Hadron damage investigation of Low Gain Avalanche Detectors

Josef Sorenson[1], Martin Hoeferkamp[1], Jiahe Si[1], Sally Seidel[1], Gregor Kramberger[2]

1. The University of New Mexico, Albuquerque, New Mexico
2. Jožef Stefan Institute, Ljubljana, Slovenia

PIXEL 2022

13 December 2022

THE UNIVERSITY OF NEW MEXICO

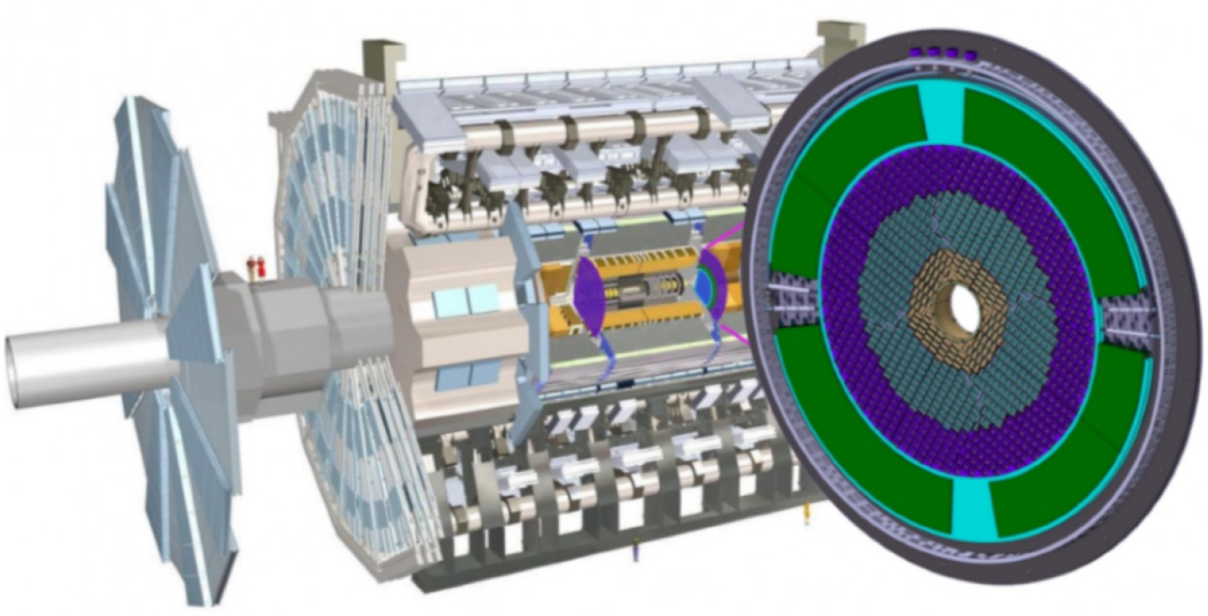
Jožef Stefan Institute

Talk Overview

1. Motivation for Low Gain Avalanche Detectors (LGADs) at the High Luminosity LHC.
2. How LGADs work.
3. Sensor specifications and radiation conditions.
4. Acceptor removal constant in proton irradiated FBK LGADs
5. Timing resolution in proton irradiated FBK LGADs
6. Outlook

High Luminosity LHC (HL-LHC) and the High Granularity Timing Detector (HGTD) and the Endcap Timing Layer (ETL)

- The HL-LHC upgrade is expected to come online in 2027 and will increase the number of interactions per collision by an order of magnitude, to about 200 interactions per bunch crossing.
- This increases the pileup and blurs the track reconstruction. The expected temporal width of one bunch crossing is ~175 ps.
- ATLAS is installing the HGTD in the forward region which will mitigate the effect of pileup by providing timing resolution of ~35 ps* at the start of the run. CMS is installing the ETL with a similar target timing resolution.



*M. P. Cassado. "A High Granularity Timing Detector for the ATLAS Phase-II Upgrade." Nuclear Inst. and Methods in Physics Research, A 1032 (2022) 166628

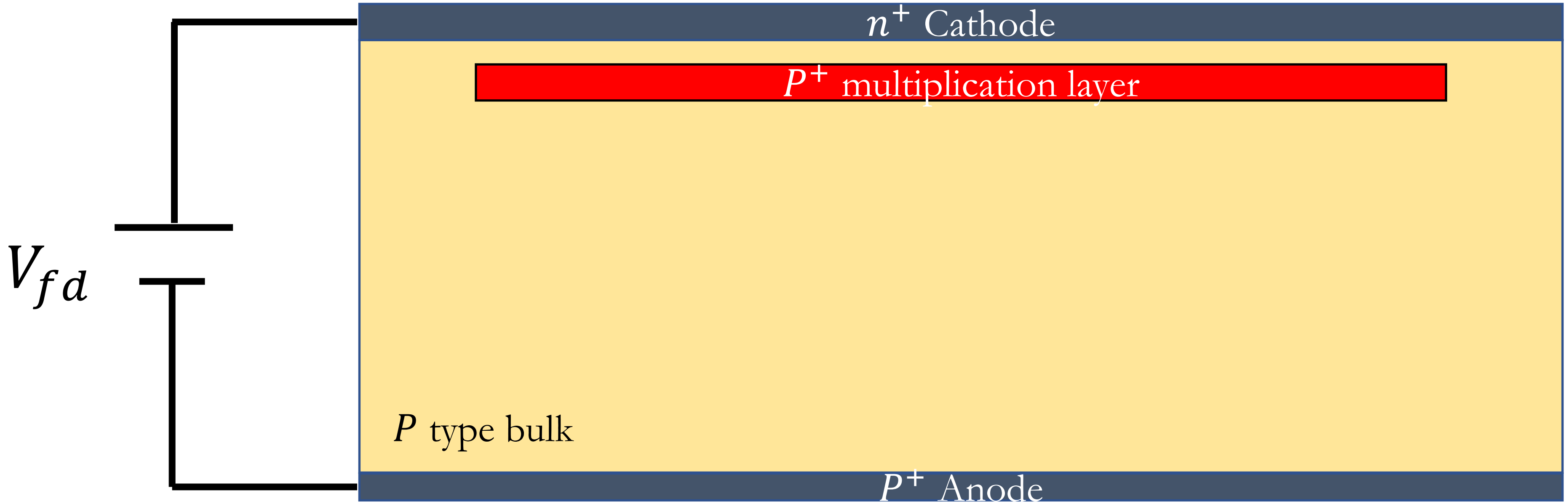
Low Gain Avalanche Detectors (LGADs)

- Both the HGTD and ETL will be made of LGADs. The specification for a LGAD sensor's timing resolution is 35 ps unirradiated and 70 ps after a maximum fluence of $2.5 \cdot 10^{15} \mathrm{neq/cm^2}$
- LGADs have excellent timing resolution, but their radiation hardness is still improving.
- Many studies have been performed investigating the survivability of LGADs to the expected HL-LHC fluences of neutrons, pions, and gamma.

Gamma Irradiations (2022) – M. Hoeferkamp *et al.* arXiv:2112.09642
Neutron, Proton, Pion Irradiations (2015) - G. Kramberger *et al.* 2015 *JINST* **10** P07006

- This year we have irradiated LGADs produced by Hamamatsu Photonics K.K. (HPK) and Fondazione Bruno Kessler (FBK) with 400 and 500 MeV protons respectively.

How do LGADs work?



- LGADs are thin sensors that have a $n^{++} - p^{+} - p - p^{++}$ structure.
- The p^+ layer is referred to as the gain layer or charge multiplication layer.
- LGADs are reverse biased until the depletion width spans the entire width of the sensor. The minimum voltage for full depletion of the sensor is called the full depletion voltage, V_{fd}.
- When fully depleted, the electric field across the gain layer can exceed $4 \cdot 10^5$ V/cm*.
- Particles passing through the sensor will produce electron hole pairs. The electrons are accelerated through the gain layer and multiply via impact ionization.

