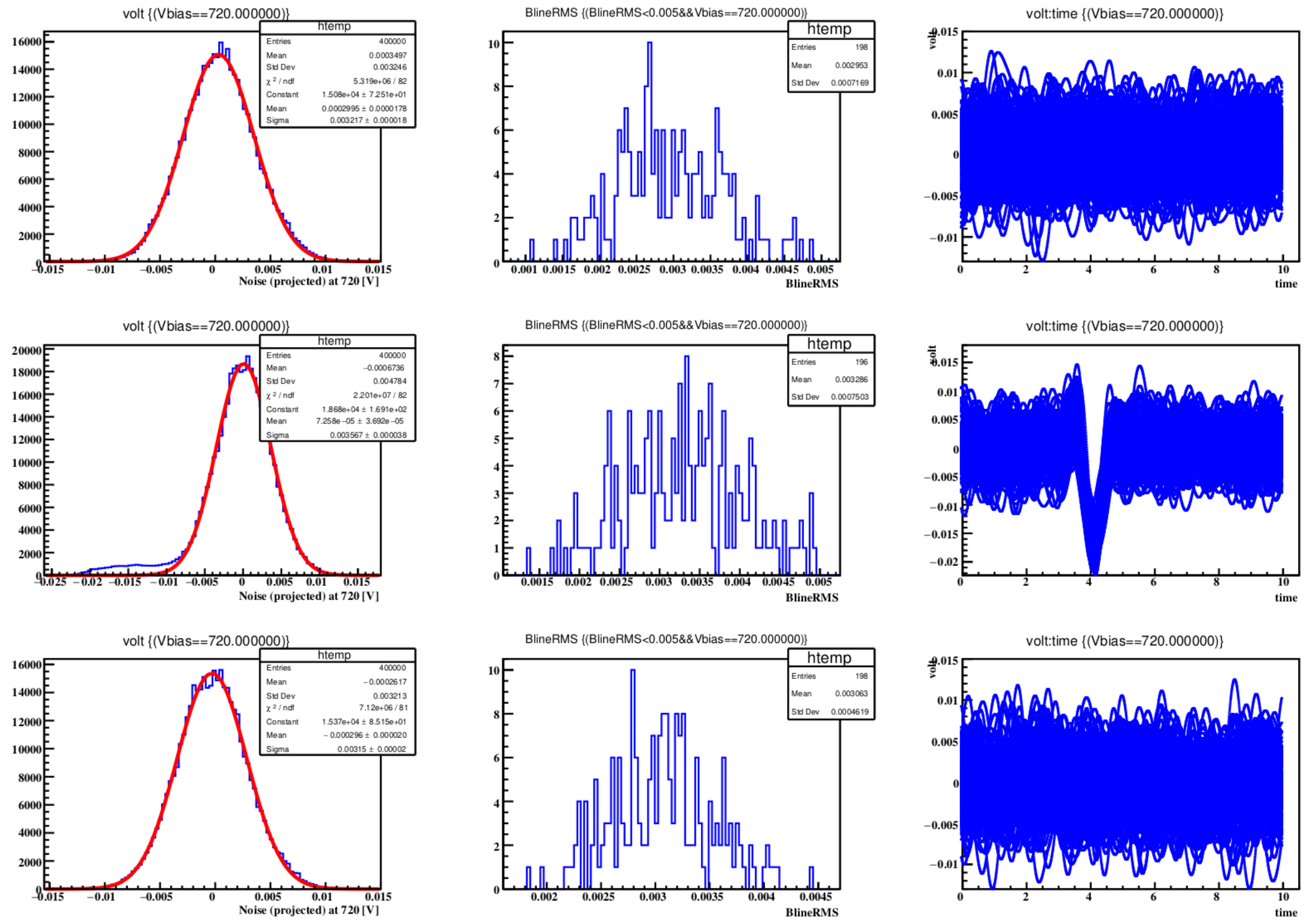
$$\delta_1 = \frac{\left((\sigma_{21}\delta_{21})^2 + (\sigma_{13}\delta_{13})^2 + (\sigma_{32}\delta_{32})^2\right)^{\frac{1}{2}}}{2\sigma_1},$$

$$\delta_2 = \frac{\left((\sigma_{21}\delta_{21})^2 + (\sigma_{13}\delta_{13})^2 + (\sigma_{32}\delta_{32})^2\right)^{\frac{1}{2}}}{2\sigma_2},$$

$$\delta_3 = \frac{\left((\sigma_{21}\delta_{21})^2 + (\sigma_{13}\delta_{13})^2 + (\sigma_{32}\delta_{32})^2\right)^{\frac{1}{2}}}{2\sigma_3}.$$

