16th Workshop on
Advanced Silicon Radiation Detectors
Trento, 16-18 February 2021

Optimization of gain layer doping/profile and carbon levels on HPK and FBK sensors

16° Trento Workshop (2021, Virtual)

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on behalf of the SCIPP UCSC group

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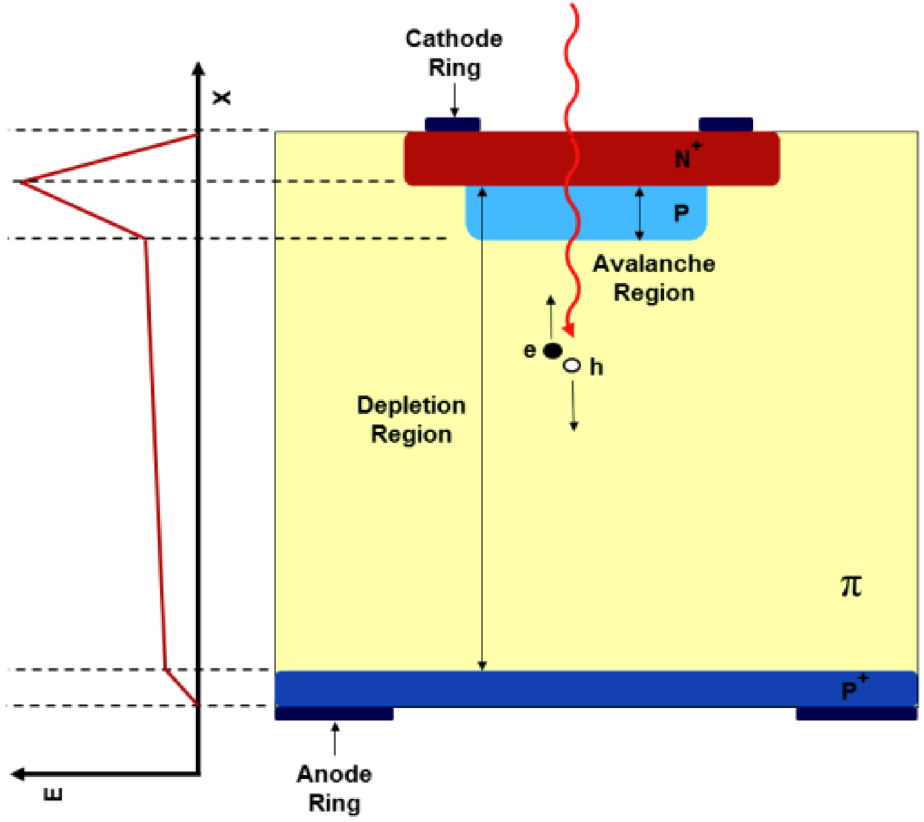
ATLAS
EXPERIMENT

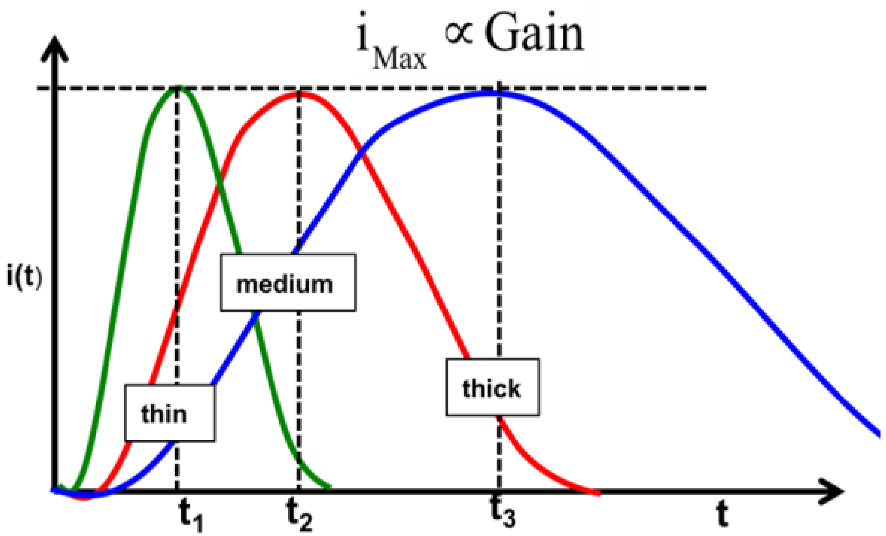
LGADs

- **LGAD: silicon detector with** a thin (<5µm) and **highly doped** (~10^{16} P++) **multiplication** (gain) **layer**
  - High electric field in the multiplication layer
- LGADs have intrinsic modest internal gain (10-50)
  - $G = \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Better signal to noise ratio, sharp rise edge
- Allows thin detectors (50 µm, 35 µm, 20 µm)
  - Thinner detectors have shorter rise time and less Landau fluctuations
- **Time resolution < 30 ps**

$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

- Several vendors of thin LGADs under study
  - HPK (Japan), FBK (Italy), CNM (Spain), BNL (USA), NDL (China)



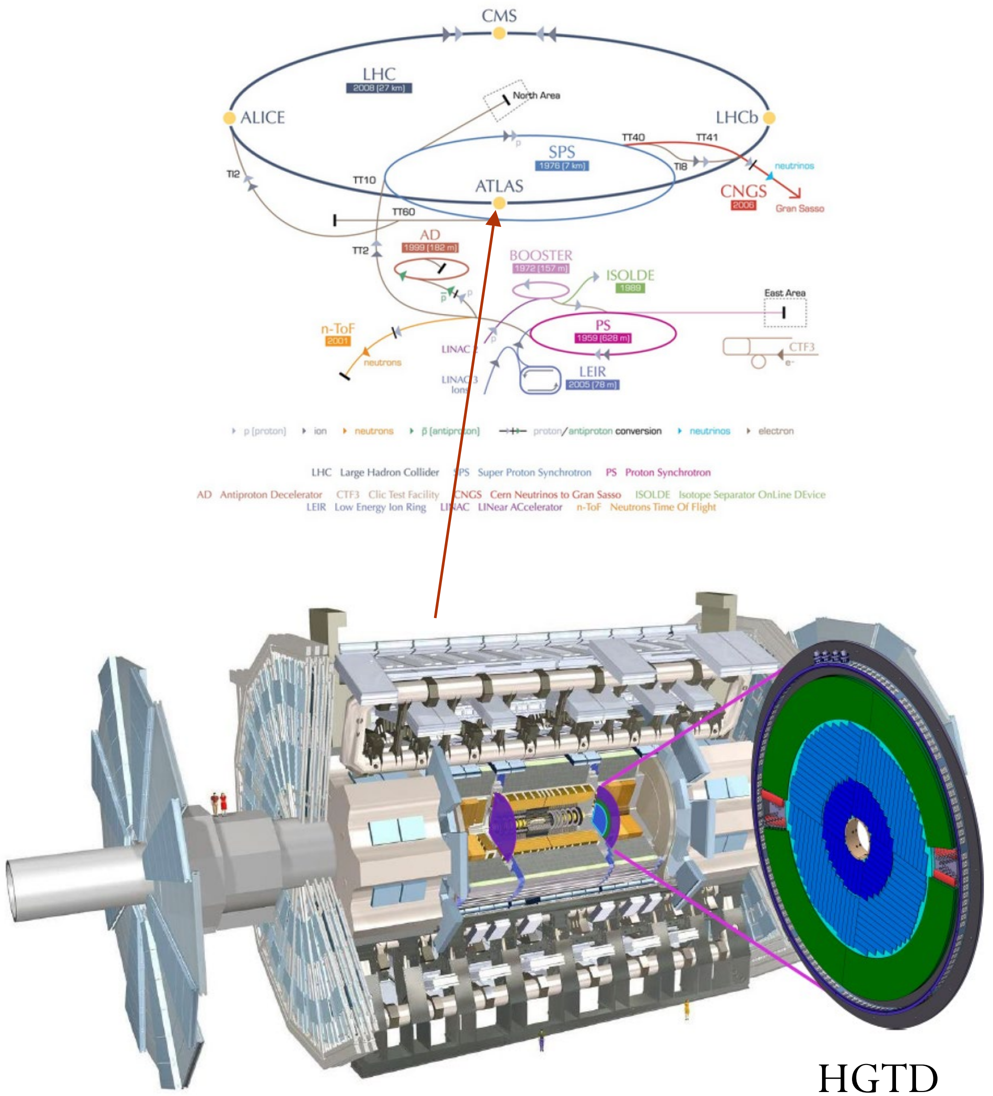


HGTD, ATLAS and LHC high luminosity

- **LHC:** 14 TeV proton-proton collider at CERN (Geneva)
- **ATLAS:** one of the four main experiments at the LHC
  - General purpose detector for discovery of new physics and precise measurements
- LHC will be upgraded in 2026 to High Luminosity LHC (HL-LHC)
  - Instantaneous luminosity higher than present conditions

- ATLAS detector will be upgraded for HL-LHC
- **HGTD: High Granularity Timing Detector**
  - 2 disk of LGAD detectors in the forward region
  - Provide timing measurements of tracks
  - **4fC of collected charge (Gain ~8)**
  - **35 to 70 ps of time resolution on hits (less on tracks)**
  - **Radiation hardness up to 2.5 · 10^{15}**Neq
  - https://cds.cern.ch/record/2719855
- CMS will also be upgraded with an end-cap timing layer (ETL)
  - http://cds.cern.ch/record/2667167

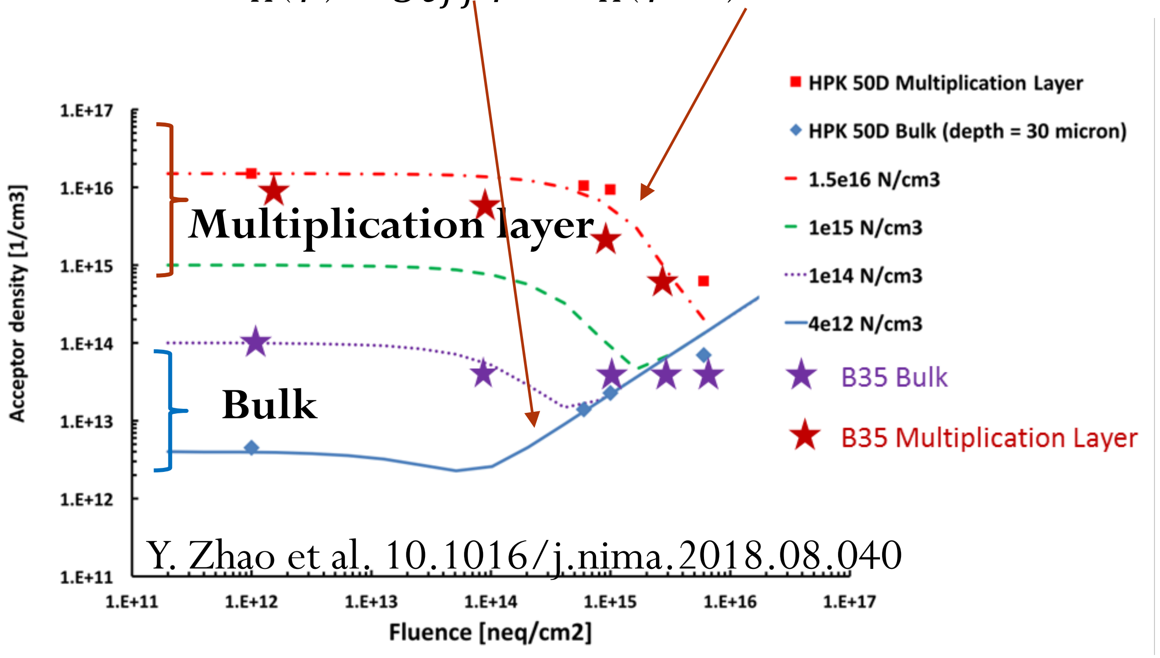
- **HGTD and ETL are the first application of LGADs in HEP**



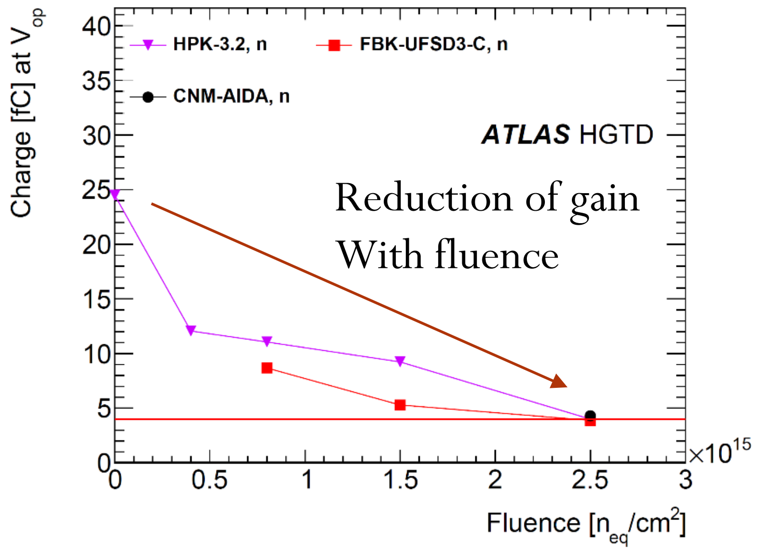
Radiation damage on LGADs

- Most widely accepted radiation damage explanation for LGADs is **acceptor removal**
  - M. Ferrero et al. arXiv:1802.01745, G. Kramberger et al. JINST **10** (2015) P07006
- Radiation damage for LGADs can be parameterized
  - $N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$
- Acceptor creation: $g_{eff}\phi$
  - By creation of deep traps
- Initial acceptor removal mechanism: $N_A(\phi{=}0)e^{-c\phi}$
  - Ionizing radiation produces interstitial Si atoms
  - Interstitials inactivate the doping elements (Boron) via kick-out reactions that produce ion-acceptor complexes
  - **Reduction of doping → reduction of gain**
- **C-factor (acceptor removal constant) depending on detector type**

