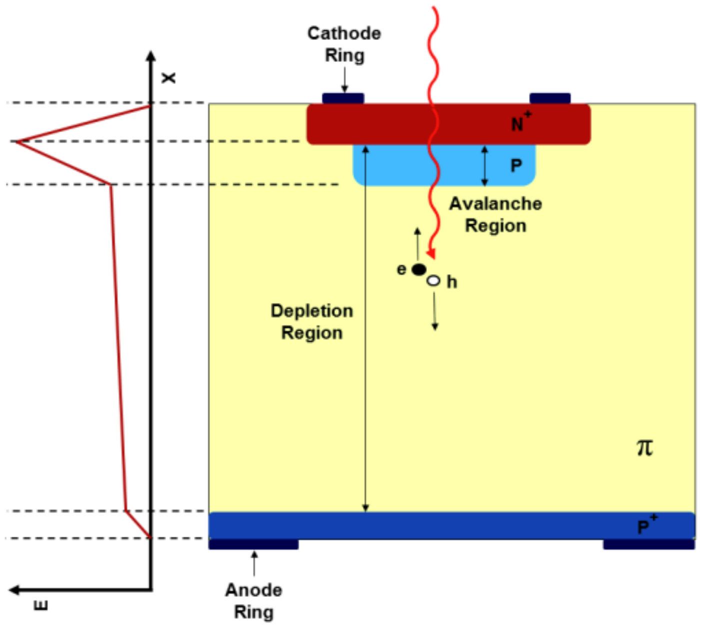
Overview of radiation resistant LGAD designs

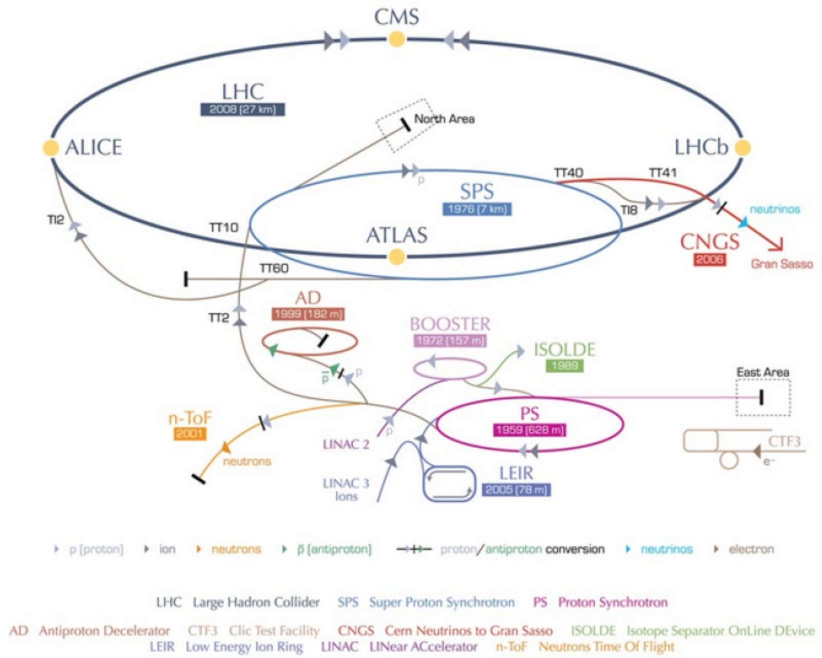
CPAD workshop (2021, Virtual)

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

LGADs in HEP

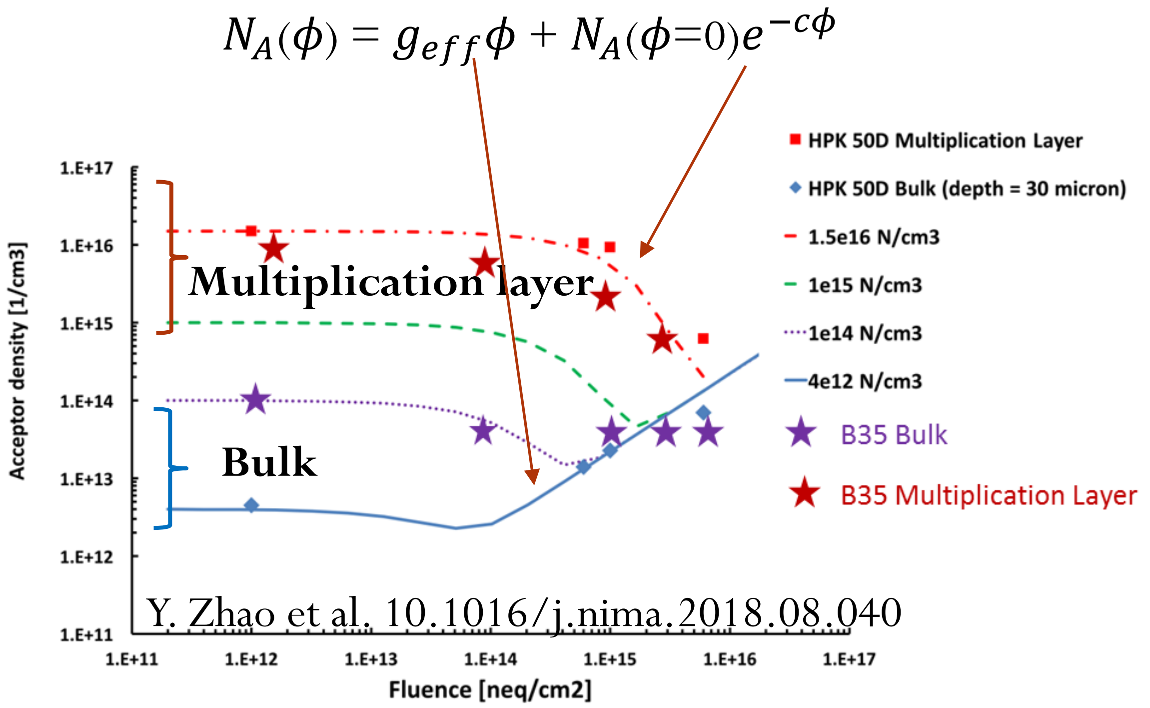
- **LGAD: silicon detector with** a thin (<5µm) and **highly doped** (~10^{16} P++) **multiplication** (gain) **layer**
  - Thin sensors (20-50 um thick) with internal gain (10-50)
  - **Time resolution < 30 ps**
- First application in HEP at HL-LHC
  - Both ATLAS and CMS experiments (https://cds.cern.ch/record/2719855, http://cds.cern.ch/record/2667167)
- ATLAS HGTD requirements: 4fC of collected charge and 35-70ps of time resolution
  - Maximum irradiation fluence: 2.5·10^15 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)

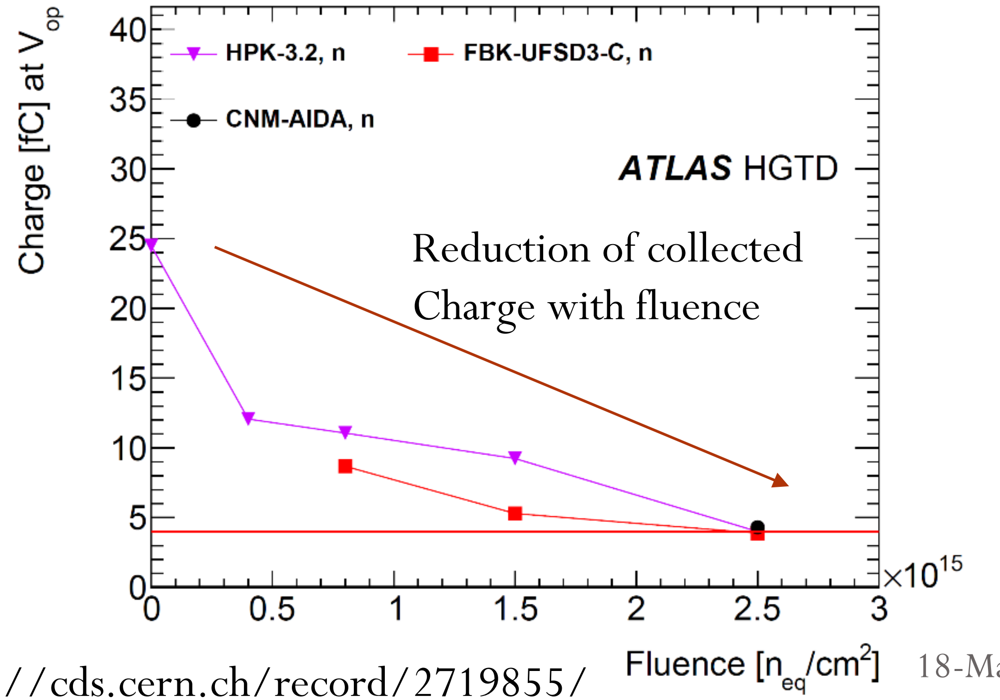




Radiation damage on LGADs

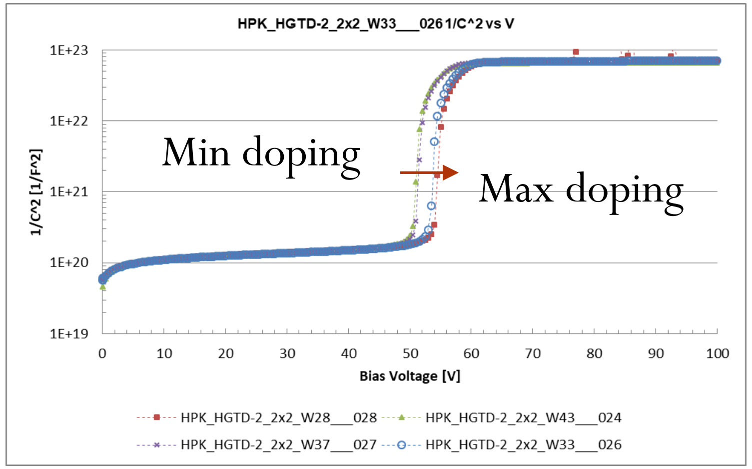
- Most widely accepted radiation damage explanation for LGADs is **acceptor removal**
  - M. Ferrero et al. arXiv:1802.01745, G. Kramberger et al. JINST **10** (2015) P07006
- Radiation damage for LGADs can be parameterized
  - $N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$
- Acceptor creation: $g_{eff}\phi$
  - By creation of deep traps
- Initial acceptor removal mechanism: $N_A(\phi{=}0)e^{-c\phi}$
  - Reduction of doping → 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
- Sensors were also proton irradiated at CERN IRRAD (CH), Los Alamos (US), KEK (Japan)

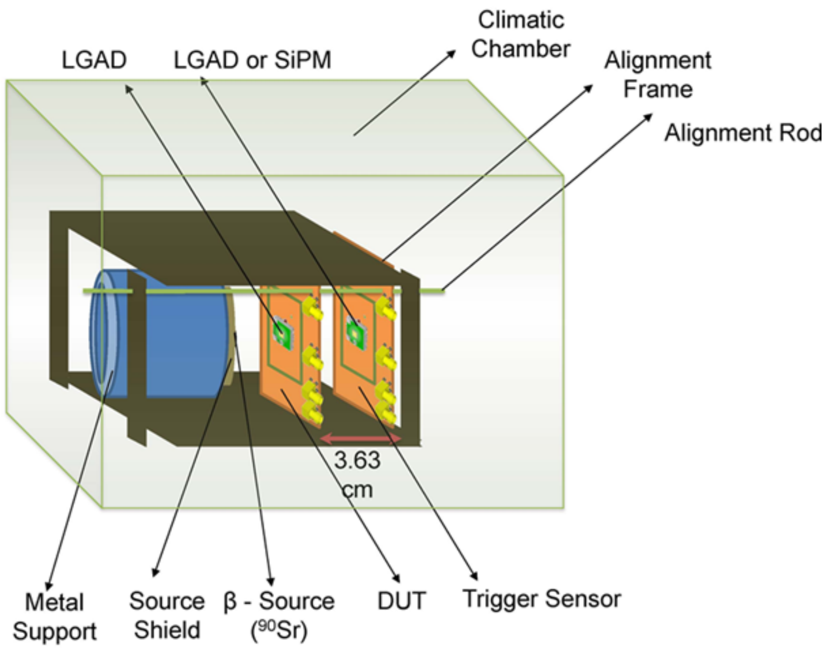




http://cds.cern.ch/record/2719855/

Sensor testing – Sr90 telescope, probe station





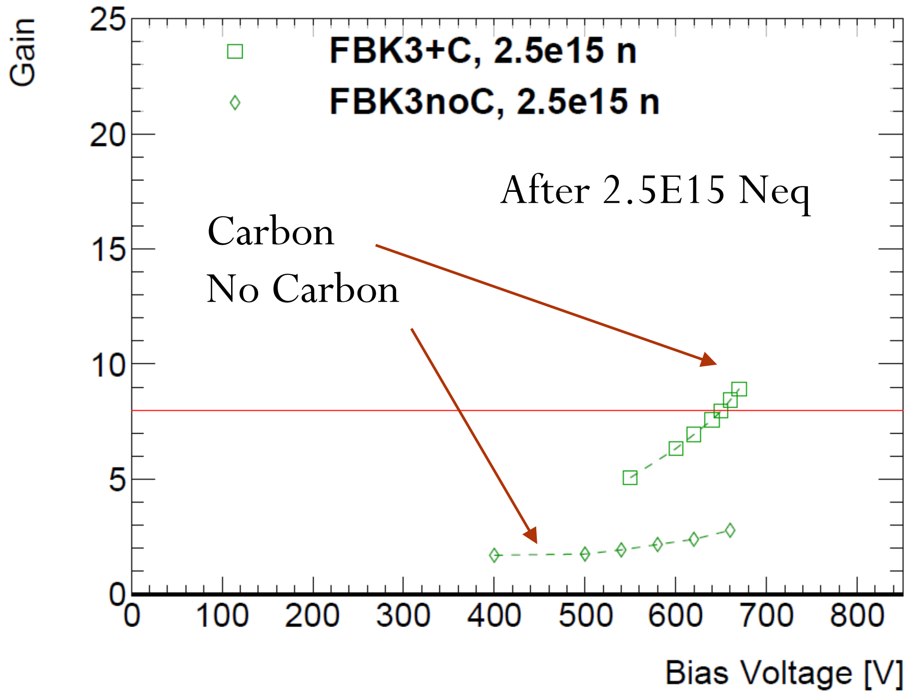
- **Probe station electrical testing**
- Capacitance over voltage (CV)
- Study of the "foot" (flat region before full depletion) for LGADs on $1/C^2$
  - Corresponding to full depletion of the gain layer
  - Variation of the foot with radiation damage

