AC-LGAD sensor irradiation test

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ePIC collaboration meeting

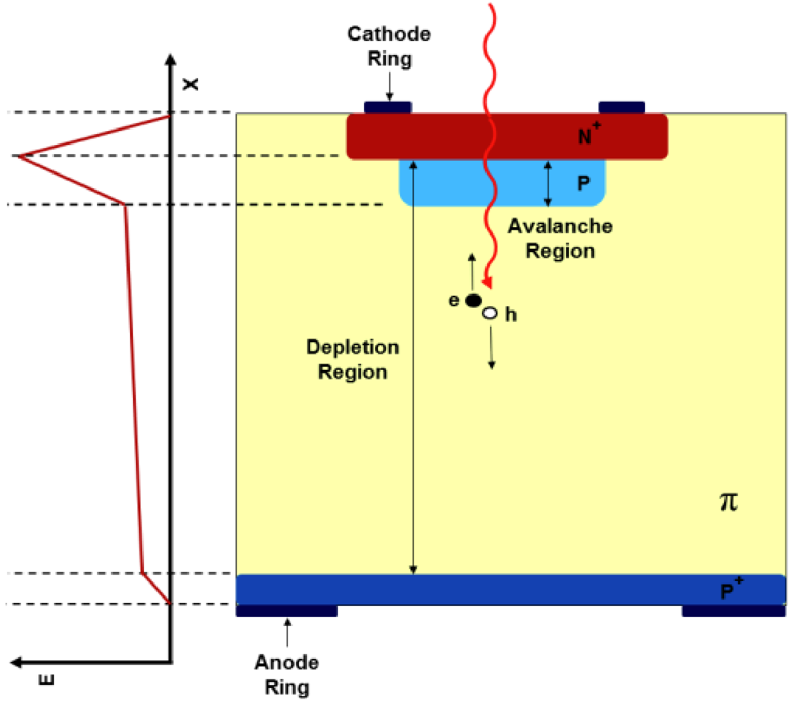
Argonne, Jan 2023

LGADs and radiation damage

Low Gain Avalanche Detectors

- LGAD: silicon detector with a thin (<5 μm) and highly doped (~10^{16} P++) multiplication layer
  - High electric field in the multiplication layer
  - Field is high enough for electron multiplication but not hole multiplication
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Not in avalanche mode → controlled tunable gain with applied bias voltage
- Great single hit time resolution (down to 20ps)
- The **granularity** of LGADs is **limited to the mm scale**
  - **Solution: high granularity LGAD prototypes**

- Several producers of experimental LGADs
  - **HPK (Japan), BNL (USA), FBK (Italy),** CNM (Spain), NDL/IMEI (China), Micron (UK)
  - AC-LGAD produced at HPK and BNL in this study funded by US-Japan grant

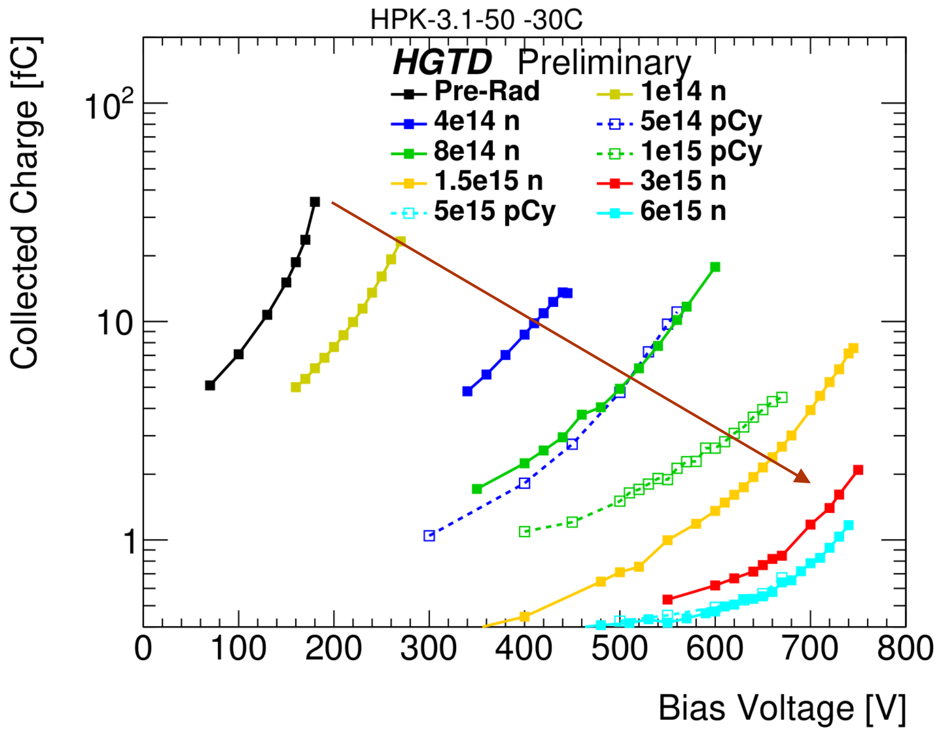


Nucl. Instrum. Meth. A765 (2014) 12 – 16.
Nucl. Instrum. Meth. A831 (2016) 18–23.

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

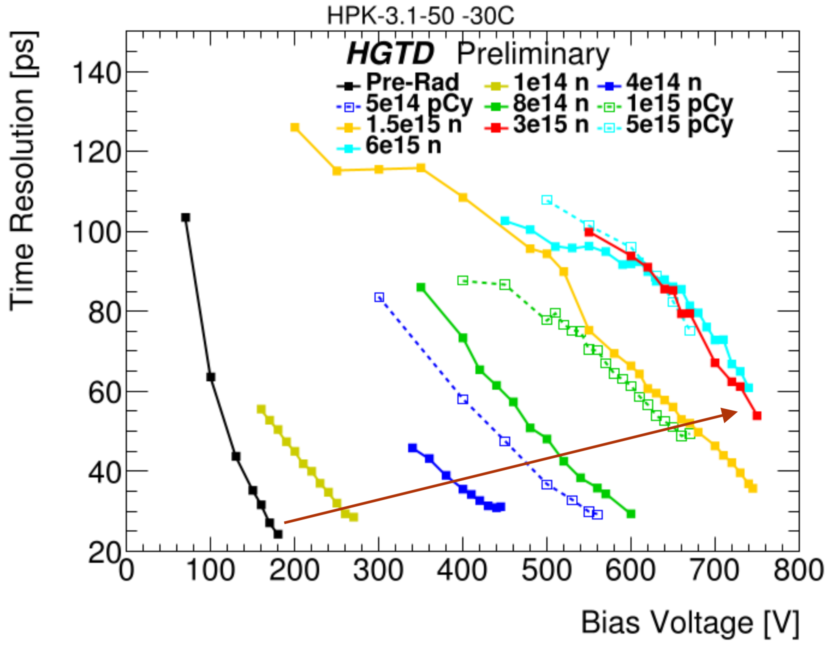
LGAD and radiation damage

- LGADs while operating in high energy physics experiments will sustain radiation damage
  - Both in terms of fluence and ionization dose
- Change in performance caused by reduced doping concentration in the gain layer by **acceptor removal mechanism**
  - Some details: https://doi.org/10.1016/j.nima.2018.11.121



Performance effects of radiation damage (E.g. on 50um sensor)

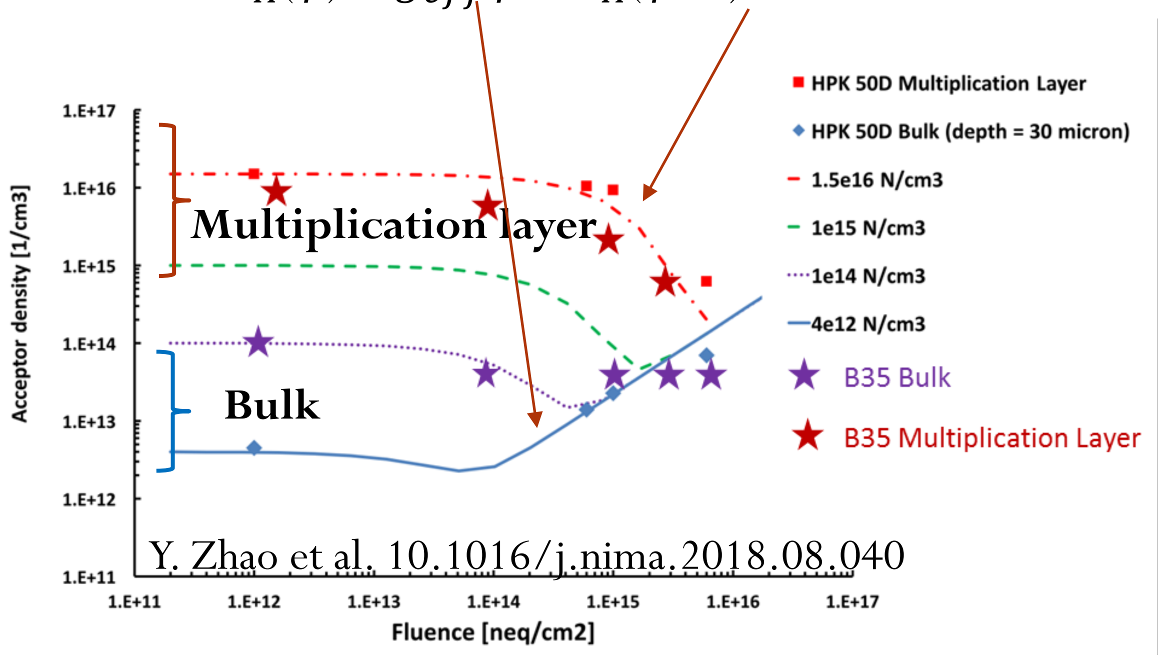
- Partly the performance can be recovered by increasing the bias Voltage applied to the diode (~200V → ~700V)
- **Reduction of gain and collected charge**
  - Charge collected up to 30fC (Gain ~50) before irradiation to 1fC (gain 2-3) after a fluence of 6E15 Neq/cm^2
  - (Neq: equivalent 1 MeV neutrons on cm^2)
- **Increased time resolution**
  - Time res. of 25ps to 60ps after a fluence of 6E15 Neq/cm^2

