37TH RD50 Workshop

LGAD Efficiency and Stability

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CERN, EP-R&D WG 1.1: Hybride Pixel Detectors

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•Introduction

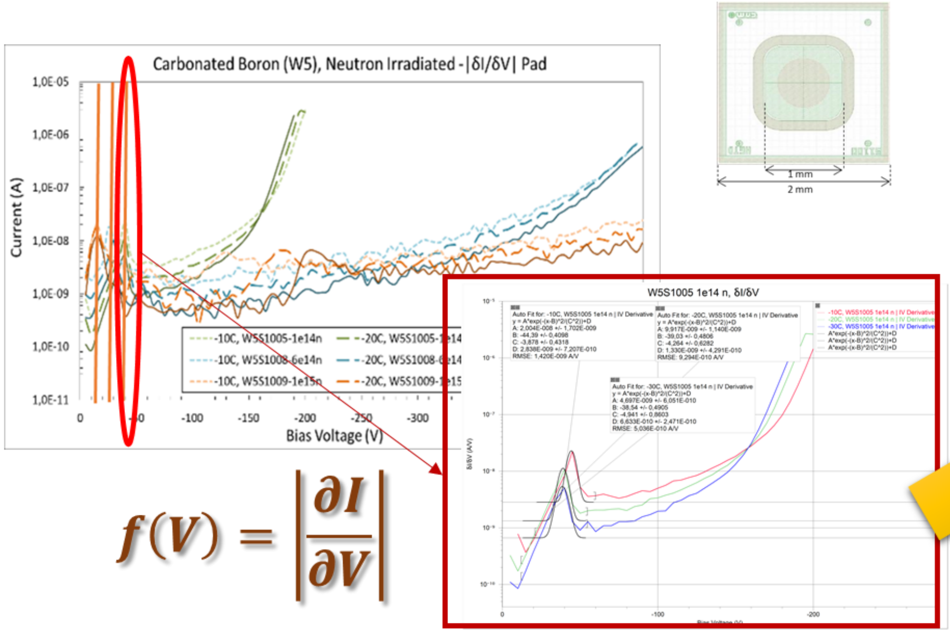
Implant radiation hardness studies

- ✓ 1x1 mm² CNM diodes, runs 10478 (W4 & W5) and 10924 (W6)
  - ✓ 50 µm on 250 µm 4” SoI wafers
  - ✓ **Boron**, **Boron + Carbon** diffused and **Gallium** implanted gain layer
- ✓ Irradiations:
  - ✓ 23 GeV PS protons
  - ✓ fast (~10MeV) neutrons at JSI
  - ✓ 5 fluences: 1e14, 6e14, 1e15, 3e15, 6e15 n_{eq}/cm^2
- ✓ Tested at -10C, -20C and -30C

30 sensors x 3 temp.
90 Series of measurements!!

- Depletion voltage by Gaussian fit on IV derivative
- Repeated for -10, -20 & -30°C
- Active dopant extrapolated

$$V_d = V_0 e^{-C_v \Phi}$$



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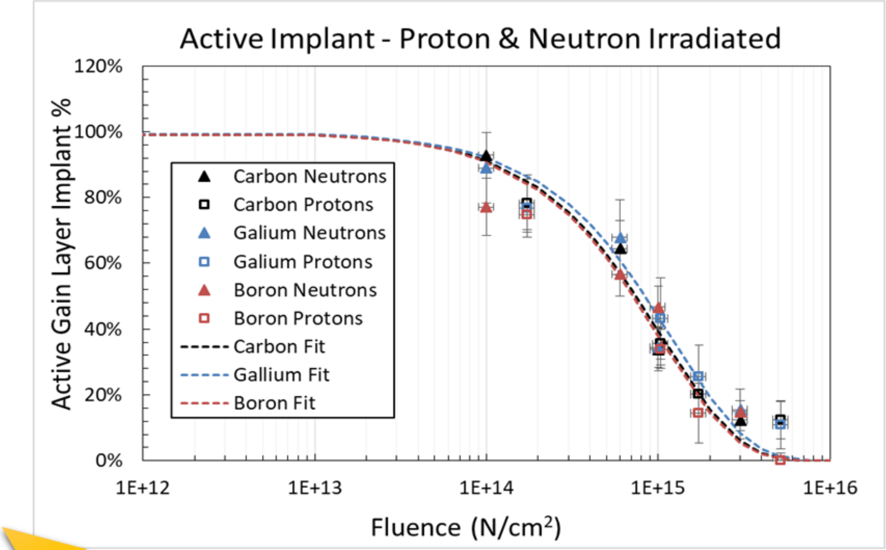
Auto Fit for: -10C, W5S1005 1e14 n | IV Derivative
y = A*exp(-(x-B)^2/(C^2))+D
A: 2,004E-008 +/- 1,702E-009
B: -44,39 +/- 0,4098
C: -3,878 +/- 0,4318
D: 2,838E-009 +/- 7,207E-010
RMSE: 1,420E-009 A/V

Auto Fit for: -20C, W5S1005 1e14 n | IV Derivative
y = A*exp(-(x-B)^2/(C^2))+D
A: 9,917E-009 +/- 1,140E-009
B: -39,03 +/- 0,4806
C: -4,264 +/- 0,6282
D: 1,330E-009 +/- 4,291E-010
RMSE: 9,294E-010 A/V

Auto Fit for: -30C, W5S1005 1e14 n | IV Derivative
