AC-LGAD sensor irradiation test

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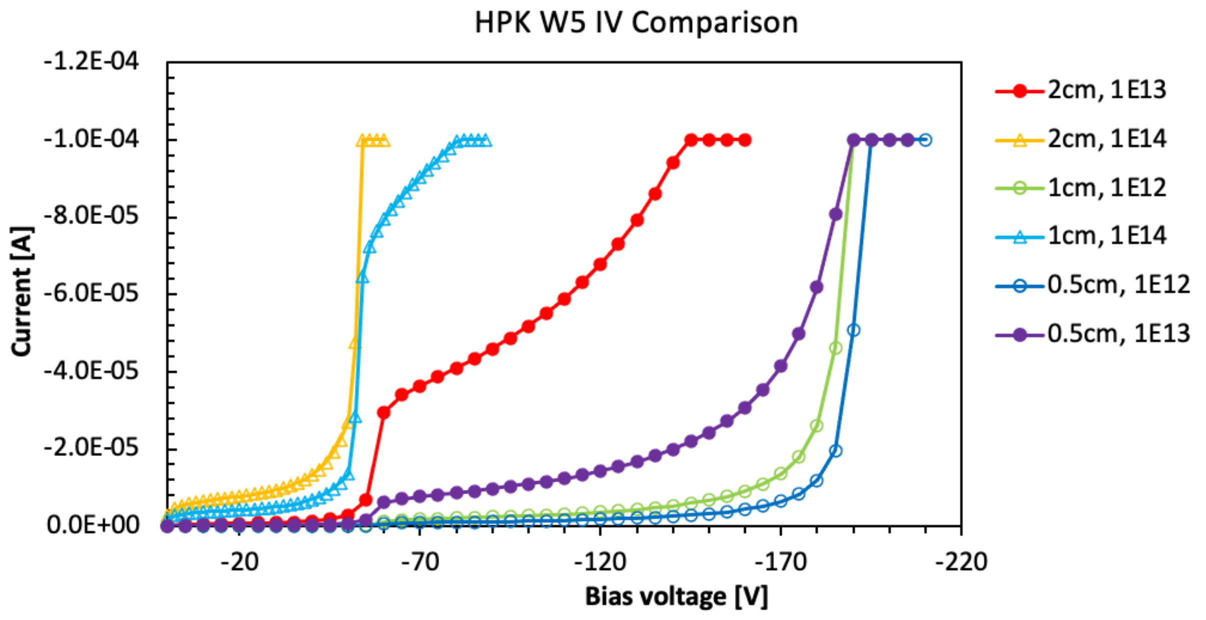
Irradiations planned

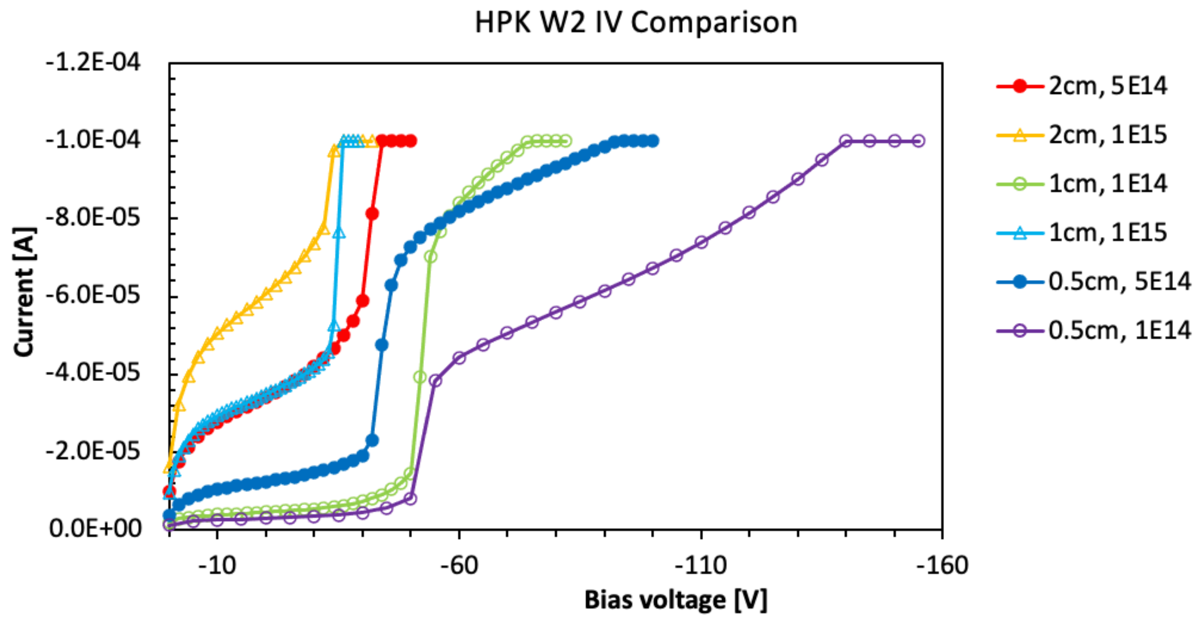
- Irradiation at IJS
  - 1 MeV neutrons
- Fluences
  - 1E12, 1E13, 1E14 Neq
- Plus higher fluence for general interest of irradiation on AC-LGADs
  - 5E14, 1E15 Neq
- **Received devices**
  - Started testing Strips