[2] See Paul McKarris' Talk: https://indico.cern.ch/event/840877/

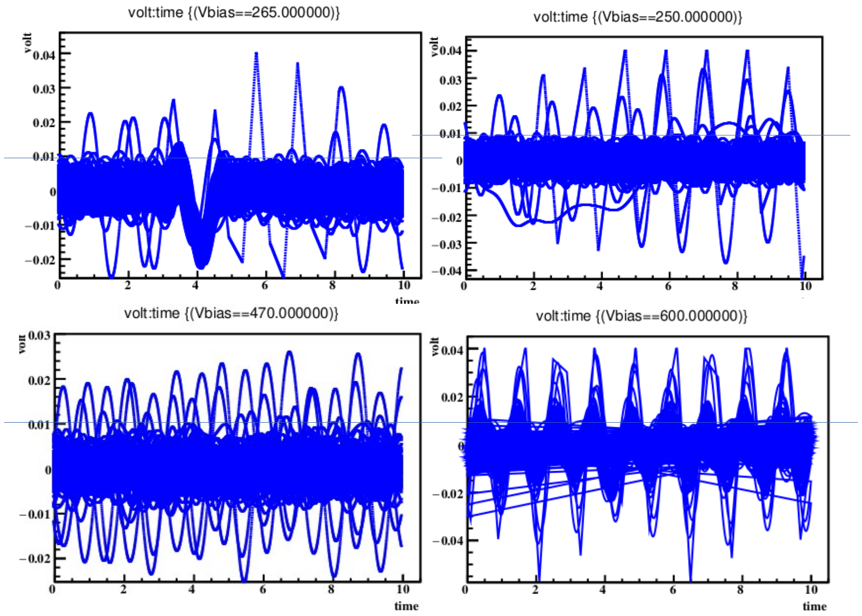
Noise RS Setup

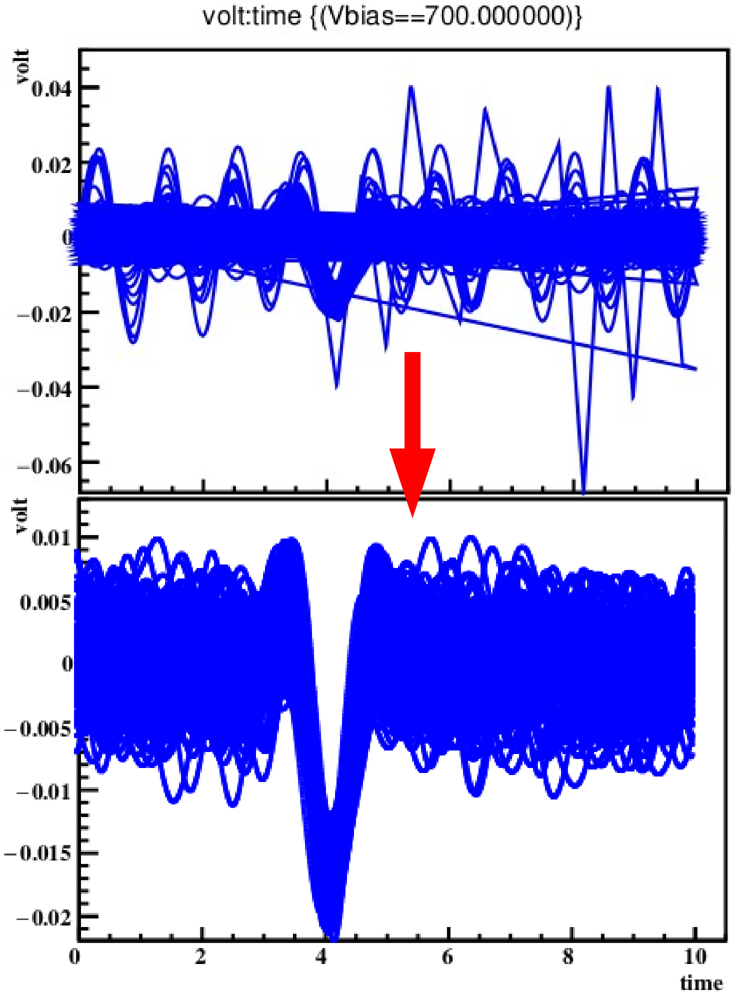


Noise Channel

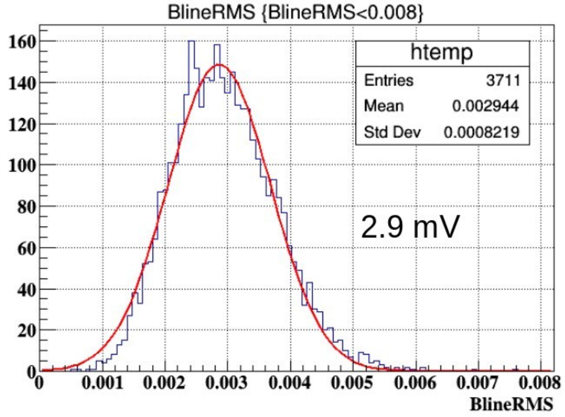
Dark Counts (Trigger)