y = A*exp(-(x-B)^2/(C^2))+D
A: 4,697E-009 +/- 6,051E-010
B: -38,54 +/- 0,4905
C: -4,941 +/- 0,8603
D: 6,633E-010 +/- 2,471E-010
RMSE: 5,036E-010 A/V
```

$$f(V) = \left|\frac{\partial I}{\partial V}\right|$$

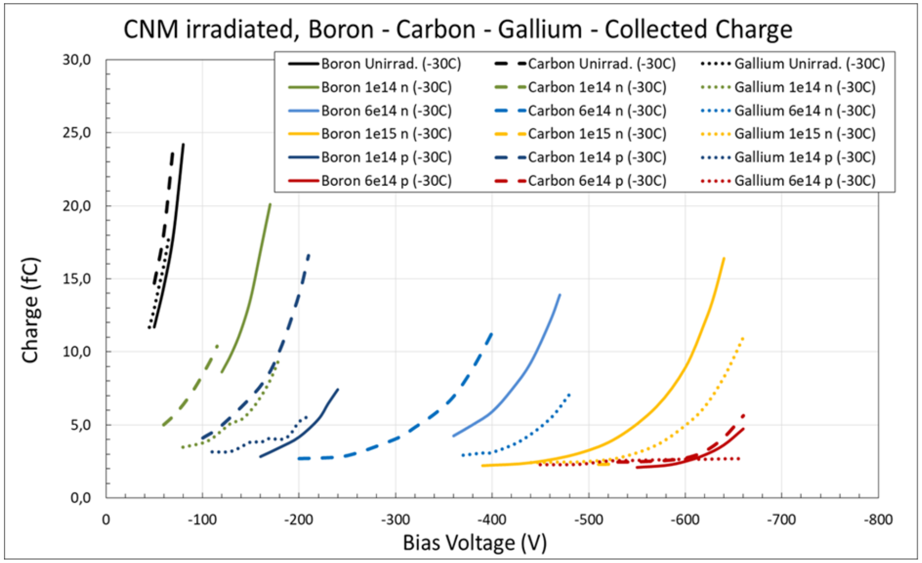


No active dopant difference between different implantation types – neutron/proton

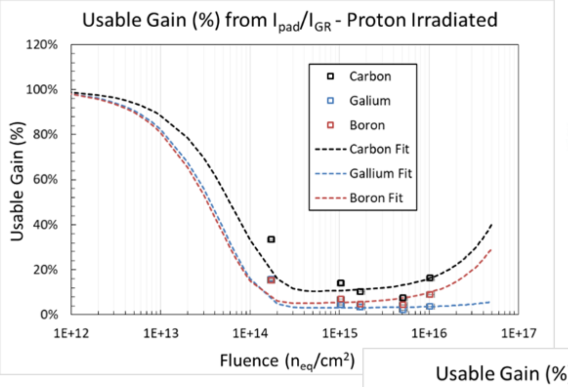
•Introduction

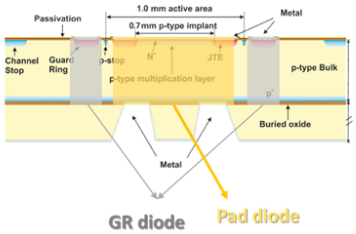
MIP measurements & Gain Extraction

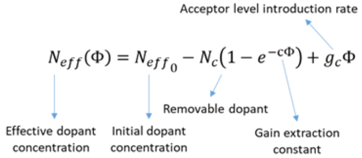
- ✓ Collected charge measured with MIPs
  - ✓ 5k events, beta measurements with Sr90
  - ✓ **Repeated in -10°C, -20°C -30°C with concurrent results**

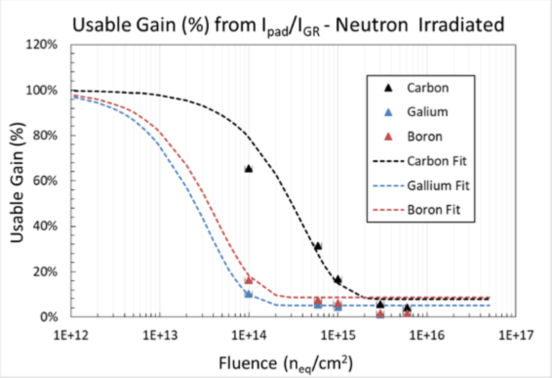

CNM irradiated, Boron - Carbon - Gallium - Collected Charge

- ✓ Usable gain estimated by comparing GR-pad leakage current
  - ✓ GR – gain region share shame cathode
  - ✓ Separate removal factors fot Protons/ neutrons
  - ✓ **Exponential behavior in depleted region**


Usable Gain (%) from I_{pad}/I_{GR} - Proton Irradiated




$$N_{eff}(\Phi) = N_{eff_0} - N_c\left(1 - e^{-c\Phi}\right) + g_c\Phi$$


Usable Gain (%) from I_{pad}/I_{GR} - Neutron Irradiated

Both methods agree: Gallium ~20% worse, carbon ~ 20% for sensors calibrated to performed equally

Acceptor removal in all three cases is the same (same fraction of active dopant from V_{GL}), trapping is not (different gain for same fluence, starting from the same point)

