Institut de Física d'Altes Energies

35th RD50 Workshop Radiation hard semiconductor devices

Review of neutron irradiated 6” SoI LGAD sensors CNM 11486

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Introduction

Electrical characterisation

Dark Rate

Charged Particle measurements

Operating parameters

Conclusions

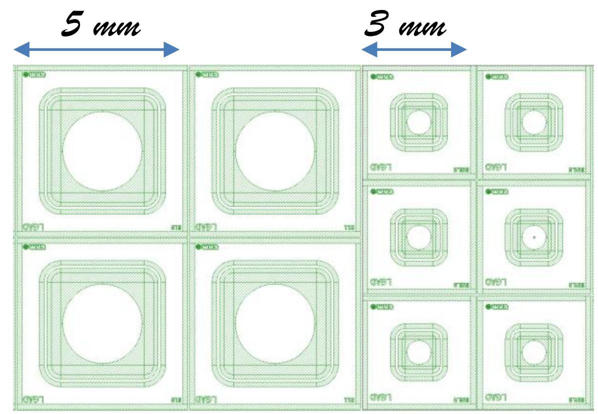
•Overview

- Introduction
  - Structure descriptio0n and irradiations
- Electrical characterisation
  - IV measurements
  - Gain modelling and breakdown definition
  - Acceptor removal coefficient
  - Gain reduction computation
- Dark Rate measurements
  - Methodology
  - Maximum operating points
- Charged particle measurements
  - Introduction and setup
  - Gain, Time resolution and charge estimation
  - Efficiency
- Operating Parameters
  - HV Envelope and headroom
  - Power dissipation
- Conclusions and plans

•Introduction

CNM 11486

- First 6” CNM LGAD run
- 50μm active on 250μm SoI substrate
- Only single diodes
- 2 types of structures:
  - 3x3 mm^2 active on 5x5mm^2 die
  - 1.3x1.3 mm^2 active on 3x3mm^2 die
- 2 gain layer doping splits: medium (wafer 2) & high (wafer 3)



Fluence (n_{eq}/cm^2)	Irradiated devices			Annealing
	Wafer 2	Wafer 3	PINs	
3e14	2 5x5mm^2	2 5x5mm^2	2 5x5mm^2	
7e14	2 5x5mm^2	2 5x5mm^2	2 5x5mm^2	
1e15	2 5x5mm^2	2 5x5mm^2	2 5x5mm^2	80 min @ 60 °C
3e15	2 5x5mm^2	2 5x5mm^2	2 5x5mm^2	
5e15	2 5x5mm^2	2 5x5mm^2	2 5x5mm^2	

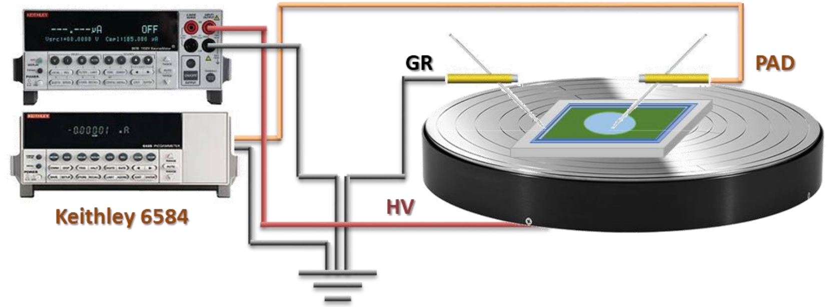
Fast Neutrons @ JSI

- Irradiated in July 2019
- Not an official campaign
- A number of groups has received them

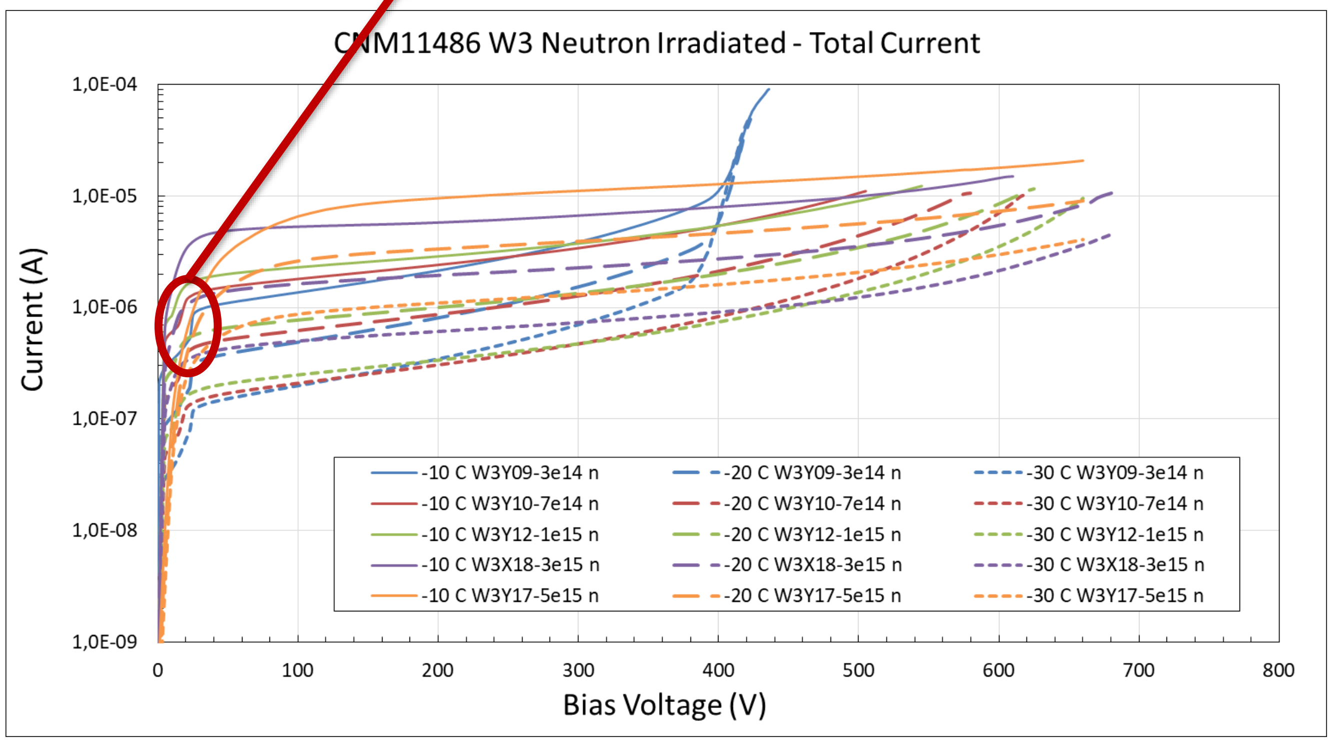
•Electrical characterization

IV measurements

- ✓ Measure separately GR and Pad current
- ✓ Measurements at -10, -20 and -30C
- ✓ Scaling with temperature and fluence corresponds to expectations



Gain layer depletion, visible up to 3e15



•Electrical characterization

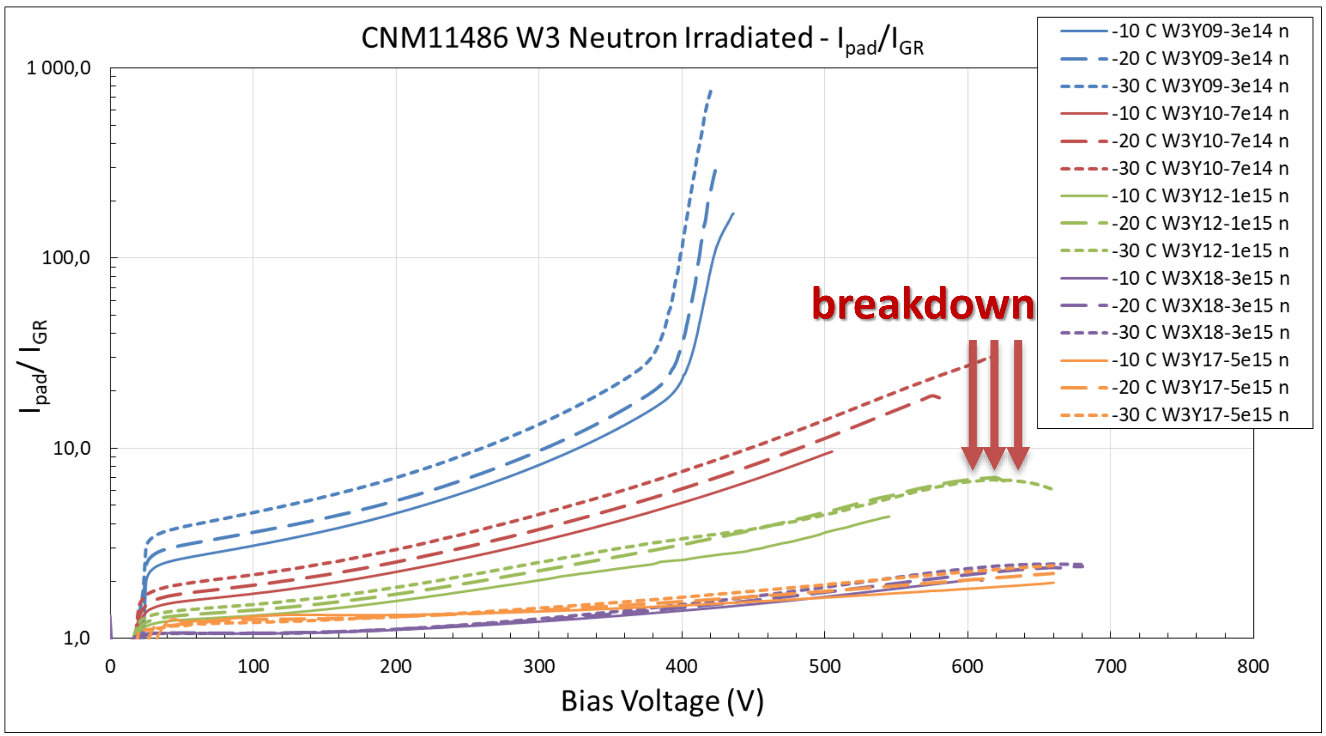
Breakdown Mode

Gain Breakdown

- Increased current from pad
- Ratio of I_{pad}/I_{GR} diverges
- Case at 3e14 and 7e14
- More gain, higher the ratio

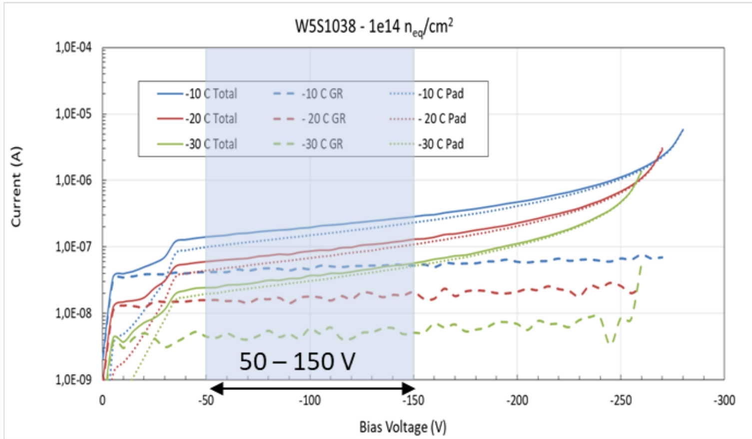
Edge Breakdown

- Increase current from Guard Ring
- Ratio of I_{pad}/I_{GR} converges
- Case for 1e15, 3e15 and 5e15
- Case also for PINs at any fluence