*N. Moffat et al 2018 JINST 13 C03014

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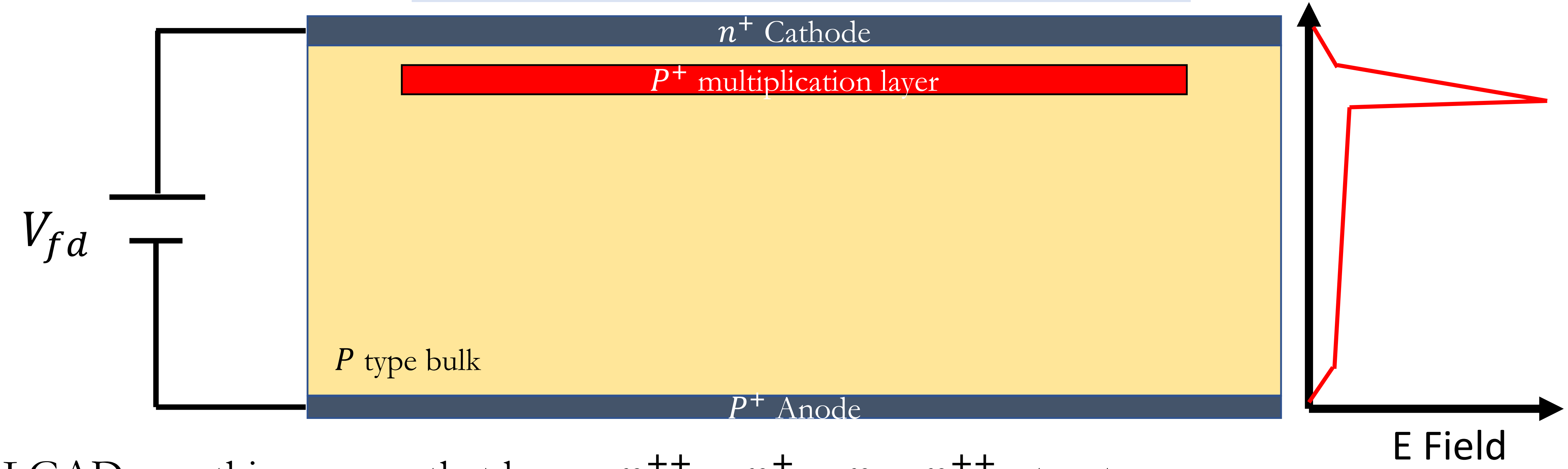

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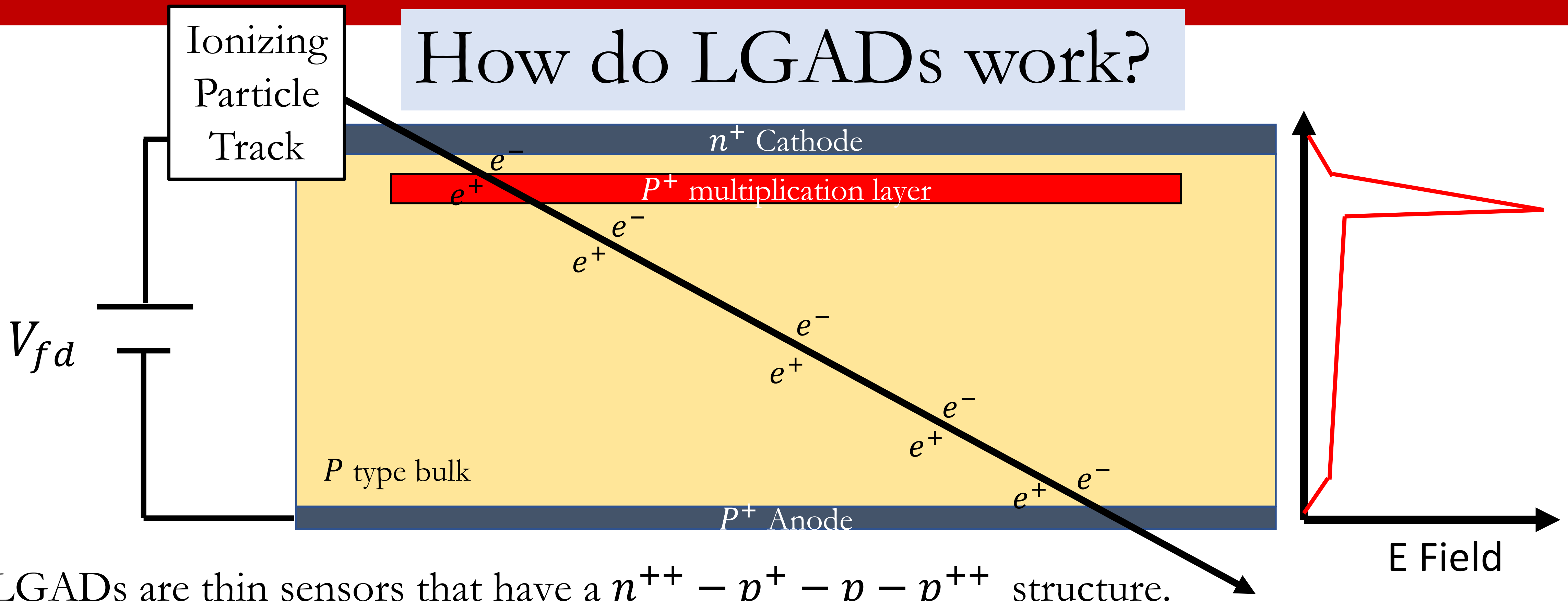

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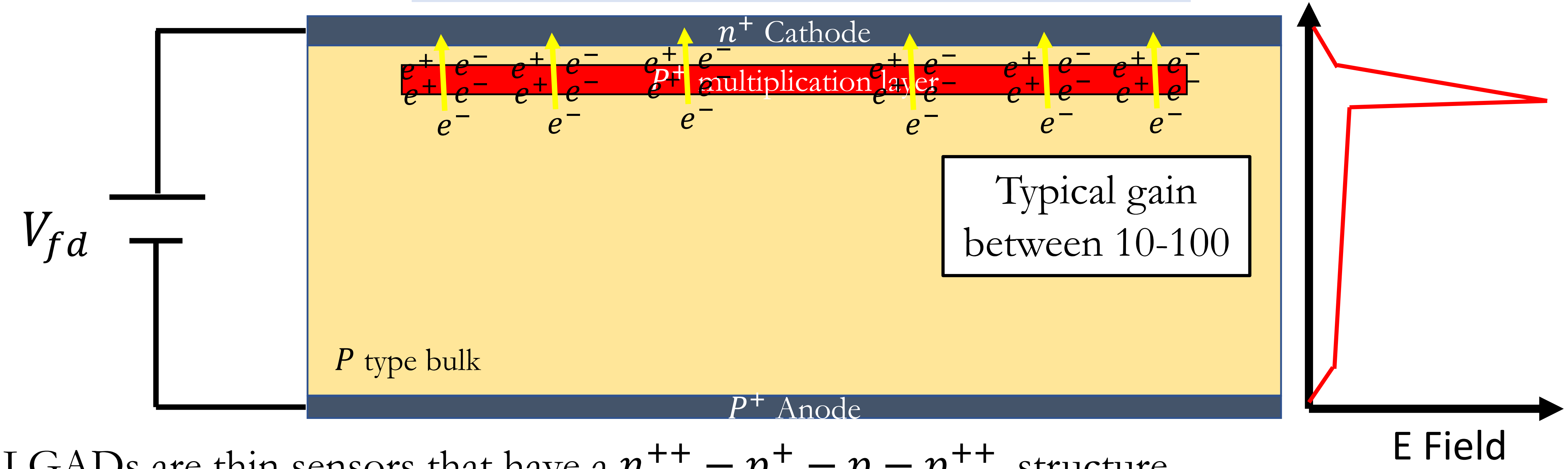

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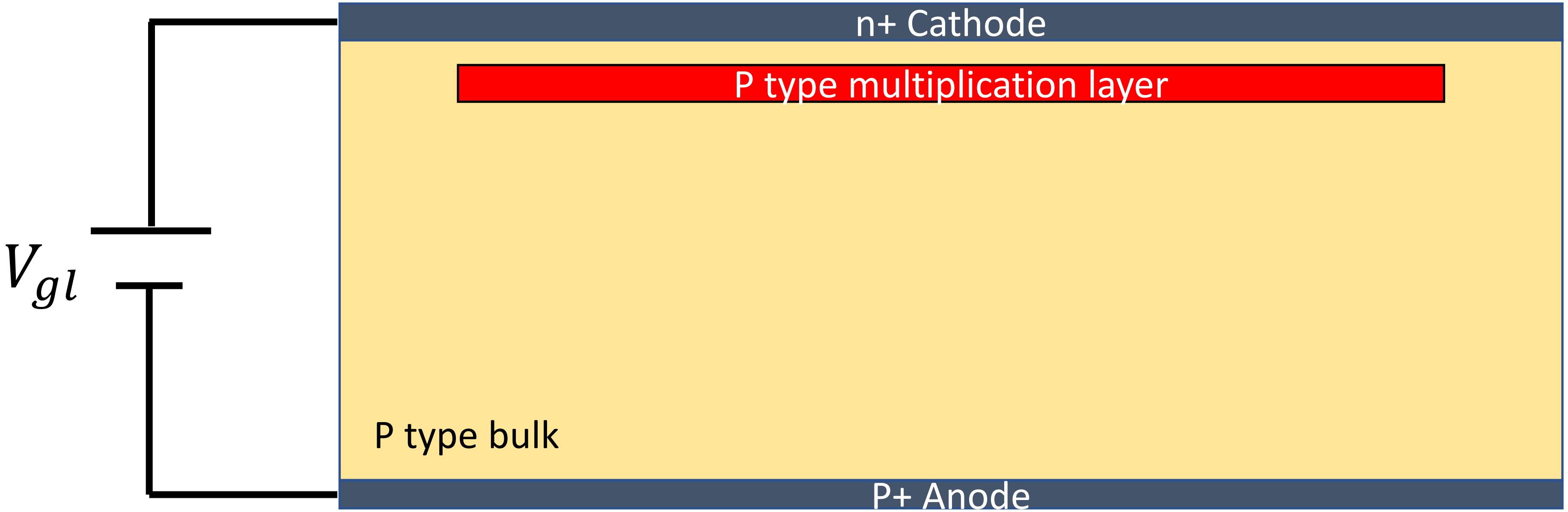


