15th Trento Workshop on Advanced Silicon Radiation Detectors

R&D on LGAD radiation hardness in the HL-LHC environment

15° Trento Workshop (2020, Wien)

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on behalf of the SCIPP UCSC group

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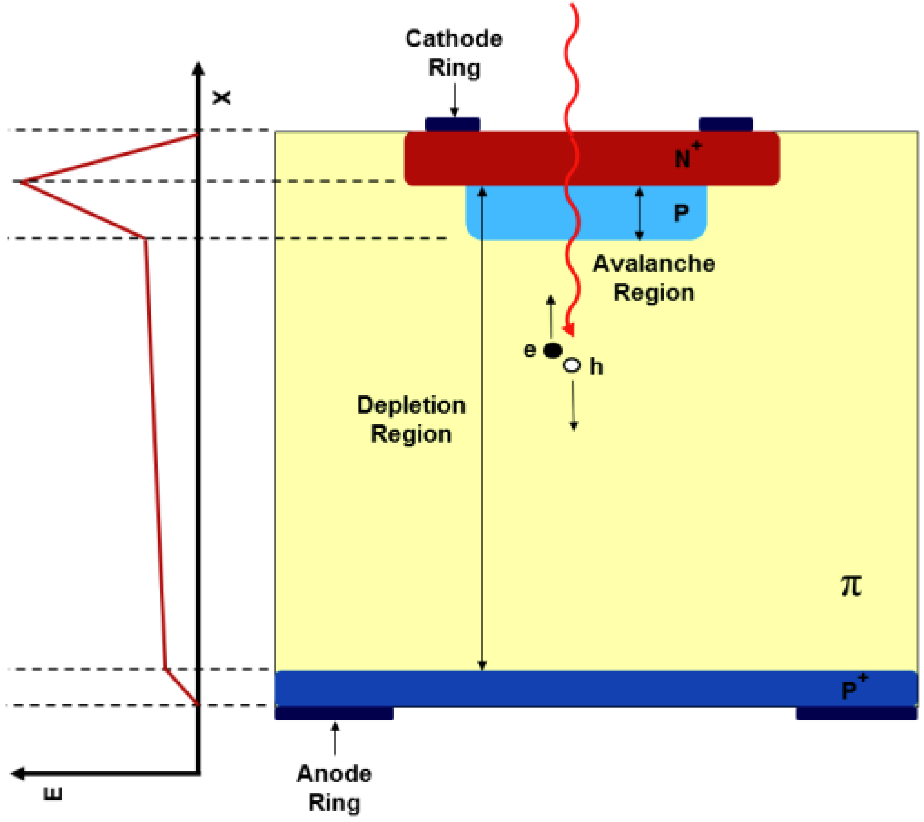
ATLAS EXPERIMENT

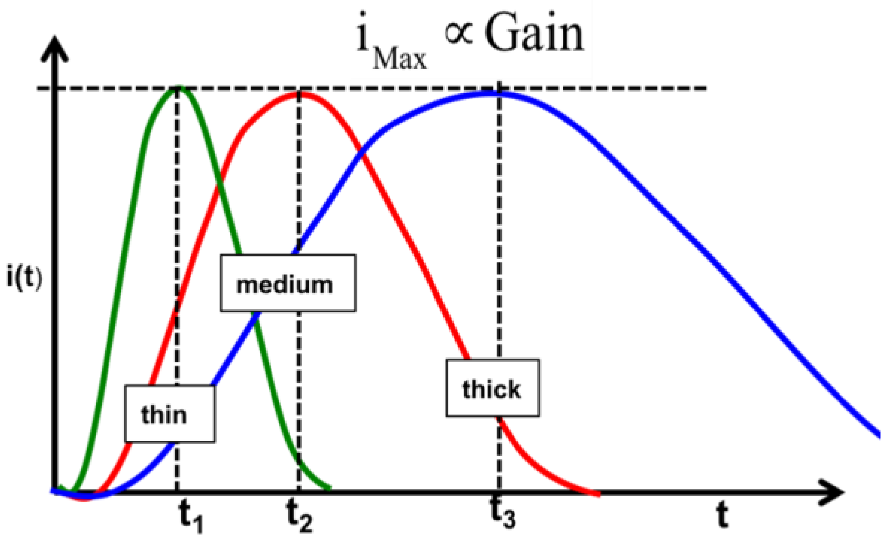
LGADs

- LGAD: silicon detector with a thin (<5μm) and highly doped ($\sim 10^{16}$ 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)



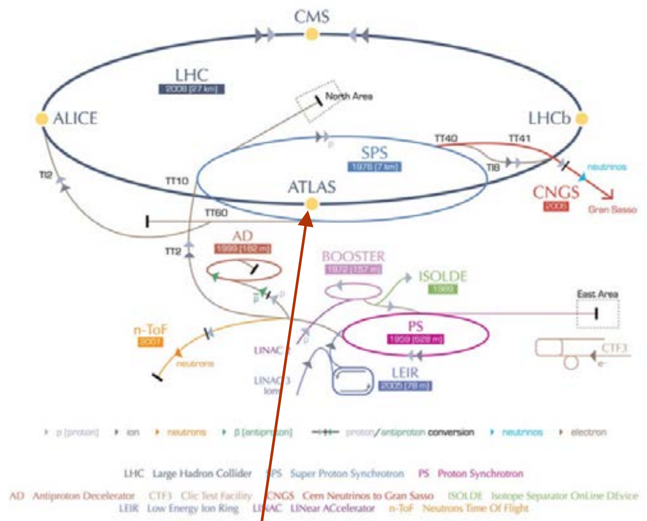


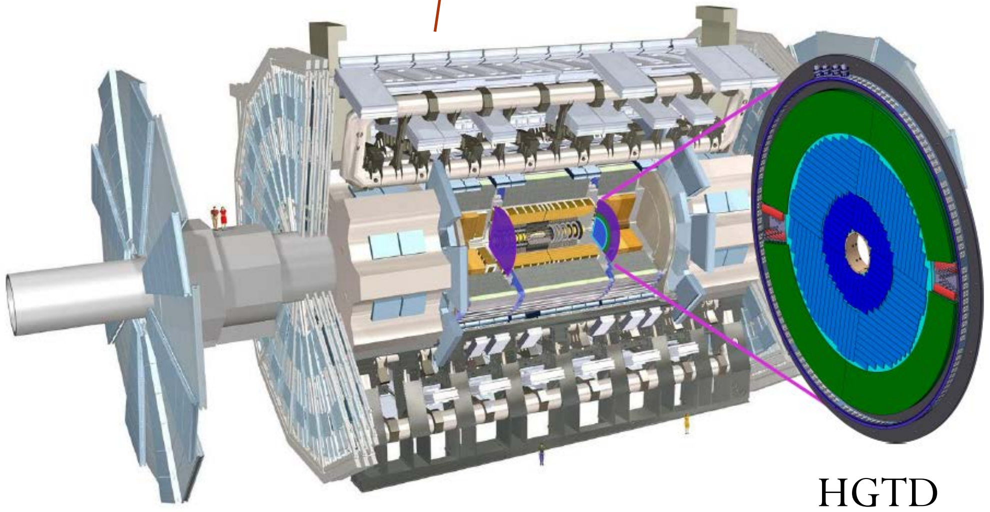
HGTD, ATLAS and LHC high luminosity

- **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
  - **35 to 70 ps of time resolution on hits (less on tracks)**
  - **Radiation hardness up to** $2.5 \cdot 10^{15}$Neq
  - http://cds.cern.ch/record/2623663
- 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**





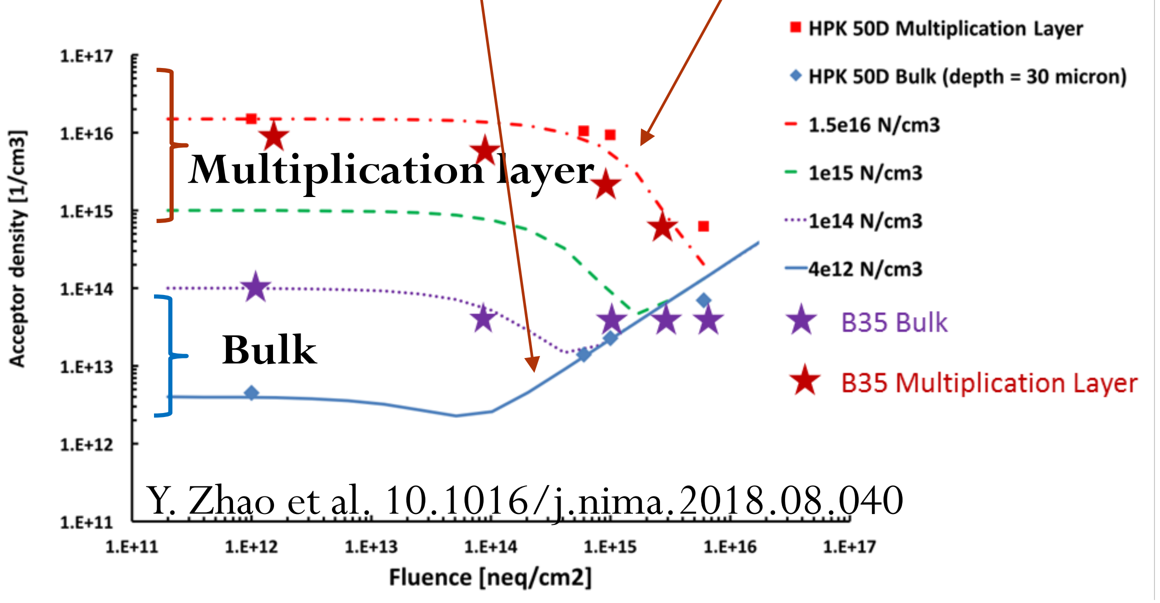
Dr. Simone M. Mazza - University of California Santa Cruz