• IV & Breakdown

Current multiplier



- ✓ Measure pad IV (-10ºC, -20ºC, -30ºC)
- ✓ Select a stable range where behaviour follows Schottky model
- ✓ Define common for all temperatures stable range, after depletion and much before breakdown
- ✓ Perform exponential fit and request $R^2 \geq 99\%$
- ✓ Calculate the multiplier with respect to the expected current
- ✓ **Define breakdown in multiplier value**

Method

exp. fit

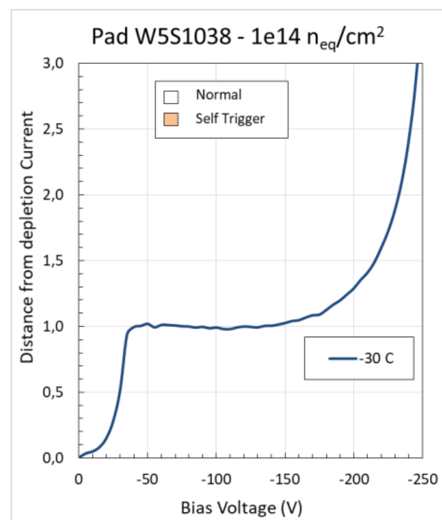
Exponential Fit: $I = b \cdot m^V$

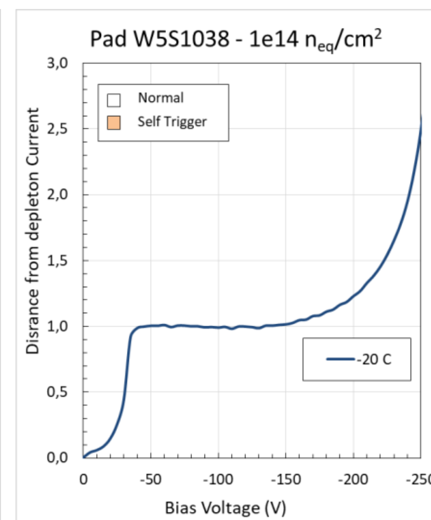
Acceptance Criteria: $R^2 \geq 99\%$

Expected current: $I_{Sc,i} = b \cdot m^{V_i}$

Current Multiplier: $M_i = I_i / I_{Sc,i}$

Breakdown: $M_i > 2$





•Electrical characterization

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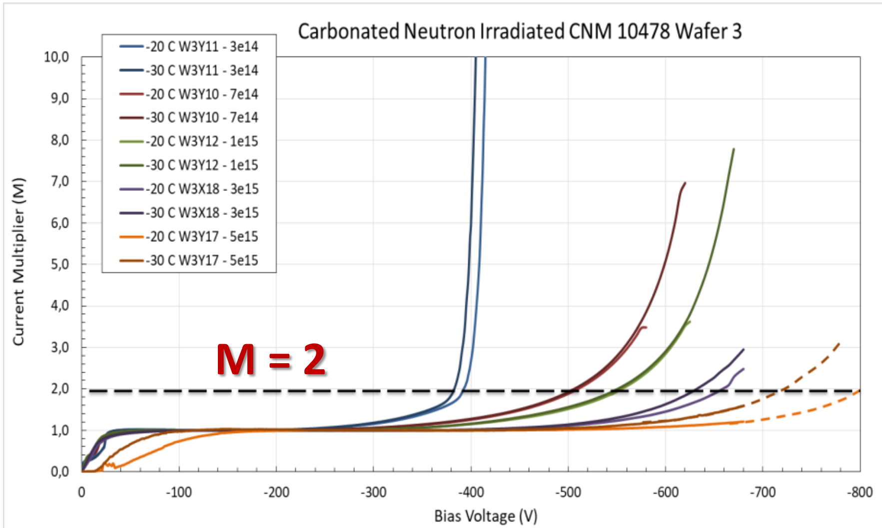
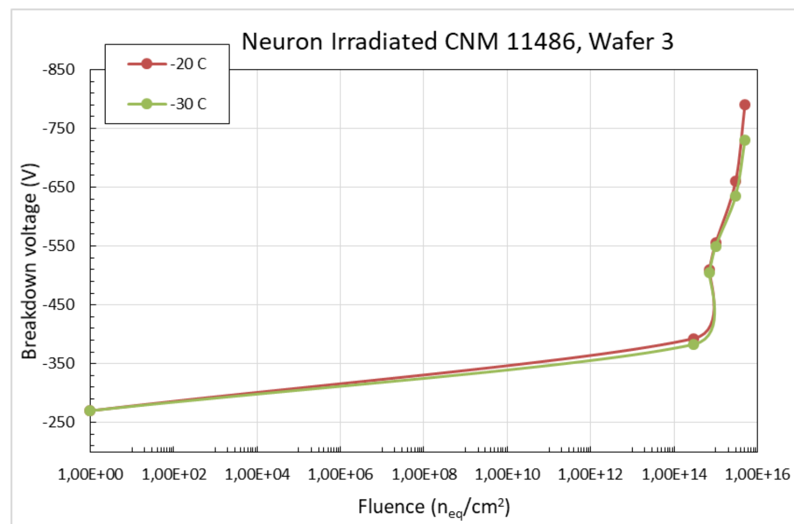
Breakdown Voltage



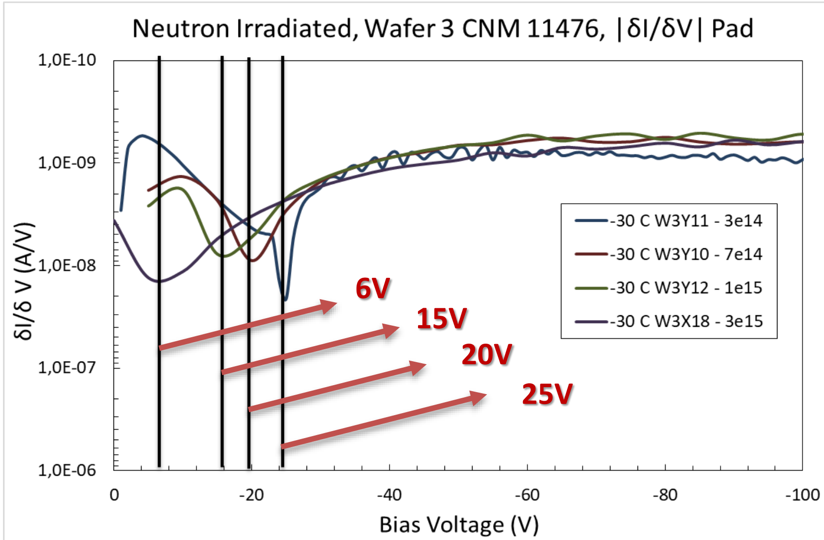
- ✓ Breakdown defined as the point where leakage current is twice the expected current
- ✓ Definition considers gain
- ✓ Gain is modeled as an exponential increase on top of the exponential bulk current
- ✓ Final model is the convolution of 2 exponentials

Breakdown Voltage		
Fluence (n_{eq}/cm^2)	*-20 °C*	*-30 °C*
unirrad.	-270	-270
3e14	-393	-383
7e14	-510	-505
1e15	-555	-550
3e15	-660	-635
5e15	-790	-730



•Electrical characterization

Acceptor removal

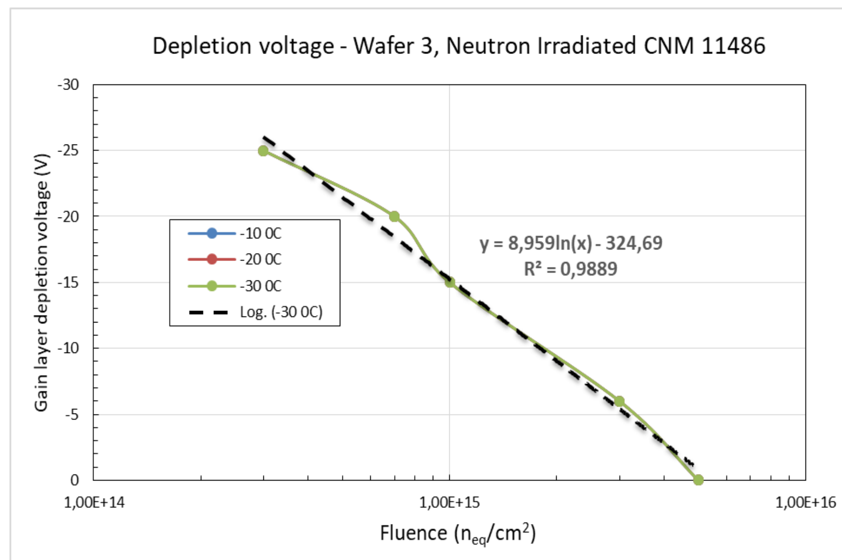


Gain depletion Voltage		
Fluence (n_{eq}/cm^2)	*-20 °C*	*-30 °C*
unirrad.	-34	-34
3e14	-25	-25
7e14	-20	-20
1e15	-15	-15
3e15	-6	-6
5e15	0	0

- ✓ Pad dI/dV presents sharp peak at gain depletion due to current change
- ✓ Depletion voltage directly related to electrically active dopant
- ✓ Exponential reduction of gain layer with irradiation
- ✓ Acceptor removal Coefficient:

Sanity Checks

- ✓ Verified with CV for un-irradiated sensor (plot in backup)
- ✓ Studied at -10C, -20C and -30C with identical results



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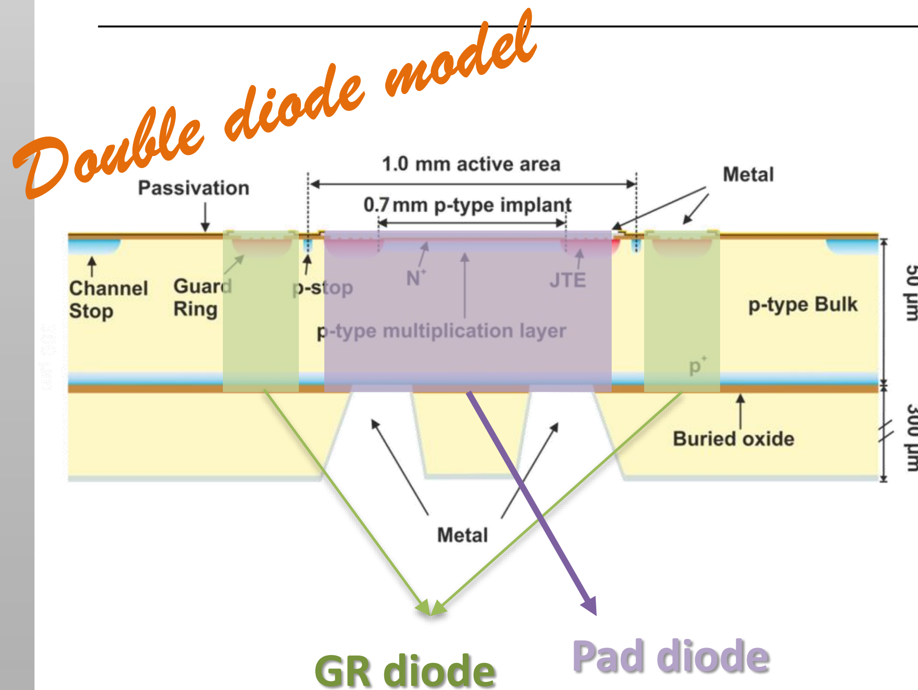
•Electrical characterization