- The voltage (below V_{fd}) at which the p-type multiplication layer becomes depleted of charge is called the gain layer depletion voltage V_{gl}.
- V_{gl} is related to the dopant concentration N_A, the electric charge q, the width of the gain layer w, and the permittivity of silicon ϵ by the following relation:

$$V_{gl} = \frac{qN_A w^2}{2\epsilon}$$

- Therefore, a measurement of the gain layer depletion voltage will be proportional to a measurement of the dopant concentration in the gain layer.

Acceptor Removal

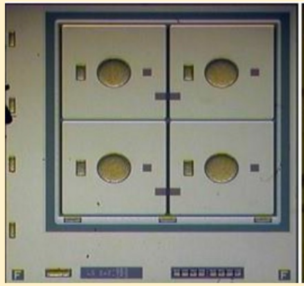
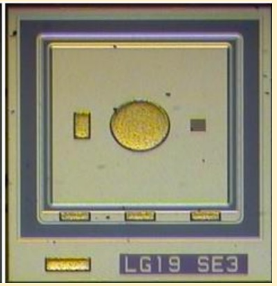
- The gain, and therefore the LGAD's timing performance, are related to the dopant concentration in the p^+ gain layer.
- Fluence from collisions at the LHC will reduce the active dopant concentration via transformation of the boron acceptors into defect complexes no longer acting as acceptors.* This is called acceptor removal.**

*M. Moll. "Acceptor removal – Displacement damage effects involving the shallow acceptor doping of p-type silicon devices" PoS (Vertex2019)027
**G. Kramberger et al. "Radiation effects in Low Gain Avalanche Detectors after hadron irradiations," 2015 JINST 10, P07006

Sensor Characteristics

- UNM has two sets of sensors from HPK and FBK that cover broad parameters.
- Both sets include single sensors and sensors manufactured in a 2x2 grid for studying inter-pad characteristics.

HPK-P2

- ➢ 50 μm active thickness
- ➢ Single guard ring
- ➢ Variations with under bump metallization (UBM)
- ➢ 2.2 to 2.5 μm thick gain layer

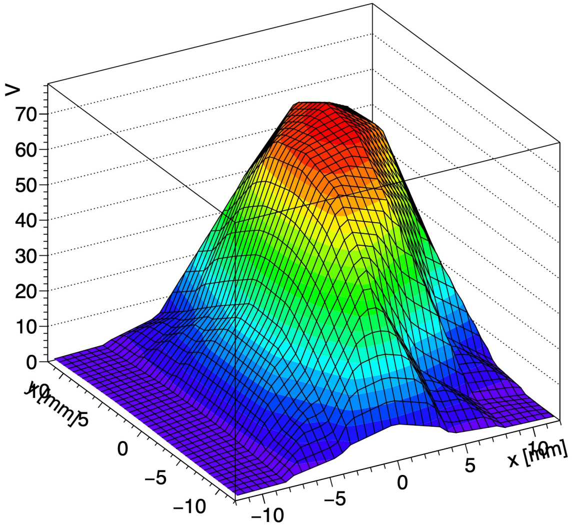
FBK4

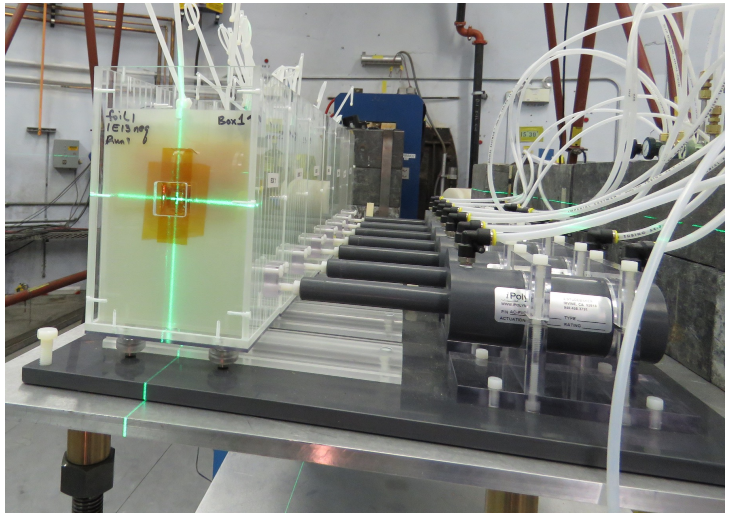

- ➢ 55 μm active thickness
- ➢ Multiple guard rings
- ➢ Shallow and deep gain layer implant
- ➢ 0.7 to 2 μm thick gain layer
- ➢ Carbon co-implantation in the gain layer, which is expected to show improved radiation hardness*

*R. Padilla *et al* 2020 *JINST* **15** P10003

Irradiation Conditions

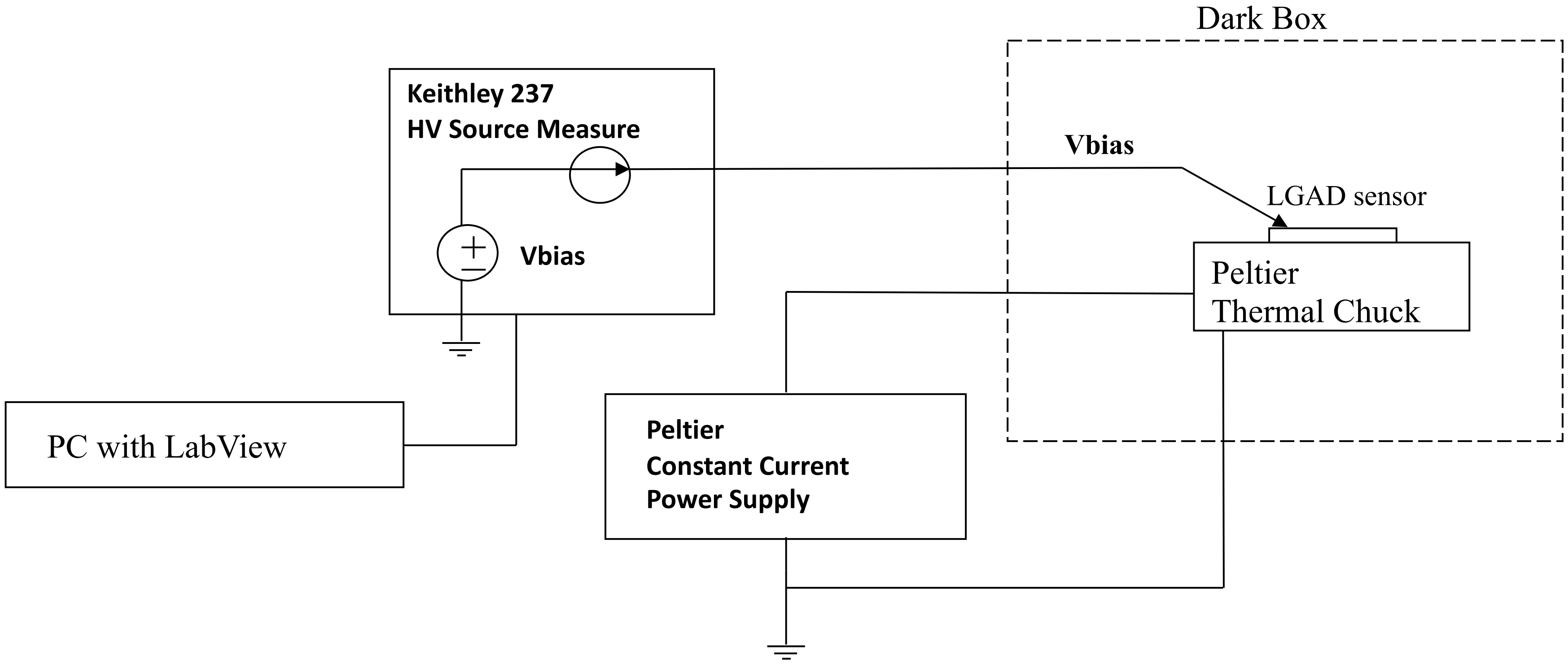
- The FBK4 sensors were irradiated by the UNM group at the Los Alamos Neutron Science Center (LANSCE) with 500 MeV protons in July of this year.
  - Representative sensors from each FBK4 wafer were irradiated at $2 \cdot 10^{14}$, $5 \cdot 10^{14}$, $1 \cdot 10^{15}$, and $1.5 \cdot 10^{15}$ neq/cm^2.





