Radiation Hardness Challenges for Vertex Detectors in the Future

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VERTEX 2023
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Outline

I. The landscape: colliders on the research horizon, and the radiation environments foreseen

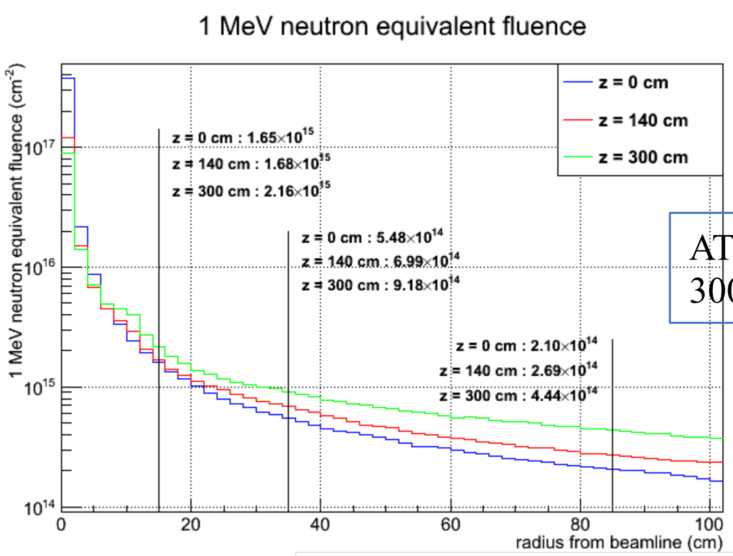
II. Some challenges

III. Nonlinear effects at the highest fluences