Gain reduction

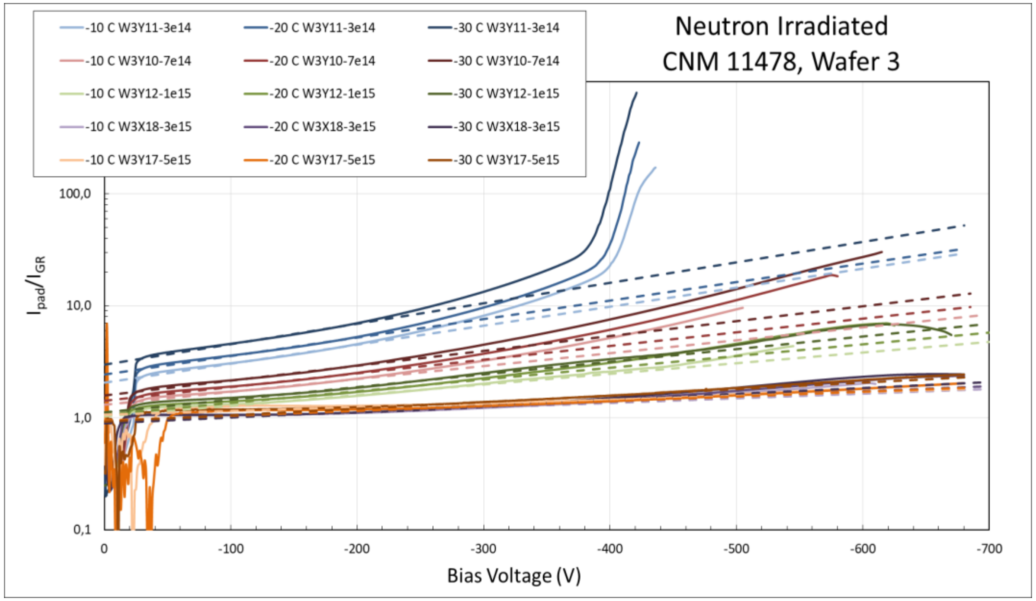
- ✓ Acceptor removal only gives information about active dopant, not gain
- ✓ Gain also depends on **diffusion profiles**
- ✓ Effects after irradiation differ for different profiles
- ✓ For same amount of acceptor removal different possible gain reduction



- ✓ Consider the Guard ring as a diode
- ✓ Consider the pad a a separate diode
- ✓ Same bulk, difference between the tow is gain layer and geometrical factor
- ✓ Implants slightly different but approximation applies due to high gain layer concentration

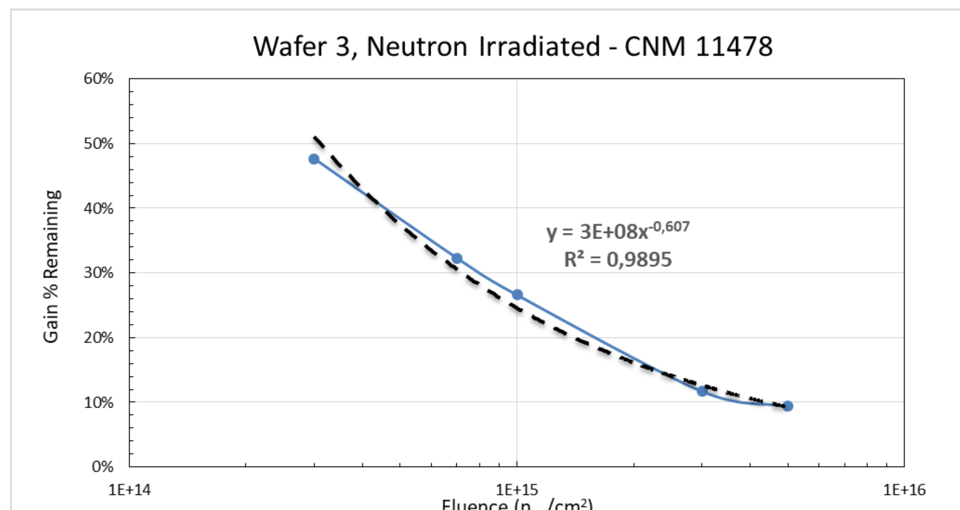
•Electrical characterization

Gain reduction



- ✓ Since GR and pad share same bulk and p back-side, have the same radiation effects
- ✓ Geometrical factor not stable across fluences
- ✓ The fit is expected to be straight line in the exponential plain

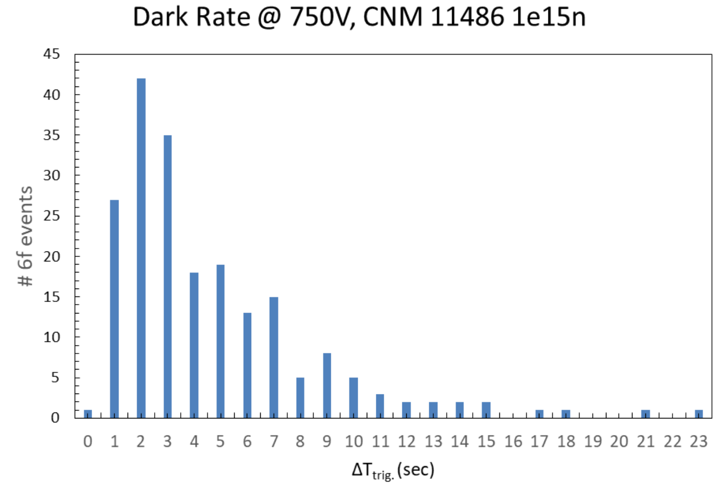
Gain Reduction	
Fluence (n_{eq}/cm^2)	*% of Gian*
unirrad.	100 %
3e14	48 %
7e14	32 %
1e15	27 %
3e15	12 %
5e15	9 %



•Dark Rate

Concepts & Methods

- ✓ Sensors with gain present dark rate at high enough voltages
- ✓ Dark rate events result of thermal movement and random in nature
- ✓ Follow the Poisson distribution



Quantification

- ✓ Study the time between consecutive self-triggering
- ✓ Use mean of 4 events (3 values) to reject cosmic background

Self-trigger time:

$$\Delta T_{trig}^{i} = \frac{\sum_{j=1}^{n-1}(T_{j+1}^{trig} - T_{j}^{trig})}{n}$$

Self-trigger Rate:

$$R_{trig}^{i} = \frac{1}{\Delta T_{trigg}^{i}}$$

Median of several rate measurements

$$\widetilde{R_{trig}} = \frac{R_{trig}\,_{\lfloor(\#k+1)\div 2\rfloor} + R_{trig}\,_{\lceil(\#k+1)\div 2\rceil}}{2}$$

•Dark Rate

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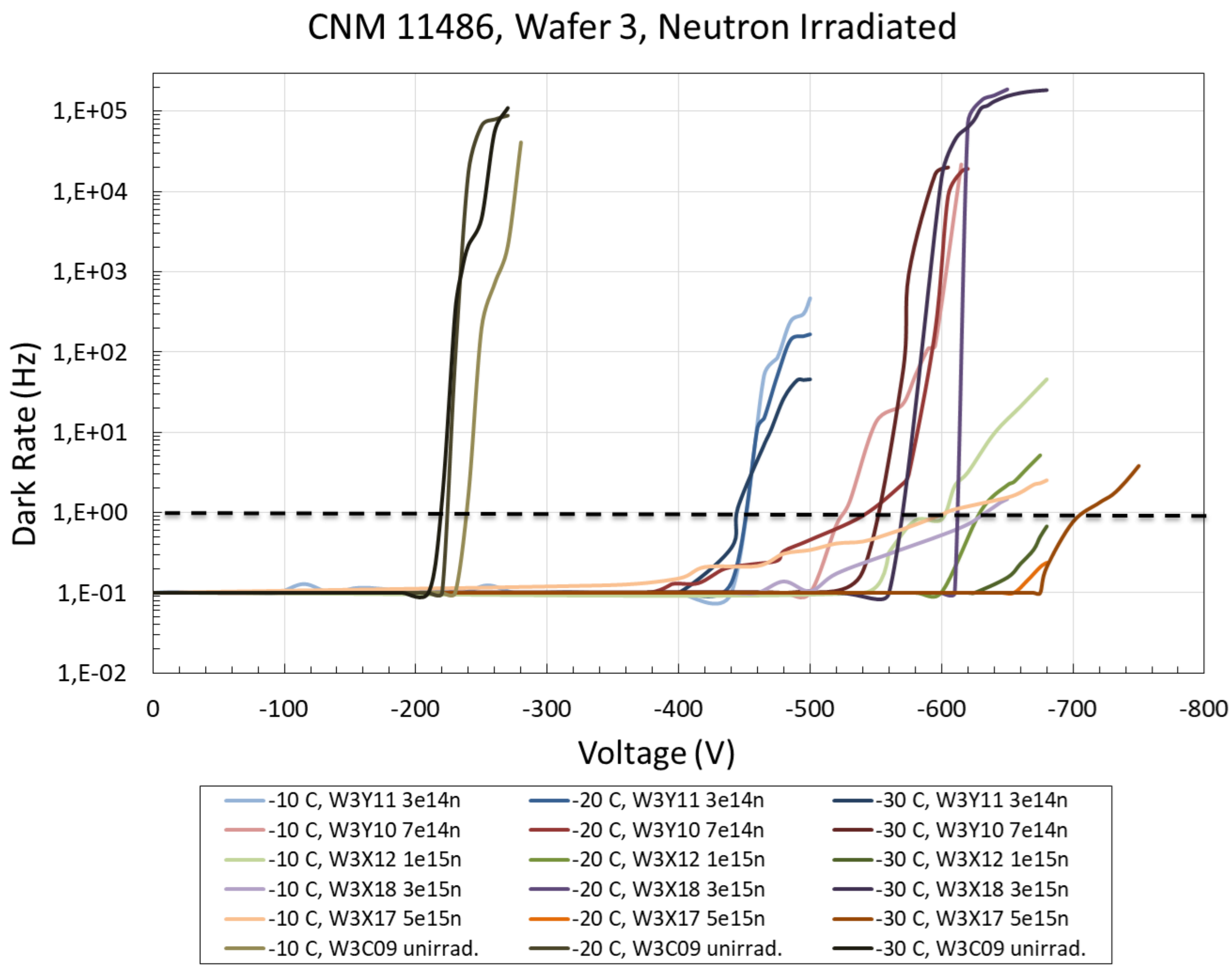
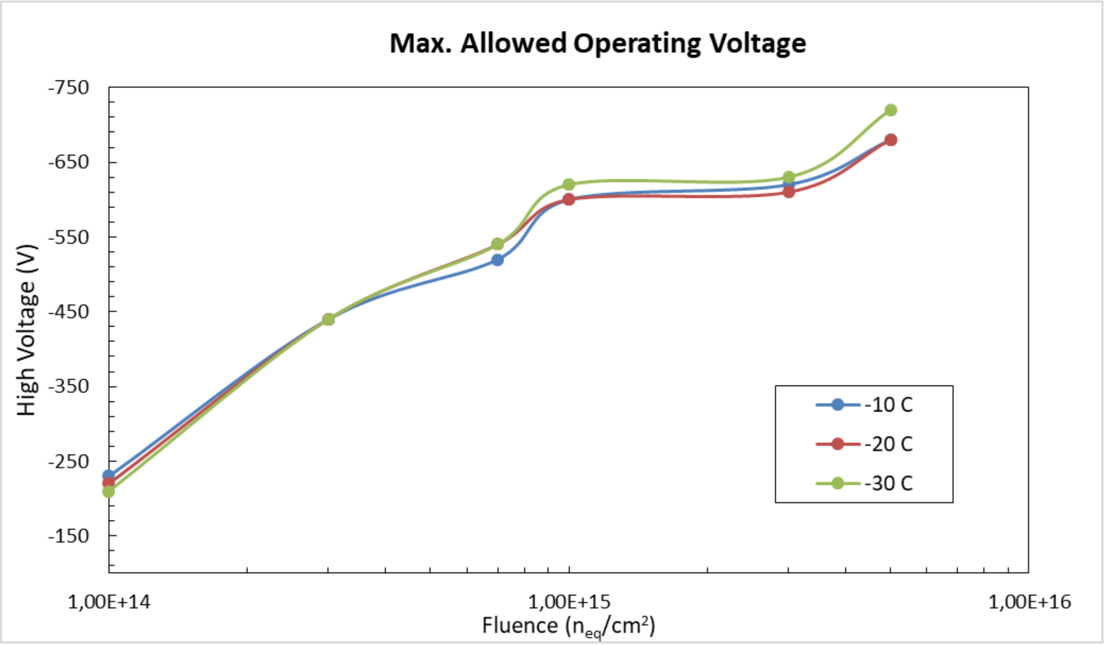
Rate vs Voltage measurement



