

12th International Conference on  
**POSITION SENSITIVE  
DETECTORS**



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**UNIVERSITY OF  
BIRMINGHAM**



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

PSD (2021, Birmingham)

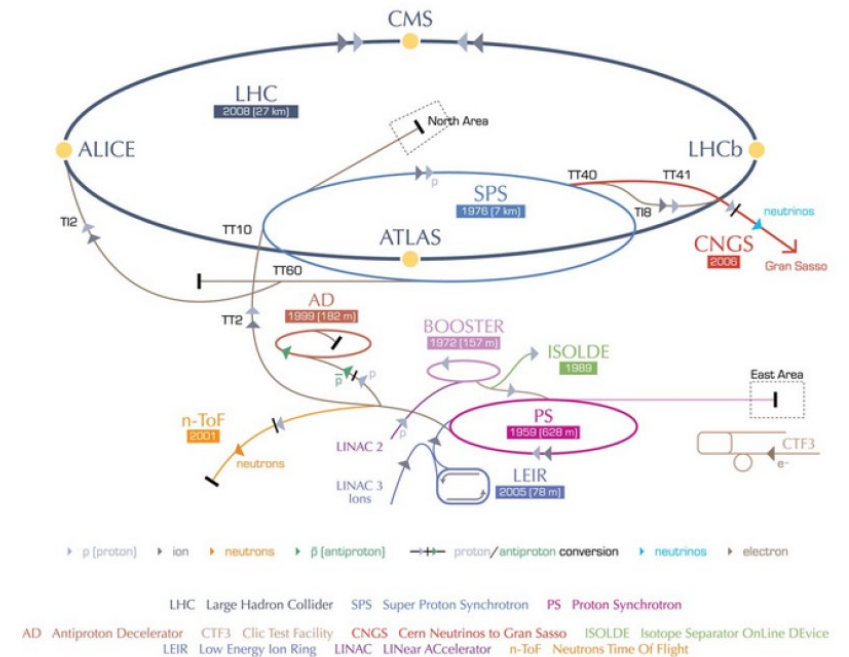
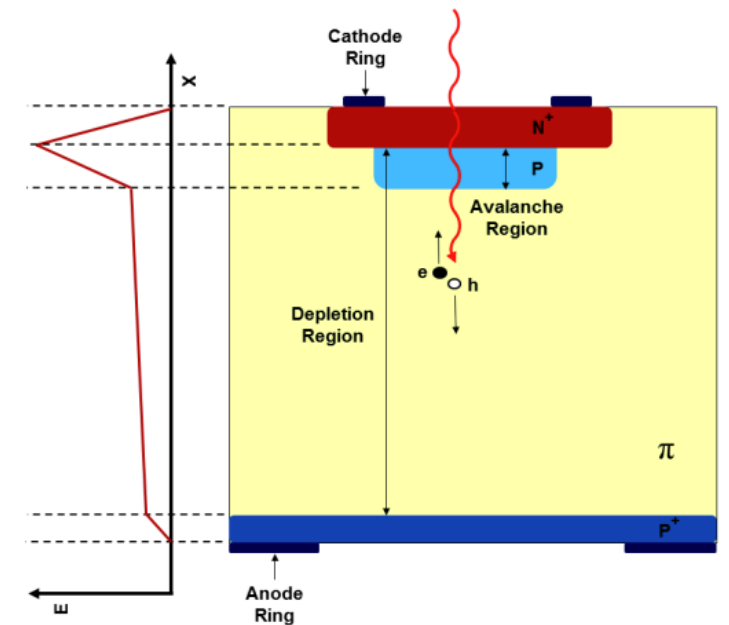
Dr. Simone M. Mazza (SCIPP, UC Santa Cruz),  
on behalf of the SCIPP UCSC group

S. M. Mazza, C. Gee, R. Padilla, Y. Zhao, F. McKinney-Martinez, H. F.-W. Sadrozinski, A. Seiden, B. Schumm, R. Arcidiacono, N. Cartiglia, M. Ferrero, M. Mandurrino, V. Sola, M. Boscardin, G. Borghi, G. Paternoster, F. Ficorella, M. Centis Vignali, G.F. Dalla Betta, L. Pancheri, V. Cindro, G. Kramberger, I. Mandić, M. Mikuž, M. Zavrtanik



# LGADs in HEP

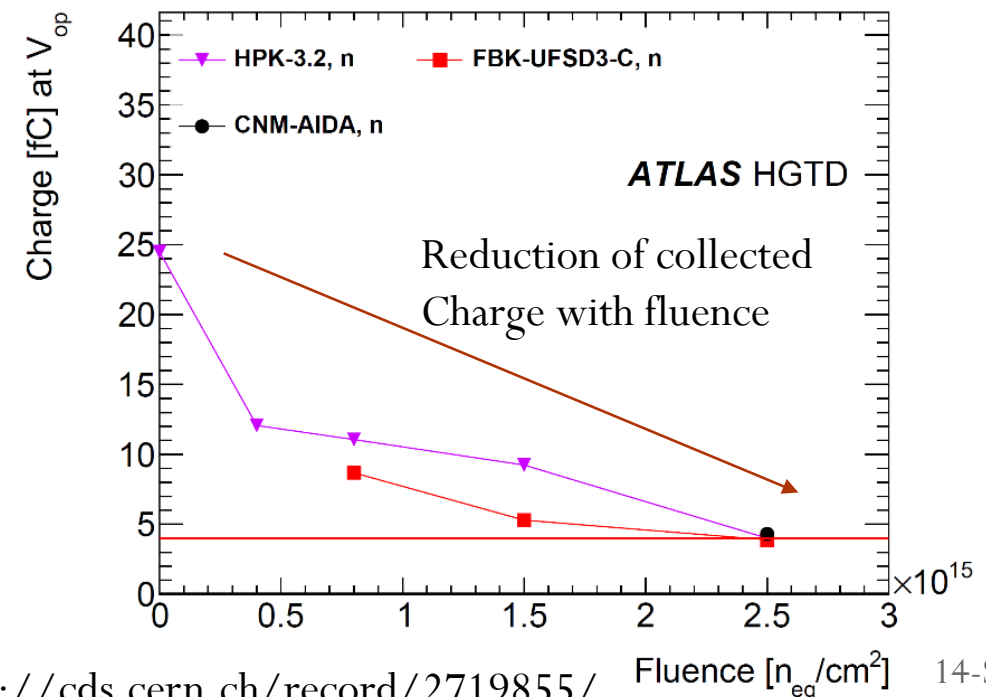
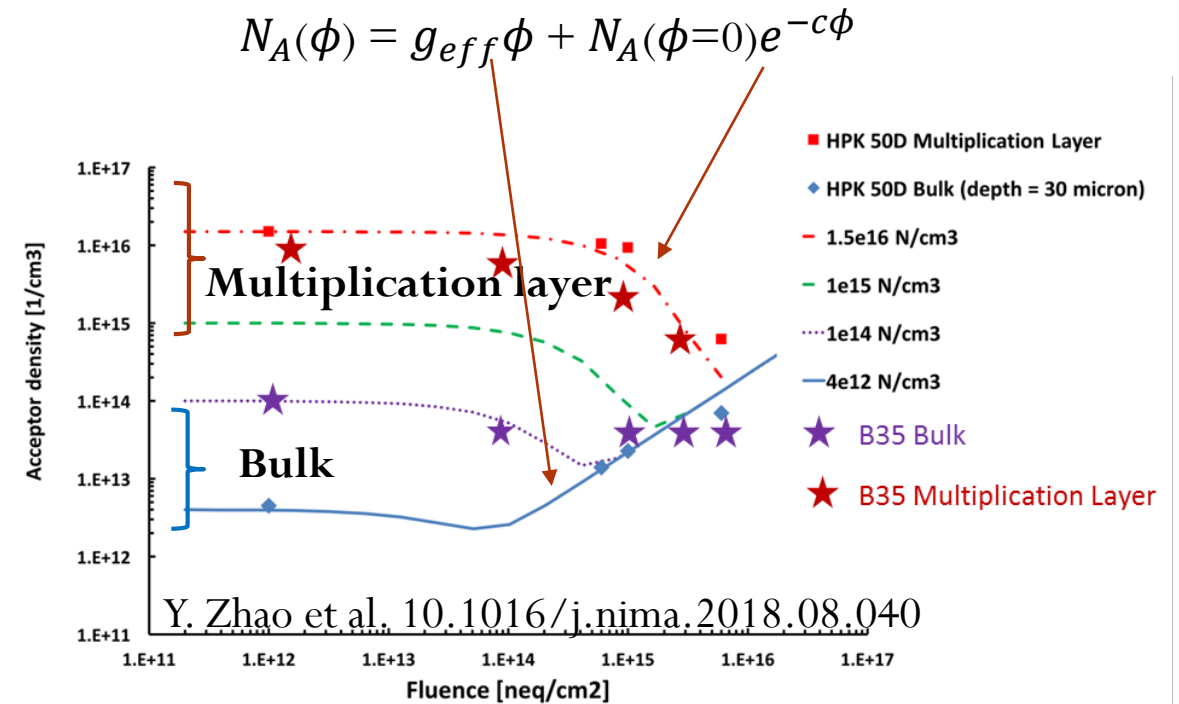
- **LGAD: silicon detector with a thin ( $<5\mu\text{m}$ ) and highly doped ( $\sim 10^{16} \text{ P}++$ ) multiplication (gain) layer**
  - Thin sensors (20-50  $\mu\text{m}$  thick) with internal gain (10-50)
  - **Time resolution  $< 30 \text{ ps}$**
- First application in HEP at HL-LHC
  - Both ATLAS and CMS experiments (<https://cds.cern.ch/record/2719855>, <http://cds.cern.ch/record/2667167>)
- ATLAS HGTD requirements: 4fC of collected charge and 35-70ps of time resolution
  - Maximum irradiation fluence:  $2.5 \cdot 10^{15} \text{ Neq}$
  - LGADs have to maintain the performance (gain, time resolution) after radiation damage
- Several institutions are fabricating LGADs: CNM (Spain), **FBK (Italy)**, **HPK (Japan)**, BNL (US), IME (China), NDL (China)





