16th Trento Workshop on Advanced Silicon Radiation Detectors

Data Driven LGAD Mortality Studies

The art of (not) burning a sensor

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CERN

Trento – February 18th, 2021

•Damaged sensor list

Unrecoverable sensors (SPS Testbeams)

Manufacturer	Run	Wafer	Structure	Rad. Fluence	Species	GR Grounded	Discharge marks	Annealing	Conditions
CNM	10478	W4	S1017	3e15	n	no	Pad	0 min	Pion beam
CNM	10478	W4	S1058	1e15	p	no	Pad	0 min	Pion beam
CNM	10478	W4	S1102	6e15	n	no	Pad	0 min	Pion beam
CNM	10478	W5	S1036	6e14	p	yes	GR	0 min	Pion beam
CNM	10478	W5	S1075	3e35	p	yes	GR	0 min	Pion beam
CNM	10478	W5	S1117P	6e14	p	yes	GR	0 min	Pion beam
CNM	10924	W6	S1028	1e14	p	yes	none	0 min	Pion beam
CNM	10924	W6	S1026	1e15	p	yes	GR	0 min	Pion beam
CNM	10924	W6	S1025	3e15	p	yes	GR	0 min	Pion beam

April 2018 Test Beam (rows 1–3)

June 2018 Test Beam (rows 4–6)

September 2018 Test Beam (rows 7–9)

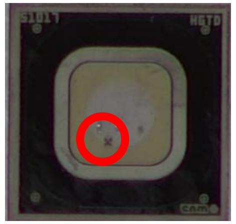
Sensors at CNM for further investigation

•Visual inspection

Post-mortum optical microscopy and conditions

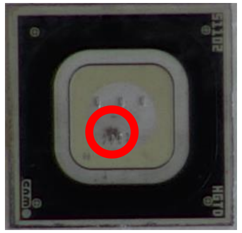
Normal

W4S1017



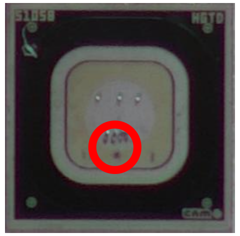
April 2018, 120GeV pion beam
Rate issues @ 620V, -30°C, N_2
(neutrons 3e15 n_{eq}/cm^2)

W4S1102



April 2018, 120GeV pion beam ,Rate issues @ 620V -30°C, N_2
(neutrons 6e15 n_{eq}/cm^2)

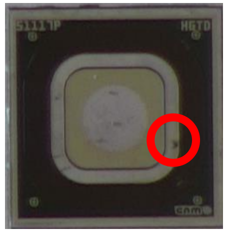
W4S1058



April 2018, 120GeV pion beam, Rate issues @ 580V
-20°C, N_2 / **-30°C completed**
(protons 1e15 n_{eq}/cm^2)

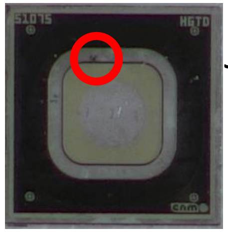
Carbon

W5S1117P



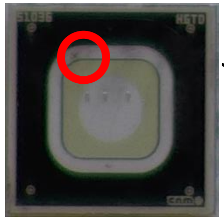
June 2018, 120GeV pion beam,
Rate issues @ 620V, -30°C, N_2
(protons 6e14 n_{eq}/cm^2)

W5S1075



June 2018, 120GeV pion beam,
Rate issues @ 600V, -30°C, N_2
(protons 3e15 n_{eq}/cm^2)
Died during alignment

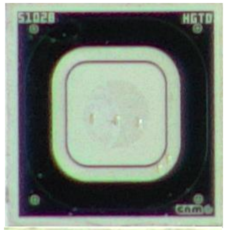
W5S1036



June 2018, 120GeV pion beam
Rate issues @ 600V, -30°C, N_2
(protons 6e14 n_{eq}/cm^2)

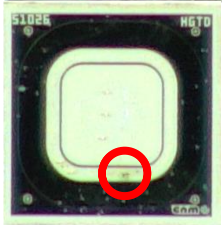
Gallium

W6S1028



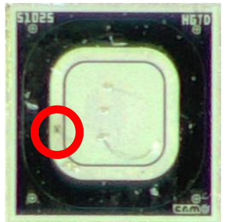
September 2018, data taking
Rate issues @ 220V
-20°C, N_2 / **-30°C completed**
(protons 1e14 n_{eq}/cm^2)

W6S1026



September 2018, data taking
Rate issues @ 590V
-20°C, N_2 / **-30°C completed**
(protons 1e15 n_{eq}/cm^2)

W6S1025



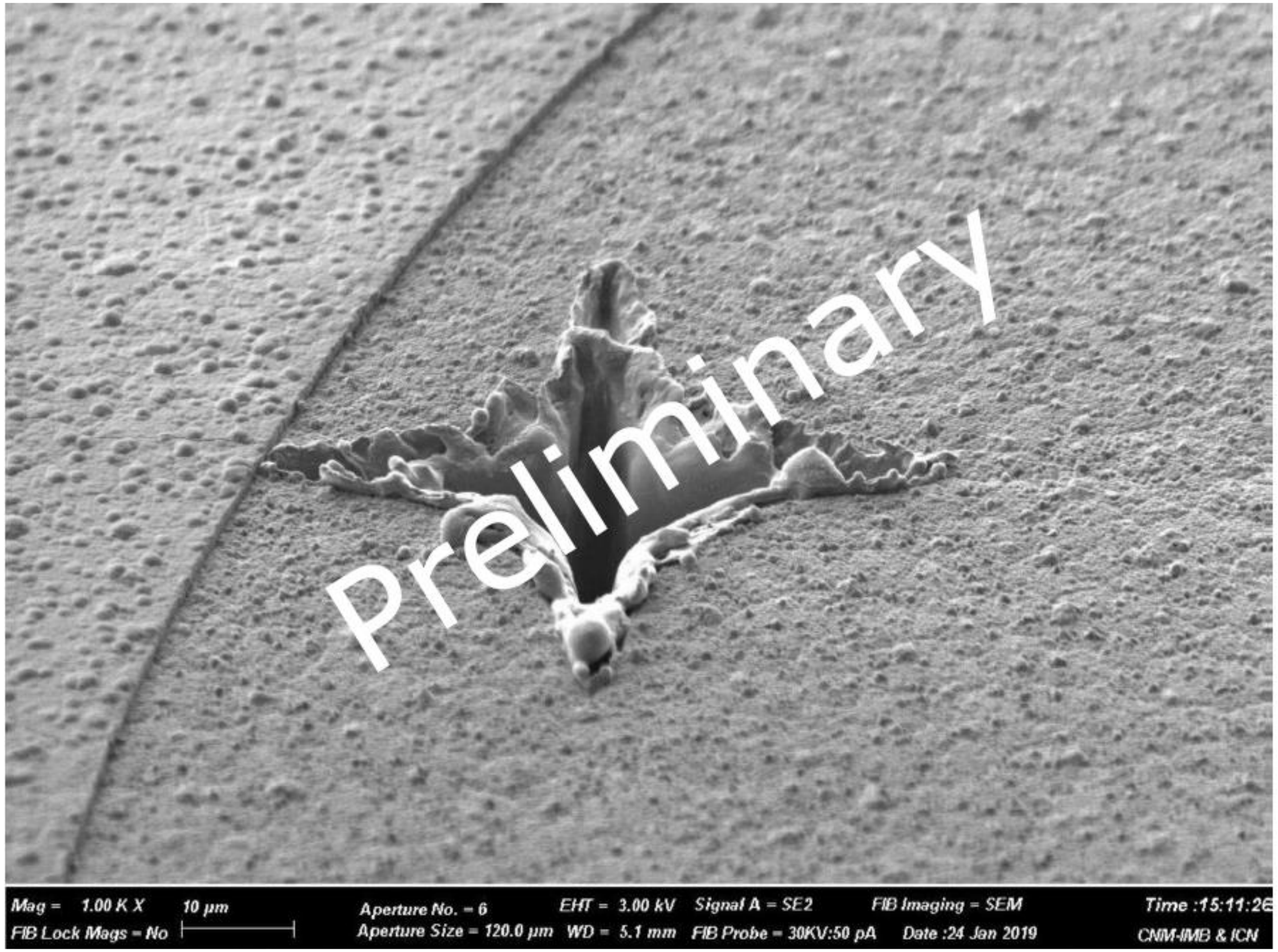
September 2018, data taking
Rate issues @ 590V -30°C, N_2
(protons 3e15 n_{eq}/cm^2)