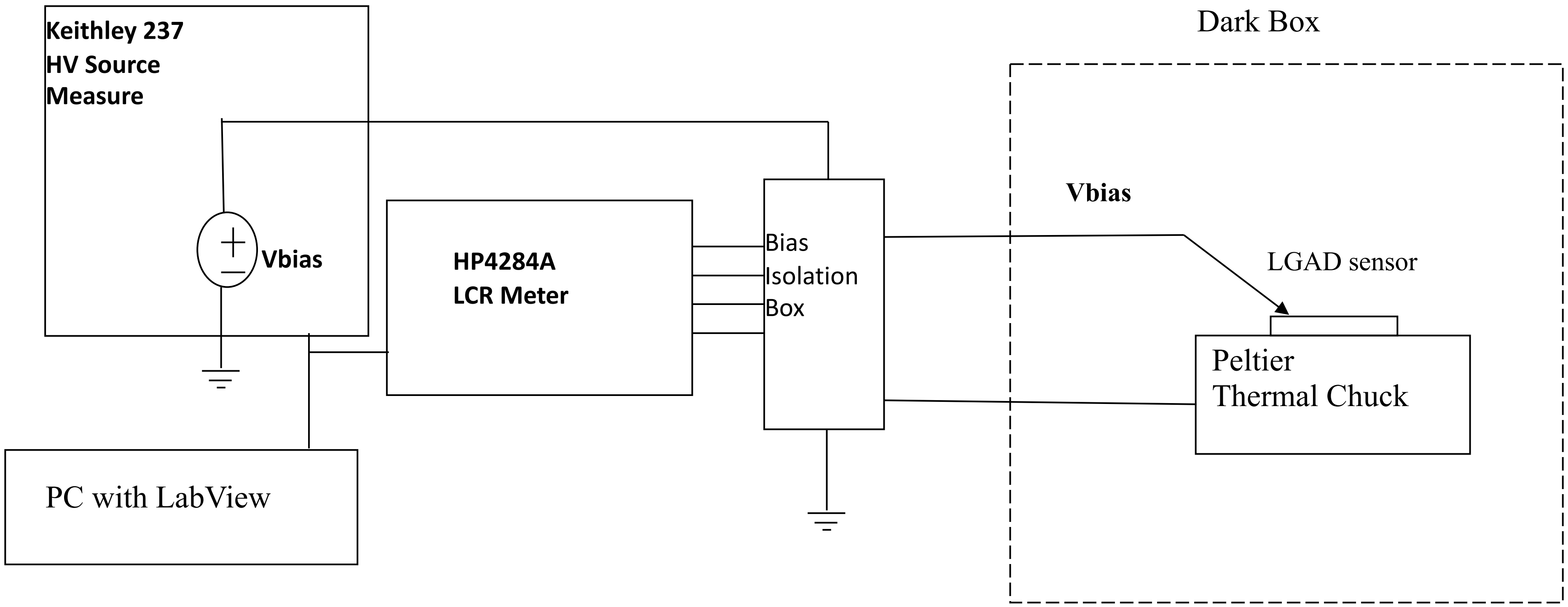
- The HPK2 sensors were irradiated at the Fermi National Accelerator Laboratory (FNAL) in May of this year at $5 \cdot 10^{14}$, $1 \cdot 10^{15}$, and $1.8 \cdot 10^{15}$ neq/cm^2 with 400 MeV protons.
- Both sensor types are stored in a -25 C freezer to prevent annealing.

Current vs. Voltage (IV) Measurement



- IV measurements are used to infer the leakage current and breakdown voltage of LGADs.
- At UNM we apply reverse bias and measure the current with the K237 V-source.
- Leakage current measurements are performed after annealing the sensors at 60 C for 80 minutes in accordance with the LGAD community's standards.

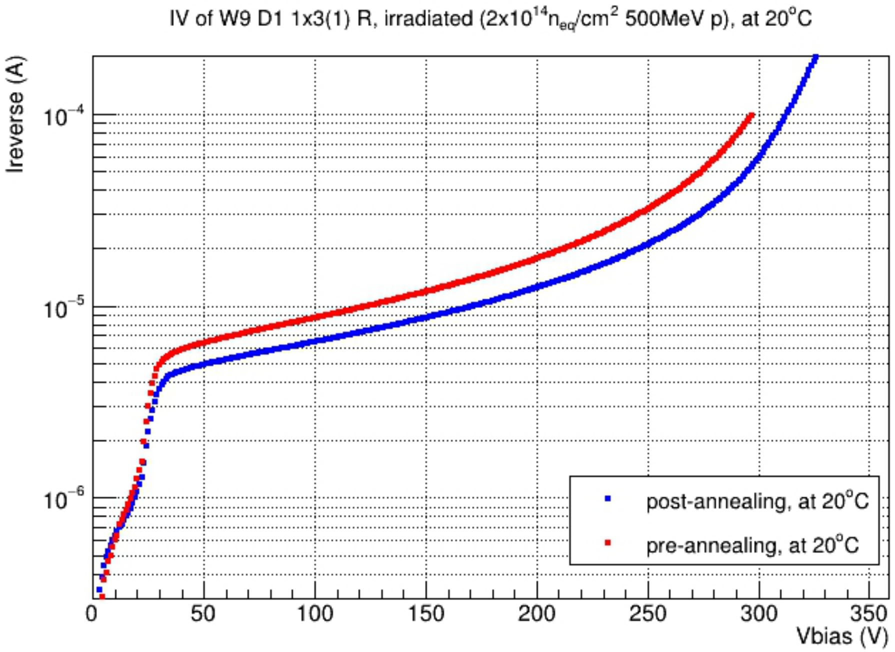
Capacitance vs. Voltage (CV) Measurement

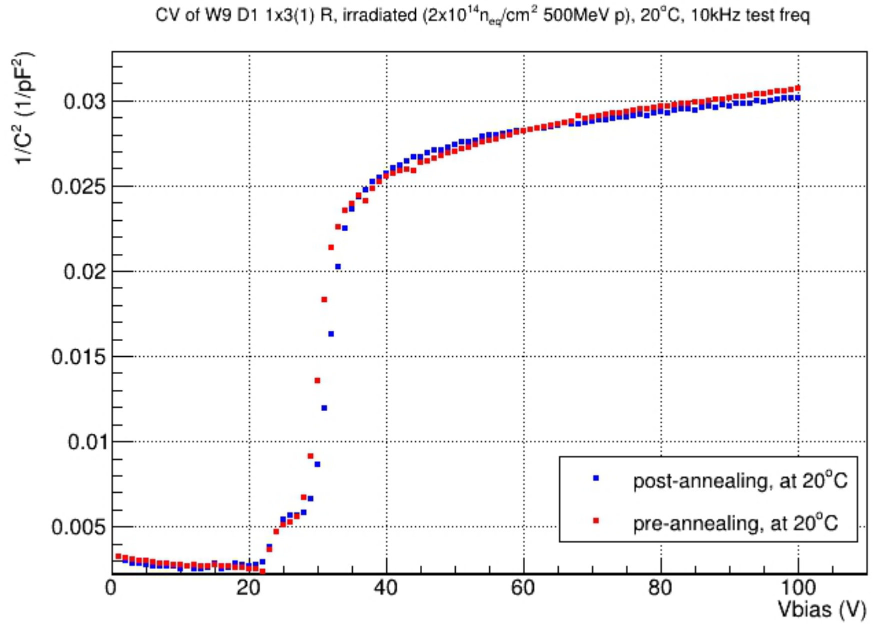


- CV measurements are used to infer V_{gl} and V_{fd}. This is because $C \propto \frac{1}{w}$ where w is the depletion width.
- At UNM we apply reverse bias with the K237 V-source and measure the sensor capacitance with the LCR meter at 1 kHz, 5 kHz, 10 kHz, 100 kHz, 1 MHz frequencies.