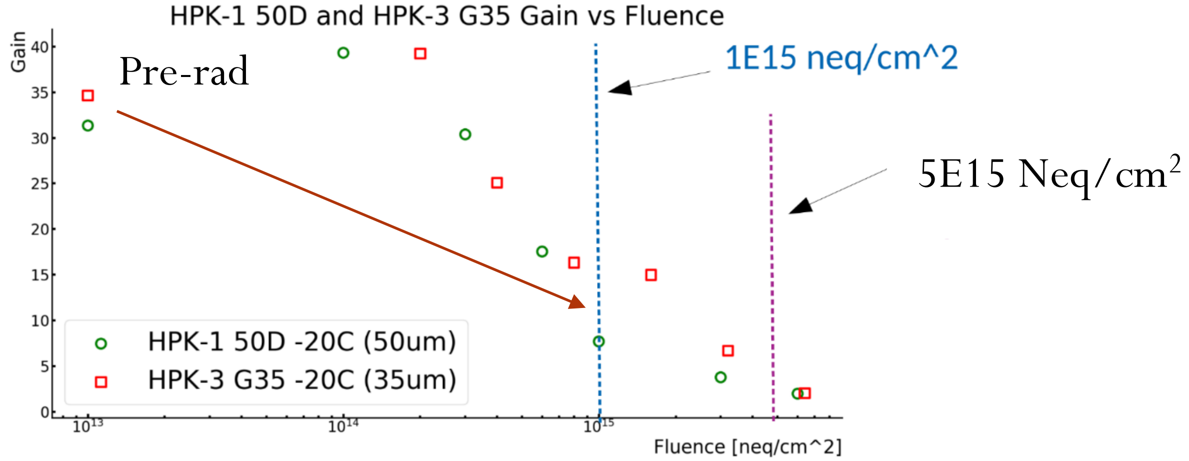
Radiation damage

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 depending on detector type**

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



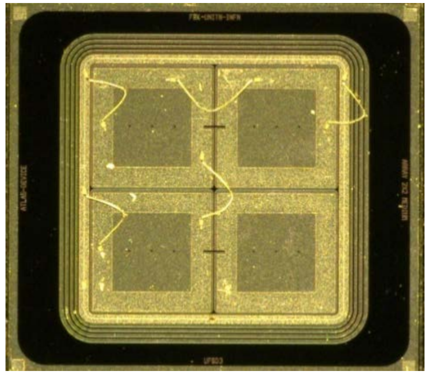


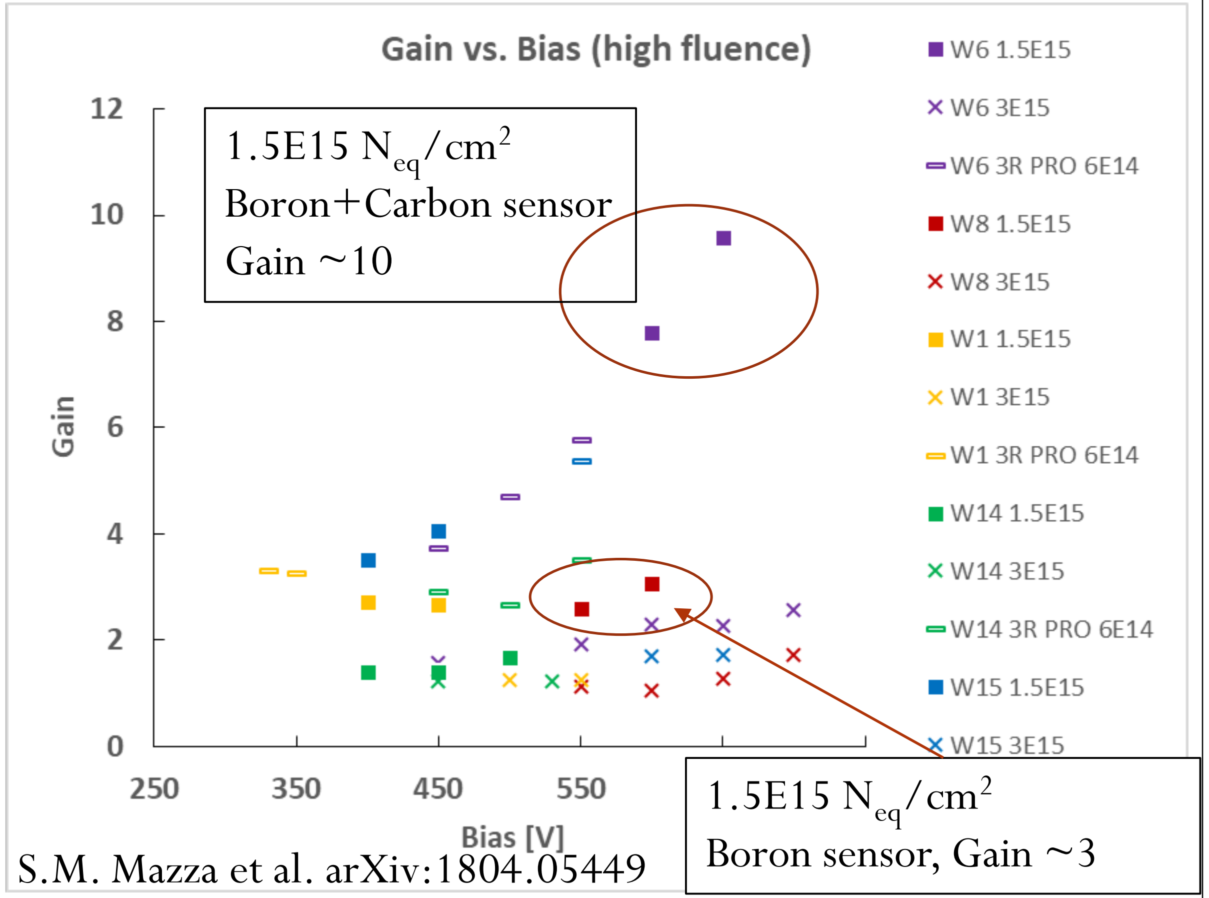
Y. Zhao presentation at ULITIMA conference

https://indico.fnal.gov/event/ANLHEP1390/session/8/contribution/68/material/slides/0.pdf

Mitigation of radiation damage: Carbon

- **FBK** (Fondazione Bruno Kessler) sensors
- With (and without) Carbon infusion
  - FBK-C and FBK-noC
- Carbon is electrically inactive (no effect pre-irradiation)
  - Slight reduction of gain from the implantation process
- Catch interstitials instead of Boron
- → Reduces acceptor removal after irradiation