GR not grounded – Pad Discharge

GR grounded – GR Discharge

•Visual inspection

Post-mortum optical microscopy and conditions



•Sensors damaged during test beam

Lab vs testbeam maximum voltage limits

	Test Beam		Lab	
Normal				
Neutrons 3e15 n_{eq}/cm^2	**620 V**	→	**660 V**	
Neutrons 6e15 n_{eq}/cm^2	**620 V**	→	**570 V**	**Stopped because of auto triggering**
Protons 1e15 n_{eq}/cm^2	**580 V**	→	**660 V**	
Carbon				
Protons 6e14 n_{eq}/cm^2	**600 V**	→	**660 V**	
Protons 3e15 n_{eq}/cm^2	**600 V**	→	**660 V**	
Gallium				
Protons 1e14 n_{eq}/cm^2	**220 V**	→	**210 V**	**Stopped because of auto triggering**
Protons 1e15 n_{eq}/cm^2	**590 V**	→	**520 V**	**Stopped because of high leakage current**
Protons 3e15 n_{eq}/cm^2	**590 V**	→	**510 V**	**Stopped because of periodic discharges**

•Rate Issue

Lab vs Testbeam

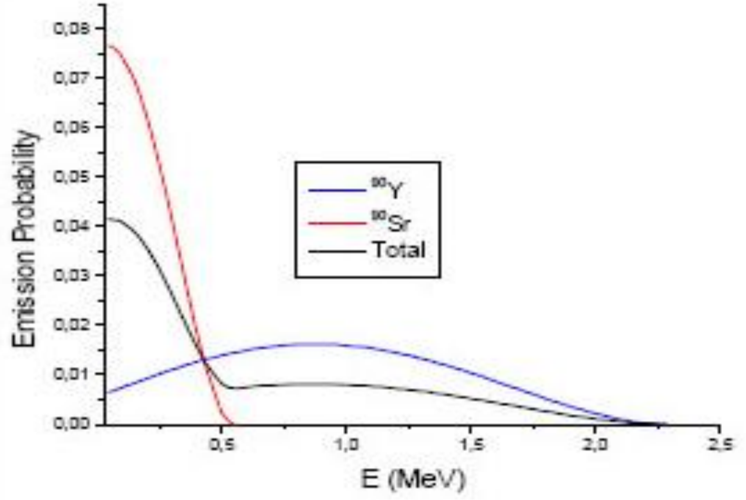
Lab measurements – ^{90}Sr source

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

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

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

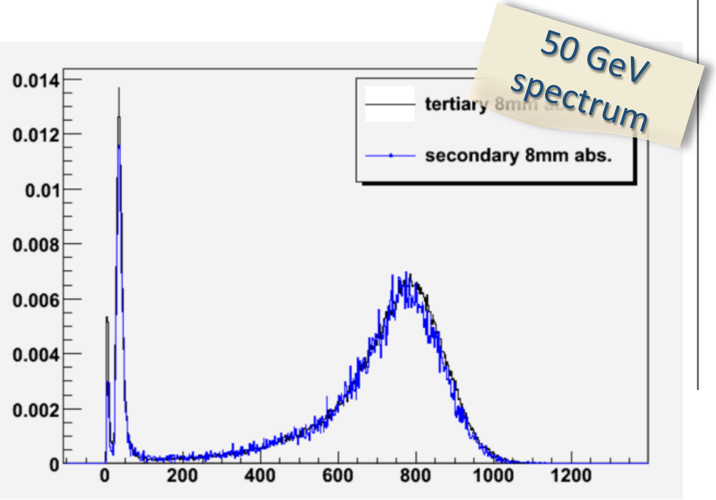
- ✓ Multi-energetic electron spectrum
- ✓ E_{max} at 2.28MeV
- ✓ Average energy ~ 939 keV from ^{90}Y decay
- ✓ Average energy ~ 188 keV from ^{90}Sr decay



Test beam measurements

$140\ GeV\ p^-, negtive\ polarity$
or
$40\ GeV\ p^-, positive\ polarity$
or
$160\ GeV\ p^-, positive\ polarity$

- ✓ SPS pion beam
- ✓ Quasi-monochromatic beam
- ✓ 1% energy dispersion



Radiative losses (Brem mainly) ignored

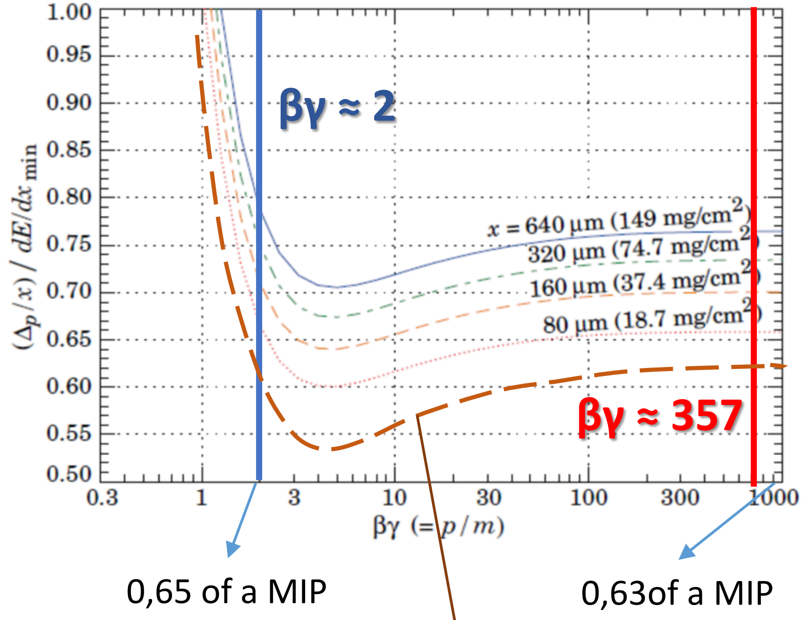
Energy loss in 50μ m Si

939 keV electrons:

$$m_e = \approx 0{,}511\ MeV \rightarrow \beta \cdot \gamma \approx 2$$

40 - 140 GeV pions:

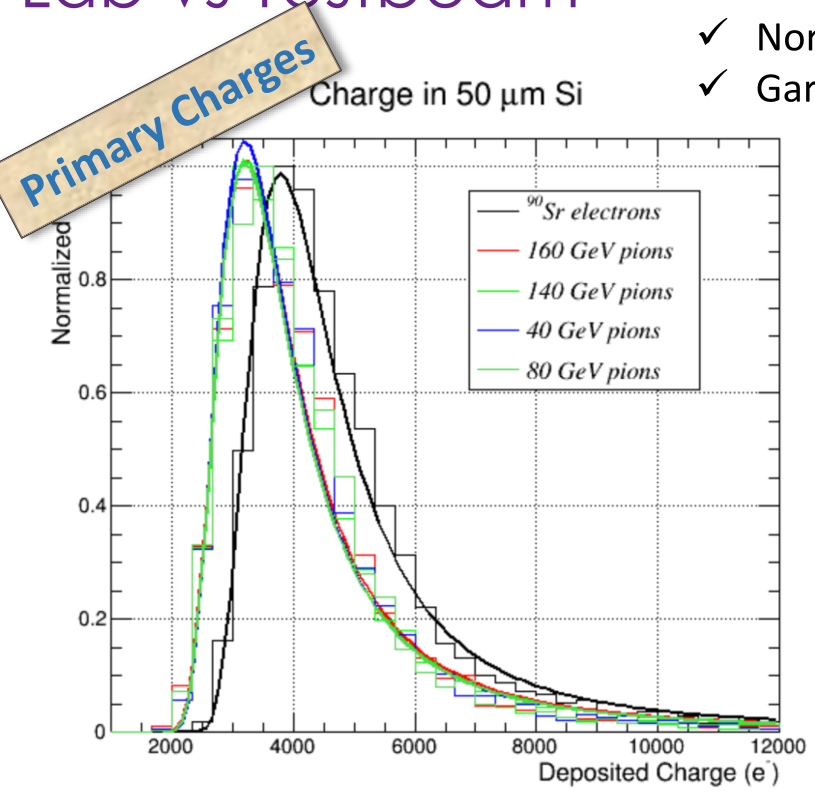
$$m_{pion} \approx 120\ MeV \rightarrow \beta \cdot \gamma \approx 333 - 1333$$