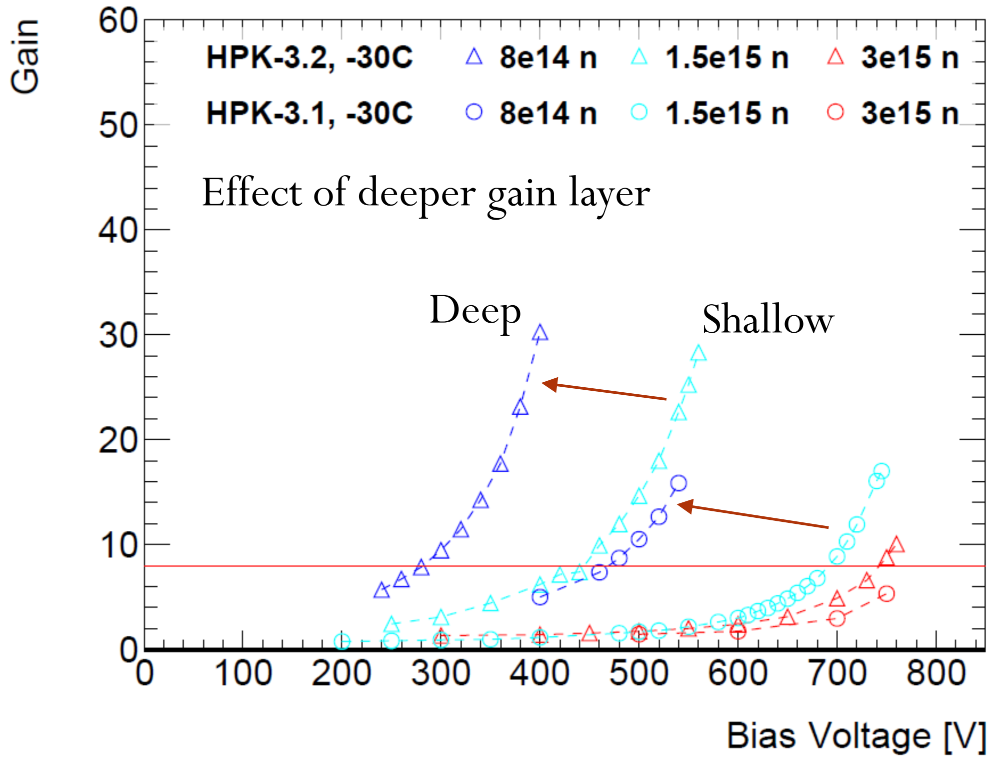
- **Laboratory charge collection**
- Using MiP electrons Sr90 β-source (β-telescope)
  - Sensors mounted on fast amplifier boards and read out by an oscilloscope
  - Signal shape, noise, **collected charge**, gain, **time resolution …**

- Results shown for measurements done at UCSC, Torino, CERN, Ljubljana, IFCA, IHEP …

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





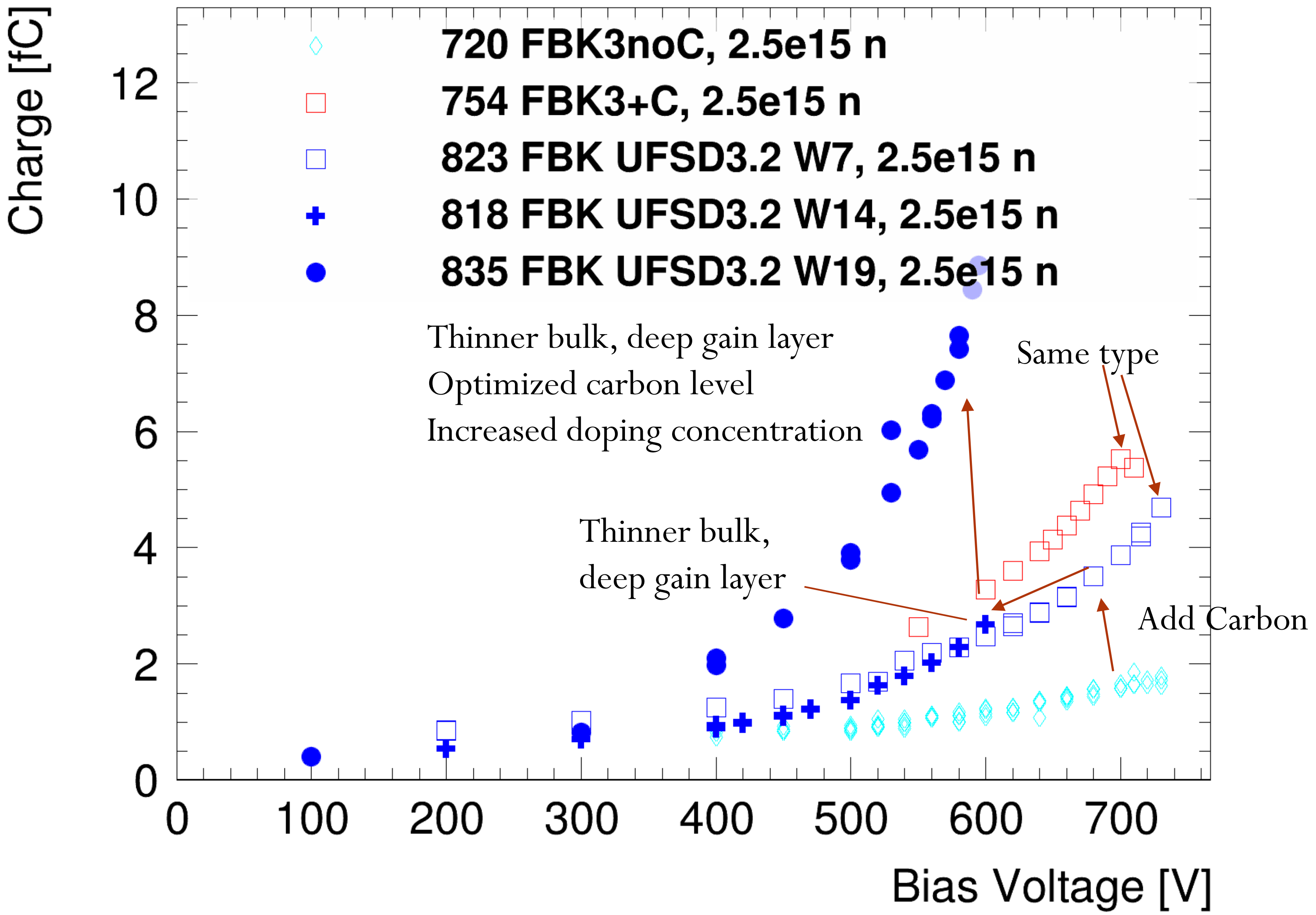
- **Thin but highly doped gain layer**
  - Higher initial doping concentration
  - Takes more time to be inactivated
- **Deep gain layer**
  - Higher field for larger volume
  - Increase effectiveness of bias voltage increase after irradiation
- **Gallium instead of Boron as dopant**
  - However no improvement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

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

Mitigation of radiation damage

- **Carbonated deep gain layer**
- Produced for the first time by FBK in year 2020
- Shown performance for 5 FBK sensors at 2.5E15 Neq of neutron fluence

- **FBK3noC** (no carbon)
- **FBK3+C and FBK UFSD3.2** (same structure with Carbon)
- **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)



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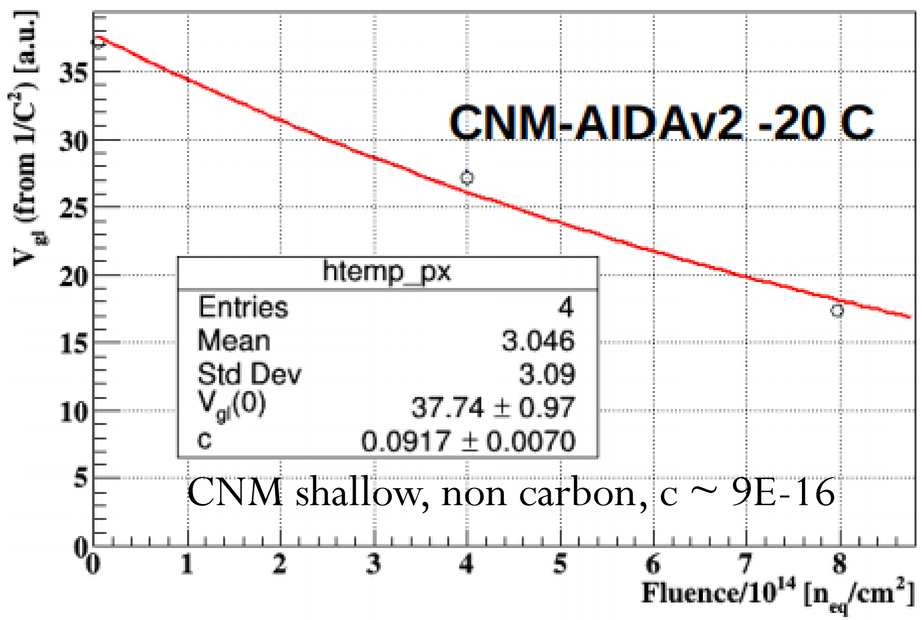
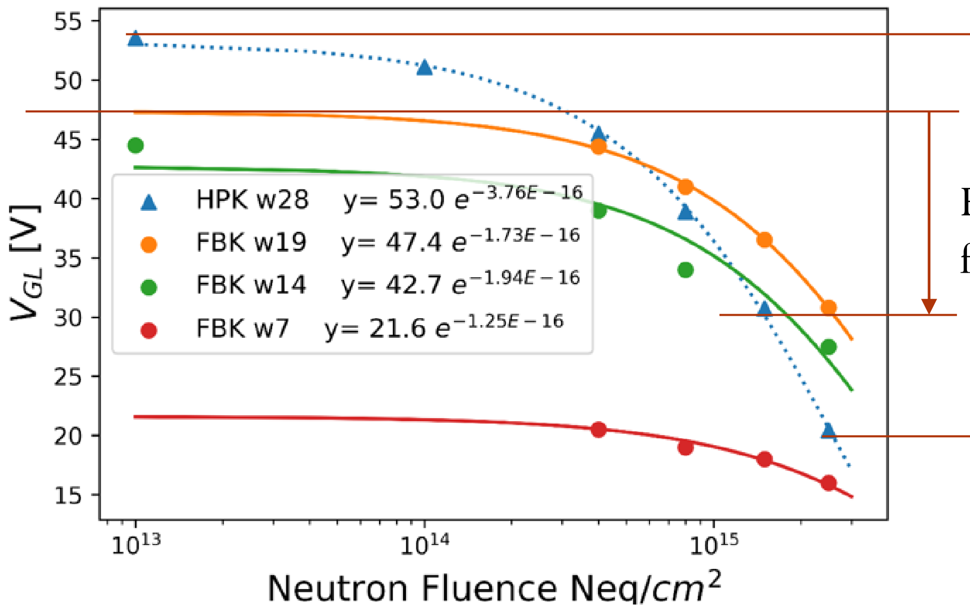
https://indico.cern.ch/event/983068/contributions/4223215/attachments/2192222/3705404/Siviero_TREDI2021.pdf

Gain layer change vs. Fluence

- Shown gain layer change as Vgl from 1/C^2 measurements vs fluence
- C-factor ranges from ~9E-16 (CNM, shallow non-Carbon) ~4E-16 (HPK non-Carbon) to ~1.2E-16 (FBK Carbon)
  - Carbon gives a significant improvement: C-factor is about 2-3 times smaller for carbonated sensors
- HPK sensor still has a higher initial doping concentration, but then degrades faster



