AC-LGAD sensor irradiation test

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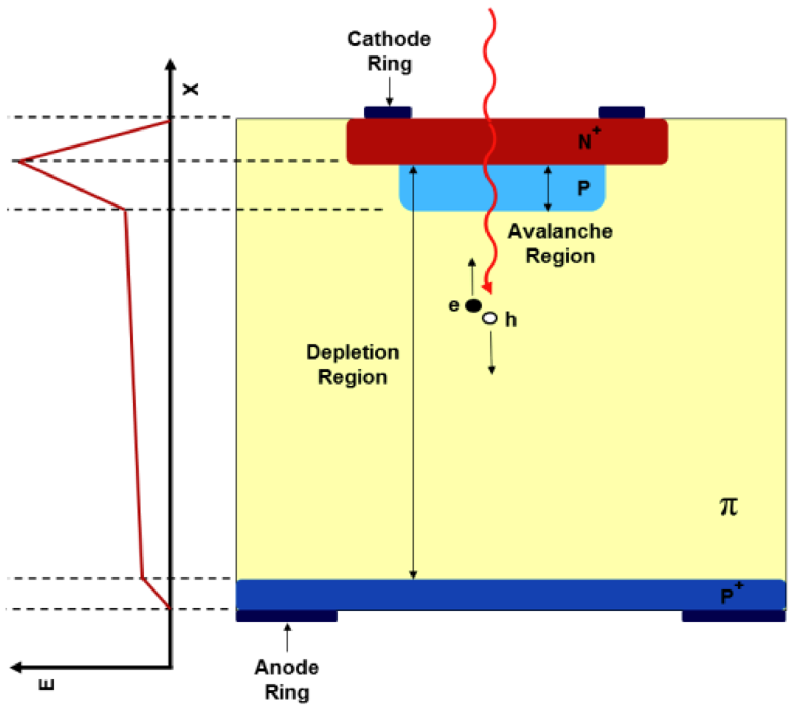
LGADs and radiation damage

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**



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

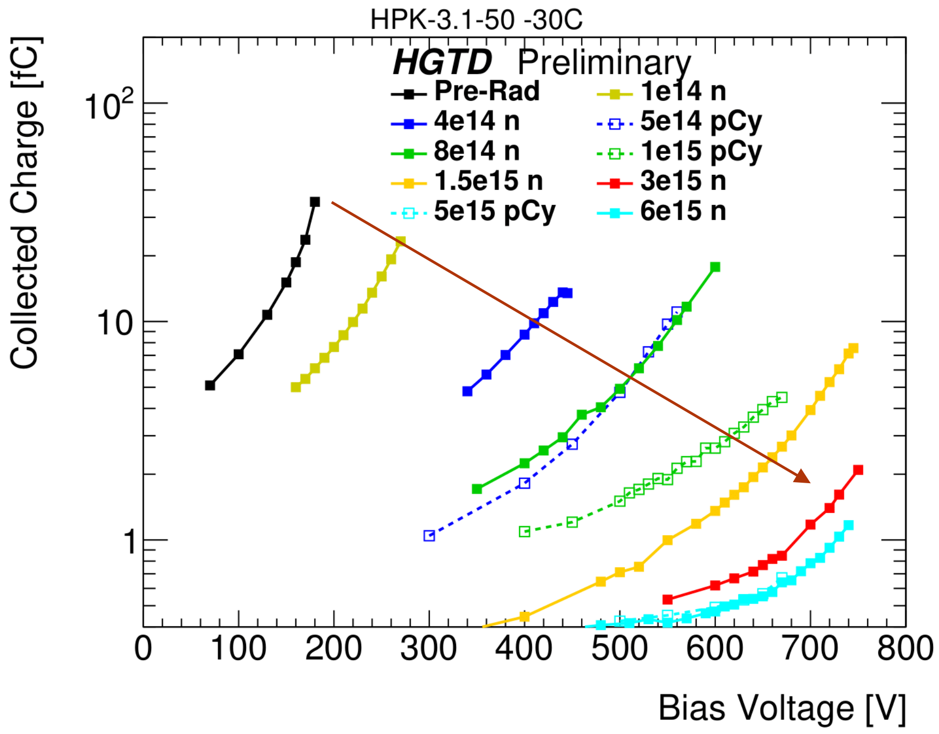
- Several producers of experimental LGADs
  - **HPK (Japan), BNL (USA), FBK (Italy),** CNM (Spain), NDL/IMEI (China), Micron (UK)
  - AC-LGAD produced at HPK and BNL in this study funded by US-Japan grant

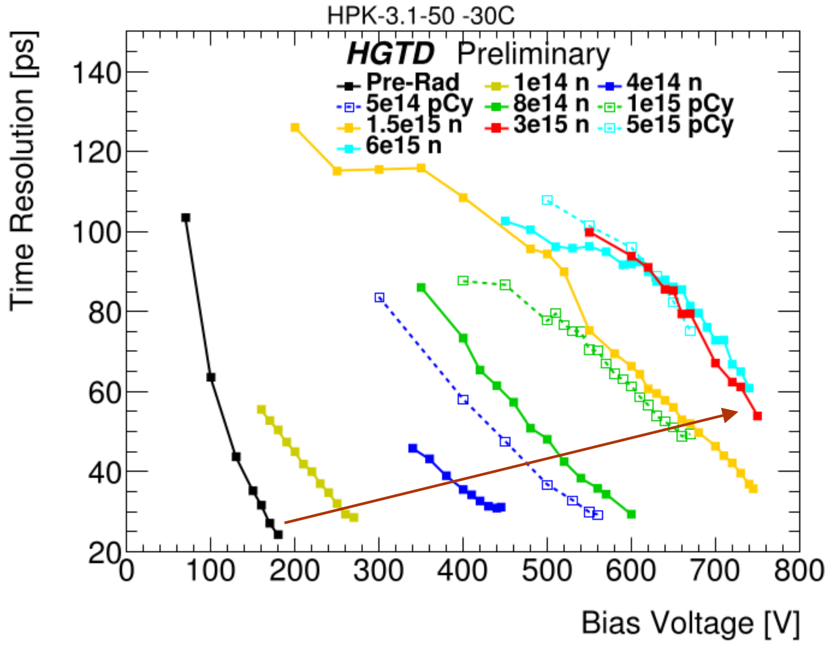
LGAD and radiation damage

- 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)