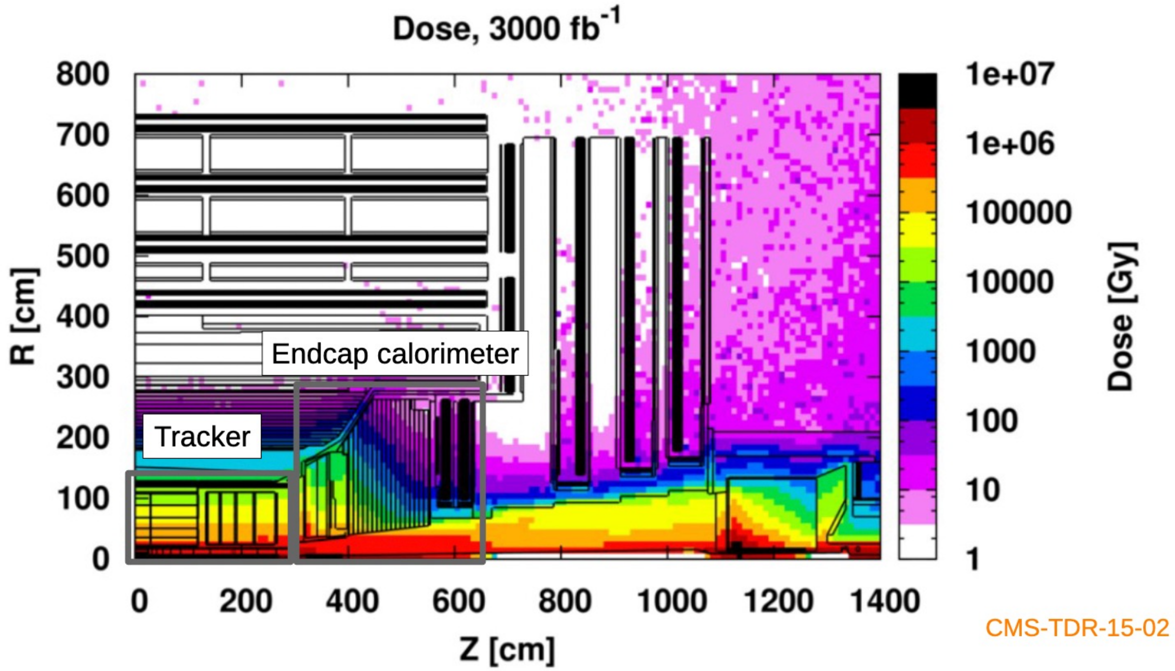
IV. Approaches and opportunities

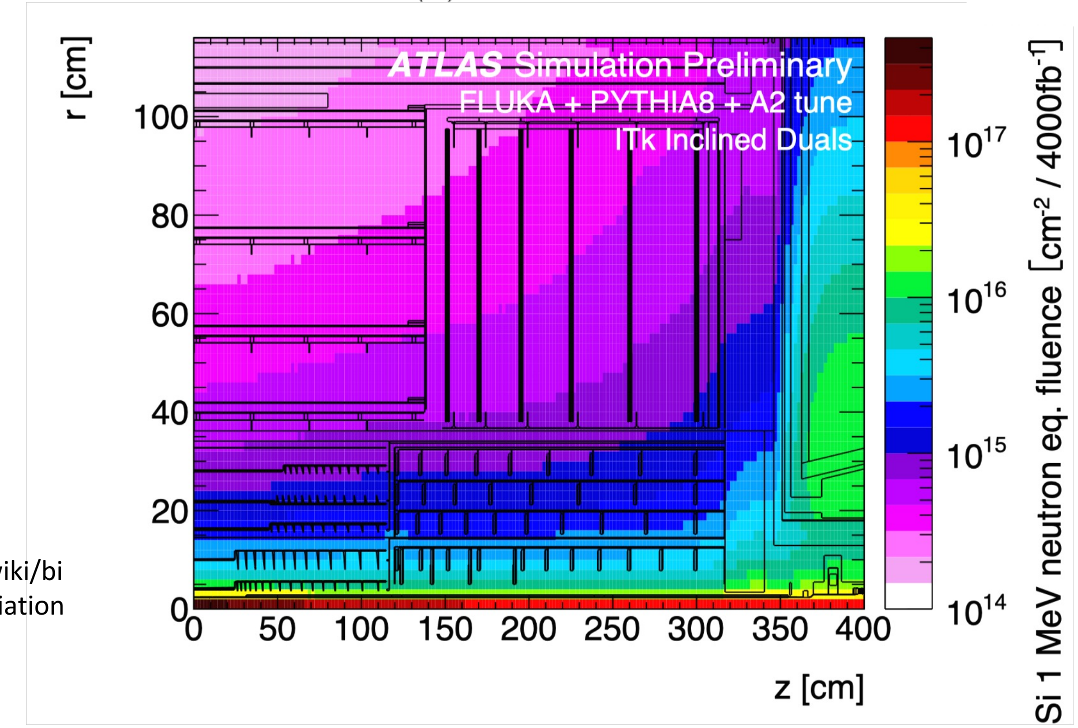
The landscape: colliders on the research horizon, and the radiation environments foreseen in them.

The landscape: radiation environments at future colliders



ATLAS ITk, 3000 fb^{-1}





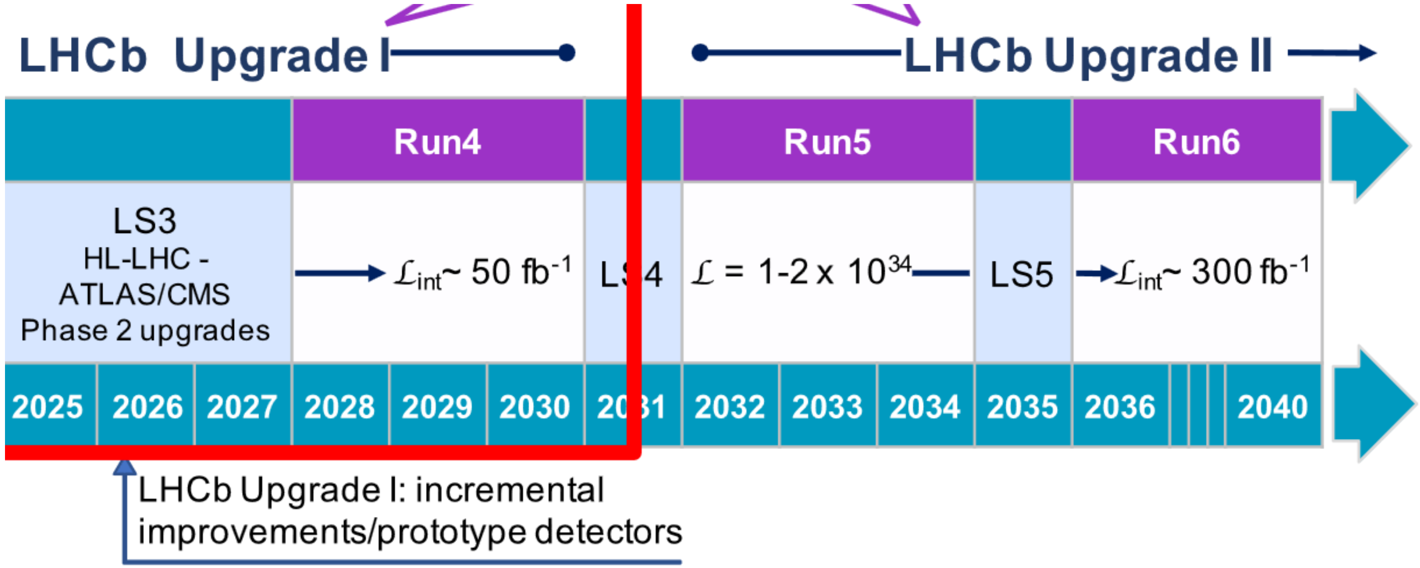
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/RadiationSimulationPublicResults