Extrapolated energy deposition at 50 mμ Si

•Rate Issue

Lab vs Testbeam



- ✓ Normalized Landau MPVs to N_{max}
- ✓ Garfield++, 5k events for 50µm

Incoming beam	Electrons	fQ
^{90}Sr	3891	0,62
160 GeV $\pi^{+/-/0}$	3310	0,53
140 GeV $\pi^{+/-/0}$	3300	0,53
40 GeV $\pi^{+/-/0}$	3288	0,53
80 GeV $\pi^{+/-/0}$	3293	0,53

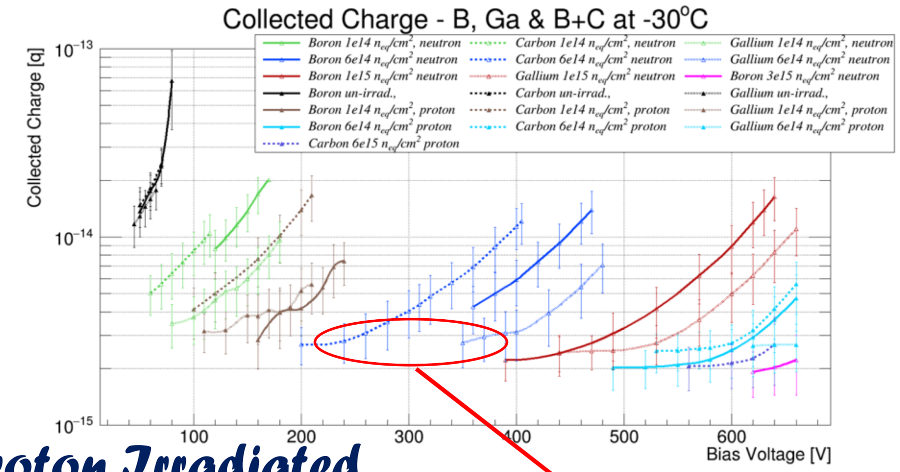
Rates at SPS of 100 – 500 kHz @ 2 x 2 mm² surface during spill

- ✓ For an 1 x 1 mm^2 sensor corresponds to max instantaneous charge introduction rate of:

$$R_c = G \times q_{prim.} \times R_{ev.} \, S_{LGAD} / S_{trigg}$$

$$132.5\, pC/s < R_c < 662.5 pC/s$$

(Gain of 5 here)



Gallium Proton Irradiated

Fluence	Acceptor removal Coeff.	Voltage	Temp (°C)	^{90}Sr Charge (Q)
1e14		220	-20	5,58E-15
1e15	2,02E-14	590	-20	X
6e15		590	-30	X

Carbon Proton Irradiated

Fluence	Acceptor removal Coeff.	Voltage	Temp (°C)	^{90}Sr Charge (Q)
6e14	1,37E-14	600	-30	2,74E-15
3e15		600	-30	2,16E-15

Boron Proton Irradiated

Fluence	Acceptor removal Coeff.	Voltage	Temp (°C)	^{90}Sr Charge (Q)
1e15	2,25E-14	580	-20	2,40E-15

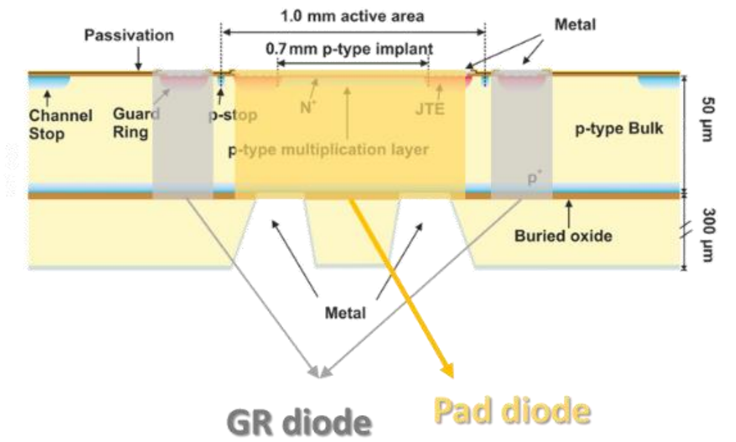
Boron Neutron Irradiated

Fluence	Acceptor removal Coeff.	Voltage	Temp (°C)	^{90}Sr Charge (Q)
3,00E+15	2,25E-14	620	-30	1,92E-15
6,00E+15		620	-30	X

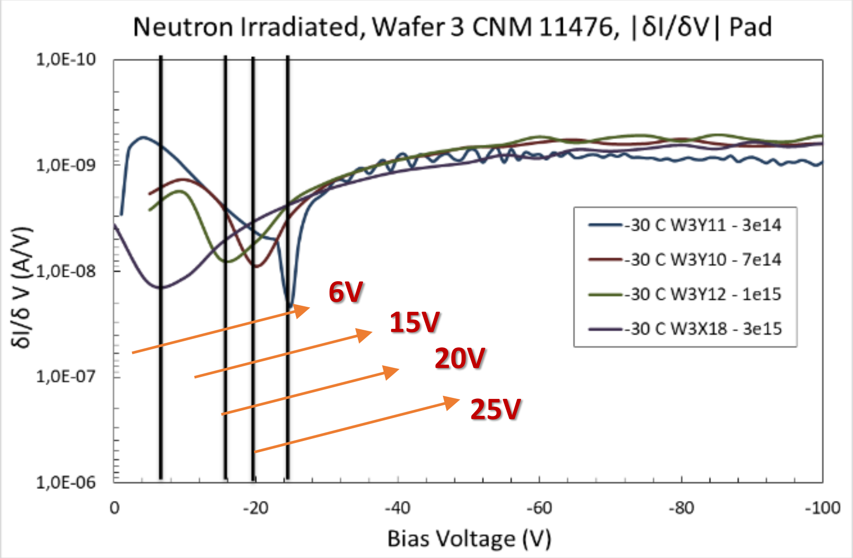
•Depletion Voltage

Pad $\left|\frac{\partial I}{\partial V}\right|$ Estimation

- ✓ Gain layer only present in pad region (GR region implanted with diffused n)
- ✓ Additional p-implantation gain layer creates secondary depletion region
- ✓ Mott–Schottky equation → **rapid leakage current variation at depletion**
- ✓ **δ-function** form of $\left|\frac{\partial I}{\partial V}\right|$ at depletion point – convoluted with instrument resolution (Gaussian) - approximated by narrow width Gaussian
- ✓ Depletion voltage determined by mean of Gaussian fit at depletion voltage
- ✓ Performed at -10ºC, -20ºC & -30ºC with independent fits on each temperature → **90 Gaussian Fits**