$N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$



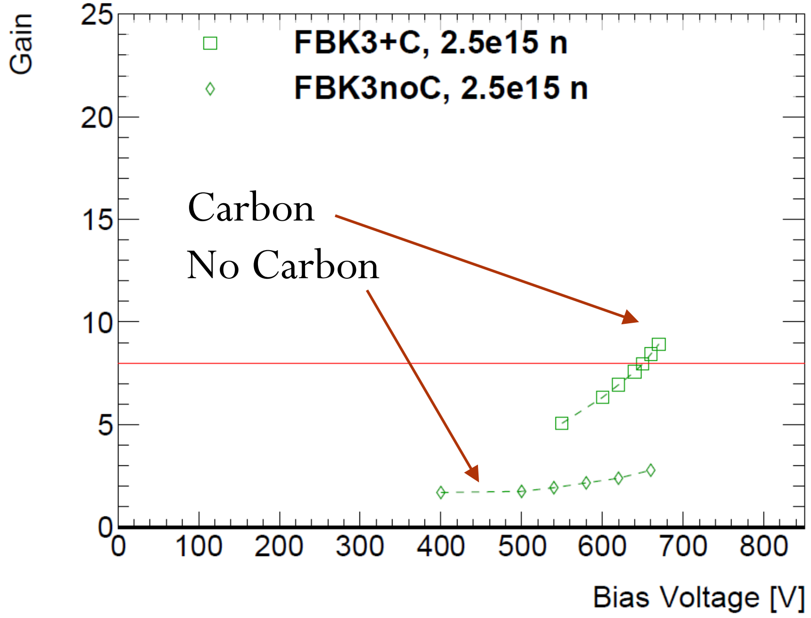
Y. Zhao et al. 10.1016/j.nima.2018.08.040

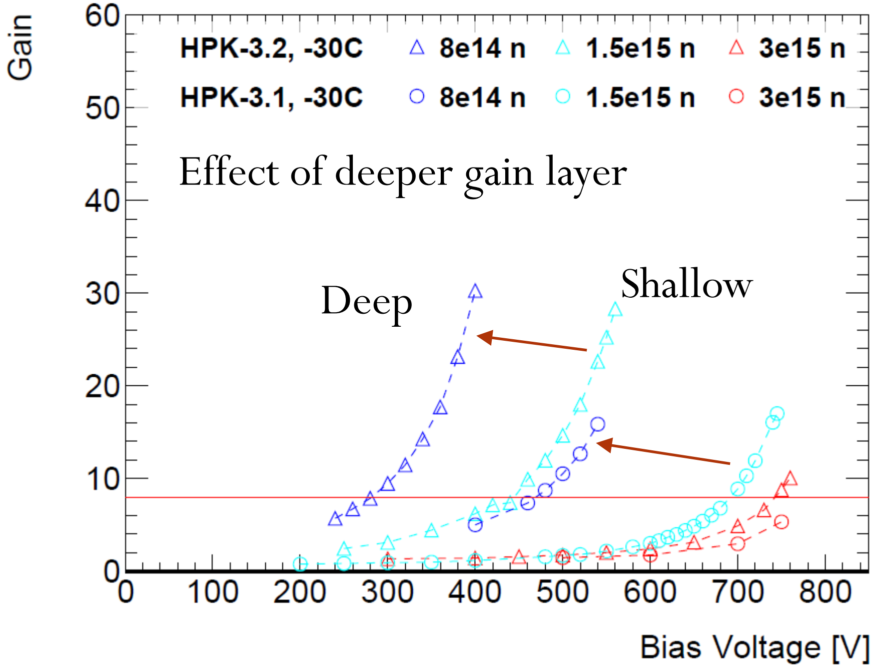


http://cds.cern.ch/record/2719855/

Mitigation of radiation damage: past productions

- **FBK-UFSD3** (Fondazione Bruno Kessler) sensors
- 55 um thin bulk sensors (nominal thickness)
- Carbon implantation in the gain layer
  - Carbon is electrically inactive (no effect pre-irradiation)
  - Catch interstitials instead of Boron
- Reduction of acceptor removal after irradiation



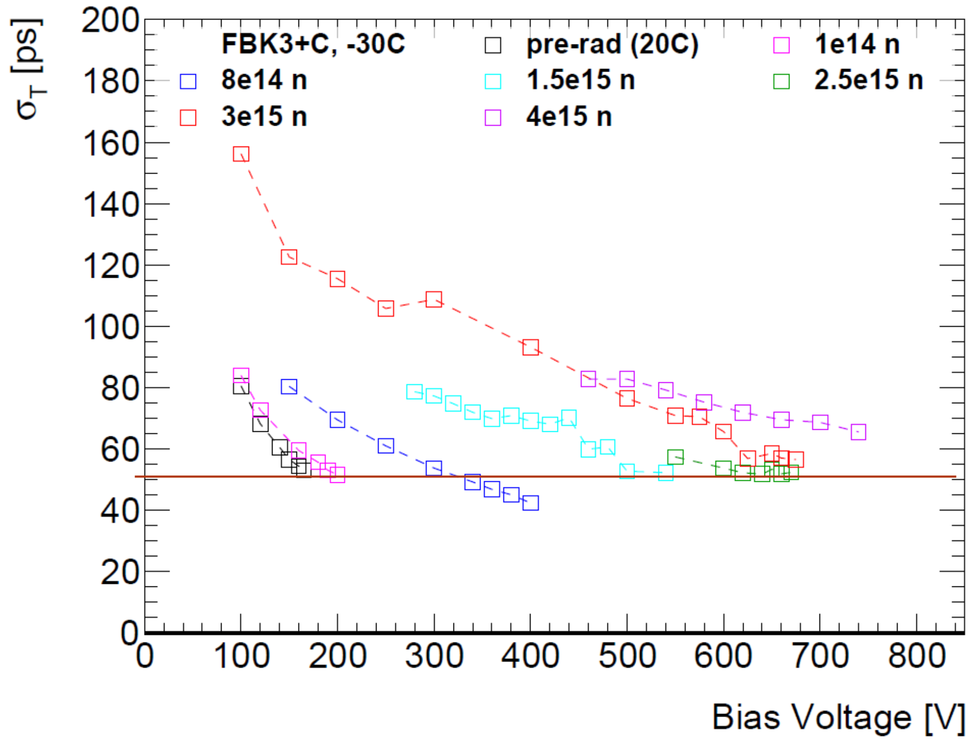


- **HPK-HGTD1** (Hamamatsu Photonics) sensors
- 50 um thin bulk sensors (nominal thickness)
- Thin but highly doped gain layer
  - Higher initial doping concentration
  - Takes more time to be inactivated
- Deep gain layer
  - **High field for larger volume**

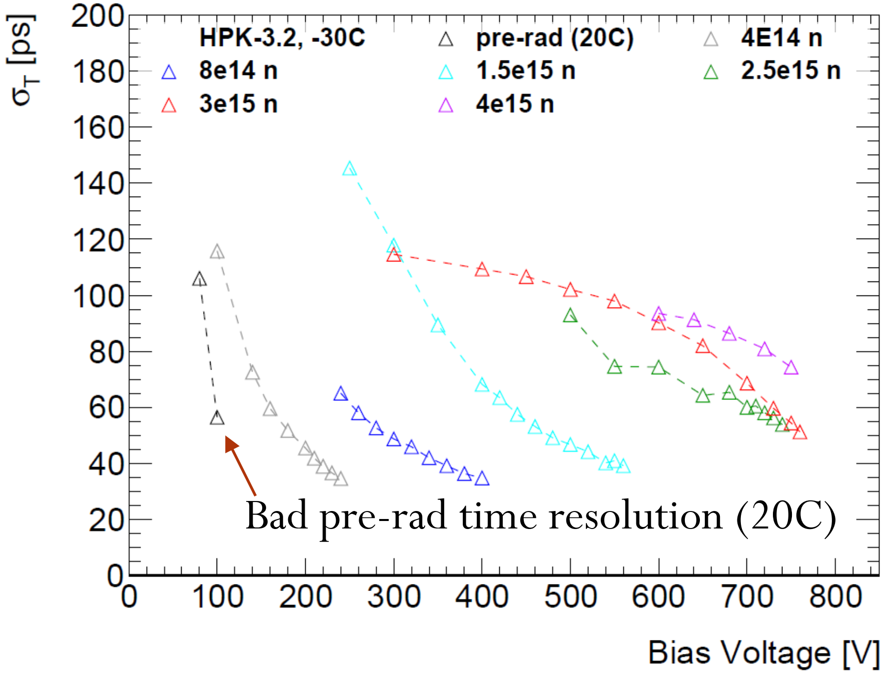
R. Padilla et al. https://doi.org/10.1088/1748-0221/15/10/P10003
S. Mazza et al. https://doi.org/10.1088/1748-0221/15/04/T04008
M. Ferrero et al. 10.1016/j.nima.2018.11.121
Y. Zhao et al. 10.1016/j.nima.2018.08.040

Issues in the past productions

Both types of sensors show good performance up to 2.5E15 Neq (HGTD maximum fluence) however



- **FBK-UFSD3** sensors
- 55um nominal thickness → minimum time resolution ~40-50ps
- Carbon level not optimized
- Shallow gain layer

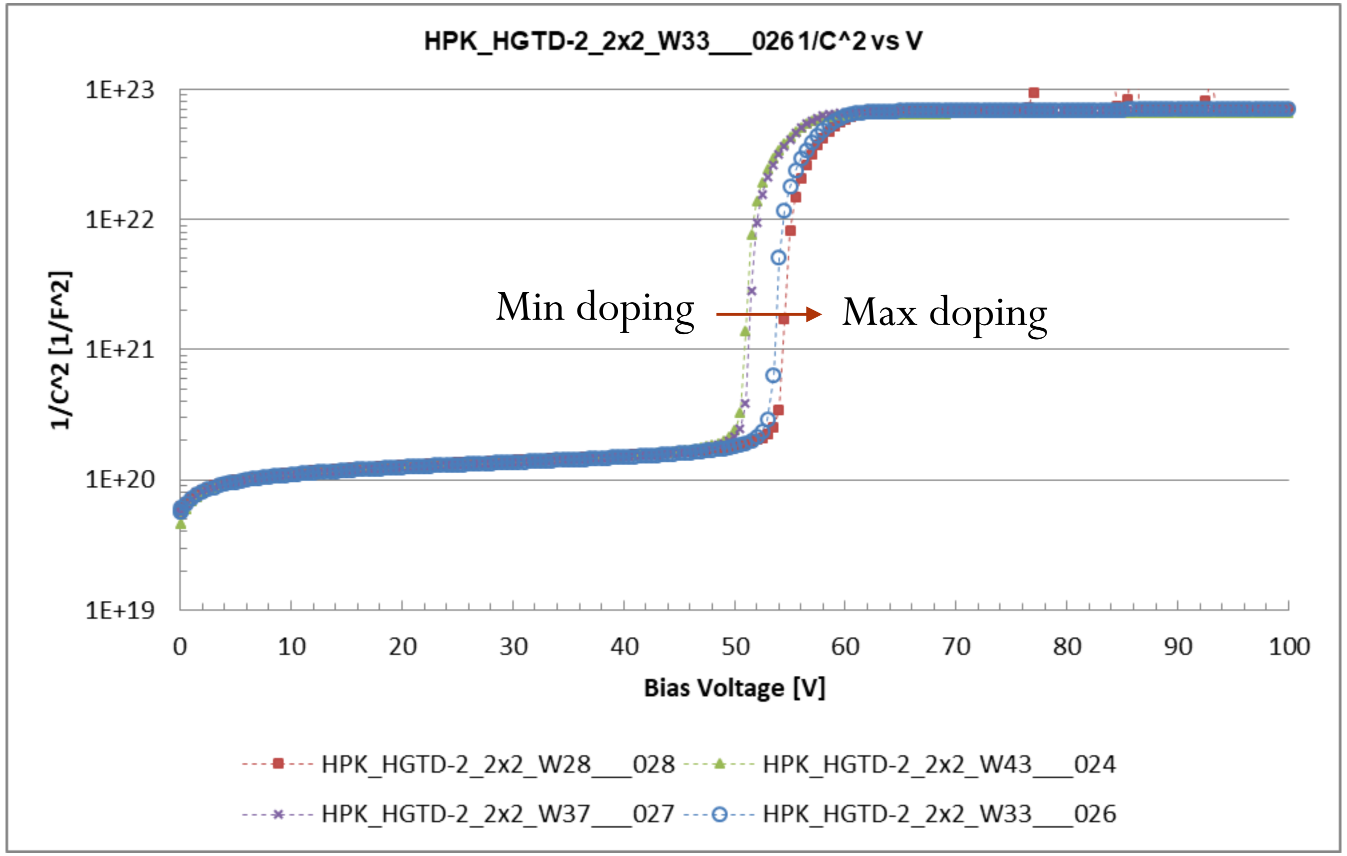


Bad pre-rad time resolution (20C)

- **HPK-HGTD1** sensors
- Deep gain layer too doped before irradiation
- Gain too high (>30 after full depletion)
- Bad behavior at 20C (time resolution >50ps)
  - Not working properly at -30C