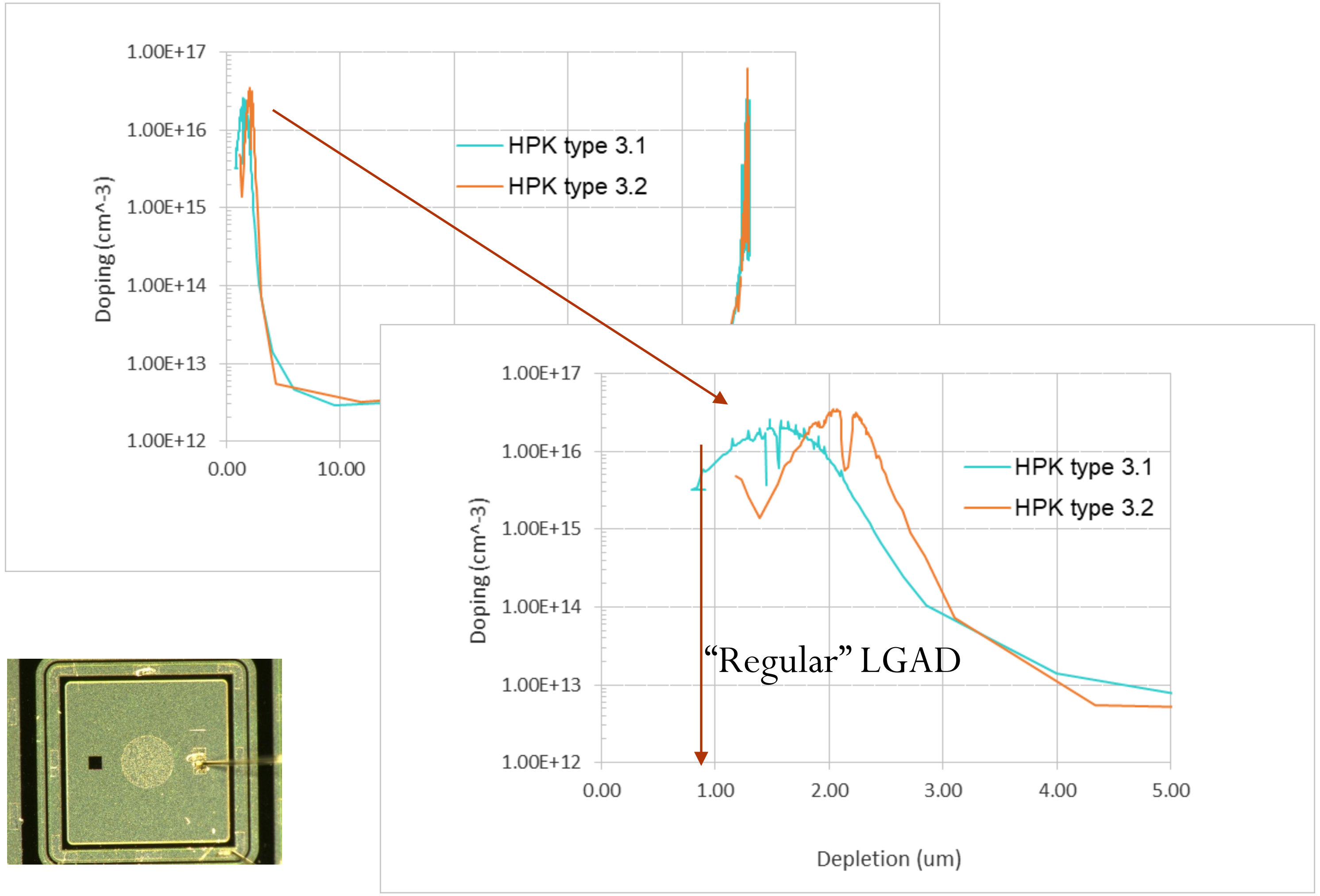




S.M. Mazza et al. arXiv:1804.05449

M. Ferrero et al. arXiv:1802.01745
Y. Zhao et al. 10.1016/j.nima.2018.08.040

Mitigation of radiation damage on LGADs

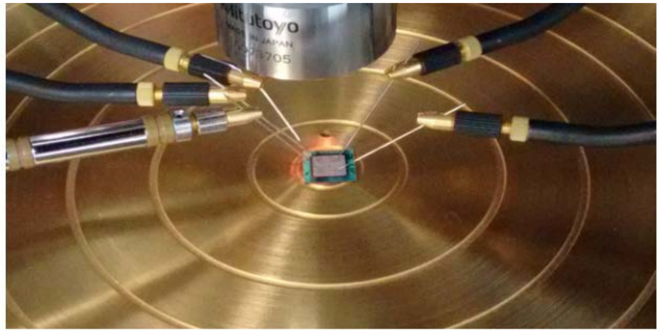


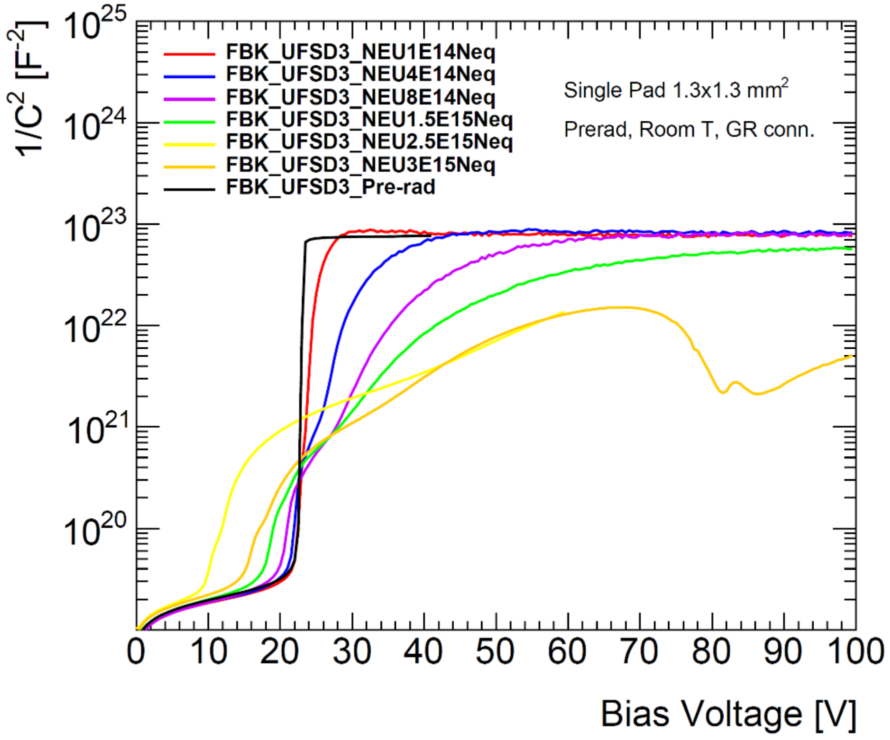
- **HPK** (Hamamatsu Photonics) sensors
  - HPK-3.1 and HPK-3.2
- Thin but highly doped gain layer
  - Higher initial doping concentration
  - Takes more time to be inactivated
- Deep gain layer
  - **High field for larger volume**
- Gain layer between 1um to 2um in instead of ~0.5-1 um