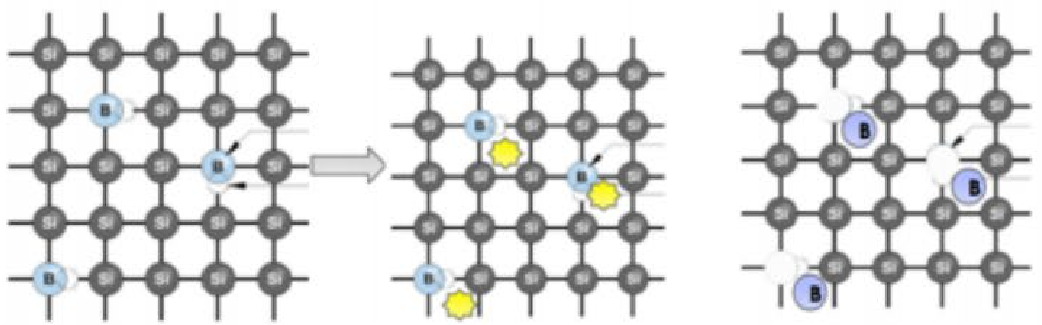


Radiation damage model

- 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 concentration in the multiplication layer → reduction of gain
  - **C-factor (acceptor removal constant) depending on detector type**
- **NOTE: this does NOT follow NIEL scaling well for fluence**

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

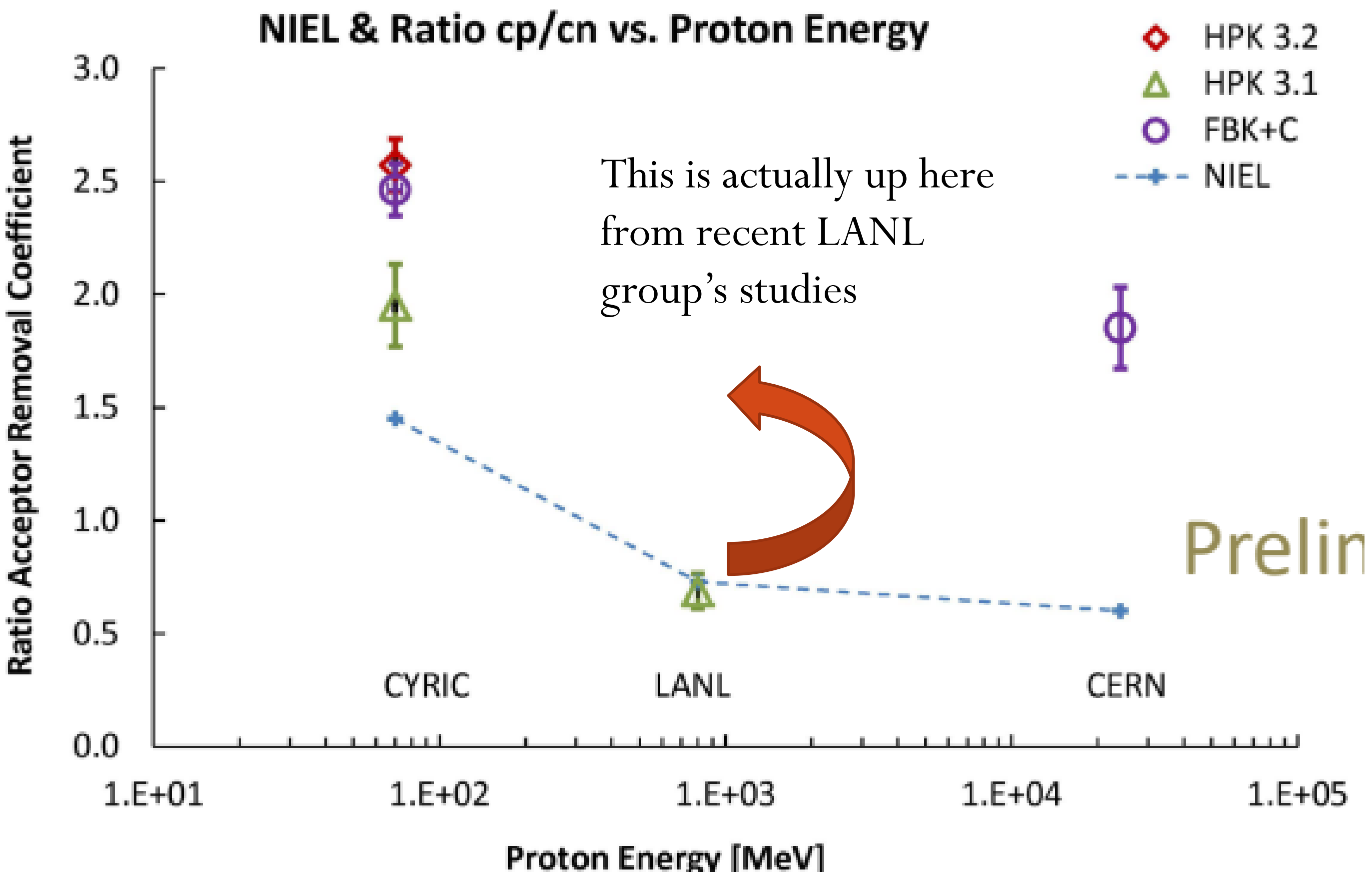




Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s ➔ Si_s + B_i
B_i might interact with Oxigen, creating a donor state

NIEL violation (old-ish data)

- Acceptor removal ratio cp/cn
  - Dependence on the proton energy seems to be sensor specific
  - Does not scale with NIEL, larger than NIEL factor. Damage can be > 2 than the expected NIEL fluence
- Need to take into account the energy distribution of the damaging particles in the fluence calculation
- Some new results: https://indico.cern.ch/event/1334364/contributions/5672075/

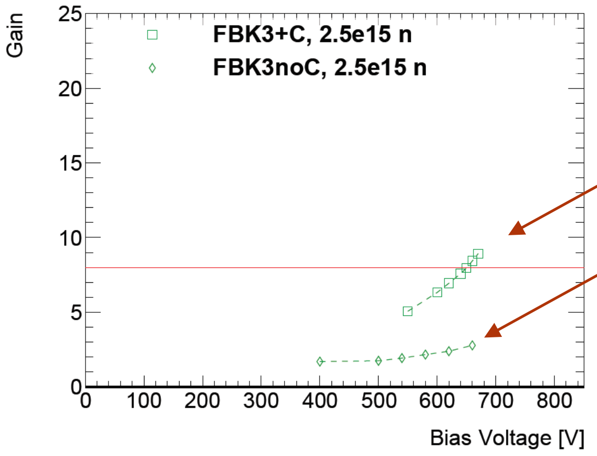


Radiation hard LGAD design

Radiation hardness of LGADs can be increased by:

- **Thin but highly doped gain layer**
- **Addition of Carbon**
  - Carbon is electrically inactive (no effect pre-irradiation), catches interstitials instead of Boron, reduces acceptor removal after irradiation
- **Deeper gain layer**
  - High field for larger volume
  - Allows for better recovery of the gain from increased bias voltage after radiation damage
- The combination of all techniques (by FBK) allowed to **produce a sensor with gain ~20 at 2.5E15 Neq**

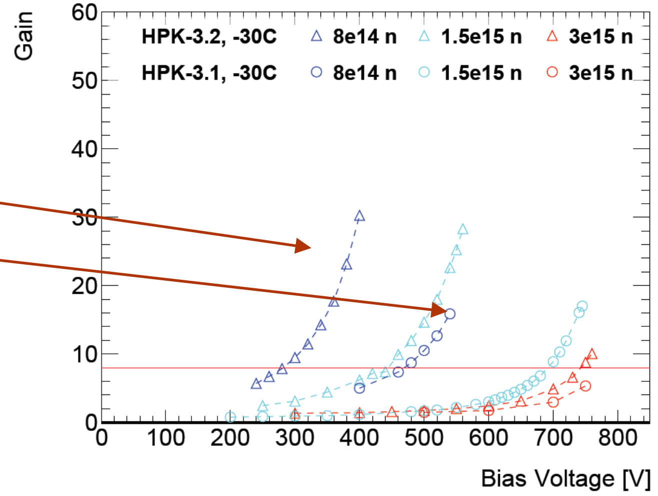
- Resources
  - https://iopscience.iop.org/article/10.1088/1742-6596/2374/1/012173/meta
  - https://iopscience.iop.org/article/10.1088/1748-0221/15/10/P10003
  - https://www.sciencedirect.com/science/article/pii/S0168900218317741
  - https://doi.org/10.1088/1748-0221/15/04/T04008
  - https://doi.org/10.1016/j.nima.2018.08.040