•Dark Rate

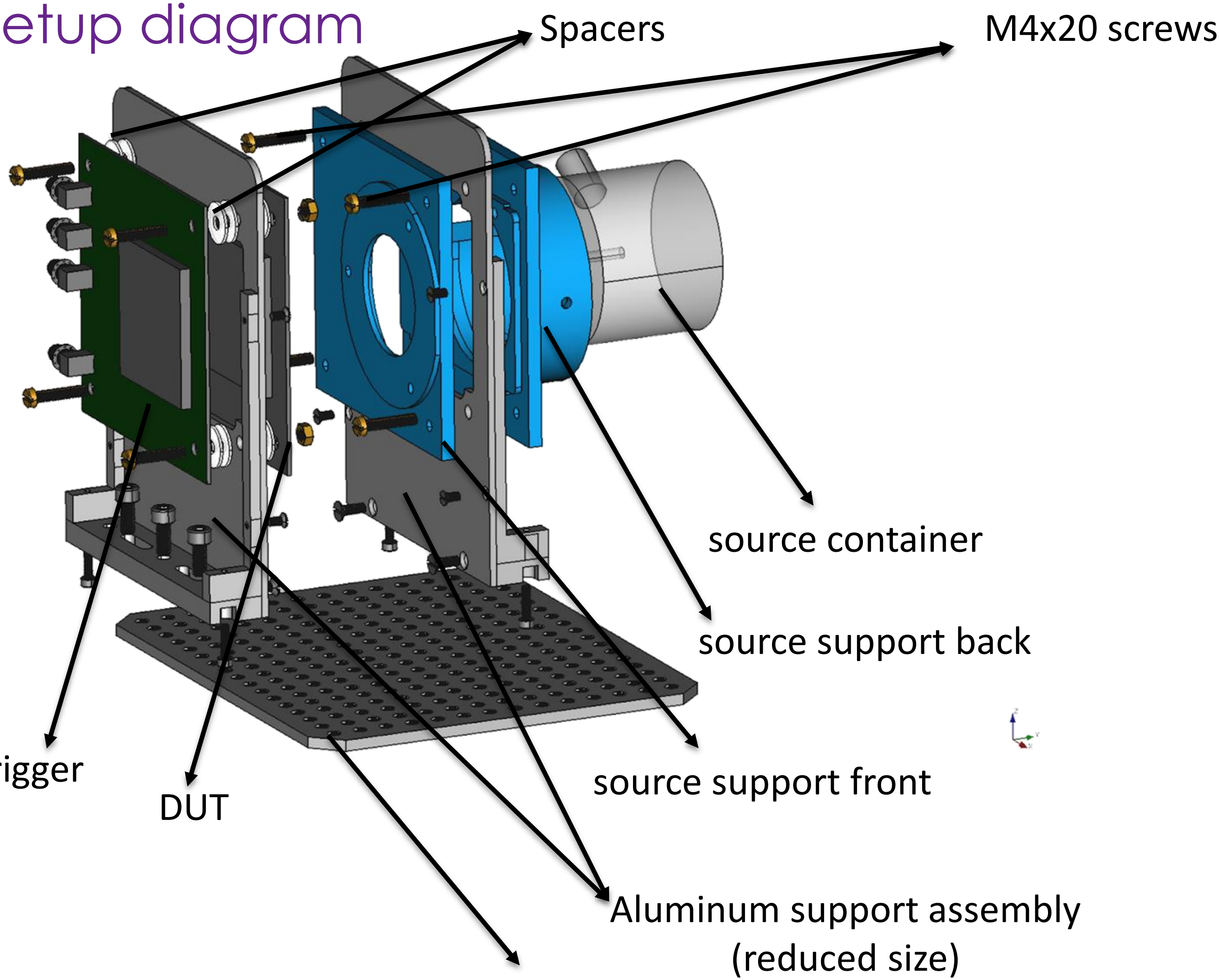
Max. operating voltage

- ✓ Limitation on operating voltage occurs from dark rate
- ✓ Appears sooner than breakdown
- ✓ As gain is removed, the operating point is pused closer to the breakdown value
- ✓ Depends highly on the diffusion profile of the gain layer
- ✓ Instabilities at high radiation fluences and dense profiles



•Charged Particle measurements

Setup diagram



•Charged Particle measurements

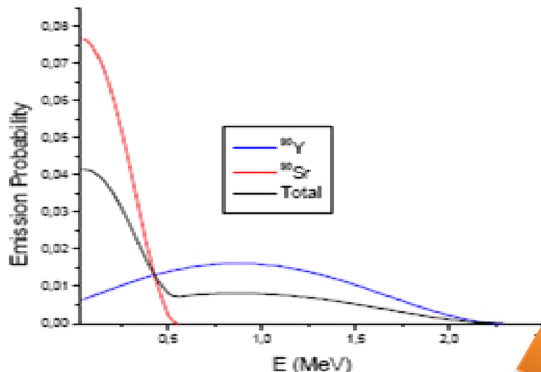
Source & Operation

Source

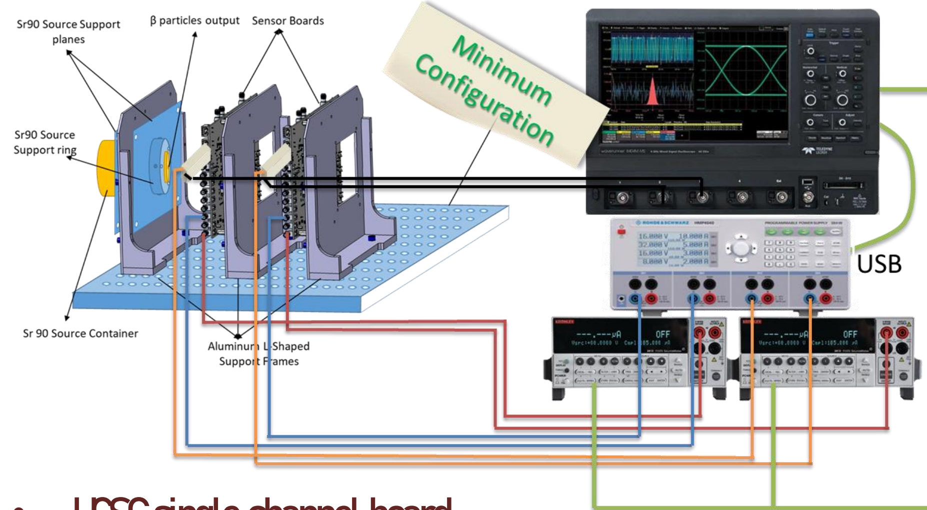
$$^{90}_{38}Sr \rightarrow e^- \; ^{90}_{39}Y \rightarrow e^- \; ^{90}_{40}Zr$$

E_{max}= 0.46 MeV
$T_{1/2}$ = 28,8 y

E_{max}= 2.28 MeV
$T_{1/2}$ = 64 h



- ✓ Multi-energetic electron spectrum
- ✓ E_{max} at 2.28MeV
- ✓ Average energy ~ 939 keV from ^{90}Y decay
- ✓ Average energy ~ 188 keV from ^{90}Sr decay



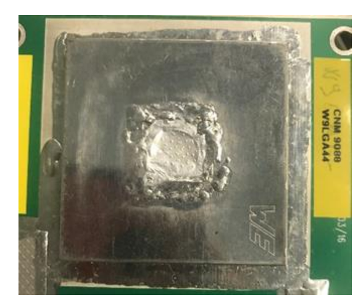
- UCSC single channel board
- RF microwave second stage voltage amplifier

Only getting higher energy particles?

Sensors placed back to back

Total absorber thinness:

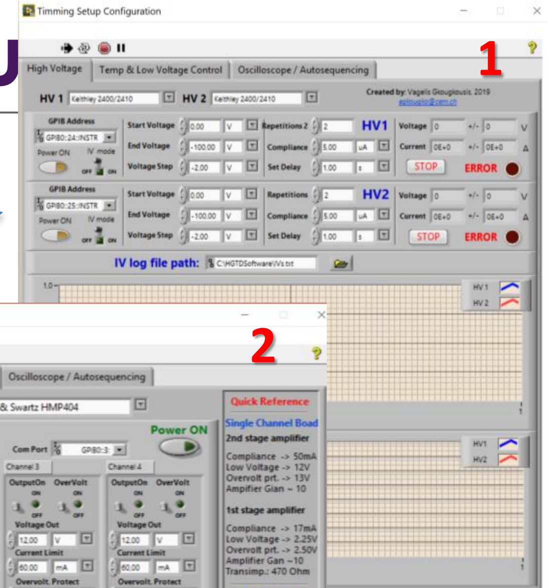
- 3 x 25μm aluminum
- 2 x 250 μm Silicon