CNM shallow, non carbon, c ~ 9E-16



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

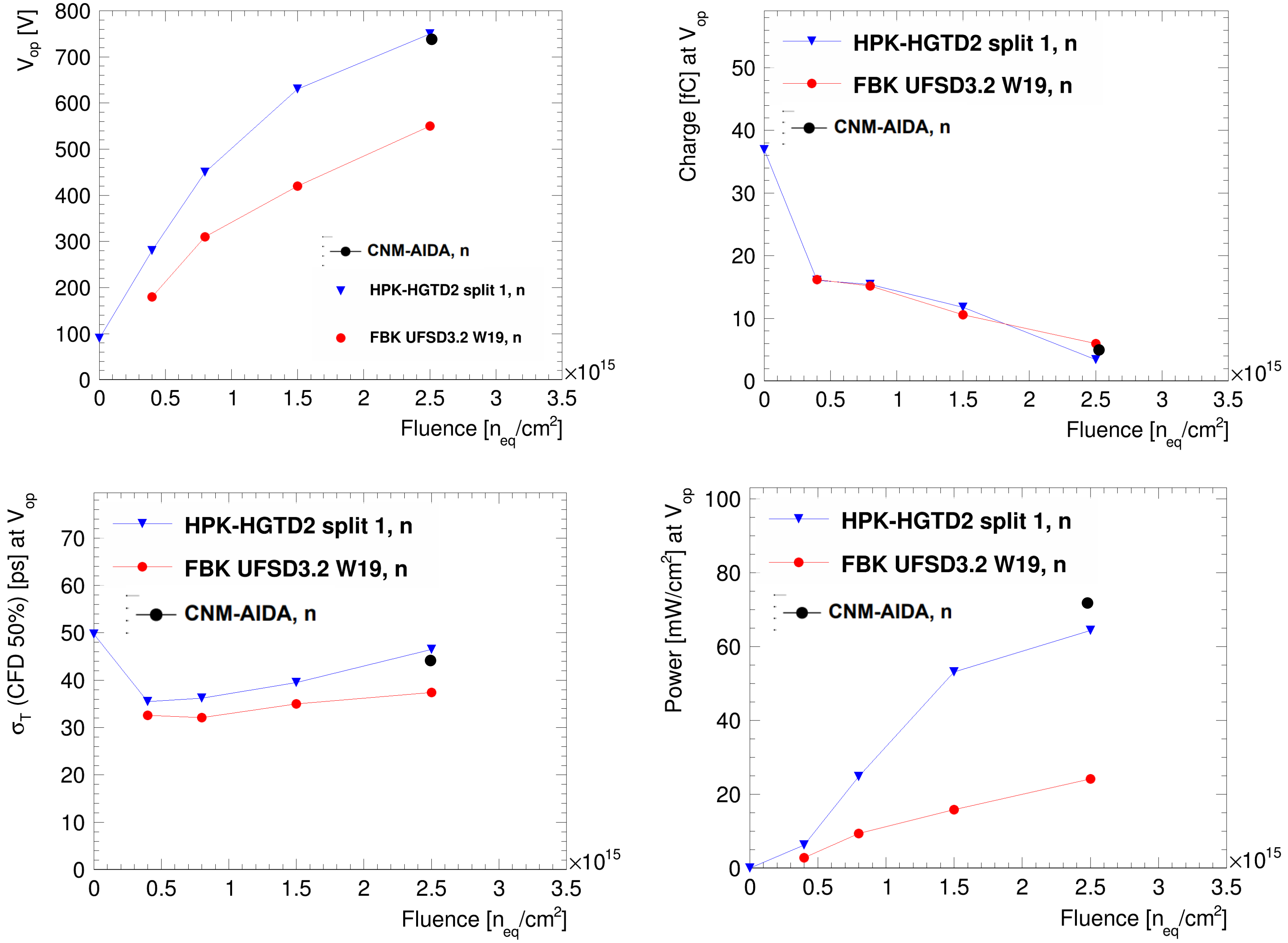
FBK has lower variation (lower c-factor) thanks to Carbon

https://indico.cern.ch/event/983068/contributions/4223171/attachments/2191347/3703735/020221_TREDI_LGAD_radhard.pdf
https://indico.cern.ch/event/983068/contributions/4223223/attachments/2191863/3704729/Tredi21_MarcosFernandez_17Feb2021.pdf

Performance comparison across different vendors

- Vop: bias voltage at which the sensor operates with good performance
  - Varies between ~100V before irradiation to over 700V after irradiation
- Performance is shown at each fluence for Vop

- Three vendors (HPK, FBK, CNM) have good performance up to 2.5E15 Neq (HGTD max fluence)
- Sensor with **combination of deep gain layer and Carbon infusion** is the most radiation hard (FBK)



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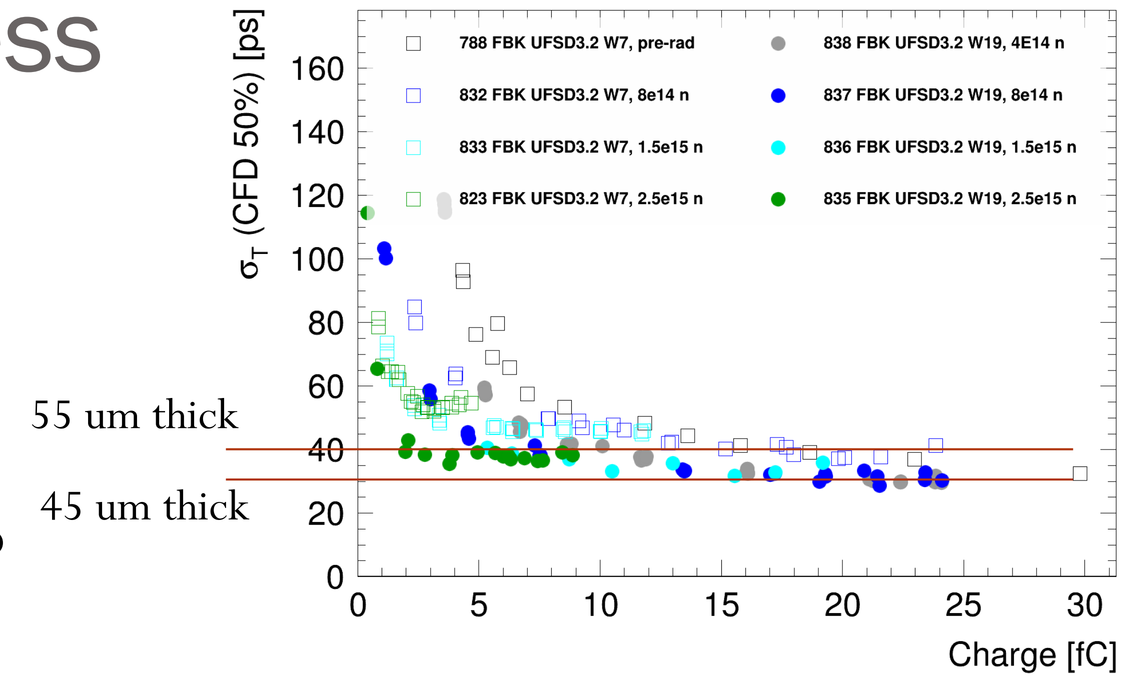
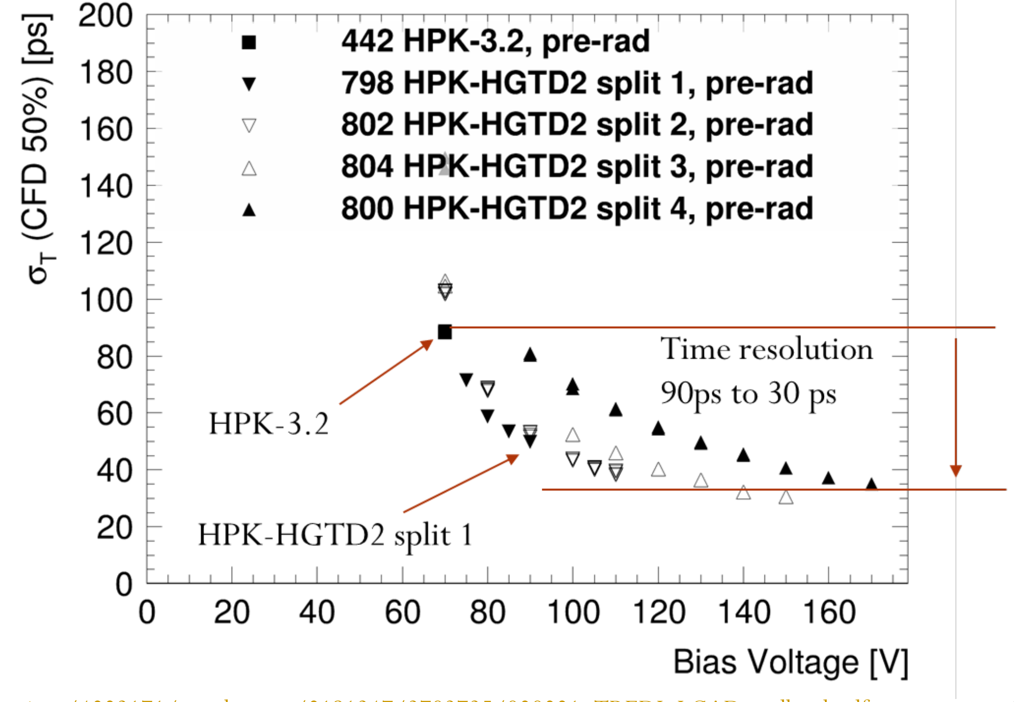
Optimization for radiation hardness

- There are several parameters that have to be optimized to gain the best pre-rad and after-rad behavior
- **Thickness**: Thinner detectors provide better time resolution (because of the Landau term), thicker detector provide more collected charge (easier for the electronics to work) and are more resilient. However thicker detectors also have increased power dissipation.
  - 35 um detectors were studied but proven to be too thin for use at HL-LHC. However they could provide < 20 ps of time resolution.
- **Gain layer optimization**: a deep gain layer works best for radiation resistance, however the doping concentration has to be fine tuned to have good behavior before/after irradiation. Too much doping causes excessive gain and bad time resolution pre-rad.





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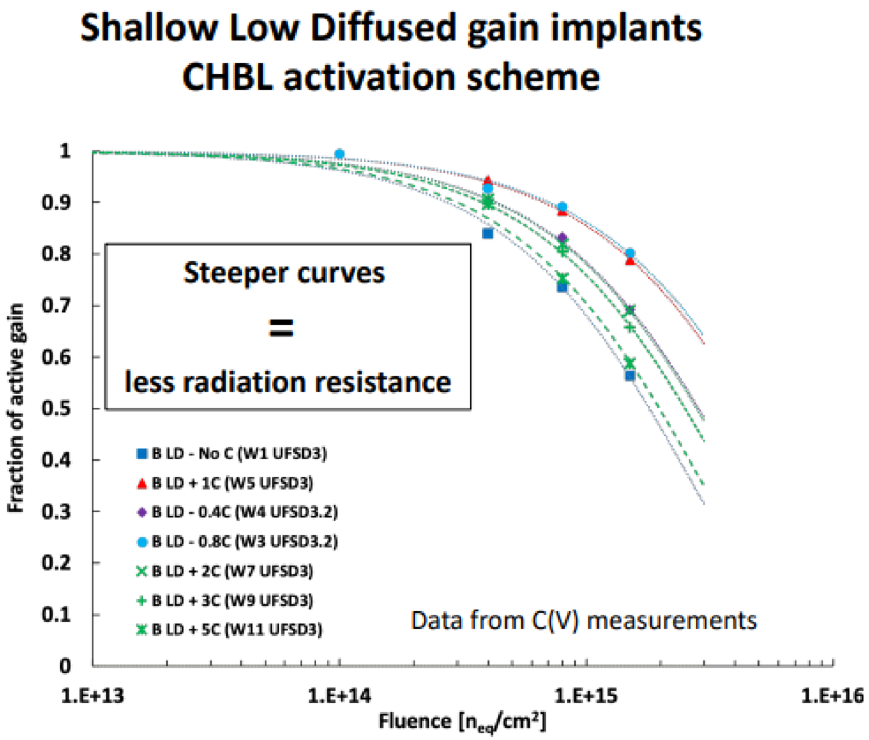
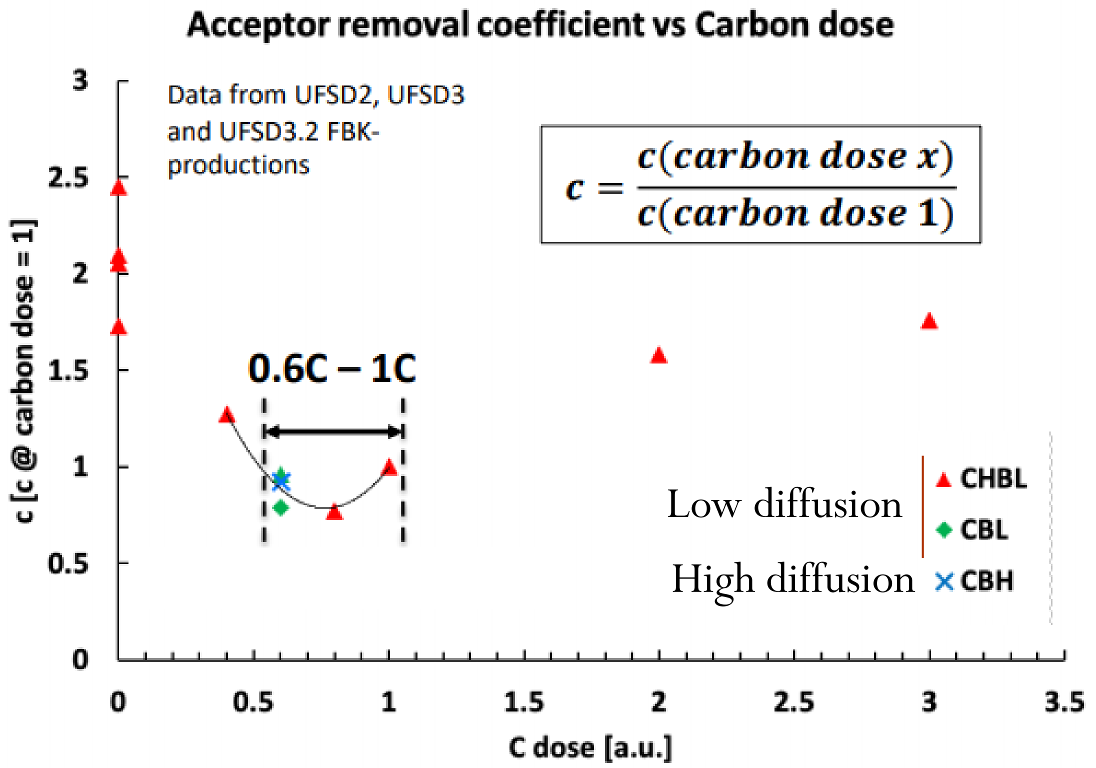
Optimization for radiation hardness