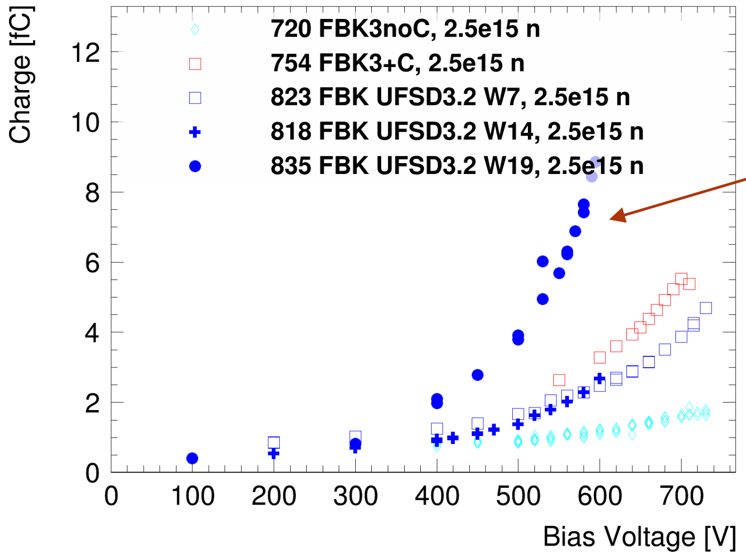


With Carbon

Without Carbon

Deeper gain layer (triangles)
Less deep gain layer (circles)
(same color, same fluence)

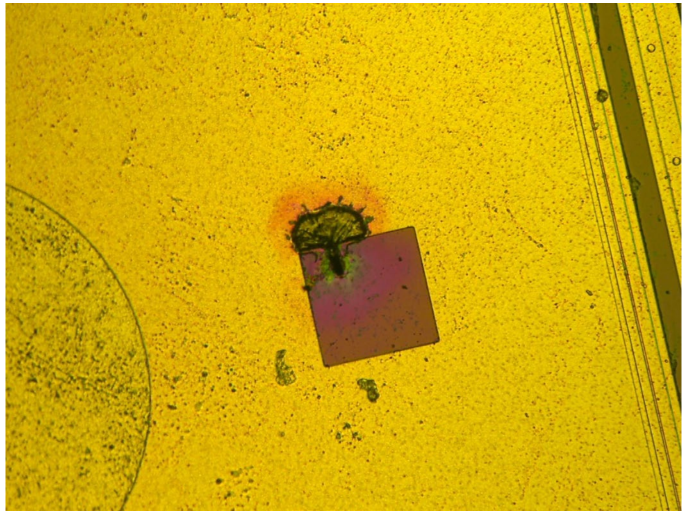


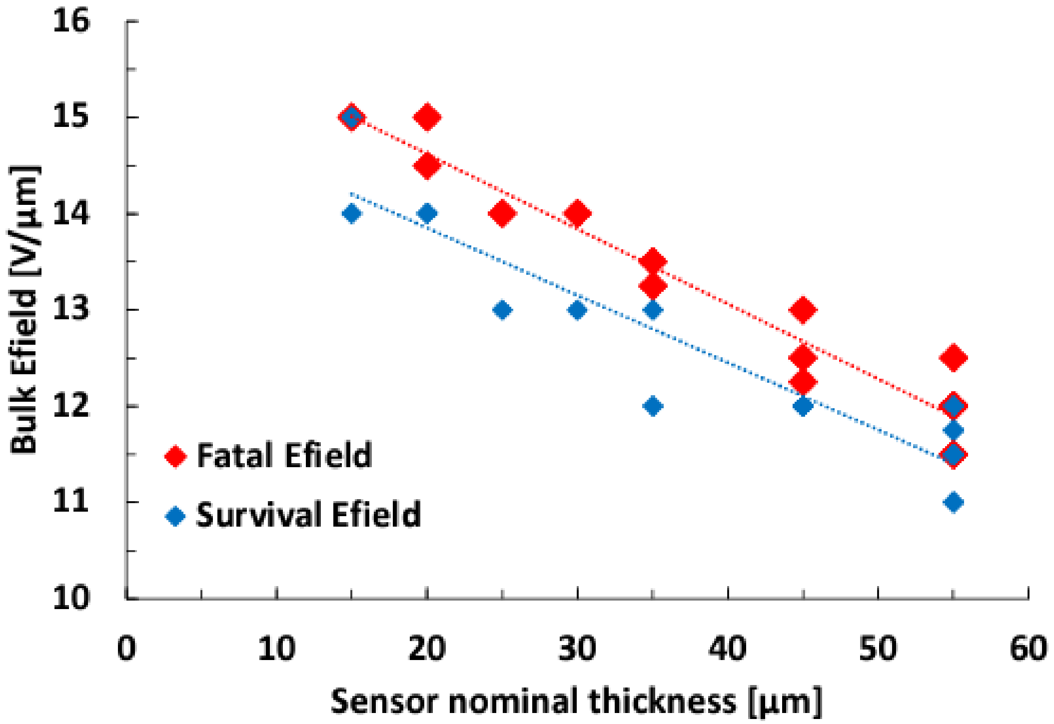


Deep gain layer + Carbon

Another issue: SEB

- Single Event Burnout can happen for highly irradiated devices
- A single highly ionizing particle under-depletes the device and causes a catastrophic breakdown
  - Device is non recoverable afterwards
- Thinner sensors seem to have a higher fatal Electric field
- See https://indico.cern.ch/event/1334364/contributions/5672087/
- (Should not be an issue for ePIC)

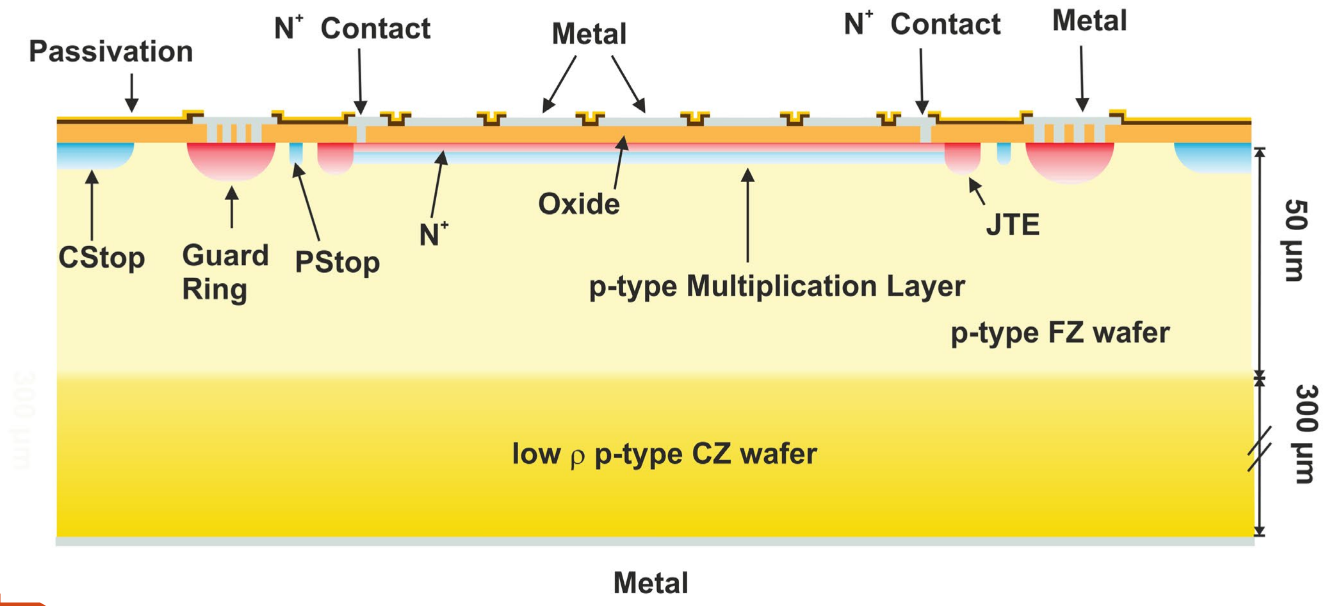




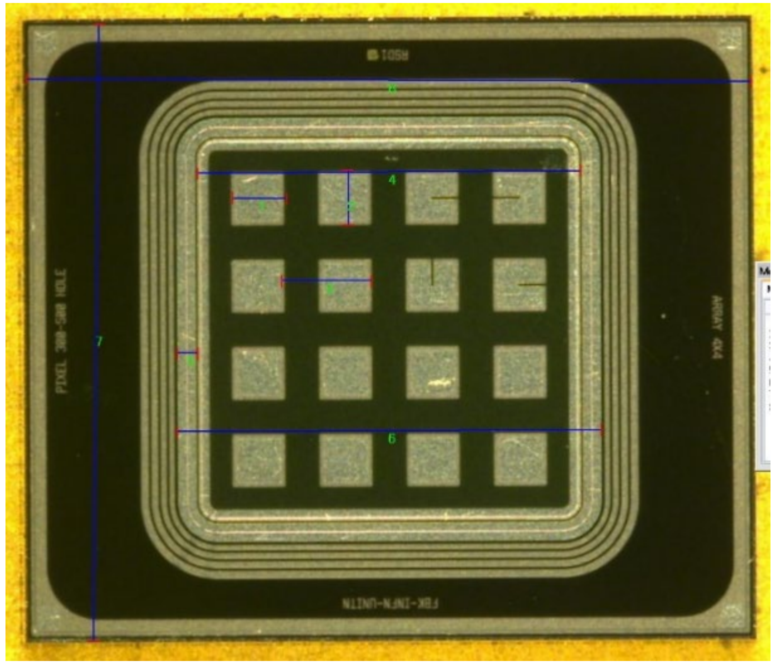
Radiation damage on AC-LGADs

AC-LGADs

- Most advanced high granularity LGADs **are AC coupled LGADs**
  - Finer segmentation and easier implantation process
  - (UCSC - US patent N. 9,613,993 B2, granted Apr. 4, 2017)
- Continuous sheets of multiplication layer and N+ layer
  - 100% fill factor
- **N+** layer is **resistive** and grounded through side connections
- **Readout pads are AC-coupled**
  - Oxide insulator layer between N+ and pads

