Investigation of LGADs exposed to proton fluences beyond 10^{15} n_{eq}/cm^2

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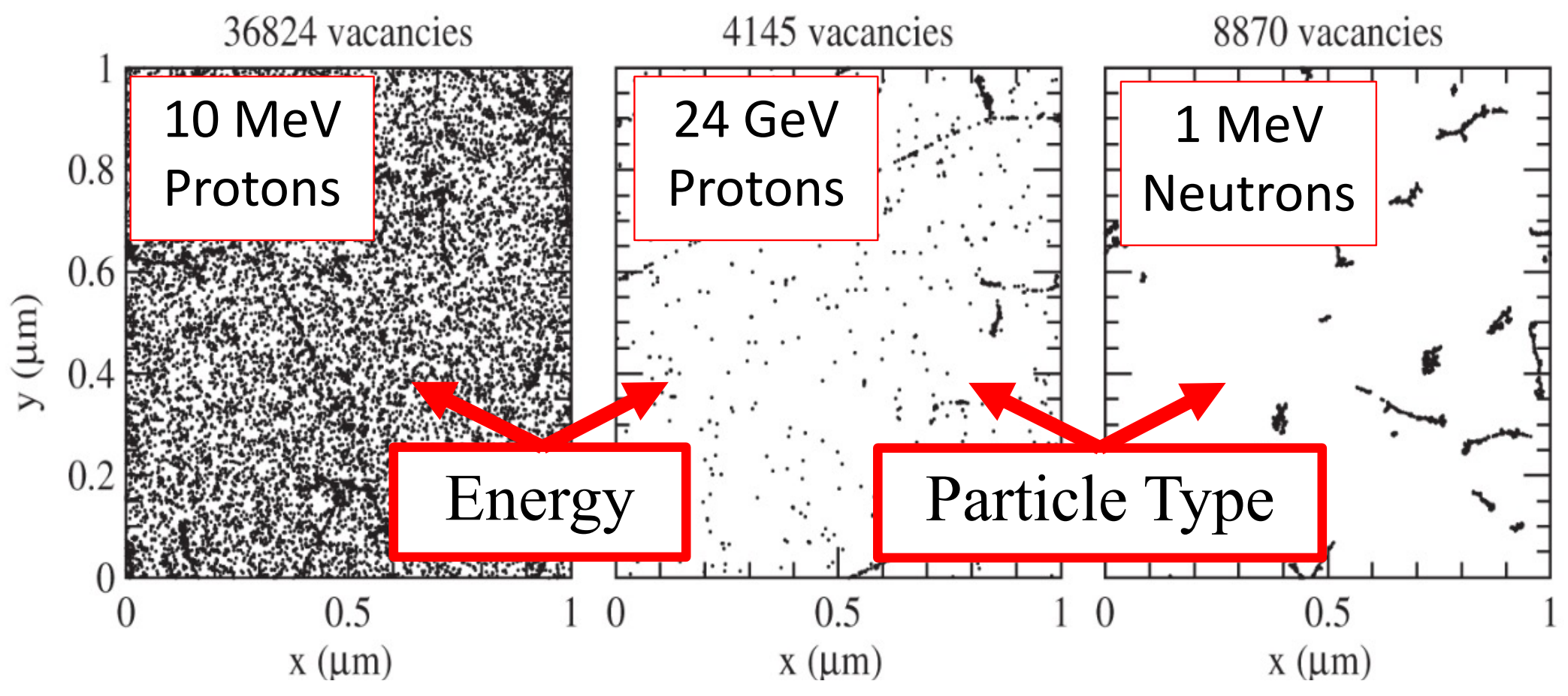
1. Motivation

- The aim of this study is better understanding of the effects of proton damage to Low Gain Avalanche Detectors (LGADs) [1].
- LGADs are silicon detectors with very good timing resolution.
- In the high luminosity LHC, the pileup will increase by a factor of 10, from $\mu = 20$ to $\mu = 200$. This will blur track reconstruction and reduce the accuracy of an LHC experiment's analysis.
- ATLAS is installing the High Granularity Timing Detector (HGTD) and CMS is installing the Endcap Timing Layer (ETL) which will be made of LGADs.