• Efficiency

Poisson Fitting

- ➢ Frequency of events of radioactive decay follows Poisson distribution
- ➢ Record trigger time and convert to event frequency
- ➢ Add normalization and scaling parameters

Poisson Distribution: $f(n) = \mu^{n} * \frac{e^{-\mu}}{n!}$

Where: **n** number of events in interval
μ *mean*
$f(n)$ *frequency*

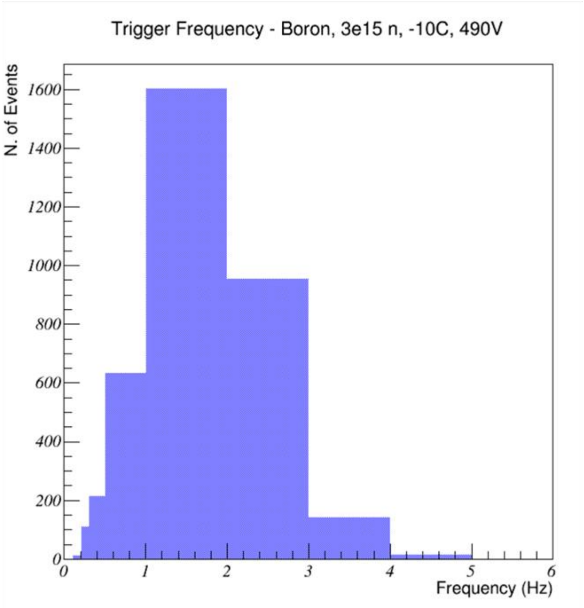
$n' = n * C$

Variable change

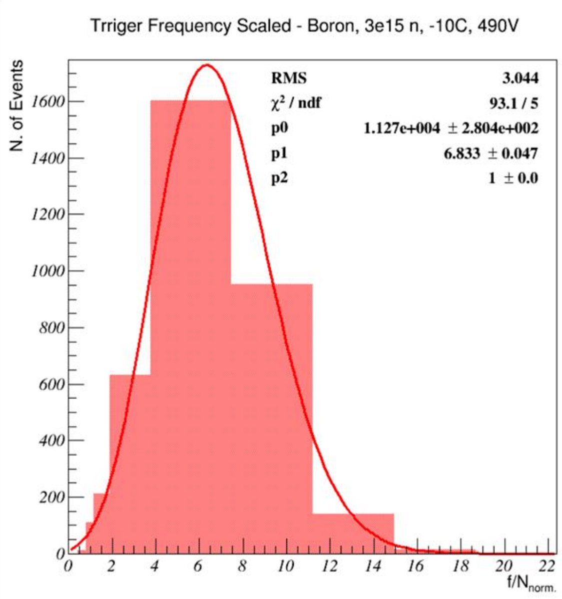
$\mu = B/C$

$$f(n') = A * \left(\frac{n'}{C}\right)^{B/C} * \frac{e^{-B/C}}{\Gamma\left(\frac{n'}{C}+1\right)}$$

Where: **A** Normalization parameter
B/C *mean*
$f(n')$ *Scaled frequency*



Trigger Frequency - Boron, 3e15 n, -10C, 490V



Trriger Frequency Scaled - Boron, 3e15 n, -10C, 490V

• Efficiency

Per event frequency calculation

- ➢ Correction applied for instrument accuracy

Trigger Frequency: $f_i^{trig} = 1/(t_{i+1}^{trig} - t_i^{trig})$

Low frequency correction: If $t_{i+1}^{trig} - t_i^{trig} = 0 \Longrightarrow f_{i+N}^{trig} = N/(t_{i+N}^{trig} - t_i^{trig})$ for least N on which $t_{i+N}^{trig} - t_i^{trig} > 0$

Iterative Re-fitting

- ➢ A number of fits is performed per distribution with different parameters
- ➢ Best fit result selected by maximizing N_{DF}/x^2 parameter

✓ Iterative refitting:

Bin size: $(\mathbf{n+1}) \bullet \mathbf{0.2} \;\bullet \mathbf{1} / \mathbf{T}_{\mathbf{acc.}}$