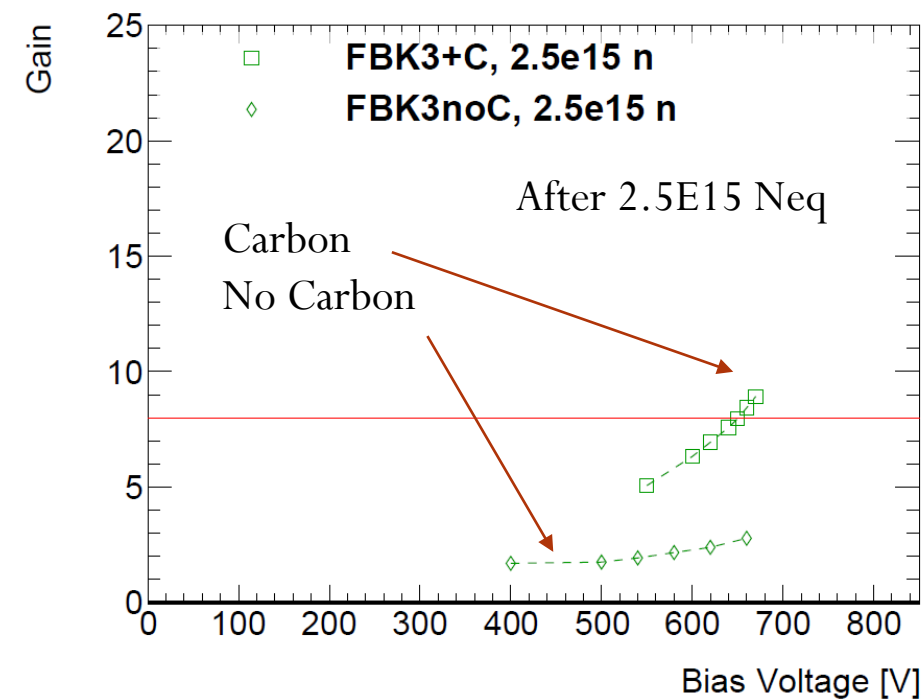
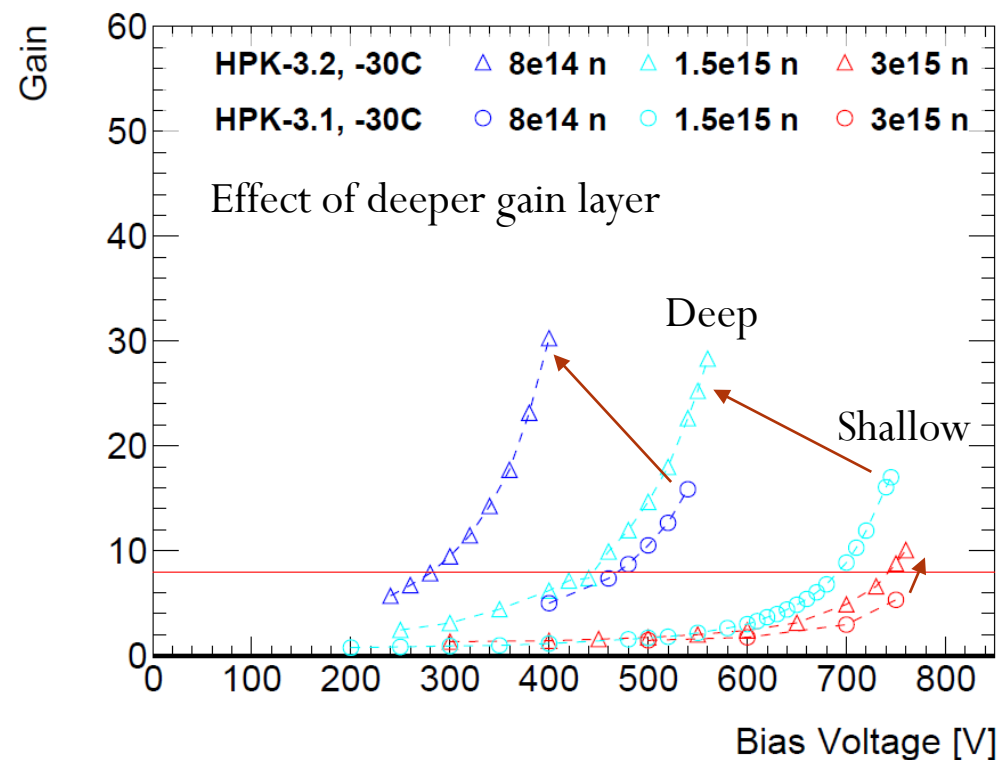
# Radiation damage on LGADs

- 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:  $N_A(\phi=0)e^{-c\phi}$ 
  - Reduction of doping  $\rightarrow$  reduction of gain
  - **C-factor (acceptor removal constant) depending on detector type (the lower the better)**
- Performance can be partially regained by increasing the applied bias voltage after irradiation
- Sensors irradiated at JSI (Ljubljana) with neutrons



# Mitigation of radiation damage

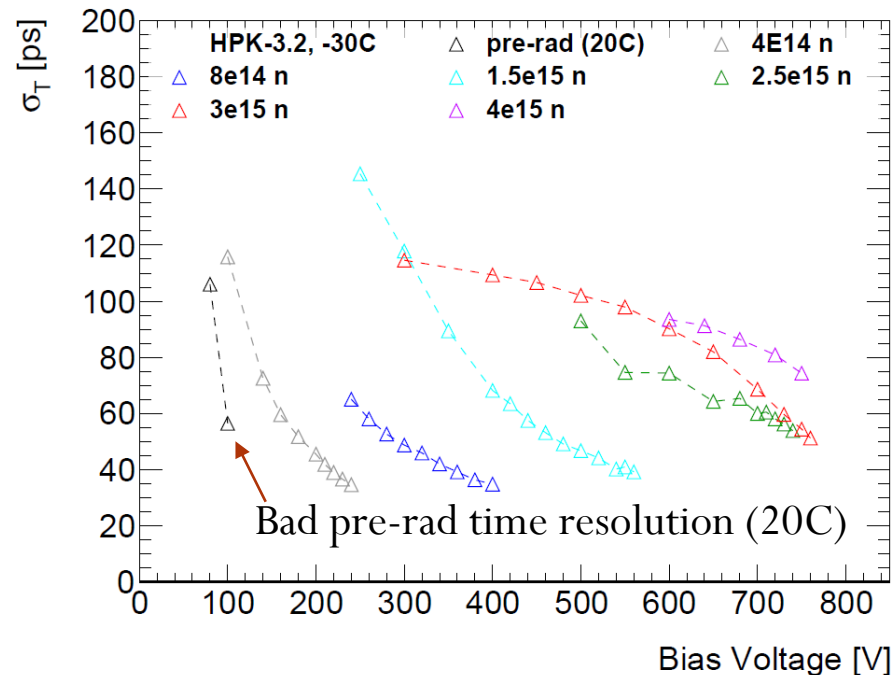
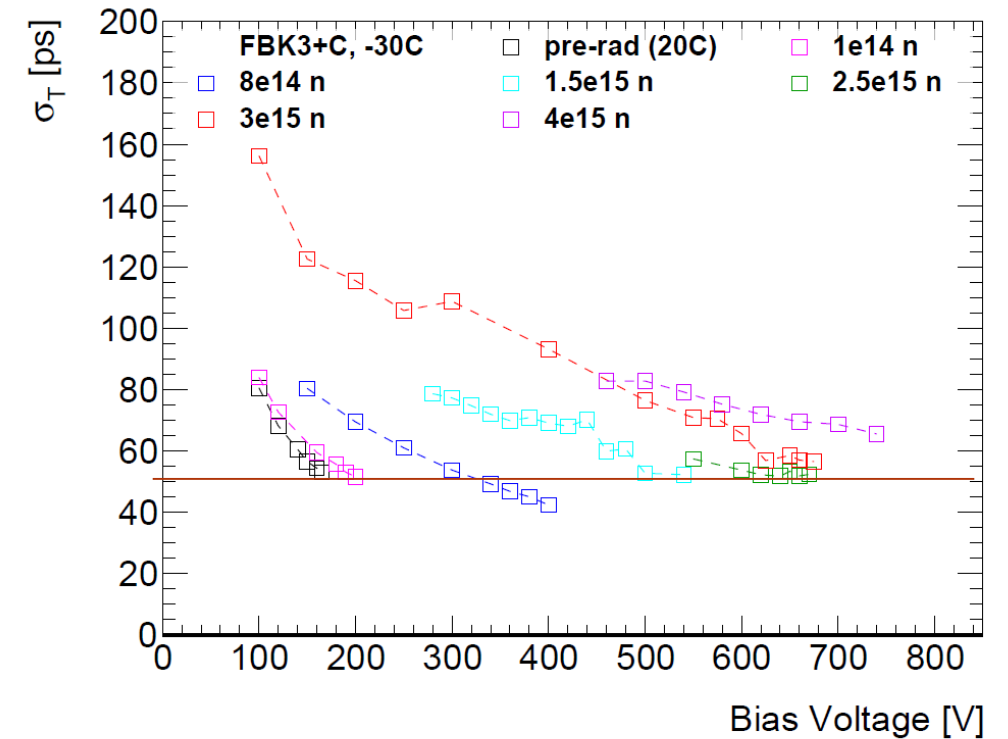
- **Carbon implantation in the gain layer**
  - Carbon is electrically inactive (no effect pre-irradiation)
  - Catch interstitials instead of Boron
- Reduction of acceptor removal after irradiation



- **Thin but highly doped gain layer**
  - Higher initial doping concentration
  - Takes more time to be inactivated
- **Deep gain layer**
  - Higher field for larger volume
  - Increase effectiveness of bias voltage increase after irradiation
- **Gallium instead of Boron as dopant**
  - However no improvement was seen

# 2018-2019 productions

- **2018-2019 FBK and HPK production for ATLAS HGTD and CMS ETL**
  - Both productions show good performance up to  $2.5E15$  Neq
  - However some optimization was still required
- **FBK-UFSD3 sensors**
  - 55um nominal thickness  $\rightarrow$  minimum time resolution  $\sim 40$ -50ps
  - Carbon level not optimized
  - Shallow gain layer

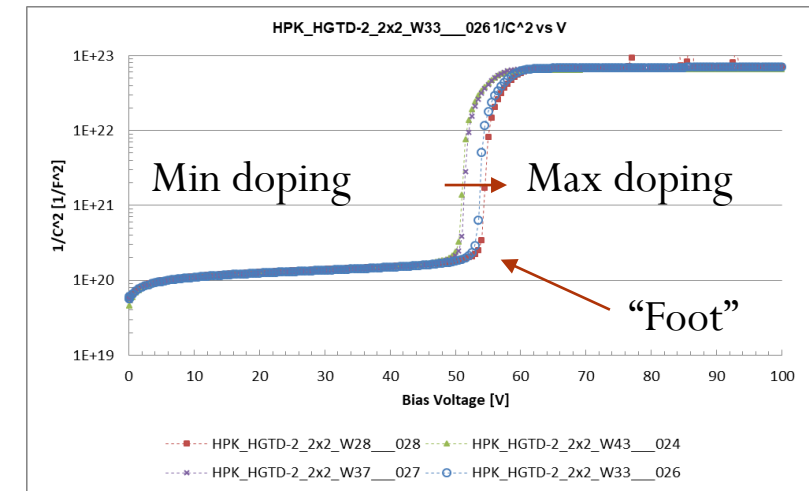


- **HPK-HGTD1 sensors**

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

# Mitigation of radiation damage: 2020 productions

- **HPK-HGTD2** production
- Optimization of doping concentration in the gain layer for best behavior before and after irradiation
- 4 splits with  $\sim 2\%$  step down in doping concentration from HPK-3.2 (previous production)
- Shown for a  $1/C^2$  (capacitance) plot (right), “foot” is proportional to gain layer doping