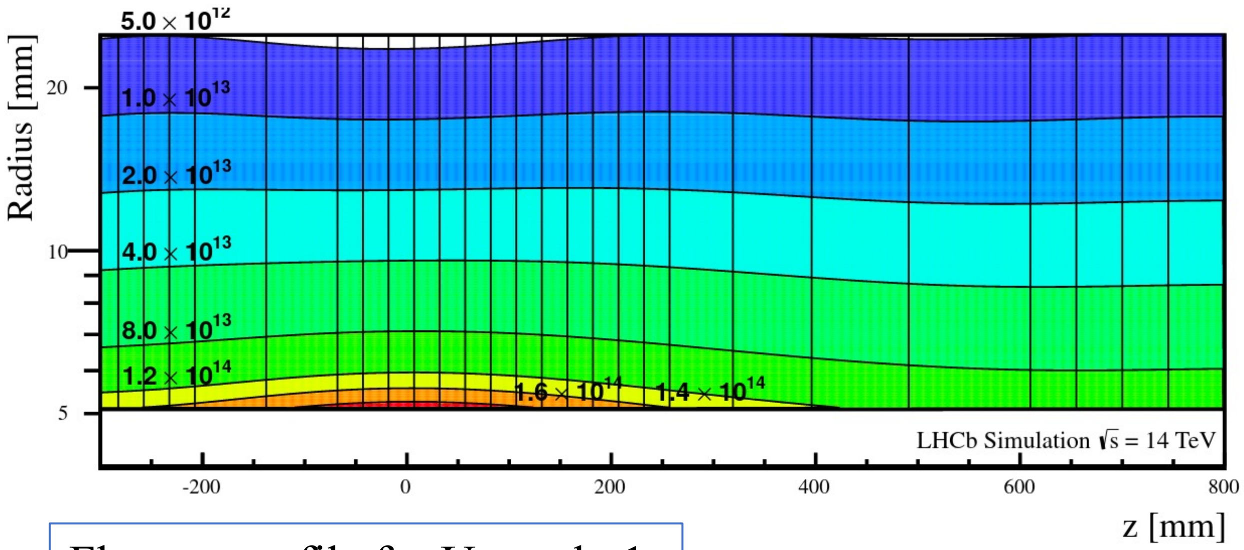
- **HL-LHC**, where the experiments anticipate integrated luminosities of
- 3 ab^{-1} for ATLAS and CMS
- 50 fb^{-1} for LHCb
- 5 fb^{-1} for ALICE

...absolute fluence and dose tolerances that were inconceivable only a few years ago are now appearing in ATLAS and CMS vertex detector specifications.