Pileup will hurt the accuracy of analysis during the HL-LHC. Detectors made of LGADs have excellent timing resolution and will reduce the pileup.

3. Radiation Damage

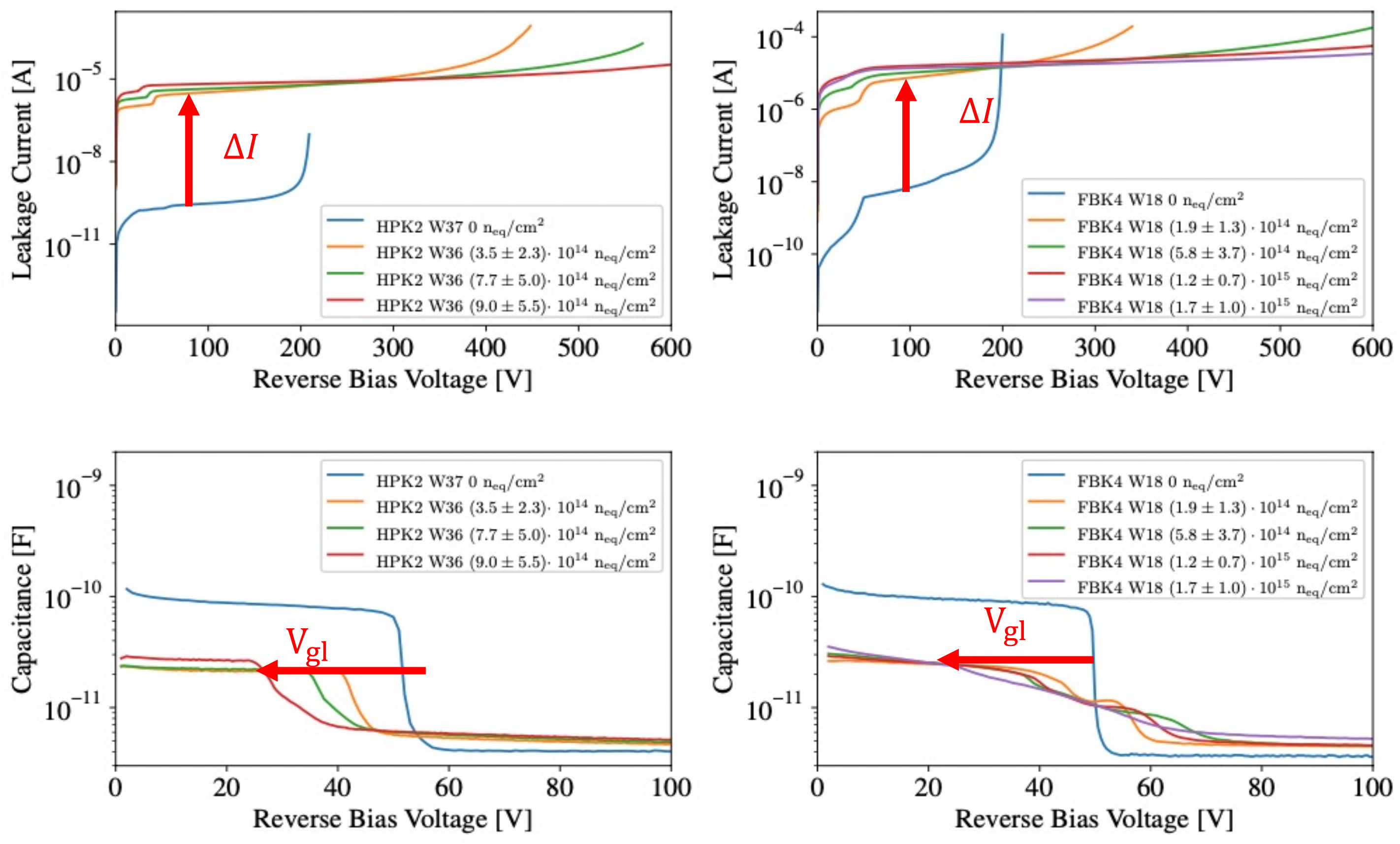
- Hadronic fluence will reduce the active dopant concentration via transformation of the boron acceptors into defect complexes no longer acting as acceptors.
- The proton and pion fluences that LGADs receive will be non-negligible.
- Characteristics of radiation damage depend on the particle type and energy [3].