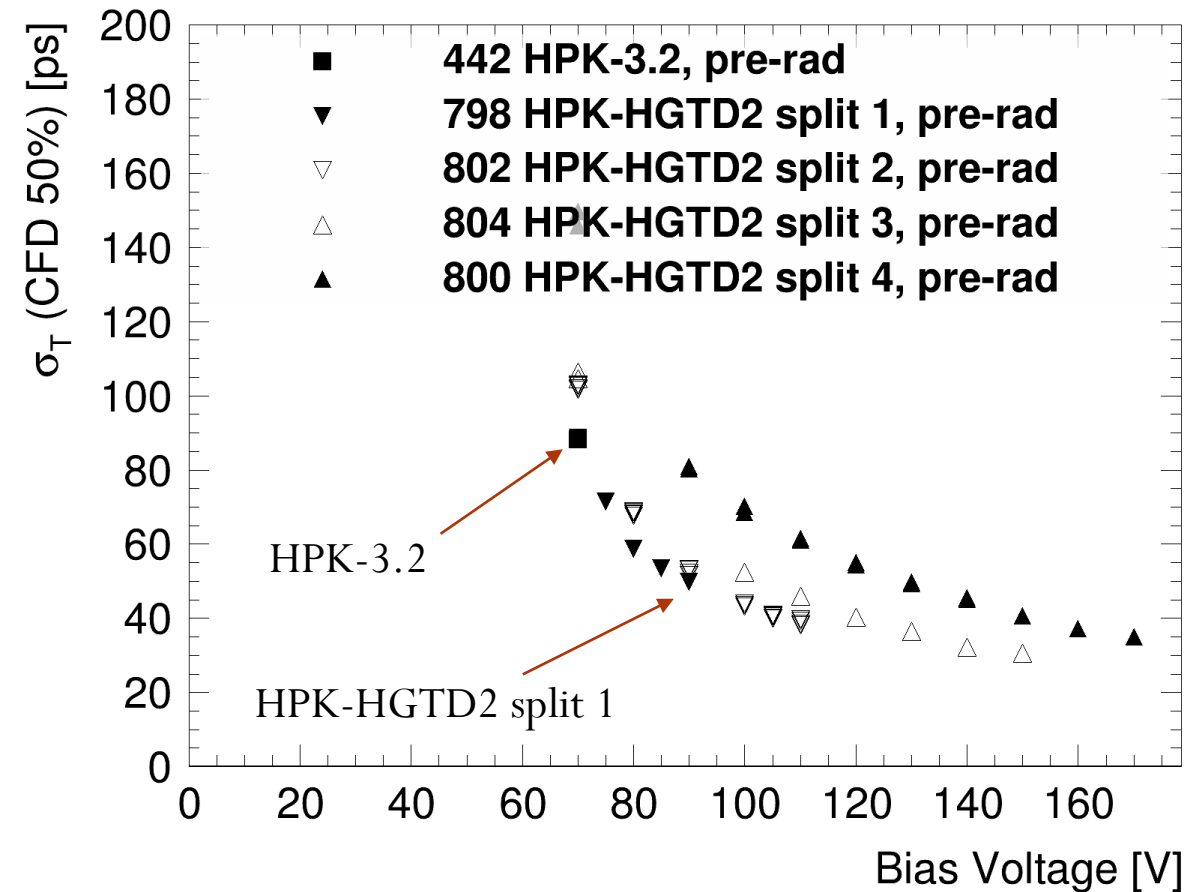
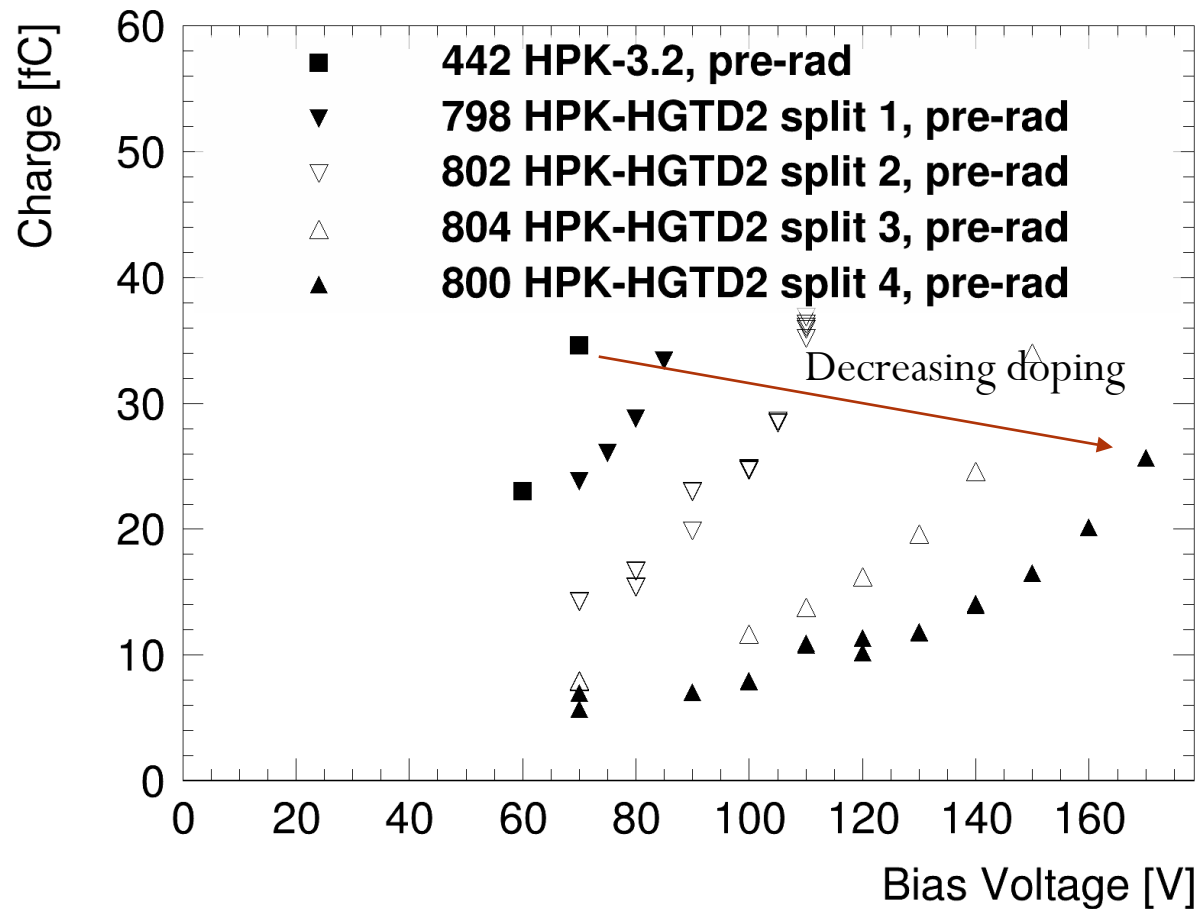


- **FBK-UFSD3.2** sensors
  - Optimization of the Carbon level
  - Thinner bulk (better time resolution)
  - Combination of deep gain layer and Carbon implantation
  - Different array inter-pad gap
- Wafers under study (quoted nominal thicknesses):
  - W7  $\rightarrow$  55um bulk, Carbon (same as previous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

Wafer #	thickness	GL DEPTH	Dose Pgain	Carbon	Diffusion
1	45	Standard	L	1*A	CHBL
3	45	Standard	L	0.8*A	L
4	45	Standard	L	0.4*A	L
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

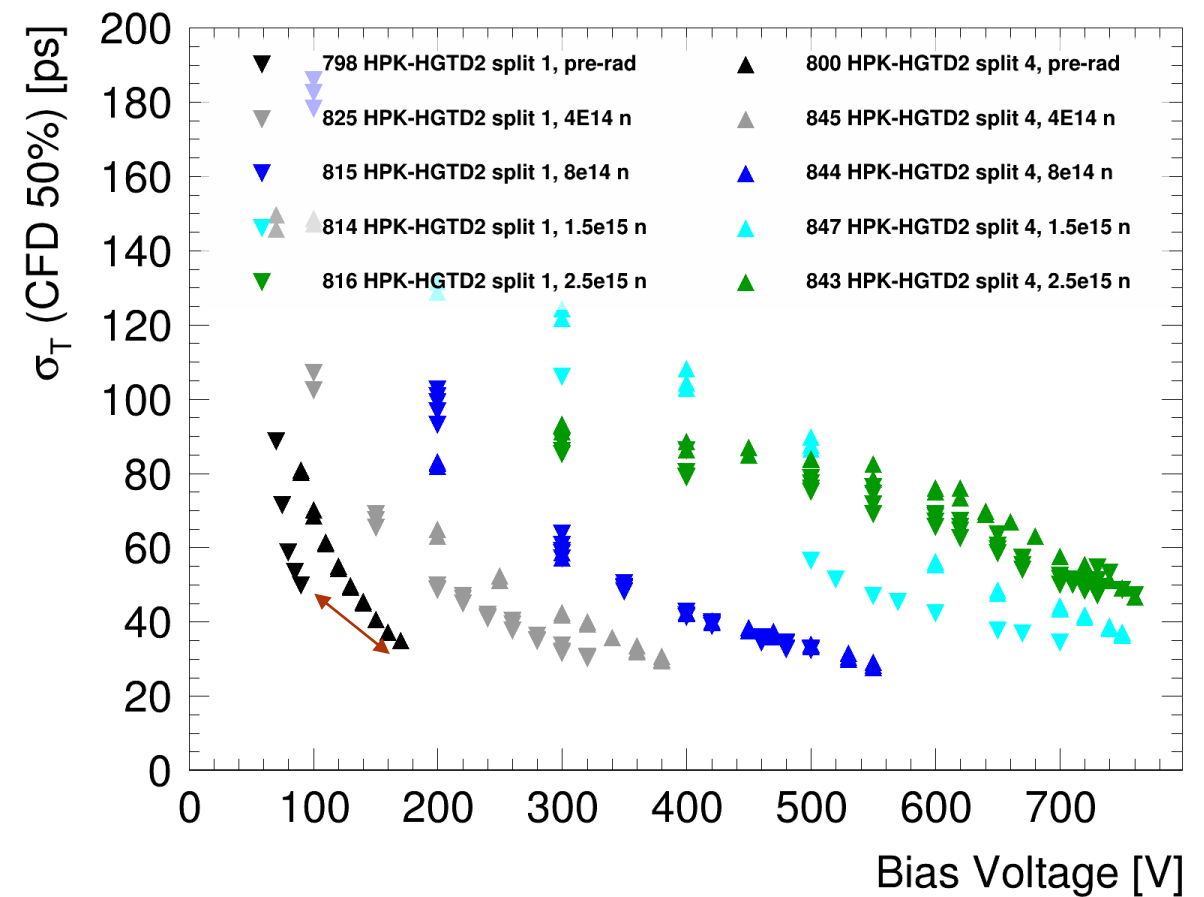
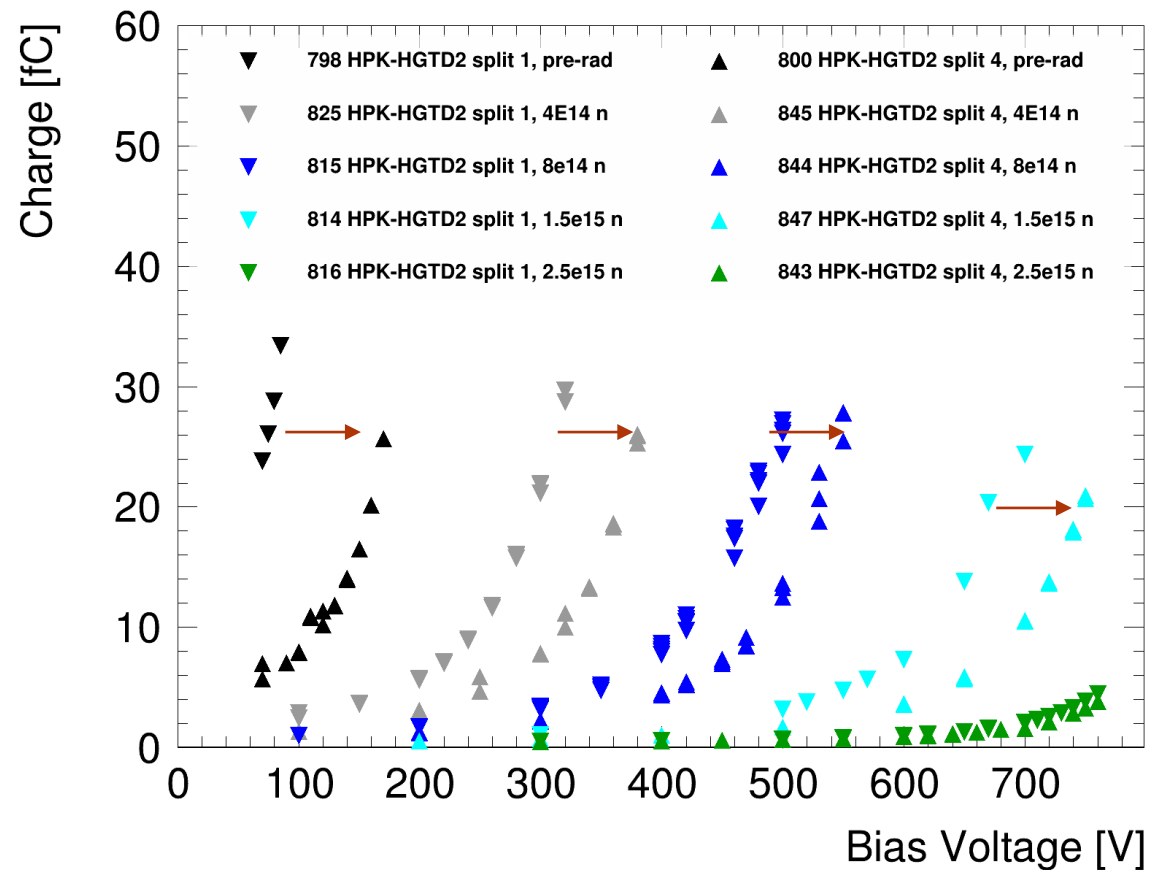
# HPK LGAD performance before irradiation