Iterations: $\mathbf{0 < n < 20}$
Acceptance : **satisfy constraints**

bin size from 0,2
to 4 times trigger
time accuracy

✓ Asymmetric fit limits:

lower: $\mathbf{x}_{\mathbf{min}} = \mathbf{0}$
upper: $\mathbf{x}_{\mathbf{max}} = \mathbf{f}_{\mathbf{max}}/\mathbf{A}_{\mathbf{norm}}$

✓ Final constraints:

$\mathbf{B/C > 0}$
$\mathbf{f}_{\mathbf{min}} < \mathbf{B/C} < \mathbf{f}_{\mathbf{max}}$
Valid Minuit uncertainties

11 out of 936
measurement series
~ 99% success

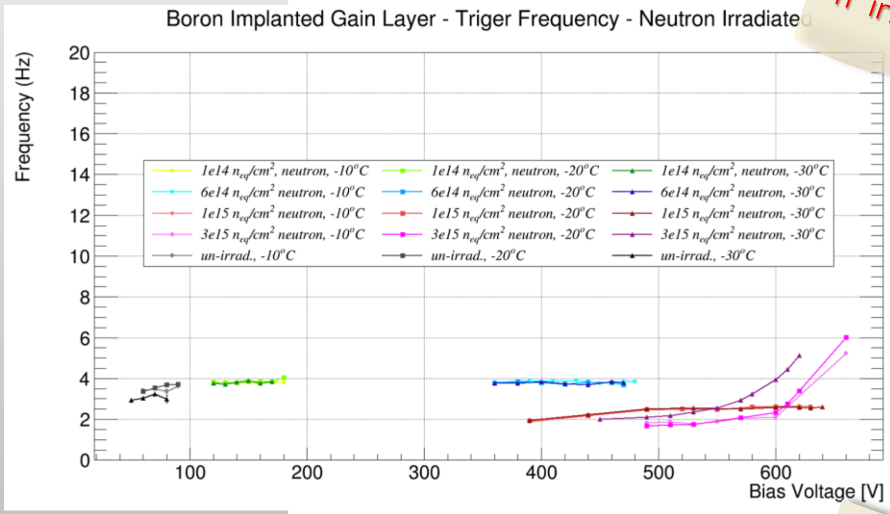
Fitting Failure rate

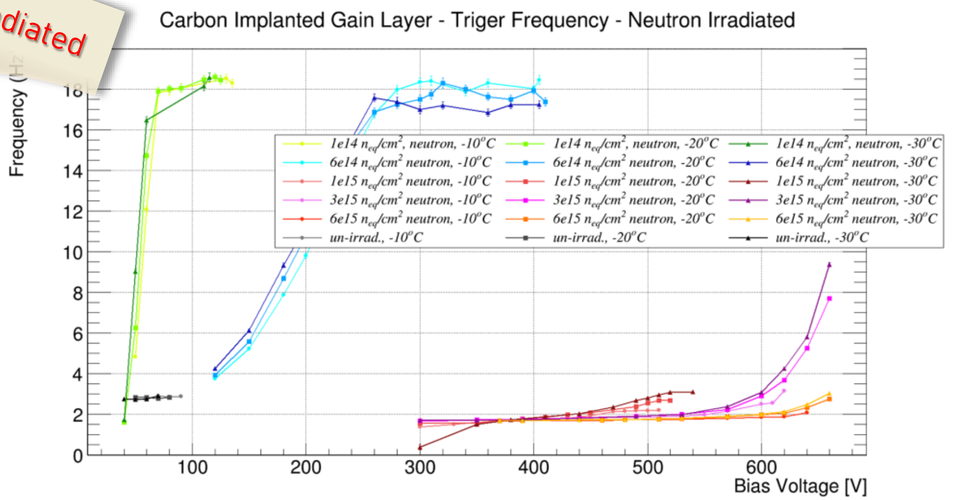
219 Boron, 1e15 p, -20C, 340
220 Boron, 1e15 p, -20C, 380
309 Carbon, 1e14 n, -10C, 120
327 Carbon, 1e14 n, -30C, 100
333 Carbon, 1e14 n, -30C, 70
335 Carbon, 1e14 n, -30C, 90
379 Carbon, 6e14 n, -30C, 400
645 Gallium, 1e14 n, -20C, 180
650 Gallium, 1e14 n, -30C, 110
654 Gallium, 1e14 n, -30C, 150
659 Gallium, 1e14 n, -30C, 80

• Efficiency

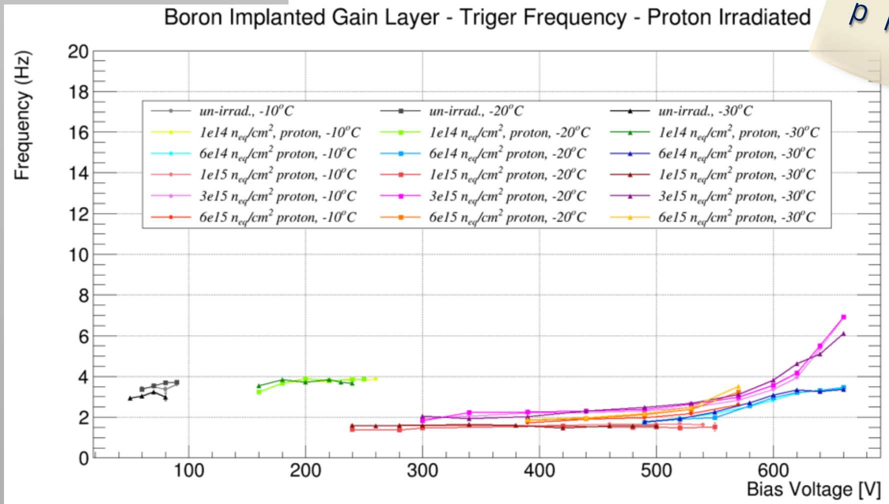
Event frequency estimation – Boron, Carbon

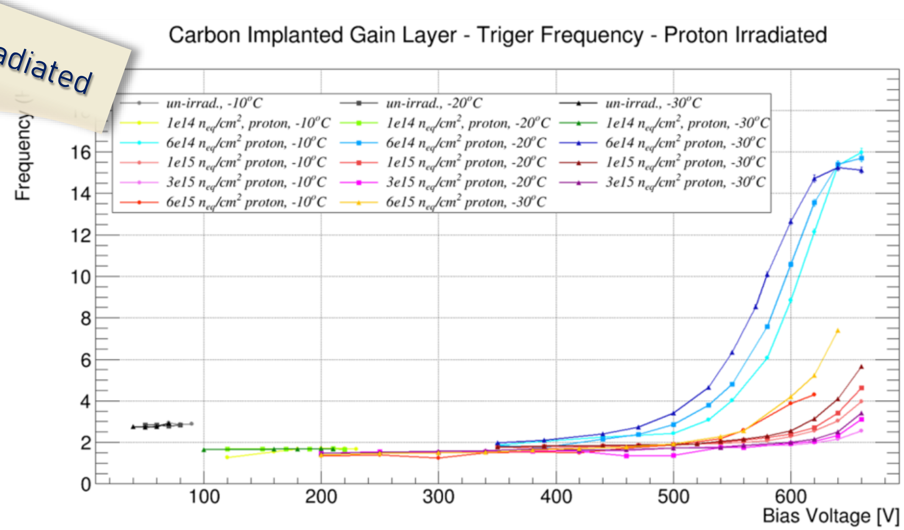
n irradiated





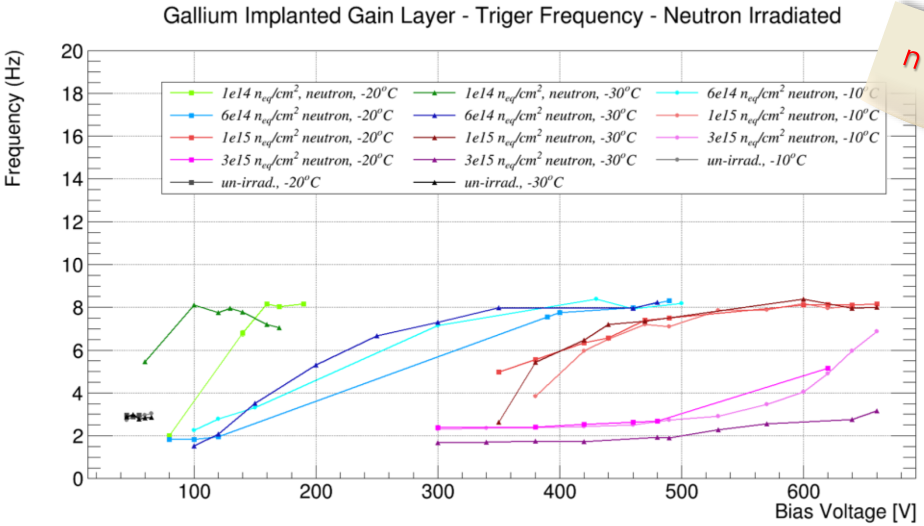
p irradiated



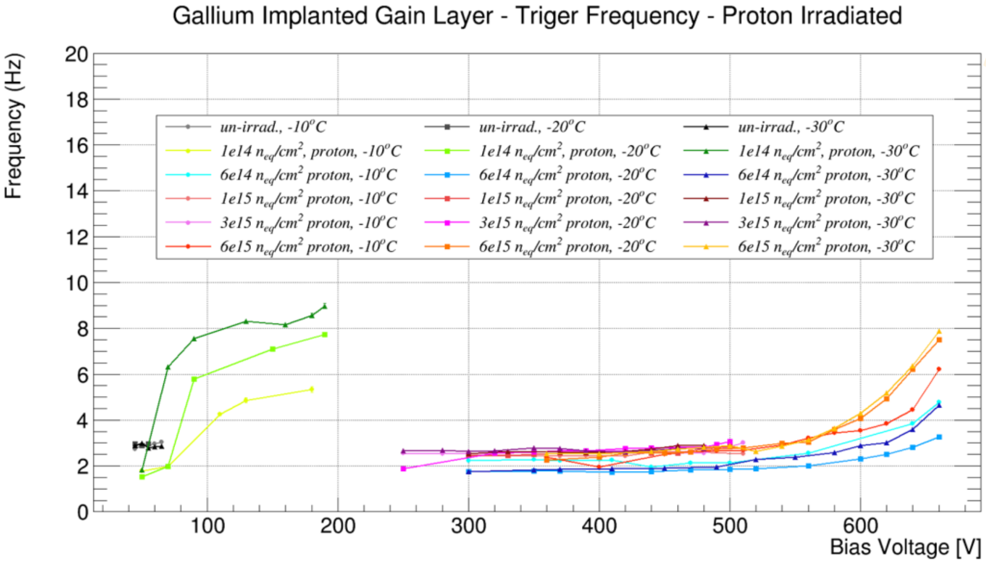


• Efficiency

Event frequency estimation - Gallium



n irradiated



p irradiated

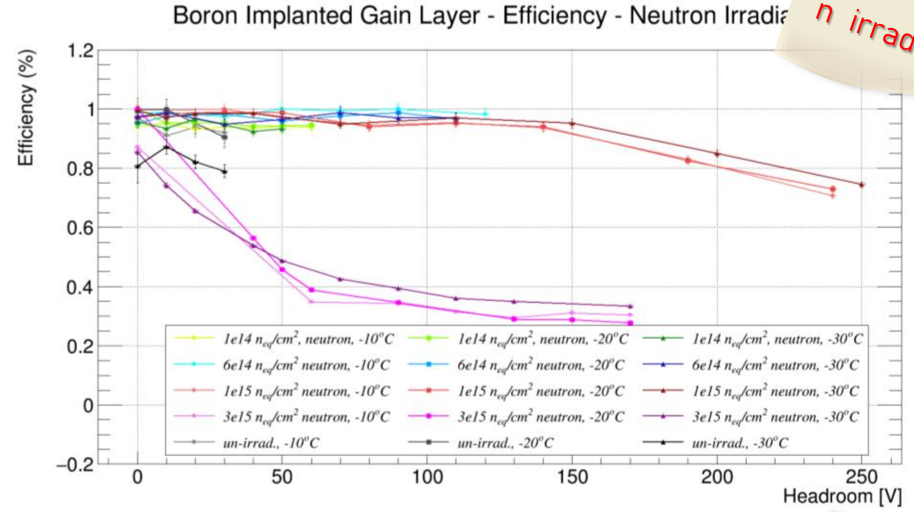
• Efficiency

Efficiency vs Headroom