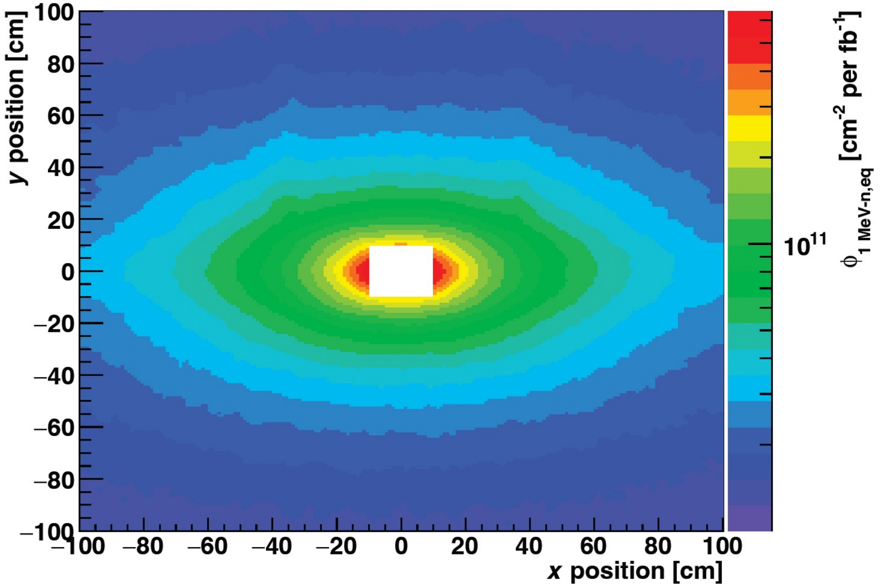
At **LHCb,** challenges from high fluence will be exacerbated by *non-uniform exposure*:

- Dose drops by a factor 6 between 5.1 and 12.5 mm. Non-uniform exposure leads to *challenges on the high voltage tolerance, guard-ring design, and technology to maintain full depletion within each sensor.*





Fluence profile for Upgrade-1.

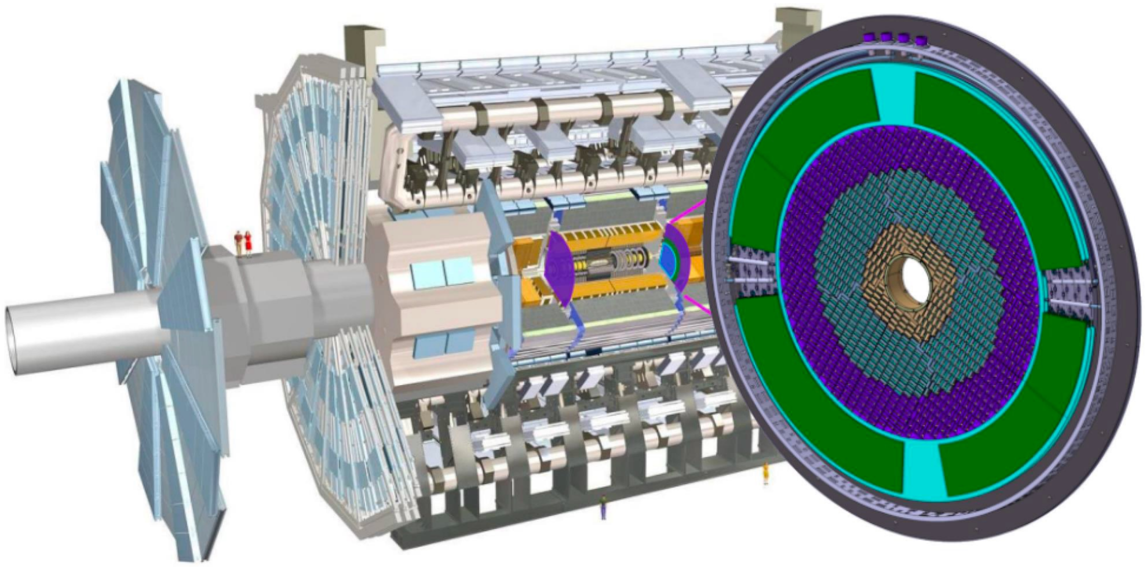


Fluence per fb^{-1} @ first layer of the Mighty Tracker. Max fluence at the center of the inner layer: 3E14 neq/cm^2. Multiply by safety factor 2.

In future experiments, vertexing requires simultaneous excellence in *position* and *timing*.