Annealing Measurement

- We performed IV and CV measurements before and after annealing the sensors at 60 C for 80 minutes in accordance with the LGAD community's standards.
- After annealing the leakage current decreased by ~30% and the breakdown voltage increased by ~20 V. There is no significant change in V_{gl} or V_{fd}.

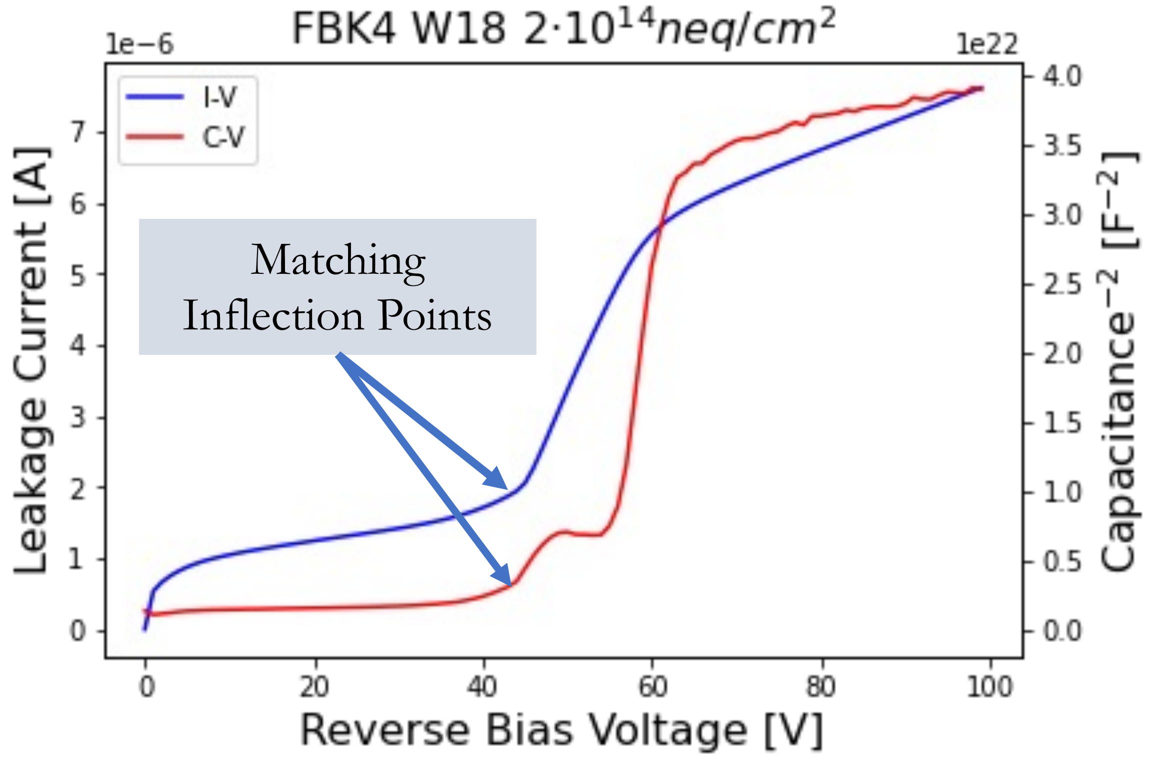


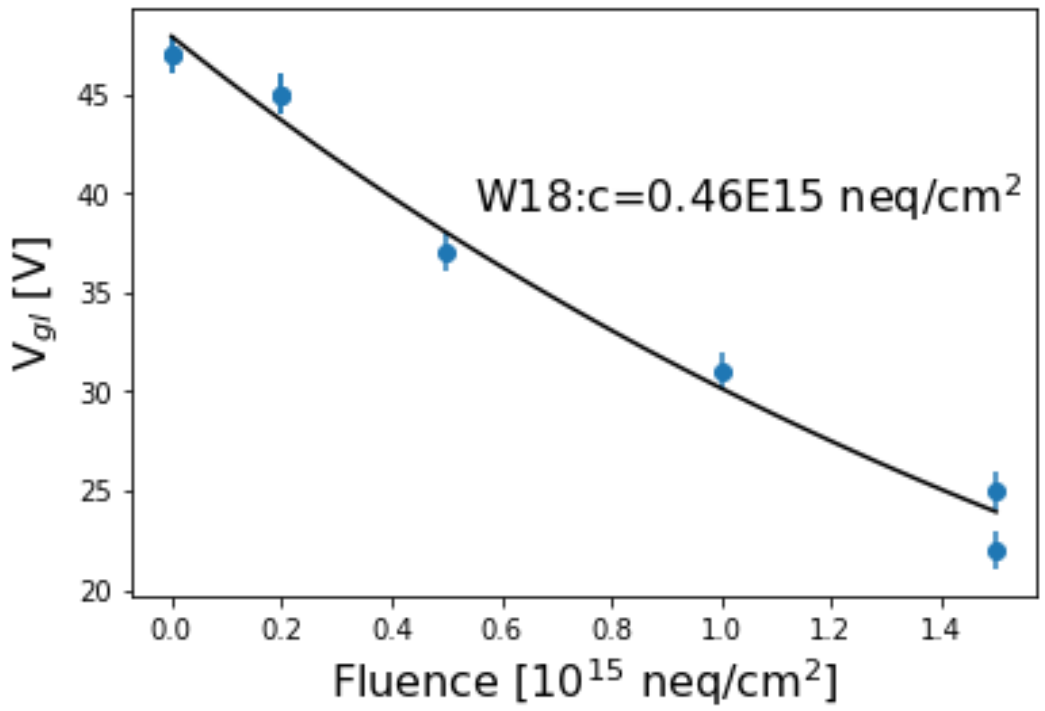


- We have unannealed sensors set aside for studying the effects of annealing after proton irradiations.

Acceptor Removal in FBK4 W18 due to Proton Irradiation

- C-V and I-V measurements of FBK W18 were used to extract V_{gl} for wafers that received different proton doses.
- The gain layer depletion voltage vs fluence is fit to $V_{gl}(\Phi) = V_{gl,0}e^{-c\Phi}$ to extract the acceptor removal constant.





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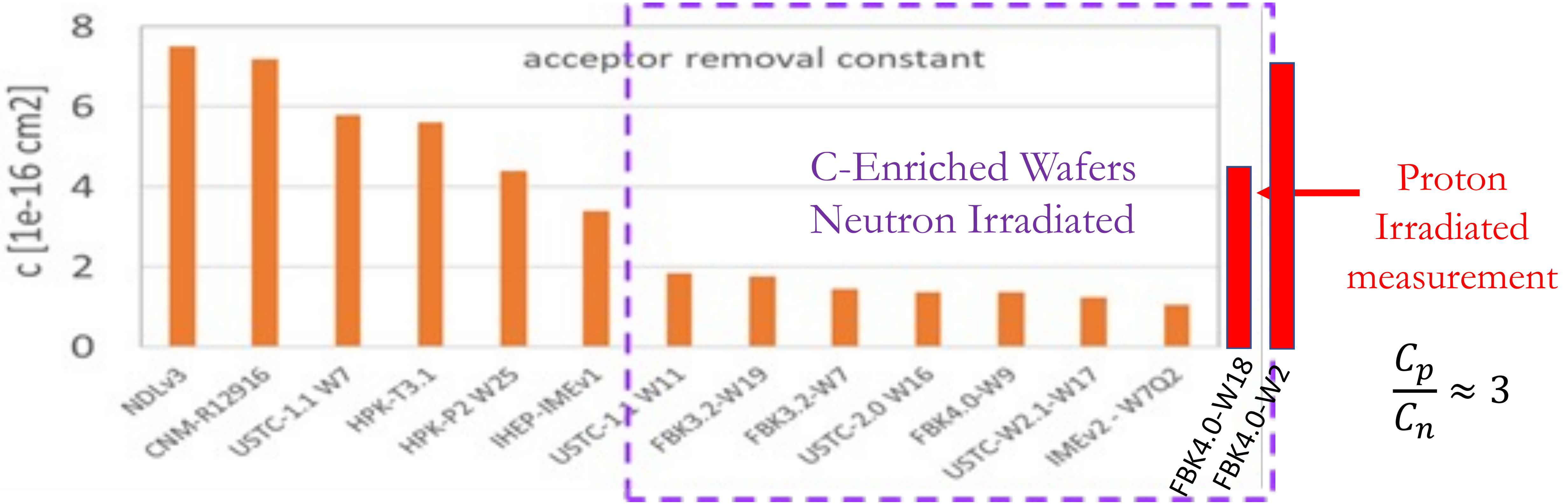
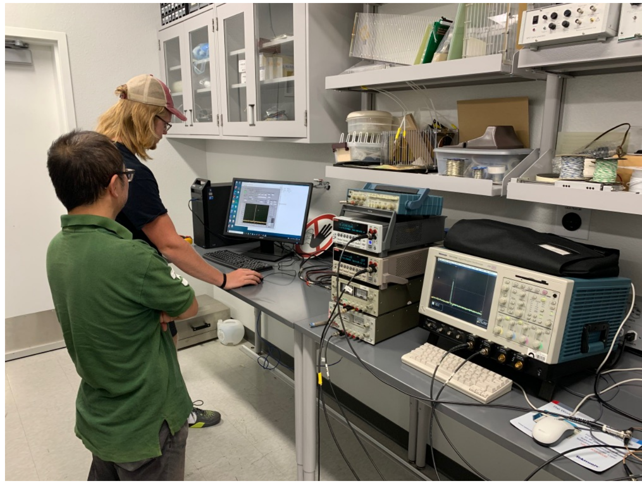