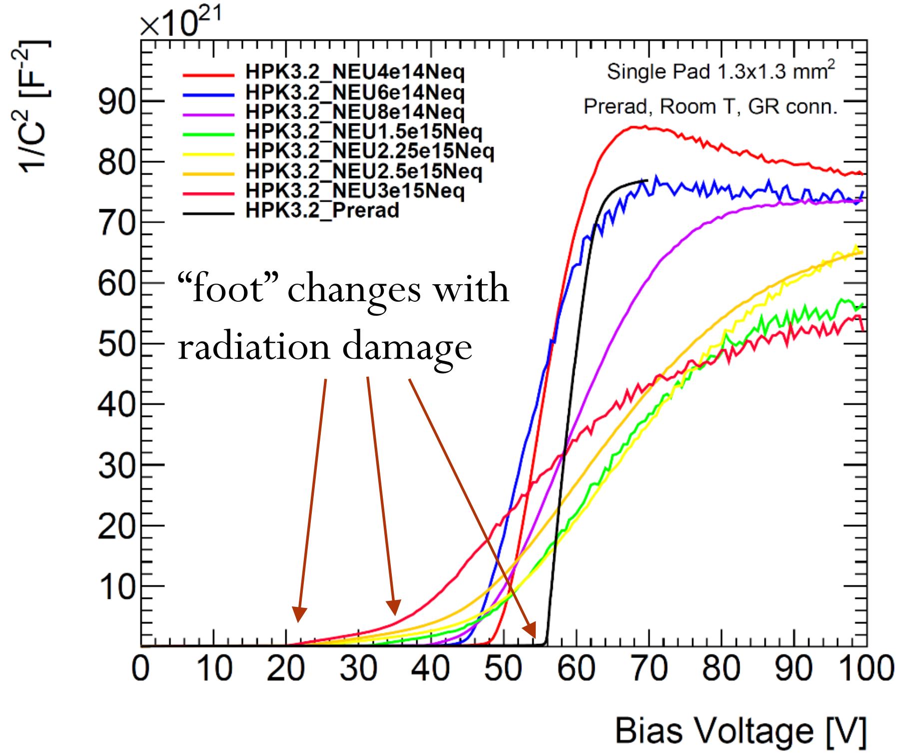
Gain layer fraction

Gain layer and CV

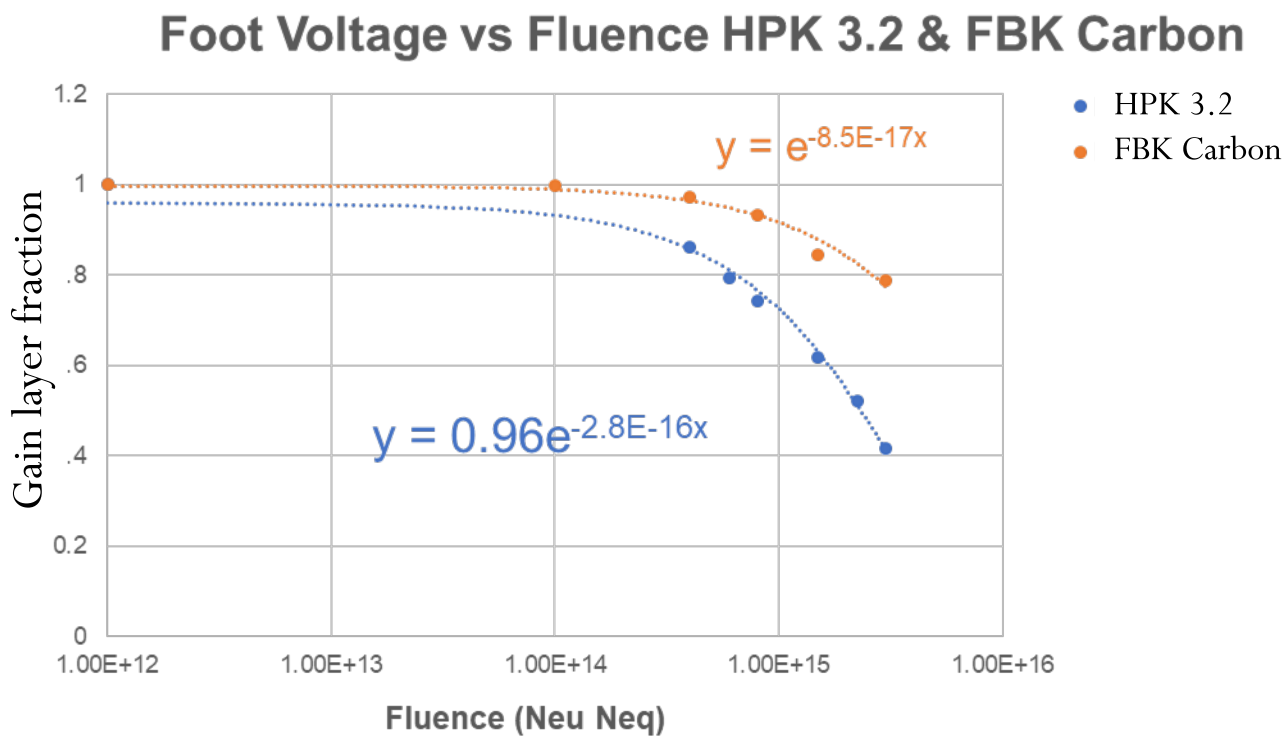
- Capacitance over voltage (CV)
  - Study doping concentration profile and full depletion of the sensor
- Study of the "foot" for LGADs on $1/C^2$:
  - $1/C^2$ flat until depletion of multiplication layer
  - Proportional to gain layer active concentration
- Bulk doping concentration proportional to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