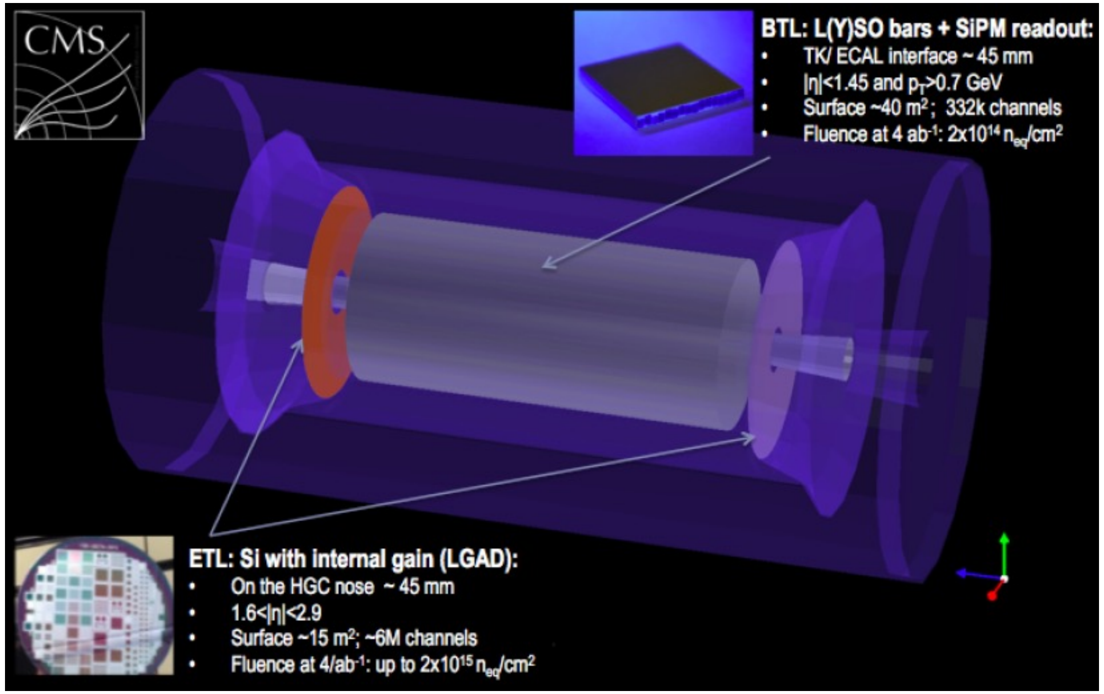
Radiation challenges to the **vertex** detectors originate mostly with particles from the primary interaction point.

Timing detectors, increasingly ***critical for identifying the right vertex by suppressing pile-up tracks***, will be located far from the primary vertex and thus are subject to radiation with a different origin, for example calorimeter backsplash.