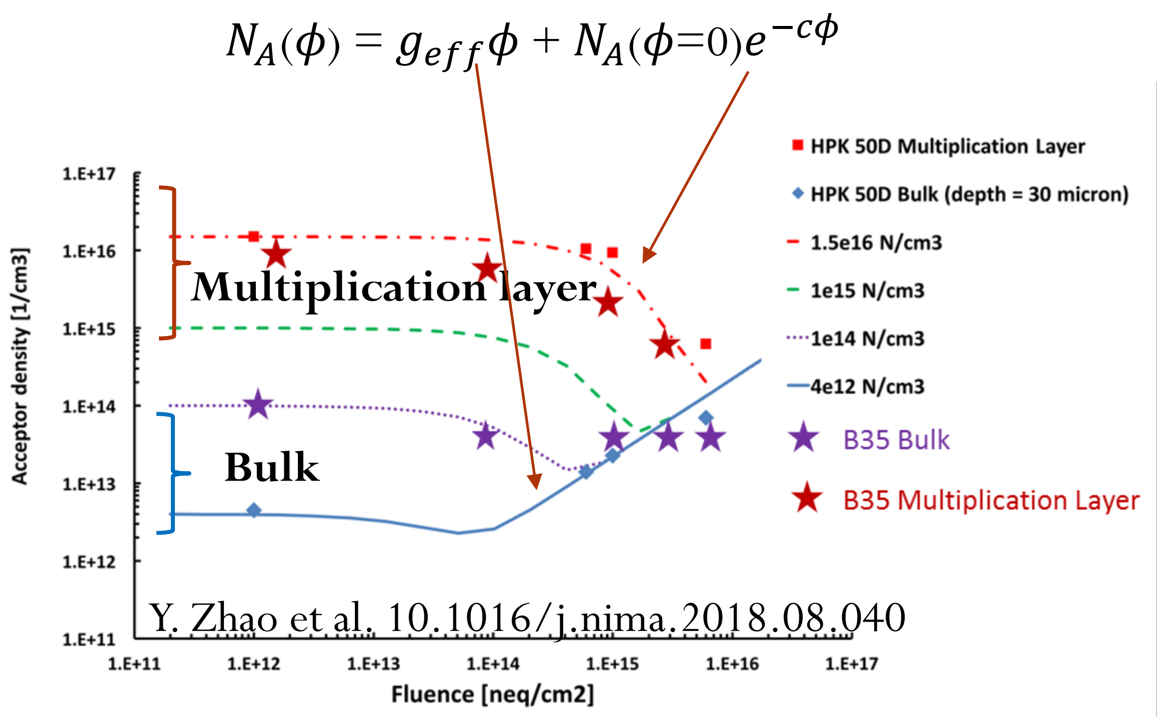
- Partly the performance can be recovered by increasing the bias Voltage applied to the diode (~200V → ~700V)
- **Reduction of gain and collected charge**
  - Charge collected up to 30fC (Gain ~50) before irradiation to 1fC (gain 2-3) after a fluence of 6E15 Neq/cm^2
  - (Neq: equivalent 1 MeV neutrons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