Mitigation of radiation damage: new productions

- **HPK-HGTD2** sensors
- Optimization of doping concentration in the gain layer
- 4 splits with ~2% step down in doping concentration from HPK-3.2 (previous production)



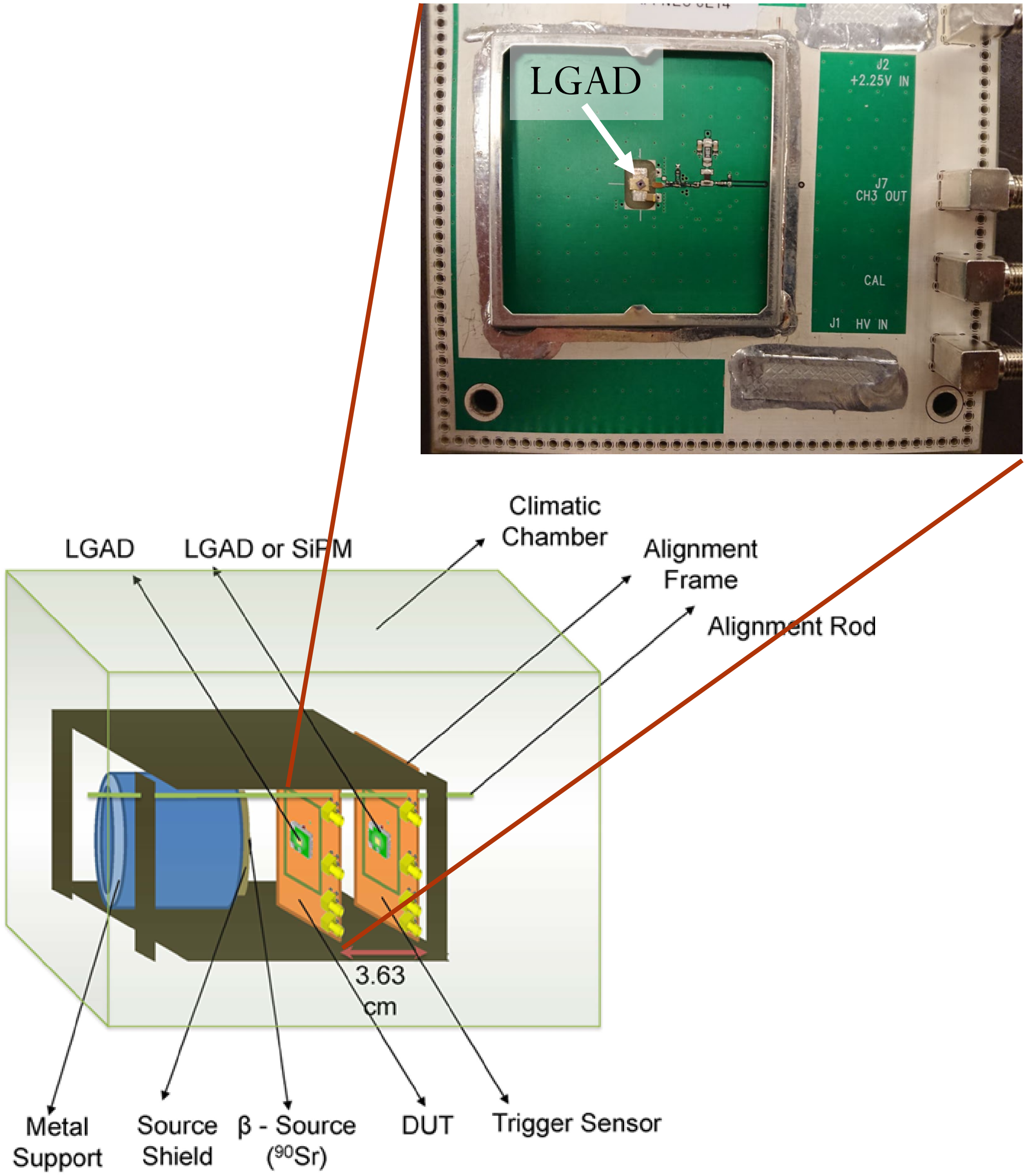
Mitigation of radiation damage: new productions

Wafer #	thickness	GL DEPTH	Dose Pgain	Carbon	Diffusion
1	45	Standard	L	1*A	CHBL
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
3	45	Standard	L	0.8*A	L
4	45	Standard	L	0.4*A	L
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
7	55	Standard	L	A	L
8	45	2 um	L'	1*A	CBL
9	55	2 um	L'	1*A	L
10	45	2 um	L'	0.6*A	L
11	45	2 um	L'		L
12	45	2 um	M'	1*A	L
13	45	2 um	M'	0.6*A	L
14	45	2 um	M'	1*A	CBH
15	55	2 um	M'	1*A	H
16	45	2 um	M'	0.6*A	H
17	45	2 um	M'		H
18	45	2 um	H'	1*A	H
19	45	2 um	H'	0.6*A	H

- **FBK-UFSD3.2** sensors
  - Optimization of the Carbon level
  - Thinner bulk (better time resolution)
  - Combination of deep gain layer and Carbon implantation
- Wafers under study (nominal thicknesses):
  - W7 → 55um bulk, Carbon (same as previous production)
  - W14 → 45um bulk, Carbon, Deep gain layer
  - W19 → 45um bulk, 0.6*Carbon, Deep gain layer, high doping

Sr90 charge collection

Sensor testing – Sr90 telescope

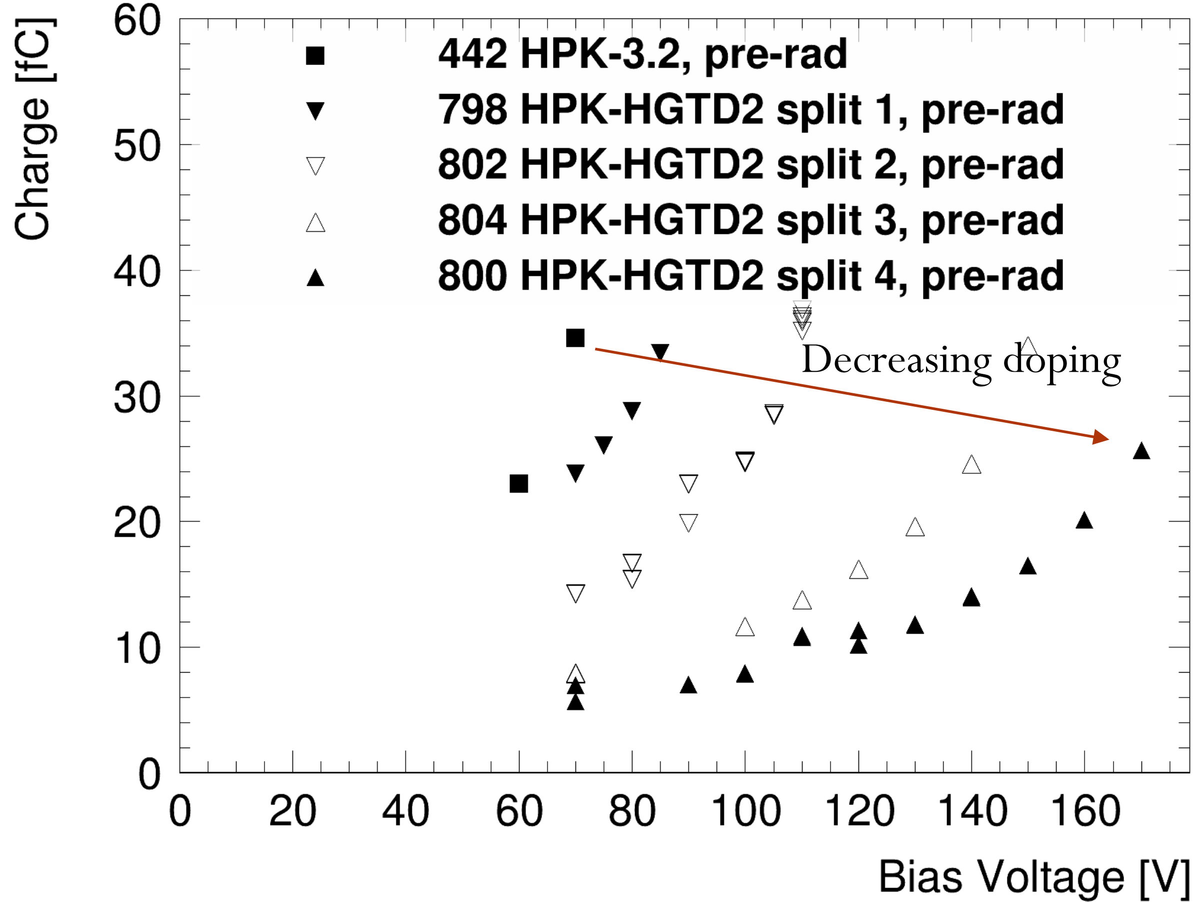


- Dynamic laboratory testing
  - Using MiP electrons Sr90 β-source (β-telescope)
  - Signal shape, noise, **collected charge**, gain, **time resolution**

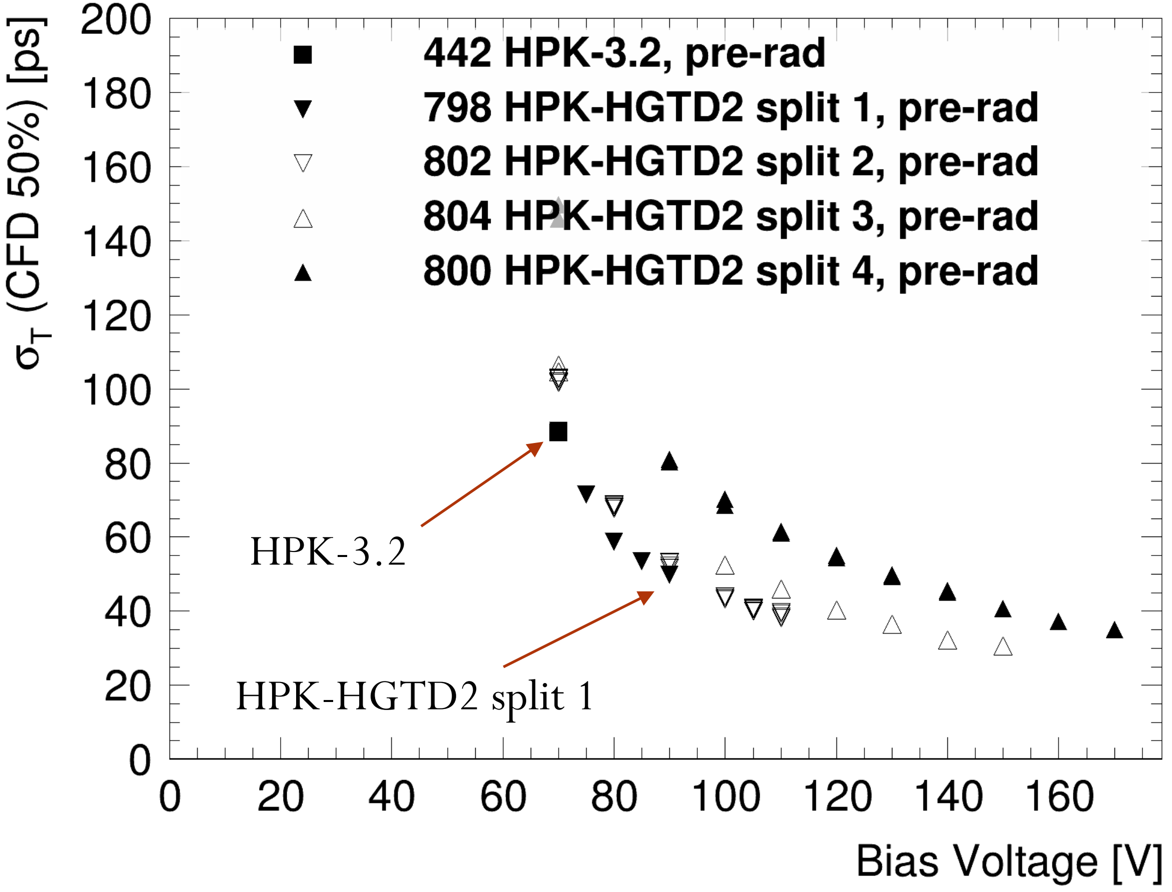
- Sensors mounted on analog readout board designed at UCSC (Ned Spencer, Max Wilder, Zach Galloway) with fast amplifier (22 ohm input impedance, bandwidth > 1GHz)
  - Readout by fast oscilloscope
- Trigger sensor (fast timing trigger) on the back
  - DUT (Device Under Test) is read in coincidence
- Setup in climate chamber to run cold and dry
  - 20C/-30C

HPK LGAD performance before irradiation

- HPK successfully tuned the gain layer to optimize performance before irradiation
- Starting point (highest gain): HPK-3.2
- At -30C HPK-3.2 has time resolution of 90 ps next split down (split 1) is better: 50ps
- Even better time resolution for following splits