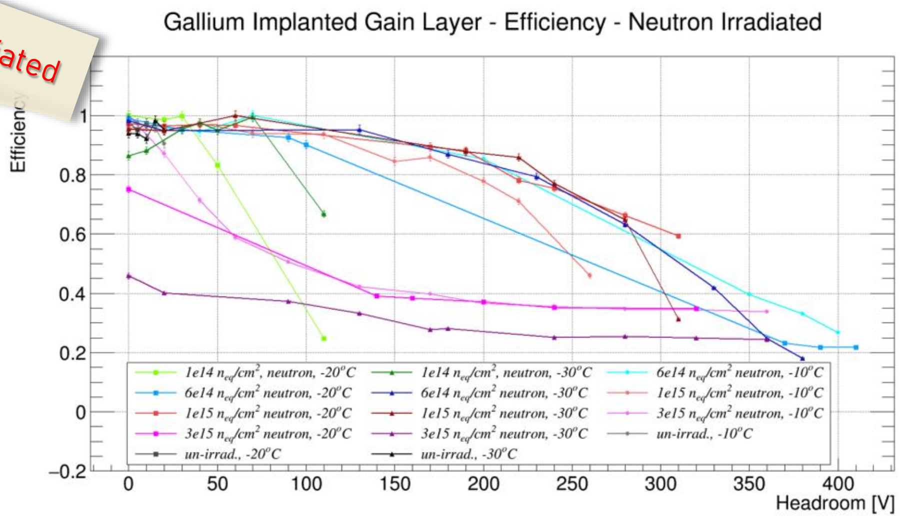
- Set maximum voltage point per temperature as 0
- Assume identical alignment between different temperature measurement series
- Define as 100% efficiency the highest measured trigger frequency using all temperature series
- Recalculate efficiency at each point with respect to max.
- Repeat for each sensor (x30)
- Plot distance from Breakdown (Headroom) vs Relative efficiency
- Since this is relative to the highest, only stability at the bigining of the curve indicates 100% efficiency
- Sensors not reaching a plateau do not achieve 100% operational efficiency
- More evident at SNR vs efficiency and Collected Charge vs Efficiency plots

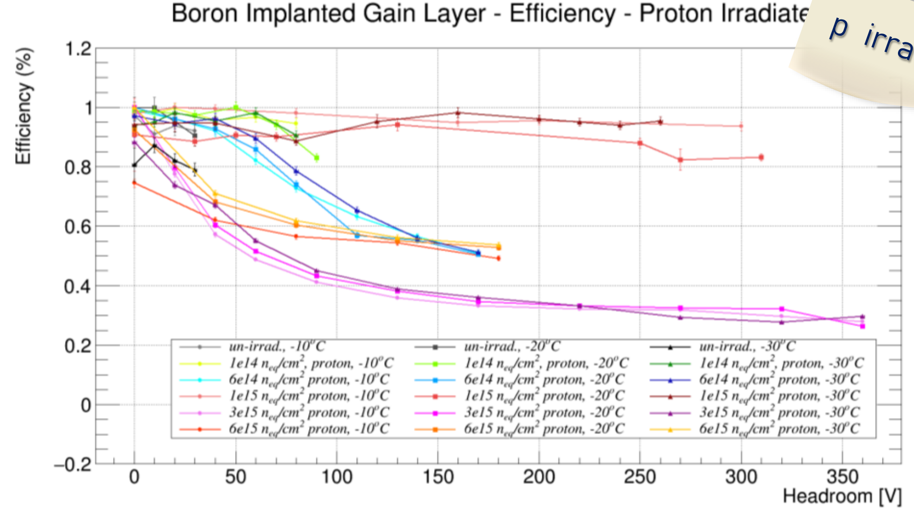
• Efficiency

Efficiency vs Headroom – Boron, Gallium

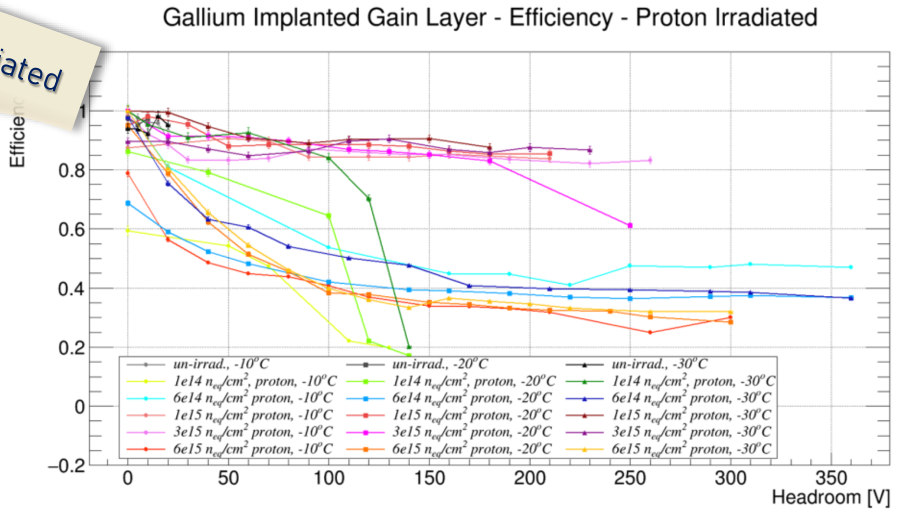

Boron Implanted Gain Layer - Efficiency - Neutron Irradia

n irradiated


Gallium Implanted Gain Layer - Efficiency - Neutron Irradiated

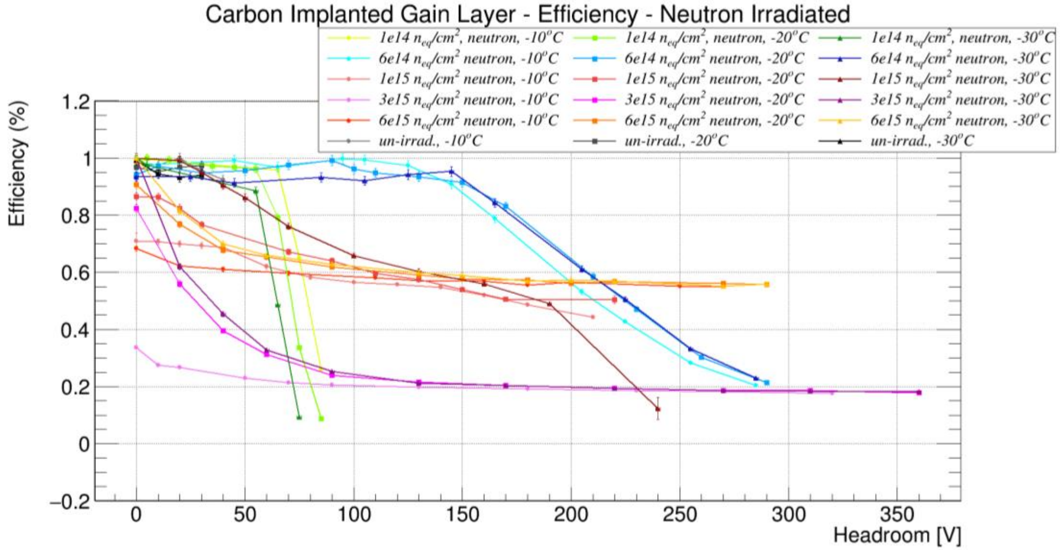

Boron Implanted Gain Layer - Efficiency - Proton Irradiate

p irradiated

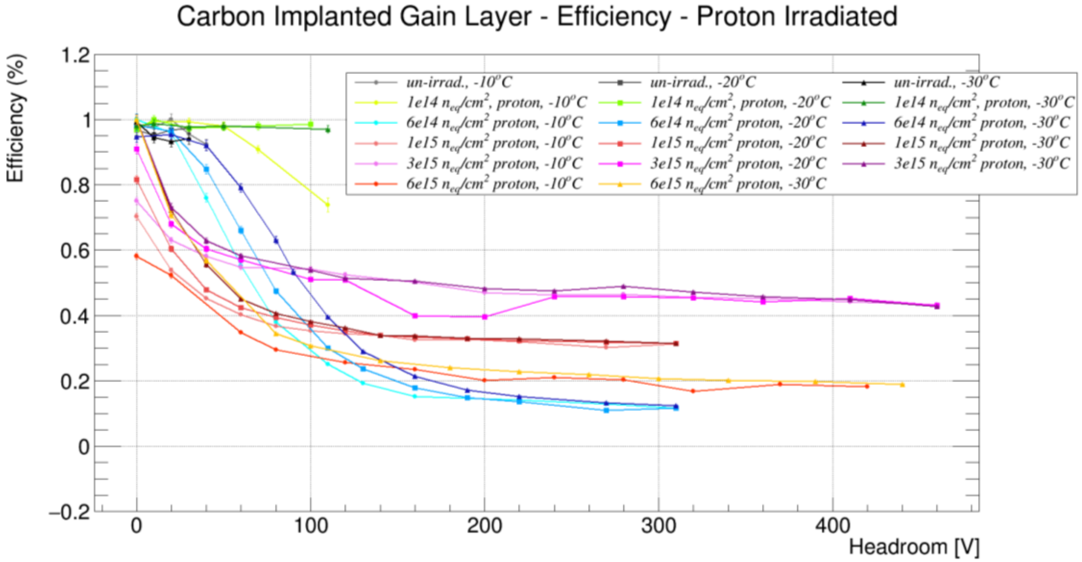

Gallium Implanted Gain Layer - Efficiency - Proton Irradiated

- **Efficiency**

Efficiency vs Headroom – Carbon



n irradiated



p irradiated

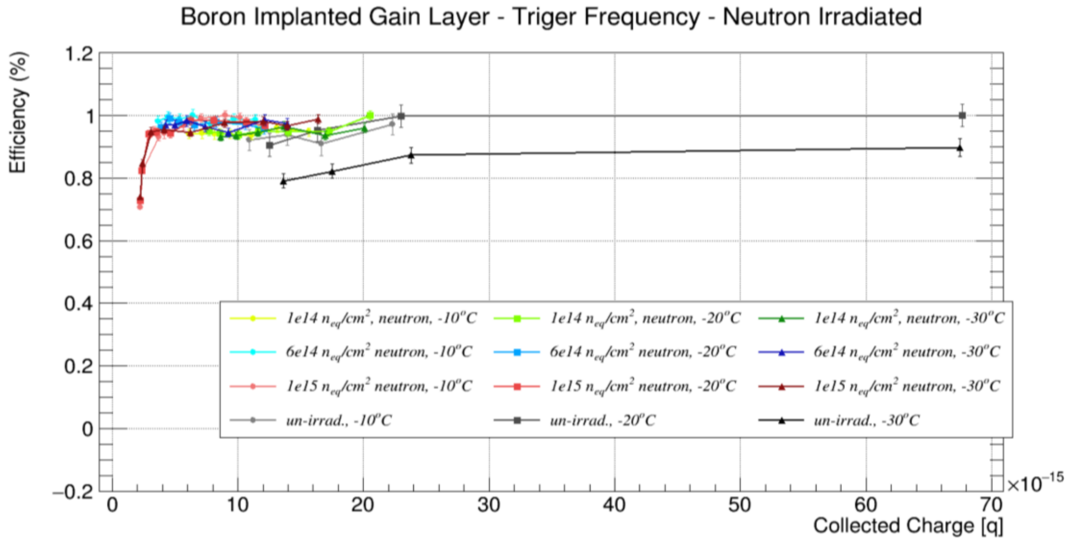
• Efficiency

Head room & efficiency conclusions

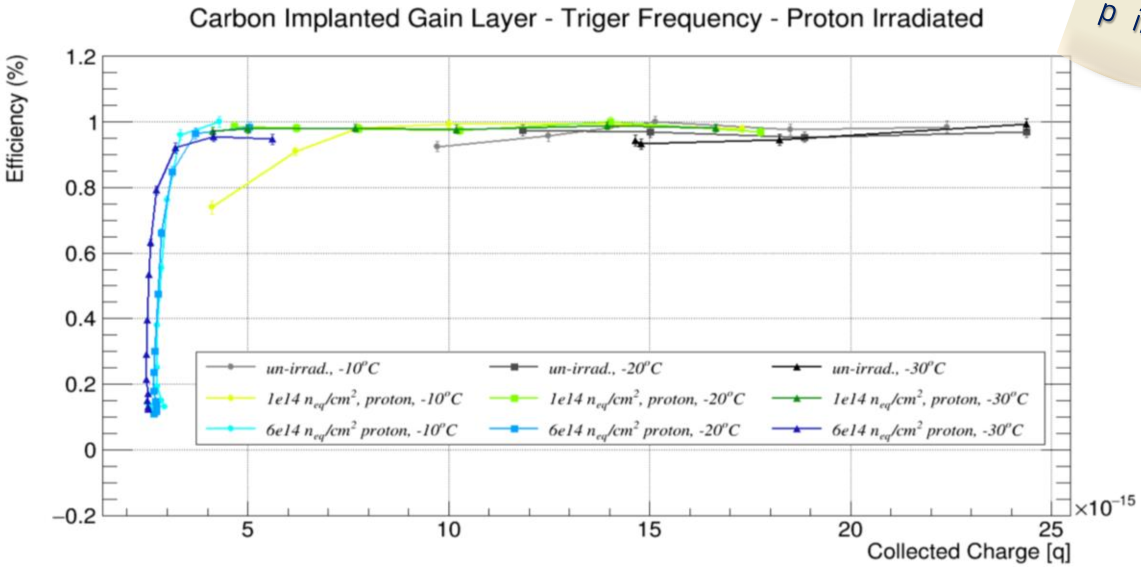