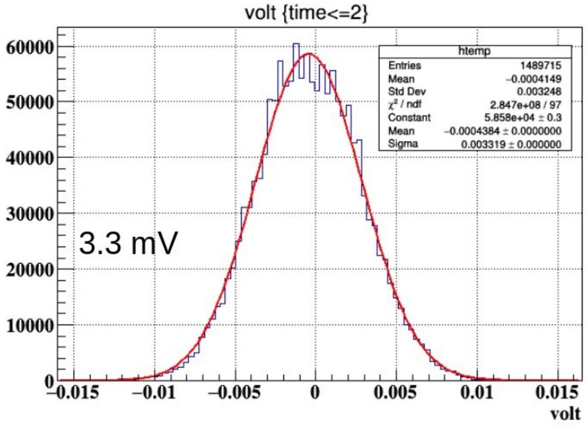
Noise RS Setup



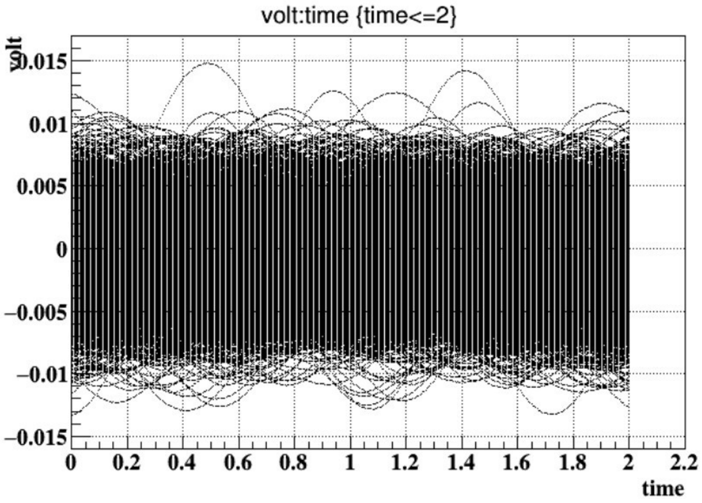


Noise RS Setup





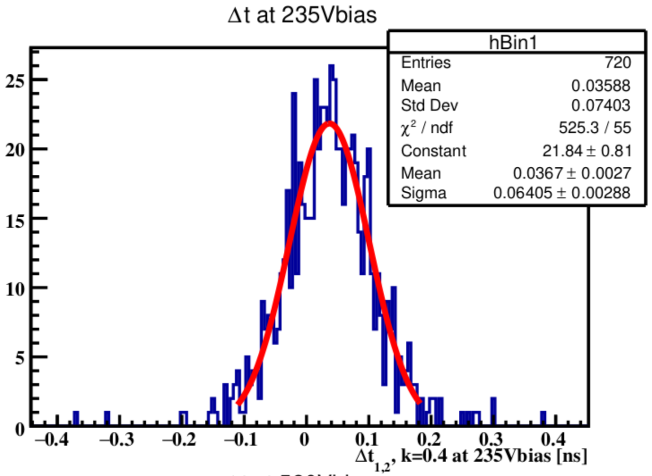
Difference between mean of BlineRMS (left plot) and the RMS of the projection (right plot)