M. Huhtinen, NIMA 491 (2002)

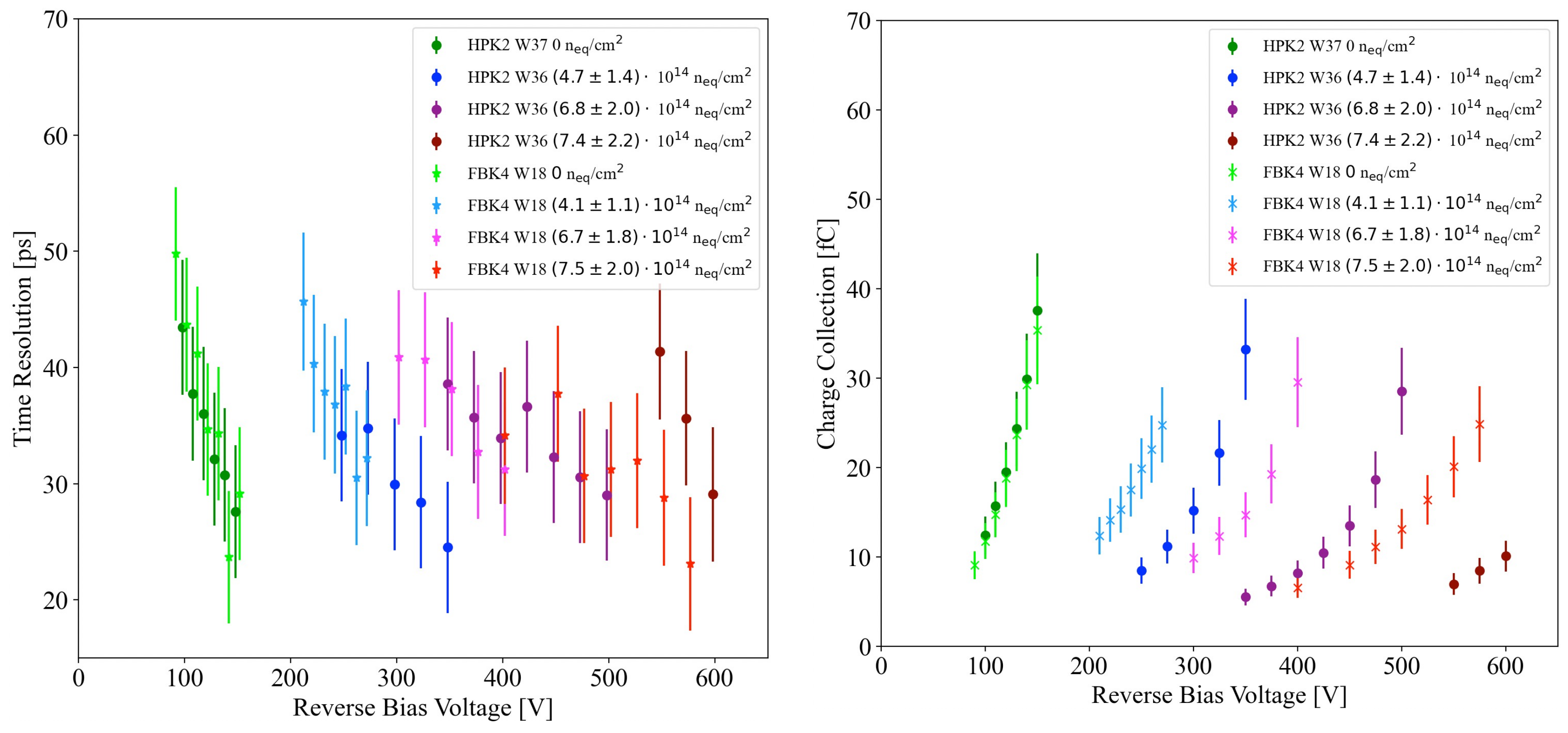
5. Leakage Current & Capacitance

- Linear increase of leakage current, I, according to $\Delta I = \alpha \cdot \phi \cdot Volume$.
- Increase in breakdown voltage from degradation of the gain layer and reduction of the electric field strength.