- ➢ We can achieve ~100% efficiency for Carbon + Boron and Boron only for up to 1e15 at neutron irradiation
- ➢ For proton irradiation we achieve 100% efficiency at 1e15 only for boron only sensors
- ➢ It seems that boron only at 3e15 neutron is close to a 100%, more study is needed
- ➢ Boron only sensors provide larger headroom at 100% efficiency that boron + carbon combination
- ➢ Proton irradiation is more damaging than neutrons if correct scaling factors are applied, reality is somewhere in the middle
- ➢ In best case scenario (boron at 3e15 neutrons) no safety factor is present

• Efficiency

Efficiency vs Charge – Boron



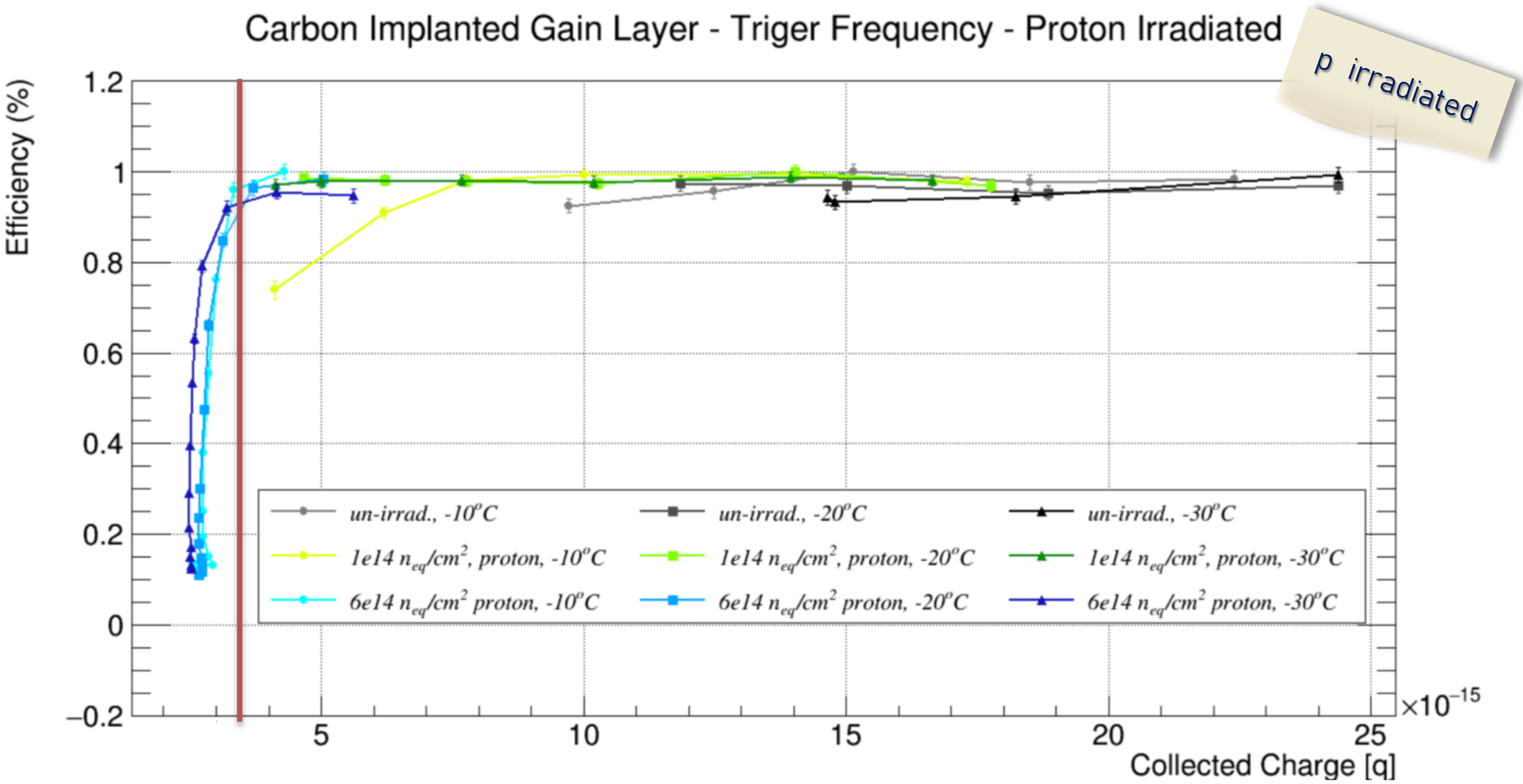
n irradiated



p irradiated

• Efficiency

Efficiency vs Charge – Carbon

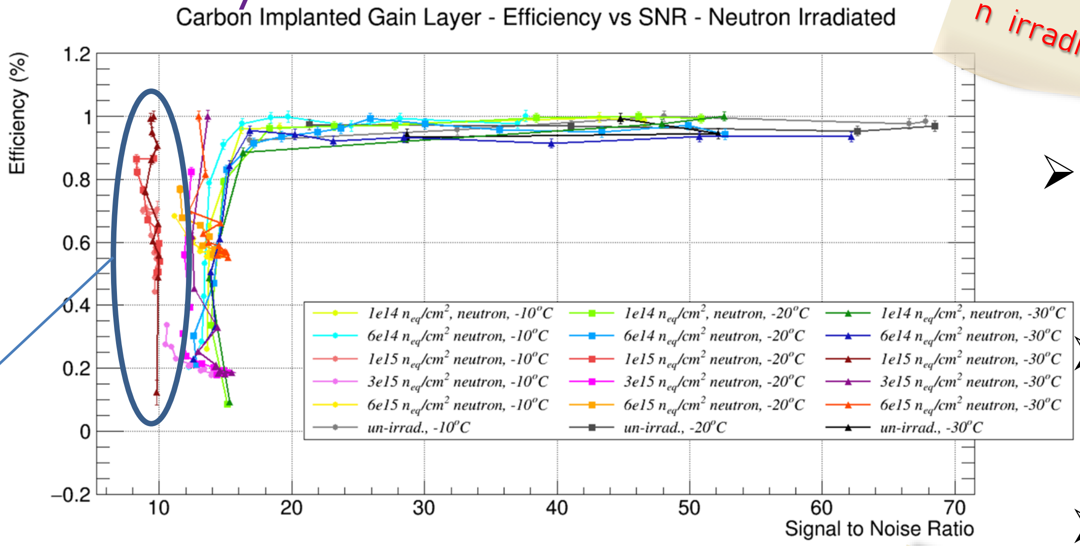


p irradiated

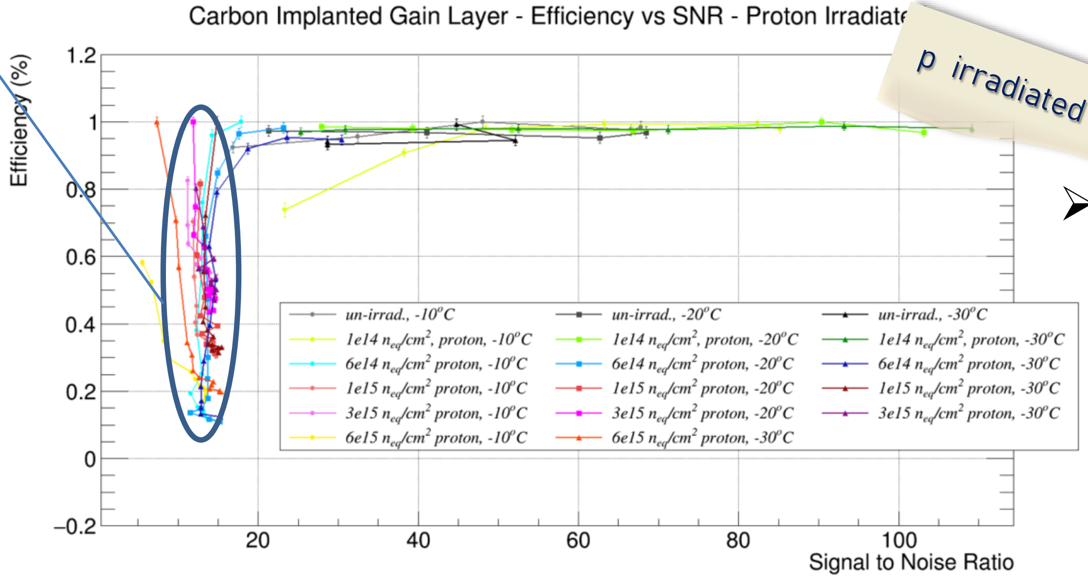
- ➢ Regardless of radiation, temperature or implant, fir Q > 3.5 fQ sensors are 100 efficient
- ➢ Similar behavior on neutron and proton irradiated sensors
- ➢ On a fixed threshold trigger 3.5 fQ → 20mV with an amplification of 100

• Efficiency

Efficiency vs SNR – Boron


Carbon Implanted Gain Layer - Efficiency vs SNR - Neutron Irradiated

n irradiated


Carbon Implanted Gain Layer - Efficiency vs SNR - Proton Irradiate

p irradiated

They never get 100% efficient

- ➢ SNR > 18 is 100 % efficient
- ➢ This is a result but not a guarantee!!