- HPK successfully tuned the gain layer to optimize performance before irradiation
- Starting point (highest doping and 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



# HPK LGAD performance after irradiation split 1 and 4

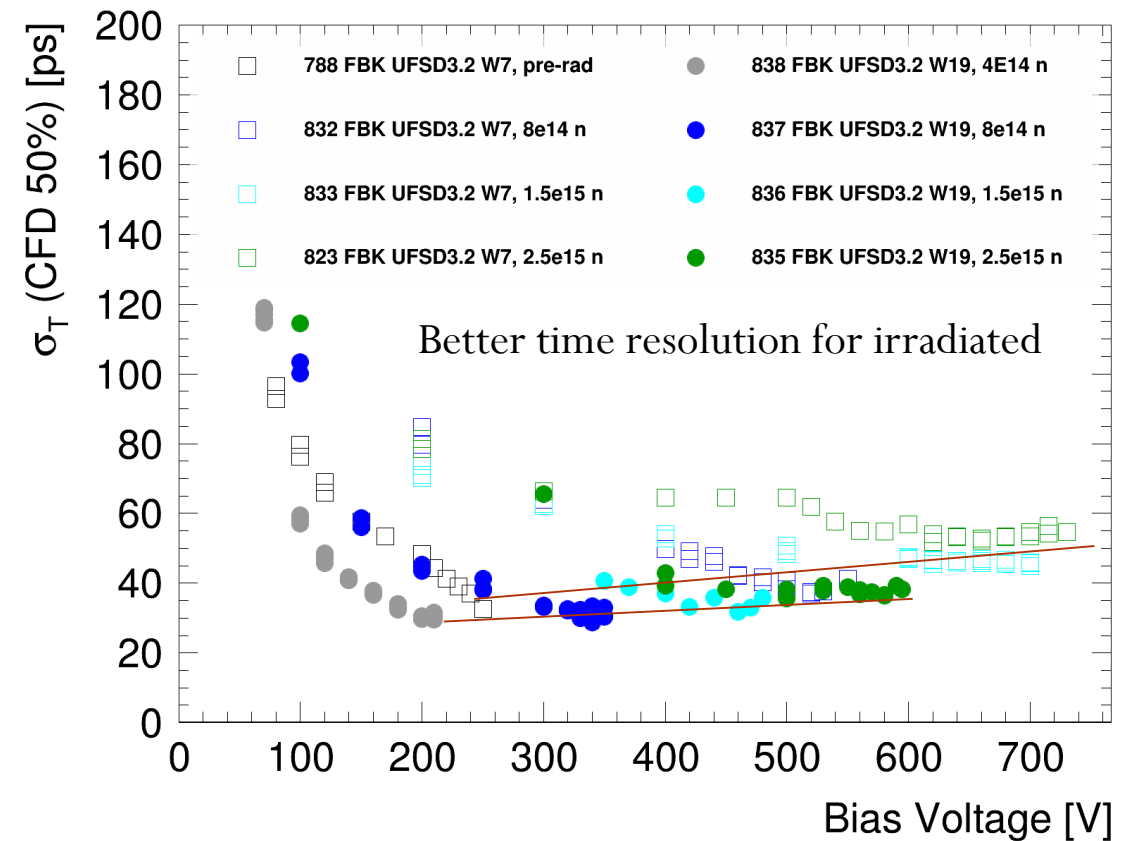
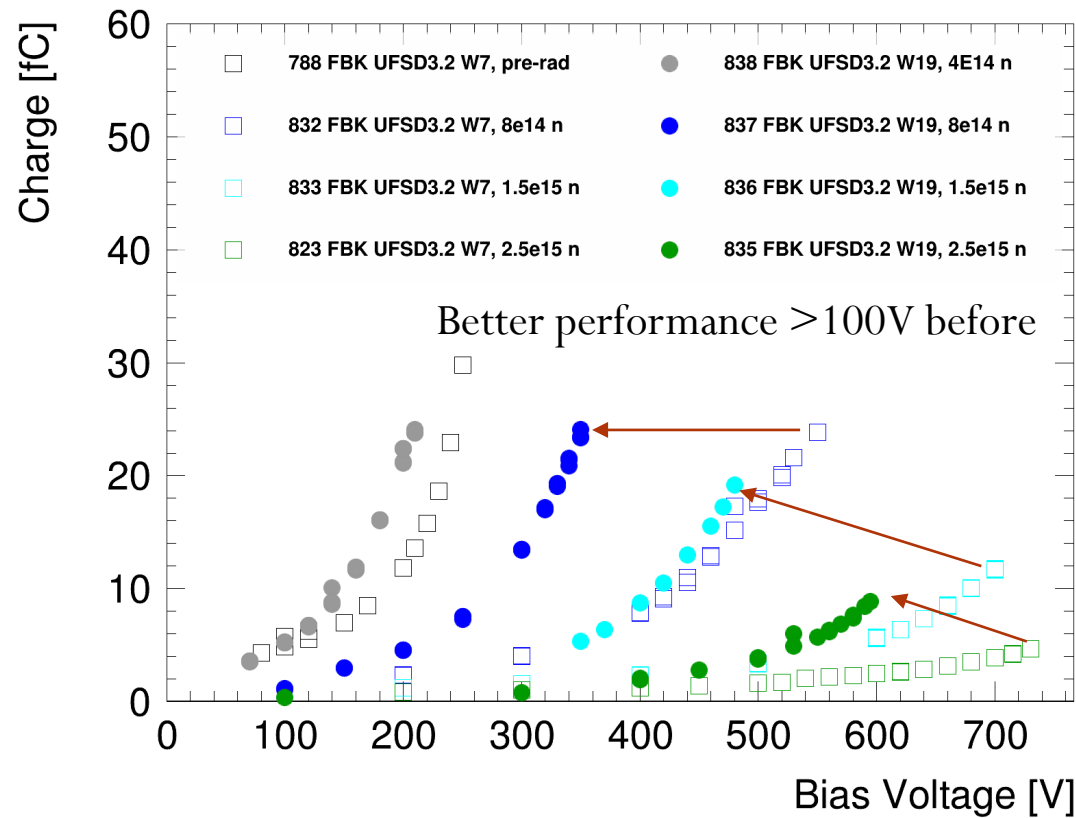
- Showing performance for HPK split 1 (highest doping) and split 4 (lowest doping)
- Distance between gain curves is more or less constant (at  $2.5E15$  Neq are very similar)
- Time resolution is better for split 4 at the beginning but at  $4E14$  Neq the two splits are the same