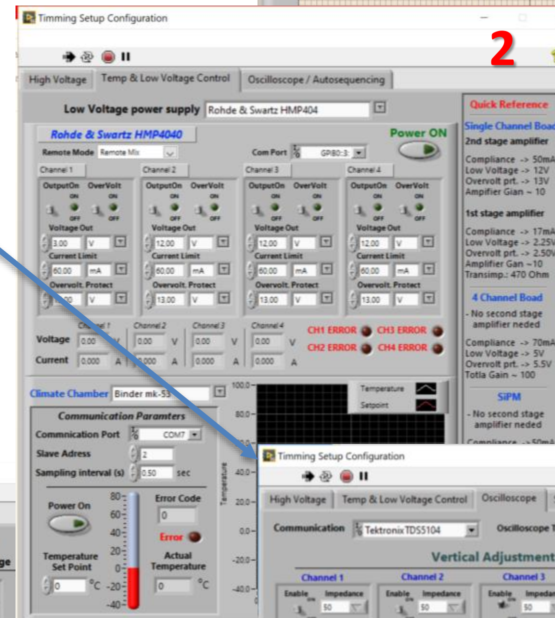


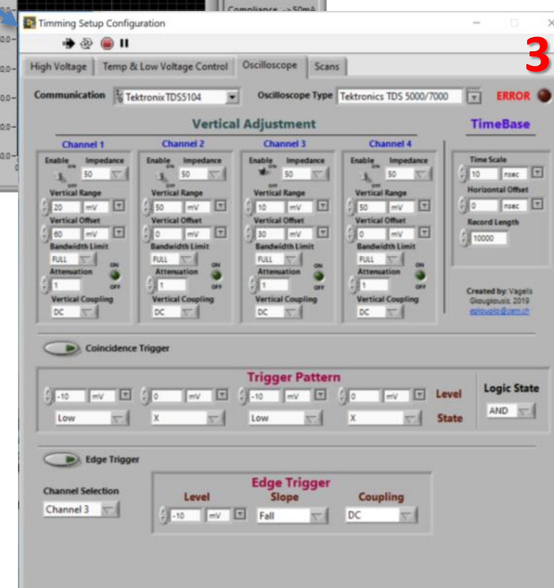
•Charged Particle measu

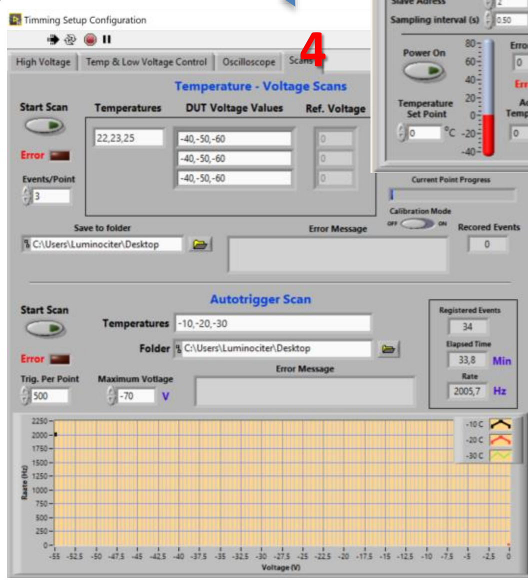
Control Software

- Tab interface organized in 4 sections:
  I. HV Control, V-I recording and visualization
  II. Low Voltage and temperature control
  III. Oscilloscope and triggering mode control
  IV. Charged particle and auto-trigger sequencing and programming
- Multiple supported instruments with **adaptive polymorphic UI**
- Integrated error handling and quai-full proof operation (☺)









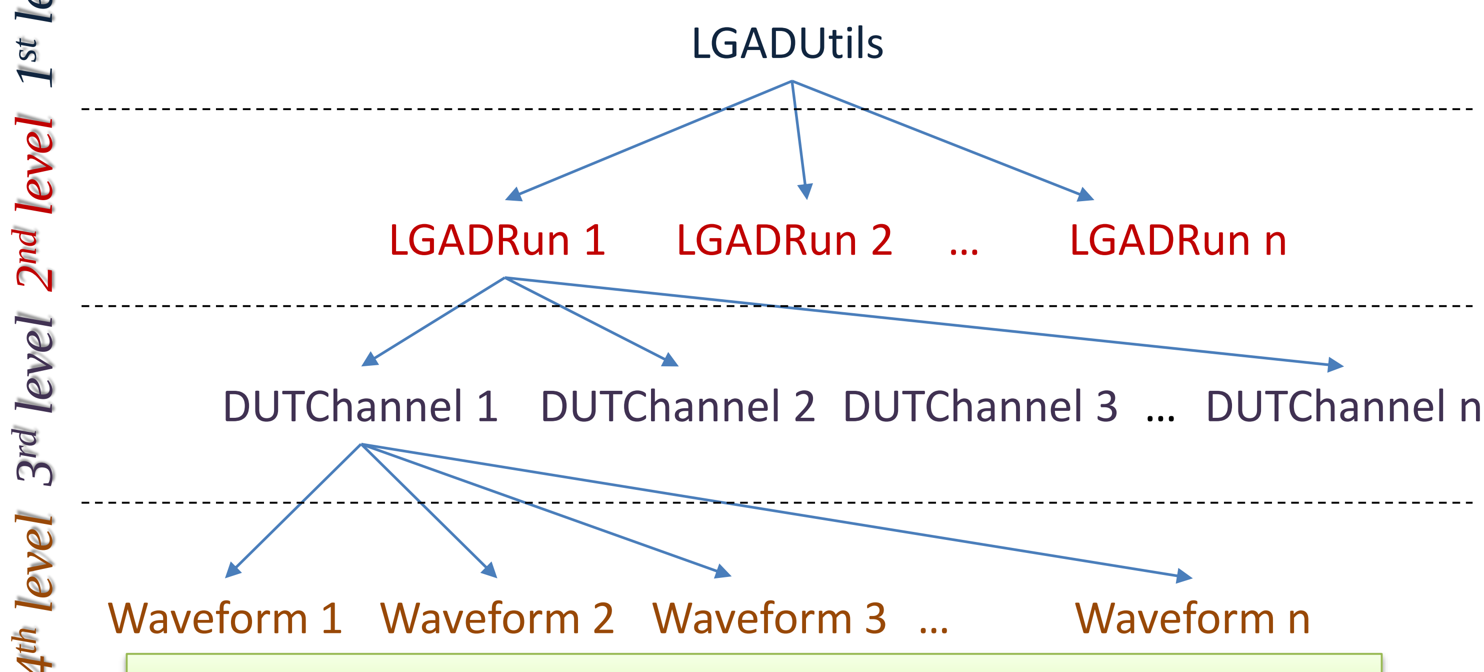
•Charged Particle measurements

C++ 11

Timing resolution Framework

https://gitlab.cern.ch/ifaepix/lgad-timing-analysis

- Four main classes with dedicated header and implementation files
  - **LGADUtils** → Main wrapper, global variables and helper functions
  - **LGADRun** → Timing resolution, CFD maps, multi DUT operations
  - **DUTChannel** → Mean pulse shape, mean pulse properties form entire run
  - **WaveForm** → Single Waveform properties and time walk corrections
  - **Bonus: LGADSel** → **Selector Class with auto-set 64 channel support**



Présentation: https://indico.cern.ch/event/782573/#preview:2889703

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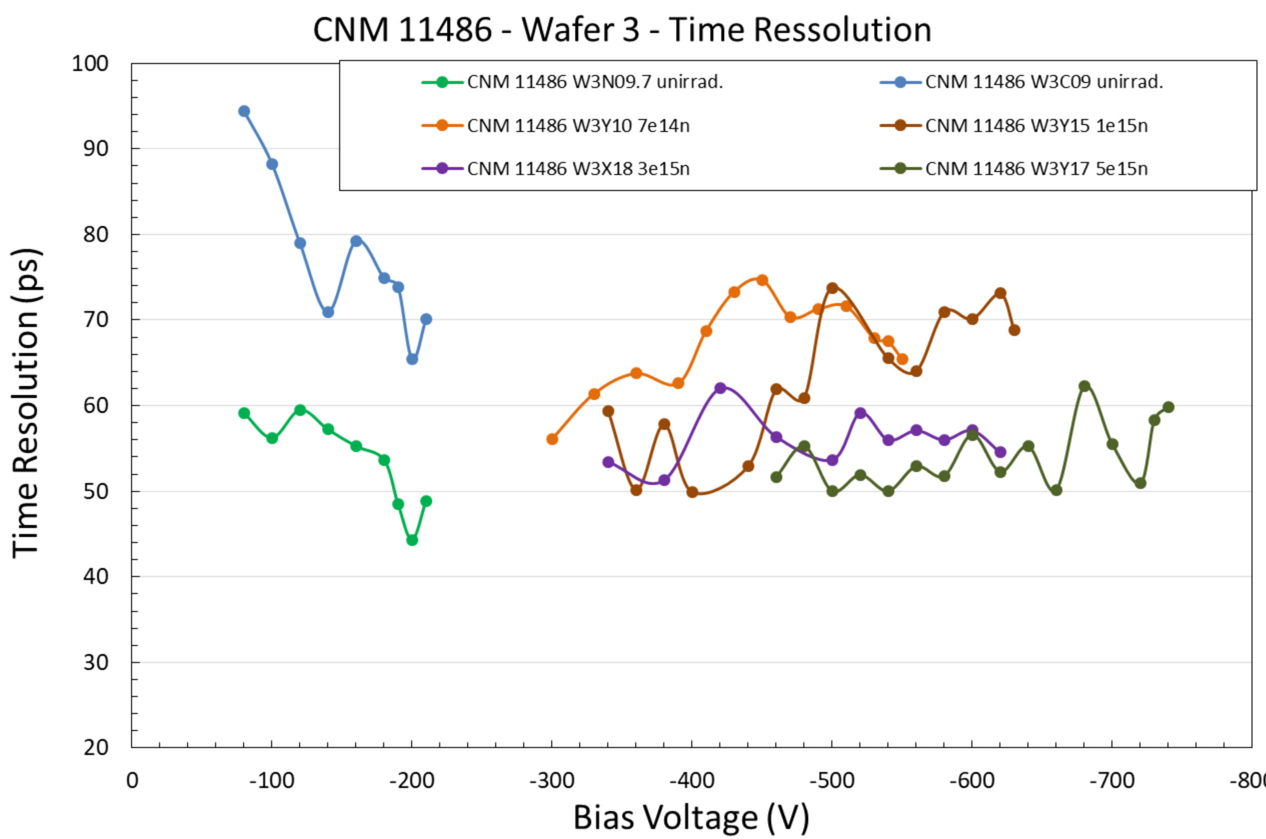
•Charged Particle measurements

Time Resolution

- ✓ 1000 events per point
- ✓ Very low collected charge (< 3fq for irradiated sensors)
- ✓ High active area with larger capacitance
- ✓ Preliminary results, study ongoing