Gain layer vs. Fluence: The Effect of Carbon

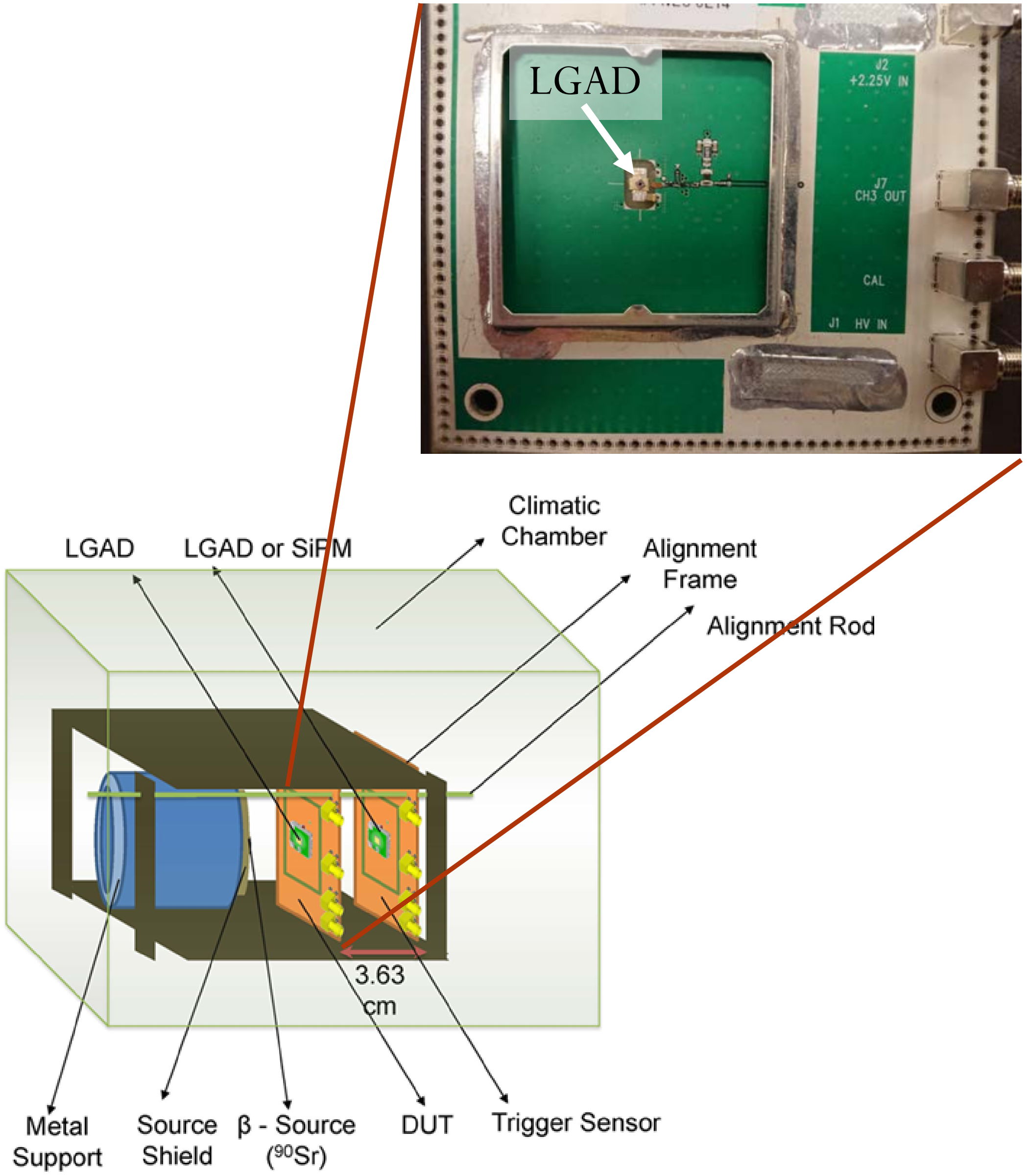


$$N_D = N_0 e^{-c\phi}$$

- 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

LGAD charge collection performance

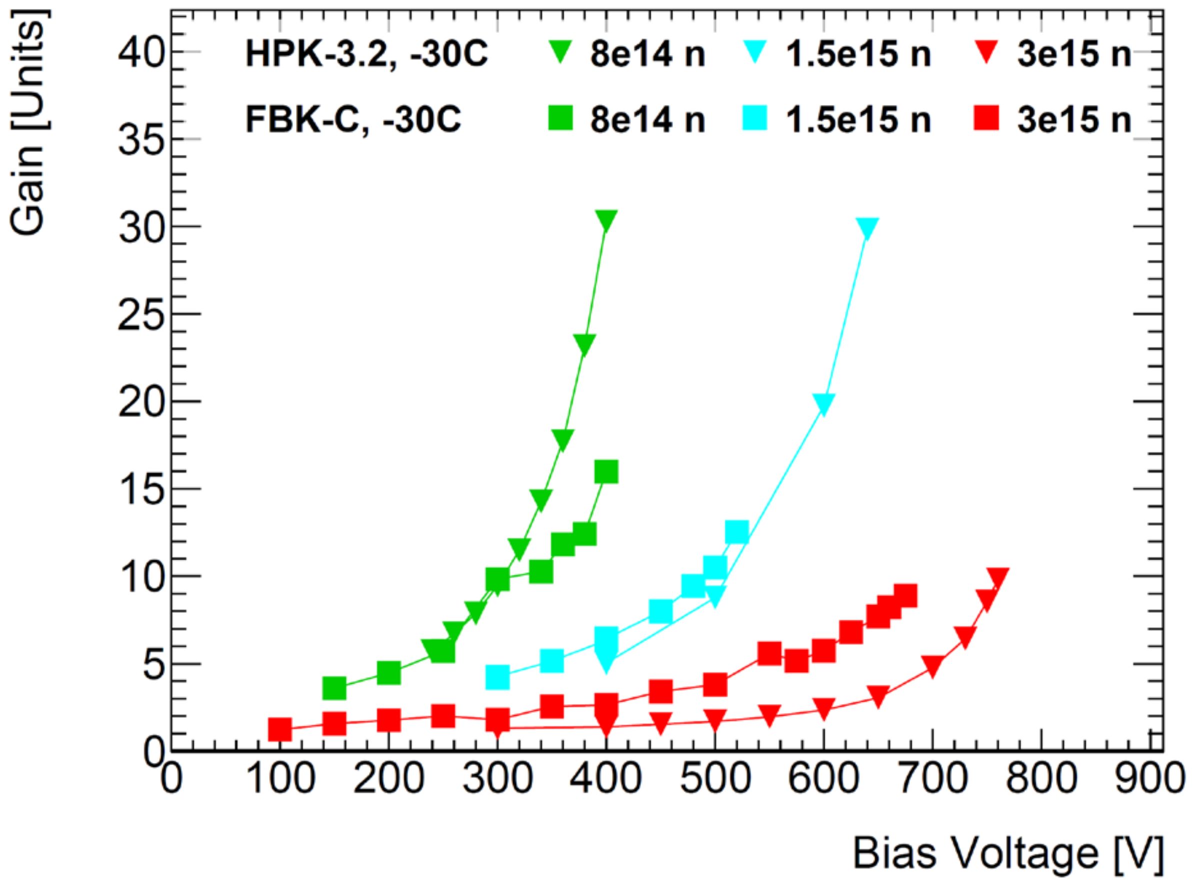
Sensor testing – Sr90 telescope

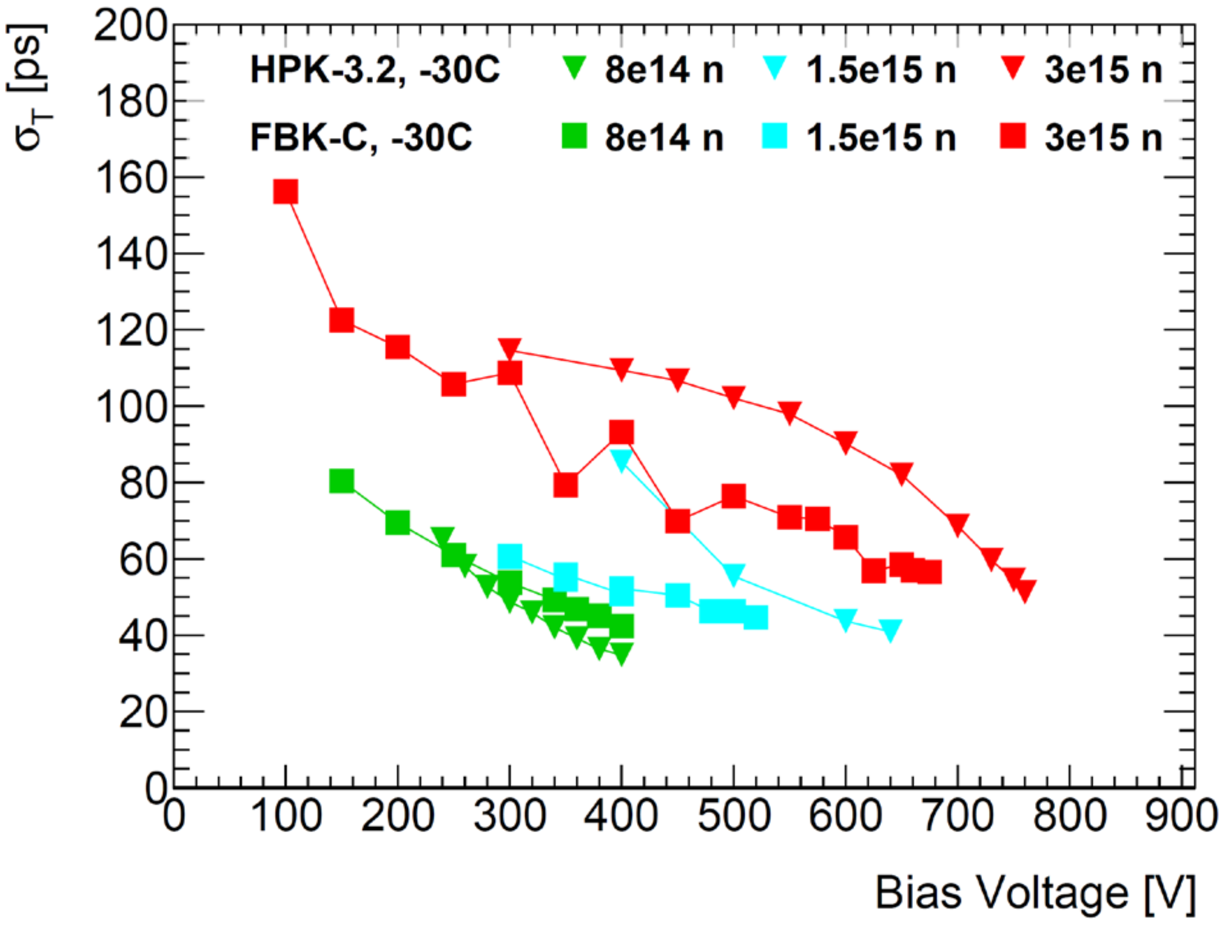


- Dynamic laboratory testing
  - Using MiP electrons Sr90 β-source (β-telescope)
  - Signal shape, noise, collected charge, gain, **time resolution**
- Sensors mounted on analog readout board designed at UCSC (Ned Spencer, Max Wilder, Zach Galloway) with fast amplifier (22 ohm input impedance, bandwidth > 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/-20C/-30C

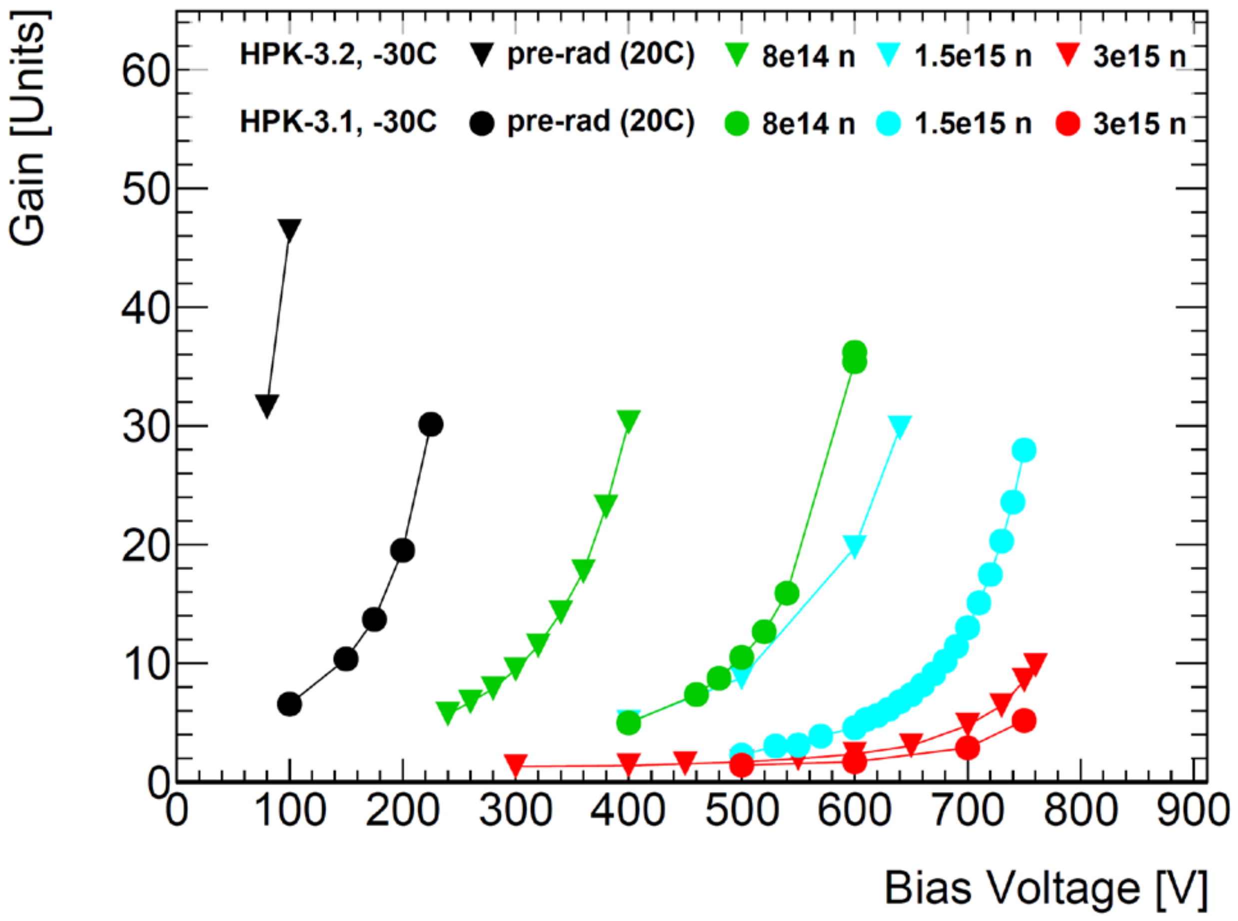
LGAD performance after irradiation

- Performance of HPK-3.2 and FBK-C is good up to 3E15Neq (sensors irradiated at JSI with neutrons)
- Gain of ~8 (~4fC of collected charge) and 50ps time resolution
- Independent effect of Carbon (FBK) and deep gain layer (HPK)