SCIPP HPK ID	Geometry	wafer	size	HPK IP layer doping	(pF/mm2)	thickness	lenght (mm)	pitch (um)	width (um)	Tested laser	Test IV	Ask for more? #	Fluence (J SI)
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					

Irradiated strips IV

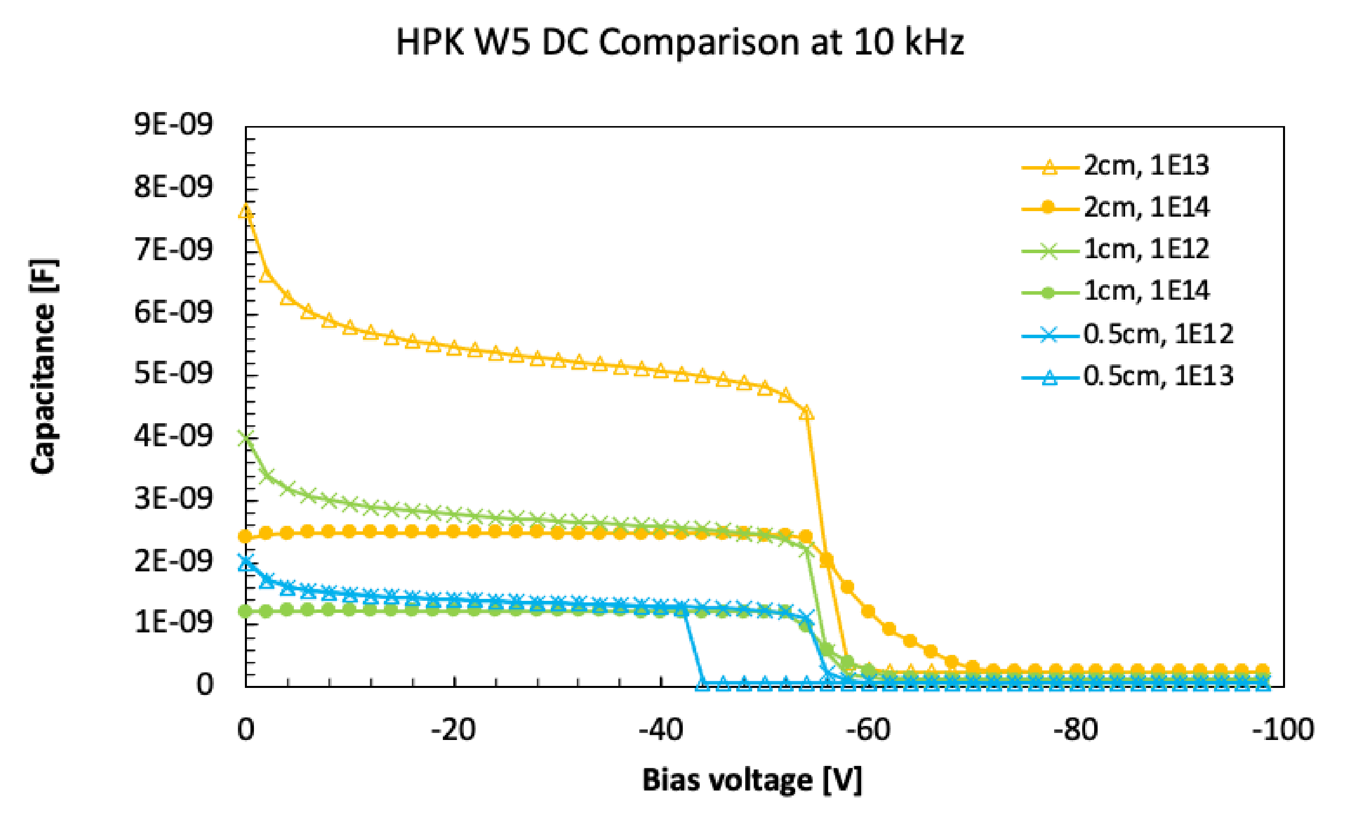
- All devices were annealed 80min at 60C to avoid rapid change in sensor behavior (similar to months at room temperature), this was standard during testing of HGTD sensors
  - After 80min the sensors behavior would change slowly if not stable
- Testing done at room temperature with probe station, current is higher for high irradiation devices and will require cold testing (need to set up the probe station)
  - Compliance is 100uA in these tests