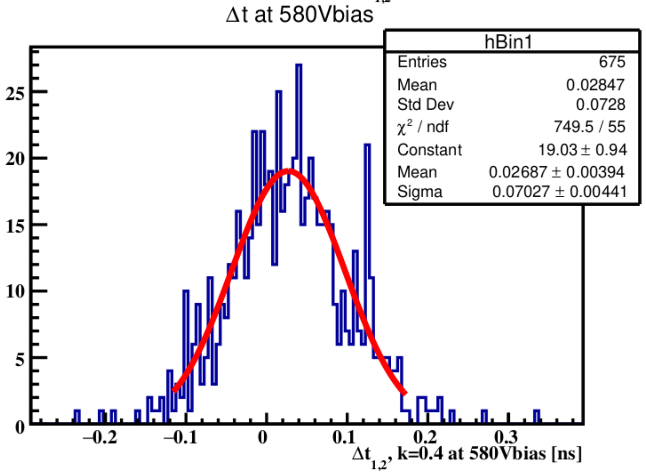
Time Resolution

Carbonated, CNM, -25º C

Non-irradiated

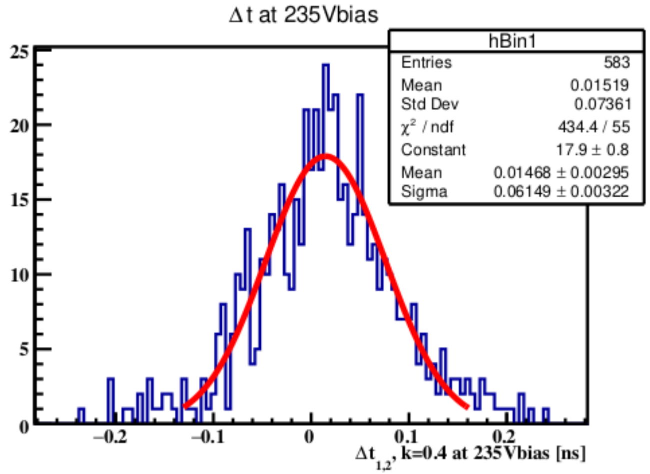


Irradiated 1E15

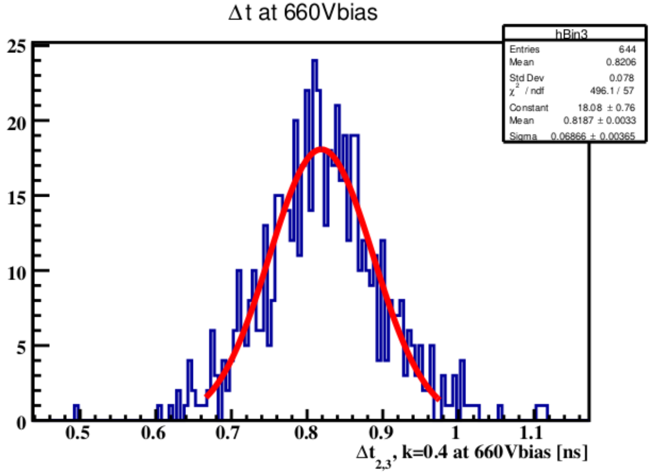


Standard, CNM, -25º C

Non-irradiated



Irradiated 1E15



Calculation of V_{gl} of irradiated devices from CV measurements is difficult. It depends on frequency. Also, double linear fit of C(V) curves is always subjective