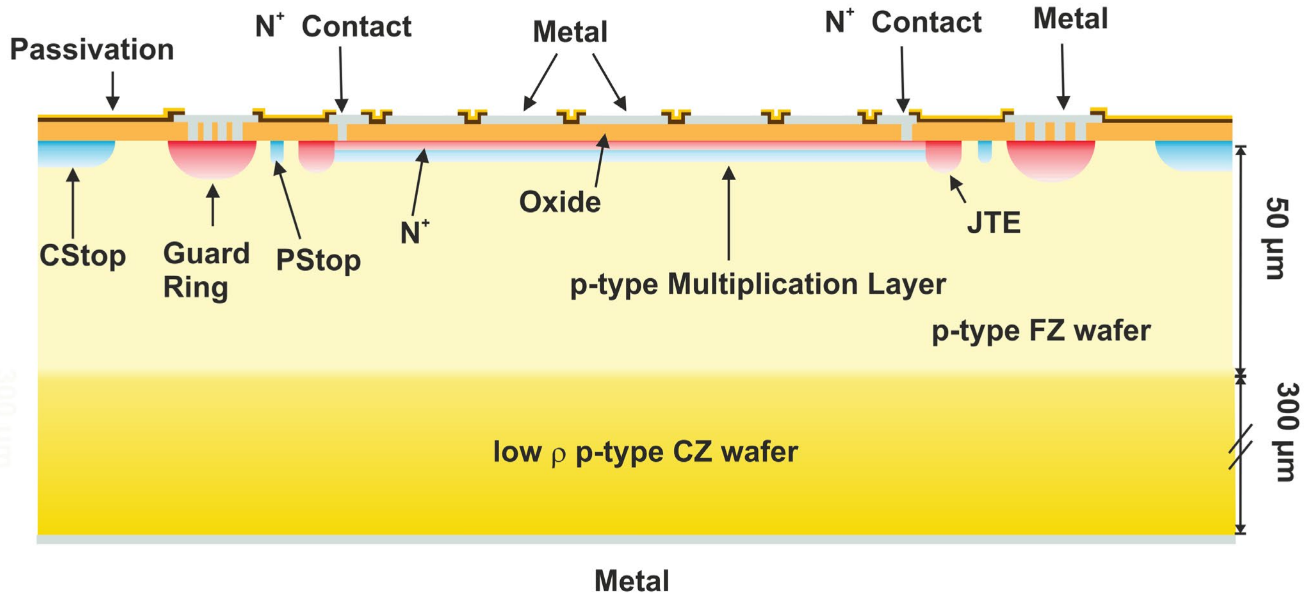


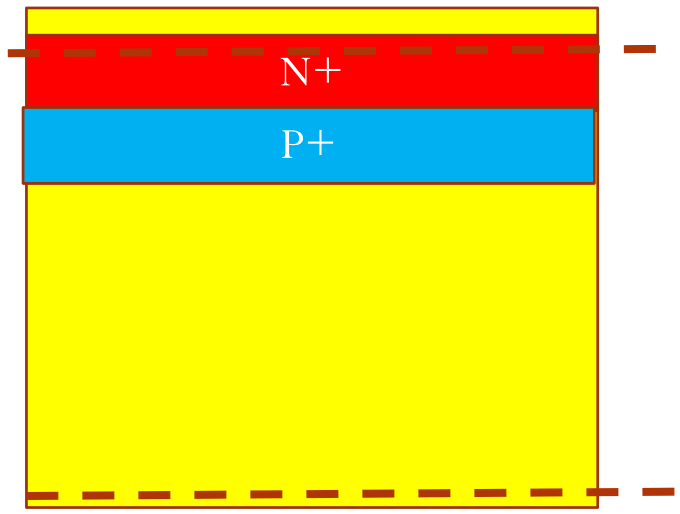
- **The response of the sensors can be tuned** by modifying several parameters
  - Pad geometry and dimension
  - Pad pitch
  - N+ layer resistivity
  - Oxide thickness



Effect of irradiation on AC-LGADs

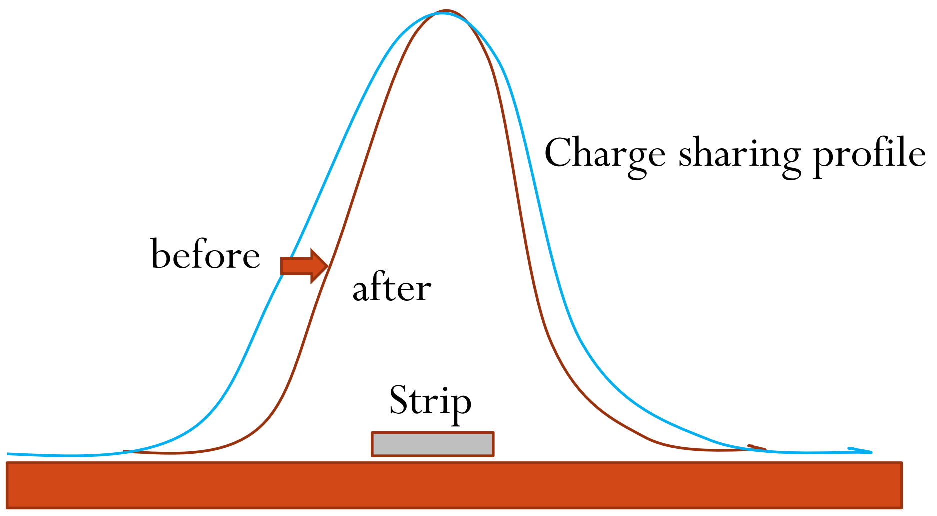
- The gain layer will have more or less the same behavior of standard LGAD devices
- The N+ can have some unexpected effects though
  - Normally is highly doped and conductive so it's not affected by radiation damage
  - We don't know well the effects of acceptor removal to N-type, might even be higher than in P-type
- In AC-LGADs the N+ has low doping to have high resistivity necessary for charge sharing
  - Cannot be too low or depletion will reach the oxide and cause premature breakdown
  - Could be affected even by low irradiation
- **If the N doping drops it could change the resistivity and the behavior of the sensors**
  - Plus, it could lead to premature breakdown due to low doping in the N+

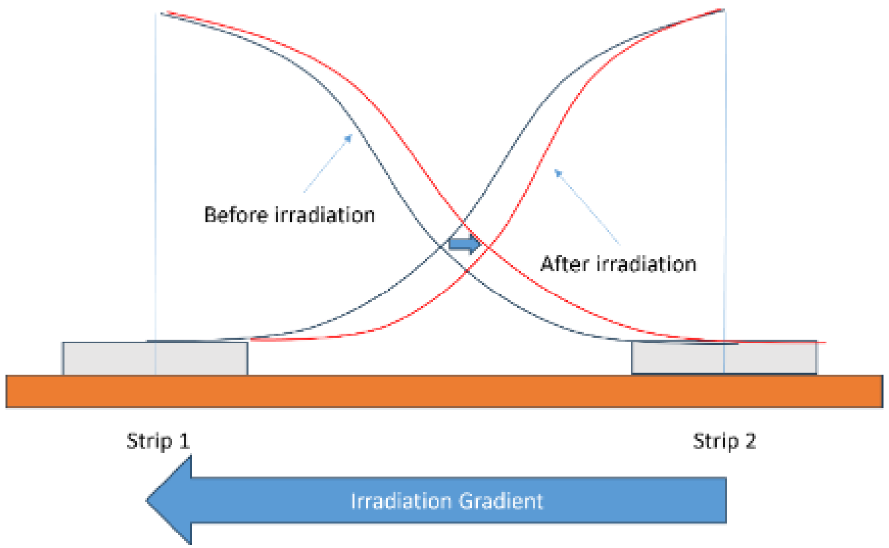




Effect of irradiation on AC-LGADs

- The change in N+ resistivity can affect the charge sharing profile around the strip/pad
- If the irradiation is not homogeneous (especially in the end-cap) it could change the centroid of the charge sharing between pads/strips and skew the reconstruction algorithm
- This could be corrected with a correction per fluence/position, but would need a very precise model!
  - Affects position resolution and might also influence time resolution since the delays are calculated per position