- **Diffusion of the gain Layer:** A low diffusion gain layer (as opposed to high diffusion gain layers) increase the radiation hardness, since the initial doping concentration is higher.
- **Carbon Level**: It has been seen that there's an optimal Carbon range, too much (Boron inactivation) or too few (no change in acceptor removal) Carbon decrease the performance
  - Credits: https://indico.cern.ch/event/983068/contributions/4223173/attachments/2191413/3703863/17022021_MarcoFerrero.pdf

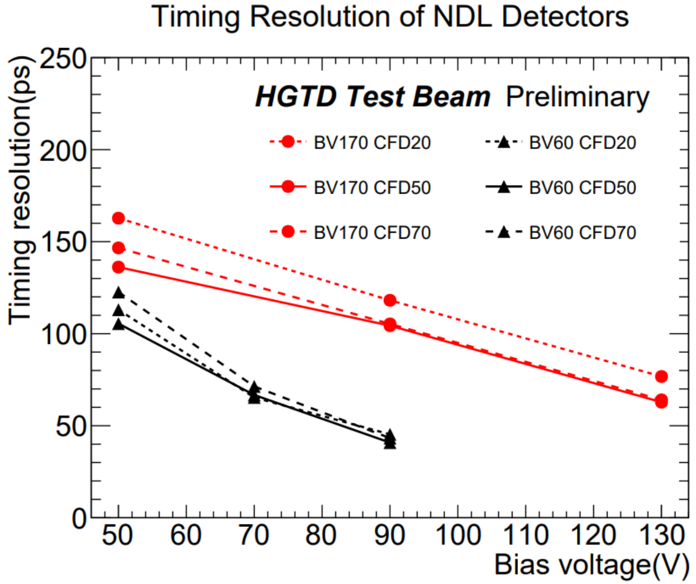


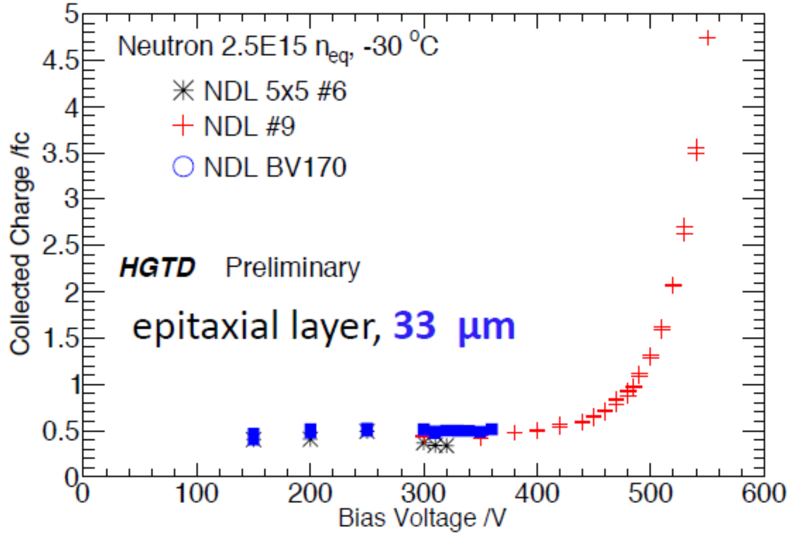


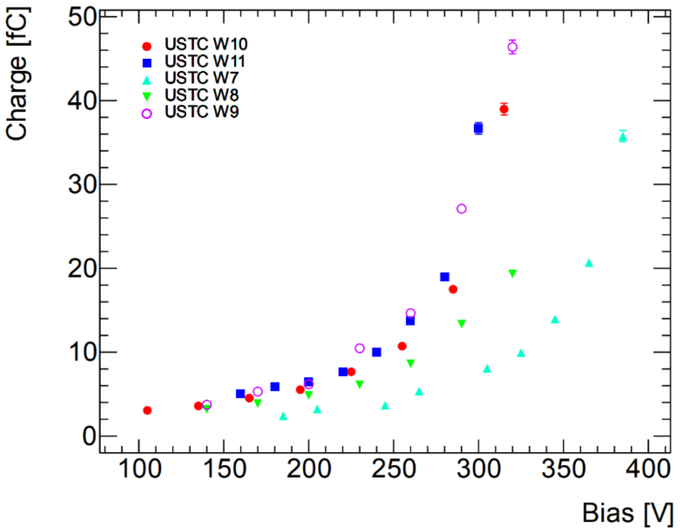
- All sensors have the same geometry but different carbon levels
- 0.8 Carbon dose (actual dose secrecy of FBK) shows the lowest c-factor (highest radiation hardness)
- Low diffusion (CHBL/CBL) is better than high diffusion (CBH)
- Increased Carbon dose is counterproductive

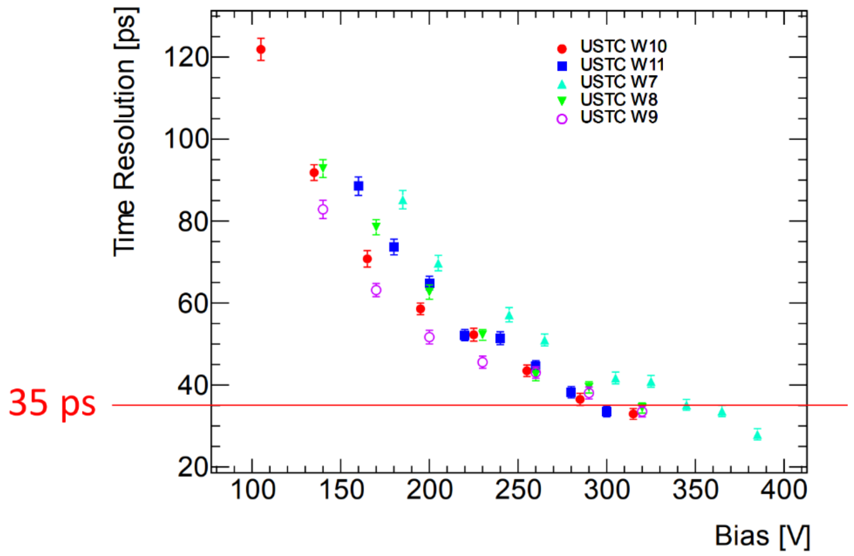
“new” LGAD providers

- First production of LGADs by new institutions in the past few years
- **BNL** (as just shown!)
  - https://indico.fnal.gov/event/46746/contributions/210255/attachments/141188/177713/CPAD_CharacterizationofAC_LGADperformancesfor4Ddetectors.pdf
- **NDL + IHEP** (China)
  - First sensor production tested before and after irradiation
  - Good performance up to 2.5E15 Neq
  - New production ongoing with improved design
- **USTC** (design) + **IMEI,CAS** (Fabrication) (China) (China)
  - First production presented at TREDI 2021
  - Promising results before irradiation
  - Design with deep gain layer + Carbon diffusion
  - Awaiting results post-irradiation









https://arxiv.org/ct?url=https%3A%2F%2Fdx.doi.org%2F10.1016%2Fj.nima.2020.164956&v=5a57a289
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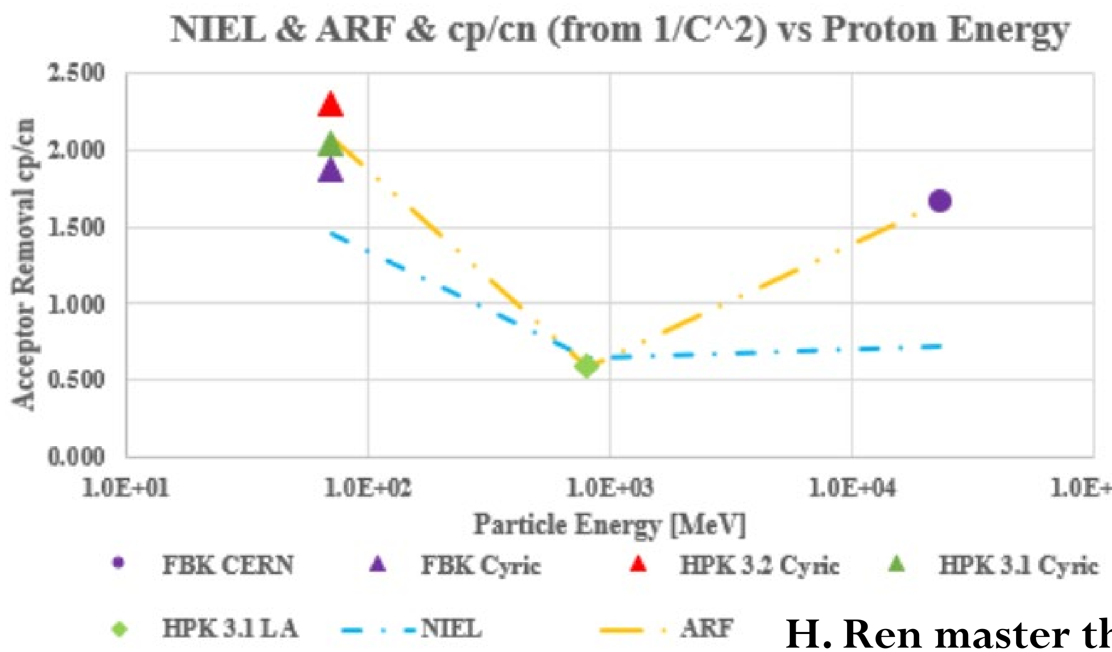
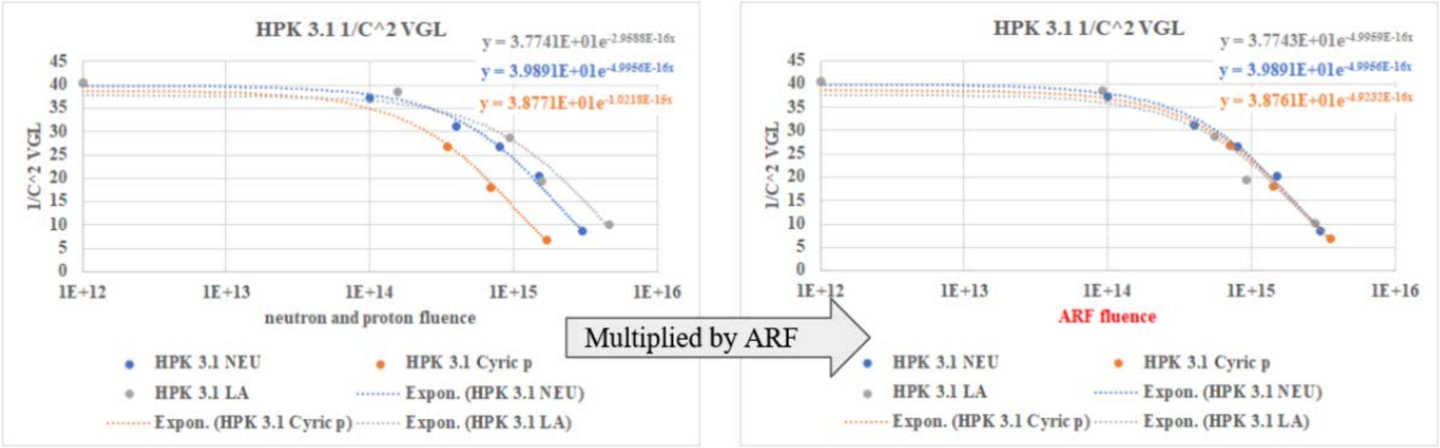
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots

LGAD proton irradiation

- Usually proton irradiation on Silicon can be adjusted to 1-MeV neutrons equivalent (Neq) with NIEL factors depending on the energy of the protons
- **However for the acceptor removal process the standard NIEL conversion doesn't work**
- Sensors irradiated in several facilities with different proton energies
  - CYRIC: 70 MeV protons
  - LANL: 800 MeV protons
  - CERN: 23 GeV protons
  - Compared to JSI ~1MeV neutrons
- **It was observed that proton damage is in general more damaging than neutron damage**
  - An additional correction factor is needed
  - Measured acceptor removal factor (ARF) 30 % to three times higher than NIEL depending on the energy
- However behavior is not the same for every sensor/facility, studies are still ongoing