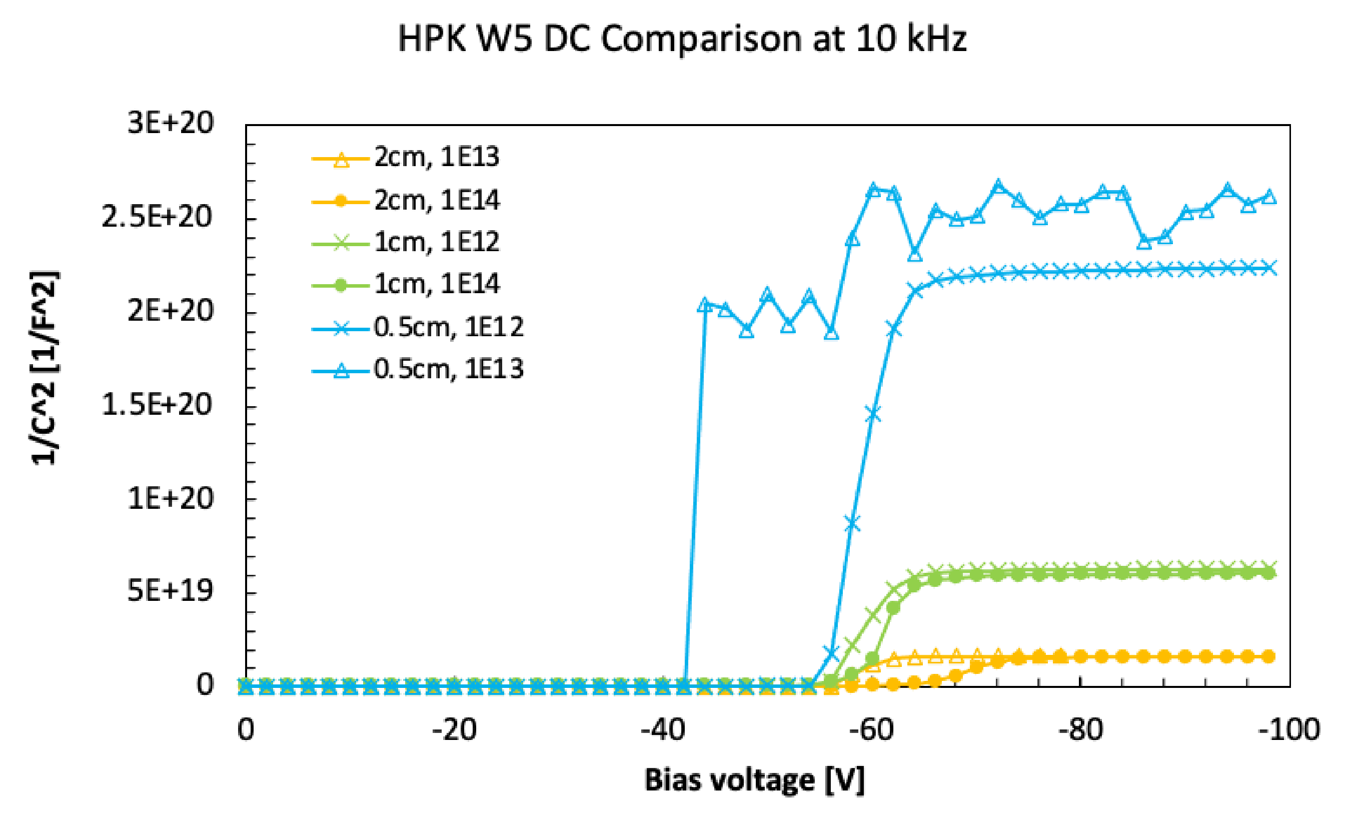




W5 irradiated strips CV

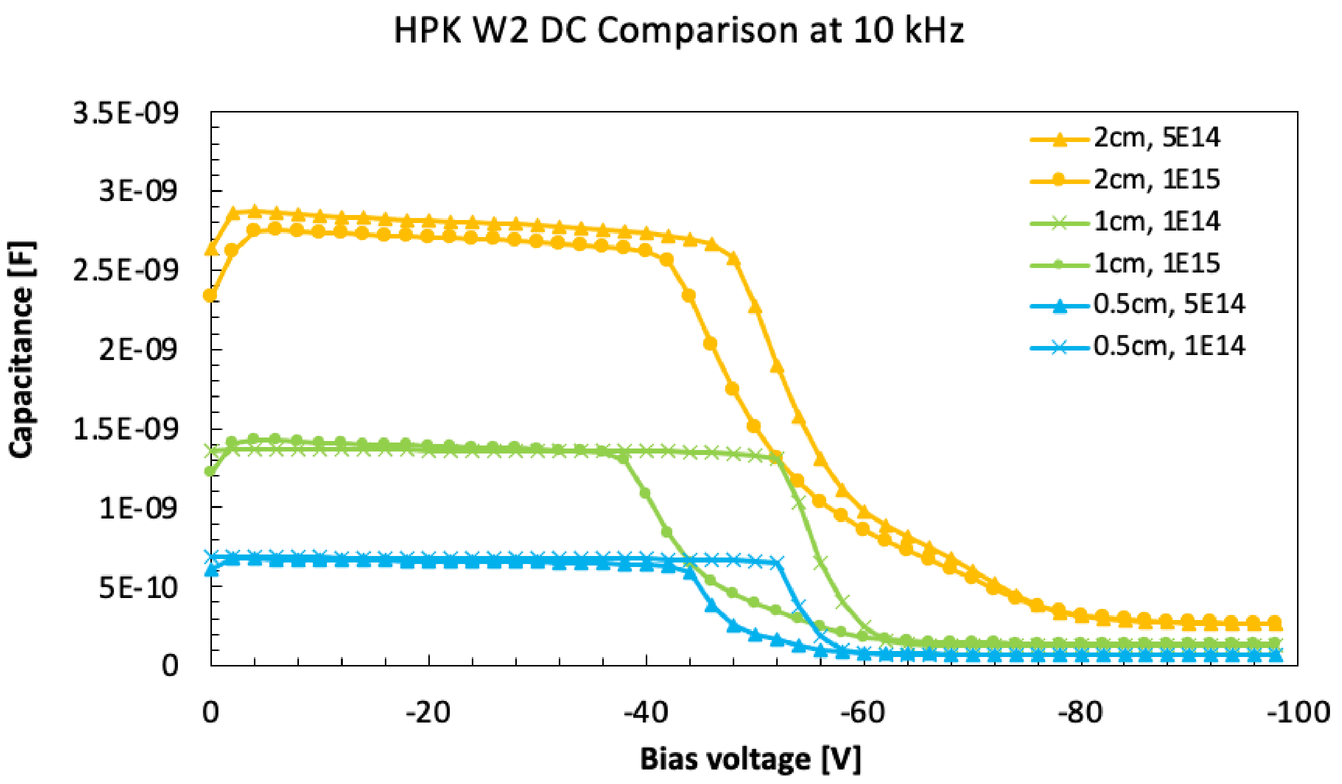
- CV on the N+ connector (full sensor), 10 KHz is usually OK for irradiated sensors
- Reduction of 'foot' as expected, but some strange behavior
  - Will test with laser to see if gain is proportional to it