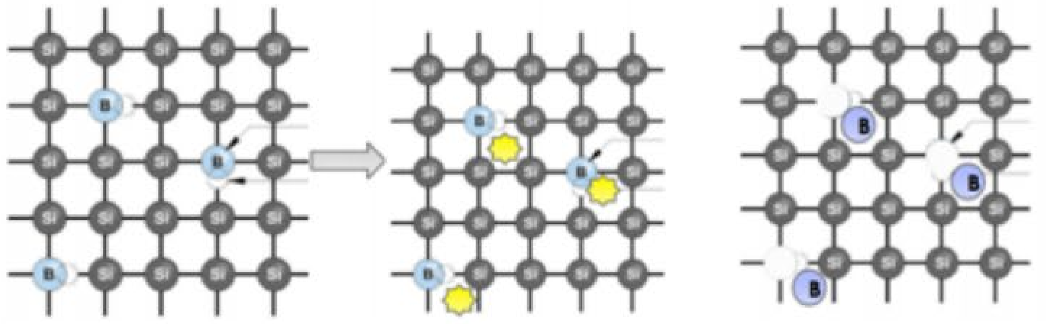




Radiation damage model

- 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**

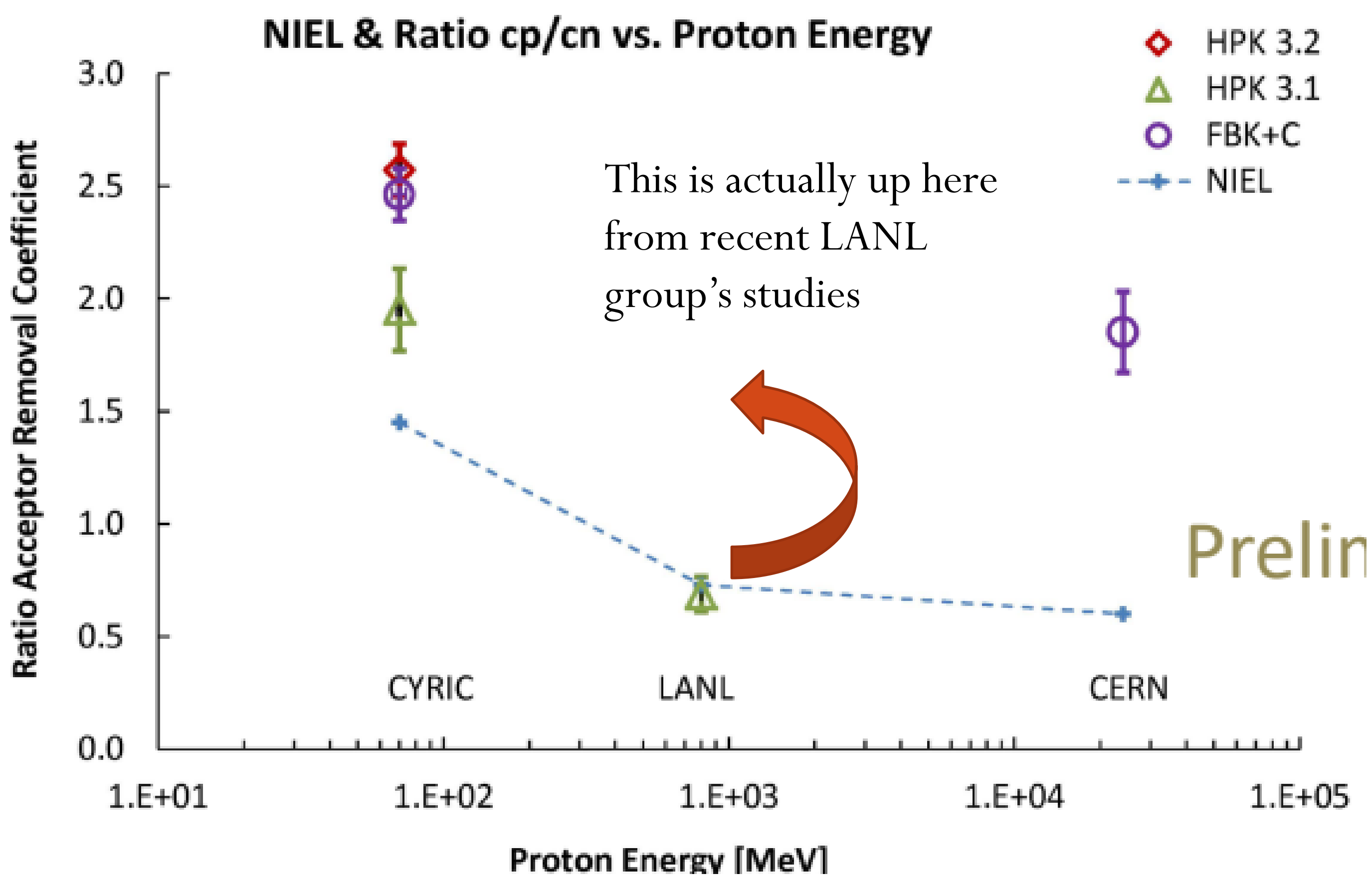




Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s ➔ Si_s + B_i
B_i might interact with Oxigen, creating a donor state

NIEL violation (old-ish data)

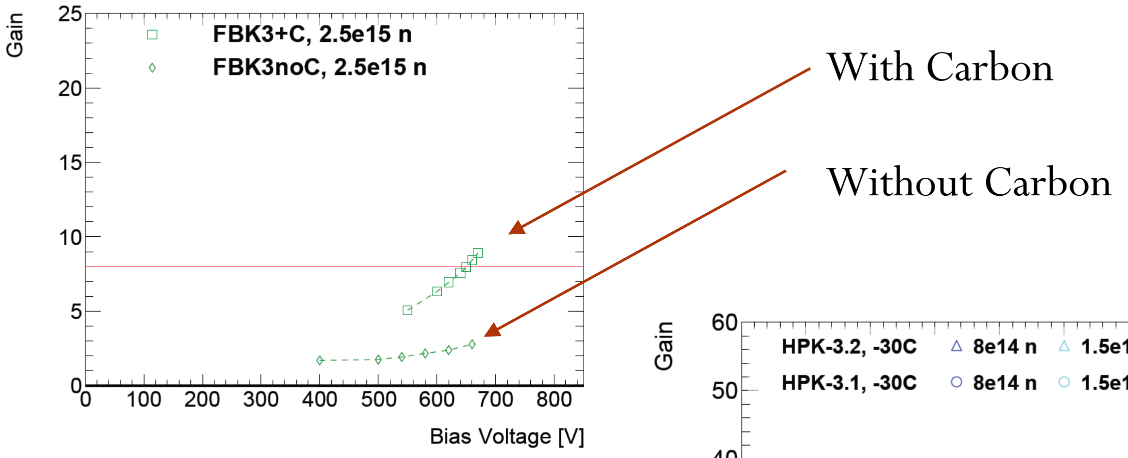
- Acceptor removal ratio cp/cn
  - Dependence on the proton energy seems to be sensor specific
  - Does not scale with NIEL, larger than NIEL factor. Damage can be > 2 than the expected NIEL fluence
- Need to take into account the energy distribution of the damaging particles in the fluence calculation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