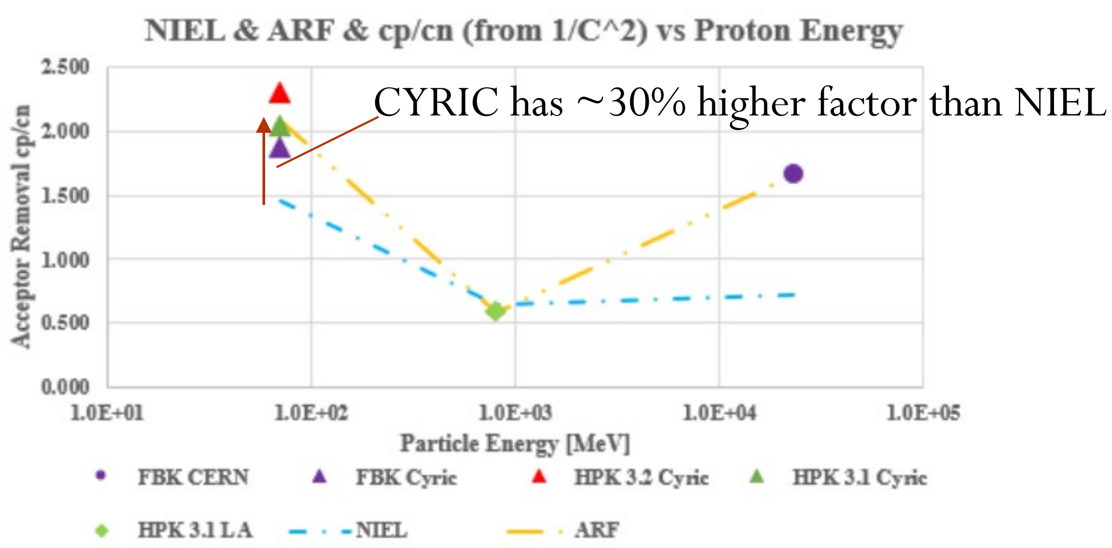
H. Ren master thesis (UCSC)



https://cds.cern.ch/record/2719855
https://indico.cern.ch/event/918298/contributions/3880522/attachments/2050445/3436767/RD50-HFWS.pptx

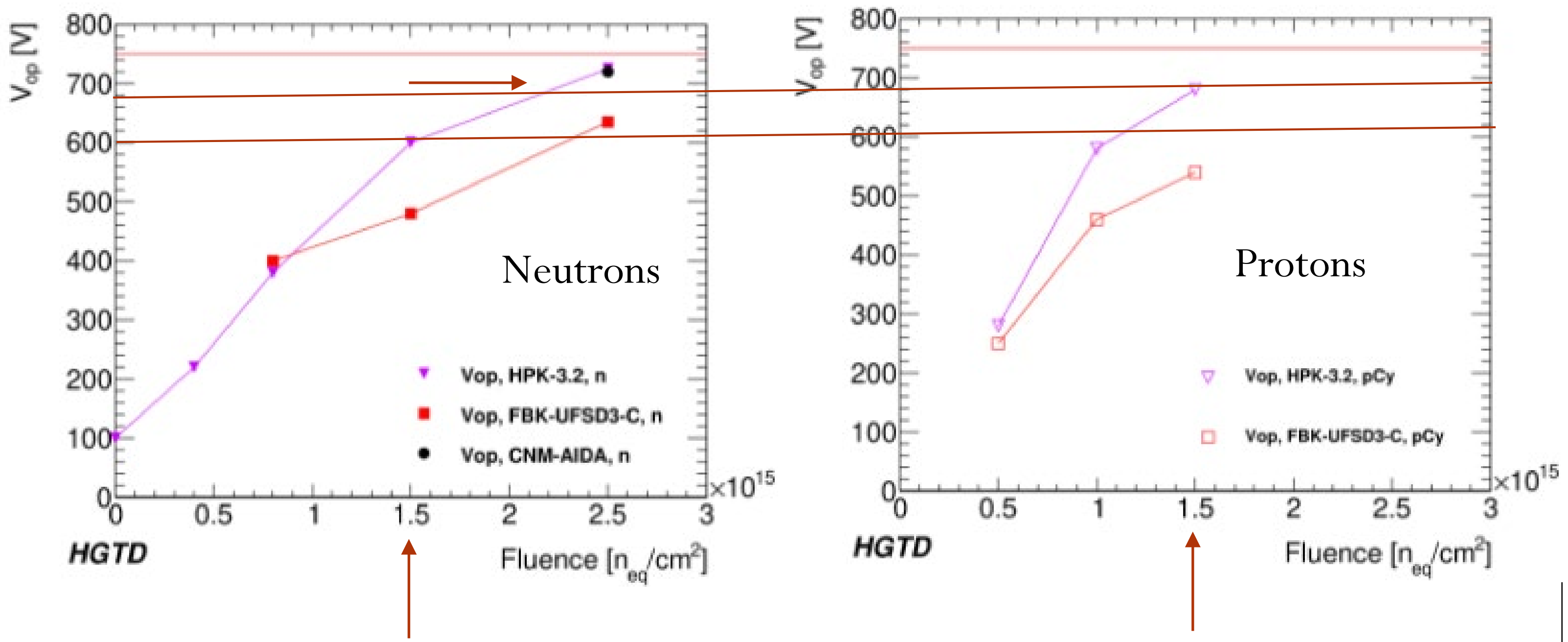
LGAD proton irradiation

- Example: same sensor type needs ~100V more to operate at fluence of 1.5E15 Neq with CYRIC protons (70 MeV) than a neutron irradiated sensor
  - Corresponding to ~2E15 Neq, 30% higher fluence
  - The acceptor removal coefficient (from CV measurements) is also 30% higher



H. Ren master thesis (UCSC)

CYRIC has ~30% higher fluence than NIEL



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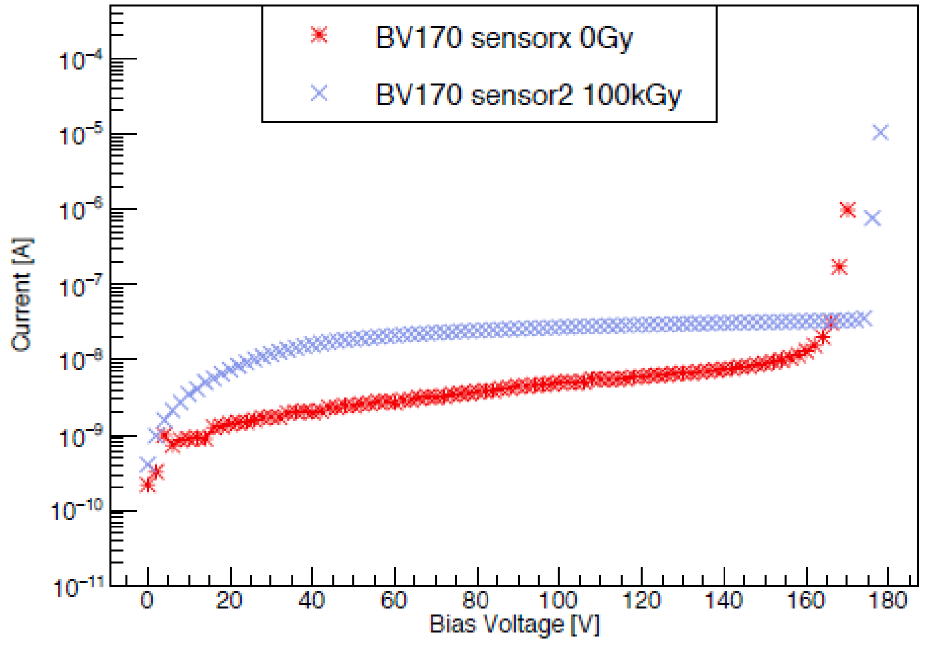
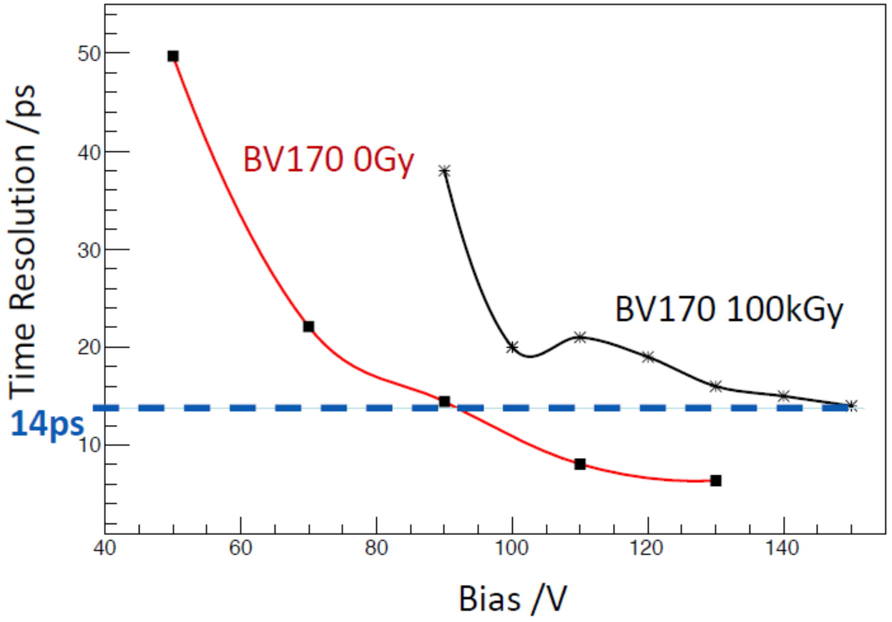
LGAD X-ray irradiation

- LGAD prototype irradiated with X-ray gun
- More extensive study just shown!
  - https://indico.fnal.gov/event/46746/contributions/210256/attachments/141097/177565/cpad2021-lgad-mar17.pdf
- Report of data from IHEP X-ray gun and laser TCT
  - https://indico.cern.ch/event/918298/contributions/3880587/attachments/2050737/3437264/202006FanYY_LGAD-irradiation_2.pdf
- TID up to 100 kGy
  - Total required for HGTD is 2MGy (tests ongoing)
- Not much effect expected on LGAD structure
- Slight increase in leakage current and noise observed
  - Slight increase in Jitter component of time resolution
  - Minor change in breakdown voltage

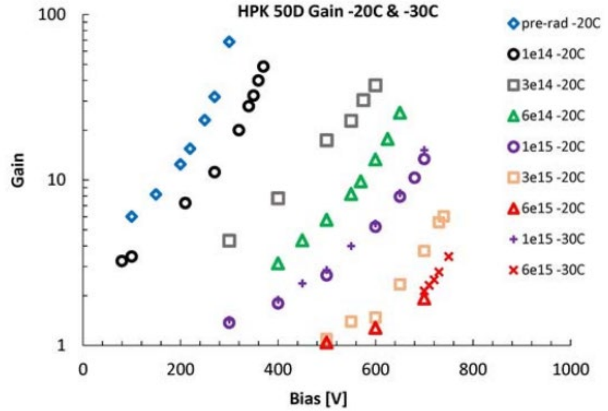




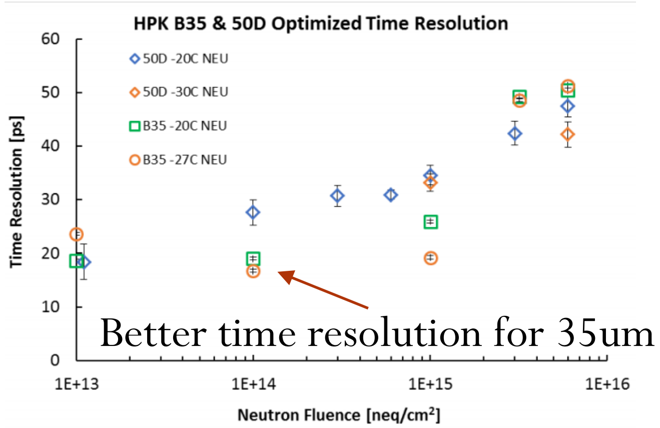
The 6 year journey of LGAD radiation hardness R&D

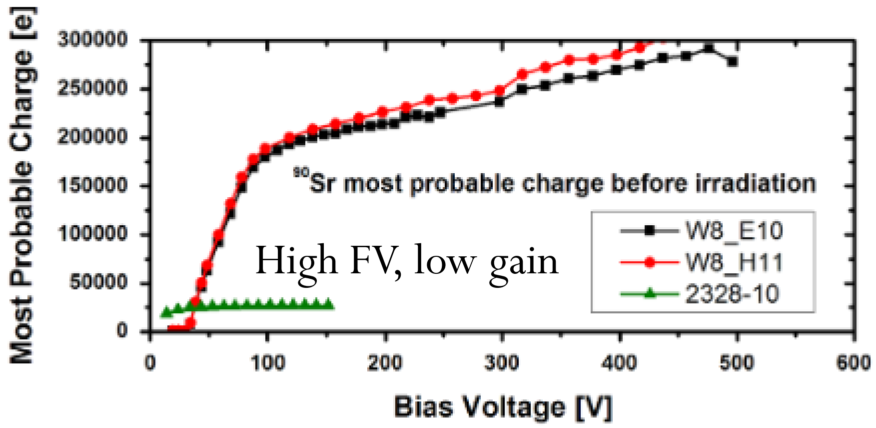
2014

- First prototype (300um thick LGADs)
  - G. Pellegrini, et al., Nucl. Instrum. Meth. A765 (2014) 24.