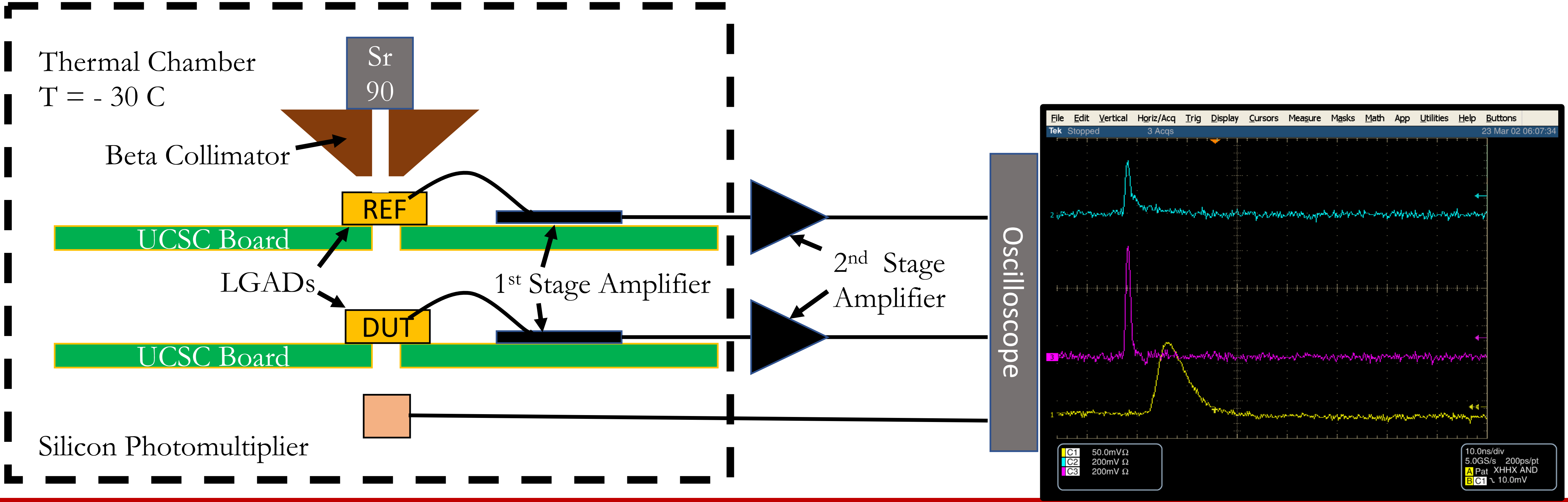
$$\frac{C_p}{C_n} \approx 3$$

- As compared to neutrons, protons are up to ~3 times as damaging to the gain layer.
- This is a major problem for experiments with a larger contribution of charged hadrons!

Timing resolution measurement

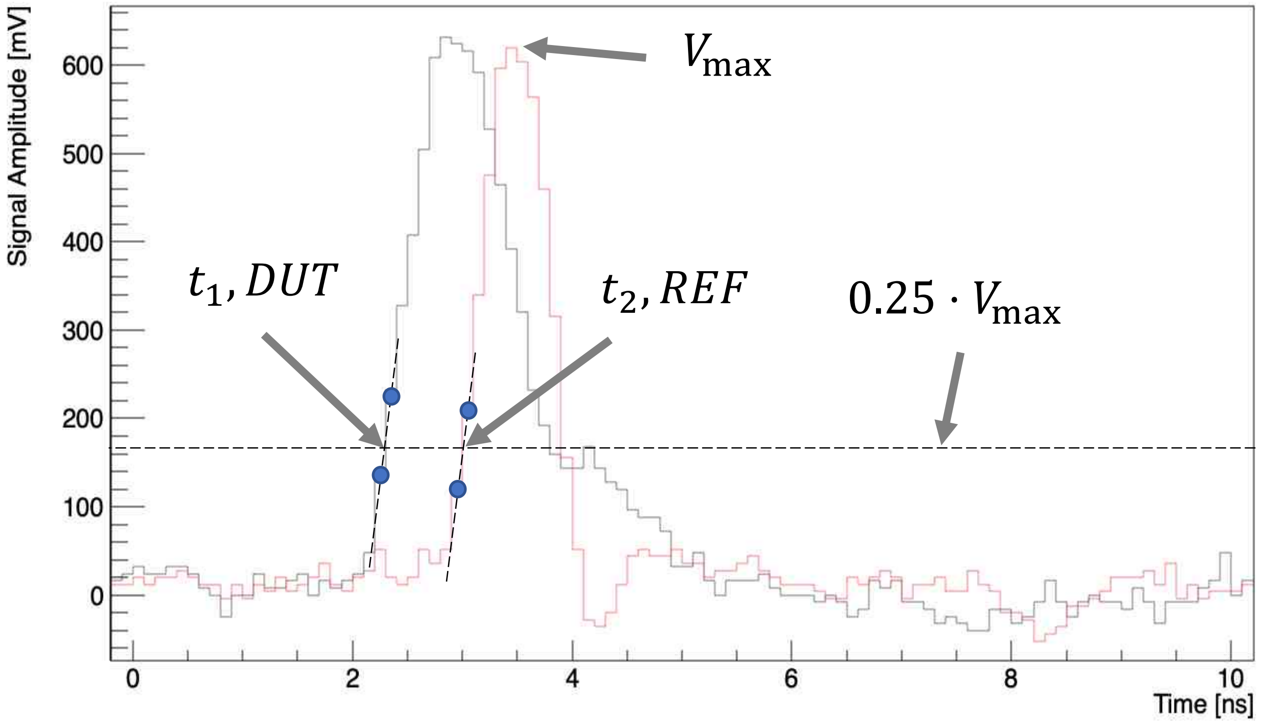
- This year I commissioned a test stand designed to evaluate the timing performance of LGADs.
- The test stand consists of a collimated beta source, a reference LGAD with known timing (REF), and a device under test (DUT) and a SiPM for triple coincidence.