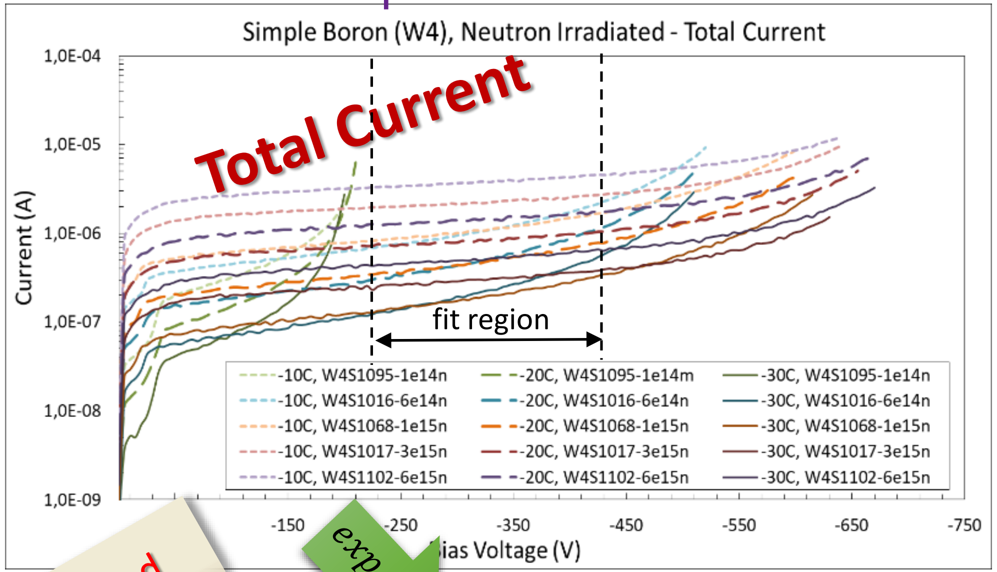
Gkougkousis V., RD50 Workshop Talk, November 2019: link



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

•Breakdown Voltage

Current Multiplier



Method

exp. fit

- ✓ Measure total leakage current (-10°C, -20°C, -30°C)
- ✓ Select a stable voltage range where behaviour follows exponential law
- ✓ Define common for all temperatures stable voltage range, after depletion and much before breakdown
- ✓ Perform exponential fit requesting $R^2 \geq 99\%$ (same range as in the gain reduction fits - same constraints)
- ✓ Calculate the multiplier with respect to the expected current
- ✓ **Define breakdown in multiplier value (Is it really exponential??)**

Un-irradiated: $I_{pad}^{\Phi=0} = I_s \times \left(e^{\frac{eV}{nkT}} - 1\right) \times G(e^V, T)$

Irradiated: $I_{pad}(\Phi) = (I_{pad}^{\Phi=0} + \alpha\Phi) \times G^*(e^V, T, \Phi)$

Function of acceptor removal, exponential to fluence and voltage plus a linear term