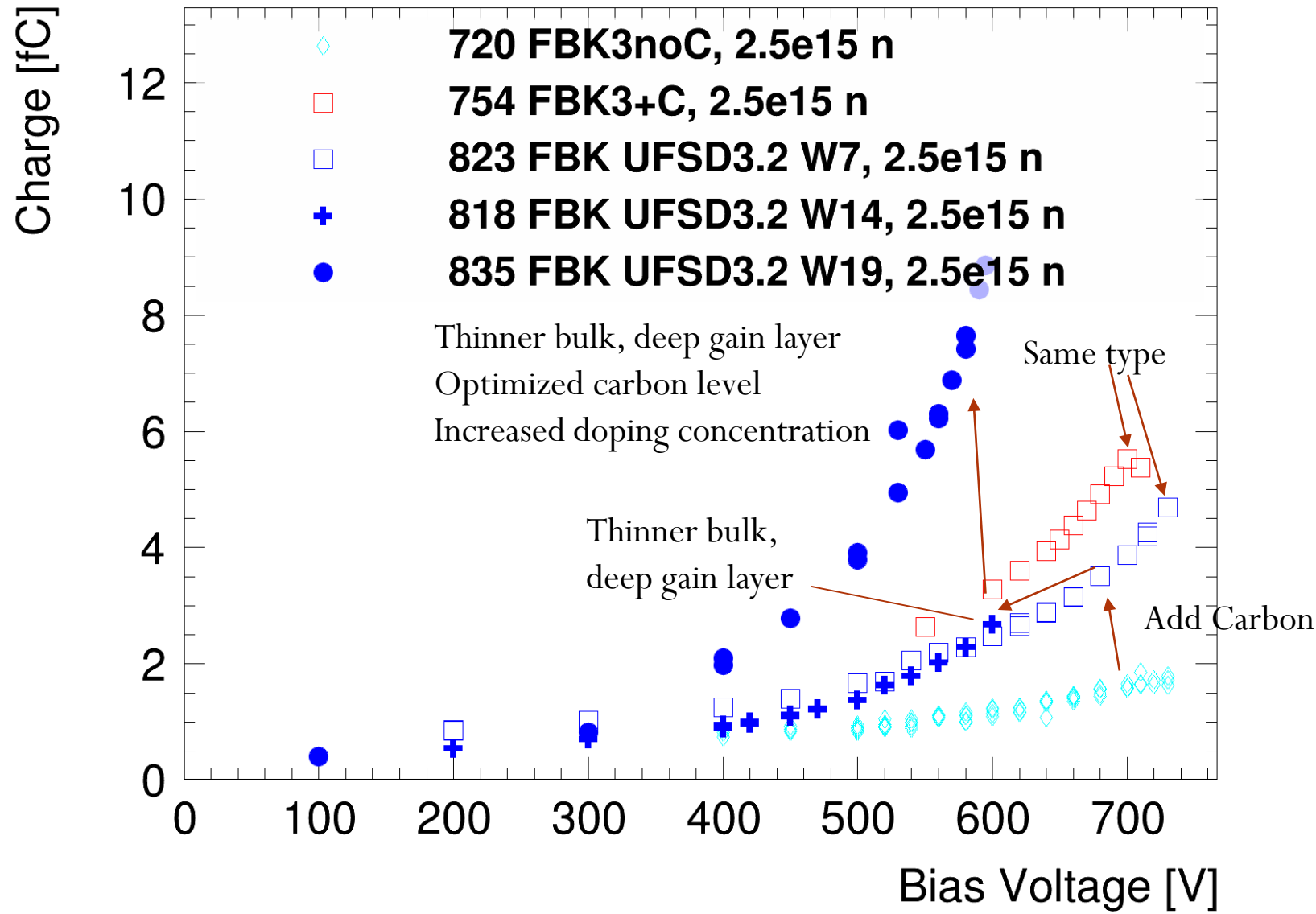


# FBK LGAD performance after irradiation

- 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

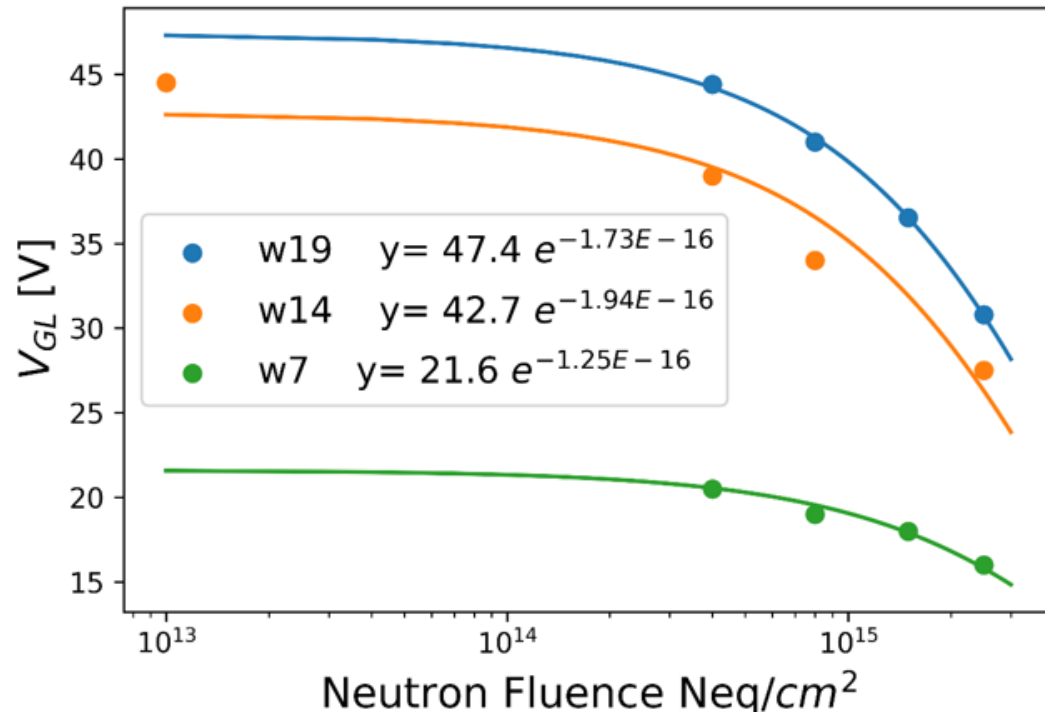


- **FBK UFSD3.2 sensors show the great potential of deep gain layer and Carbon implantation**
- FBK3noC (no carbon) has the worse performance
- FBK3+C and FBK UFSD3.2 (same structure with Carbon) have much better performance
- FBK UFSD3.2 W14 with deep gain layer is similar to FBK3+C but has thinner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

[https://indico.cern.ch/event/983068/contributions/4223171/attachments/2191347/3703735/020221\\_TREDI\\_LGAD\\_radhard.pdf](https://indico.cern.ch/event/983068/contributions/4223171/attachments/2191347/3703735/020221_TREDI_LGAD_radhard.pdf)  
[https://indico.cern.ch/event/983068/contributions/4223173/attachments/2191413/3703863/17022021\\_MarcoFerrero.pdf](https://indico.cern.ch/event/983068/contributions/4223173/attachments/2191413/3703863/17022021_MarcoFerrero.pdf)  
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# 1/C^2 Foot vs fluence

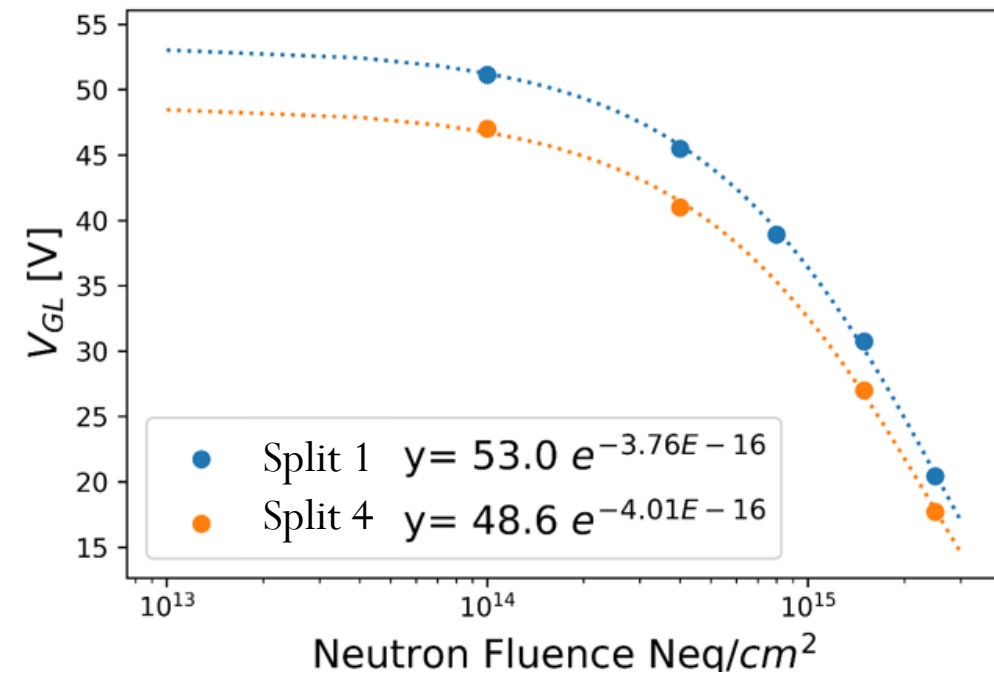
Fitted with  $N_D = N_0 e^{-c\phi}$



- “Foot”: flat part of a CV before full depletion
  - Proportional to gain layer doping concentration
  - Fitted vs fluence to extract c-factor
- **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

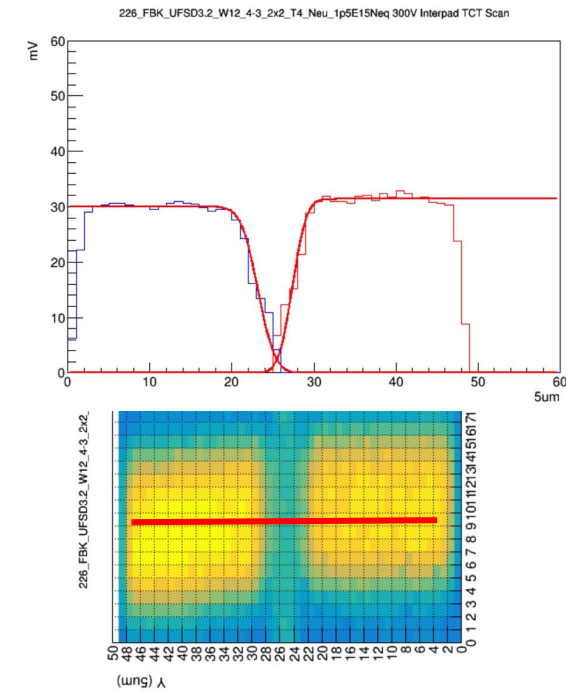
## • HPK-HGTD2

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



# 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 ( $\sim 0$  C for irradiated,  $\sim 20$  C for non irradiated)
  - Sensors mounted on fast boards, read out by fast oscilloscope and probed with a 1064 nm laser
  - Pulse maximum (Pmax) as a function of position
- FBK array tested
  - Type 4: safe, nominal IP 24  $\mu$ m
  - Type 10: super safe, nominal IP 49  $\mu$ m
  - Type 2: medium, nominal IP 21  $\mu$ m
- Fit the Pmax distribution using error function.
- Inter-pad gap measured as distance from each 50% point.
- Sensors measured before and after irradiation



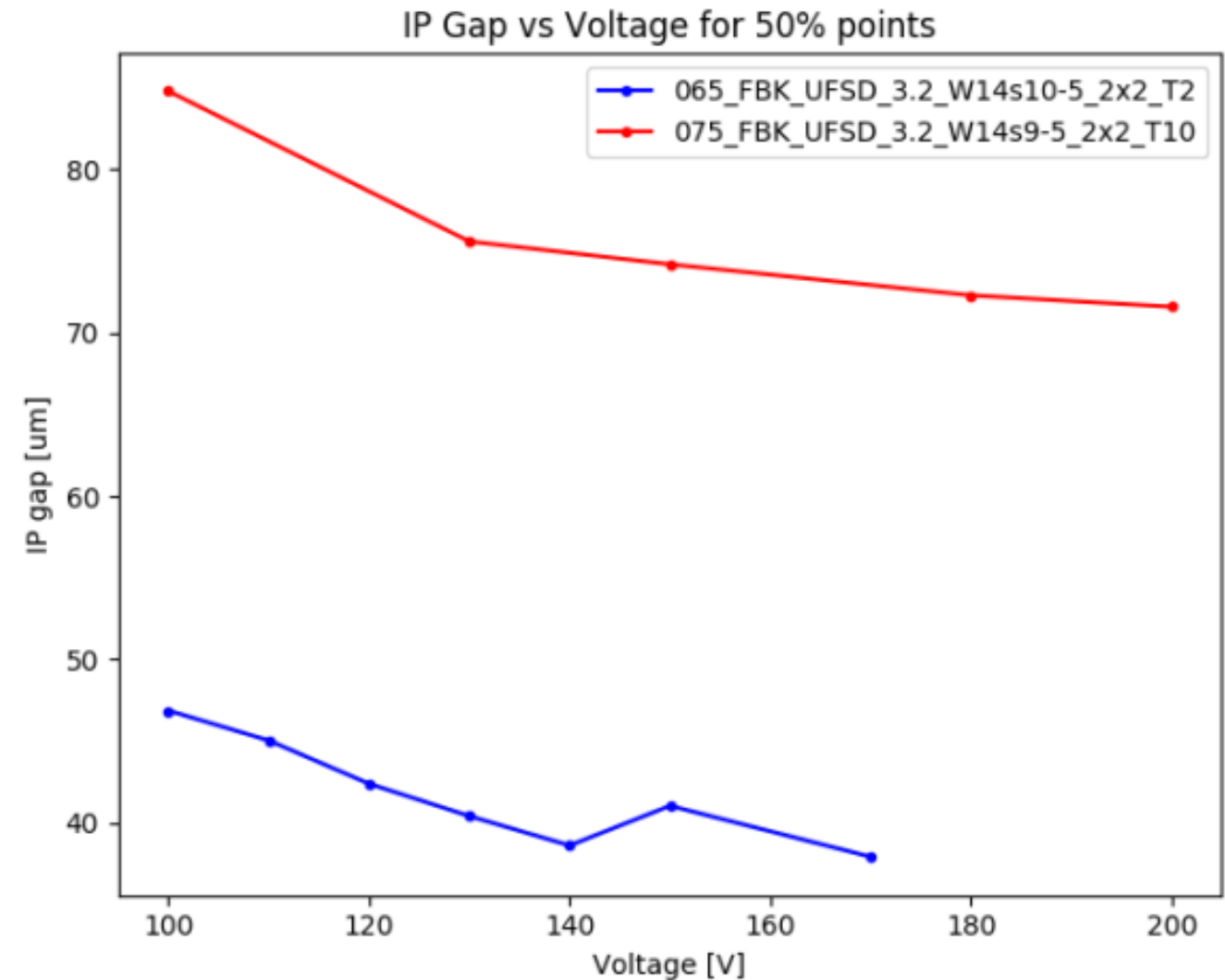
Type	Nominal width [ $\mu$ m]	Inter-pad design	Strategy
1	16	grid + extra grid	Aggressive
2	21	grid	Medium
4	24	grid	Safe
5	25	grid	
7	28	grid + extra grid	
8	28	grid + extra grid	Super safe
9	38	2 p-stop	
10	49	2 p-stop + bias grid	
11	21	grid	Medium