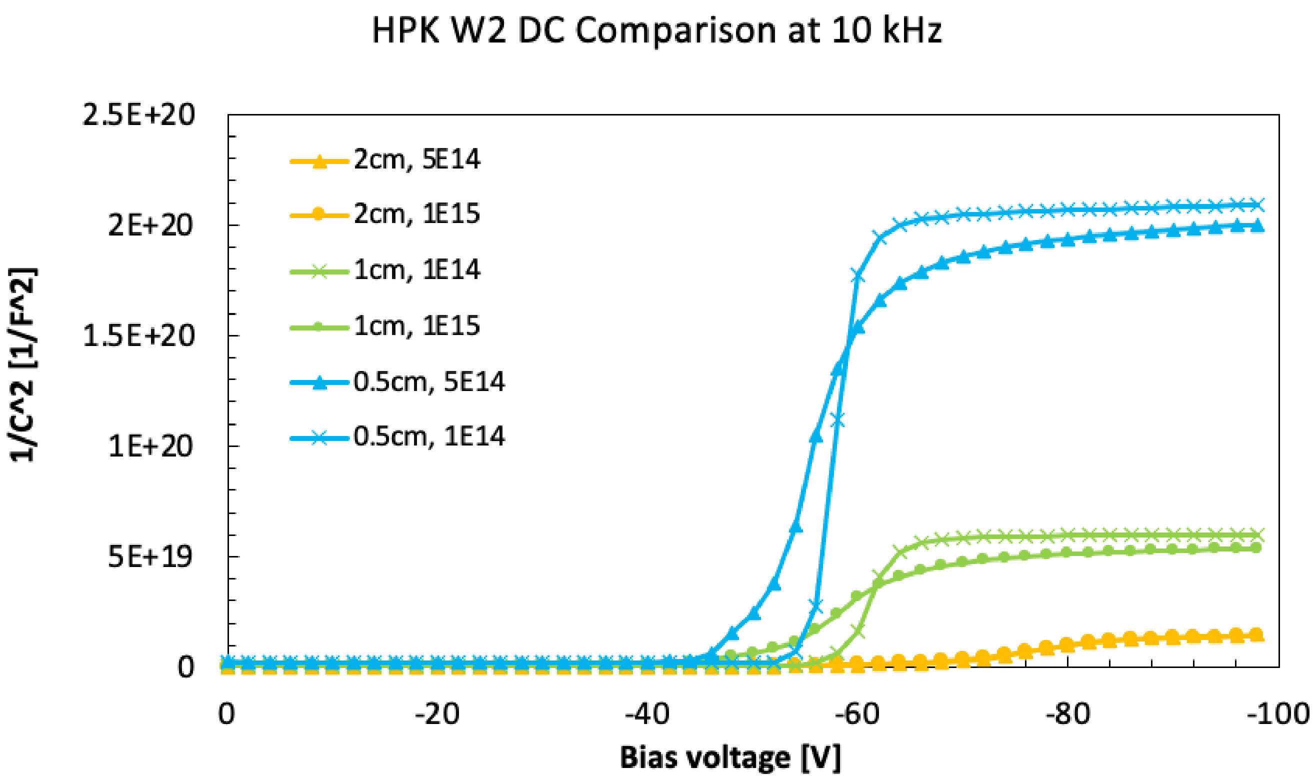




W2 irradiated strips CV

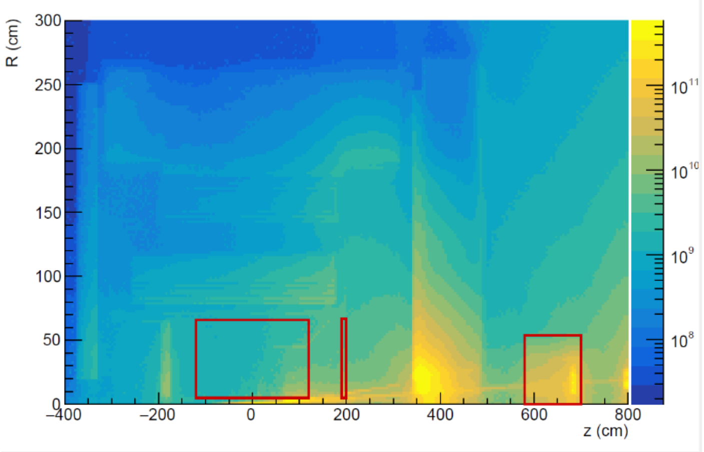
- CV on the N+ connector (full sensor), 10 KHz is usually OK for irradiated sensors
- Reduction of 'foot' as expected, for 1E15Neq quite some gain left