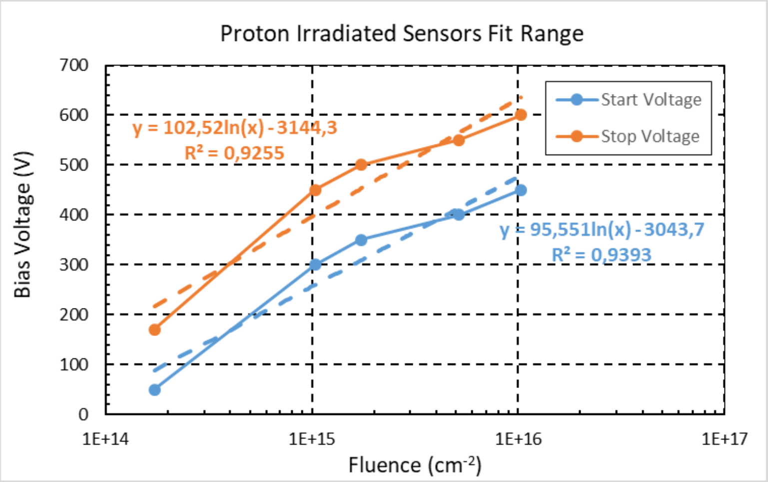
Exponential Fit: $I = b \cdot m^V$

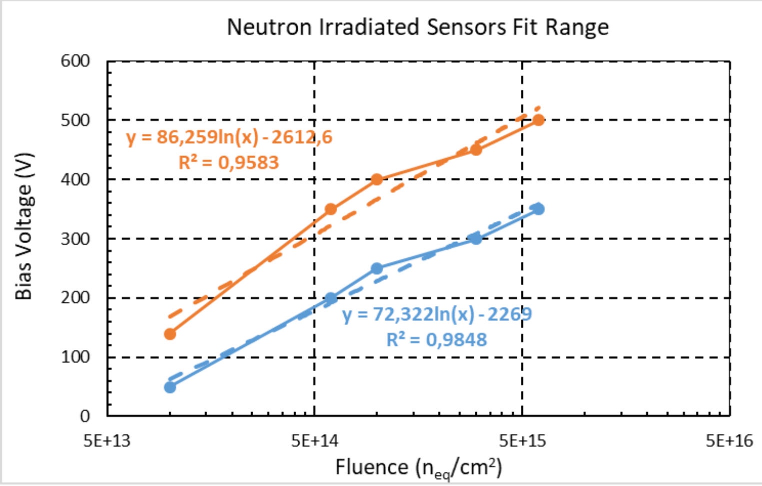
Acceptance Criteria: $R^2 \geq 99\%$

Expected current: $I_{norm} = b \cdot m^{V_i}$

Current Multiplier: $M(V) = \left|\frac{I_{pad} + I_{GR}}{I_{norm}}\right|$

Breakdown: $V_{brw} \rightarrow M(V) > 2$

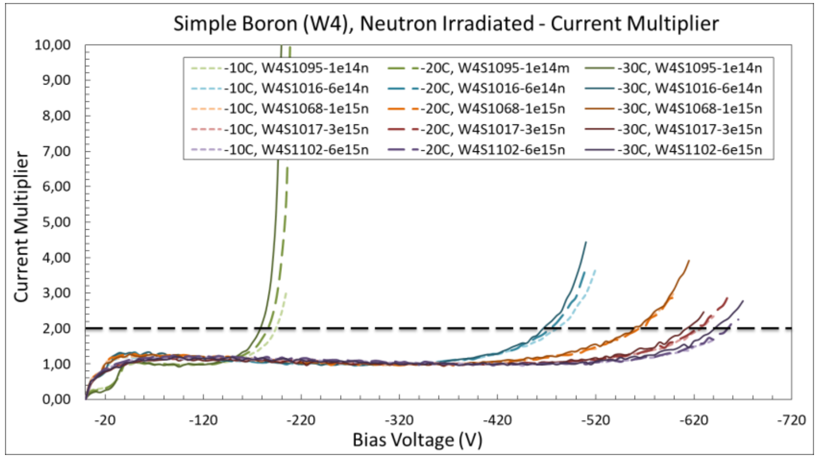


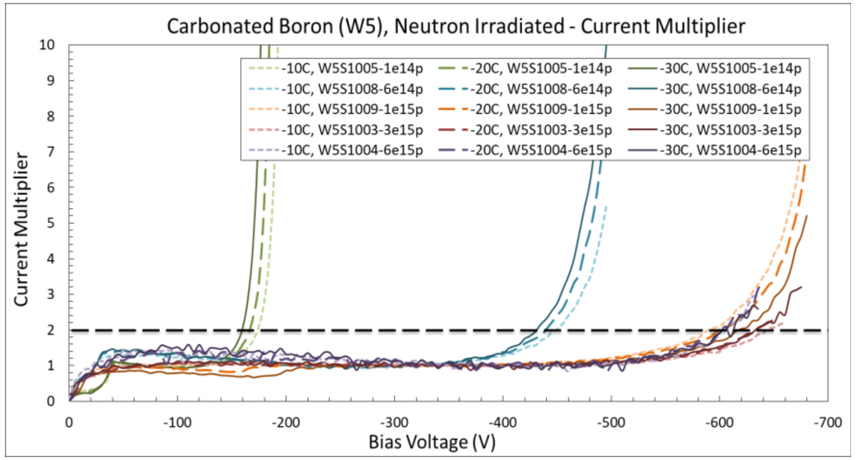


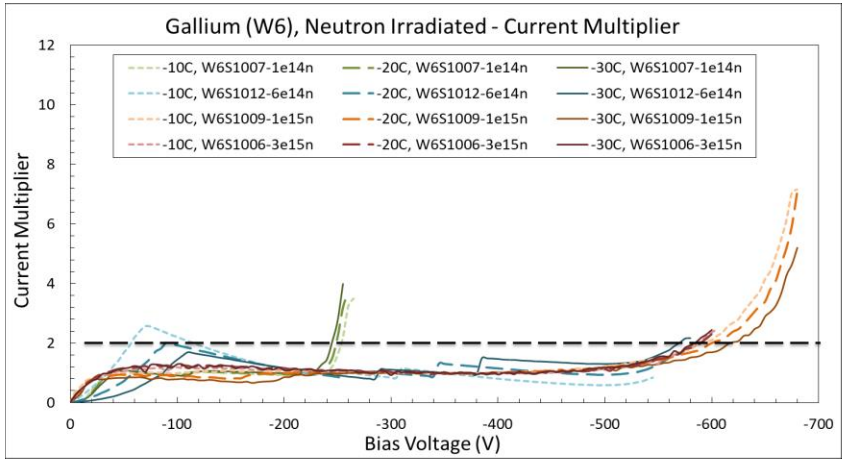
•Breakdown Voltage

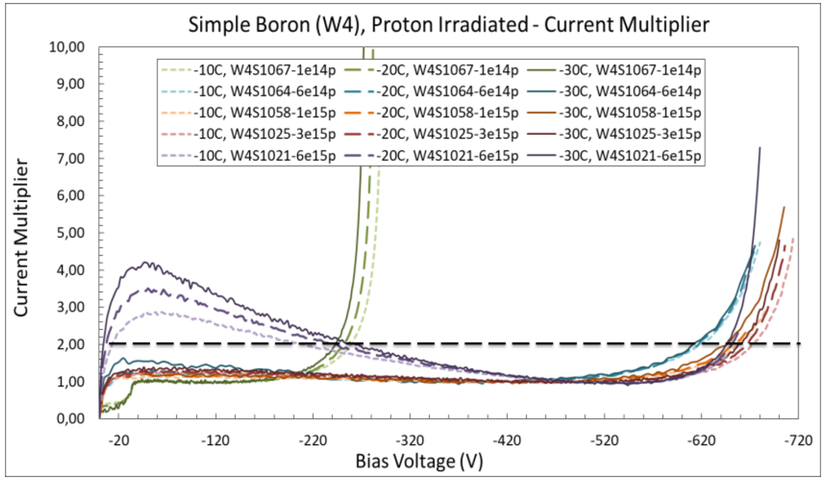
- ✓ Independent fit for each temperature
- ✓ Identical fit regions across all temperatures
- ✓ Identical fit regions for same fluence across all three implants