Decreasing doping

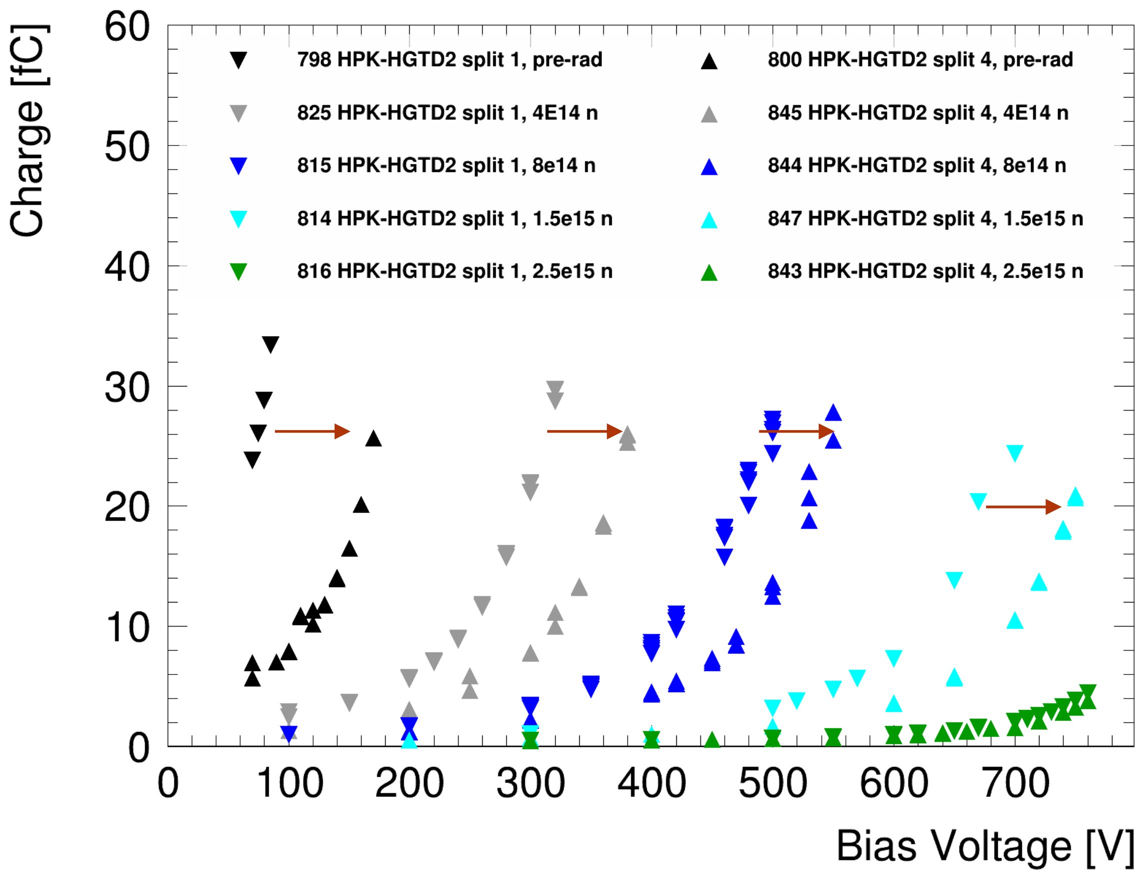


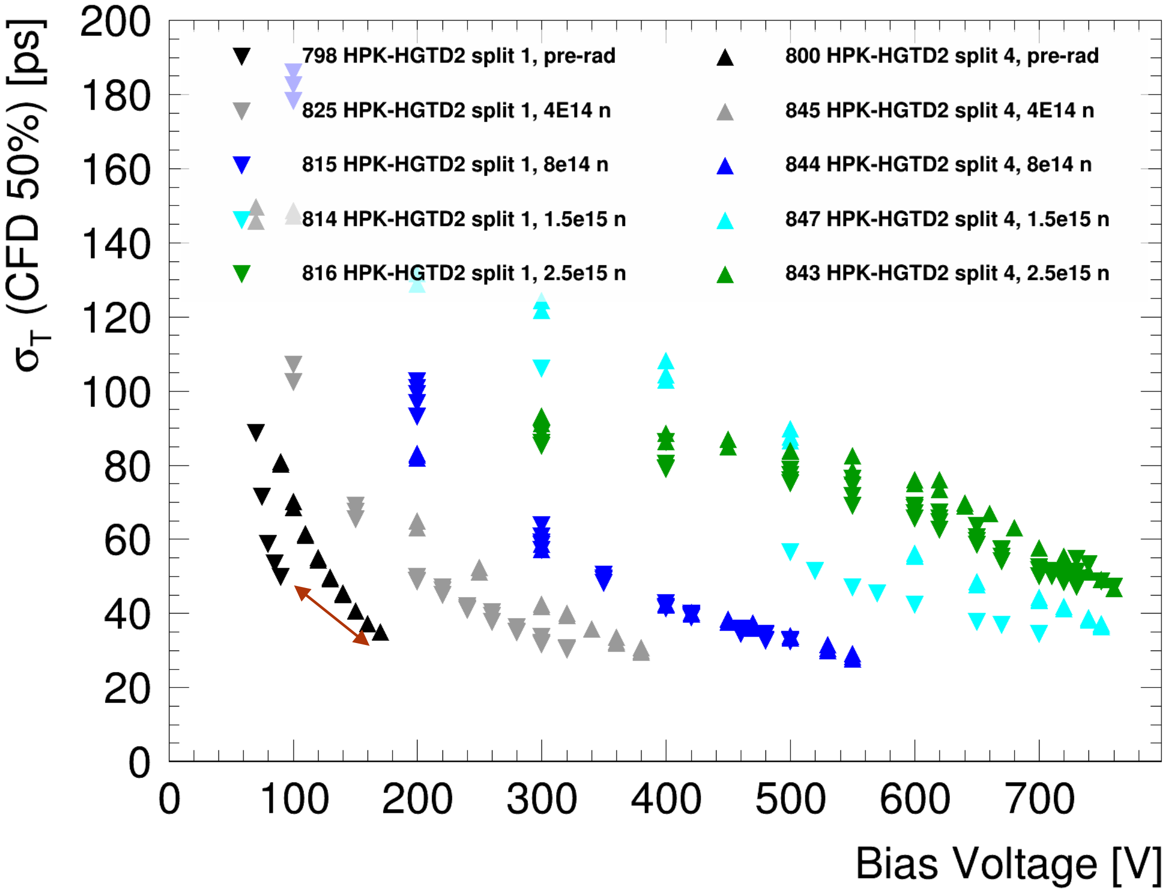
HPK-3.2

HPK-HGTD2 split 1

HPK LGAD performance after irradiation split 1 and 4

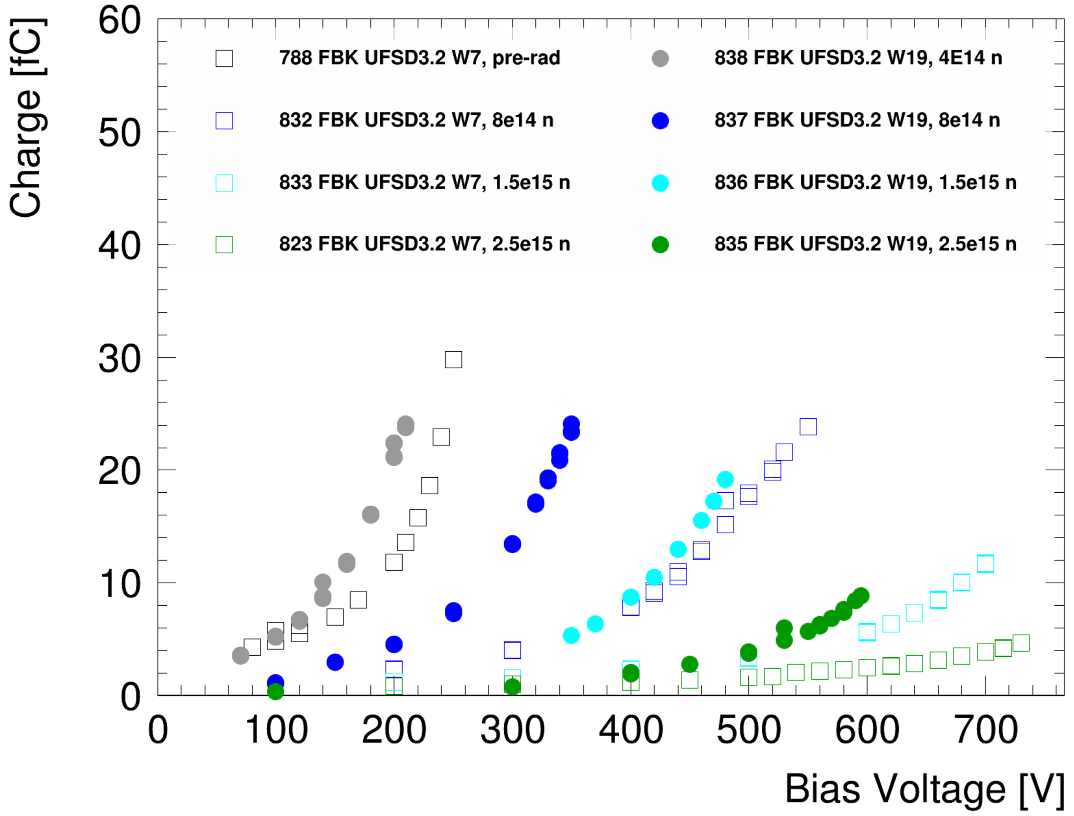
- Showing performance for HPK split 1 (highest doping) and split 4 (lowest doping)
- Distance between gain curves is more or less constant (at 2.5E15 Neq are very similar)
- Time resolution is better for split 4 at the beginning but at 4E14 Neq the two splits are the same