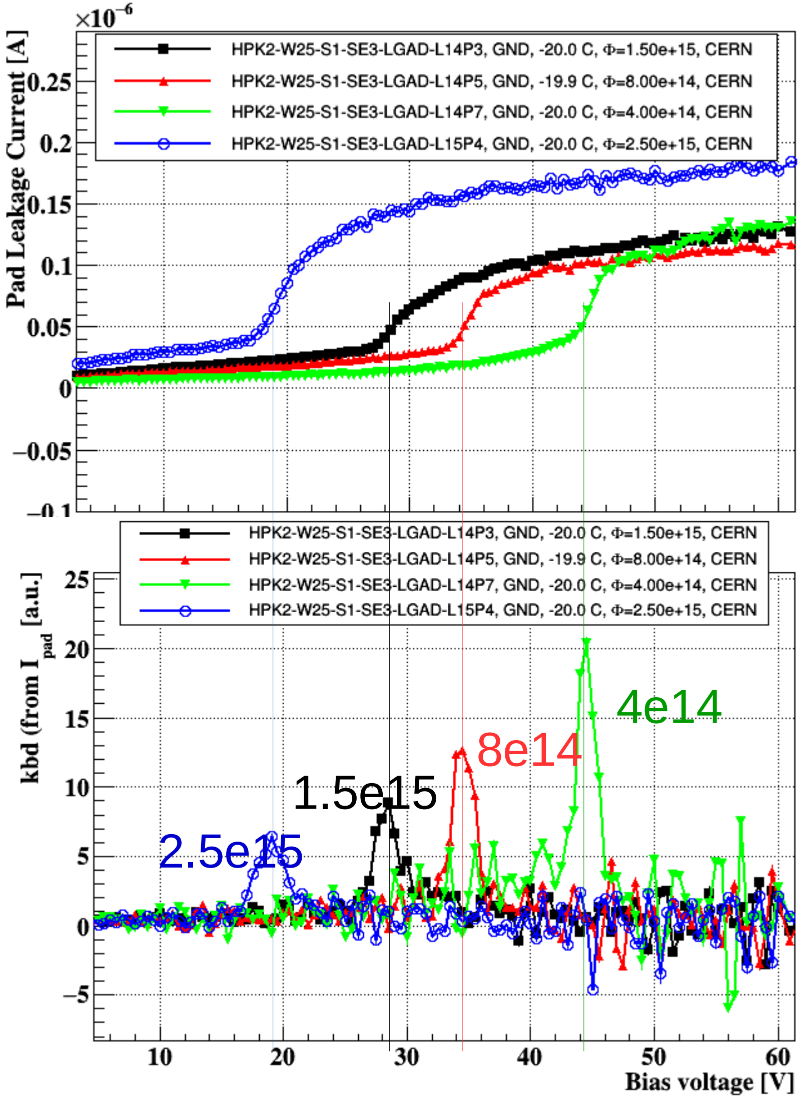
A new method to calculated Vgl in LGADs, based on leakage current measurements only, was presented by us in 16th Trento meeting:

When gain layer is depleted, the bulk current gets multiplied: kink in leakage current observed

Using "automatic" variable [1], based on the derivative of current, to identify depletion transition from gain layer to bulk.

$$K(I,V)=\frac{dI}{dV}\frac{V}{I}$$

Marcos Fernandez
16th Trento Workshop on Advanced Silicon Radiation Detectors, 17th Feb 2021