Gain of ~10 up to 1E15 Neq





2016-2017

- Highly doped gain layer for **increased radiation hardness**: arXiv:1707.04961

https://agenda.infn.it/event/11109/contributions/7057/attachments/5182/5766/20160607_RD50Workshop_HGTDCT-PPS_MarCarulla.pdf

- Thinner detectors give **better time resolution 20 ps** (50um, 35um): arXiv:1803.02690,
  - But lower collected charge

2018

- The addition of Carbon and Gallium doping:
  - arXiv:1802.01745, arXiv:1804.05449
- **Carbon works, Gallium not much**

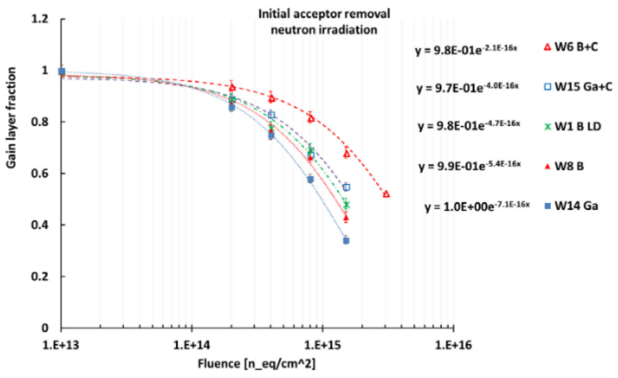
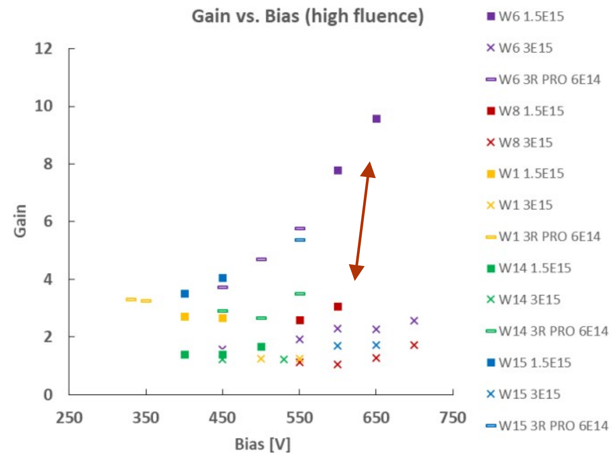


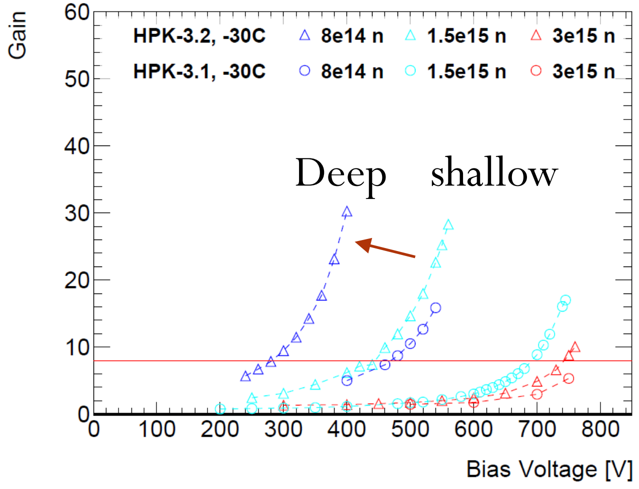
Fig. 12. Fraction of gain layer still active as a function of neutron irradiation.

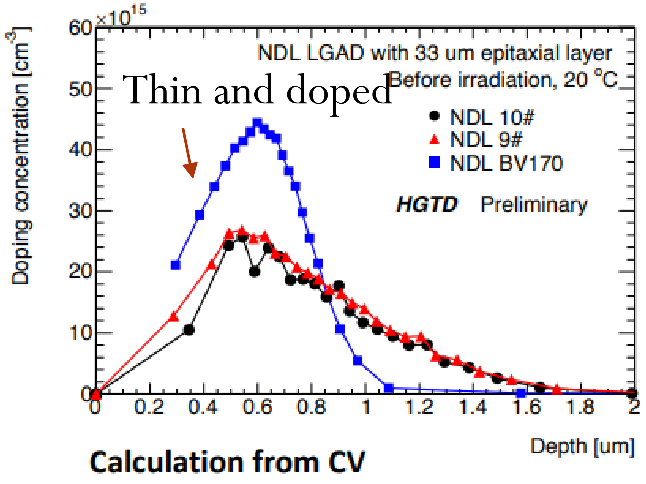


*** Cited papers as examples, not a full list!**

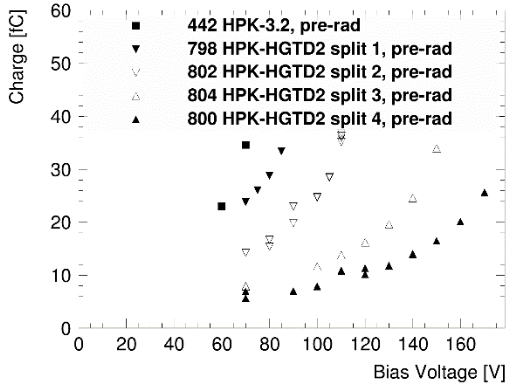
The 6 year journey of LGAD radiation hardness R&D

2019



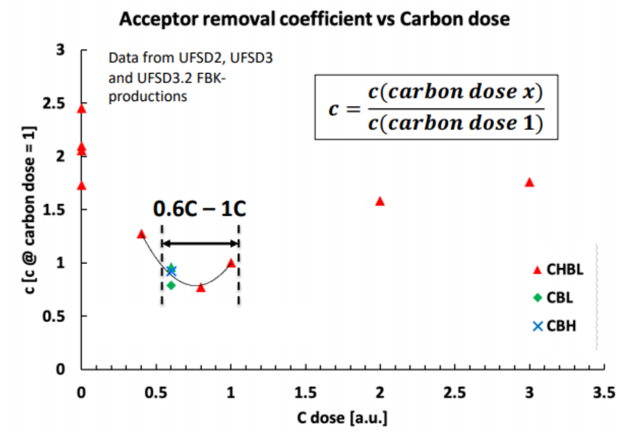


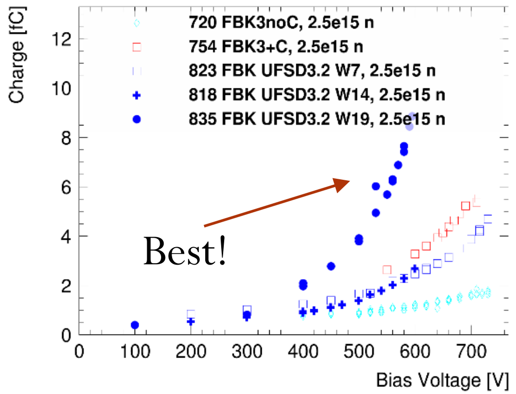
- Gain layer improvements
  - Thin and highly doped gain layer
  - Deeper gain layer
- arXiv:2004.05260, arXiv:2004.13895, arXiv:2003.07076



2020

- Parameters tuning
  - Tuned gain layer doping and geometry
  - Tuned Carbon level
  - Optimal thickness
- Combination of technologies (deep + Carbon)





?

- **Thick sensors (2014) → Thin (50um) sensors with gain of 10 at 1E15 Neq (2016) → thin sensors with gain of 20 at 2.5E15 Neq (2020)!**

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https://indico.cern.ch/event/983068/contributions/4223215/attachments/2192222/3705404/Siviero_TREDI2021.pdf

Conclusions

- **To increase the radiation hardness of LGADs:**
  - Carbon, optimized gain layer
  - **Combination of the two**
- **R&D allowed the optimization of several parameters to maximize radiation hardness**
  - Thickness has to be chosen carefully to balance collected charge (post-rad) and time resolution
  - Tuned gain layer doping and geometry to have good behavior before and after irradiation
  - Tuned Carbon dose and gain layer diffusion

- LGADs from several vendors now show **good performance up to 2.5E15Neq** (Max fluence at HGTD)
  - **Sensors** with **deep gain layer and Carbon** show **exceptional performance**
- Several new LGAD producers are fabricating well functioning LGADs
- **Worldwide effort with several vendors allowed to more than double the radiation damage reach of LGADs**
  - Effect of proton irradiation to be fully understood yet

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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!