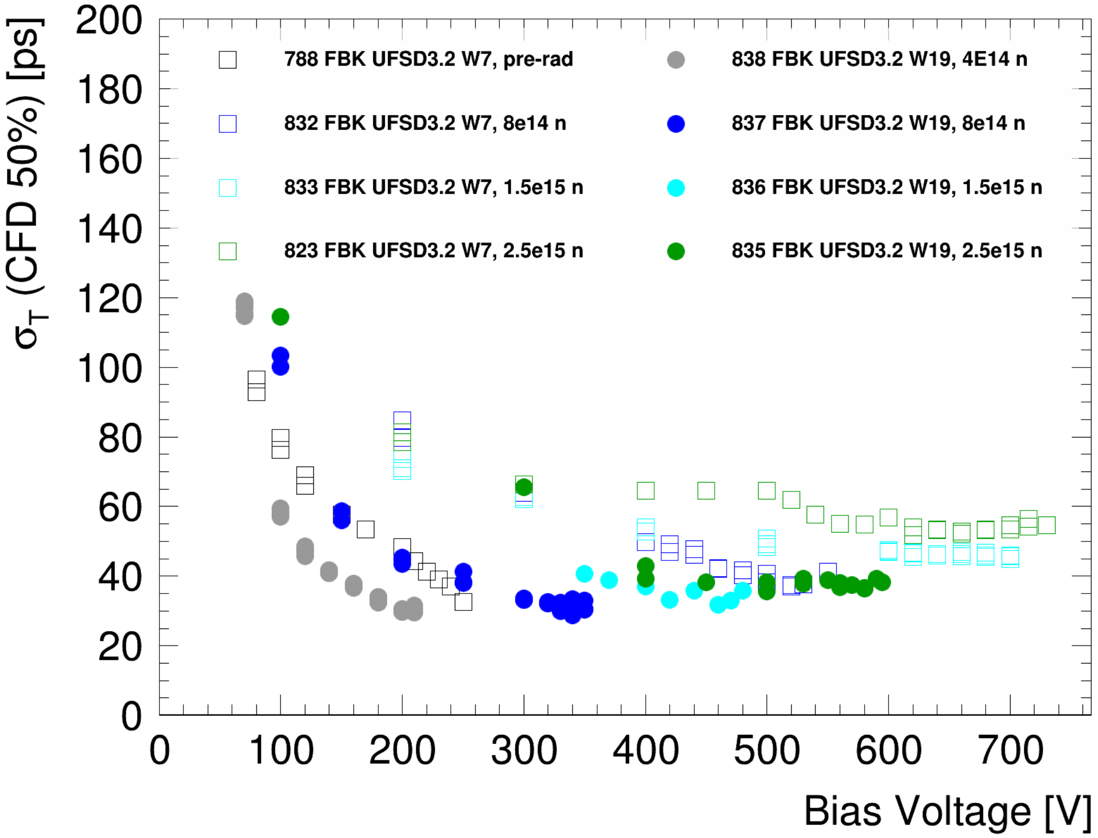




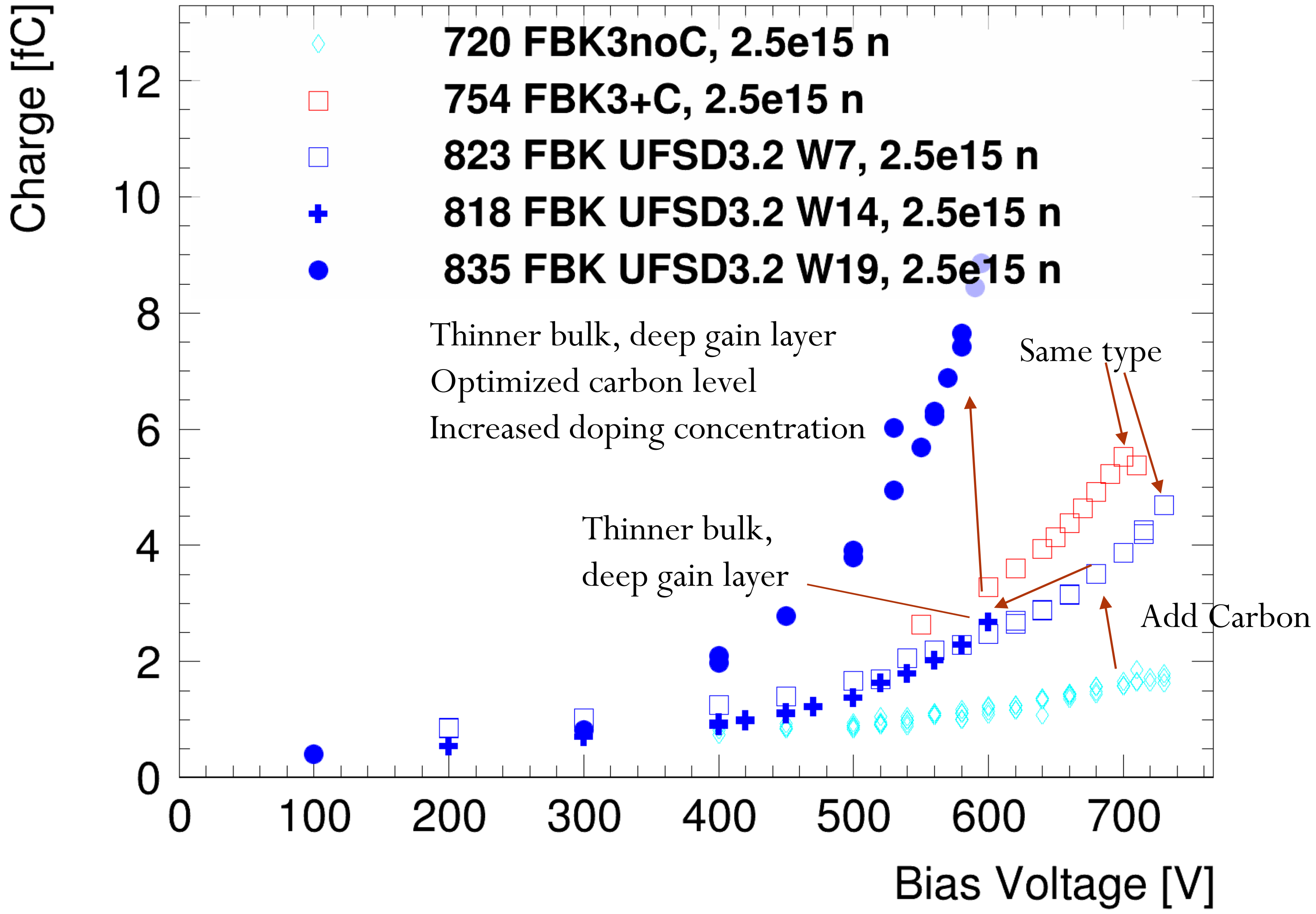
FBK LGAD performance after irradiation

- Combination of deep gain layer, high doping and Carbon implantation show exceptional performance
  - FBK USFD3.2 W19 (deep gain layer, Carbon), compared with W7 (shallow gain layer, Carbon, same type as FBK old production UFSD3)
  - (Missing pre-rad data for W19, showing 4E14 Neq instead)
- 10 fC of collected charge reached at the maximum fluence of 2.5E15 Neq
- Better time resolution at higher fluence





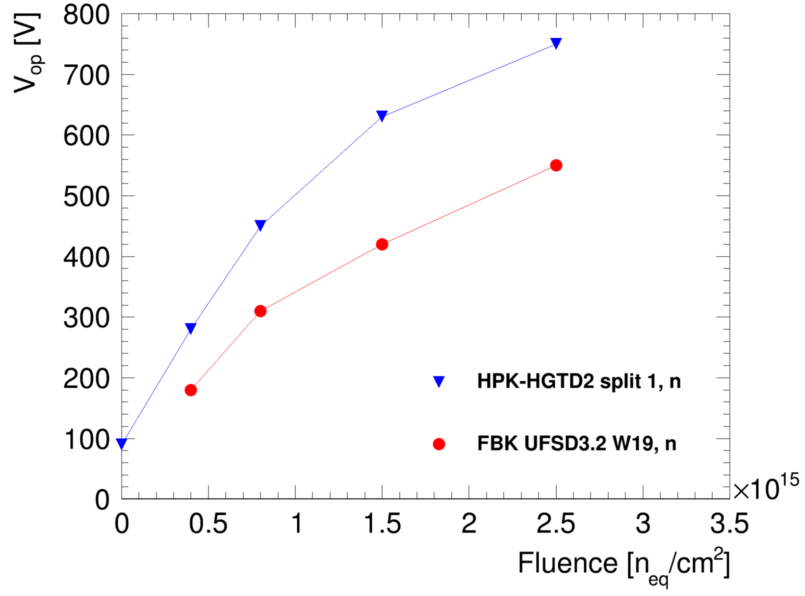
FBK LGAD performance at maximum irradiation

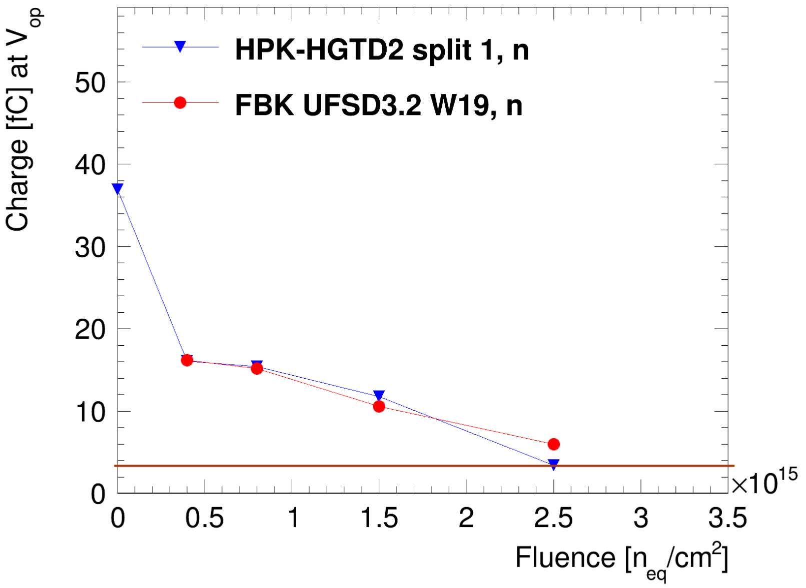


- **FBK UFSD3.2 sensors show the great potential of deep gain layer and Carbon implantation**

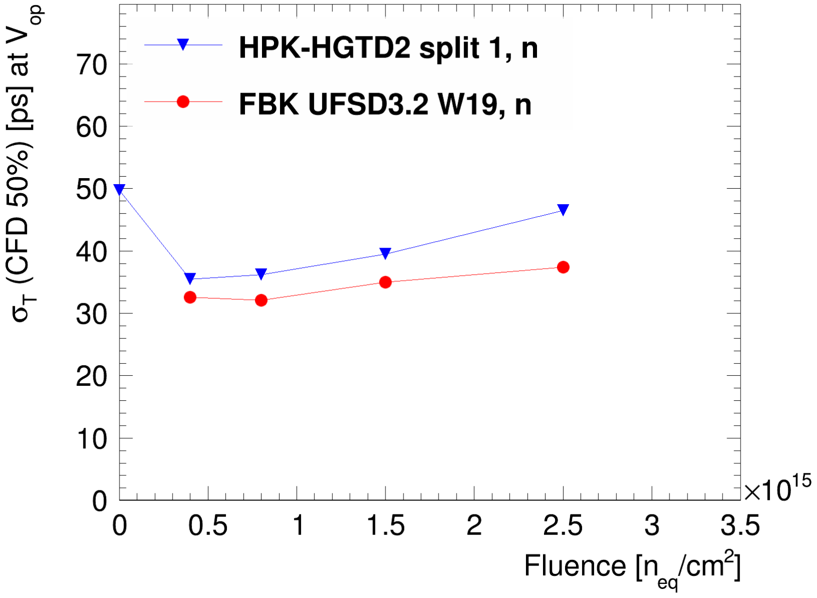
- FBK3noC (no carbon) has the worse performance
- FBK3+C and FBK UFSD3.2 (same structure with Carbon) have much better performance
- FBK UFSD3.2 W14 with deep gain layer is similar to FBK3+C but has thinner bulk (lower initial charge)
- FBK UFSD3.2 W19 (highly doped, deep gain layer, optimized Carbon) has the best performance
  - **W19 has a higher starting point in gain layer doping to increase the radiation reach**

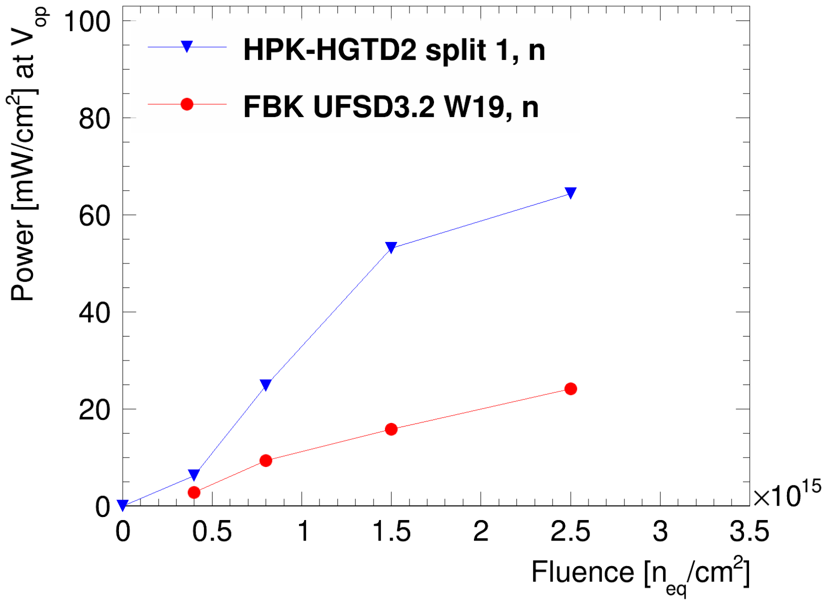
HPK-FBK best type comparison



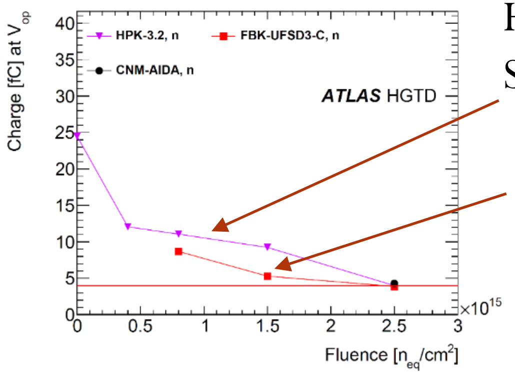


- Characterization similar to HGTD TDR
  - https://cds.cern.ch/record/2719855
- Chosen Vop (operating voltage) per fluence per type of sensor that gives good performance
- Both sensors can fulfill ATLAS HGTD requirements
  - CC>4fC, time resolution <50 ps,
  - power <100mW/cm^2





- FBK UFSD3.2 W19 shows great behavior:
  - Lower voltage for similar charge, better time resolution and lower power dissipation



HPK HGTD-2 split 1
Similar to HPK-3.2

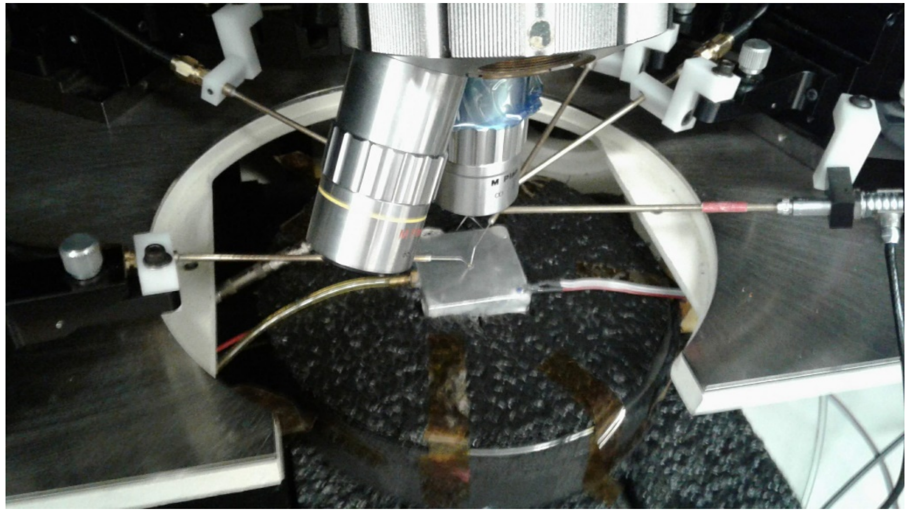
FBK UFSD3.2 W19
much better than
FBK UFSD3

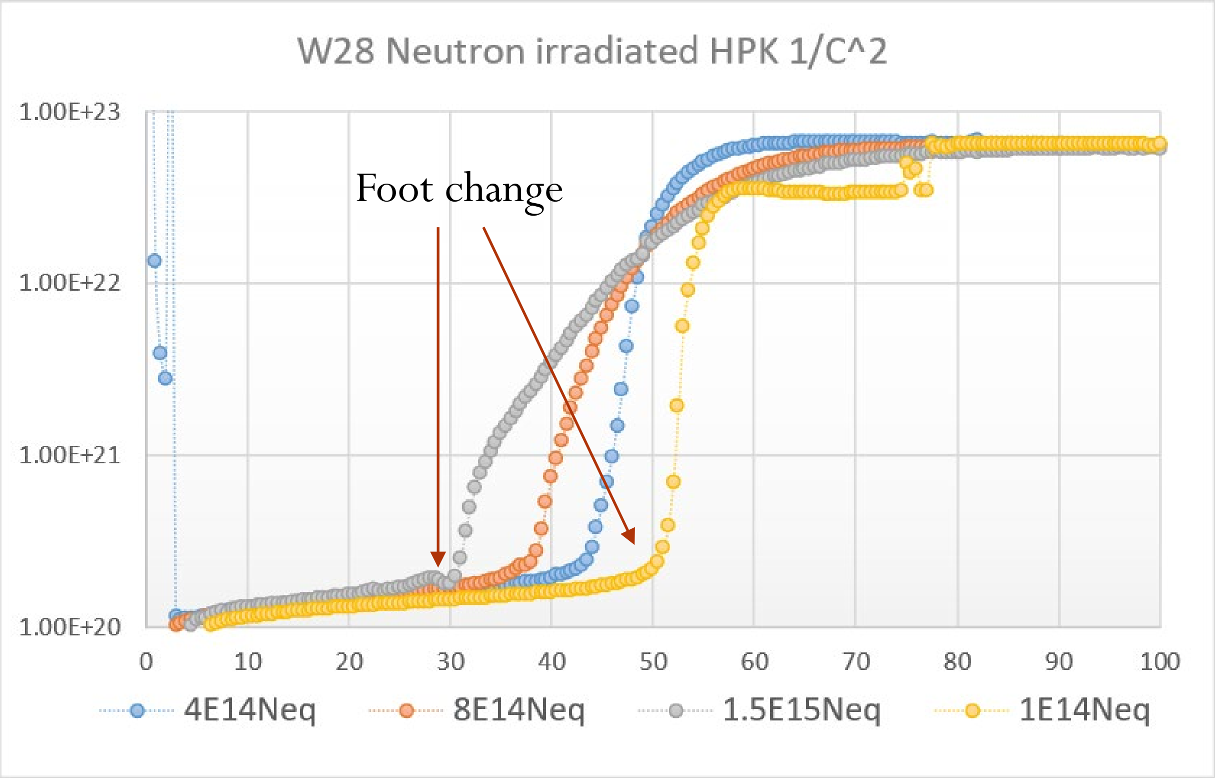
Probe station measurements

Many thanks to Nikita Tournebise!