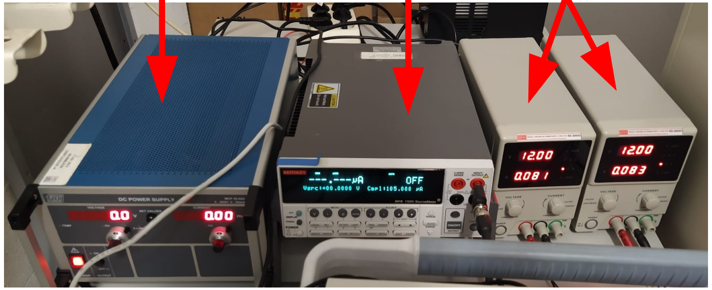


Radioactive Source Setup

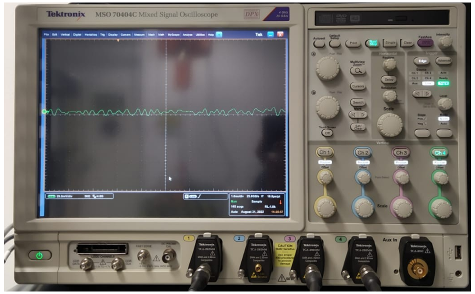
High Voltage source

Source Meter

Sources for CIVIDECs



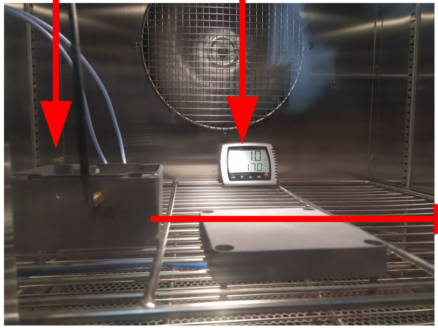
Oscilloscope Tektronix MSO 7404C



Climate Chamber

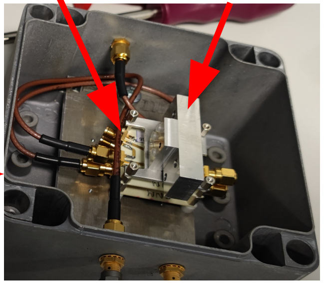
Faraday Cage

Humidity monitor



Stack of sensors

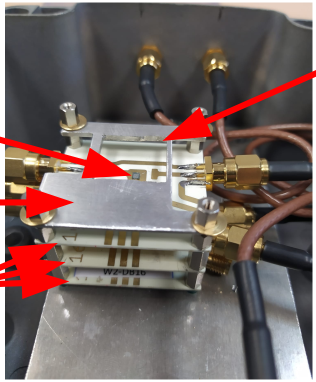