Jožef Stefan Institute

CERN | IRRAD Proton Facility

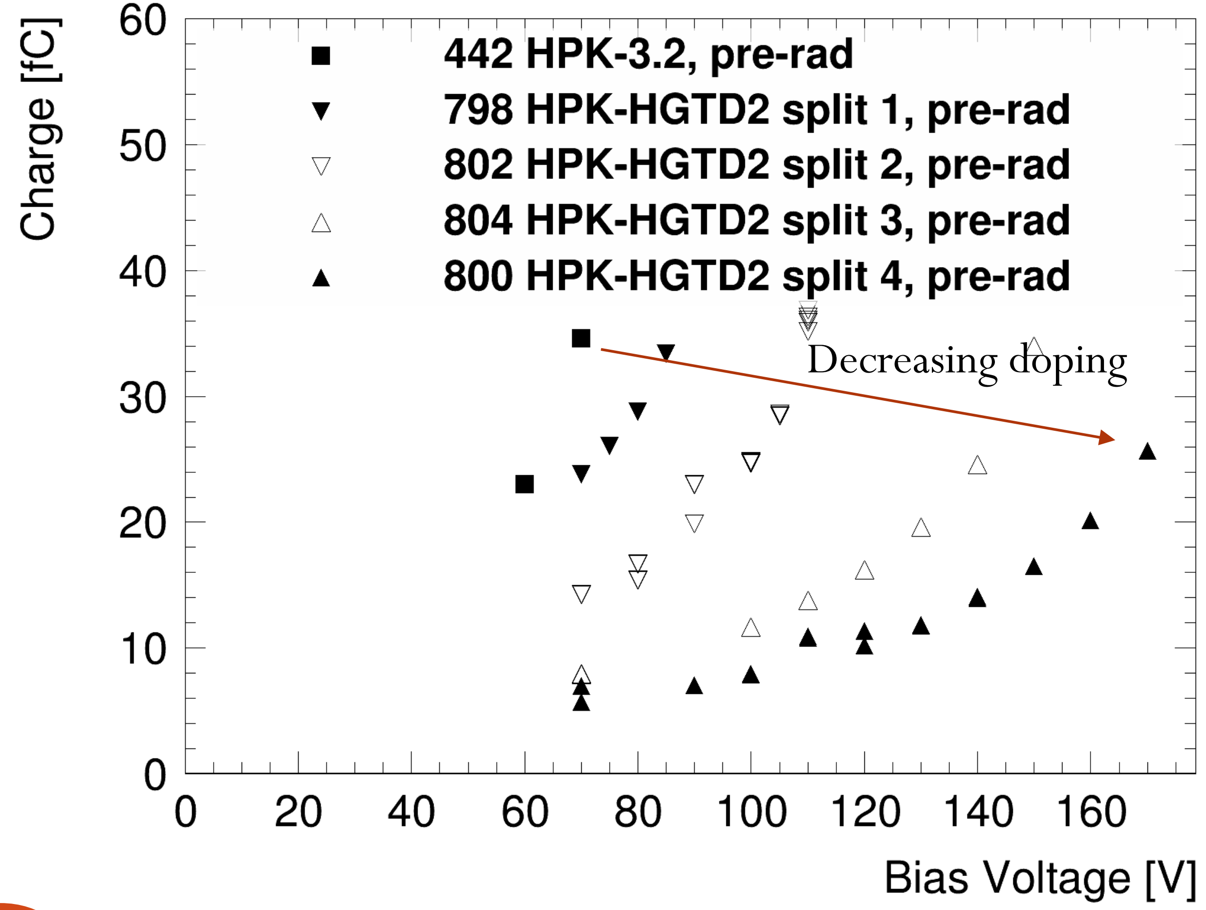
Sandia National Laboratories

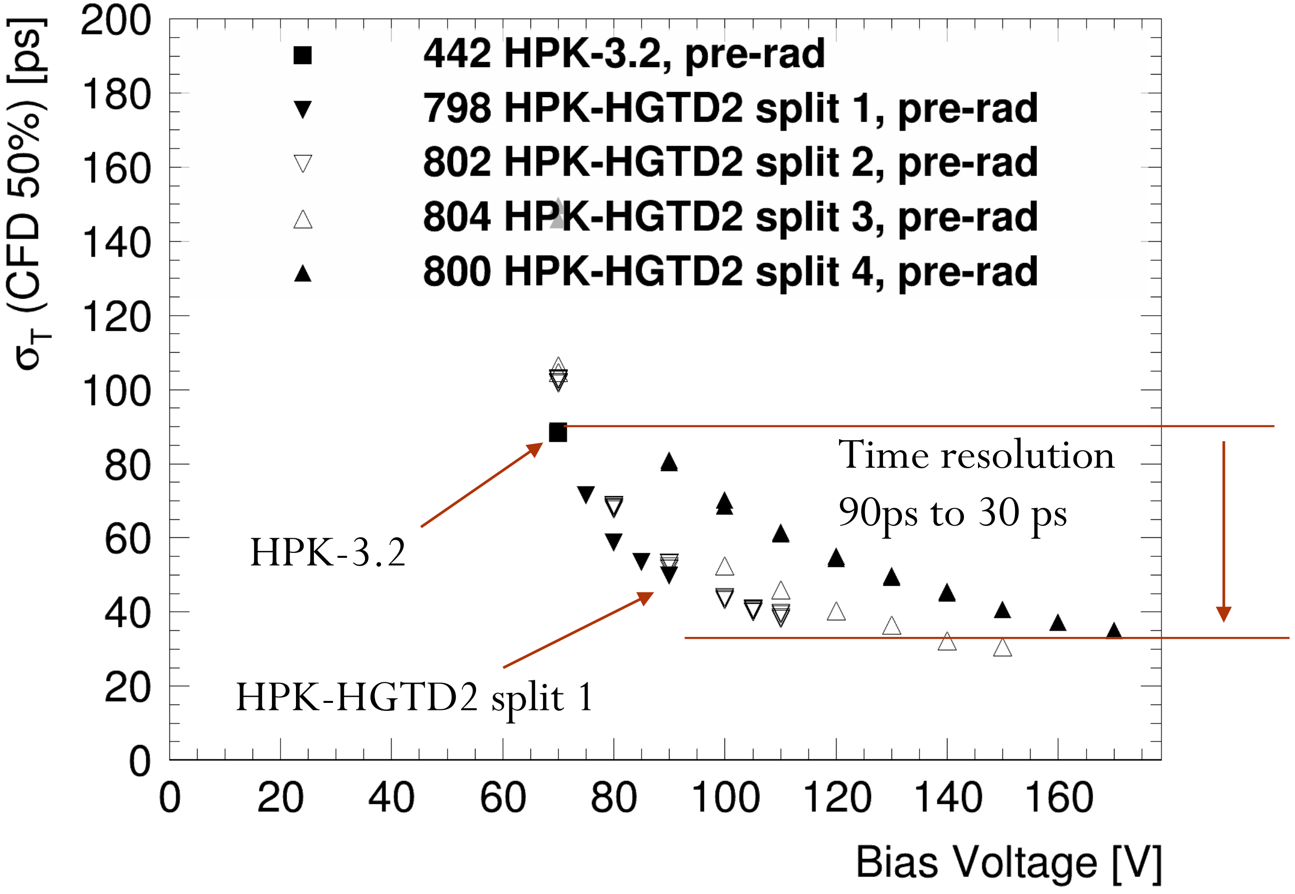
Los Alamos NATIONAL LABORATORY

KEK

HPK LGAD performance before irradiation

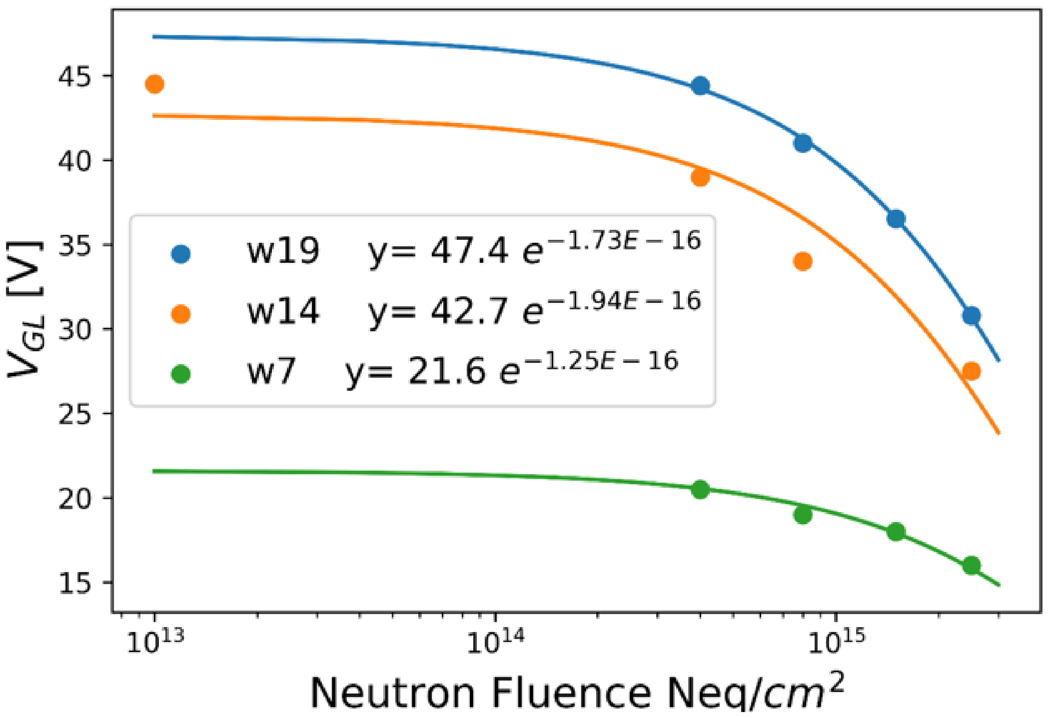
- HPK successfully tuned the gain layer to optimize performance before irradiation
- Starting point (highest gain): HPK-3.2
- At -30C HPK-3.2 has time resolution of 90 ps next split down (split 1) is better: 50ps
- Even better time resolution for following splits





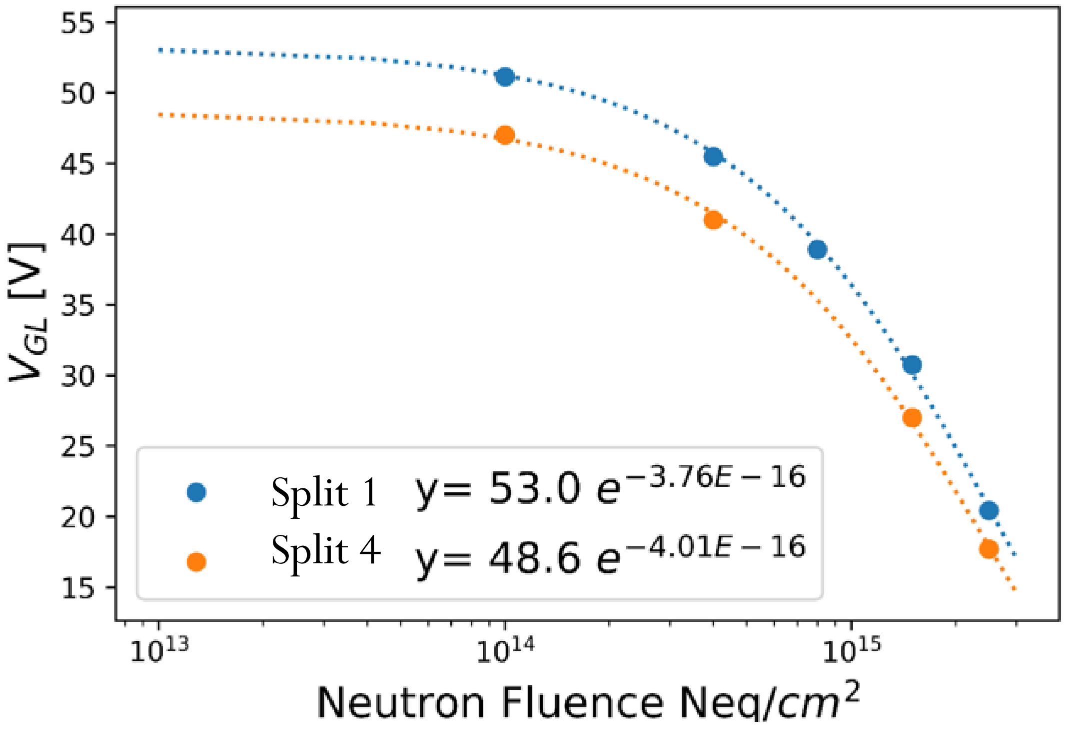
1/C^2 Foot vs fluence

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



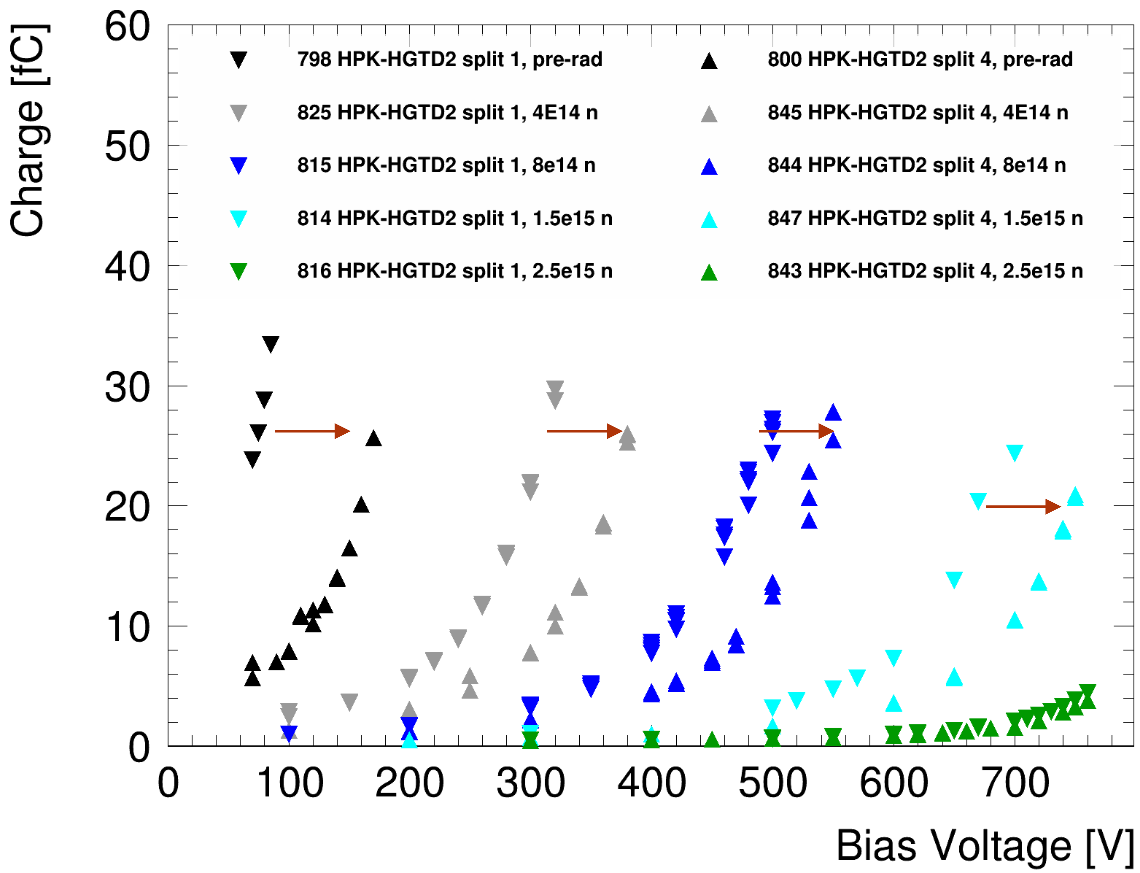
- FBK UFSD3.2
  - Both W14/W19 have a higher starting point than W7 because of the deep gain layer
  - W19 has the highest starting point (highest doping) and 10% lower c-factor (optimized carbon level) than W14

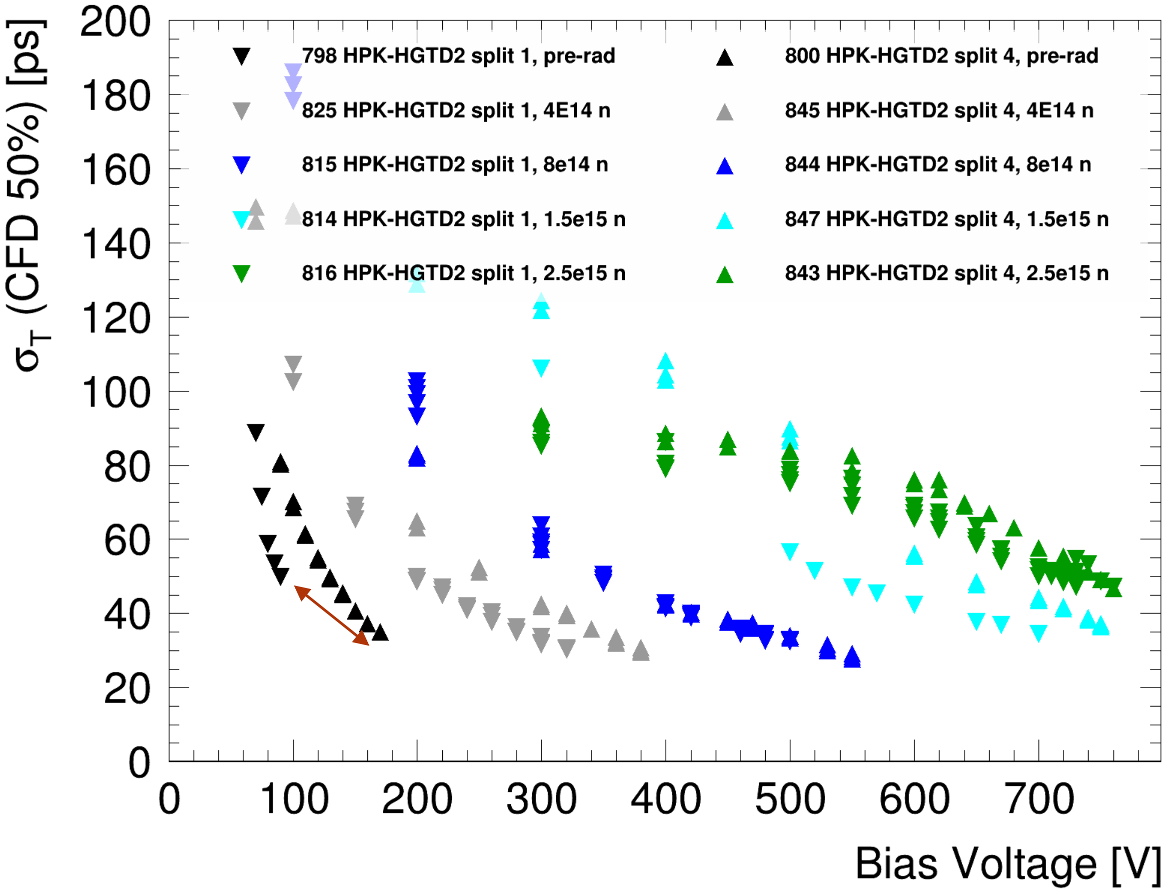
- HPK-HGTD2
  - Same gain layer geometry for split 1 and split 4
  - Similar fits and c-factors
  - But with different starting point