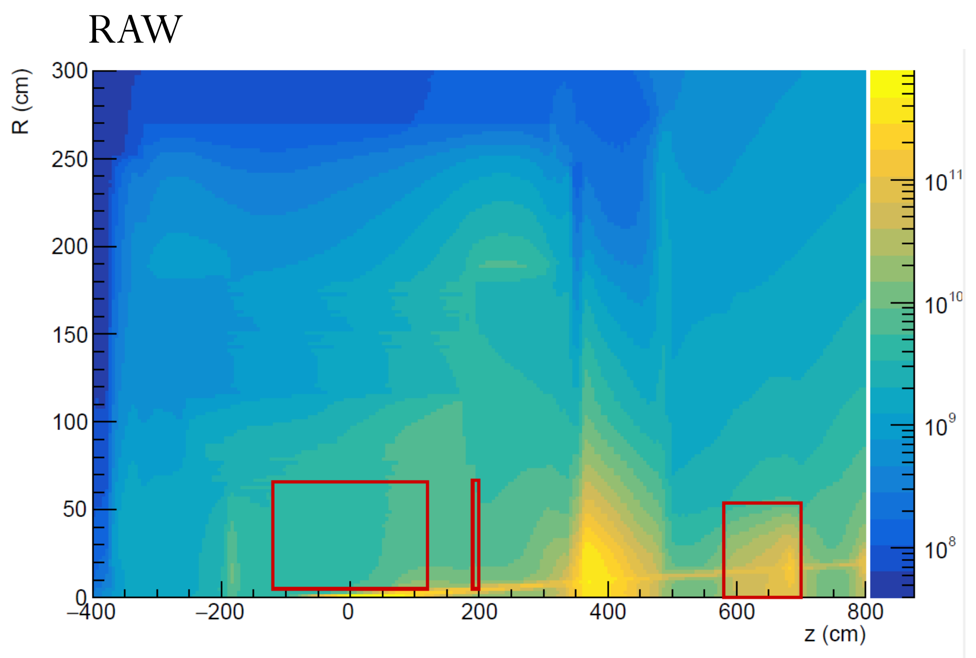


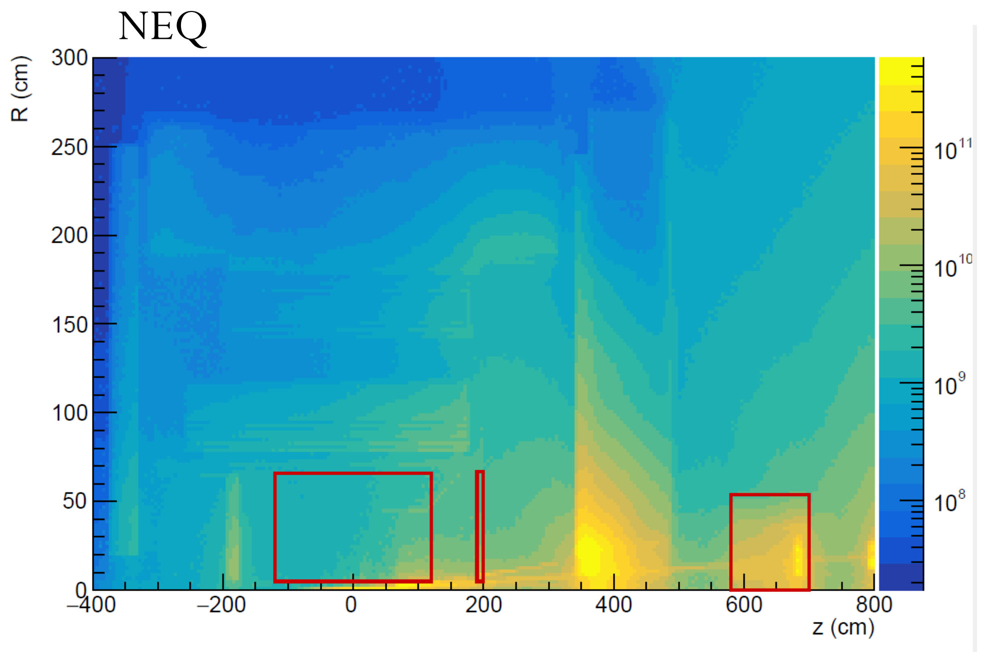
Radiation damage at ePIC

- RAW
  Barrel average: 5.4e+09 | max: 5.9+10 | min: 3.4+09
  End-cap average: 1.3e+10 | max: 1.6e+11 | min: 5.1e+09
  FF average: 3.9e+10 | max: 1.8e+11 | min: 3.3+09

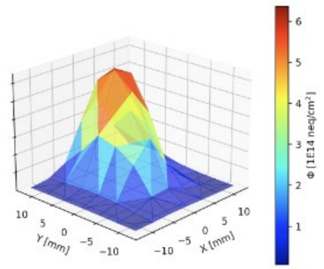
- NEQ – (not correct for LGADs gain layer)
  Barrel average: 3.6e+09 | max: 1.3e+11 | min: 1.1+09
  End-cap average: 1.2e+10 | max: 8.4e+10 | min: 3.2e+09
  FF average: 4.5e+10 | max: 4.2e+11 | min: 2.7e+09

- Safe to assume MAX damage is <1e+12, almost negligible for LGADs gain layer (effects start at >1e+13)





Irradiation campaigns



Current irradiation planned

- Original plan: irradiation at LANSCE (Los Alamos) with 800 MeV protons
  - 7e12 Neq to 2e14Neq
  - Try graded irradiation using beam edge and multiple foils
- However, Last summer the LANSCE accelerator encountered a problem
  - delay the start of the run for something like 8 weeks to allow for repair
  - This restricted all of the scheduled users, and the run was postponed
  - Currently schedule is fluid and we don't know when the run might happen

	A	B	C	D	E	F	G	H	I	J
1	Producer	ID	Sensor	Production	Wafer	Type	Thickness	Geometry	Fluences	Simplified
2	HPK		HPK 3.1	HGTD1		DC-LGAD		1.3x1.3 mm single pad	8e14 Neq, 1.5e15 Neq, 2.5e15 Neq	
3	HPK		HPK 3.2	HGTD1		DC-LGAD		1.3x1.3 mm single pad	8e14 Neq, 1.5e15 Neq, 2.5e15 Neq	
4										
5	FBK					AC-LGAD		0.5x2	1.78E+14	2.00E+14
6	FBK					AC-LGAD		0.5x2	9.26E+13	1.00E+14
7	FBK					AC-LGAD		0.5x2	1.78E+14	2.00E+14
8	FBK					AC-LGAD		0.5x2	9.26E+13	1.00E+14
9										
10	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	7.13E+12	1.00E+13
11	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	9.26E+13	1.00E+14
12	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	1.78E+14	2.00E+14
13	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	7.13E+12	1.00E+13
14	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	9.26E+13	1.00E+14
15	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	1.78E+14	2.00E+14
16	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	7.13E+12	1.00E+13
17	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	9.26E+13	1.00E+14
18	HPK	?			?	?	?	0.5x1? or 0.5x0.5?	1.78E+14	2.00E+14
19										
20	HPK	?			?	?	?	0.5x2	Graded 4e14 Neq to 2e14 Neq, parallel to strip	
21	HPK	?			?	?	?	0.5x2	Graded 4e14 Neq to 2e14 Neq, parallel to strip	
22	HPK	?			?	?	?	0.5x2	Graded 4e14 Neq to 2e14 Neq, parallel to strip	
23										
24	BNL	12			W3074, 2,1	AC-strips	20um	0.5x0.5 strips (500-50)	9.26E+13	1.00E+14
25	BNL	15			W3074, 2,4	AC-strips	20um	0.5x1 strips (500-50)	1.78E+14	2.00E+14
26	BNL	12			W3074, 1,7	AC-strips	20um	0.5x0.5 strips (500-100)	9.26E+13	1.00E+14
27	BNL	15			W3074, 1,1	AC-strips	20um	0.5x1 strips (500-100)	1.78E+14	2.00E+14
28	BNL	24			W3072, 1,2	AC-strips	20um	0.5x1 strips (500-100)	9.26E+13	1.00E+14
29	BNL	25			W3072, 2,1	AC-strips	20um	0.5x1 strips (500-200)	1.78E+14	2.00E+14
30	BNL	18			W3052, 2,1	AC-strips	50um	0.5x0.5 strips (500-50)	9.26E+13	1.00E+14
31	BNL	19			W3052, 2,1	AC-strips	50um	0.5x1 strips (500-100)	1.78E+14	2.00E+14
32	BNL	31			W3075, 1,2	AC-strips	20um	0.5x1 strips (500-100)	9.26E+13	1.00E+14
33	BNL	30			W3075, 1,2	AC-strips	20um	0.5x0.5 strips (500-100)	7.13E+12	1.00E+13
34	BNL	17			W3052, 2,2	AC-strips	50um	0.5x0.5 strips (500-50)	7.13E+12	1.00E+13
35	BNL	16			W3074, 2,3	AC-strips	20um	0.5x0.5 strips (500-50)	7.13E+12	1.00E+13
36										
37										