- ➢ One way relationship SNR > 18 → 100 eff,
- ➢ 100 % efficiency does not guarantee SNR

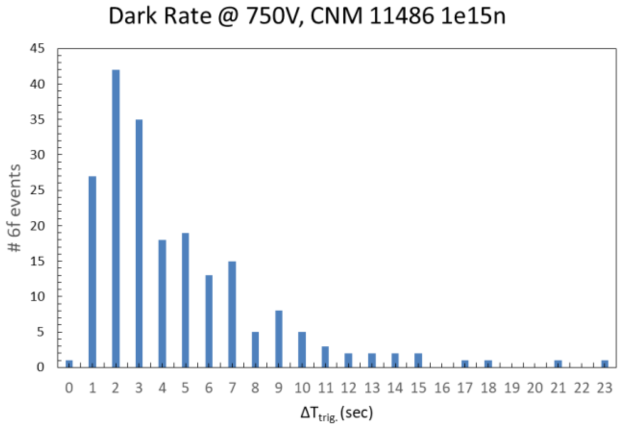
•Conclusions on Efficiency

Charge and SMR

- Independently of implant, irradiation type and temperature all sensors seem to follow the same trend
- More fitting necessary to distinguish possible minute differences (at the level of statistical uncertainties)
- Once an SNR of ~18 is reached, a 100% efficiency is expected
- At a charge of ~4fq also a 100% efficiency is to be expected
- Because of the direct relation between SNR and collected charge, assuming a noise of 0.2fq, a100% efficiency should be reached at 3,6 fq

•Stability

Concept and measurement



- ✓ Sensors with gain present dark rate at high bias voltage values
- ✓ Dark rate events are result of thermal Brownian electron movement
- ✓ At high fields, these events can get amplified and induce pulses
- ✓ Effect follows the Poisson distribution

Dark Rate Estimation Method

- ✓ **For each bias point:**
  - ✓ Set a fixed threshold unilateral trigger
  - ✓ Remove any external stimulai
  - ✓ Record 4 consecutive events
  - ✓ For each event calculate trigger time distance frim first event
  - ✓ Recorde mean of 3Δt values to reject background (cosmics, noise)
  - ✓ Reject values < 0.01 Hz
  - ✓ Calculate the median and the uncertainty of all (500) accepted values
- ✓ **Repeat process for all voltage points until breakdown**
- ✓ **Repeated the process for different temperatures**
- ✓ **Scan constant threshold trigger if required**

X 500

•Sensor Stability

Concept and measurement

Self-trigger time:

Self-trigger Rate:

$$\left.\boxed{\begin{aligned}\Delta \mathrm{T}^{i}_{trig} &= \frac{\sum_{j=1}^{n-1}\left(T^{trig}_{j+1} - T^{trig}_{j}\right)}{n}\\ \mathrm{R}^{i}_{trig} &= \frac{1}{\Delta \mathrm{T}^{i}_{trigg}}\end{aligned}}\right\}$$

X 500

Median of several rate measurements

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

Uncertainty on trigger rate:

$$\delta\widetilde{R_{trig}}(\%) = \sqrt{\frac{(\mathrm{N}_{over}+1)\times(\mathrm{N}_{over}+2)}{(\mathrm{N}+2)\times(\mathrm{N}+3)} - \frac{(\mathrm{N}_{over}+1)^2}{(\mathrm{N}+2)^2}}$$