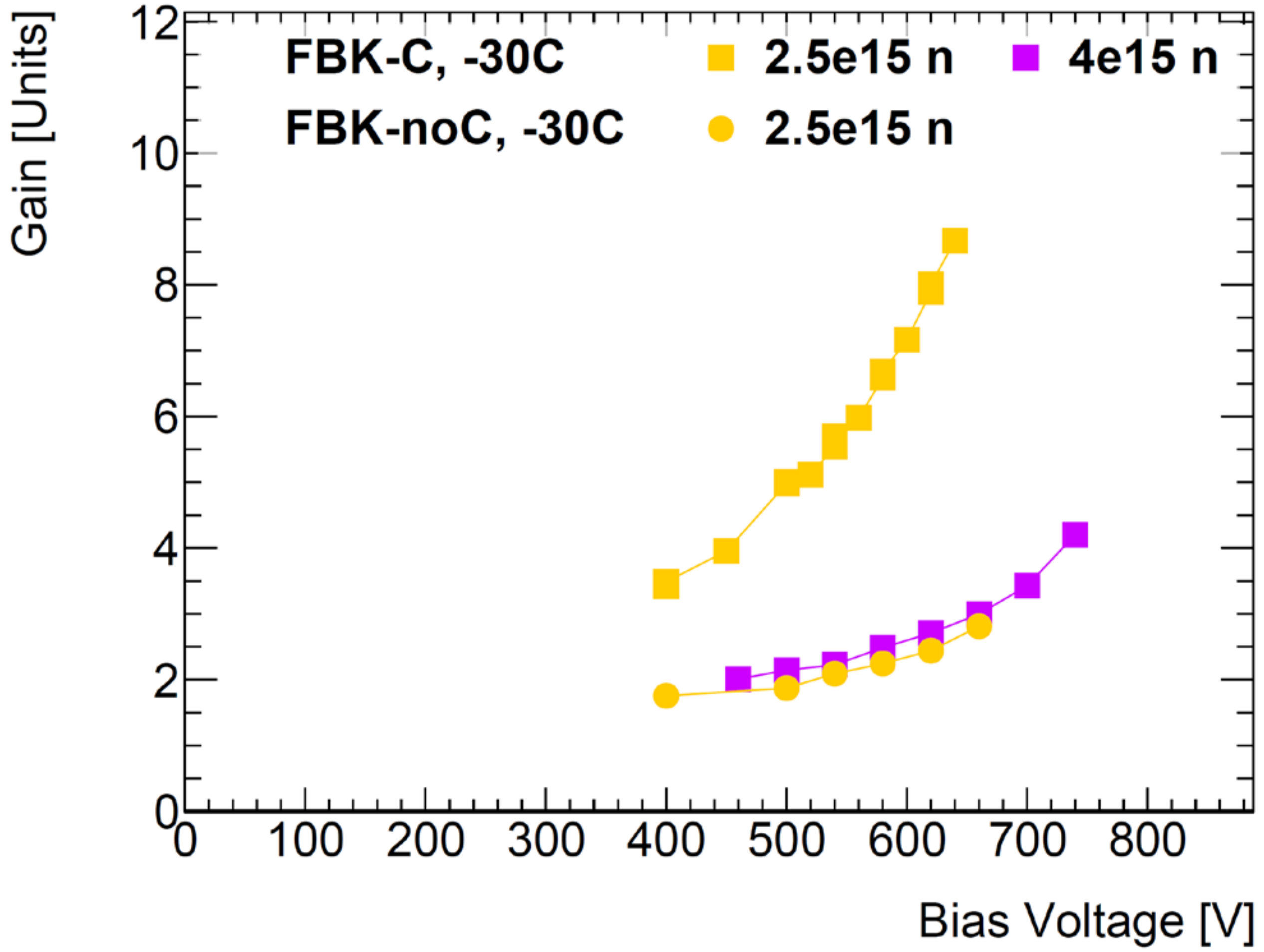




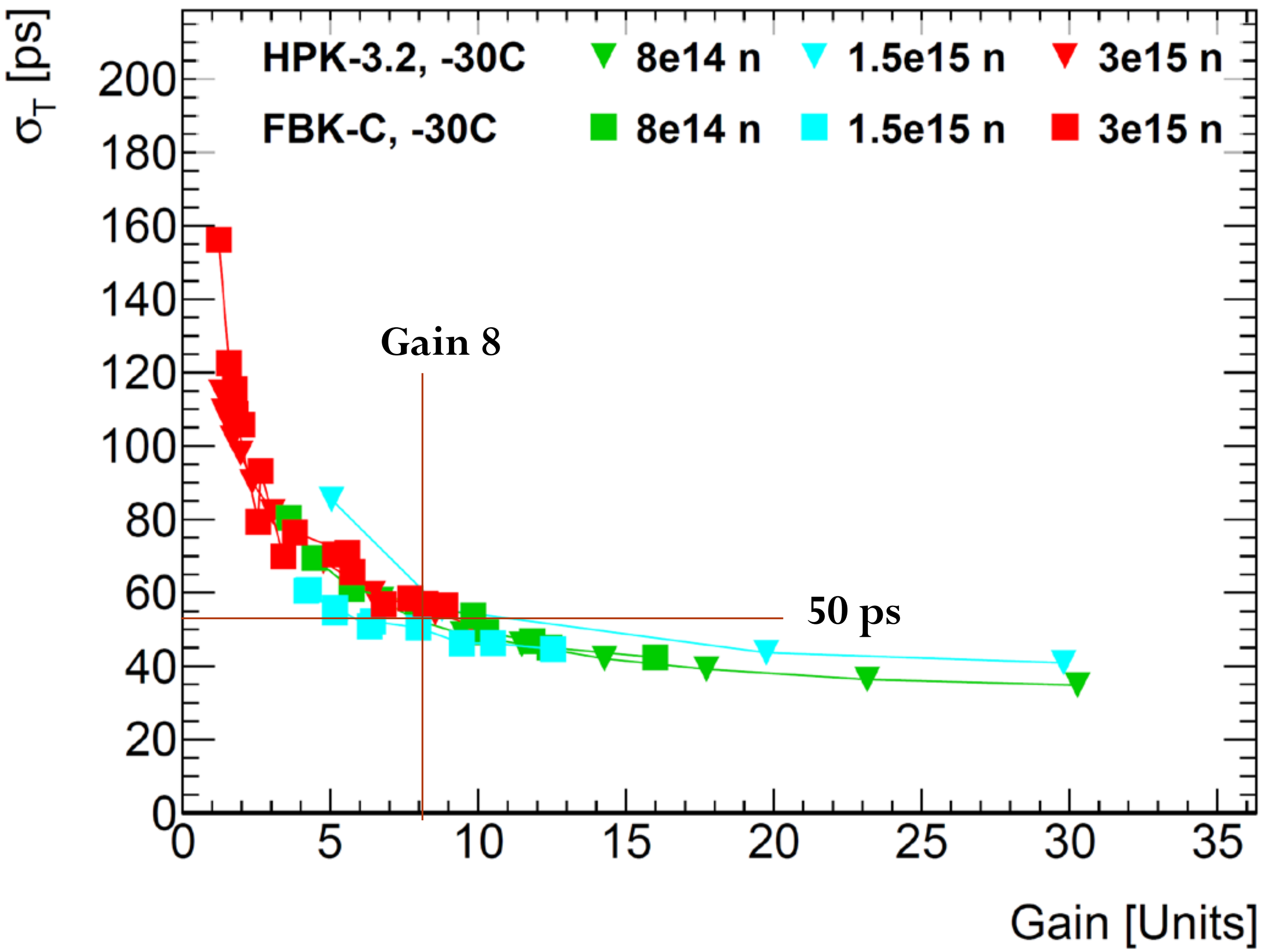
Deep (HPK-3.2) vs non deep (HPK-3.1)