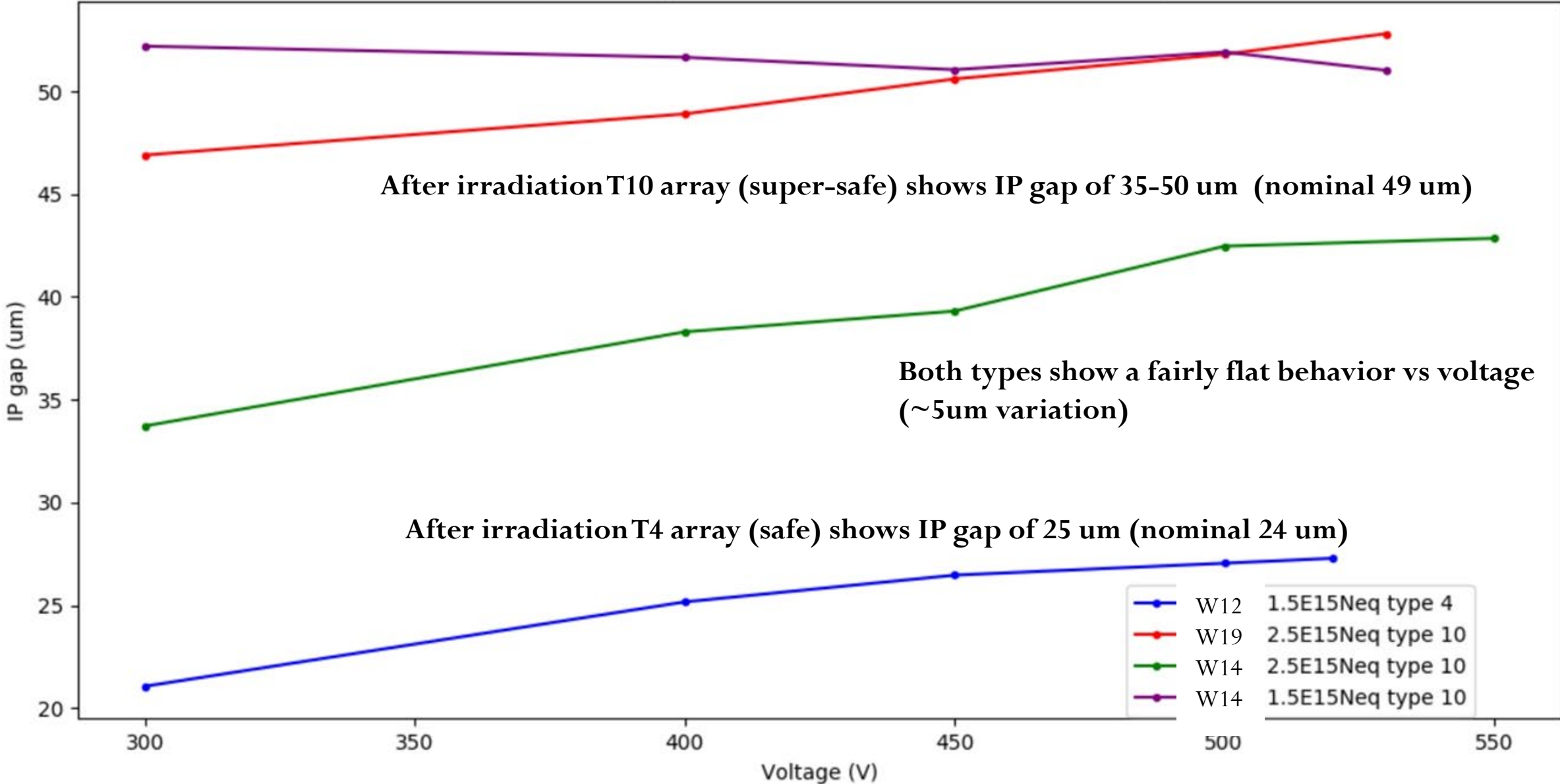
# TCT IP gap measurements

Many thanks to Basil Darby!

- FBK UFSD3.2 pre-rad sensors show an IP gap larger than nominal
  - Type 2, nominal 21  $\mu\text{m}$ , real  $\sim 50 \mu\text{m}$
  - Type 10, nominal 49  $\mu\text{m}$ , real  $\sim 75 \mu\text{m}$
- Variation of  $\sim 10 \mu\text{m}$  with applied bias voltage
- After irradiation the IP gap is more similar to the nominal value (see next slide)
  - Before irradiation the IP gap is usually larger because of the lower bias voltage applied



IP Gap vs Voltage for FBK at 1.5E15Neq and 2.5E15Neq



# Conclusions

- **To increase the radiation hardness of LGADs:**
  - Carbon
  - Deep gain layer
  - **Combination of the two**
- LGADs from previous production of HPK and FBK showed **reasonable performance up to  $2.5E15\text{Neq}$**  (Max at HGTD)
  - However further optimization was needed
- **New HPK production with tuned gain layer shows good behavior before and after irradiation**
- **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
- With IP gap  $\sim 50$   $\mu\text{m}$  or less after irradiation for the “super-safe” array type ( $\sim 75$   $\mu\text{m}$  before irradiation)



## **Many thanks to the SCIPP group students and technicians!**

Thanks to the FBK team for producing and providing the sensors for this study

Thanks to HPK for producing and providing the sensors for this study

Thanks to the IJS Lubjiana group for irradiating sensors for this study

This work was supported by the United States Department of Energy,  
grant DE-FG02-04ER41286

This work was partially performed within the CERN RD50 collaboration.

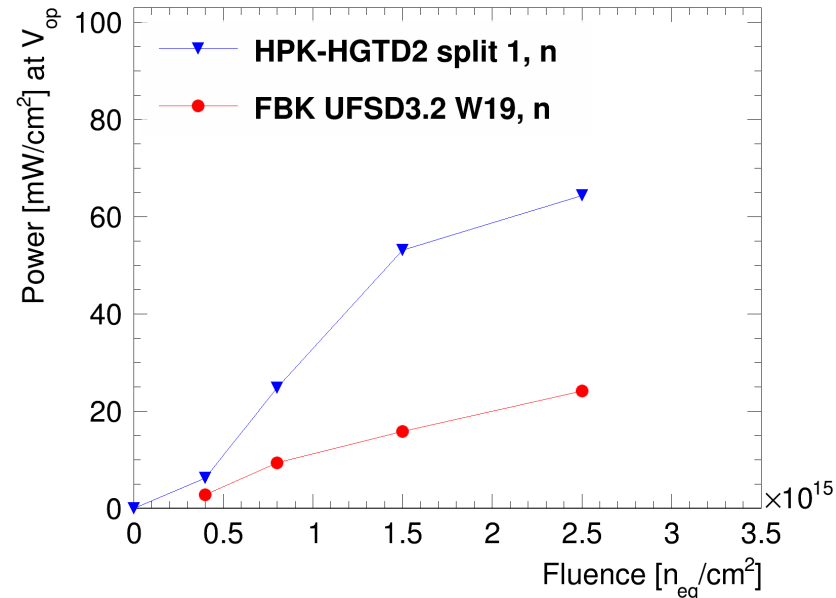
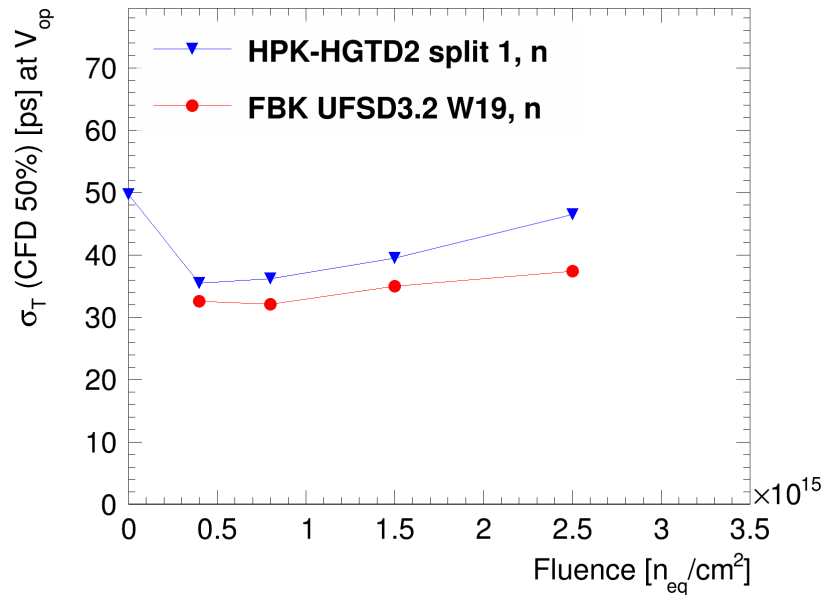
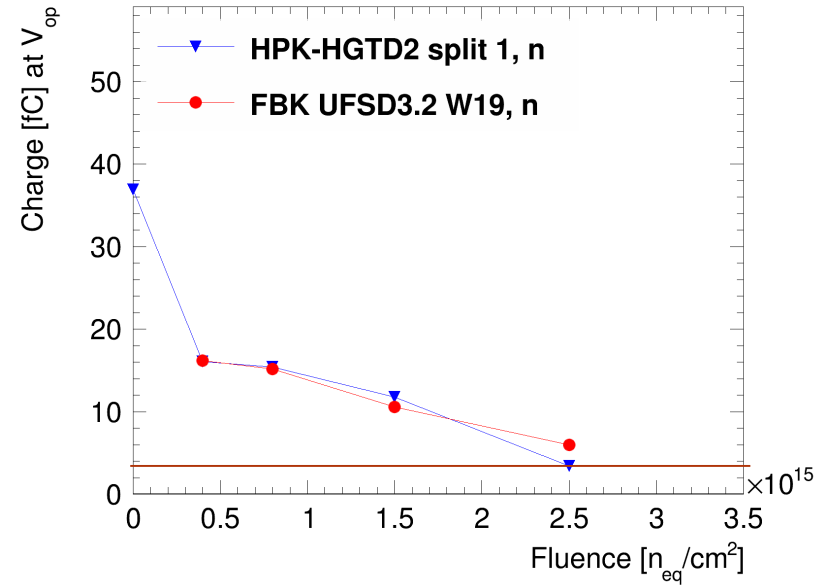
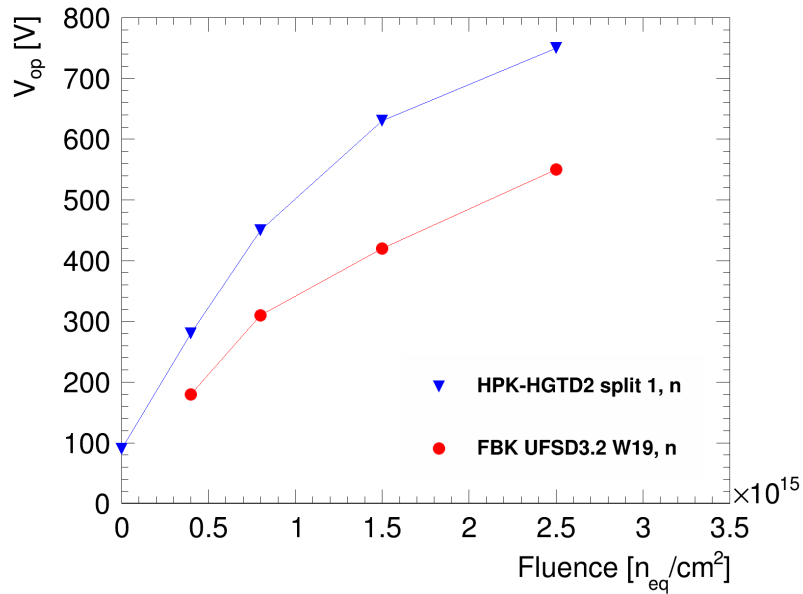
Part of this work has been financed by the European Union's Horizon 2020 Research and Innovation funding program, under Grant Agreement no. 654168 (AIDA-2020) and Grant Agreement no. 669529 (ERC UFSD669529), and by the Italian Ministero degli Affari Esteri and INFN Gruppo V.