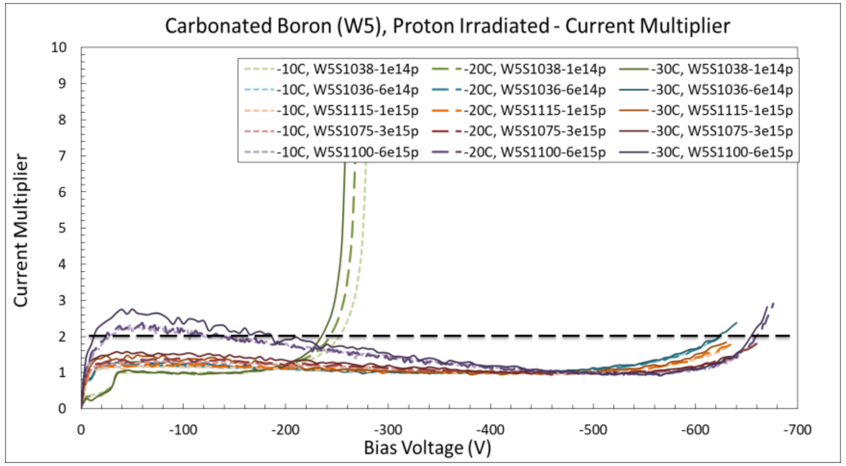
Constraints

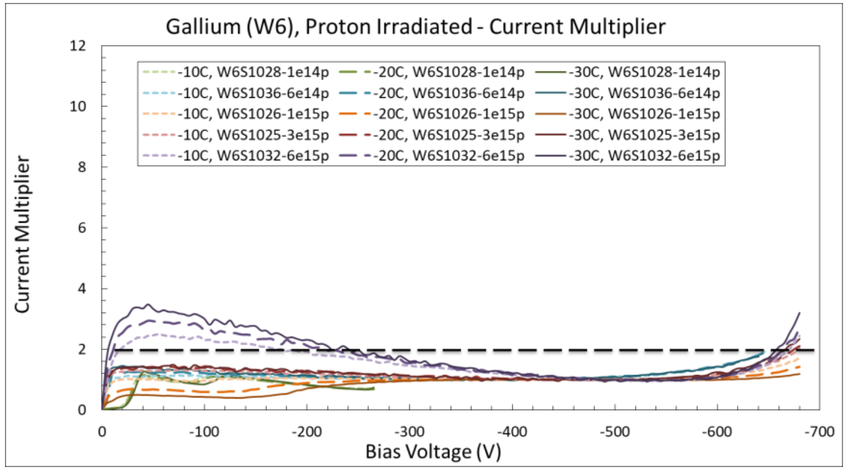










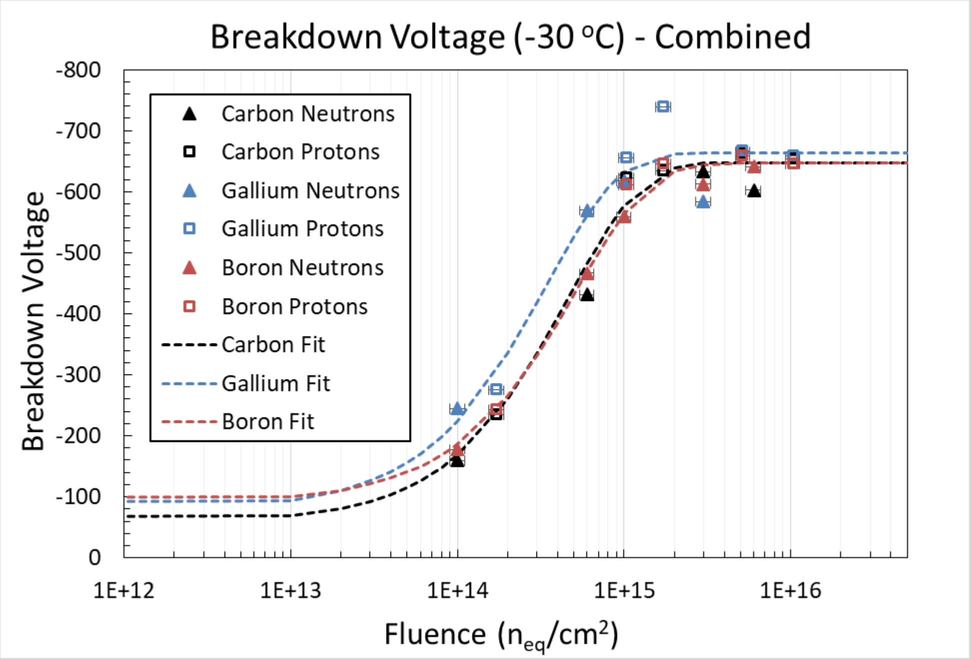


•Breakdown Voltage

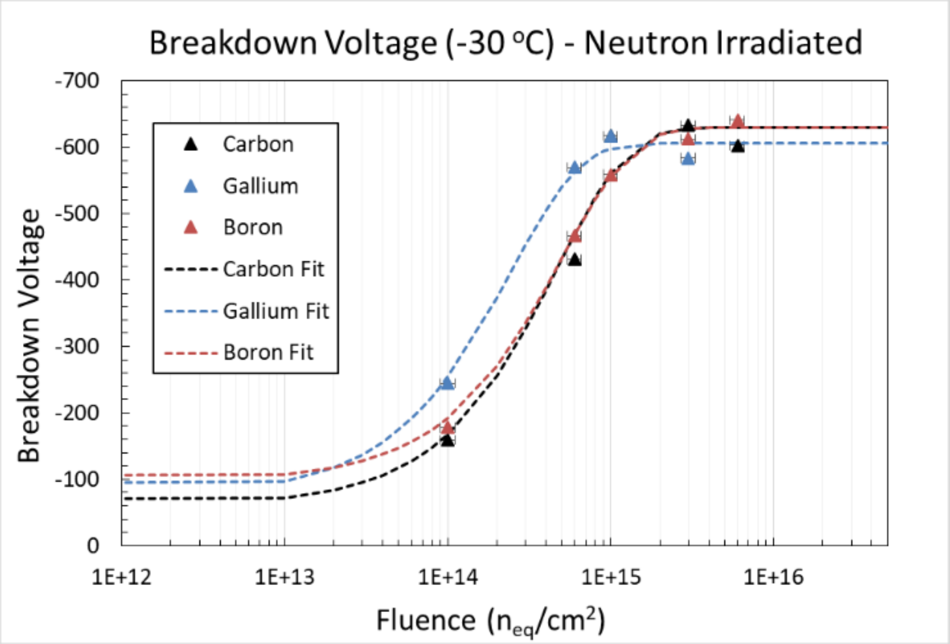
Model

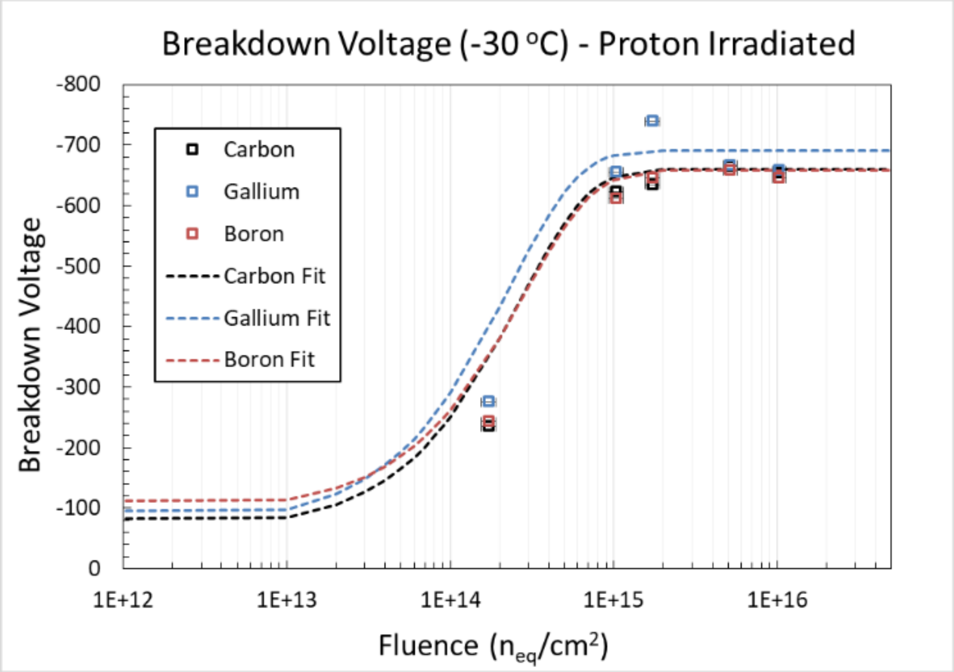
Breakdown of PIN — Un-irradiated breakdown voltage

$$V_b = (V_{max} - V_0)\left(1 - e^{-c\Phi}\right) + V_0$$



- ✓ Carbon and boron are compatible
- ✓ Gallium presents higher breakdown voltage (most possibly due to process variation)
- ✓ All implants compatible with sigmoid approach
- ✓ Highest breakdown voltage after irradiation independent of gain – exclusively process dependent

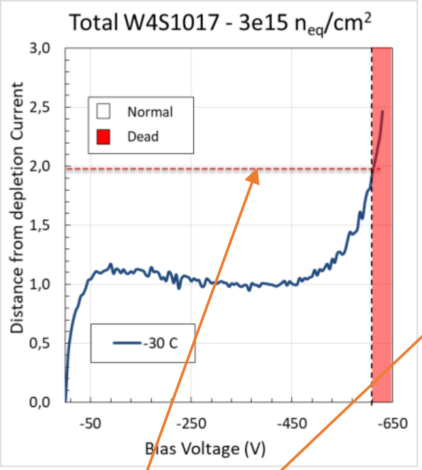


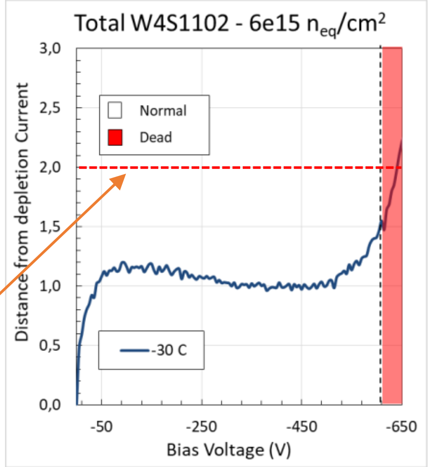


•Were our sensors in breakdown?