With (FBK-C) and without (FBK-noC) Carbon



LGAD performance

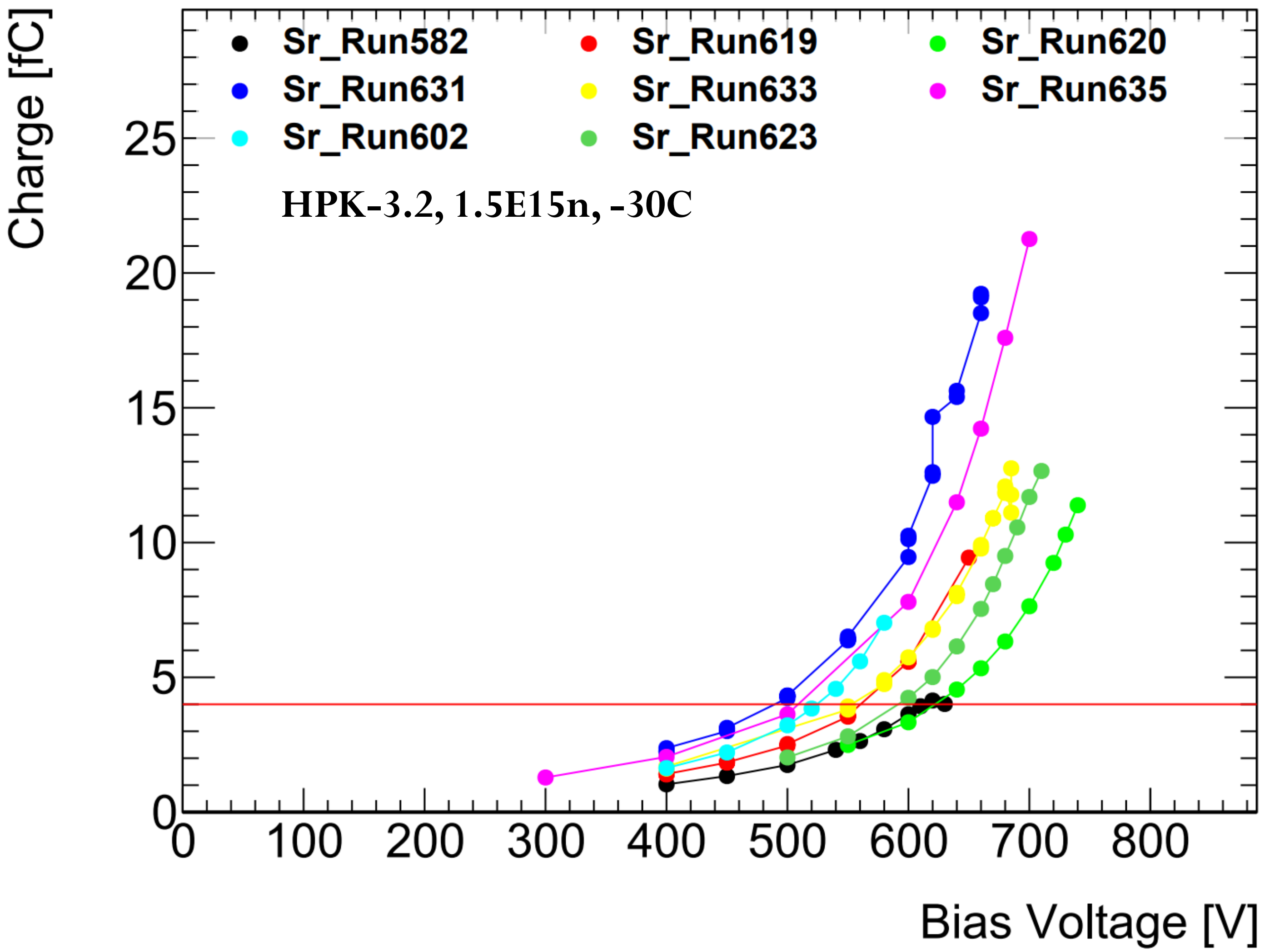


- Time resolution vs gain has a behavior that is mostly independent from radiation damage
  - Collected charge of ~8 needed to achieve ~50ps of time resolution
- Both sensor show reasonable performance up to 3E15 Neq
  - Fulfilling requirements for HL-LHC timing layers
  - After 3E15 Neq still a challenge
  - Combination of Deep gain layer and Carbon?
- Other LGAD manufacturers under study:
  - CNM (Spain), NDL (China), BNL (US)

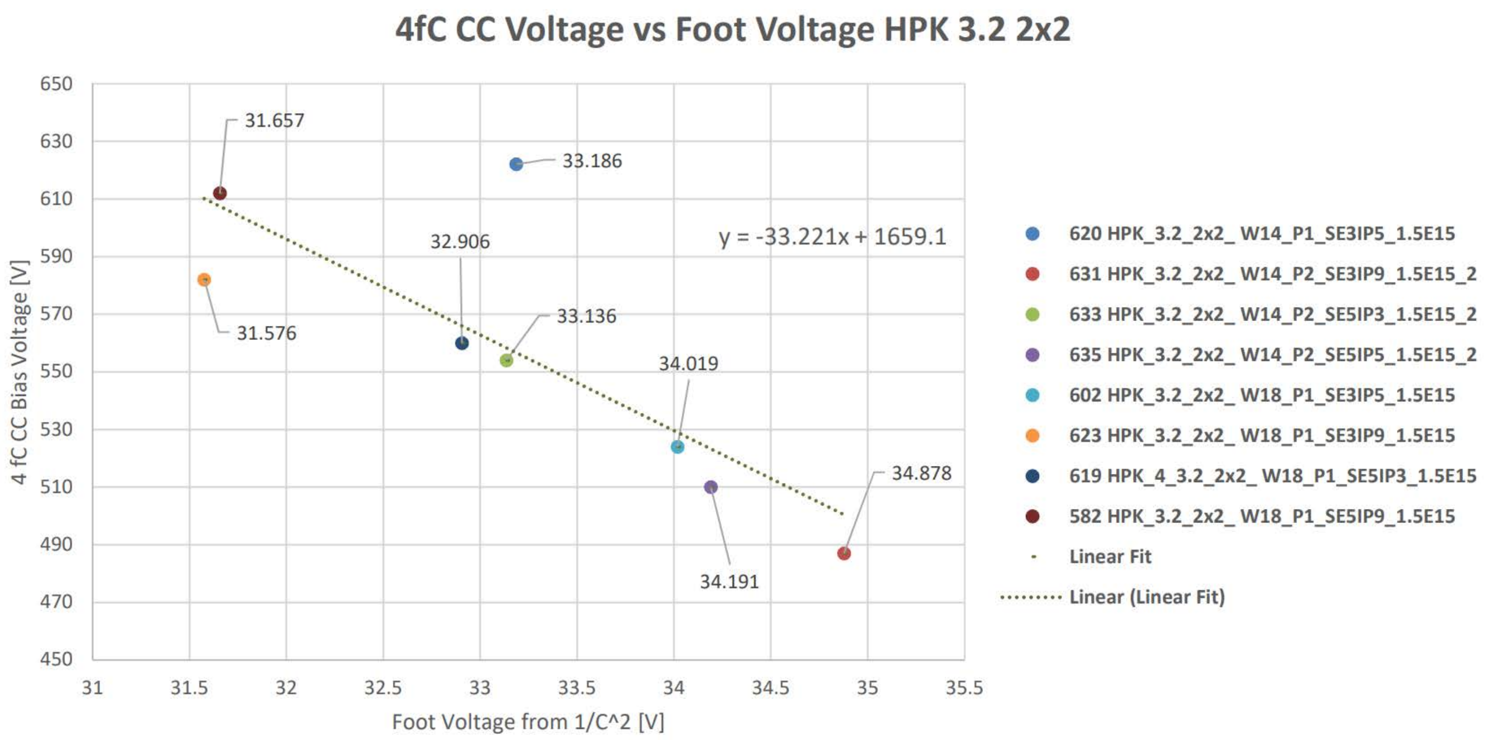
Fluence uncertainty

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)
- Pre-rad difference in performance instead is <1%
  - Where is the variation coming from?
- Plot on the right: HPK Type 3.2 sensors all irradiated at 1.5E15 Neq



Correlation of foot and gain layer



- Gain layer can be probed by
  - Measuring the gain (beta-scope)
  - Measuring the foot (CV)
- Gain shows a 10% variation after irradiation
- Measured foot also shows a 10% variation
- Plot together foot voltage and voltage to achieve 4fC (Gain ~8)
  - Linear correlation (a few outliers)
  - **Performance variation is real**

- JSI quoted fluence uncertainty is ~10%
  - Most probably is the cause of performance uncertainty

Conclusions

- **Options available to increase the radiation hardness of LGADs**
  - Carbon
  - Thin and deep gain layer
- LGADs from several vendors show **reasonable performance up to 3E15Neq**
  - Good gain (8-10) and time resolution (50-60ps)
- Making the mark for the first applications at timing layers of ATLAS/CMS at HL-LHC

- New productions from HPK, FBK, CNM and NDL are coming in 2020
- Including the **combination of deep gain layer and carbon**: FBK-UFSD-3.2
  - **Stay tuned!**

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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)
- Fluence: 1E13 Neq/cm^2 → 1E16 Neq/cm^2
- Ionizing dose up to 4MGy
- Waiting for the FNAL facility!