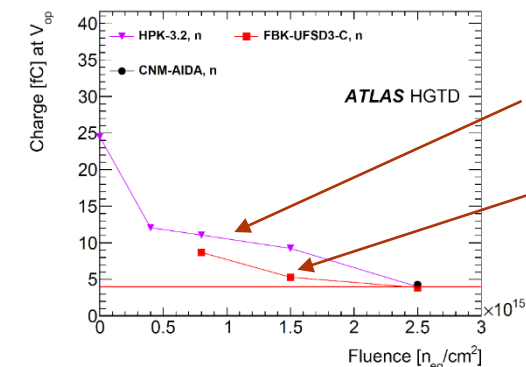
# Backup

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# HPK-FBK best type comparison



- Characterization similar to HGTD TDR
  - <https://cds.cern.ch/record/2719855>
- Chosen  $V_{op}$  (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



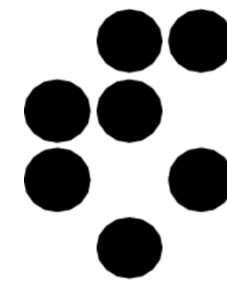
HPK HGTD-2 split 1  
Similar to HPK-3.2

FBK UFSD3.2 W19  
much better than  
FBK UFSD3

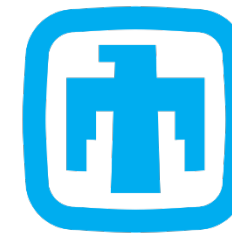
14-Sep-21

# Irradiation campaigns on LGADs

- Irradiation campaign on LGADs
- Sensors were irradiated at
  - JSI (Lubiana) with  $\sim 1$  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:  $1\text{E}13 \text{ Neq}/\text{cm}^2 \rightarrow 1\text{E}16 \text{ Neq}/\text{cm}^2$
- Ionizing dose up to 4MGy



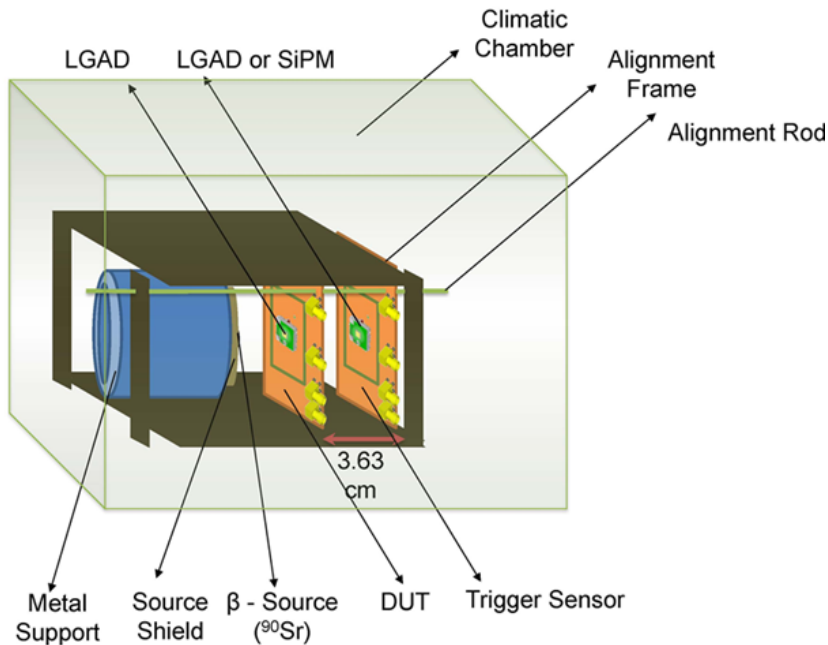
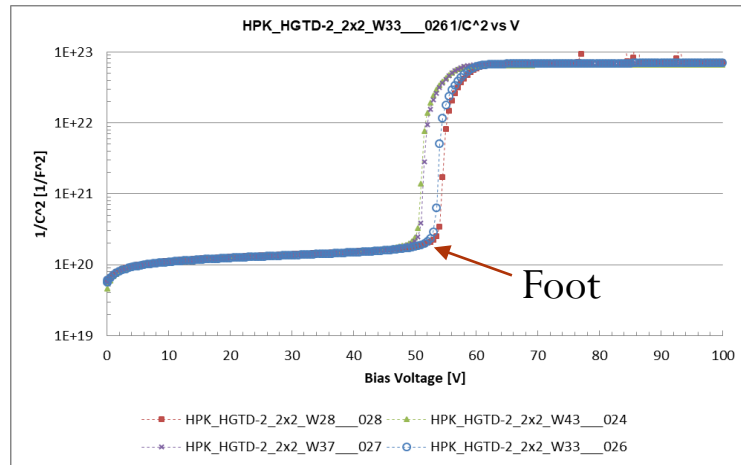
**Jožef Stefan Institute**



**Sandia  
National  
Laboratories**



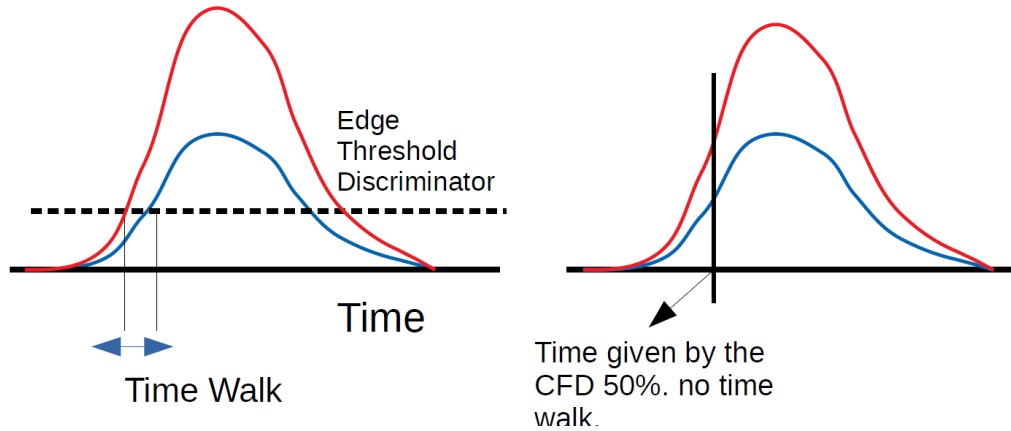
# Sensor testing – Sr90 telescope, probe station



- **Probe station electrical testing**
- Capacitance over voltage (CV)
- Study of the “foot” (flat region before full depletion) for LGADs on the  $1/C^2$  distribution
  - Corresponding to full depletion of the gain layer
  - Variation of the foot with radiation damage
- **Laboratory charge collection**
- Using MiP electrons Sr90  $\beta$ -source ( $\beta$ -telescope)
  - Sensors mounted on fast amplifier boards and read out by an oscilloscope
  - Signal shape, noise, **collected charge**, gain, **time resolution**



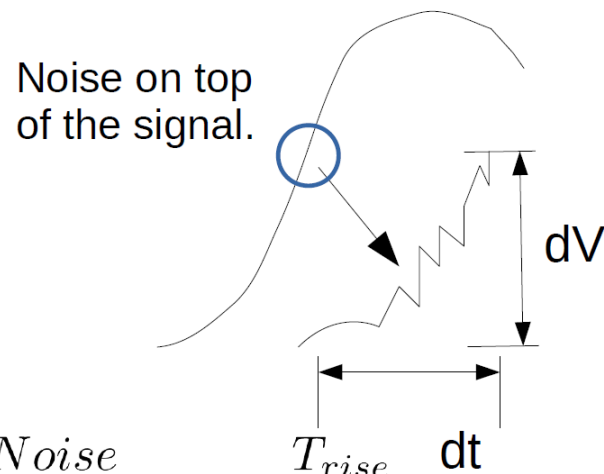
# LGADs timing resolution



## Sensor time resolution main terms

$$\sigma_{\text{timing}}^2 = \sigma_{\text{time walk}}^2 + \sigma_{\text{Landau noise}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2$$

- 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  $\mu\text{m}$ )
- Jitter:
  - Proportional to  $1/\frac{dV}{dt}$
  - Reduced by increasing S/N ratio with gain

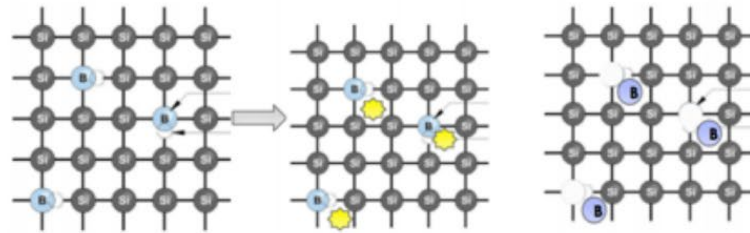
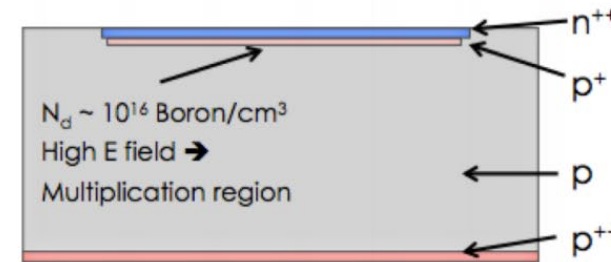


$$\sigma_{\text{Jitter}} = \frac{\text{Noise}}{dV/dt[\text{CFD}\%]} \approx \frac{T_{\text{rise}}}{\text{SNR}}$$

# Acceptor removal

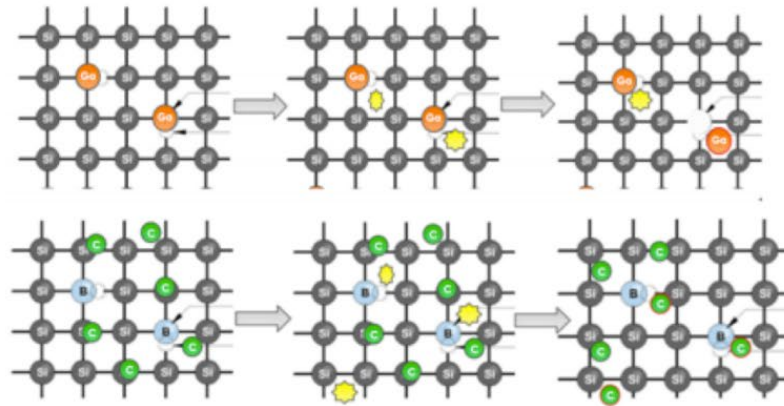
**Unfortunate fact:** irradiation de-activate p-doping removing Boron from the reticle

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



**Boron**  
Radiation creates interstitial defects that inactivate the Boron:  $Si_i + B_s \rightarrow Si_s + B_i$   
 $B_i$  might interact with Oxygen, creating a donor state