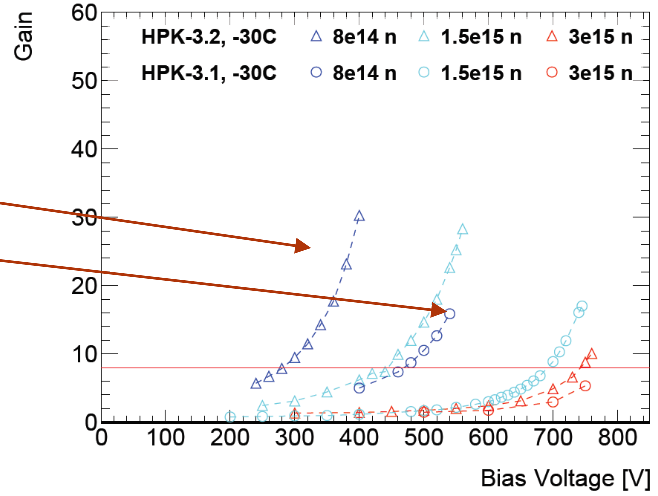


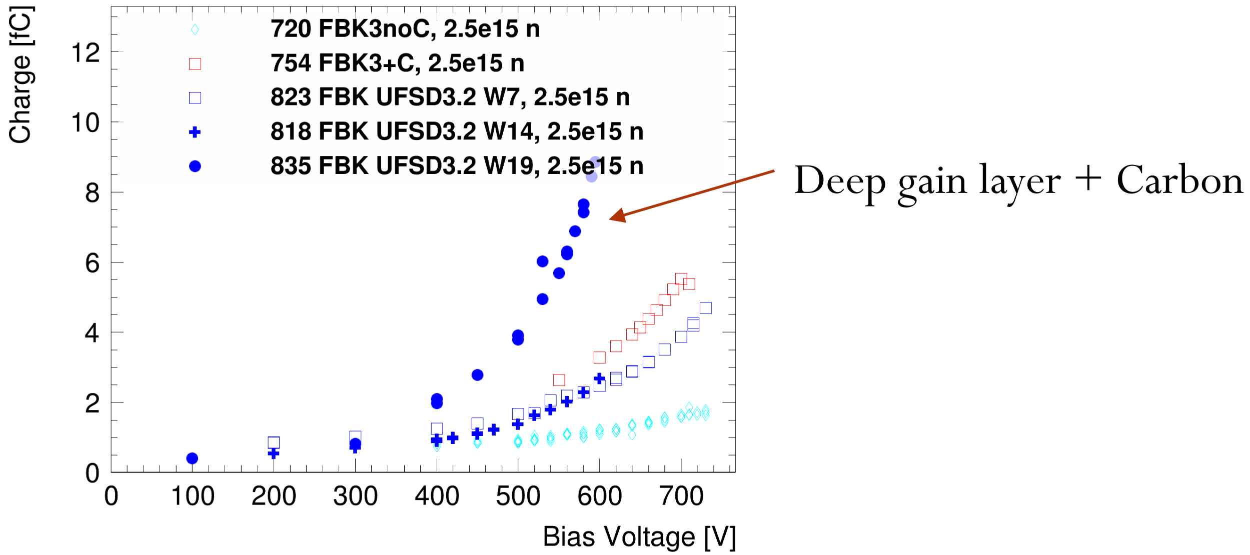
Radiation hard LGAD design

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**



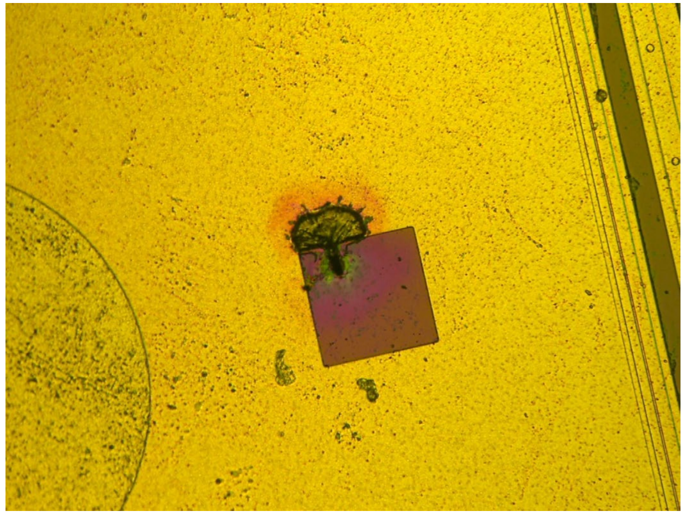


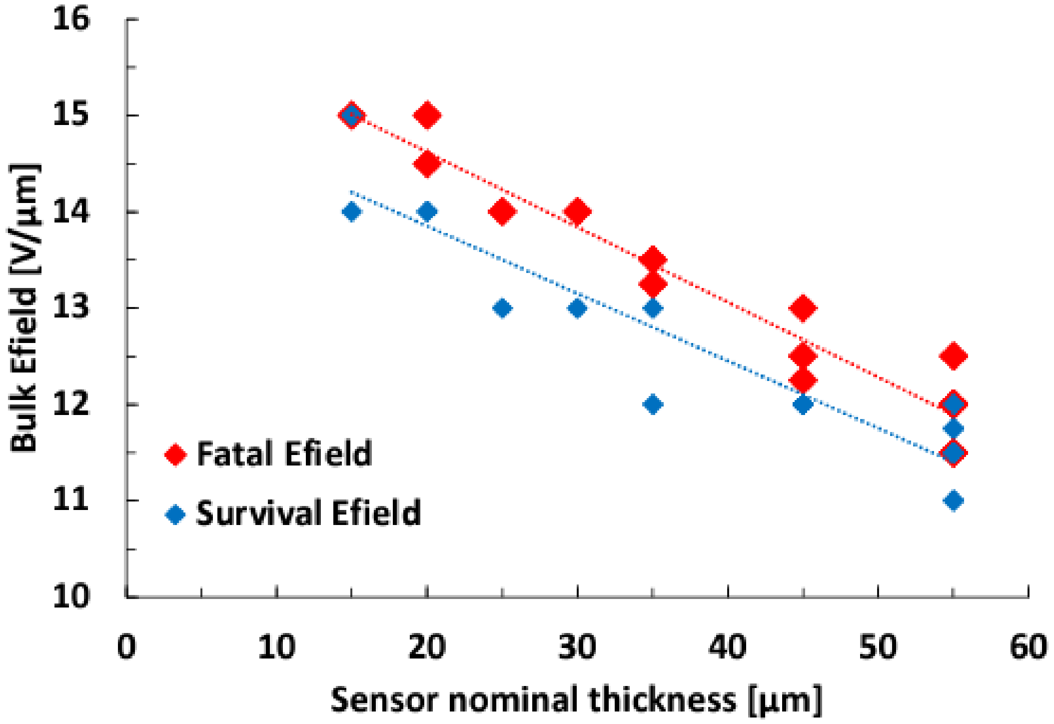


- Resources
  - https://iopscience.iop.org/article/10.1088/1742-6596/2374/1/012173/meta
  - https://iopscience.iop.org/article/10.1088/1748-0221/15/10/P10003
  - https://www.sciencedirect.com/science/article/pii/S0168900218317741
  - https://doi.org/10.1088/1748-0221/15/04/T04008
  - https://doi.org/10.1016/j.nima.2018.08.040

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)