Jožef Stefan Institute

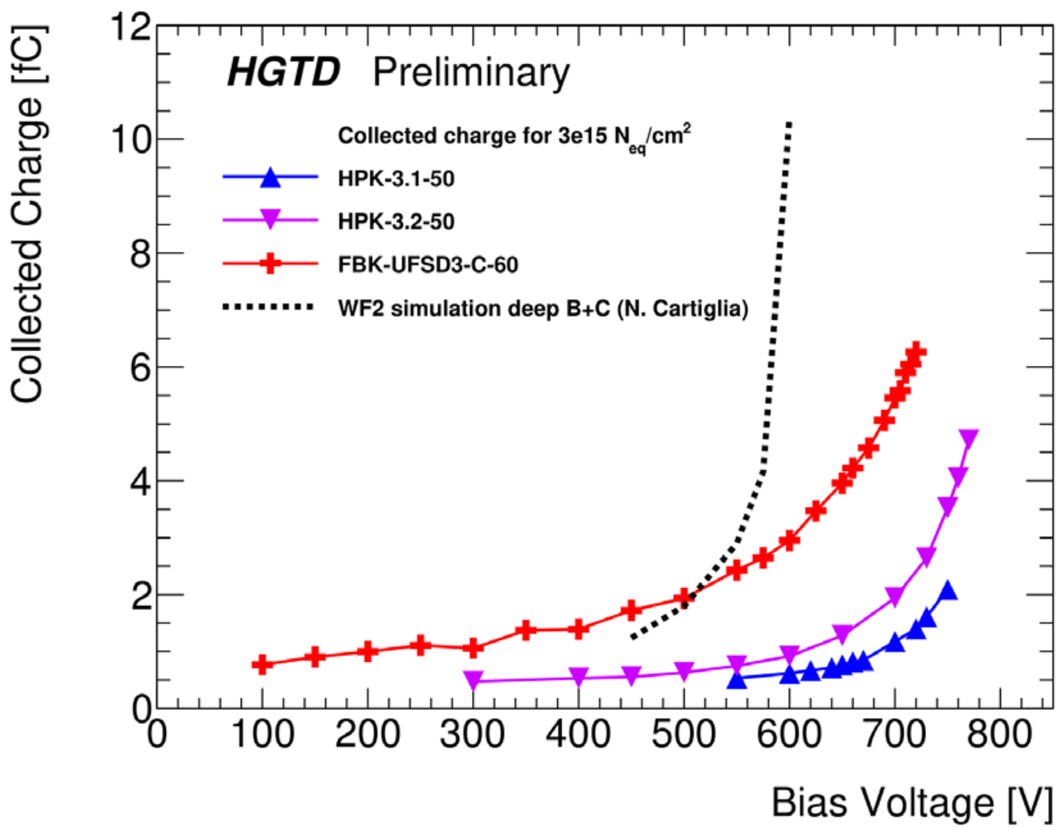
CERN IRRAD Proton Facility

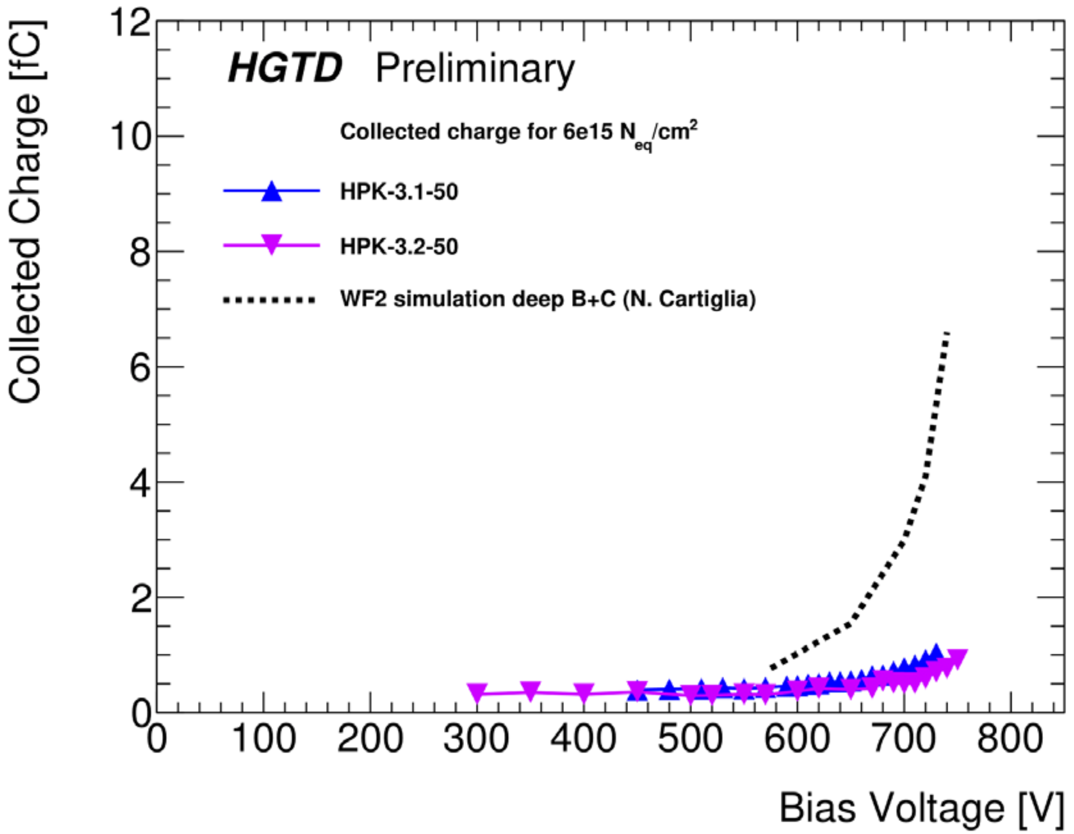
Los Alamos NATIONAL LABORATORY

KEK

Future prospect – deep gain layer + Carbon

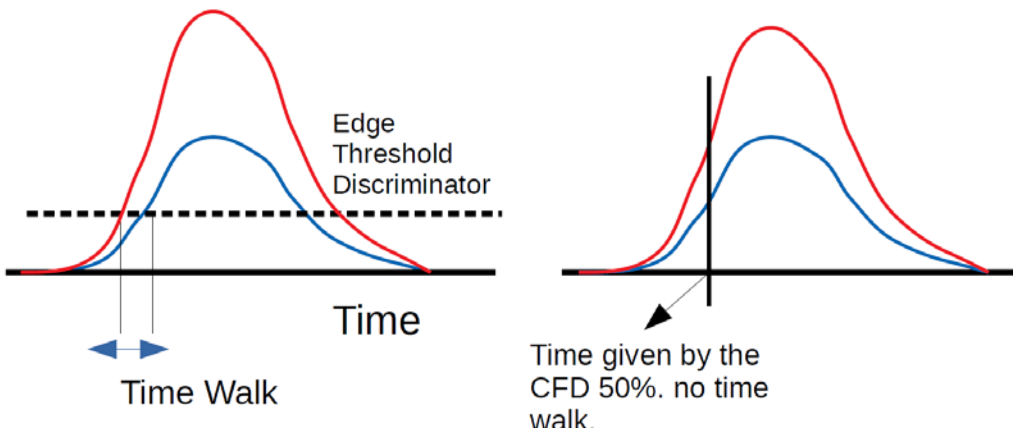
- Combine Carbon (FBK-UFSD-3) with deep implantation (HPK-3.2)
- Preliminary simulation with Weightfield2 predict a collected charge of 5 fC at 6E15 Neq!

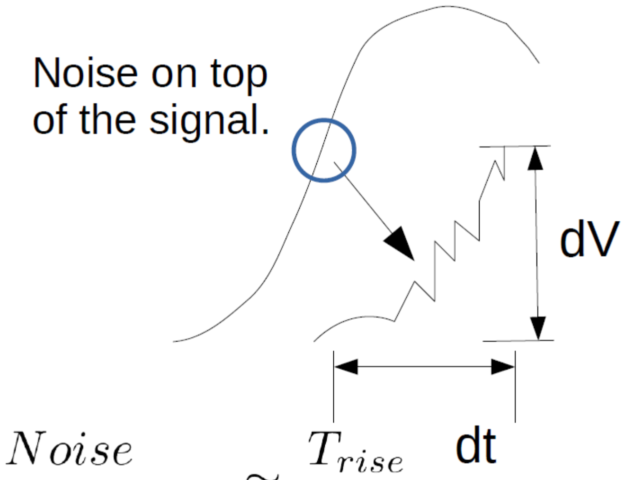




https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots#2018_2019_Sensor_Performance_TDR

LGADs timing resolution





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

Sensor time resolution main terms

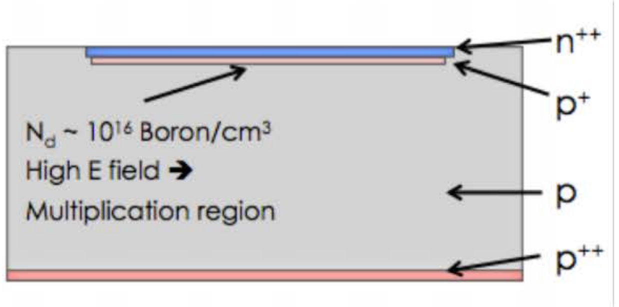
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

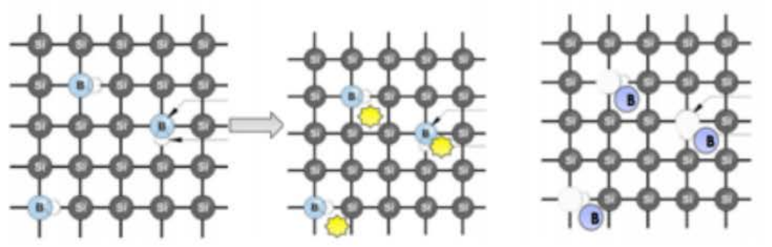
- Time walk:
  - Minimized by using for time reference the % CFD (constant fraction discriminator) instead of time over threshold
  - In HGTD electronics TOA (Time of Arrival) of the signal is corrected with TOT (Time over threshold)
- Landau term:
  - Reduced for **thinner sensors** (50,35 μm)
- Jitter: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

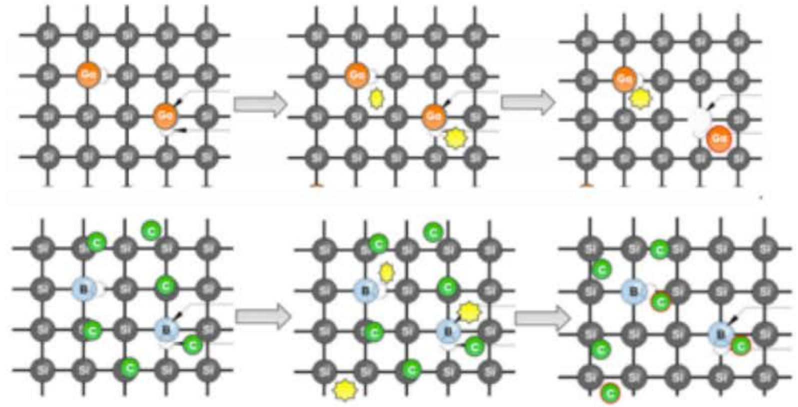
$$N(\emptyset) = N(0) * e^{-c\emptyset}$$





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

41