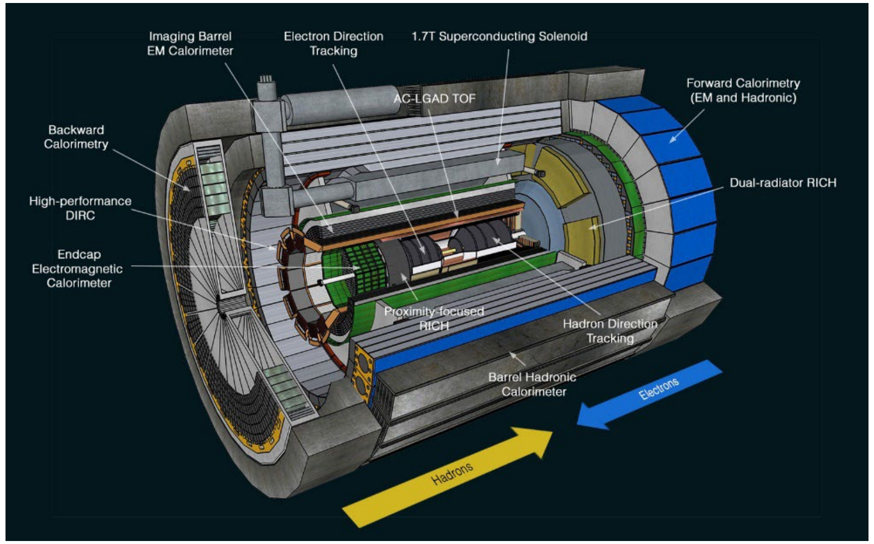




Conclusions

- **Received sensors from Triga reactor (neutrons)**
  - First IV/CV tests on strip sensors
  - Next: laser TCT tests to check homogeneity of response
- Then test pixel sensors as well