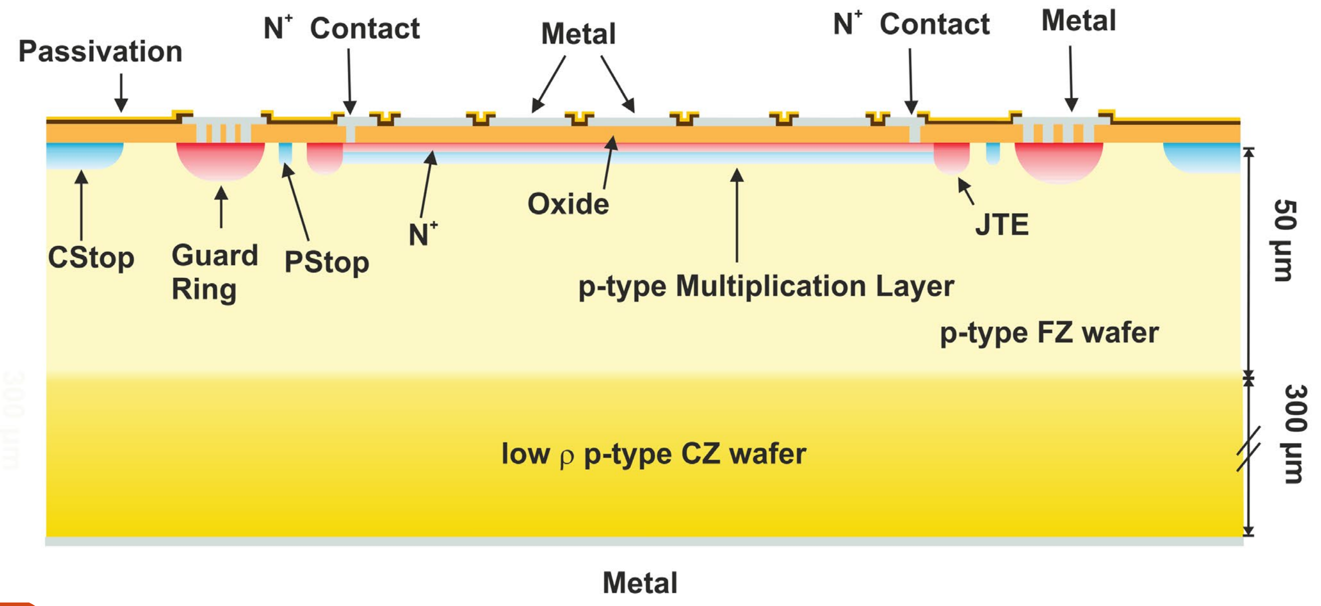




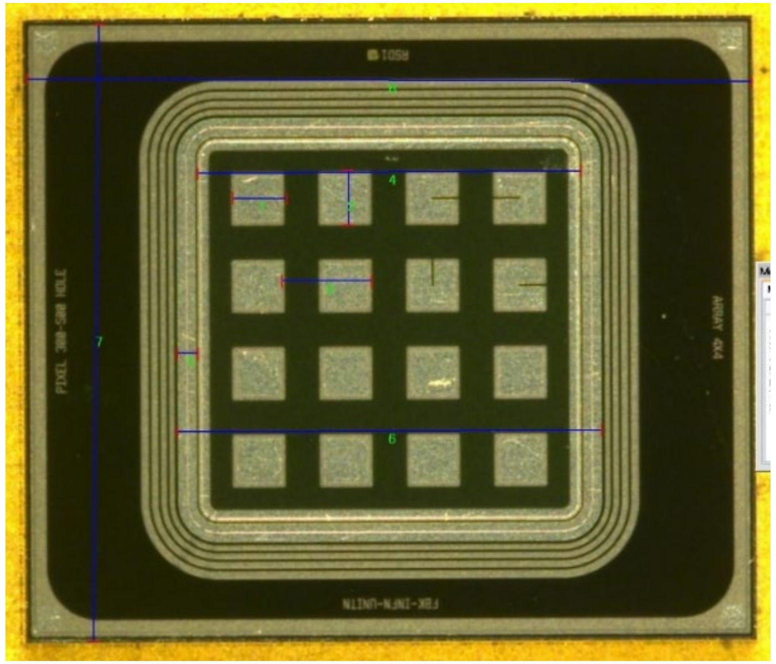
Radiation damage on AC-LGADs

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

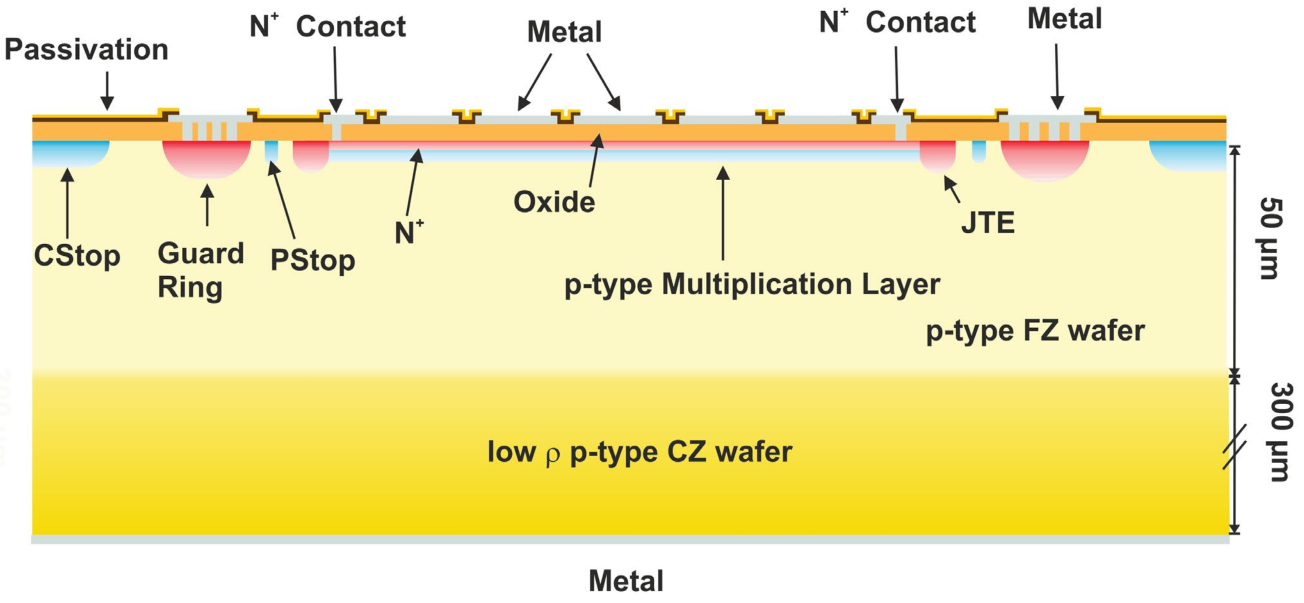


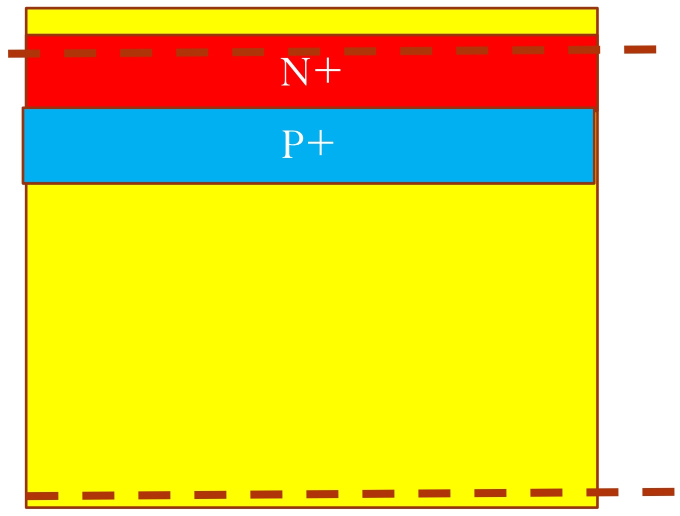
- **The response of the sensors can be tuned** by modifying several parameters
  - Pad geometry and dimension
  - Pad pitch
  - N+ layer resistivity
  - Oxide thickness