HPK LGAD performance after irradiation split 1 and 4

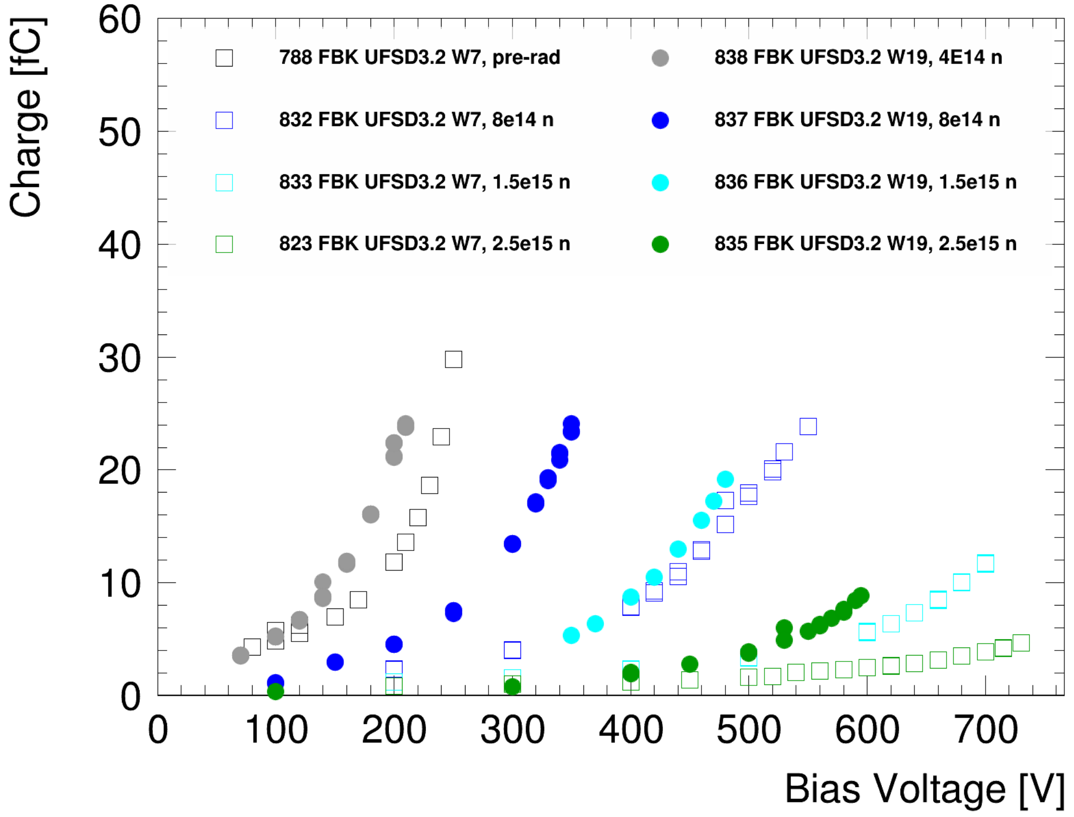
- Showing performance for HPK split 1 (highest doping) and split 4 (lowest doping)
- Distance between gain curves is more or less constant (at 2.5E15 Neq are very similar)
- Time resolution is better for split 4 at the beginning but at 4E14 Neq the two splits are the same

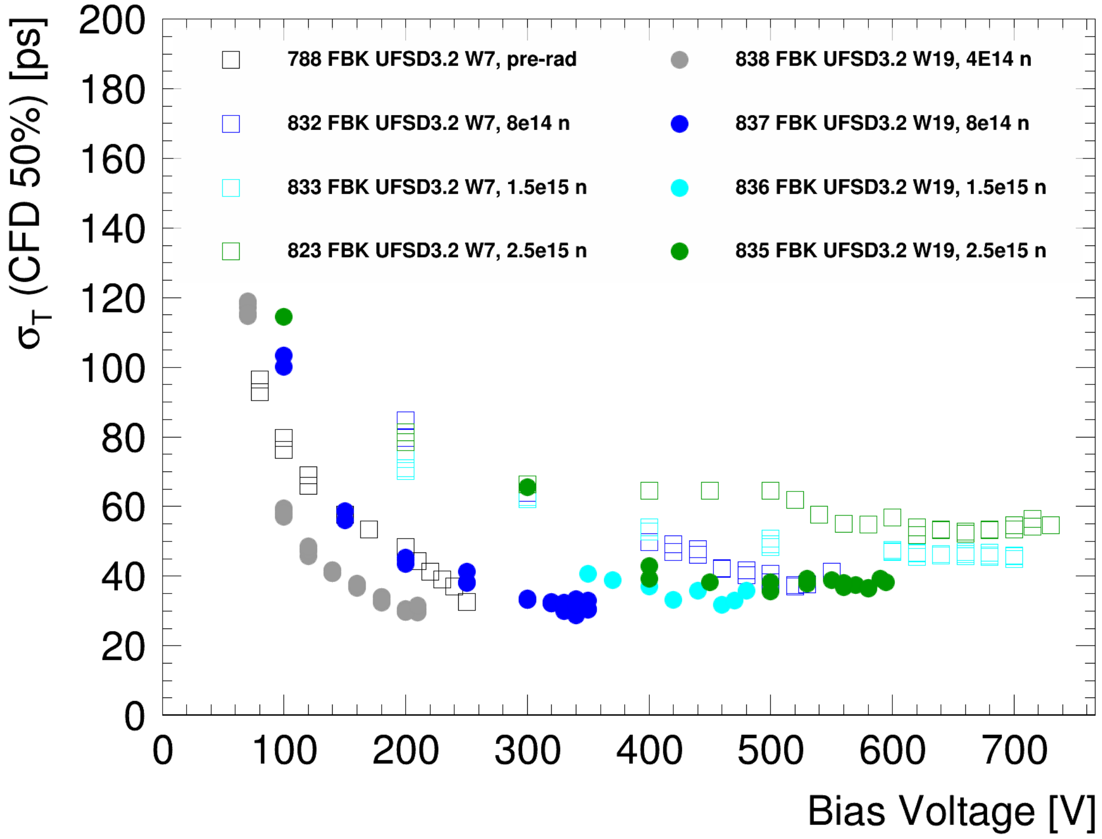




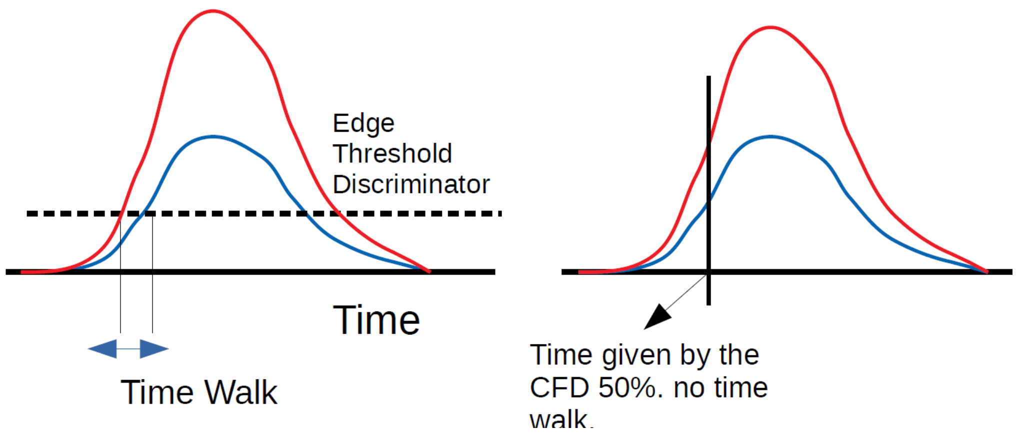
FBK LGAD performance after irradiation

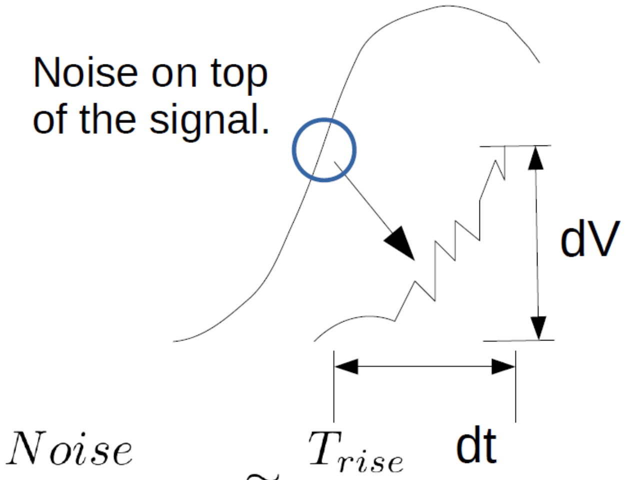
- Combination of deep gain layer, high doping and Carbon implantation show exceptional performance
  - FBK USFD3.2 W19 (deep gain layer, Carbon), compared with W7 (shallow gain layer, Carbon, same type as FBK old production UFSD3)
  - (Missing pre-rad data for W19, showing 4E14 Neq instead)
- 10 fC of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





LGADs timing resolution





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

Sensor time resolution main terms

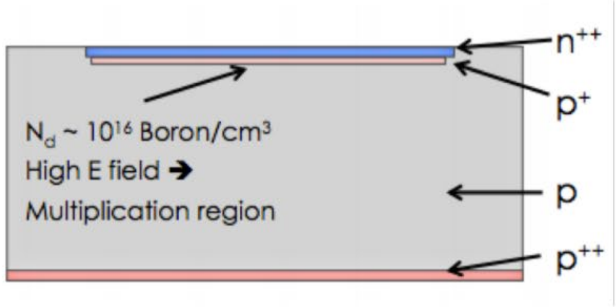
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

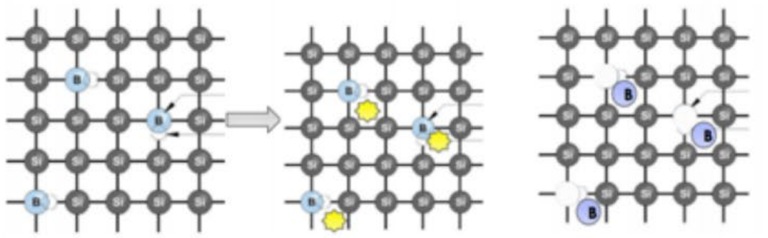
- Time walk:
  - Minimized by using for time reference the % CFD (constant fraction discriminator) instead of time over threshold
  - In HGTD electronics TOA (Time of Arrival) of the signal is corrected with TOT (Time over threshold)
- Landau term:
  - Reduced for **thinner sensors** (50,35 µm)
- Jitter:
  - 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

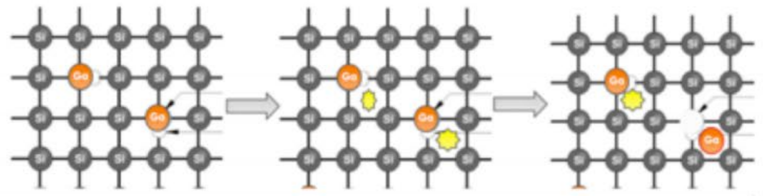
$$N(\emptyset) = N(0) * e^{-c\emptyset}$$



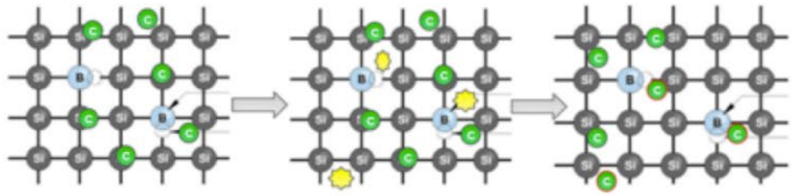


Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s ➔ Si_s + B_i
B_i might interact with Oxigen, creating a donor state

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

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