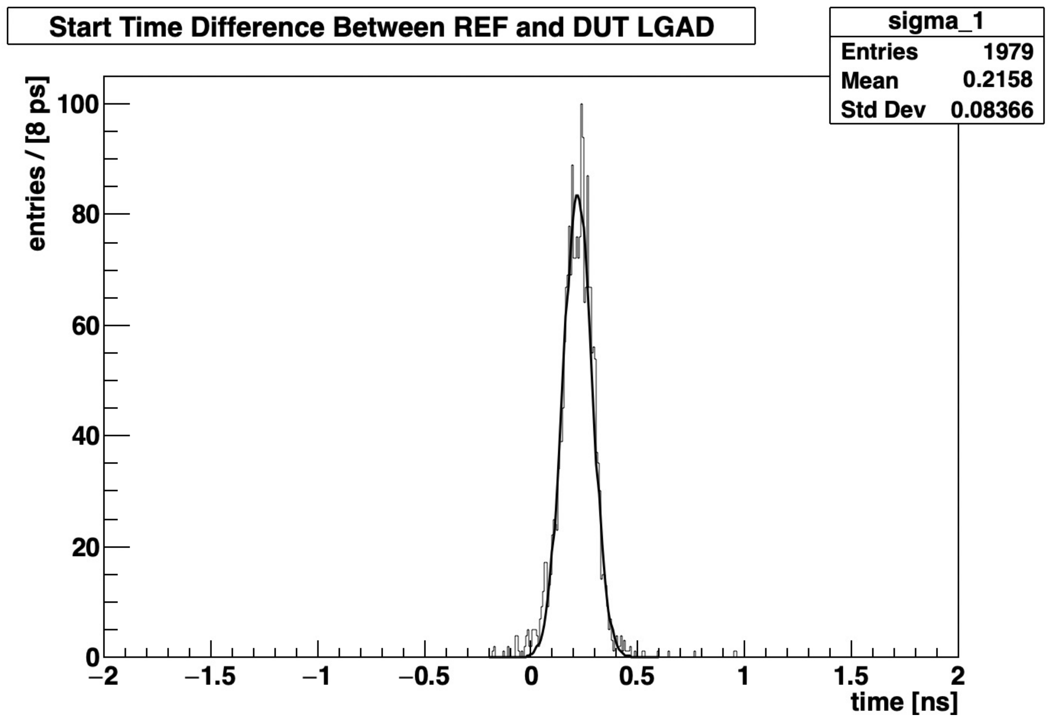




Timing Analysis

- The beta's arrival time is extracted with a 25 % constant fraction discriminator.
- The difference between the arrival time of the beta in the DUT and REF LGADS is stored in a histogram.
- The mean of this distribution is a constant depending on the travel time of the beta between the LGADs, and the signal travel time in the cables. The standard deviation of the distribution depends on the timing resolution of the detectors according to the following relation: $\sigma^2_{measured} = \sigma^2_{DUT} + \sigma^2_{REF}$





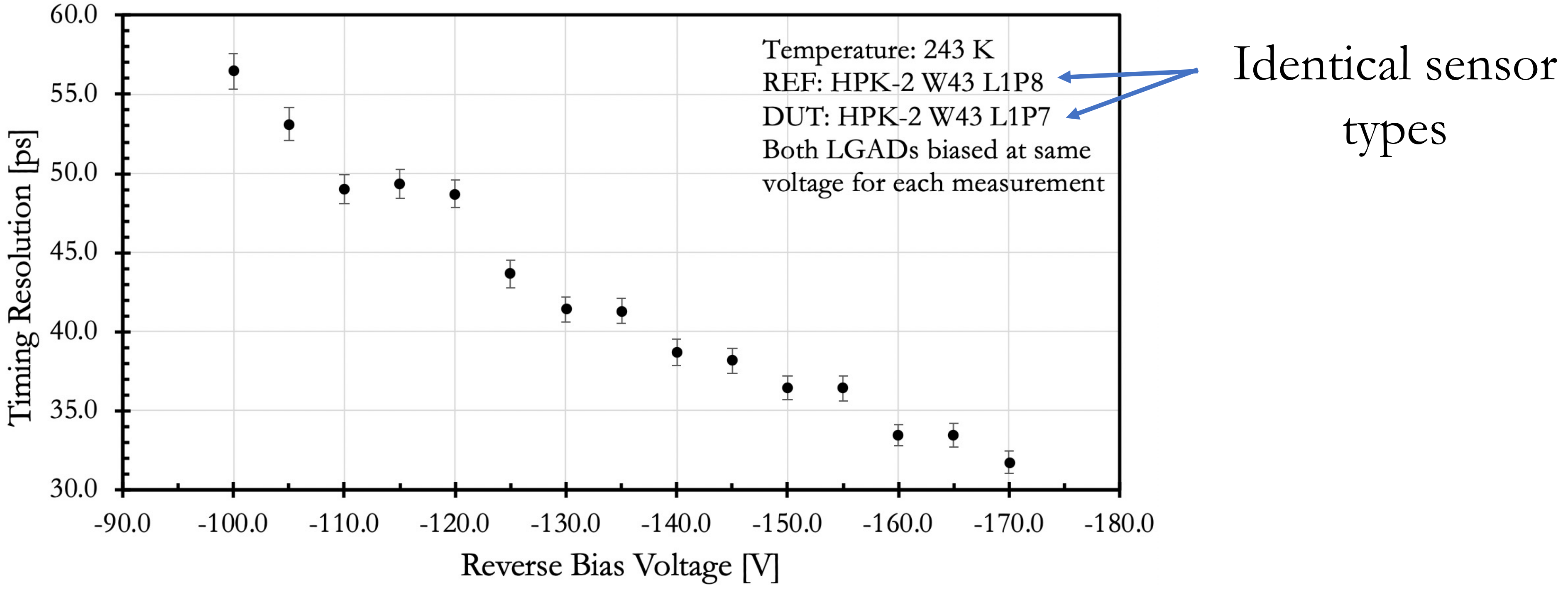
Reference Sensor Calibration

- We calibrated a reference by measuring two identical sensors,

$$\sigma_{DUT}^2 = \sigma_{REF}^2 \Rightarrow \sigma_{measured}^2 = 2\sigma_{REF}^2$$

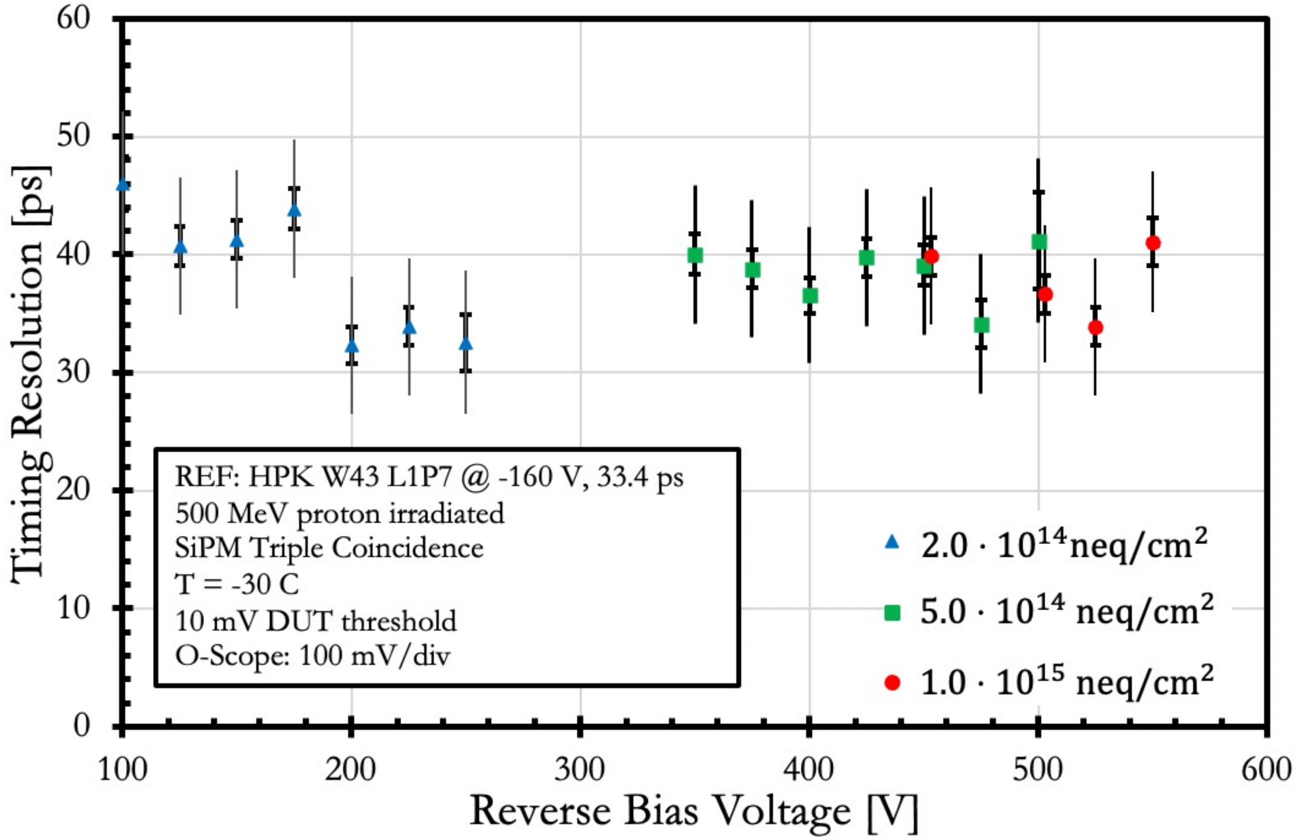
- For these reported measurements, we used an HPK-2 W43 L1P7 LGAD sensor biased at -160 V which has a timing resolution of 33.4(6) ps