Effect of irradiation on AC-LGADs

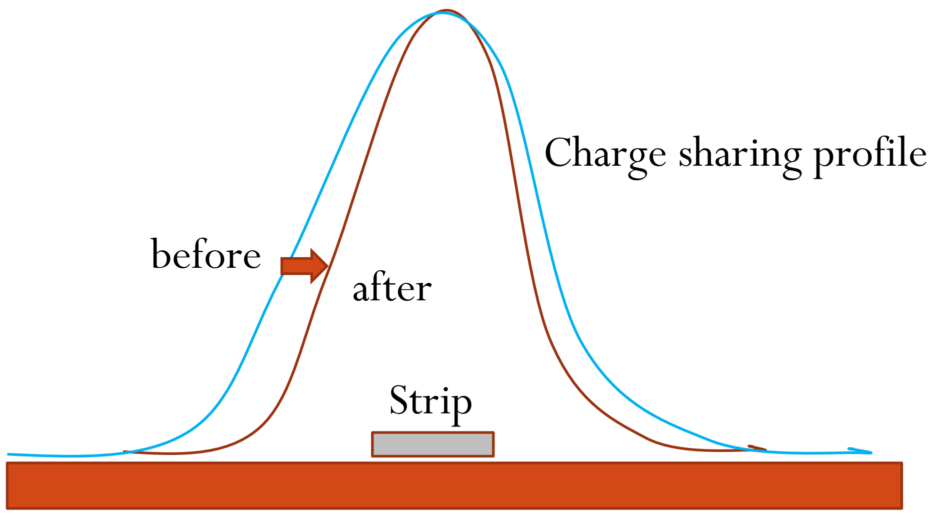
- The gain layer will have more or less the same behavior of standard LGAD devices
- The N+ can have some unexpected effects though
  - Normally is highly doped and conductive so it's not affected by radiation damage
  - We don't know well the effects of acceptor removal to N-type, might even be higher 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+