Efficiency is a binary magnitude, Bayesian approach implemented

Sigmoid Dark rate Fit:

$$R_{Dark\ Rate} = \frac{R_{max}}{1 + e^{C\times(V_{50\%} - V)}} + R_{BaseLine}$$

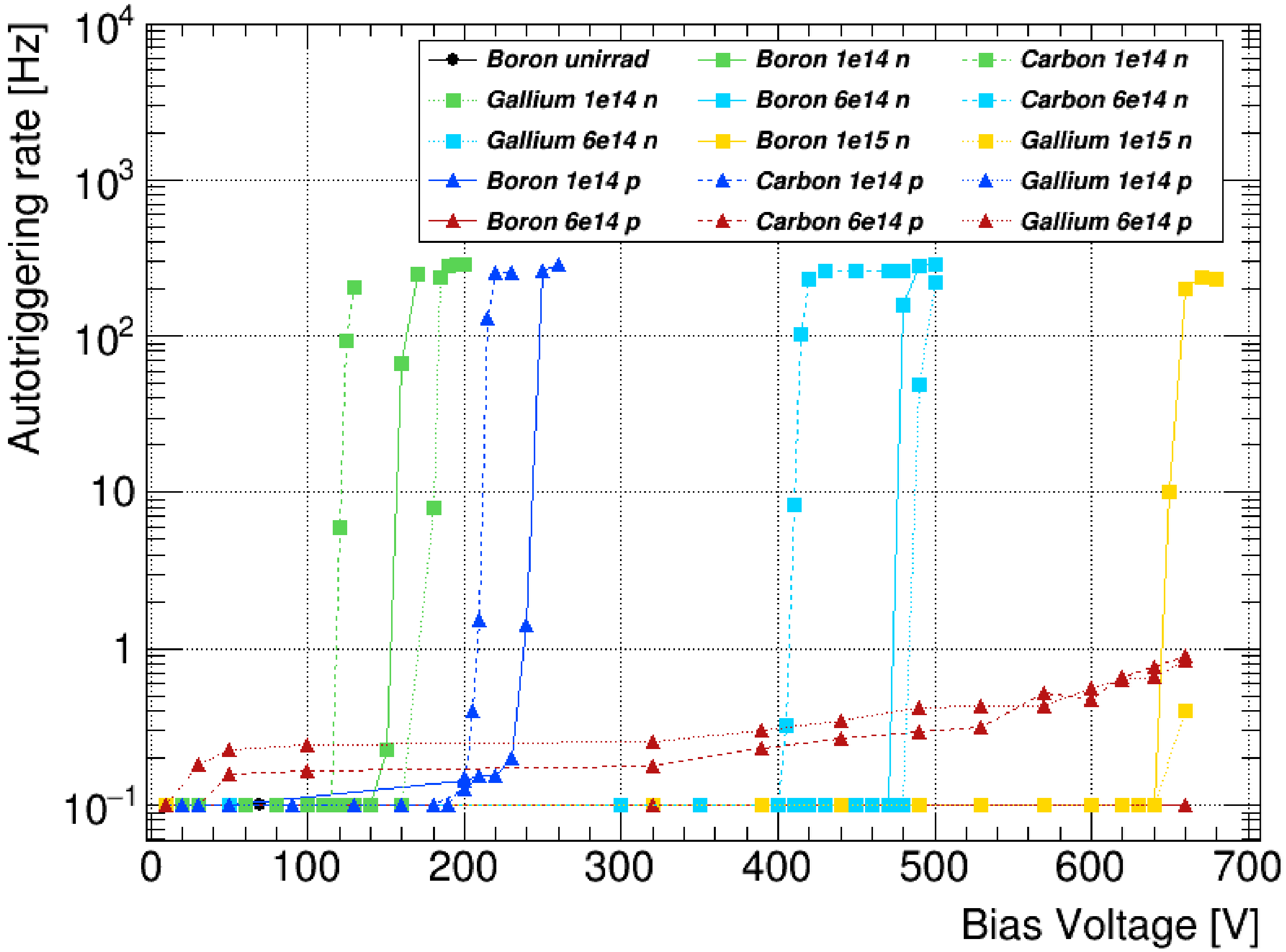
Max, recordable rate
Inst. saturation point

50% of maximum
voltage point

Baseline trigger rate
(noise, radioactivity)

•Sensor Stability

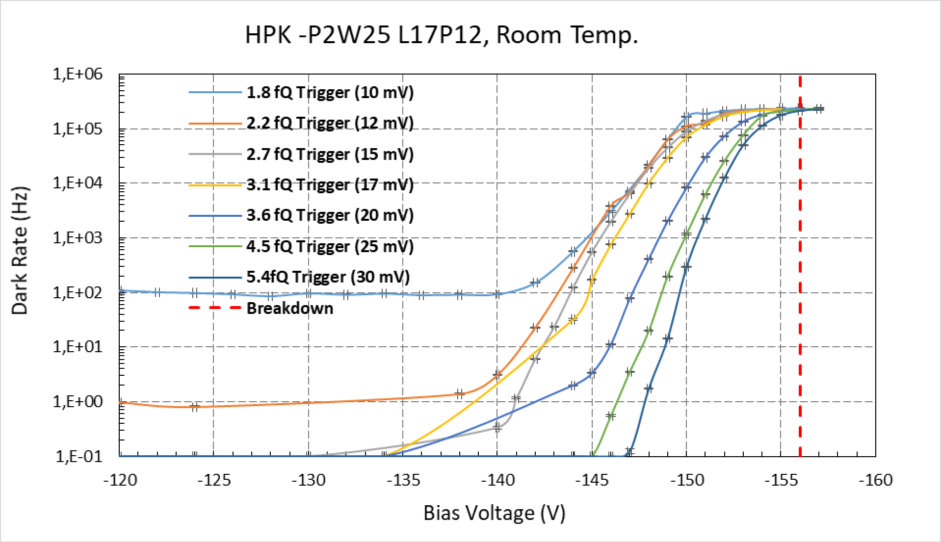
Boron, Gallium, Carbon @ - 30°C



- ✓ Carbon presents the most unstable implementation with respect to dark rate
- ✓ Boron is the better solution across the board with higher stability points

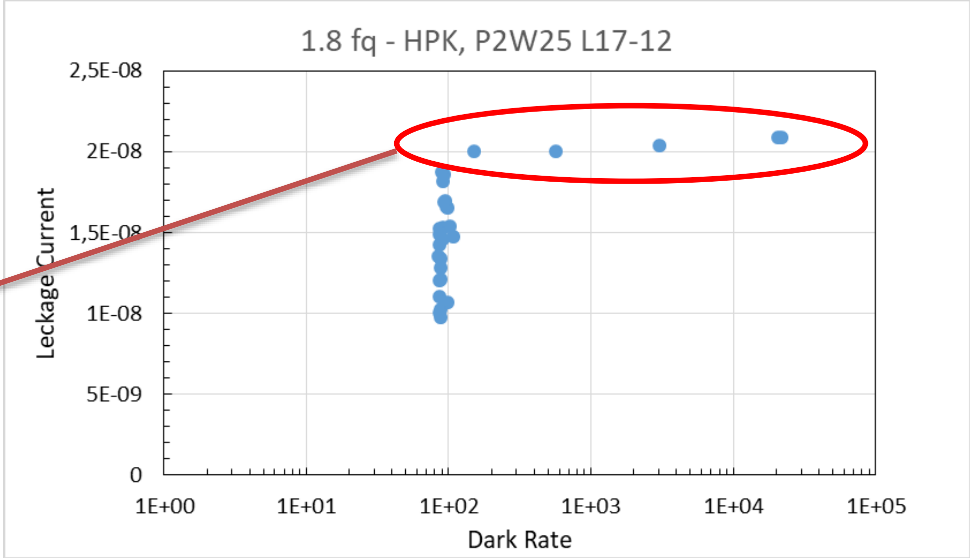
•Sensor Stability

HPK P2 @ Room Temp



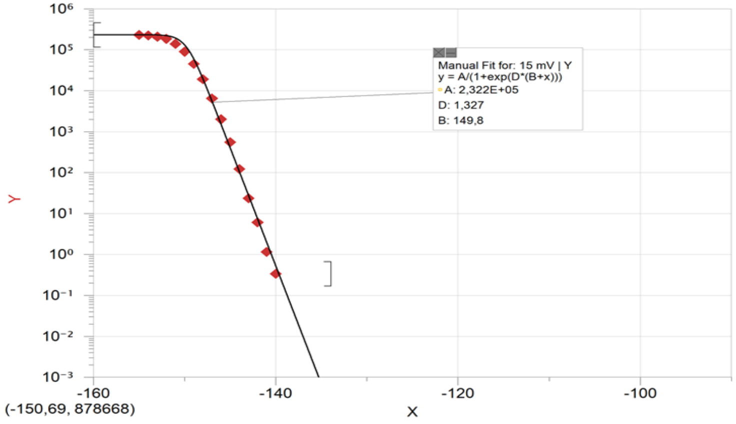
- ✓ Uneradicated HPK P2
- ✓ Breakdown ~ 156V
- ✓ Measured at room temp
- ✓ Different Constant threshold triggers (1.8 – 5.4 fQ) applied
- ✓ Uncertainties using Bayesian approximation
- ✓ Max saturation rate 230 kHz

- ✓ Sensor far from breakdown
- ✓ Leakage current not demonstrate significant variation
- ✓ Stationary lockage current at exponential rate increase

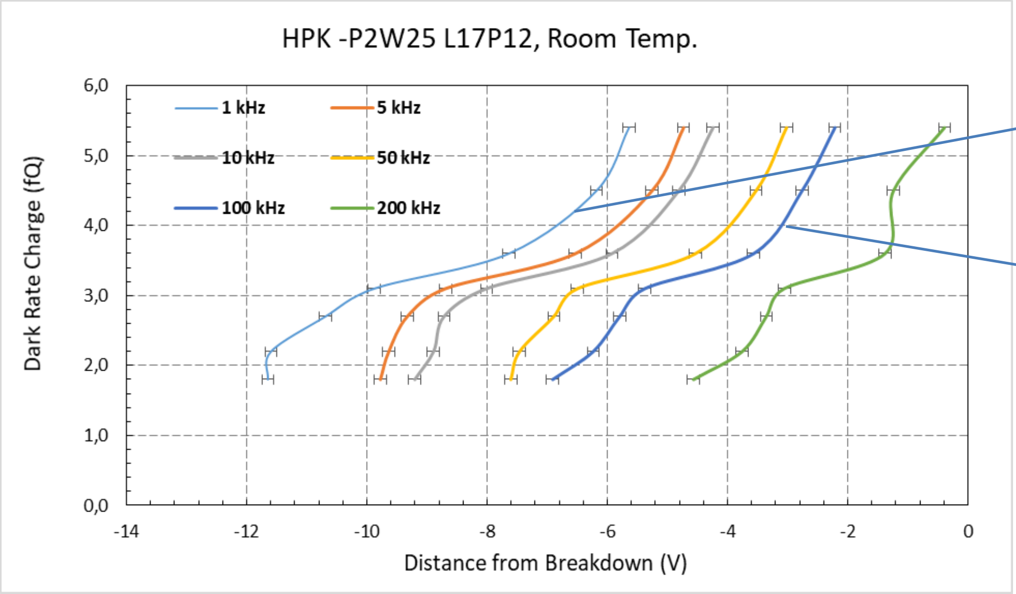


•Sensor Stability

HPK P2 @ Room Temp



- ✓ Analytical expressions derived from sigmoid fits in each threshold
- ✓ Estimate expected voltage point for a given dark rat
- ✓ Calculate distance from breakdown voltage per given rate and threshold trigger



- ✓ Depending on dark rate requirements, operation has to stay on the left of the curve
- ✓ For a 4 fQ sensitive ASIC, maxim operating voltage is 3.5V less than breakdown fir a 05 % dark rate (assuming full 20 MHz)
- ✓ Dark rate not synchronous

•Conclusions

Stability and Dark rate

- ✓ Dark rate is an intrinsic characteristic of all gain sensors
- ✓ The effect present itself close to breakdown but clearly before
- ✓ It is common on all producers, productions and implants
- ✓ Carbon is more unstable with respect to Boron
- ✓ Moderate dark rate might be accepted with respect to application
- ✓ On a 4 fq sensitive ASIC one can operate no closer to 4 V below the breakdown to maintain 1% occupancy at 20 MHz
- ✓ Qualification has to be carried out in every producer
- ✓ Strongly depends on gain layer gradiant