•Charged Particle measurements

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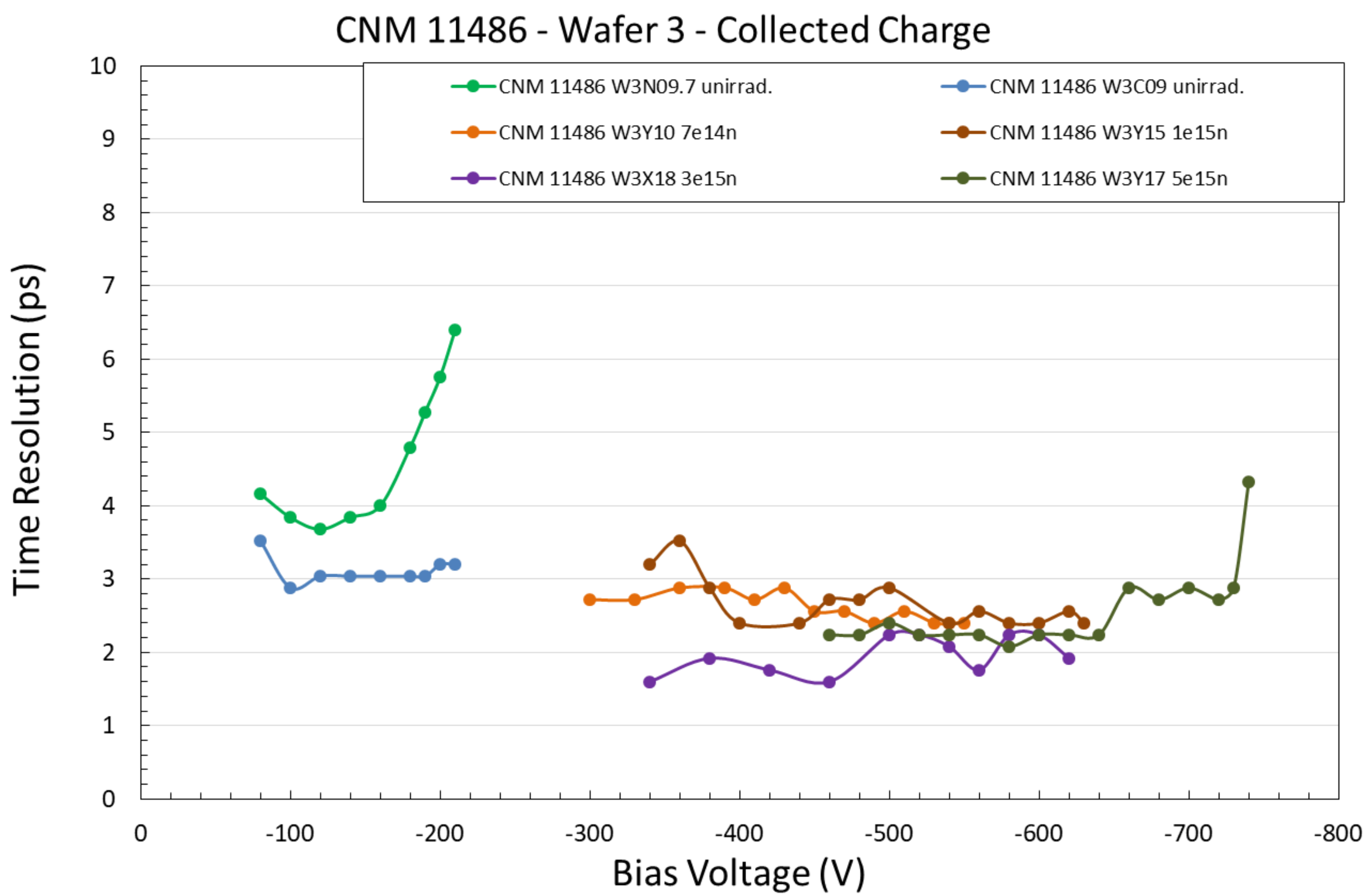
Collected Charge



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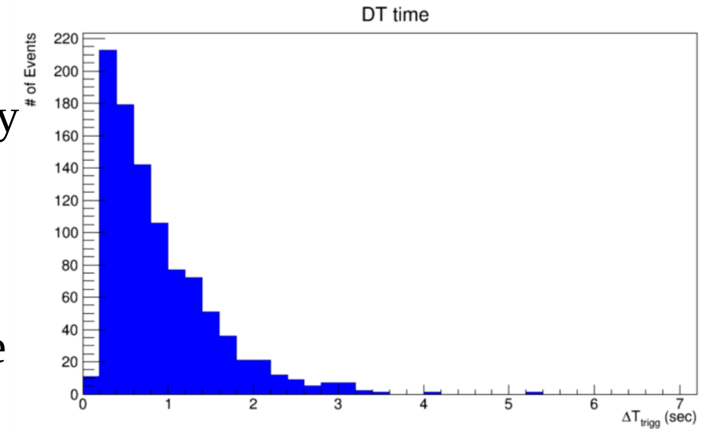
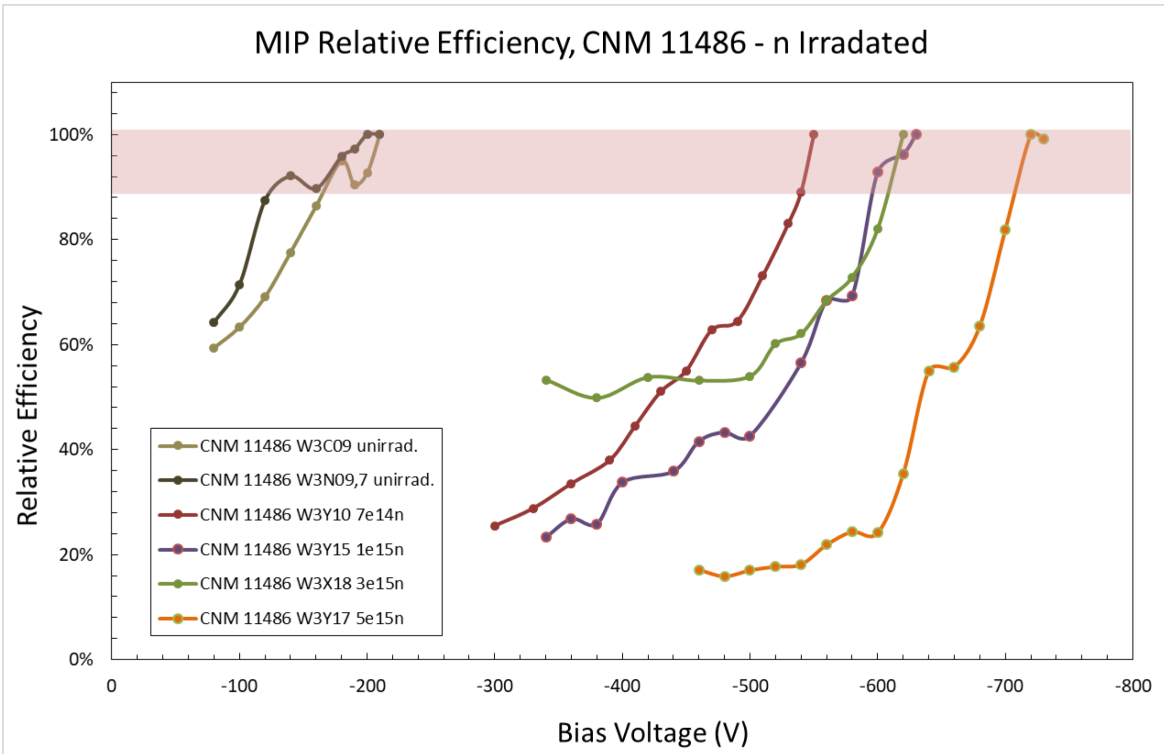
Efficiency vs HV

- ✓ Sr90 source follows exponential decay
- ✓ Sensor trigger distribution is convoluted with efficiency
- ✓ For 100% efficient sensor, median of trigger rate corresponds to radioactive decay

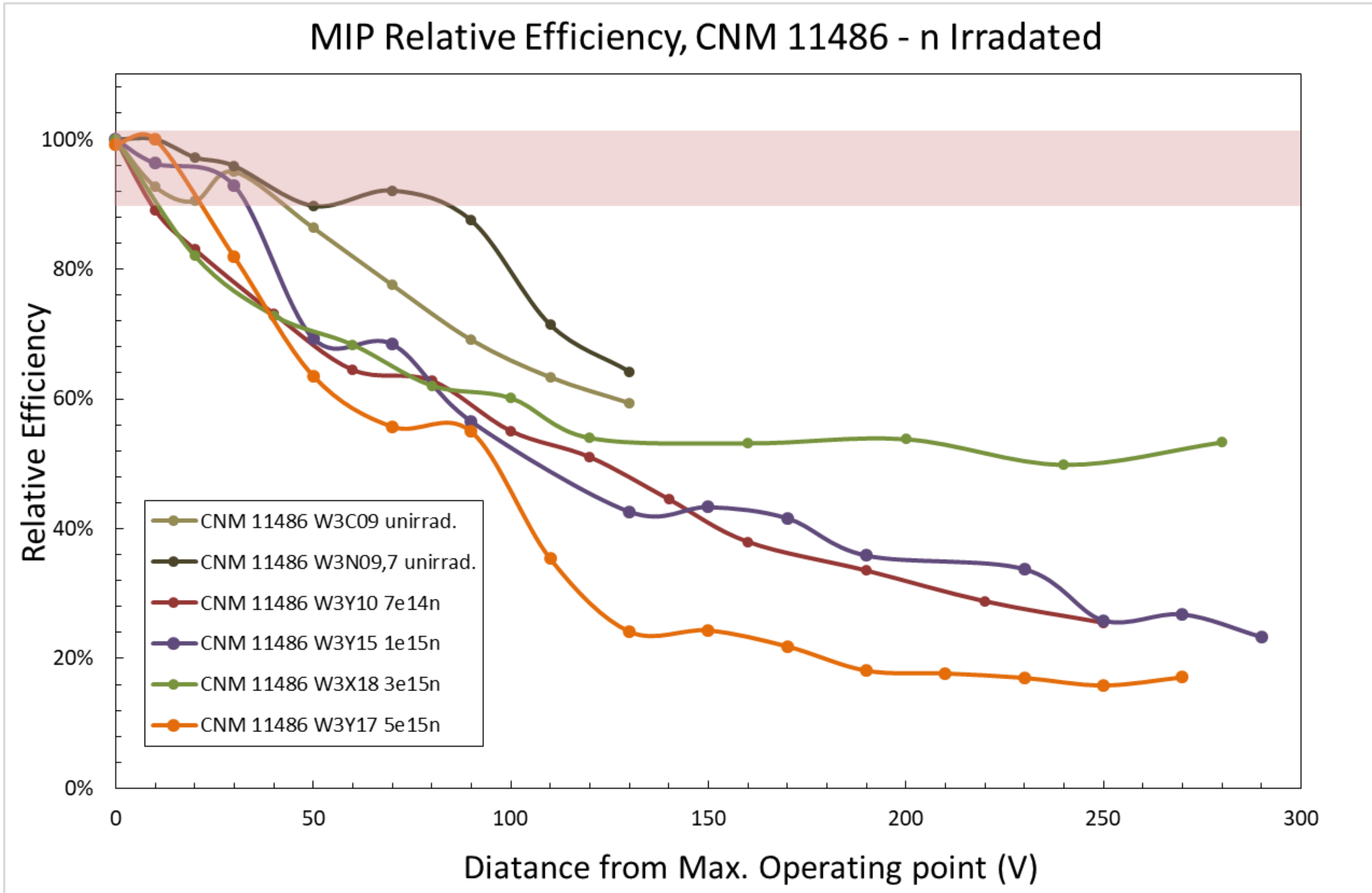




Efficient zone (+/- 5% uncertainty)