Gain layer and CV

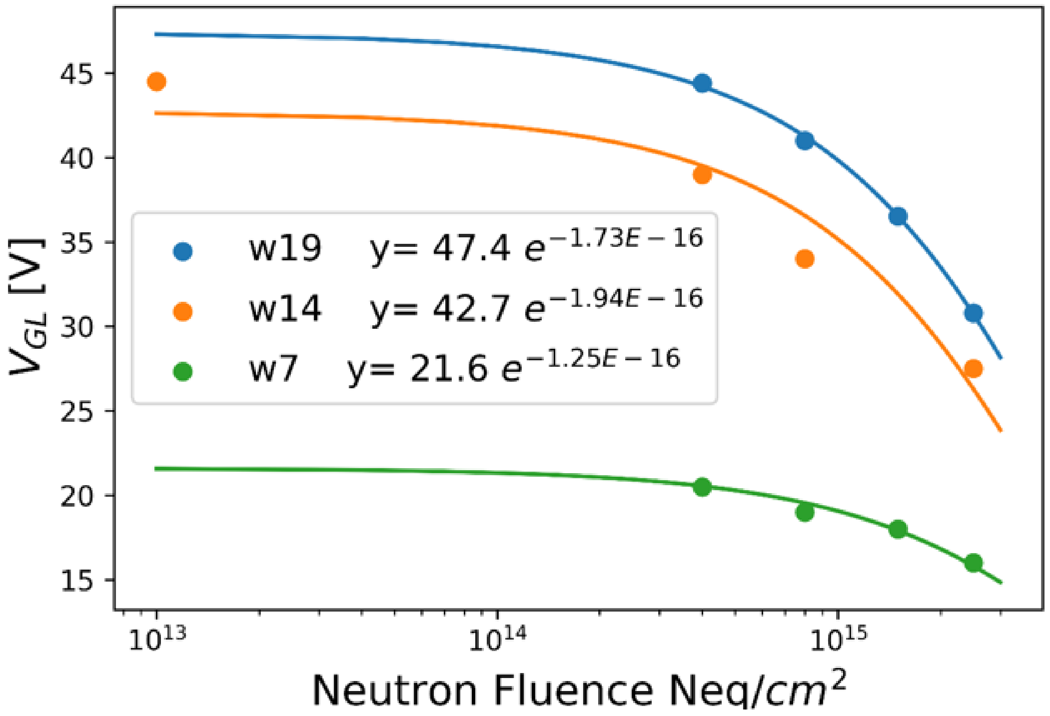
- Capacitance over voltage (CV)
  - Measured on probe station at 20C
- Study of the "foot" (flat region before full depletion) for LGADs on $1/C^2$
  - Bulk doping concentration proportional to the slope in $1/C^2$
- After radiation damage the "foot" changes proportionally to the gain layer doping
- Example: $1/C^2$ for HPK HGTD2 split 1





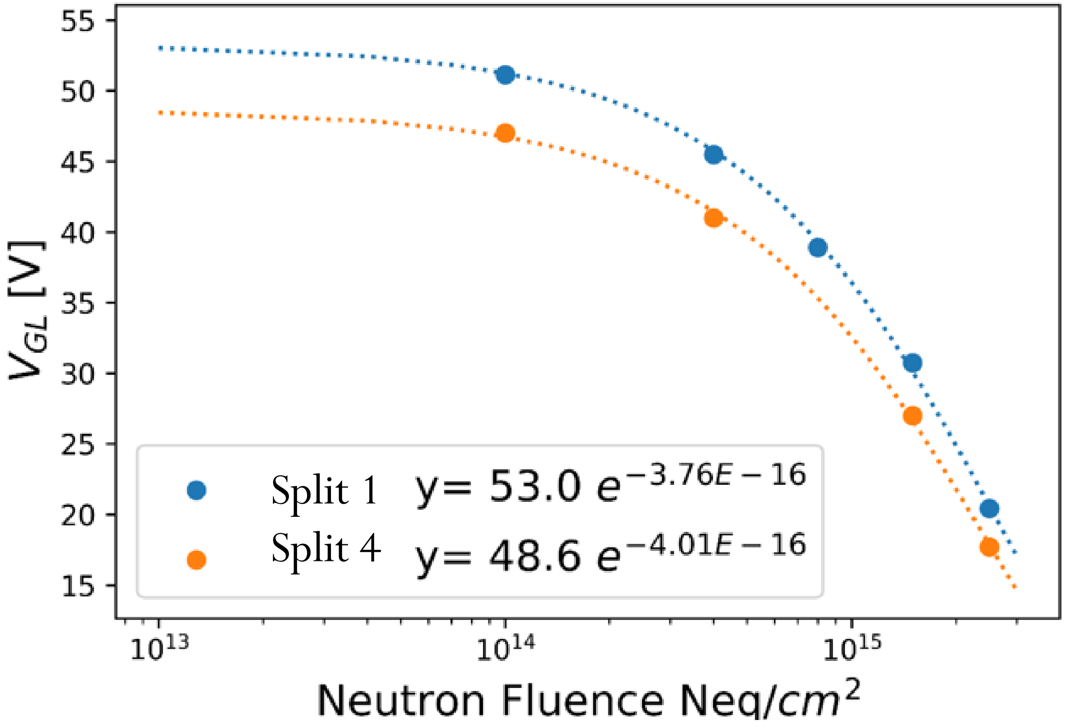
1/C^2 Foot vs fluence

Fitted with $N_D = N_0 e^{-c\phi}$



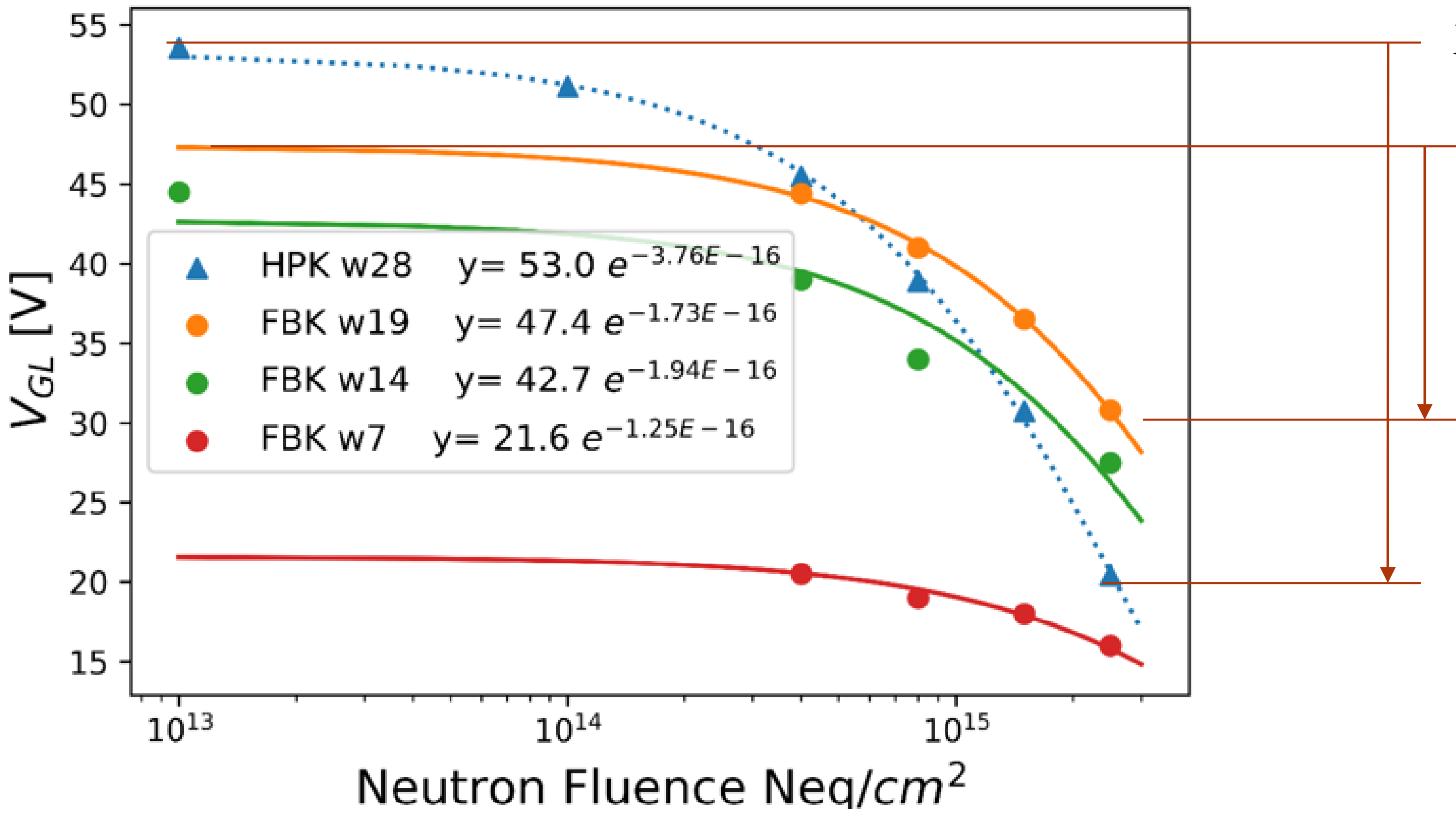
- FBK UFSD3.2
  - Both W14/W19 have a higher starting point than W7 because of the deep gain layer
  - W19 has the highest starting point (highest doping) and 10% lower c-factor (optimized carbon level) than W14

- HPK-HGTD2
  - Same gain layer geometry for split 1 and split 4
  - Similar fits and c-factors
  - But with different starting point



Gain layer vs. Fluence: comparison

- Carbon seems to give significant improvement: C-factor is about 2-3 times smaller for FBK
- HPK-HGTD2 still has a higher initial doping concentration



HPK starts higher (highly doped gain layer)
but decreases faster

FBK has lower variation (lower c-factor) thanks to Carbon

Conclusions

- **To increase the radiation hardness of LGADs:**
  - Carbon
  - Deep gain layer
  - **Combination of the two**
- LGADs from previous production of HPK and FBK show **reasonable performance up to 2.5E15Neq** (Max fluence at HGTD)
  - However both productions had issues
- **New HPK production** with tuned gain layer shows **good behavior <u>before and after irradiation</u>**
- **FBK sensors** with **deep gain layer and Carbon** show **exceptional performance**
  - Lowering the needed bias voltage at maximum fluence for the timing layers of ATLAS/CMS at HL-LHC

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Backup

Irradiation campaigns on LGADs

- Irradiation campaign on LGADs
- Sensors were irradiated at
  - JSI (Lubiana) with ~1 MeV neutrons
  - PS-IRRAD (CERN) with 23 GeV protons
  - Los Alamos (US) with 800 MeV protons
  - CYRIC (KEK, Japan) with 70 MeV protons
  - X-rays at IHEP (China)
  - Gamma irradiation (Sandia, Uni. of new Mexico)
- Fluence: 1E13 Neq/cm^2 → 1E16 Neq/cm^2
- Ionizing dose up to 4MGy

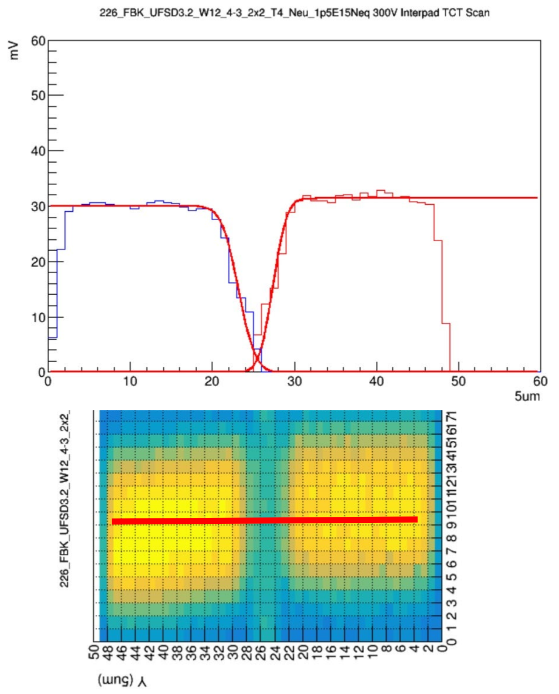
- Waiting for the FNAL facility!