7. Timing Resolution & Charge Collection

- Timing resolution and charge collection are measured with a beta source test stand.
- The FBK wafers have better charge collection at lower voltage.
- The timing resolution is very good up to $7 \cdot 10^{14}$ n_{eq}/cm^2 for both productions.
- The FBK wafers irradiated to $11 \cdot 10^{14}$ n_{eq}/cm^2 and $15 \cdot 10^{14}$ n_{eq}/cm^2 had no measurable charge collection below 600 V.



Funding & References

1. G. Pellegrini et al., *Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications*, Nucl. Instrum. Meth. A765 (2014) 12 -16.
2. N. Cartiglia et al., *Performance of ultra-fast silicon detectors,* 2014 *JINST* **9** C02001.
3. M. Huhtinen, Simulation of non-ionising energy loss and defect formation in silicon, Nucl. Instrum. Meth. Phys. Res. A 491 (1-2) (2002) 194–215, https://doi. org/10.1016/S0168-9002(02)01227-5.

This work was made possible by support from U.S. Department of Energy grant DE-SC0020255 and from ARIS grant J7-4419, Slovenia. It was also supported by the National Aeronautics and Space Administration (NASA) under Federal Award Number 80NSSC20M0034 (2020-RIG).

2. How LGADs Work

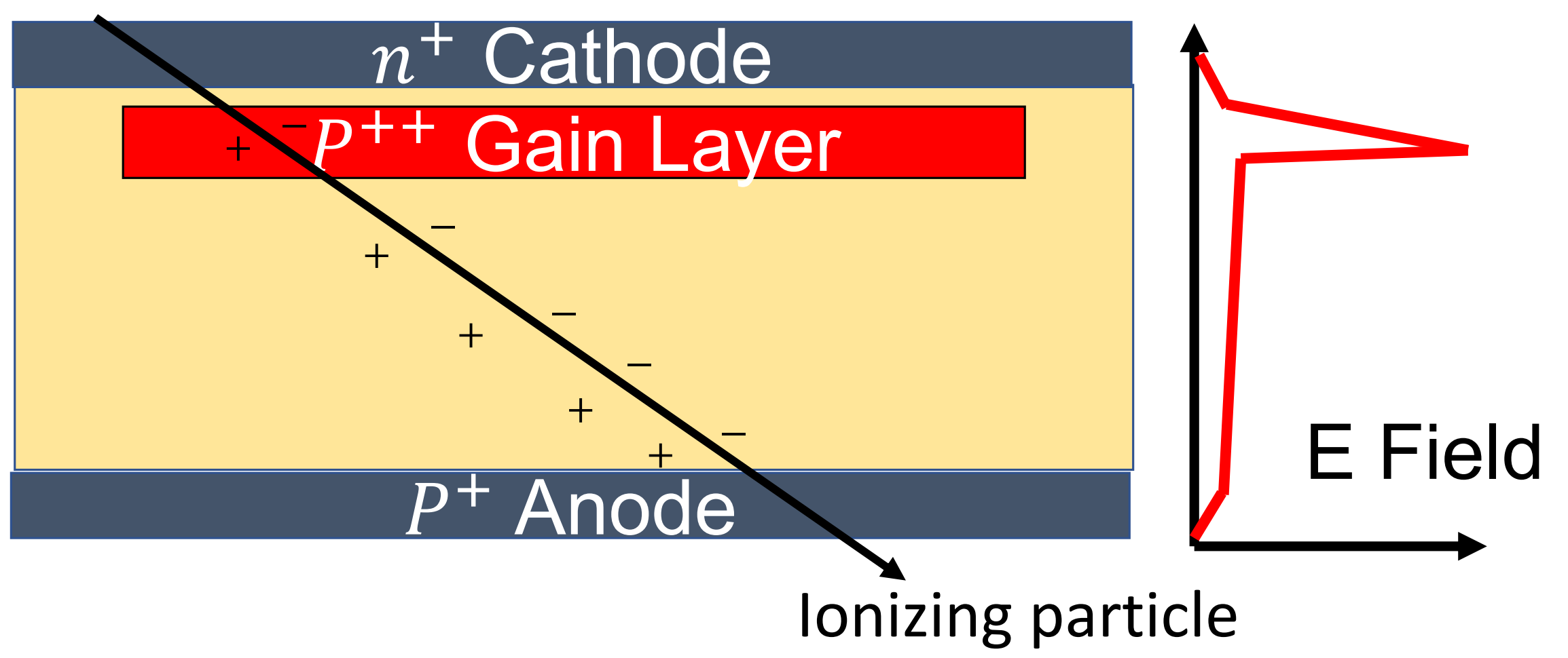
LGADs are thin sensors (~50 µm).