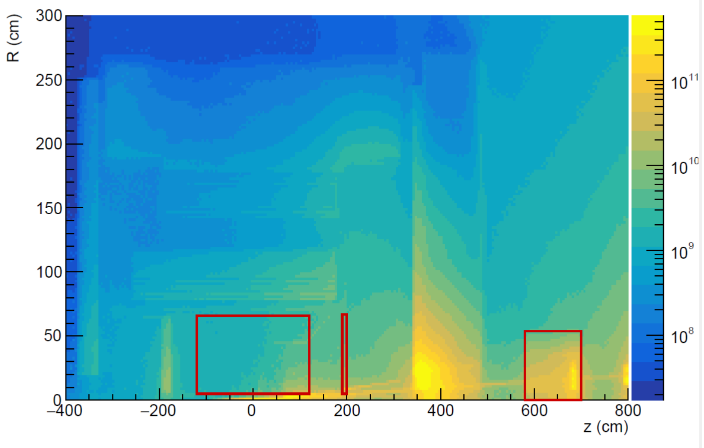
Possible solutions

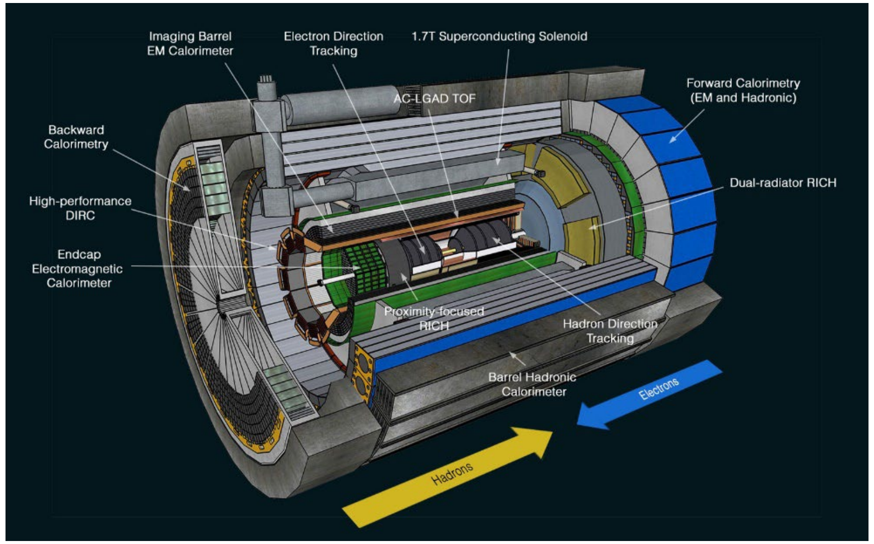
- It's necessary to irradiate and test the devices before Q4 2024
- Option 1: wait for LANL to sort out options, it's very possible that we'll get the irradiated sensors before summer but it's not certain. Everything is packed and organized at LANL so it's the option with less effort.
- Option 2: explore other irradiation facilities, with either new sensors (if available it's the best option) or recalling LANL sensors
- Facilities "Certified" for LGADs
  - CERN IRRAD: beam energy 23 GeV. CERN should open the floor to proposal in 2024 soon, slots from mid-April to mid-October. No support team there, might need to have someone travel to prepare samples and chip back.
  - CYRIC (Japan): beam energy 80 MeV. CYRIC had trouble since last summer and all beam time cancelled until March. Next beam time if all solved should be around May-June 2024
  - IJS Lubjiana TRIGA reactor: 1 MeV neutrons. Irradiation pretty much anytime. (I have to inquire if they can do 1E12Neq)
- Personally never used the facility
  - FNAL: beam energy 400 MeV. FNAL has paused operations until various issues associated with the accident last fall are resolved. Evan thinks we can probably get beam time in April/May
  - LBNL BASE facility: Beam up to 55 MeV. To be explored.

Conclusions

Conclusions

- Radiation damage at ePIC is not a concern regarding acceptor removal effect in the gain layer
  - However, need to check carefully the effect of low energy particles flux
- It might affect AC-LGADs devices in other ways due to the resistive N+
  - Premature breakdown or change in charge sharing mechanism, especially in end-cap and FF with fluence variation across the device
  - It's critical to prove it's not an issue at ePIC
  - Also check SEB in AC-LGADs
- LANL irradiation of last summer was postponed, need to find an alternative solution
  - Number of facilities to choose from, but mostly starting operations after April
- My take: if we have enough spare sensors, irradiate in parallel at a few facilities and keep the LANL run possible
  - It would also provide more information on NIEL violation





Thanks for the attention

Many thanks to the SCIPP group students and technicians!

Thanks to FBK, HPK, BNL to have provided sensors for this study

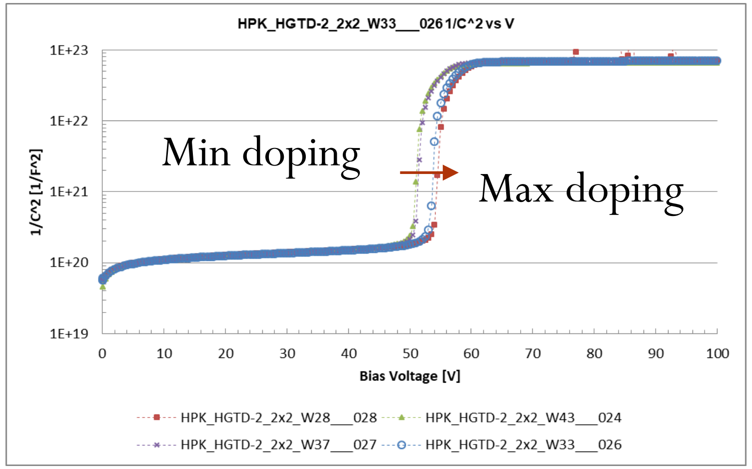
This work was supported by the United States Department of Energy, grant DE-FG02-04ER41286

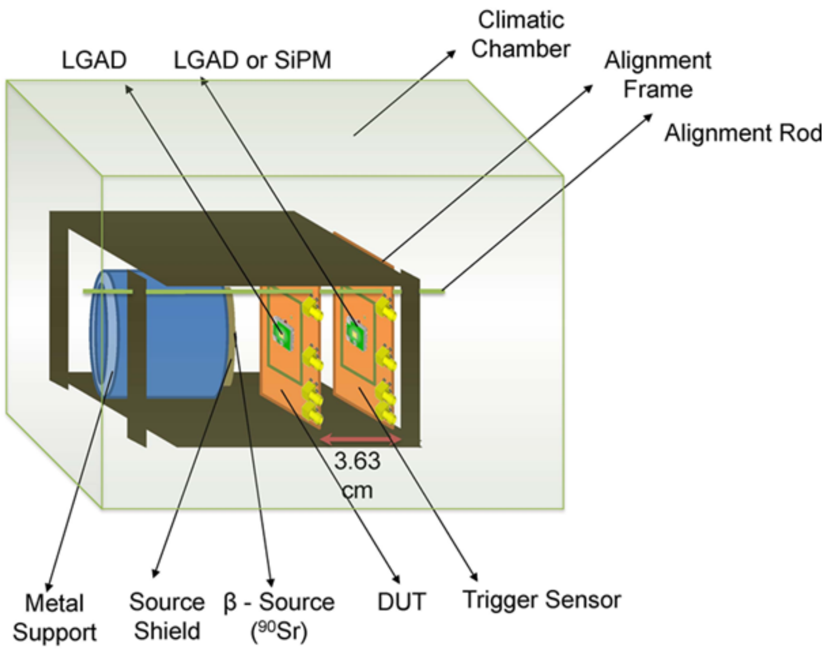
This work was partially performed within the CERN RD50 collaboration.

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.

This work was supported by the United States Department of Energy, grant DE-FG02-04ER41286.
CACTUS DJ-LGAD SBIR
Use of the Stanford Synchrotron Radiation Lightsource, SLAC National Accelerator Laboratory, is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF00515.
The group from USP acknowledges support from FAPESP (grant 2020/04867-2) and CAPES.