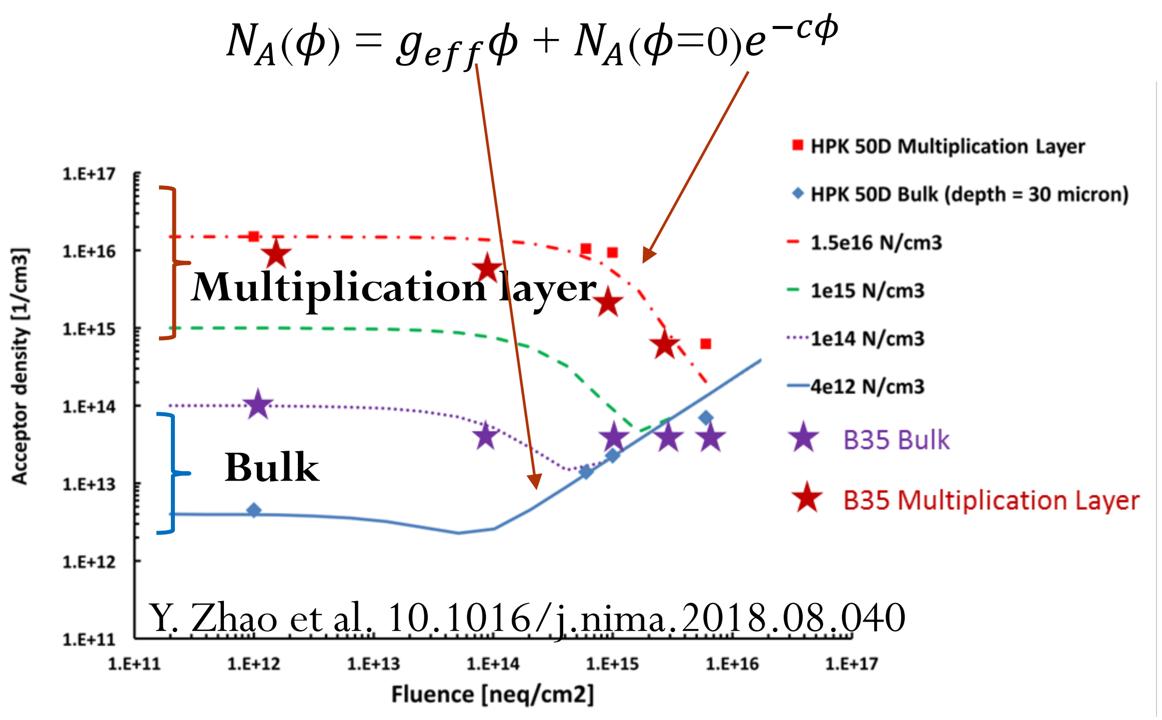


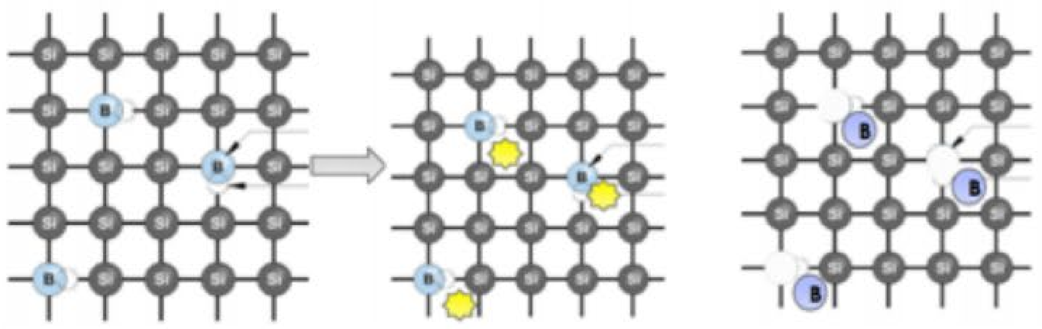


Backup

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**

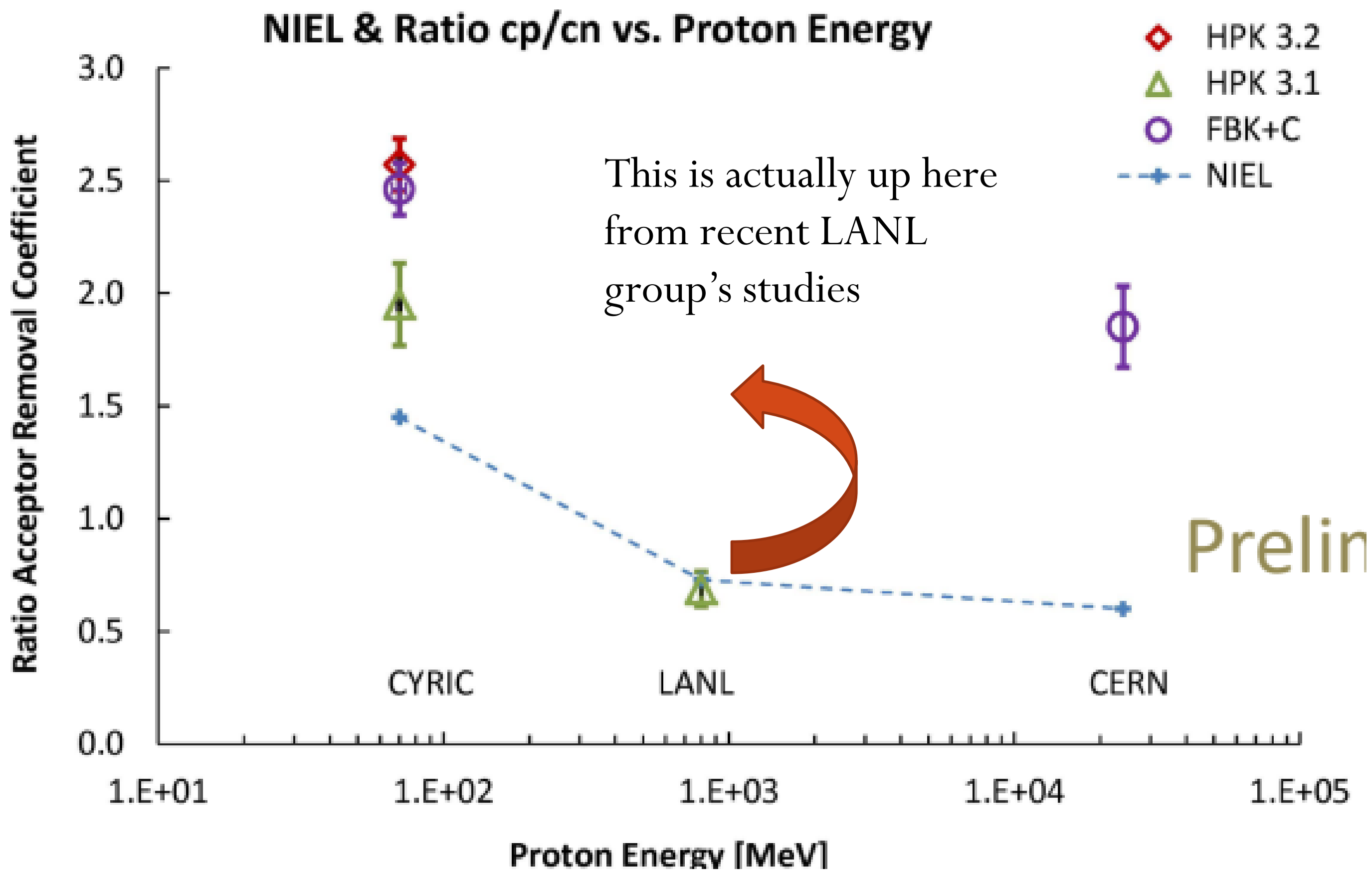




Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s → Si_s + B_i
B_i might interact with Oxigen, creating a donor state

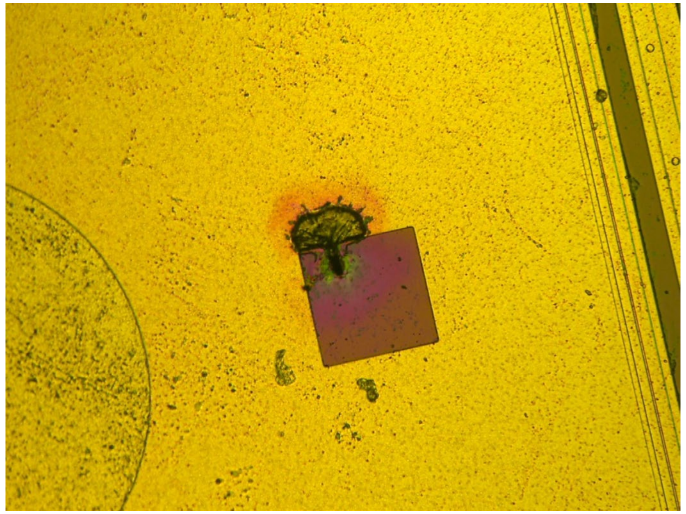
NIEL violation (old-ish data)