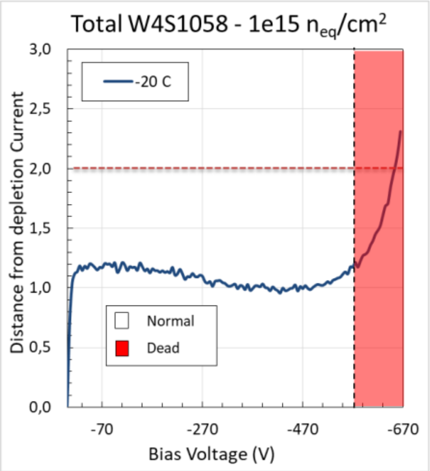
Carbon Protons

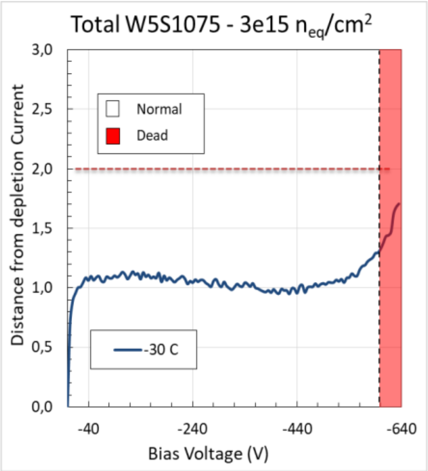
Boron Neutrons

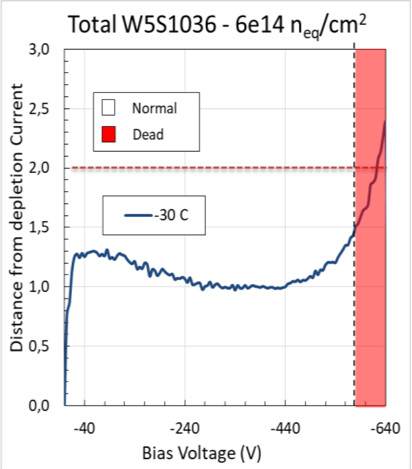




Boron Protons

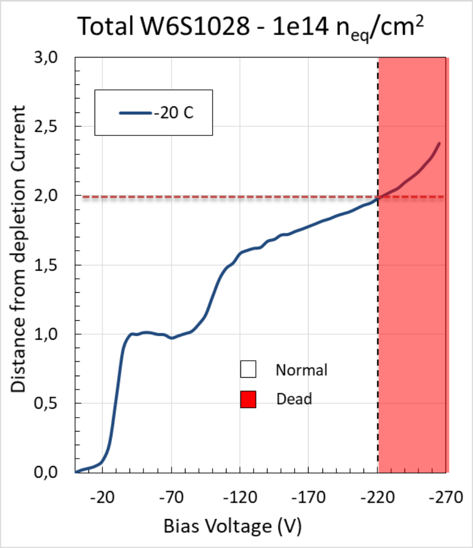


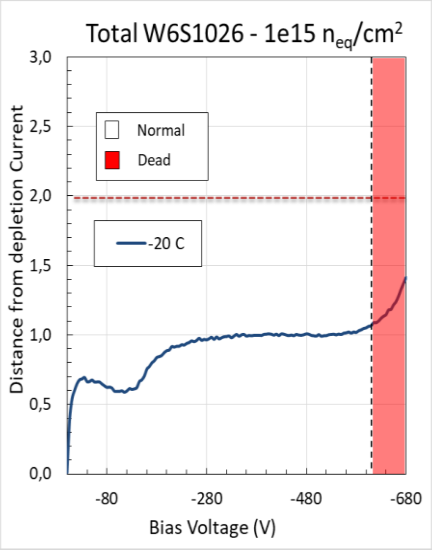


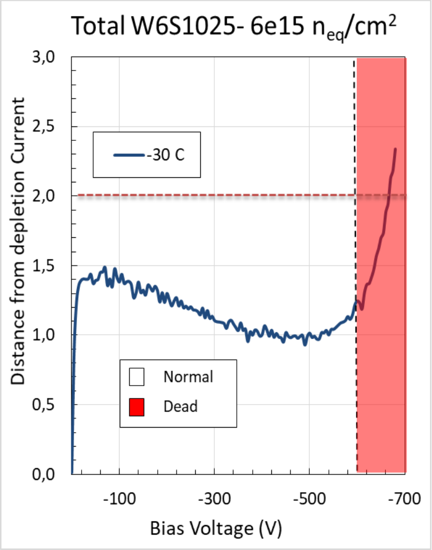


Gallium Protons

Breakdown Line

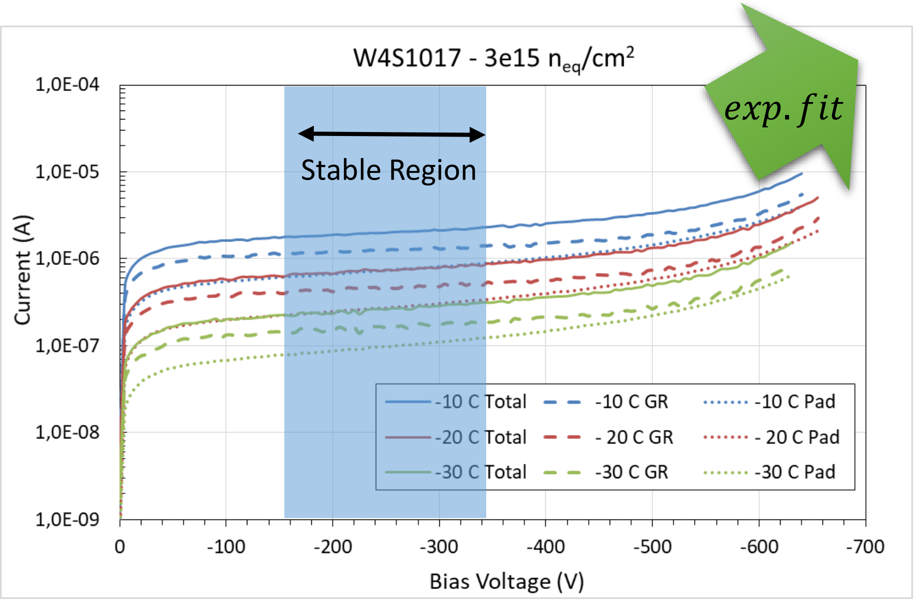






•Stability Estimation

Model



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

Analytical derivative: $$\left.\frac{\mathrm{d}I}{dV}\right|_i = \frac{\left|b \cdot m^{V_{i+1}} - b \cdot m^{V_i}\right|}{|V_{i+1} - V_i|}$$

Actual Derivative: $$\left.\frac{\Delta I}{\Delta V}\right|_i = \frac{|I_{i+1} - I_i|}{|V_{i+1} - V_i|}$$

For all points N inside fitting region

Stability defined as average deviation between estimated and real derivative:

$$\bar{S} = \frac{1}{N}\sum_N \left| \left.\frac{\mathrm{d}I}{dV}\right|_i - \left.\frac{\Delta I}{\Delta V}\right|_i \right|$$

Standard deviation of Stability

$$\sigma_s = \sqrt{\frac{\sum_N |s - \bar{s}|^2}{N}}$$

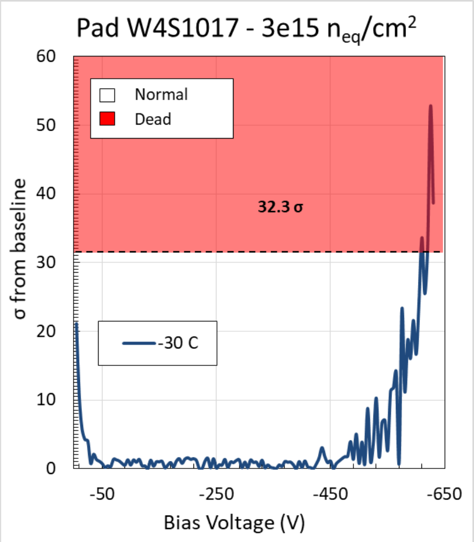
For each other point outside of fitting region

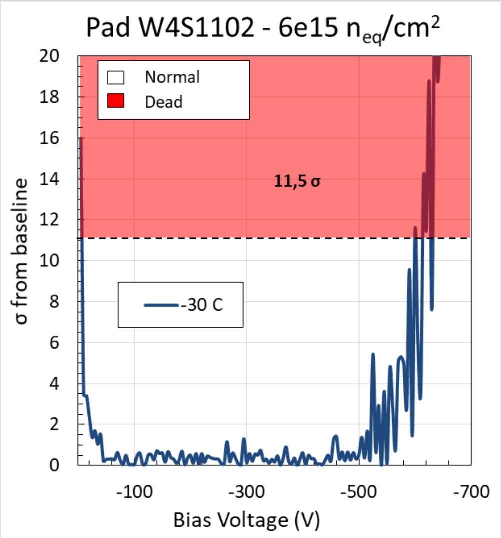
$$D = \frac{\left| \left.\frac{\mathrm{d}I}{dV}\right|_i - \left.\frac{\Delta I}{\Delta V}\right|_i \right| - \bar{s}}{\sigma_\sigma}$$

- ✓ Probe local stability with respect to normal deviation
  - ✓ Sensitive only to **local** variations
- ✓ Not dependent on breakdown, only on point to point instabilites