Sensor testing –probe station, charge collection





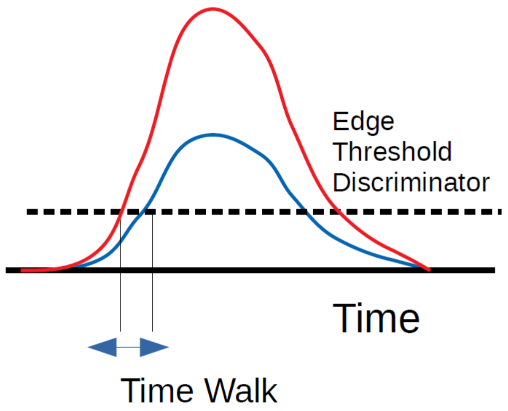
- **Probe station electrical testing**
- Current of voltage (IV) and Capacitance over voltage (CV)
- CV is used to probe the doping profile of the gain layer

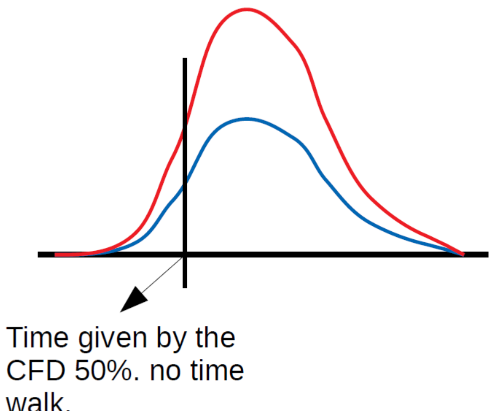
- **Laboratory charge collection**
- Using MiP electrons from a Sr90 β-source (β-telescope)
  - Signal shape, noise, **collected charge**, gain, **time resolution**
- Using Alpha source in vacuum (Am237), ~100 MIPs deposition
- Using X-ray gun

- **Laser TCT studies**
  - IR laser mimics a MiP response and allows charge injection as a function of position
  - Particularly useful to test arrays and AC-LGADs (see later)

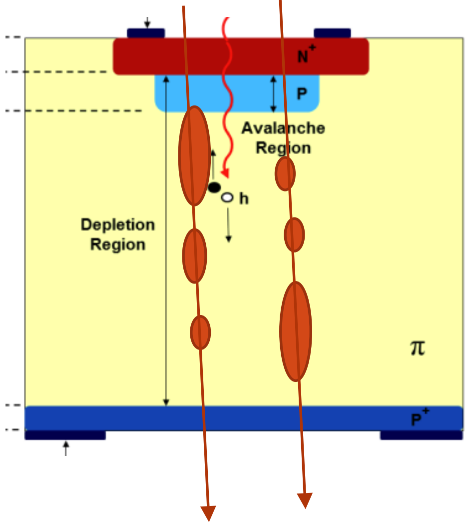
- **Test beam at facilities (CERN, DESY, FNAL)**
  - Allows the study of MiP response with position information through an external tracker

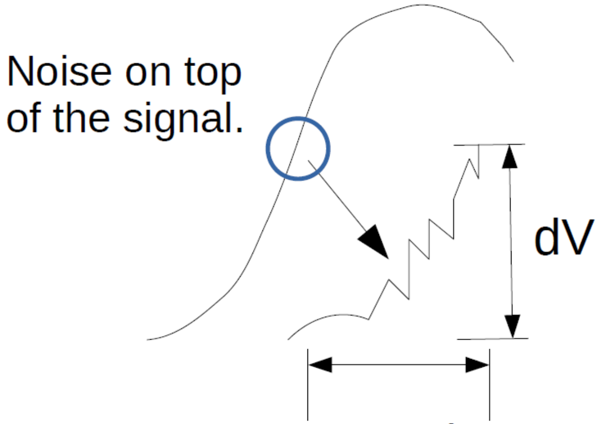
Time resolution





Landau variations





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

Sensor time resolution main terms

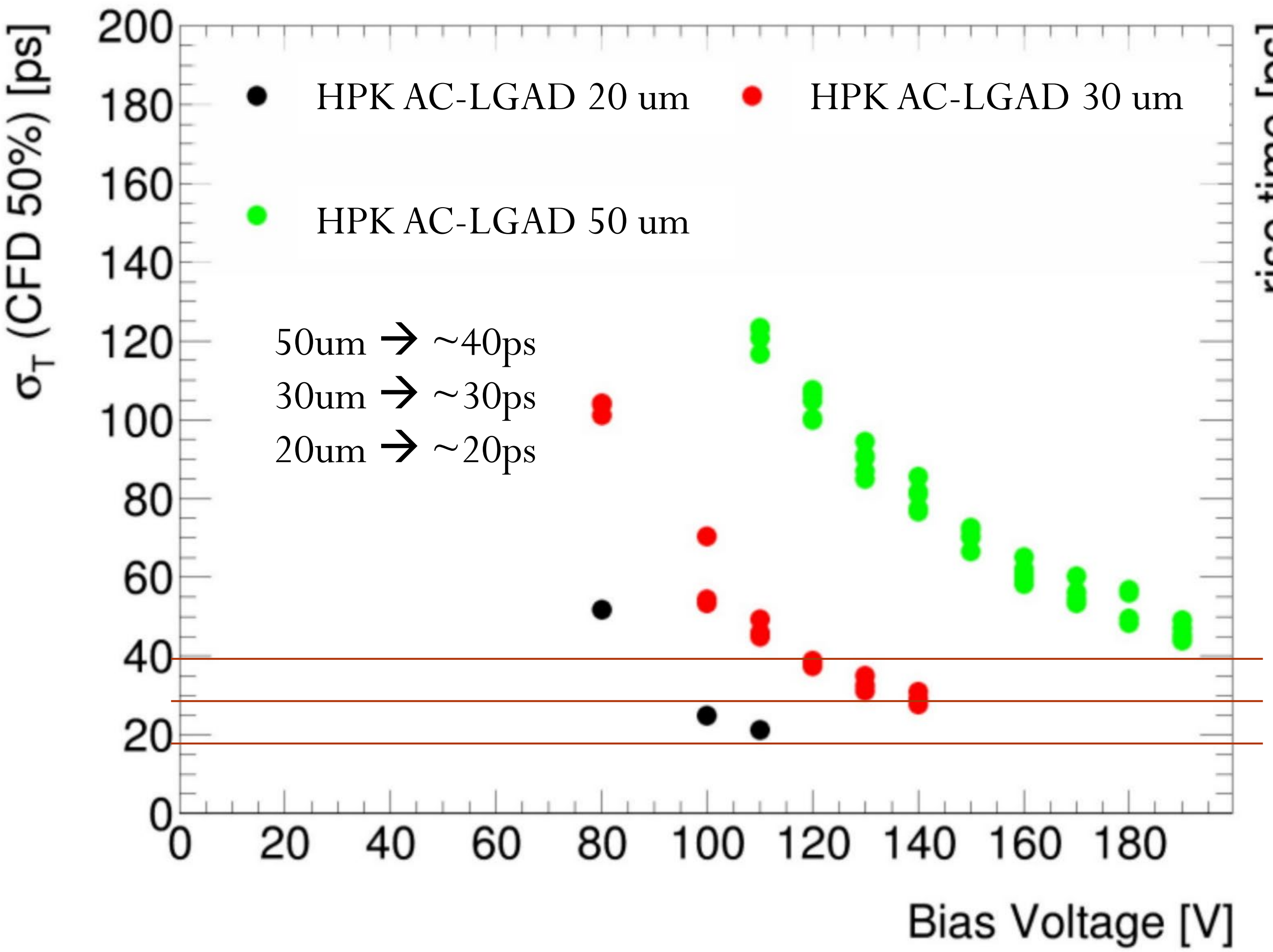
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

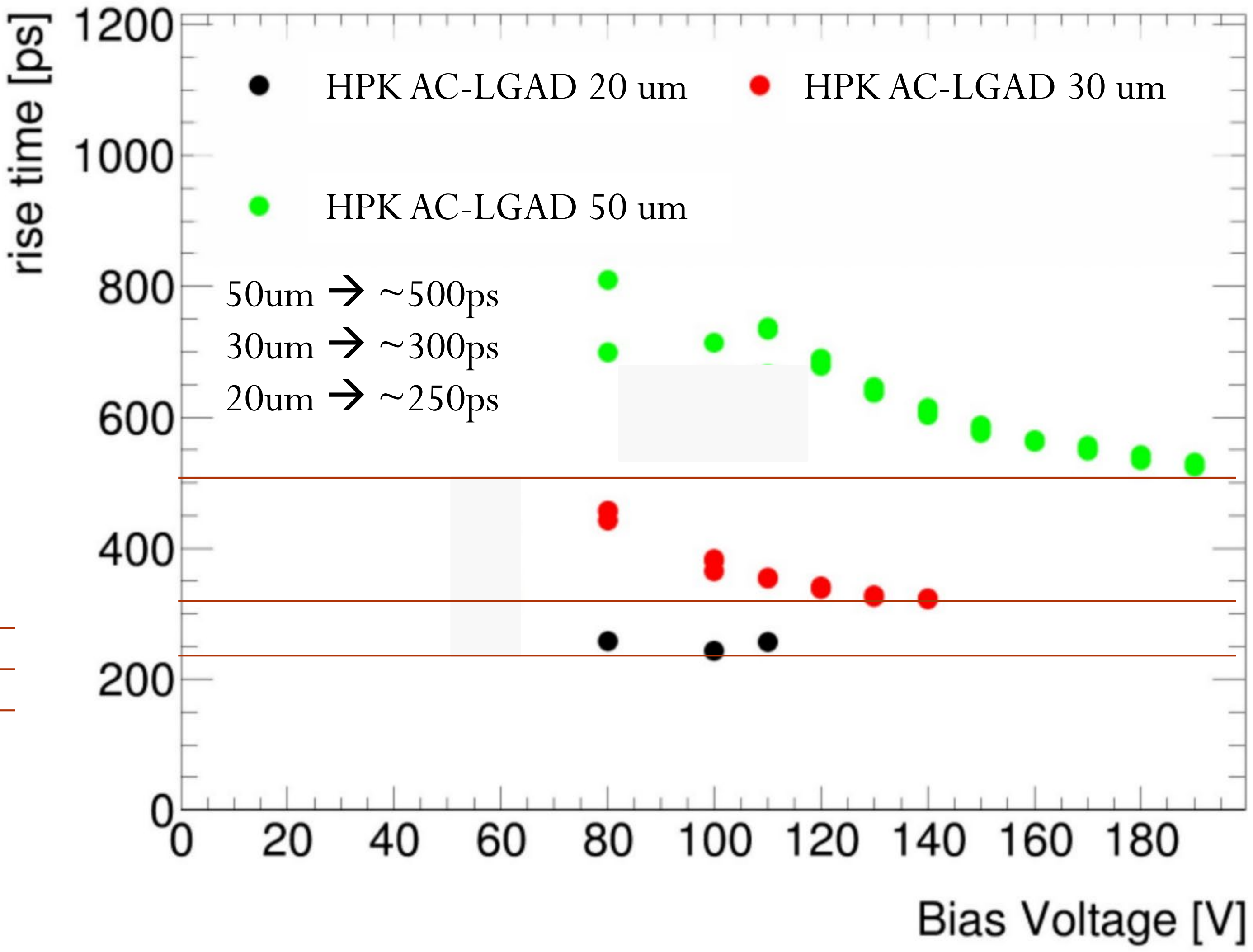
- **Time walk**:
  - Minimized by correcting the time of arrival using pulse width or pulse height (e.g., use 50% of the pulse as ToF)
- **Jitter**: from electronics
  - Proportional to $^1/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain
- **TDC term**: from digitization clock (electronics)
- **Landau term**: proportional to silicon sensor thickness
  - Reduced for thinner sensors
  - Dominant term at high gain