•Charged Particle measurements

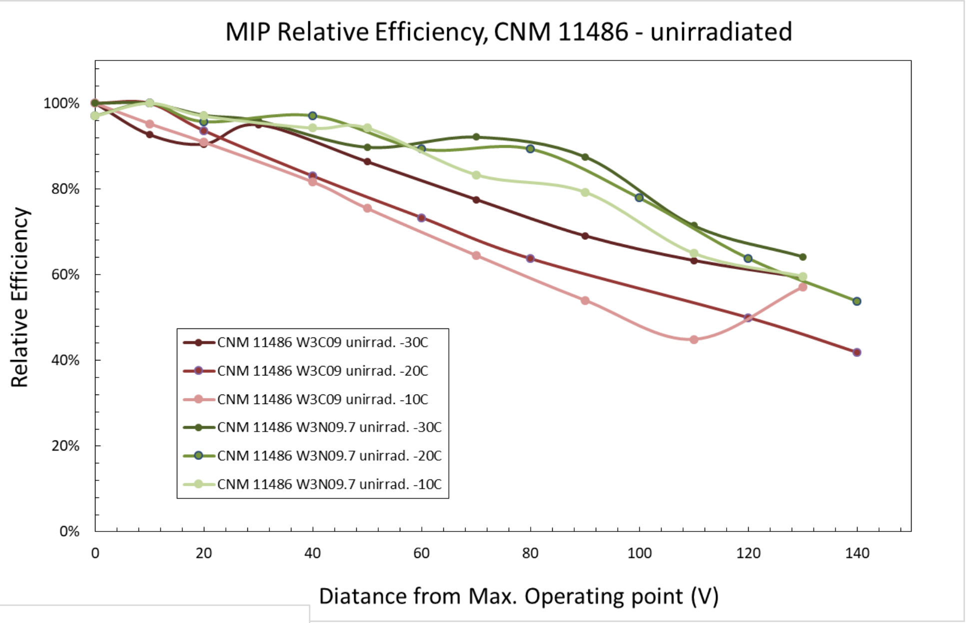
Efficiency vs Headroom

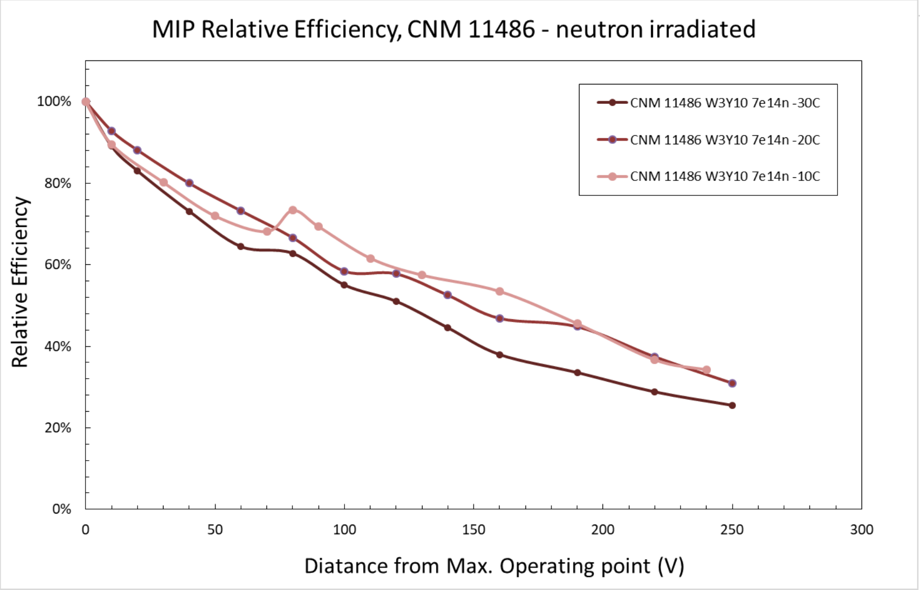


•Charged Particle measurements

Efficiency vs Temp.

- ✓ 1.3x1.3 active area sensor becomes efficient rapidly
- ✓ Larger area (3x3) sensor has a hysteresis
- ✓ Possibly due to metallization opening over pad where field is reduced





- ✓ No significant effect on temperature variations
- ✓ 7e14 sensor never becomes fully efficient
- ✓ Limited in operating voltage by sensor stability

•Conclusions & Outlook

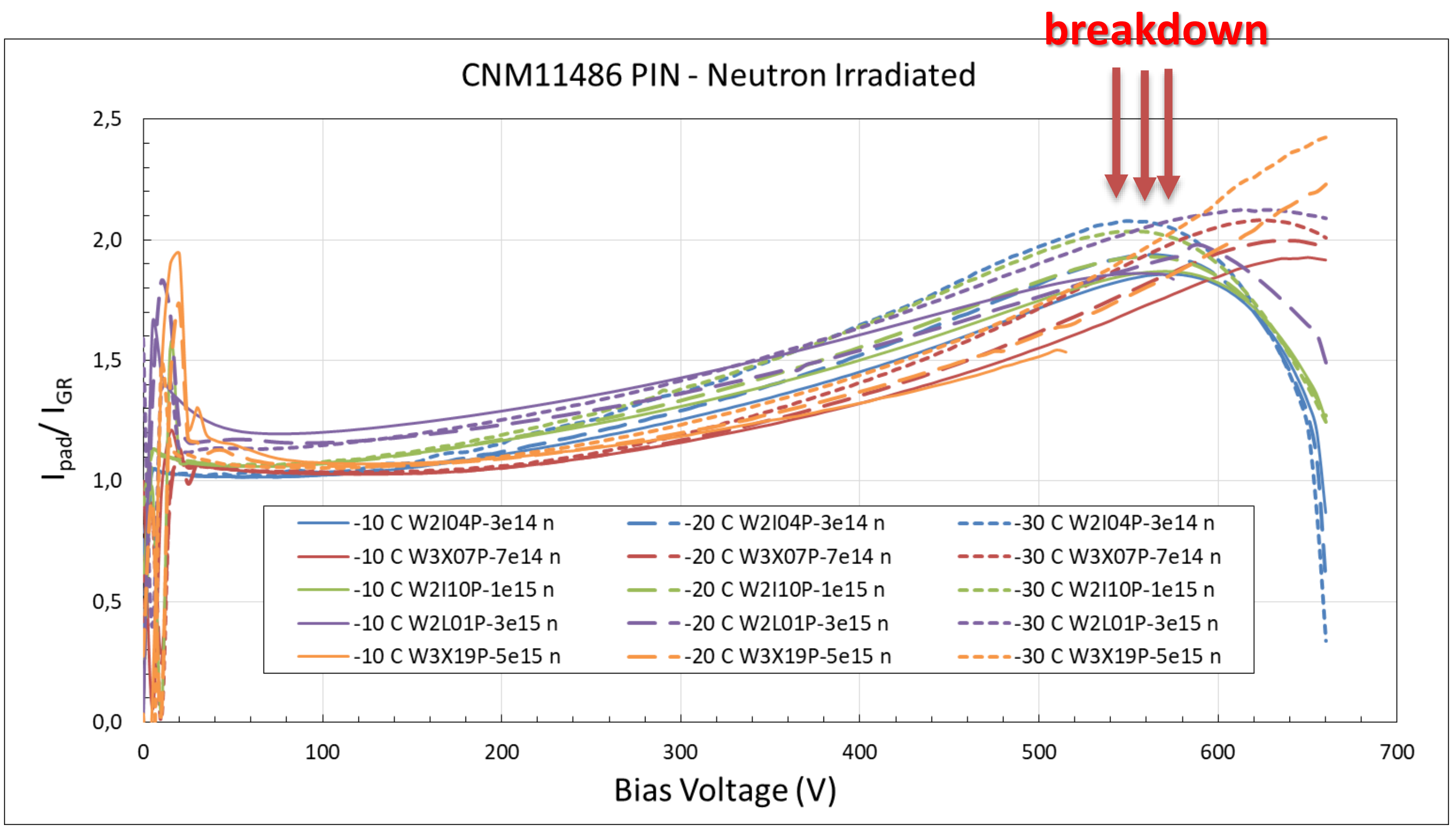
✓ The CNM 11486 6” run was tested

1. Electrical tests
   - ✓ A gain reduction was observed with 12% expected gain left at 3e15
   - ✓ Breakdown voltage was defined and is expected to no be a limiting factor
   - ✓ Acceptor removal observed following the exponential decrease
2. Dark rate
   - ✓ Dark rate was observed for non-irradiated and mildly irradiated sensors up to 10khz at lower than breakdown voltage
   - ✓ Main limiting factor in voltage operation
3. Charge particle studies
   - ✓ 50psec time resolution for the 1.3x1.3 diodes and 70psec for the 3x3mm2
   - ✓ Low collected charge for both irradiated and uneradicated
4. Efficiency
   - ✓ 3e15 & 7e14 fluences never become fully efficient
   - ✓ Unirradiated and higher fluences reach 100% efficiency with st least 20V headroom