TCT IP gap measurements

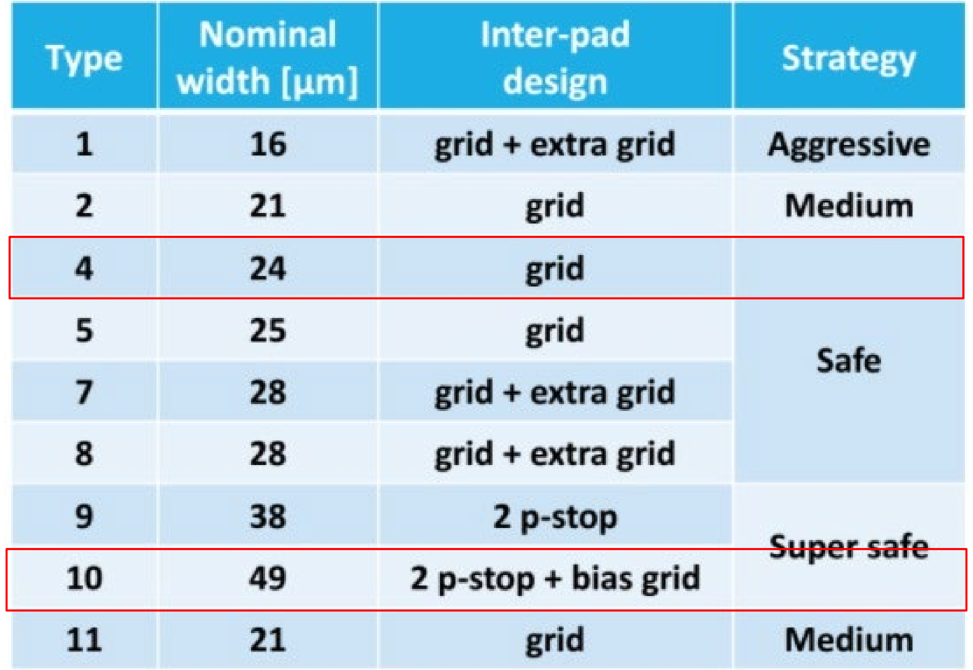
Many thanks to Basil Darby!

FBK UFSD3.2 TCT IP gap measurements

- Measurement of the Inter-pad (IP) gap in arrays of FBK UFSD3.2 arrays using a TCT laser
- Array tested
  - Type 4: safe, nominal IP 24 um
  - Type 10: super safe, nominal IP 49 um

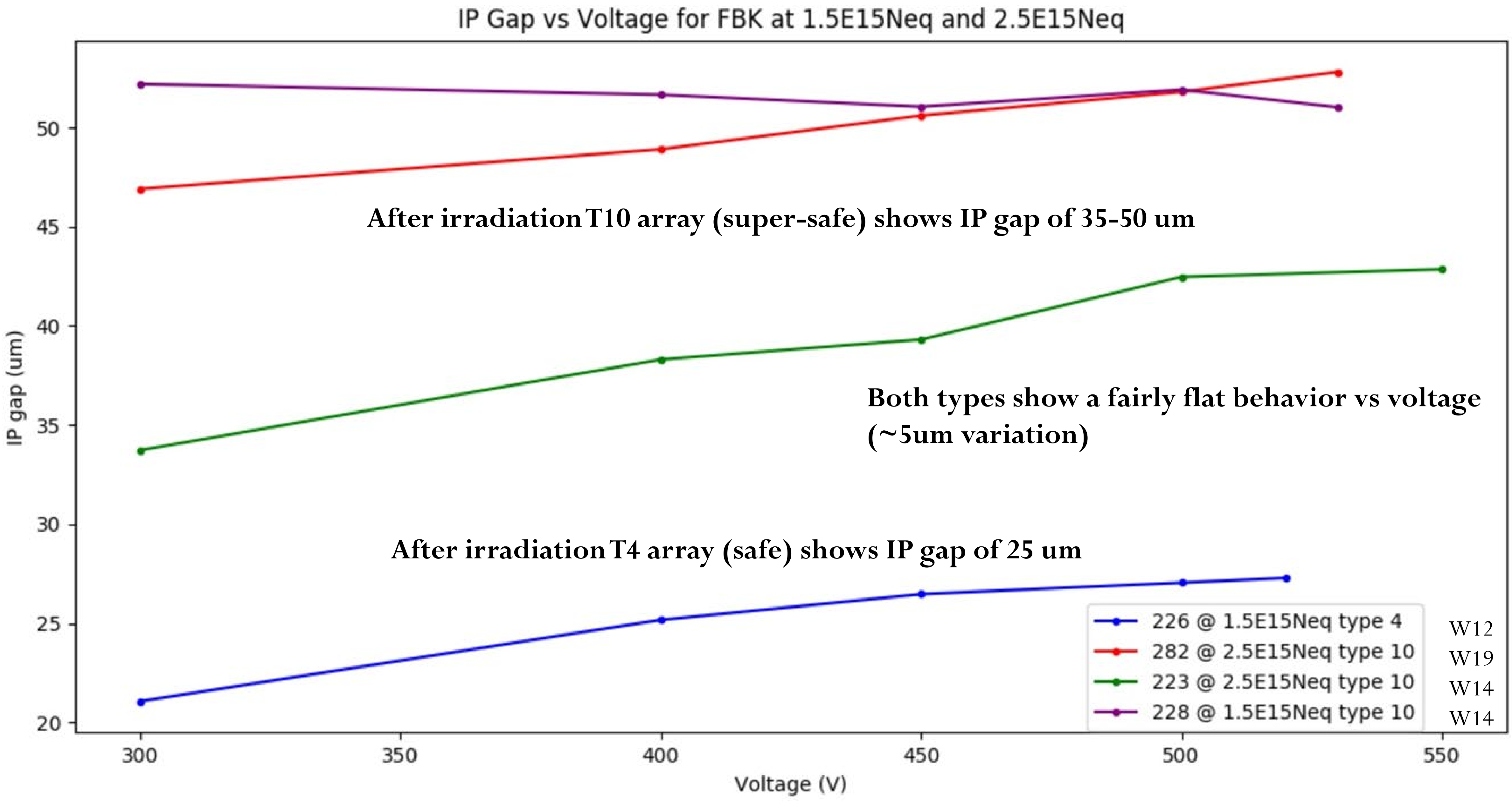


- Fit using error function.
- Inter-pad gap measured as distance from each 50% point.
- Sensors measured after irradiation
  - Next: measure sensors before irradiation
  - In the past increased IP gap was observed before irradiation (other groups will show results for this new production)



Type	Nominal width [µm]	Inter-pad design	Strategy
1	16	grid + extra grid	Aggressive
2	21	grid	Medium
4	24	grid	Safe
5	25	grid	
7	28	grid + extra grid	
8	28	grid + extra grid	
9	38	2 p-stop	Super safe
10	49	2 p-stop + bias grid	
11	21	grid	Medium

[From V.Sola et al., 35th RD50 Workshop, CERN]



After irradiation T10 array (super-safe) shows IP gap of 35-50 um

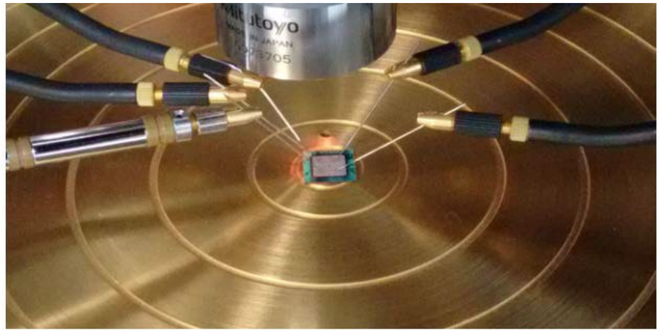
Both types show a fairly flat behavior vs voltage (~5um variation)

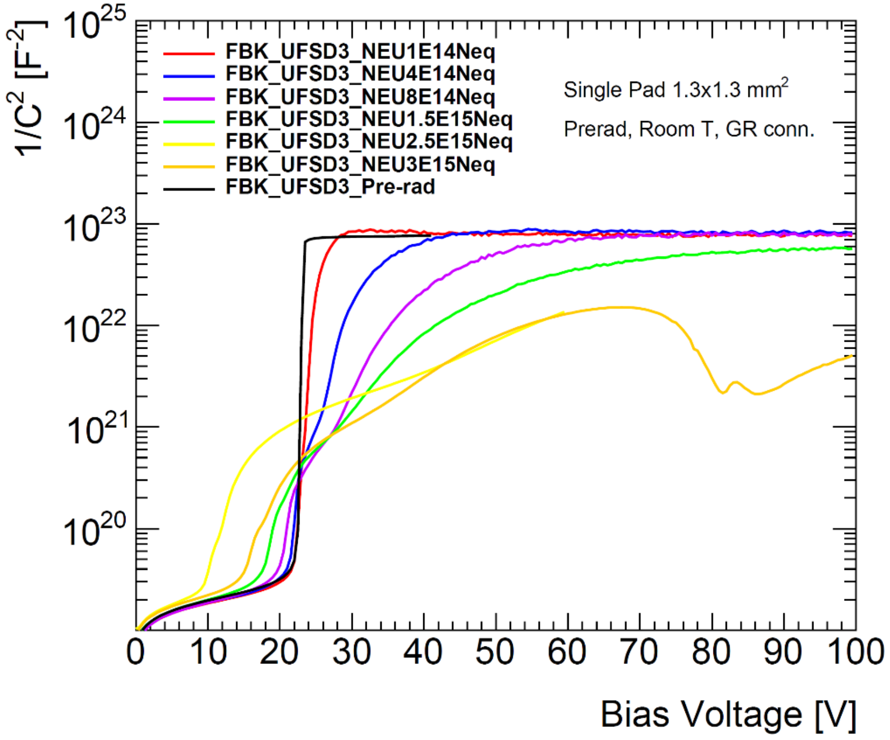
After irradiation T4 array (safe) shows IP gap of 25 um

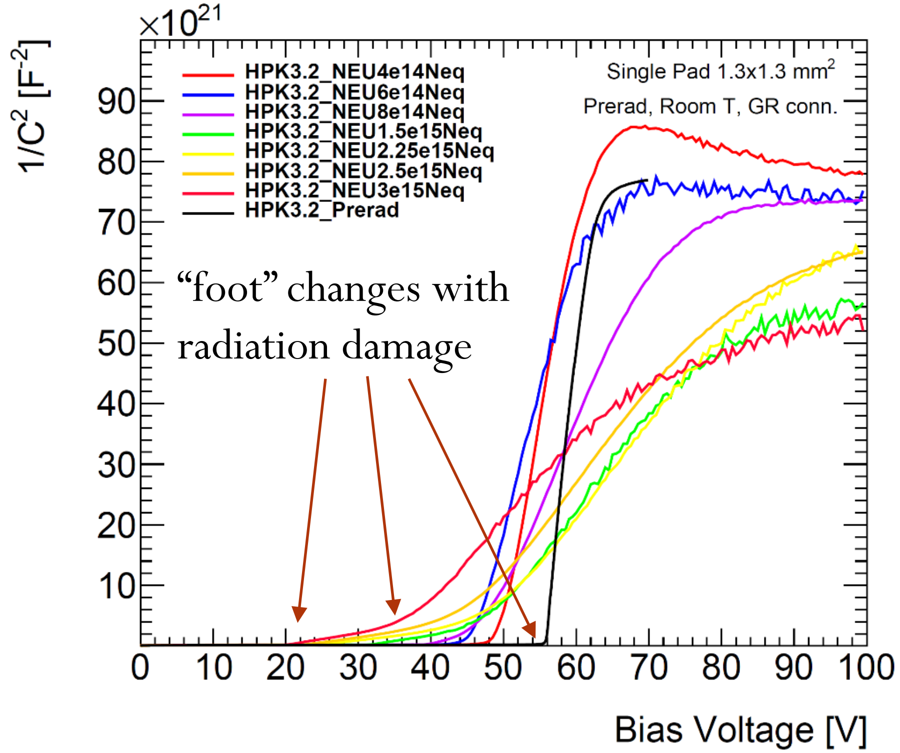
W12
W19
W14
W14

Gain layer and CV

- Capacitance over voltage (CV)
  - Study doping concentration profile and full depletion of the sensor
- Study of the “foot” for LGADs on $1/C^2$:
  - $1/C^2$ flat until depletion of multiplication layer
  - Proportional to gain layer active concentration
- Bulk doping concentration proportional to the slope in $1/C^2$
- After radiation damage the “foot” changes proportionally to the gain layer doping