- **Bottom line: thin detectors with high S/N**

Time resolution vs thickness

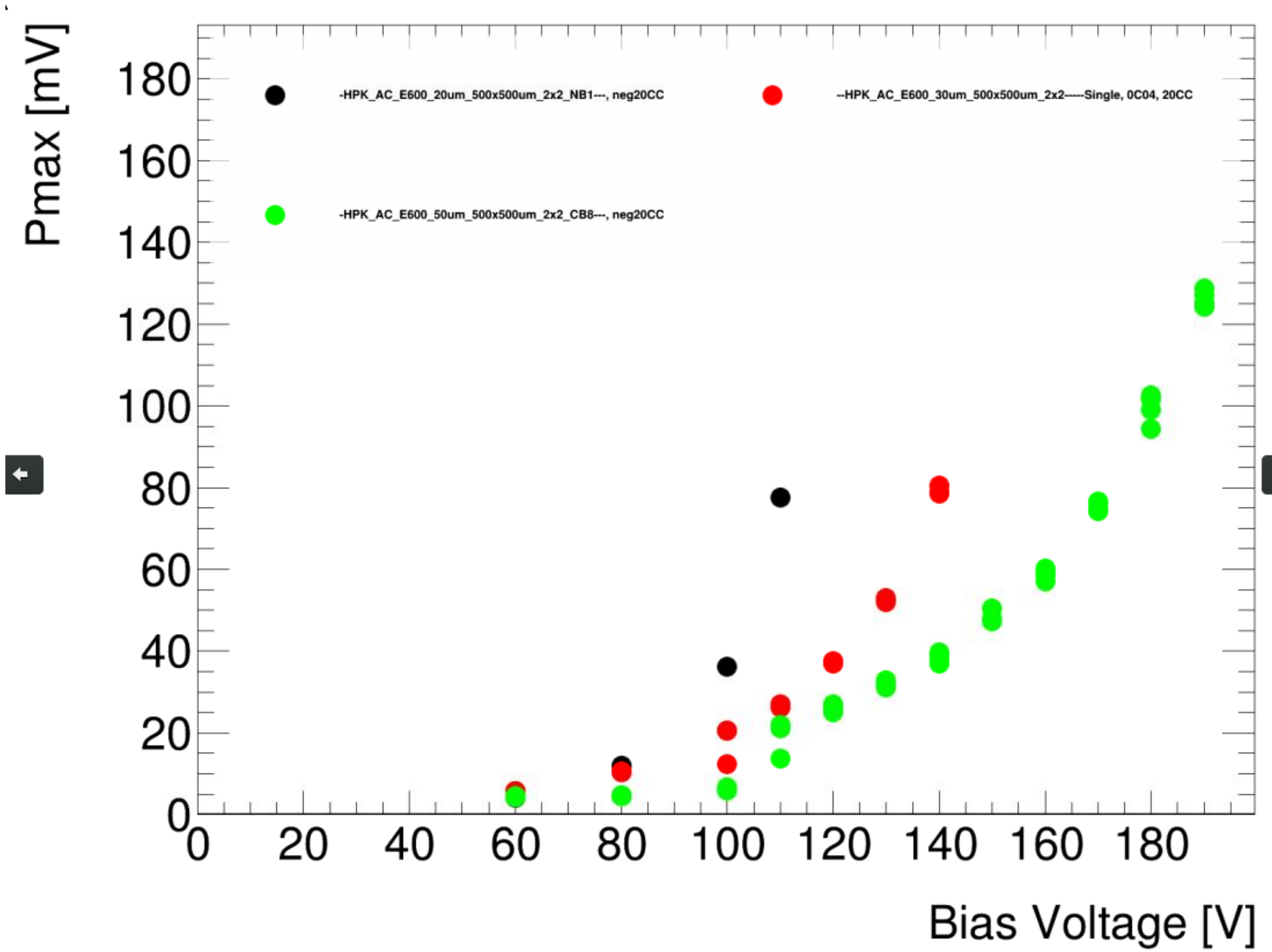
- When sensor has high gain there's **very low jitter contribution** to the time resolution, ultimately driven by Landau component → **Depends on sensor thickness**

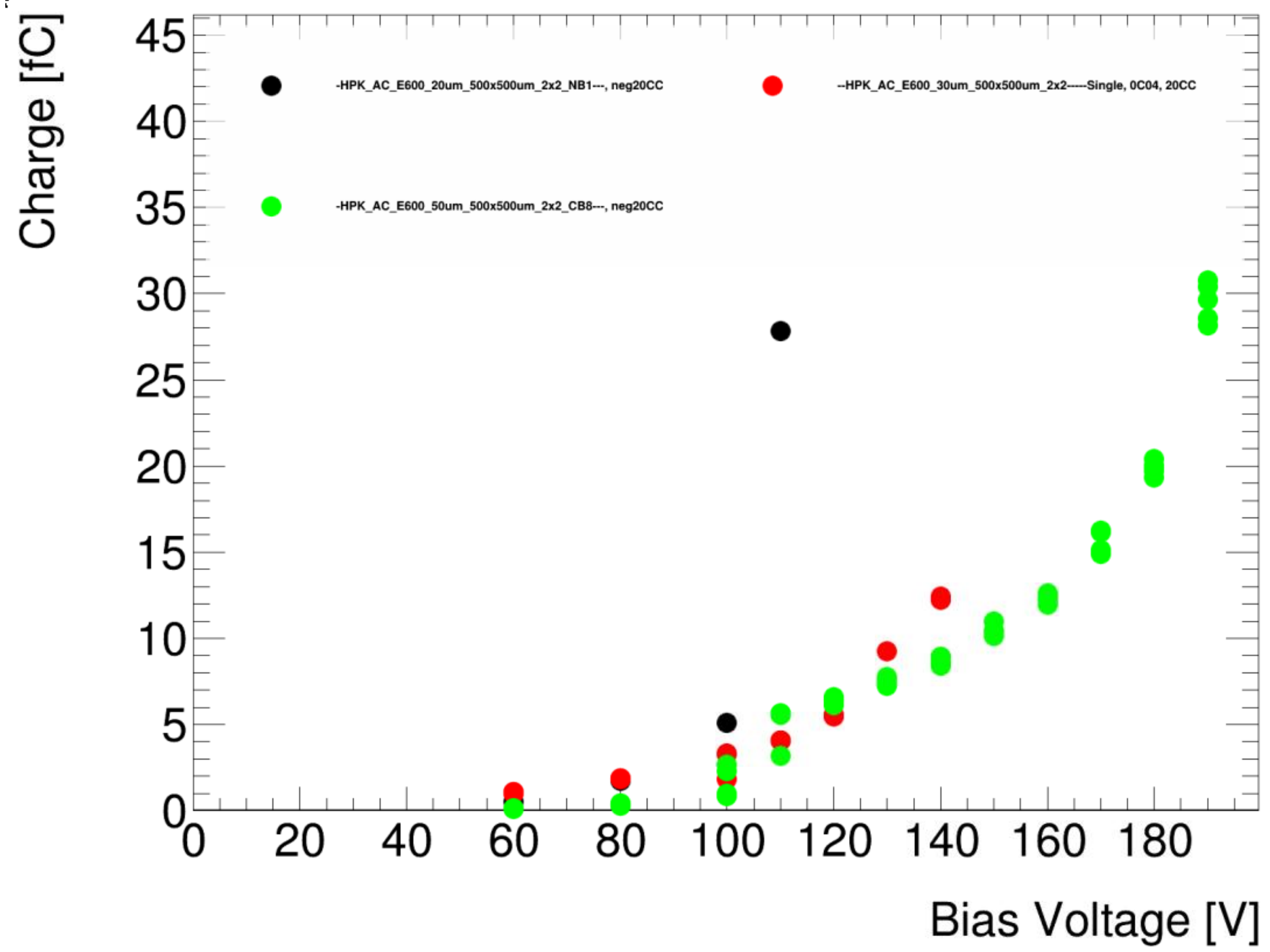




Data by: J. Ding

Pmax/charge vs thickness





Data by: J. Ding