W43-L1P7 and W43-L1P8 Timing Measurement



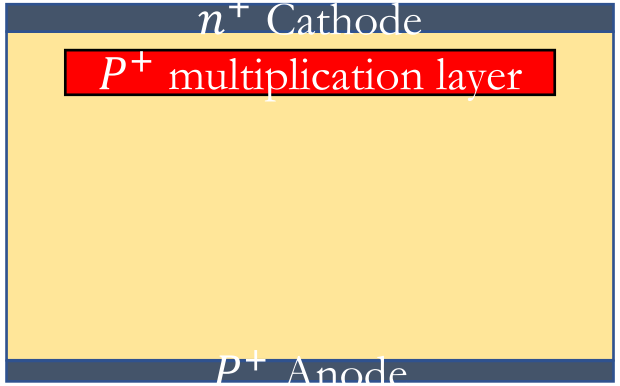
Response of Timing Resolution to Proton Irradiation

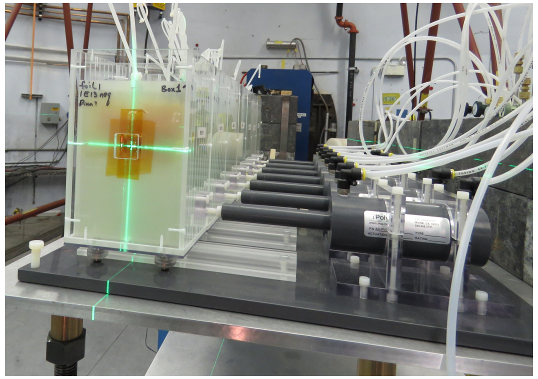
- Measurements of the proton irradiated sensors are done with a trigger threshold of 25 mV to avoid cutting off the lower edge of the Landau power spectrum.
- If the Landau power spectrum of the DUT fell below this threshold (low bias), or if the noise exceeded the power spectrum (bias near breakdown), the measurement was discarded.
- Preliminary measurements show degradation of the resolution with proton irradiation up to 1E15 neq/cm^2. The resolution does not exceed 70 ps.

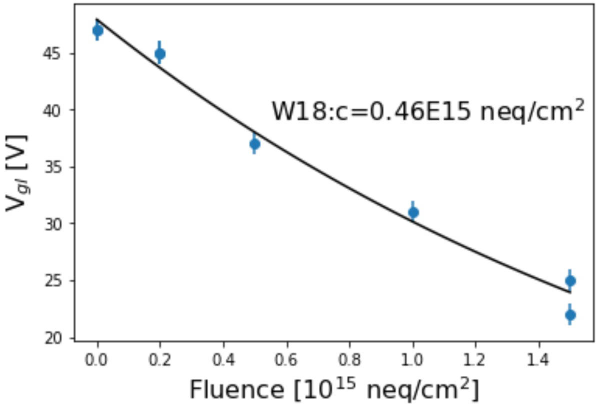


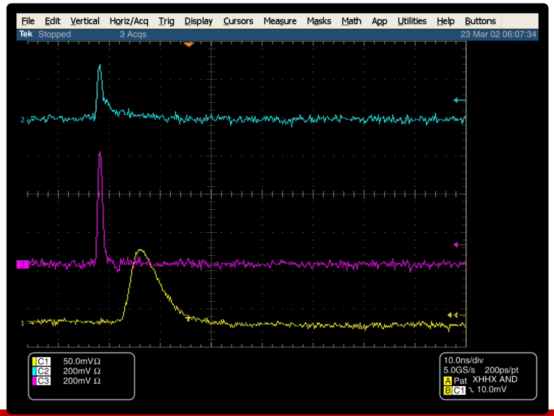
Outlook

- Preliminary measurements of the acceptor removal constant due to fluence with 500 MeV protons in carbon doped FBK4 sensors indicate protons are up to 3x more damaging to the gain layer than neutrons.
- Timing resolution after 1E15 neq/cm^2 does not exceed 70 ps.
- We have many more measurements to conduct, on the remaining FBK4 wafers and the recently returned HPK2 wafers that will further illuminate the effects of proton damage.



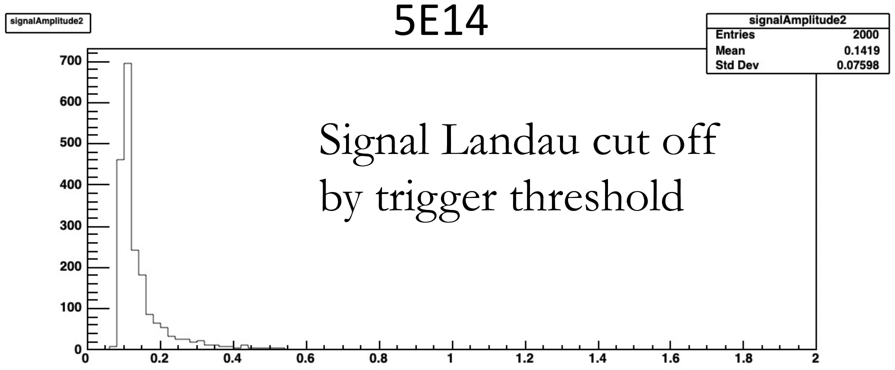




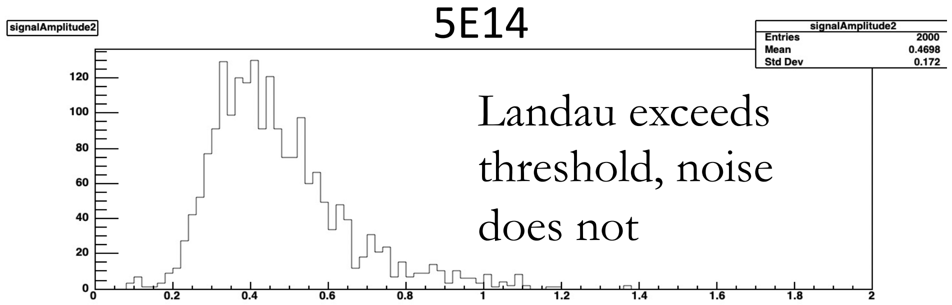


Back-up Slides

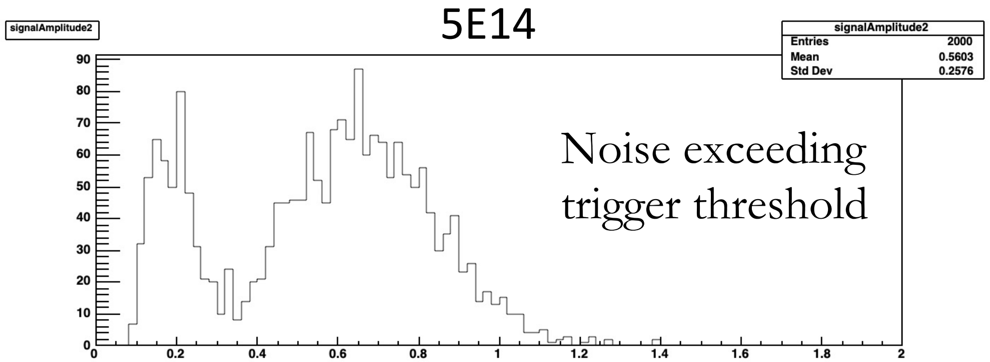
Landau Distribution Observed in timing measurement



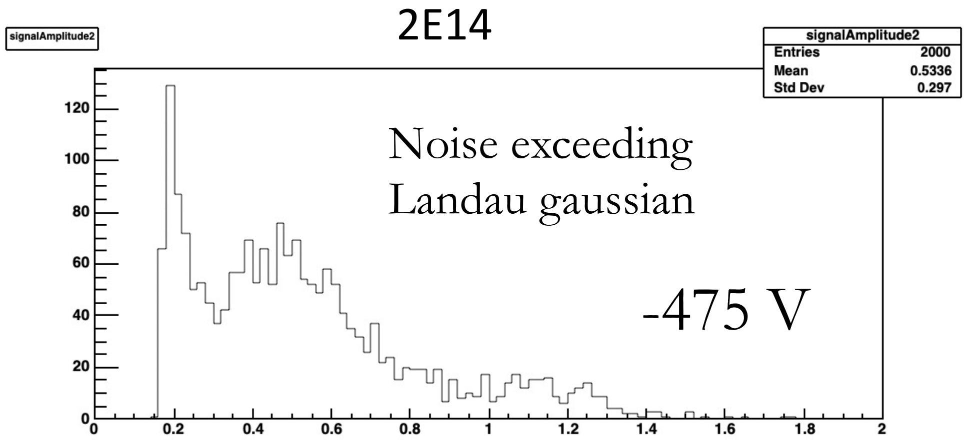
-150 V



-450 V



- 500 V



-475 V

- We are still investigating optimal trigger threshold, bias voltage ranges, etc for the timing resolution measurement.
- We have completed charge collection calibration but are still doing analysis.