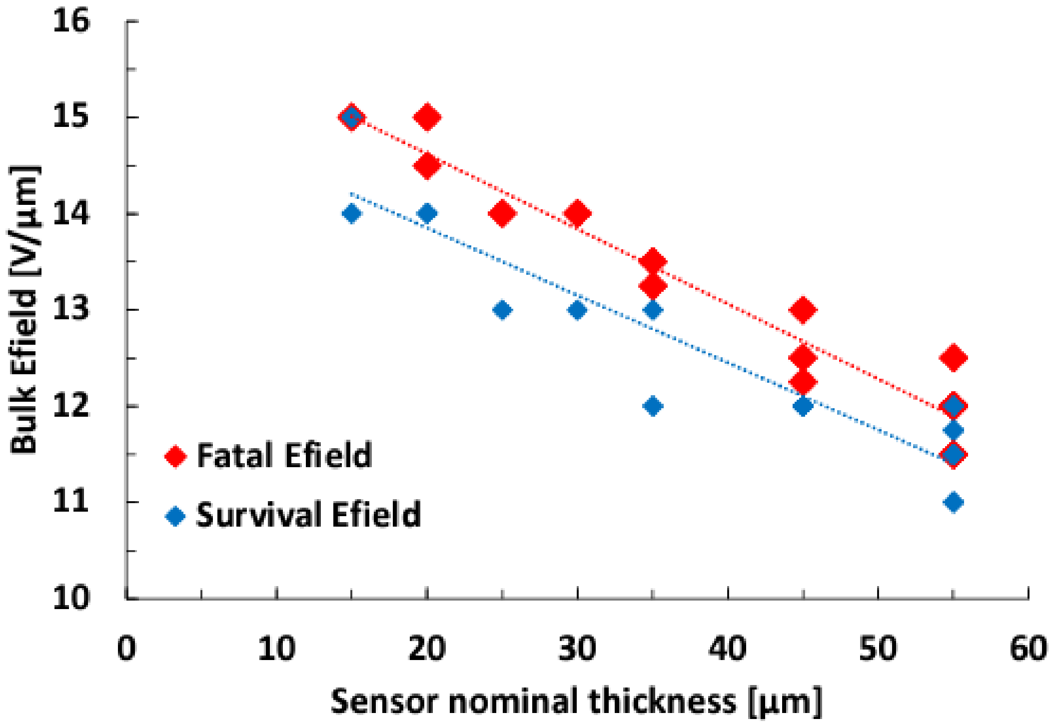
- Acceptor removal ratio cp/cn
  - Dependence on the proton energy seems to be sensor specific
  - Does not scale with NIEL, larger than NIEL factor. Damage can be > 2 than the expected NIEL fluence
- Need to take into account the energy distribution of the damaging particles in the fluence calculation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



Another issue: SEB

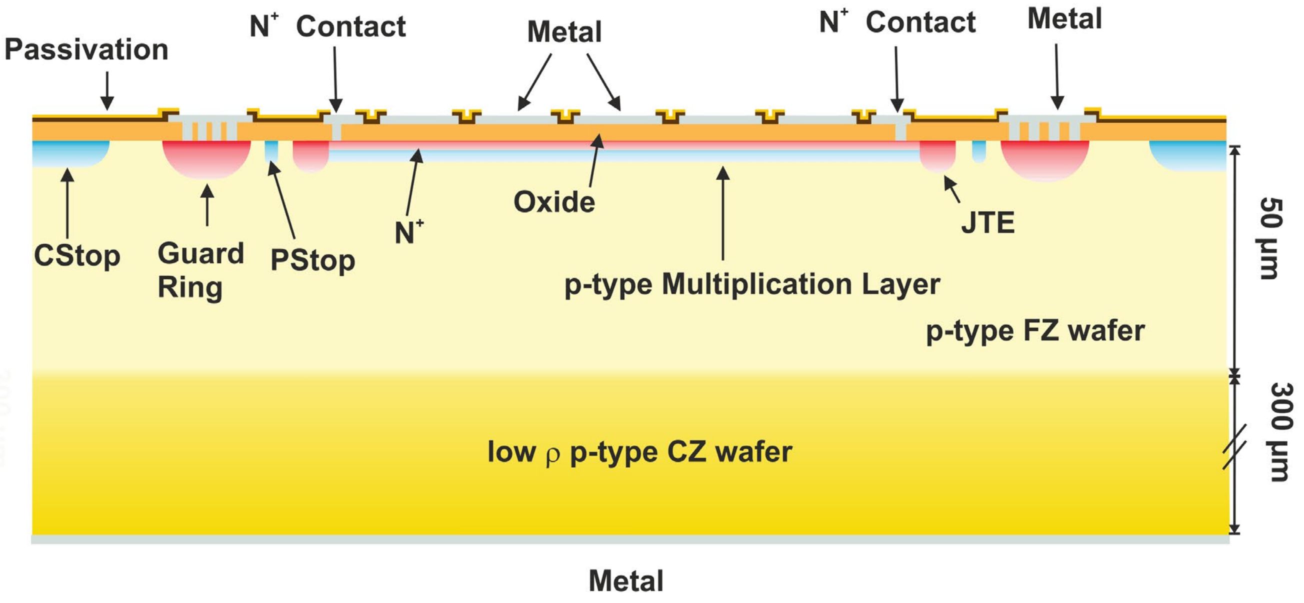
- Single Event Burnout can happen for highly irradiated devices
- A single highly ionizing particle under-depletes the device and causes a catastrophic breakdown
  - Device is non recoverable afterwards
- Thinner sensors seem to have a higher fatal Electric field
- See https://indico.cern.ch/event/1334364/contributions/5672087/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