- The small thickness allows a short collection time with a short rise-time (t_r) that results in precise timing.
- The smaller thickness results in smaller charge generation, which requires LGADs to have some internal gain for larger signal to noise ratio (S/N) [2].

$$\sigma_t = \sqrt{\sigma^2_{jitter} + \sigma^2_{Time\ Walk} + \sigma^2_{Landau} + \sigma^2_{Time\ to\ Digital} + \sigma_{SignalDistortion}}$$

LGADs have a heavily doped (p^{++}) layer – the "gain layer."

- The electric field caused by the difference in dopant concentrations is large enough to multiply free electrons via impact ionization.



$$\sigma_{jitter} = \frac{t_r \cdot N}{S}$$

$$\sigma_{TimeWalk} = \frac{t_r \cdot V_{th}}{S}$$

$$V_{gl} = \frac{q\mathbf{N_A} w^2}{2\epsilon}$$

4. Methods

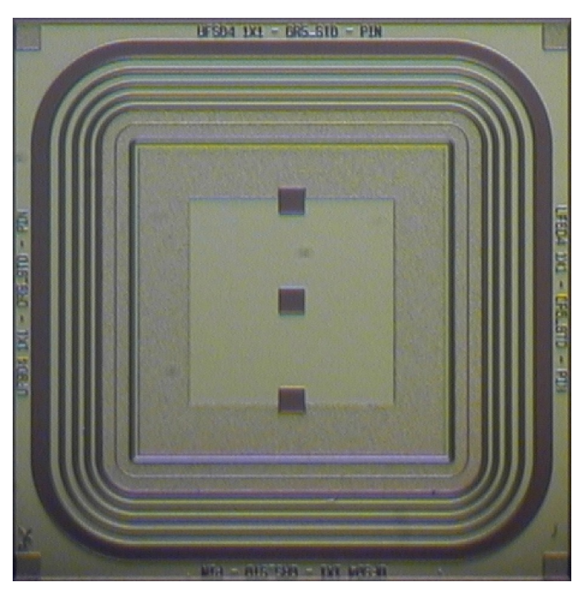
Irradiation Campaign #1

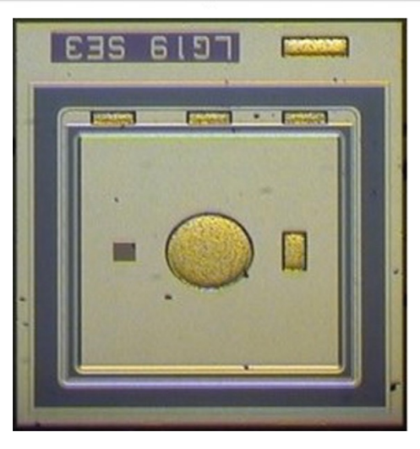
- **500 MeV proton irradiation** at LANSCE
  - Hardness factor of 0.78
  - Irradiated up to $9 \cdot 10^{14} n_{eq}/cm^2$
- FBK Production 4: singles, quads, and pins
  - Carbon doping in the FBK3-4 LGADs has already improved radiation hardness

Irradiation Campaign #2

- **400 MeV proton irradiation** with the Fermilab Irradiation Test Area (ITA)
  - Hardness factor of 0.83
  - Irradiated up to $1.7 \cdot 10^{15} n_{eq}/cm^2$
- HPK Production 2: singles, quads, and pins