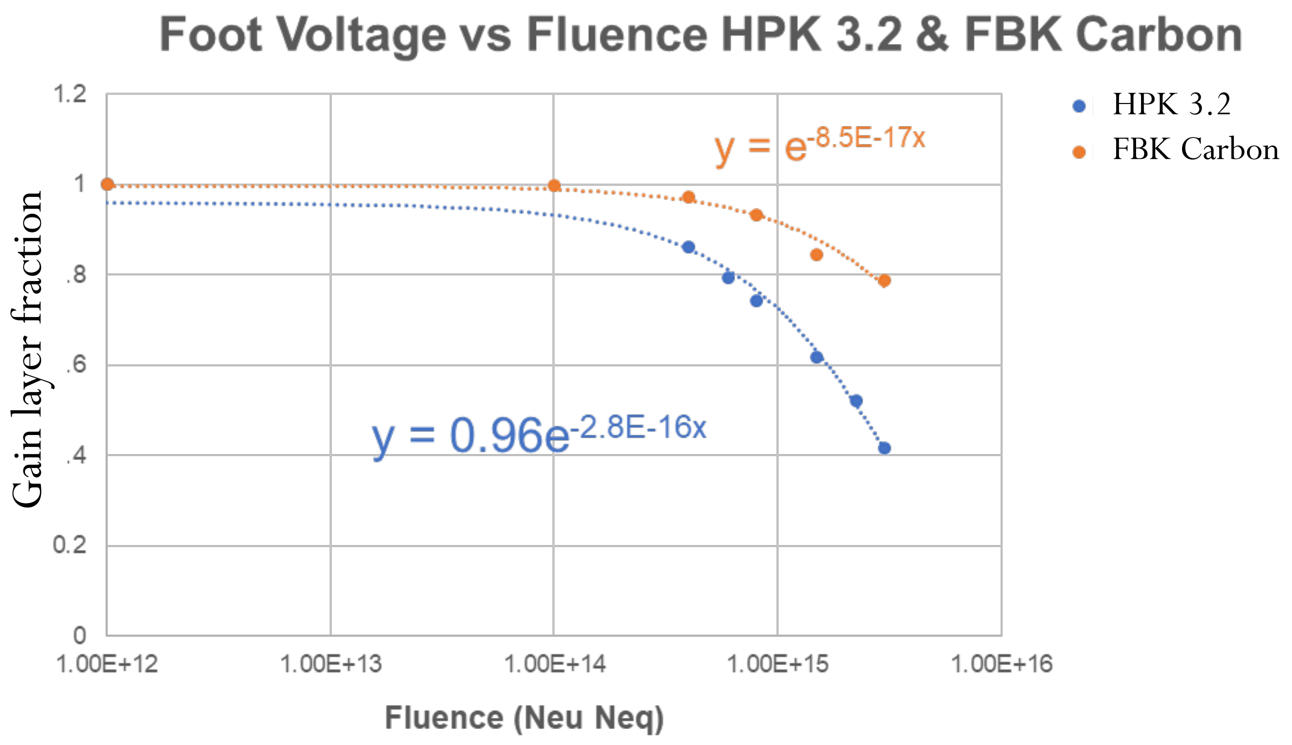






“foot” changes with radiation damage

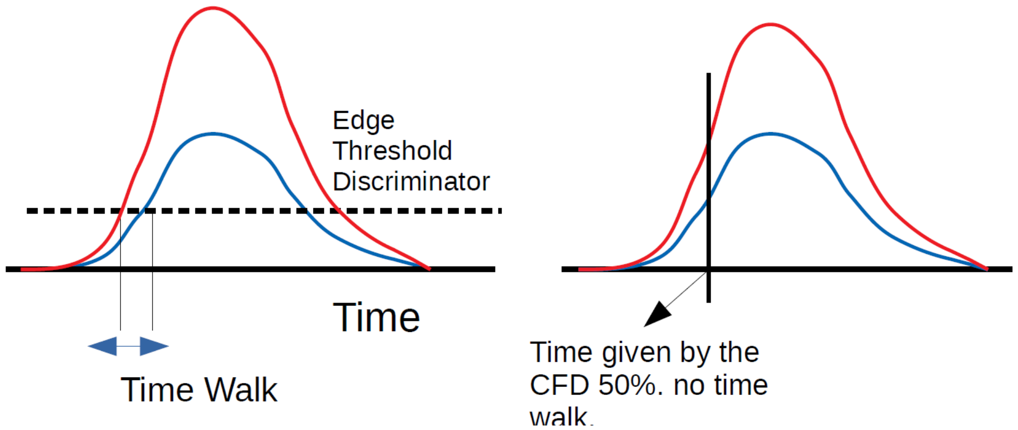
Gain layer vs. Fluence: The Effect of Carbon

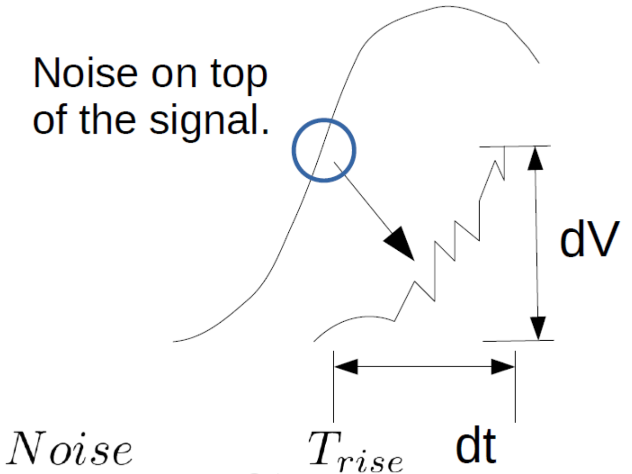


$$N_D = N_0 e^{-c\phi}$$

- Acceptor removal constant (C) is different for different types of sensors
  - The FBK Carbon sensors has smaller range for "foot" voltage
  - The HPK 3.2 shows a much larger declination and broader range of "foot" voltages
- Carbon seems to give significant improvement where C is about factor 3 smaller for FBK
- However HPK has a much higher initial foot due to the buried gain layer

LGADs timing resolution





$$\sigma_{Jitter} = \frac{Noise}{dV/dt[CFD\%]} \approx \frac{T_{rise}}{SNR}$$

Sensor time resolution main terms

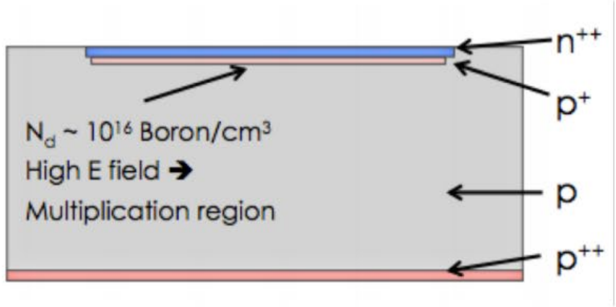
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

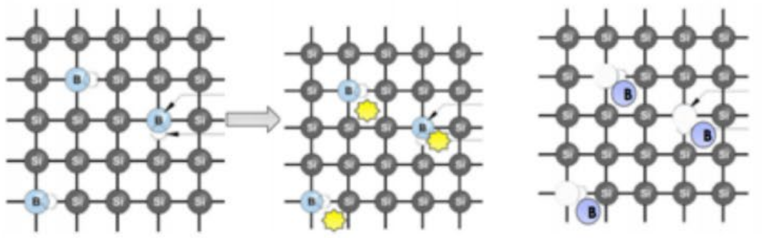
- Time walk:
  - Minimized by using for time reference the % CFD (constant fraction discriminator) instead of time over threshold
  - In HGTD electronics TOA (Time of Arrival) of the signal is corrected with TOT (Time over threshold)
- Landau term:
  - Reduced for **thinner sensors** (50,35 µm)
- Jitter:
  - Proportional to ${}^{1}\!/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain

Acceptor removal

Unfortunate fact: irradiation de-activate p-doping removing Boron from the reticle

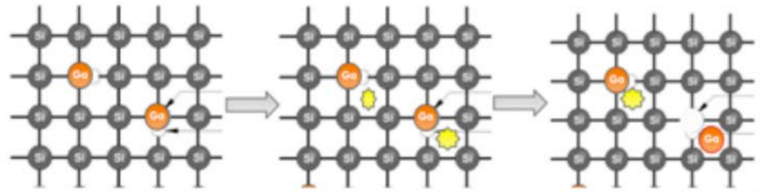
$$N(\emptyset) = N(0) * e^{-c\emptyset}$$



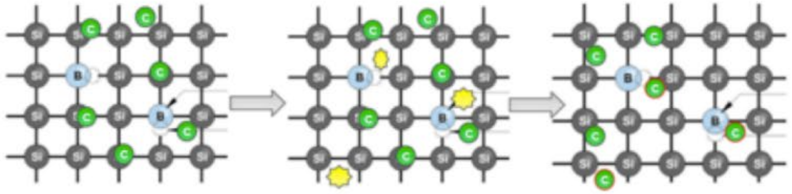


Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s ➔ Si_s + B_i
B_i might interact with Oxigen, creating a donor state

Two possible solutions: 1) use Gallium, 2) Add Carbon



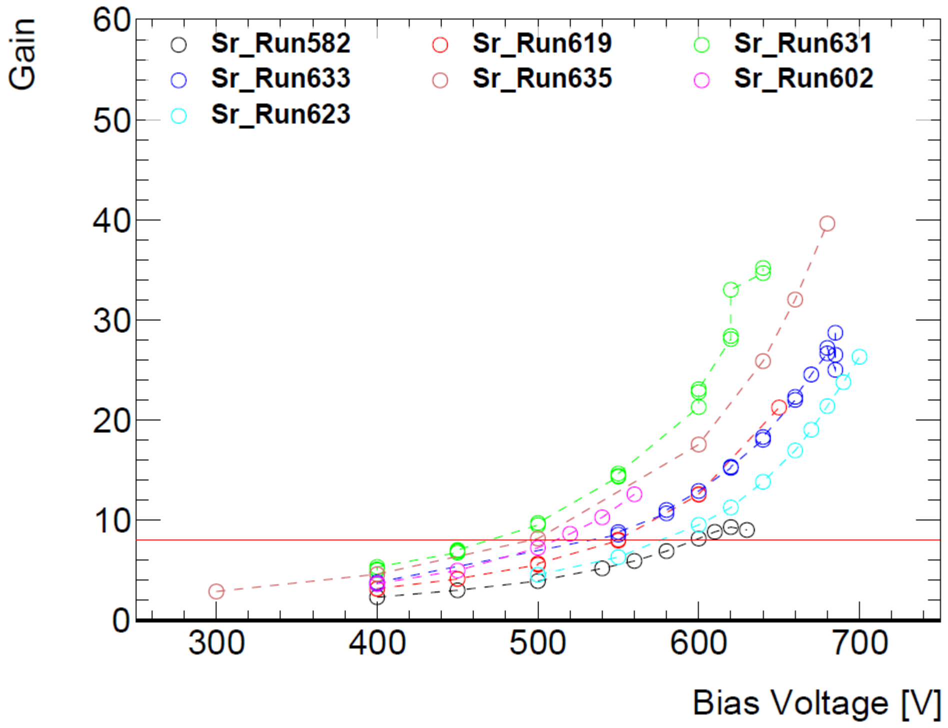
Gallium
From literature, Gallium has a lower probability of becoming interstitial

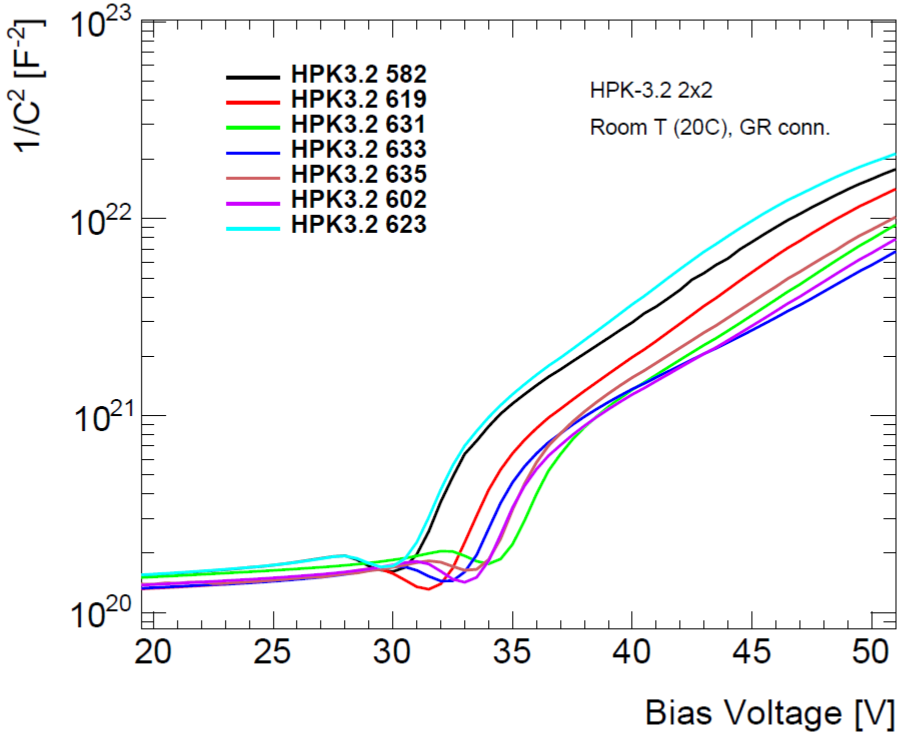


Carbon
Carbon competes with Boron and Gallium in reacting with Oxigen

Variation of performance after irradiation

- HPK sensors irradiated with neutrons at JSI (Lubjiana)
- Variation of performance of the order of 10%: in the voltage to obtain X fC of charge (or gain X)
- Seen both in charge collection and in CV





Variation of performance after irradiation

- Correlation of voltage to reach gain of 8 with foot from CV shows that the variation is real
- Correction using the correlation to the performance