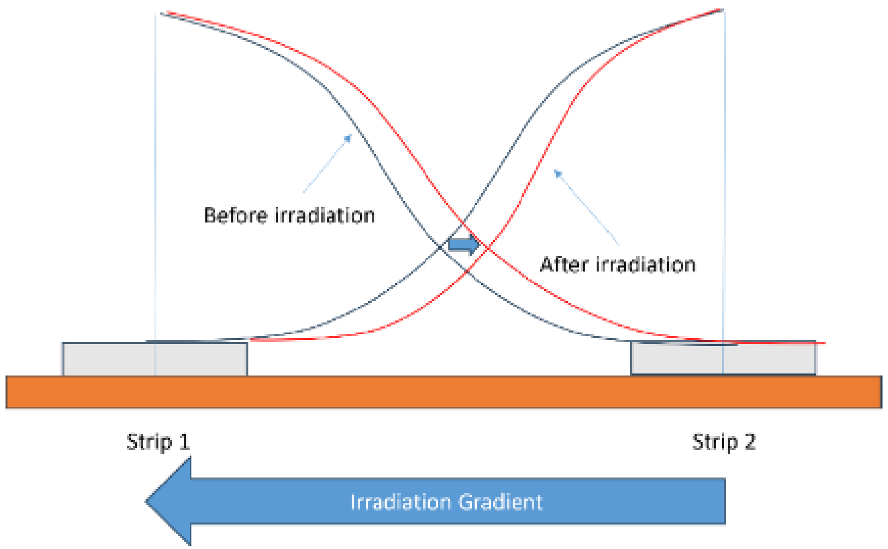




Effect of irradiation on AC-LGADs

- 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



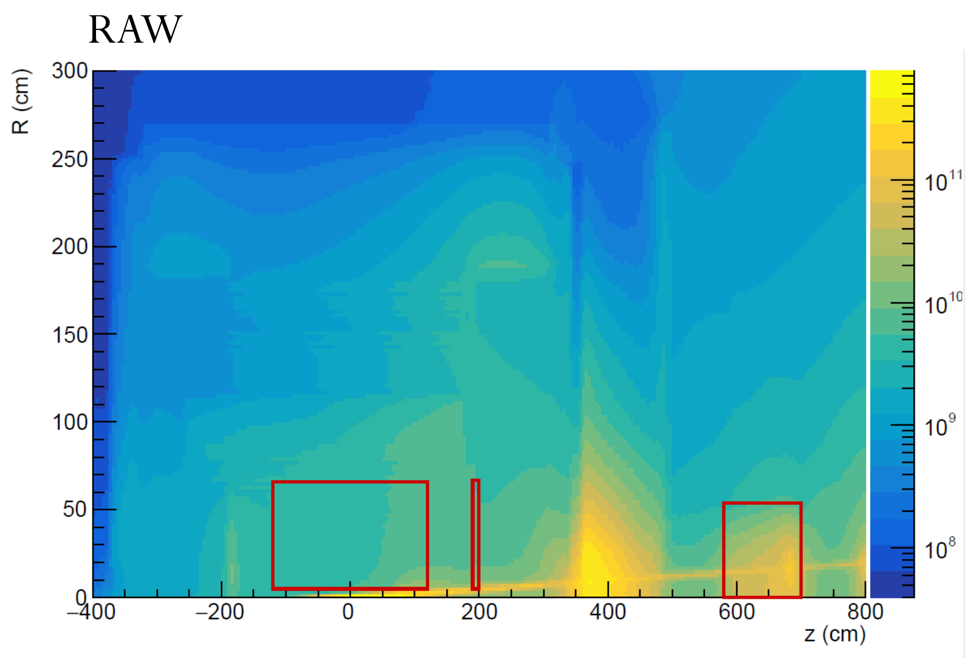


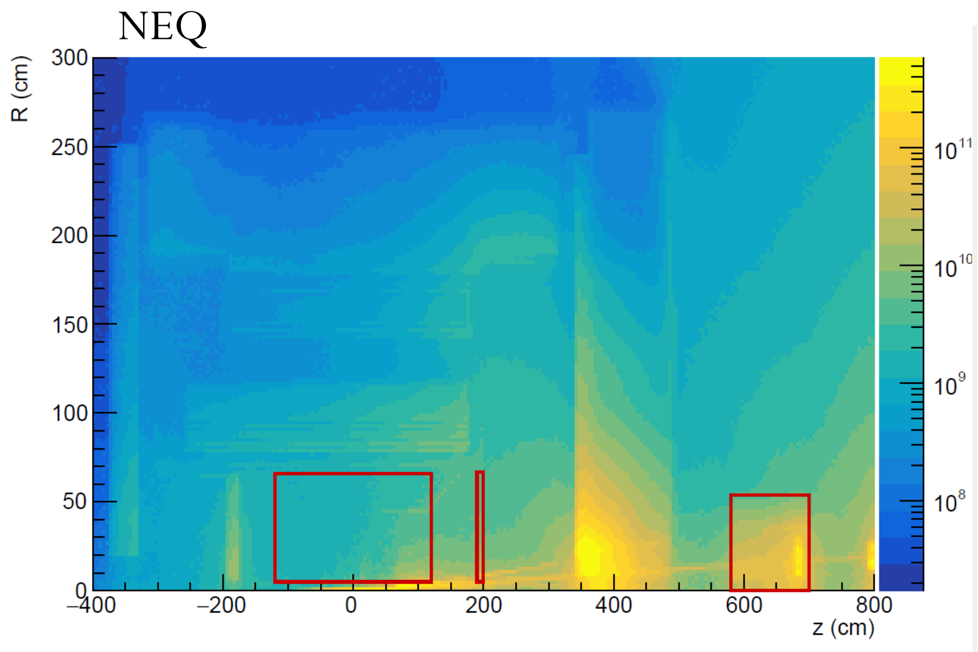
Radiation damage at ePIC

- 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

Irradiations 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
- Moved the sensors to irradiated to **FNAL ITA** (400MeV protons)
  - Plans for last week irradiation but due to setbacks in the beam is now **planned end of April, beginning of May**
  - Not sure if graded irradiation is possible
- Fluences 1E13 to 2E14 Neq
  - Plus higher fluences for some old LGADs for facility characterization

	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										

Irradiations planned

- Irradiation at IJS
  - 1 MeV neutrons
- Fluences
  - 1E12, 1E13, 1E14 Neq
- Plus higher fluence for general interest of irradiation on AC-LGADs
  - 5E14, 1E15 Neq