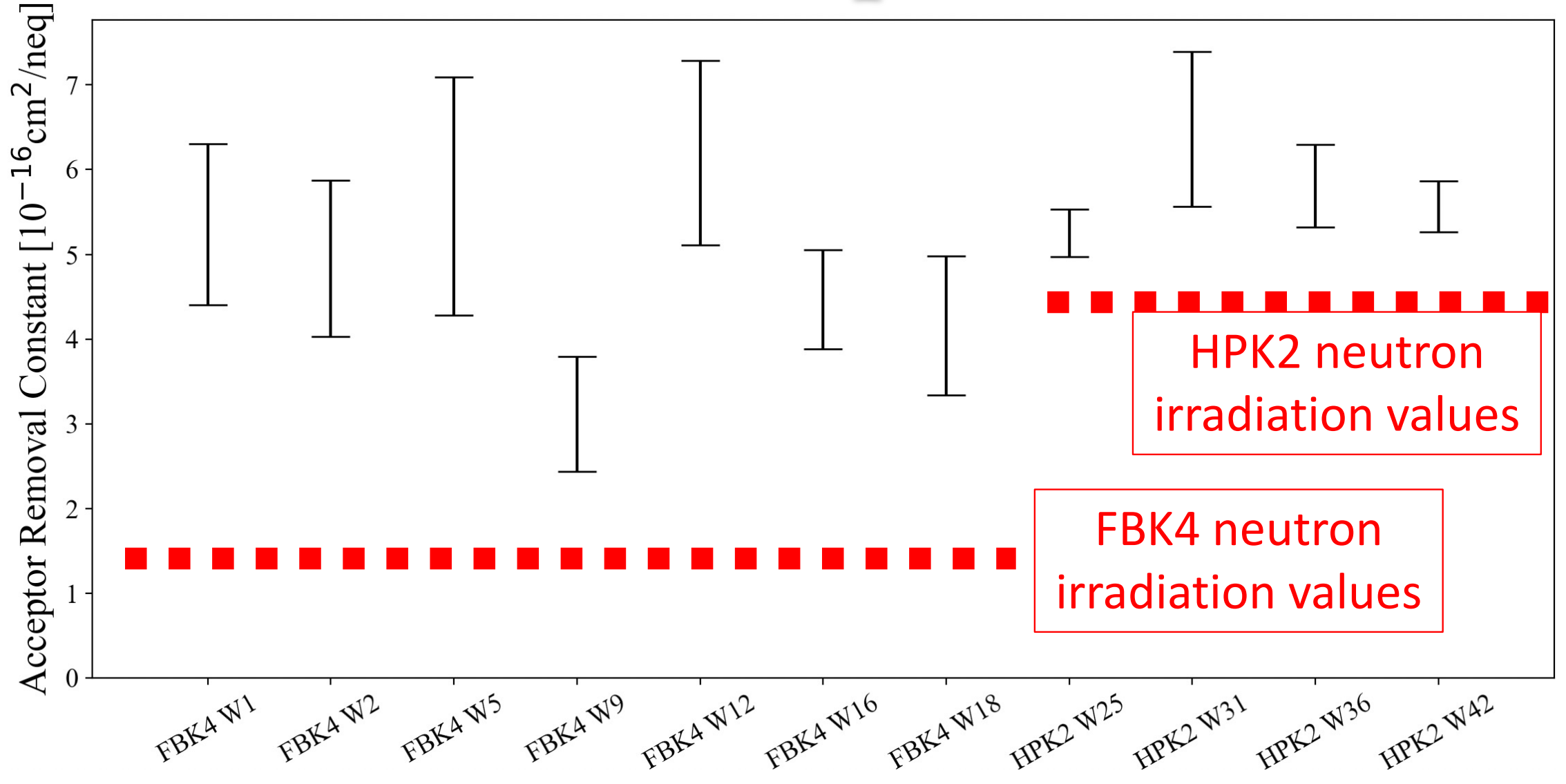
FBK4 Wafer ID	Gain Layer Depth	Relative Boron Concentration	Relative Carbon Concentration	Diffusion	$V_{gl,0}$[V]	$V_{fd,0}$[V]
1	Shallow	0.98	0.6	CH-BL	21.5	23.0
2	Shallow	1.02	1	CH-BL	22.0	23.5
5	Shallow	1.04	1	CH-BL	22.5	24.0
9	Shallow	1.06	1	CH-BL	22.5	24.5
12	Deep	0.77	0.6	CH-BH	50.5	51.5
16	Deep	0.81	0.6	CL-BL	48.0	49.0
18	Deep	0.93	0.6	CL-BL	48.5	49.5