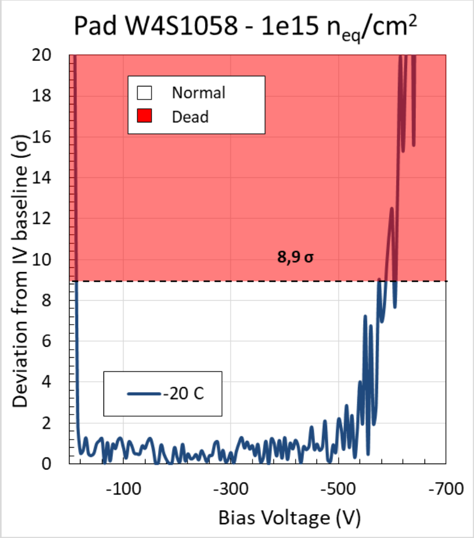
•Stability Estimation

Boron Neutrons

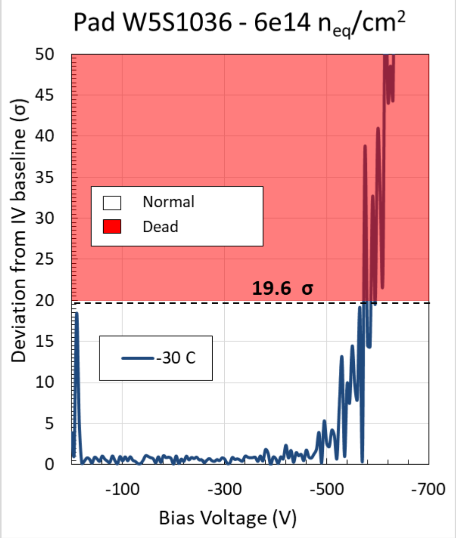


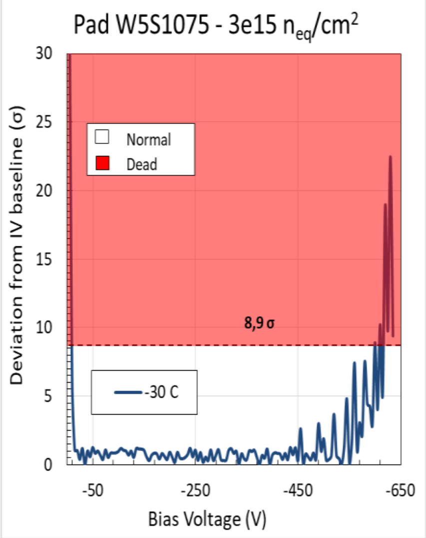


Boron Protons

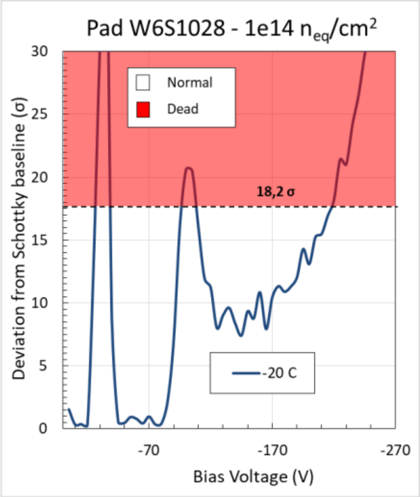


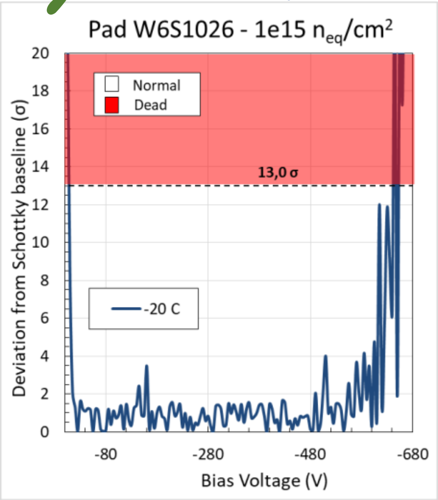
Carbon Protons

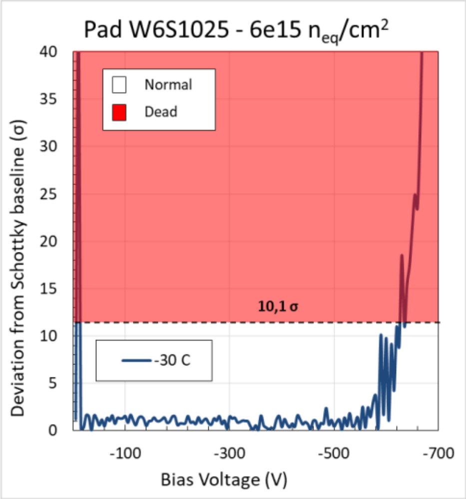




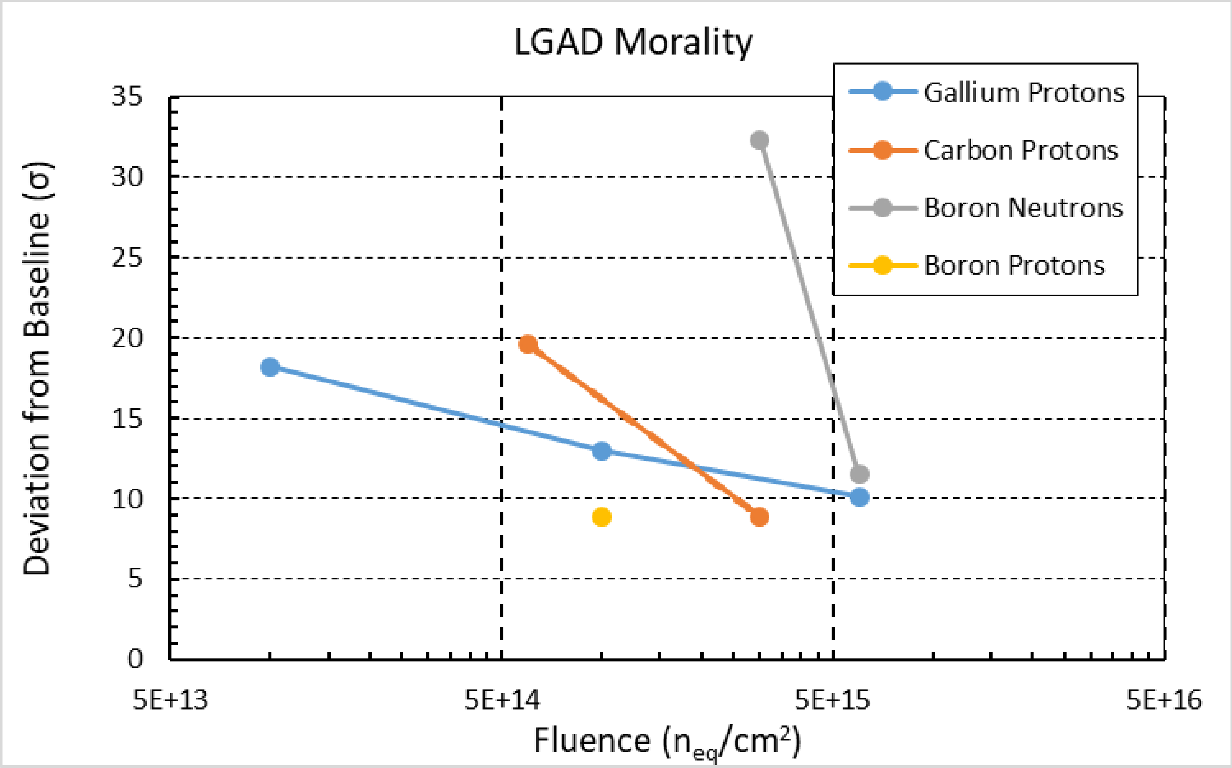
Gallium Protons







•Stability Estimation



- ✓ Decrease of the instability point associated with a breakdown behavior with fluence increase
- ✓ Fit demonstrates almost linear behaviors for same type sensors
- ✓ With a less than 10 σ allowed point one is relatively safe, but this leads to decreased bias voltages
- ✓ More points necessary for additional study
- ✓ Relatively high fluence sensors reach high instability points sooner than lower fluence with respect to their estimated breakdown

•Additional Ideas and next steps

Summary

- A first study of test beam damaged sensors is presented
- An association with local HV stability is explored and shown to decrease with irradiation
- Damaged sensors are proven not to be in breakdown at damage point
- An association with introduction rates is made but durther studies necessary

Next steps

- Dedicated “sensor series” for mortality studies
- Beam studies might be necessary (more than laser or ^{90}Sr)
- If polarization or trapping effects, one should be able to prove with CVs or varied frequency lasr