3.7MBq ^{90}Sr

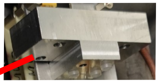


DUT diode

RS alignment support

3-sensors Stack



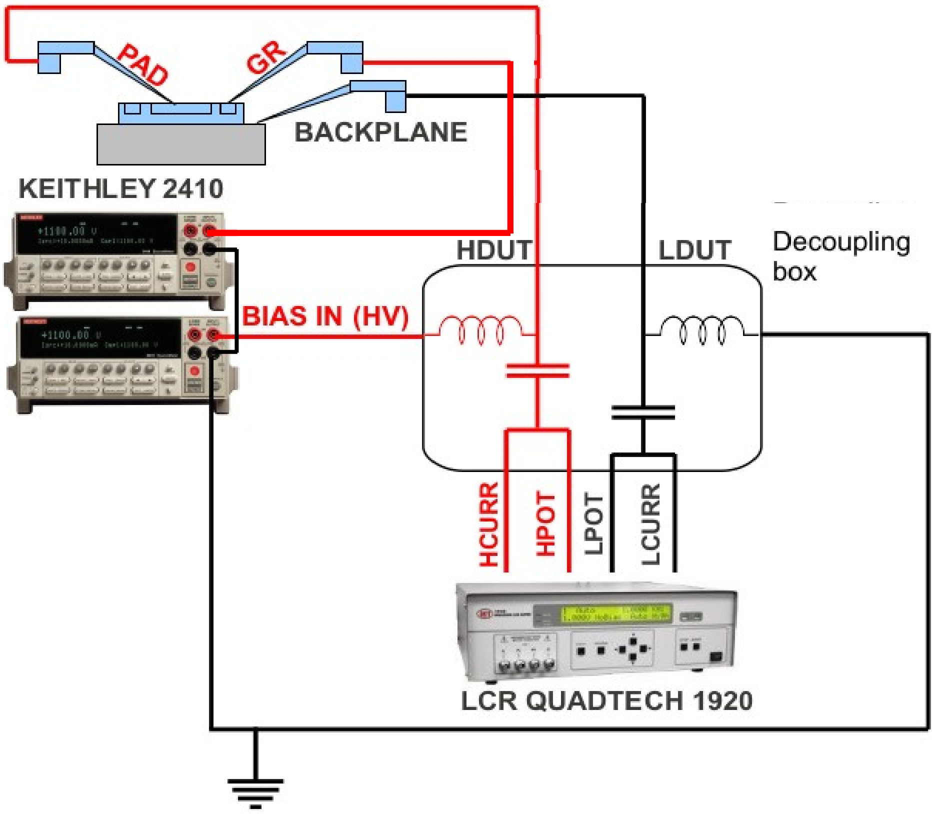


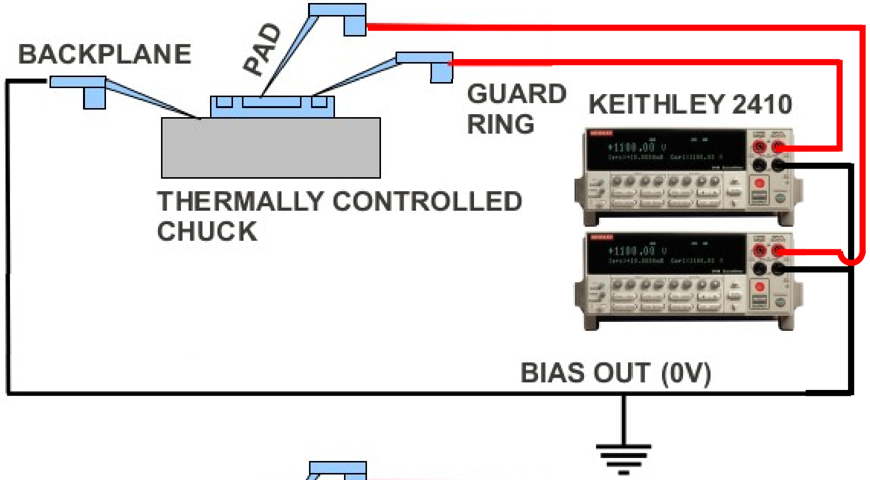
RS

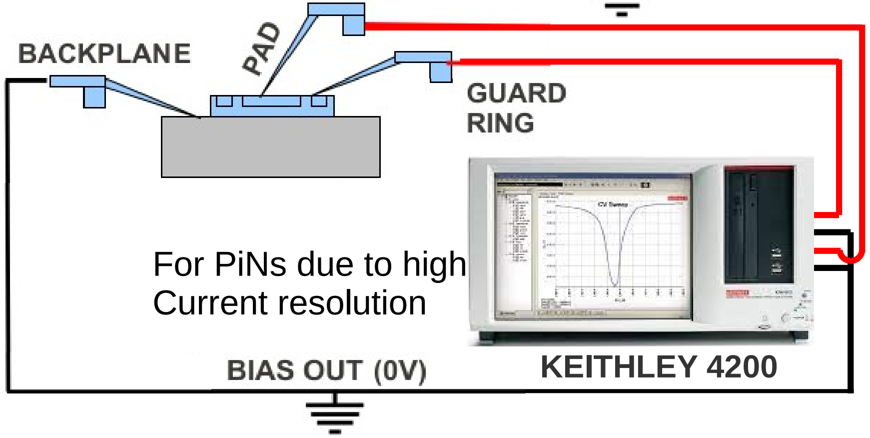
efren.navarrete@cern.ch - 18th Trento Workshop

CV Setup

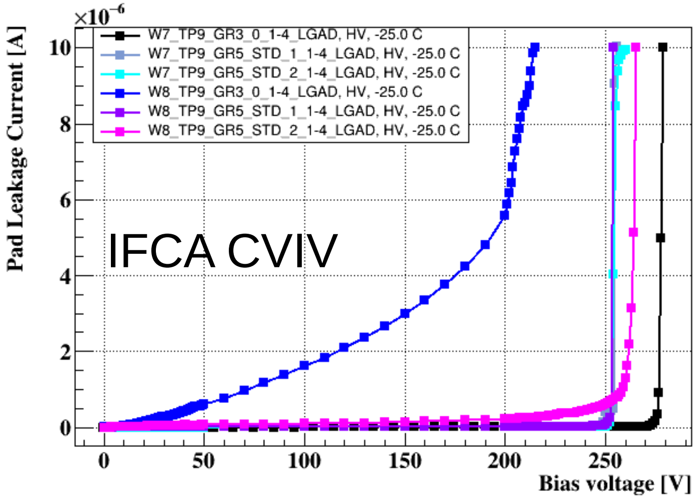
IV Setup



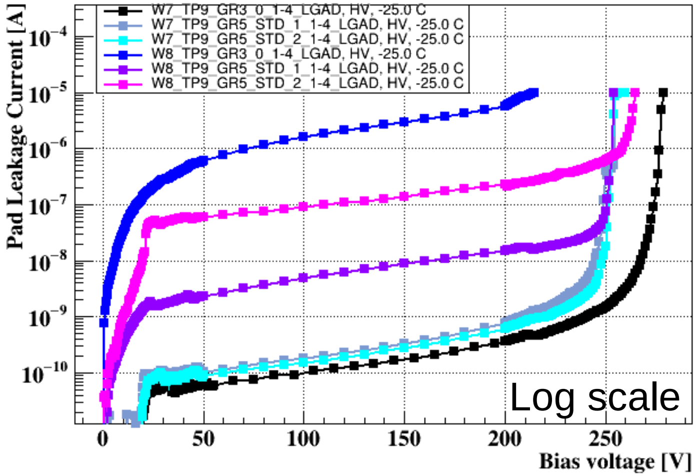




FBK IV (fresh)