HPK2 Wafer ID	Gain Layer Doping Profile	$V_{gl,0}$[V]	$V_{fd,0}$[V]
25	1	53.0	55.0
31	2	52.0	54.0
36, 37	3	49.5	52.0
42, 43	4	49.0	51.0

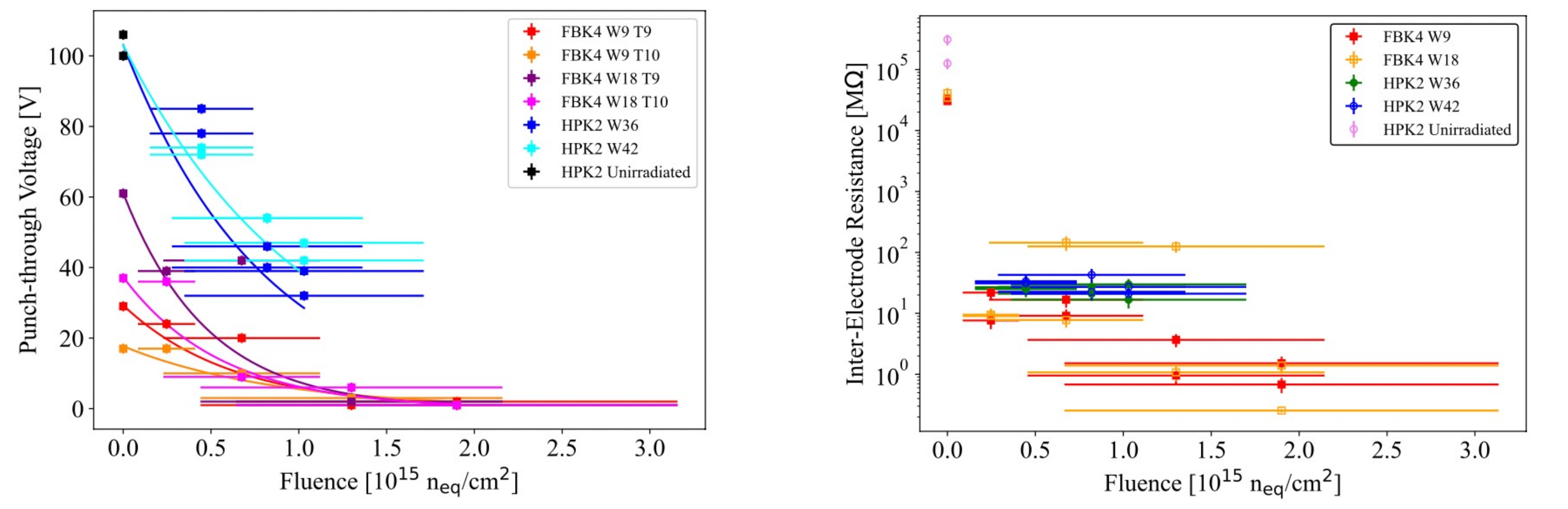
6. Acceptor Removal Constant



- Fluence causes a decrease in the gain layer depletion voltage: $V_{gl}(\phi) = V_{gl,0} \cdot e^{-c \cdot \phi}$.
- The acceptor removal constant is extracted for each wafer.

The acceptor removal constant (c) is higher in proton irradiations than in comparable neutron irradiations.

8. Inter-electrode Isolation



- Measurements of the punch-through voltage and inter-electrode resistance with quad LGADs indicate a rapid decline in resistance of the inter-electrode region.
- However, measurements of charge collection in electrodes adjacent to an electrode being pulsed with a laser show no cross-talk between the sensors, even with low inter-electrode resistance.

Conclusions

- **Proton damage to LGAD sensors is greater than neutron damage, even when scaled with the NIEL hypothesis.**
- **Both the FBK4 and HPK2 wafers have good timing resolution and charge collection up to ~ $7 \cdot 10^{14}$ n_{eq}/cm^2, but the FBK4 wafers reach the required charge collection with lower voltage.**