SCIPP HPK ID	Geometry	wafer	size	HPK n+ layer doping	dielectric C (pF/mm2)	thickness	lenght (mm)	pitch (um)	width (um)	Tested laser	Test IV	Ask for more? #	Fluence (JSI)
HPK1	Strip	W02		E	240	50	5	500	50	X	x	1	1.00E+14
HPK3	Strip	W05		E	600	50	5	500	50	X	x	1	1.00E+12
HPK4	Strip	W08		C	600	50	5	500	50	X	x	1	
HPK5	Strip	W09		E	600	20	5	500	50				
HPK6	Strip	W11		C	600	20	5	500	50				
HPK7	Strip	W02		E	240	50	5	500	100			1	5.00E+14
HPK8	Strip	W04		C	240	50	5	500	100	X	x	1	
HPK9	Strip	W05		E	600	50	5	500	100			1	1.00E+13
HPK10	Strip	W08		C	600	50	5	500	100				
HPK11	Strip	W09		E	600	20	5	500	100				
HPK12	Strip	W11		C	600	20	5	500	100				
HPK13	Strip	W02		E	240	50	10	500	50	X	x	1	1.00E+15
HPK14	Strip	W04		C	240	50	10	500	50				
HPK15	Strip	W05		E	600	50	10	500	50			1	1.00E+14
HPK16	Strip	W08		C	600	50	10	500	50	Nalu board #1			
HPK17	Strip	W09		E	600	20	10	500	50				
HPK18	Strip	W11		C	600	20	10	500	50				
HPK19	Strip	W02		E	240	50	10	500	100			1	1.00E+14
HPK20	Strip	W04		C	240	50	10	500	100				
HPK21	Strip	W05		E	600	50	10	500	100	X	x	1	1.00E+12
HPK22	Strip	W08		C	600	50	10	500	100	X	x	1	
HPK23	Strip	W09		E	600	20	10	500	100				
HPK24	Strip	W11		C	600	20	10	500	100				
HPK25	Strip	W02		E	240	50	20	500	50			1	5.00E+14
HPK26	Strip	W04		C	240	50	20	500	50				
HPK27	Strip	W05		E	600	50	20	500	50	X	x	1	1.00E+13
HPK28	Strip	W08		C	600	50	20	500	50	X	x	1	
HPK29	Strip	W09		E	600	20	20	500	50	X	x	1	
HPK30	Strip	W11		C	600	20	20	500	50				
HPK31	Strip	W02		E	240	50	20	500	100			1	1.00E+15
HPK32	Strip	W04		C	240	50	20	500	100				
HPK33	Strip	W05		E	600	50	20	500	100			1	1.00E+14
HPK34	Strip	W08		C	600	50	20	500	100				
HPK35	Strip	W09		E	600	20	20	500	100	X	x	1	
HPK36	Strip	W11		C	600	20	20	500	100				
HPK37	Pixel	W02	4x4	E	240	50	150	500				3	1E12, 1E13, 1E14
HPK38	Pixel	W04	4x4	C	240	50	150	500				3	1E12, 1E13, 1E14
HPK39	Pixel	W05	4x4	E	600	50	150	500				2	5E14, 1E15
HPK40	Pixel	W08	4x4	C	600	50	150	500				3	1E12, 1E13, 1E14
HPK41	Pixel	W09	4x4	E	600	20	150	500				3	1E12, 1E13, 1E14
HPK42	Pixel	W11	4x4	C	600	20	150	500				2	5E14, 1E15
HPK43	Pixel	W02	4x4	E	240	50	300	500				2	5E14, 1E15
HPK44	Pixel	W04	4x4	C	240	50	300	500				2	5E14, 1E15
HPK45	Pixel	W05	4x4	E	600	50	300	500				3	1E12, 1E13, 1E14
HPK46	Pixel	W08	4x4	C	600	50	300	500					
HPK47	Pixel	W09	4x4	E	600	20	300	500				3	1e12, 5e14, 1e15
HPK48	Pixel	W11	4x4	C	600	20	300	500					

Other irradiations

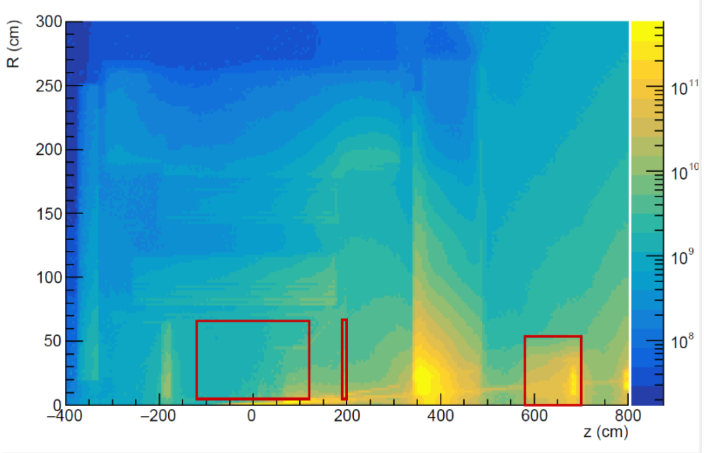
- Plans for irradiation at UC Davis (high energy neutrons, protons, ions) in summer
- TBD plans for irradiation at UC Berkely (high energy neutrons, protons, ions)

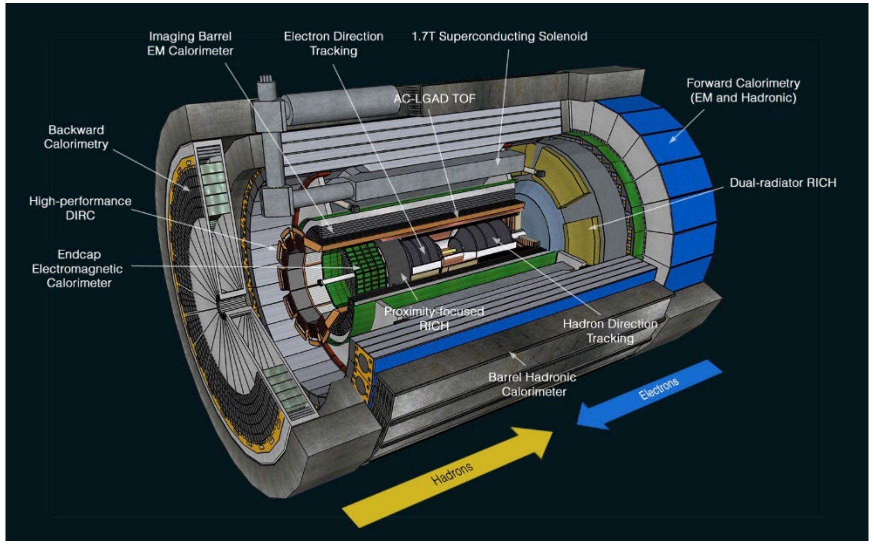
Sensors	Facility	Time	Particles	Fluences (Neq)	Expected back
HPK Pixels, strips BNL strips FBK strips	FNAL ITA	End of April	400 MeV Protons	1E13, 1E14, 2E14	?
HPK Pixels, strips	Triga Reactor	Shipped, <1month	1MeV neutrons	1E12, 1E13, 1E14, 5E14, 1E15	~3-4 months
TBD	UC Davis	Summer	Neutrons, protons, ions	TDB	?
TBD	LBNL	TBD	Neutrons, protons, ions	TDB	?

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
- Irradiation at FNAL ITA (protons) and Triga reactor (neutrons) ongoing
  - Hopefully, sensors will be back by summer
  - Plans for irradiations also at UC Davis and LBNL






Thanks for the attention

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