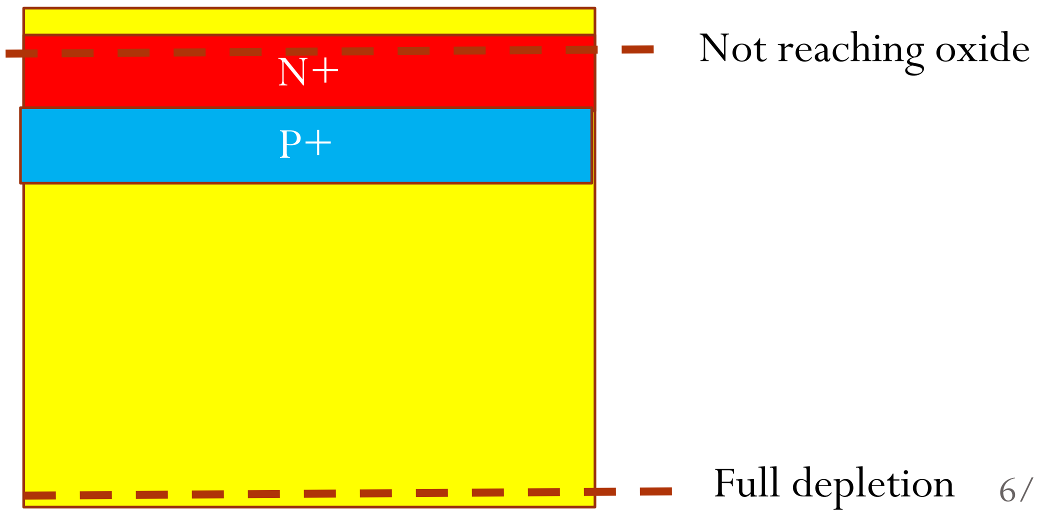




Effect of irradiation on AC-LGADs

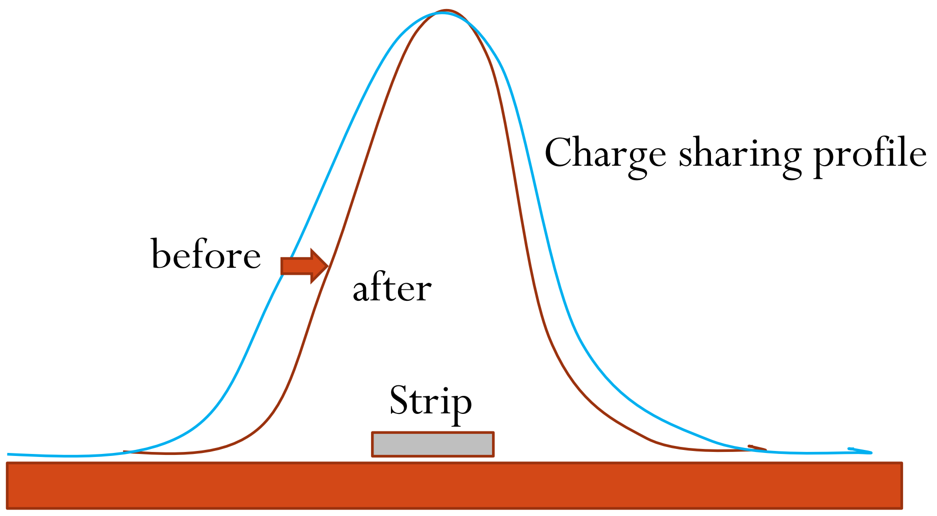
- The gain layer will have more or less the same behavior of standard LGAD devices
- The N+ can have some unexpected effects though
  - Normally is highly doped and conductive so it's not affected by radiation damage
  - We don't know well the effects of acceptor removal to N-type, might even be higher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

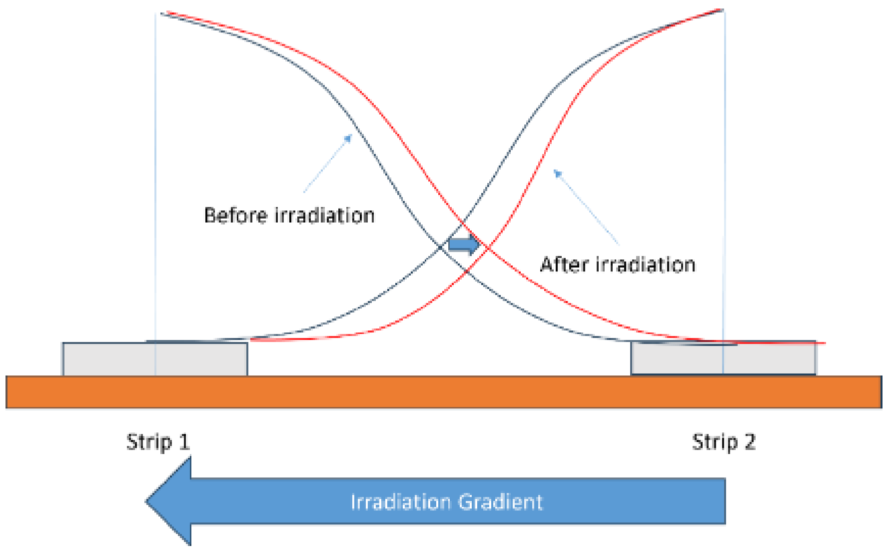




Effect of irradiation on AC-LGADs

- 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)