•Backup

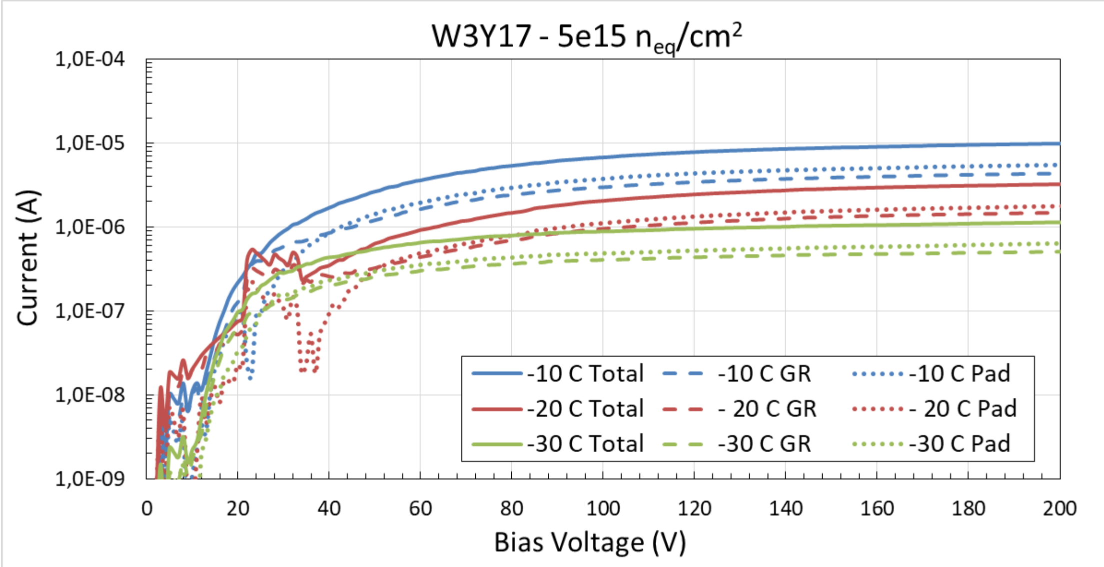
•Electrical characterization

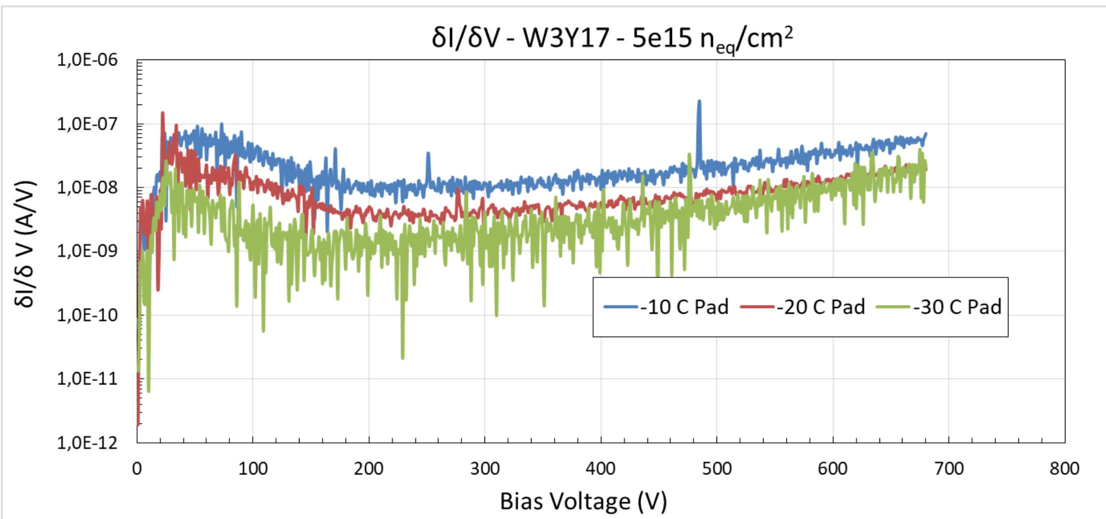
PIN Breakdown Mode



•Electrical characterization

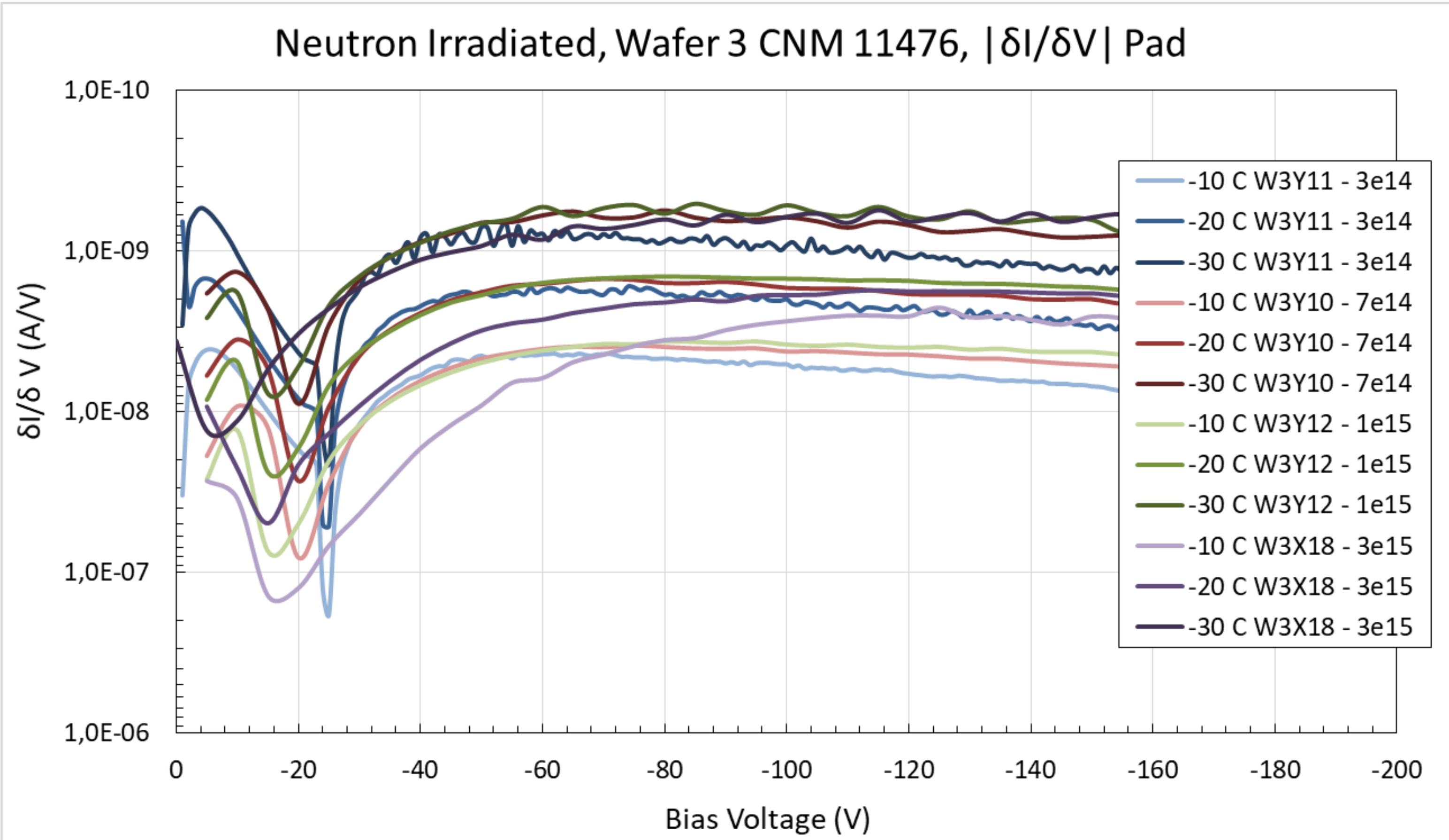
5e15, double junction





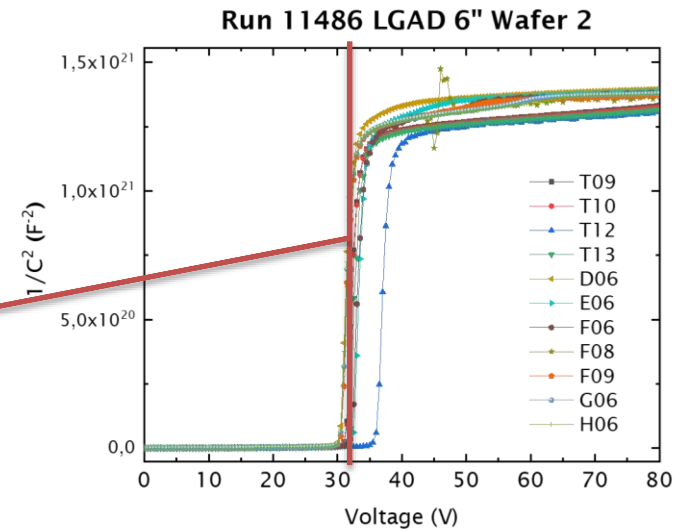
•Electrical characterization

Acceptor removal



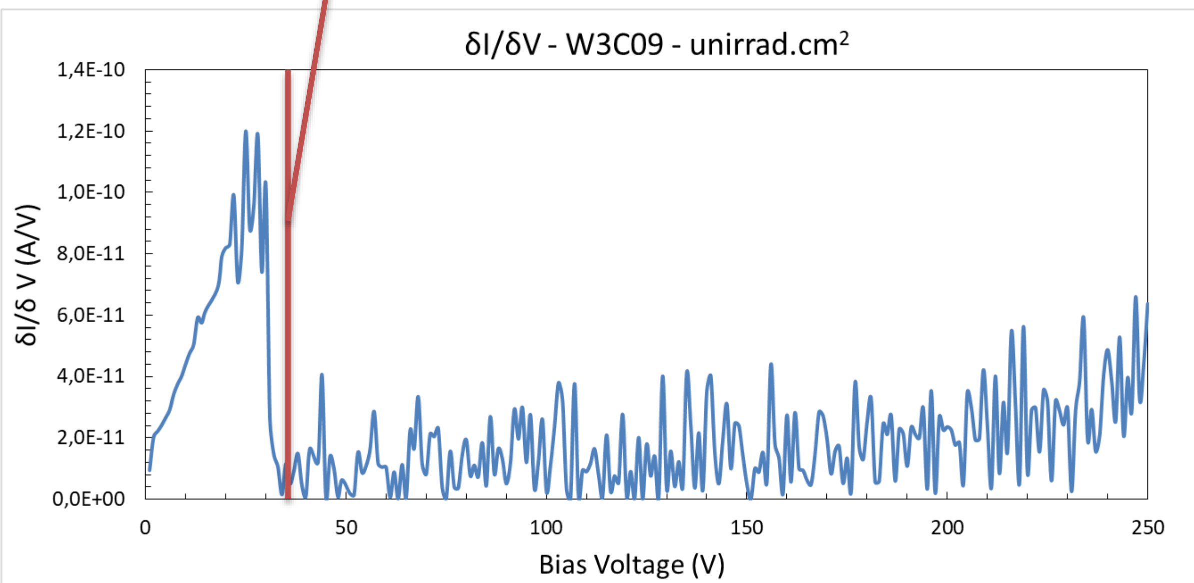
•Electrical characterization

Gain depletion



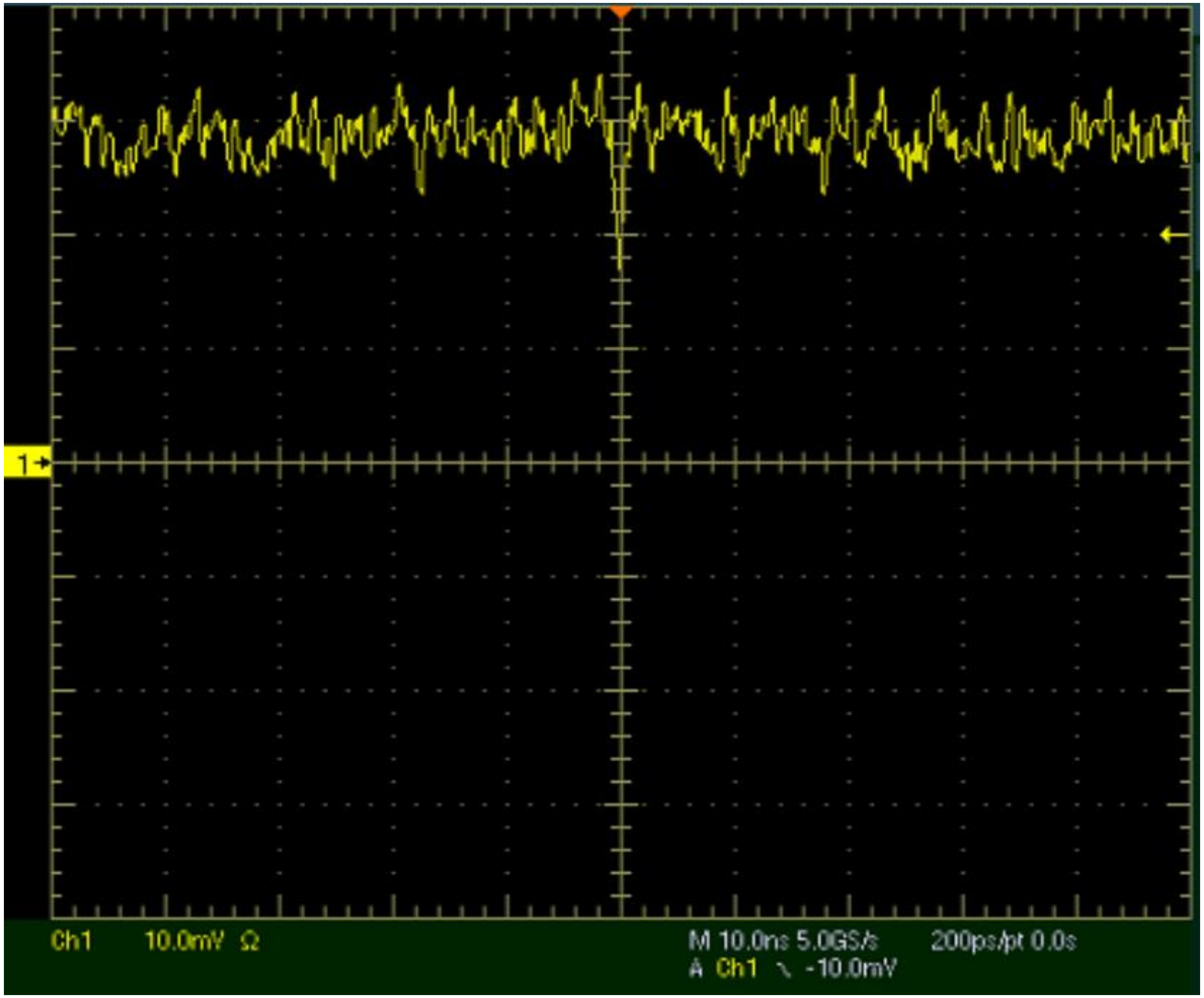
34V

35V



•Dark Rate

WaveForm



•Dark Rate

PIN Diodes