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

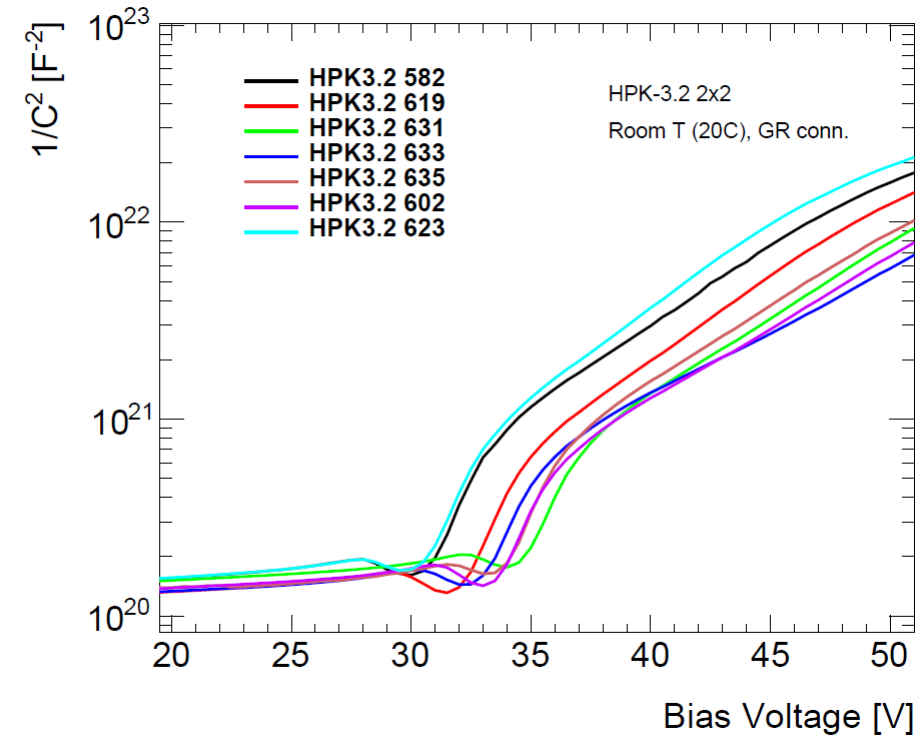
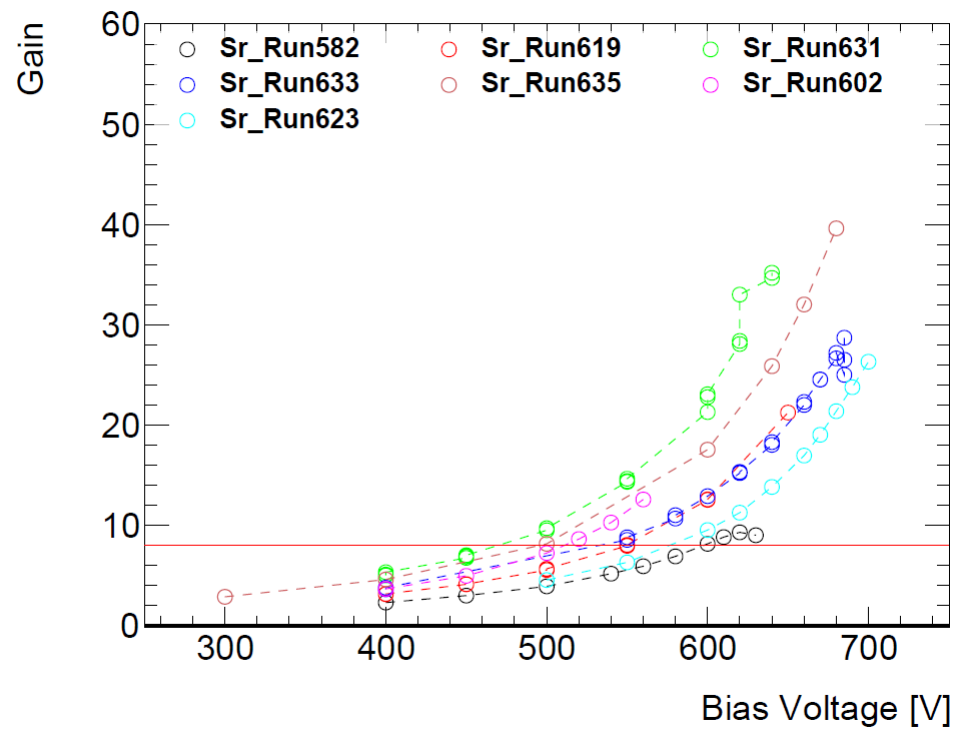


**Gallium**  
From literature, Gallium has a lower probability of becoming interstitial

**Carbon**  
Carbon competes with Boron and Gallium in reacting with Oxygen

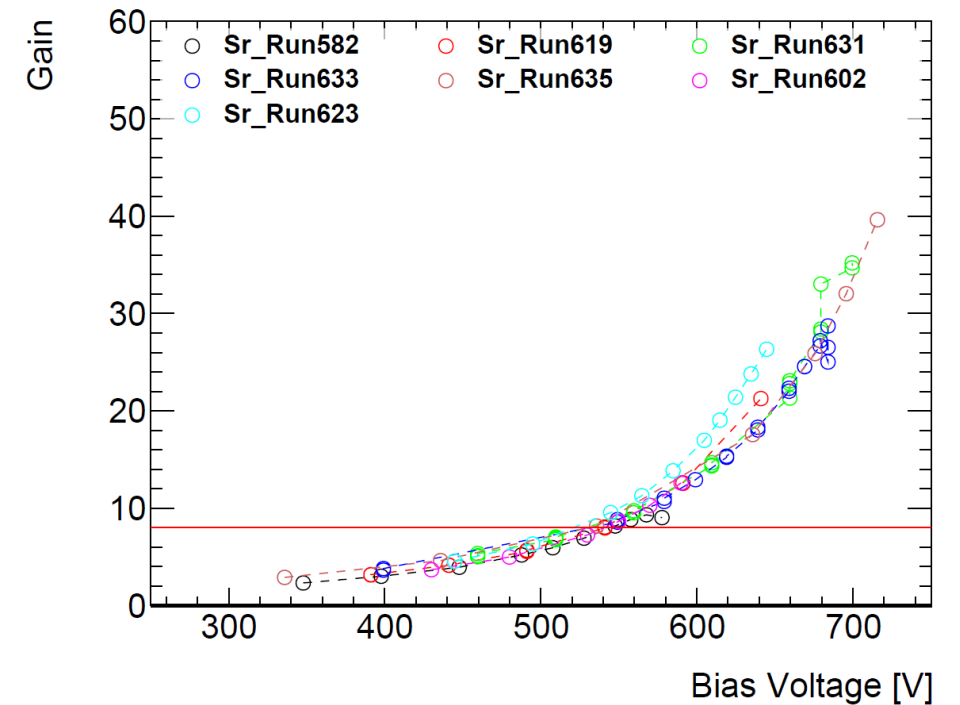
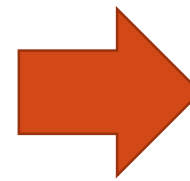
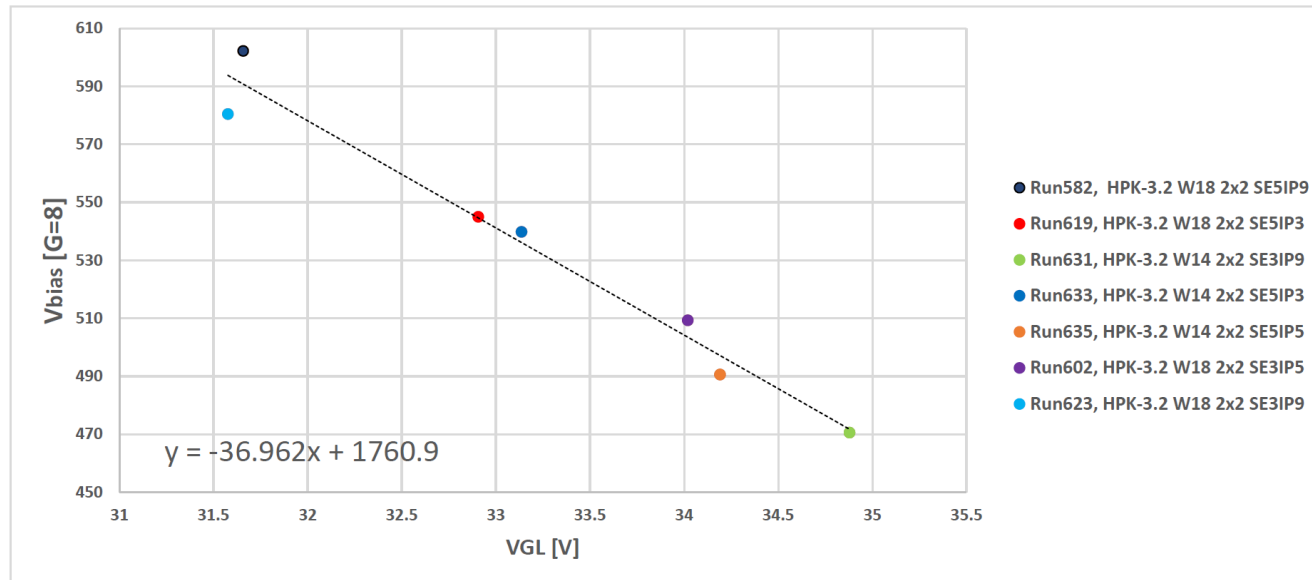
# Variation of performance after irradiation

- 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





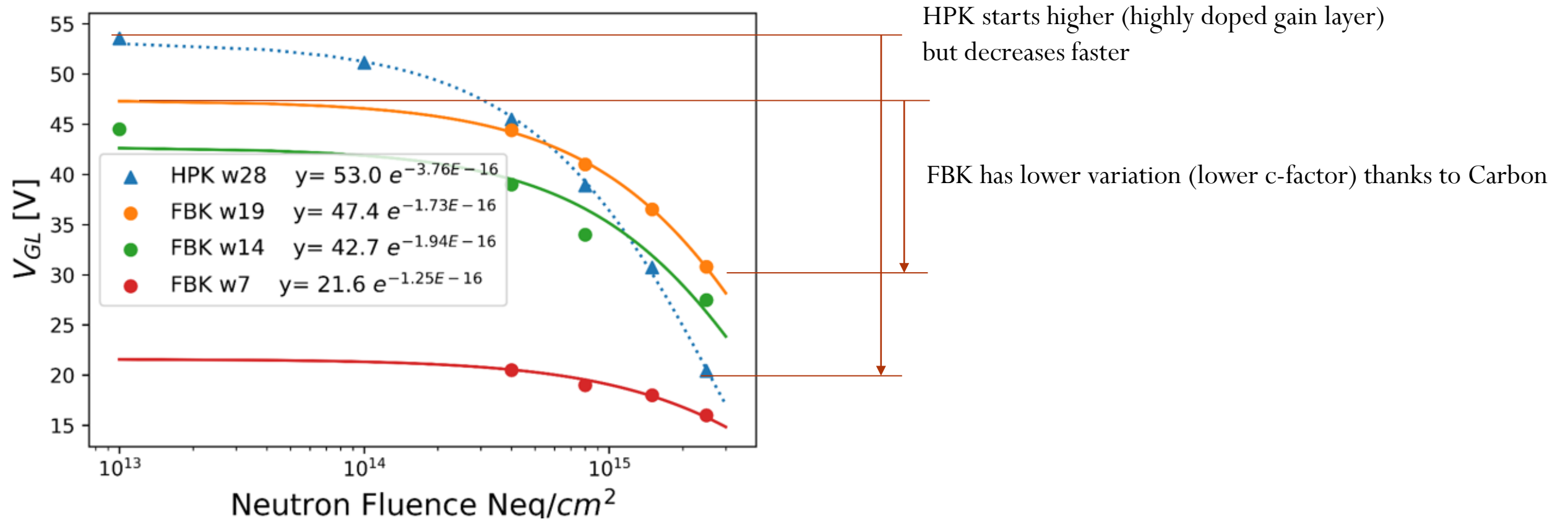
# Probe station measurements

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Many thanks to Nikita Tournebise!

# Gain layer vs. Fluence: comparison

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



# Correlation of $V_{GL}$ and $V(CC=4)$

- Correlation of voltage needed to reach 4fC of charge (HGTD requirement) and foot measured from CV
- Good linear correlation observed
  - A couple points to be verified