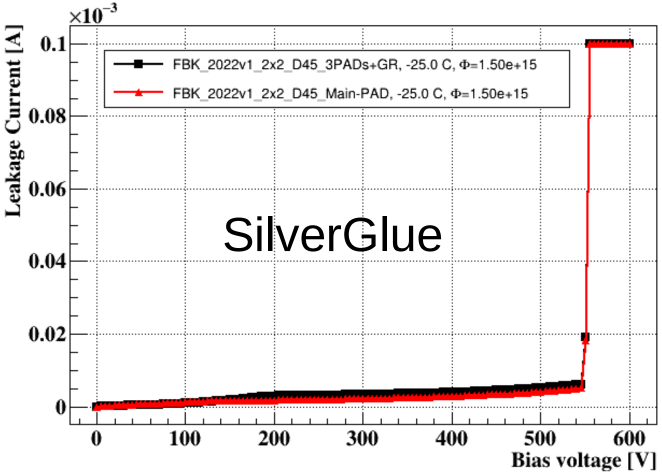


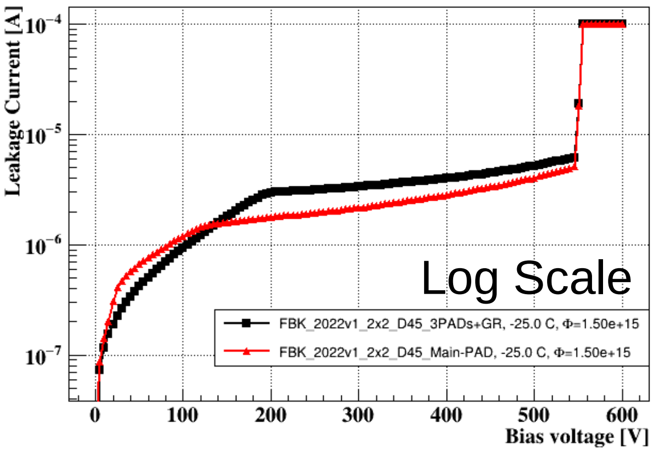
$\times10^{-6}$
Pad Leakage Current [A]
Bias voltage [V]
W7_TP9_GR3_0_1-4_LGAD, HV, -25.0 C
W7_TP9_GR5_STD_1_1-4_LGAD, HV, -25.0 C
W7_TP9_GR5_STD_2_1-4_LGAD, HV, -25.0 C
W8_TP9_GR3_0_1-4_LGAD, HV, -25.0 C
W8_TP9_GR5_STD_1_1-4_LGAD, HV, -25.0 C
W8_TP9_GR5_STD_2_1-4_LGAD, HV, -25.0 C
IFCA CVIV



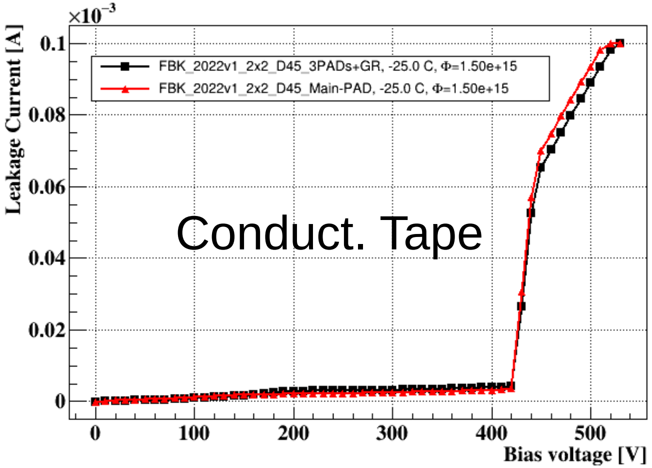
Pad Leakage Current [A]
Bias voltage [V]
W7_TP9_GR3_0_1-4_LGAD, HV, -25.0 C
W7_TP9_GR5_STD_1_1-4_LGAD, HV, -25.0 C
W7_TP9_GR5_STD_2_1-4_LGAD, HV, -25.0 C
W8_TP9_GR3_0_1-4_LGAD, HV, -25.0 C
W8_TP9_GR5_STD_1_1-4_LGAD, HV, -25.0 C
W8_TP9_GR5_STD_2_1-4_LGAD, HV, -25.0 C
Log scale

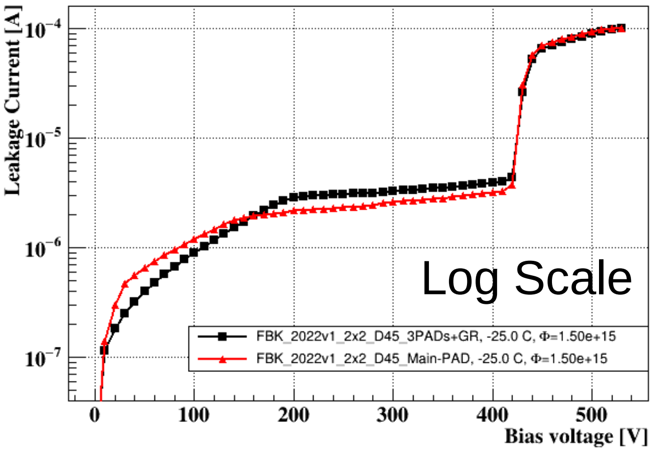
FBK 2x2 Irradiated, IV (fromRS)





BD starts after 540V, Comp. reached at 555V





BD starts after 420V, Comp. reached at 520V