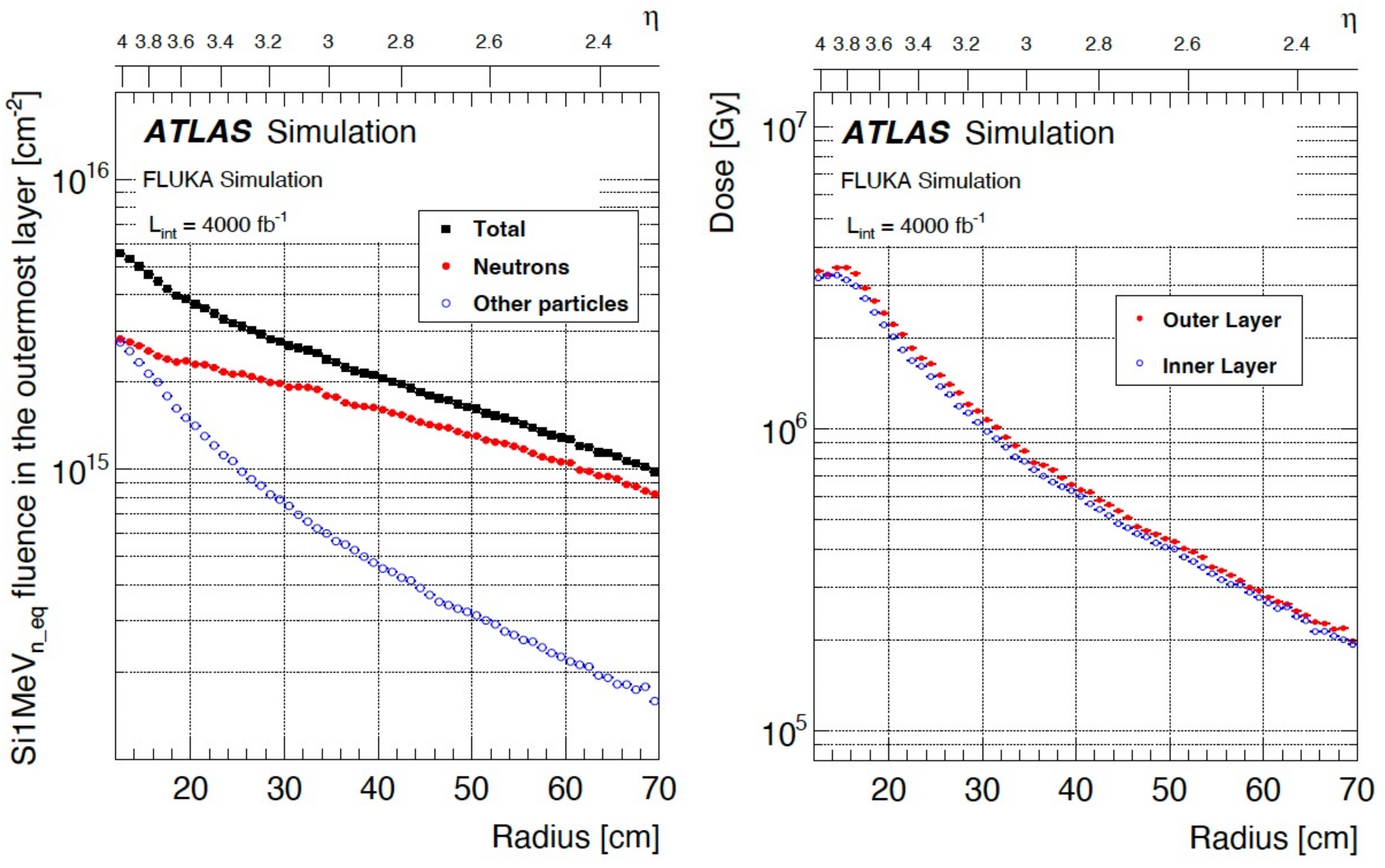
ATLAS HGTD, located ±3.5 m from the IP, radii 120 – 640 mm

CMS ETL: located ±3.0 m from the IP, radii 315 – 1200 mm



For the ATLAS High Granularity Timing Detector (HGTD),

- At radius 120 mm, expect 5.6×10^{15} neq cm^{-2} and total ionising dose (TID) ~3.3 MGy.
- Apply safety factor of 1.5 on both estimates. Apply second factor of 1.5 to the TID due to uncertainties in the behaviour of the electronics after irradiation, primarily for low-doses-rate effects.
- With safety factors: 8.3×10^{15} neq cm^{-2} and 7.5 MGy.
- Minimum charge of 4 fC needed for high efficiency signal. This can be achieved up to a radiation damage of 2.5×10^{15} neq cm^{-2} and 2.0 MGy with present design.



(a) Nominal Si1MeV$_{n_{eq}}$ fluence for HL-LHC. (b) Nominal ionising dose for HL-LHC.

Figure 2.14: Expected nominal Si1MeV$_{n_{eq}}$ fluence and ionising dose as functions of the radius in the outermost sensor layer of the HGTD for 4000 fb^{-1}, i.e. before including safety factors. The contribution from charged hadrons is included in 'Others'. These estimations used Fluka simulations using ATLAS Fluka geometry 3.1Q7 (from December 2019).

http://cds.cern.ch/record/2623663

For the CMS Barrel Timing Layer (BTL) and Endcap Timing Layer (ETL),

- BTL: TID 30 kGy and 1.9 $\times 10^{14}$ neq/cm^2
- ETL: TID 450 kGy and 1.6 $\times 10^{15}$ neq/cm^2 in the high-η part of the endcap
- Multiply by 1.5 safety factor to get: 3 x 10^{14} (barrel) and 3 x 10^{15} (endcap) neq/cm^2
- ASICs must be radiation tolerant and single event upset (SEU) compliant to the same fluence.

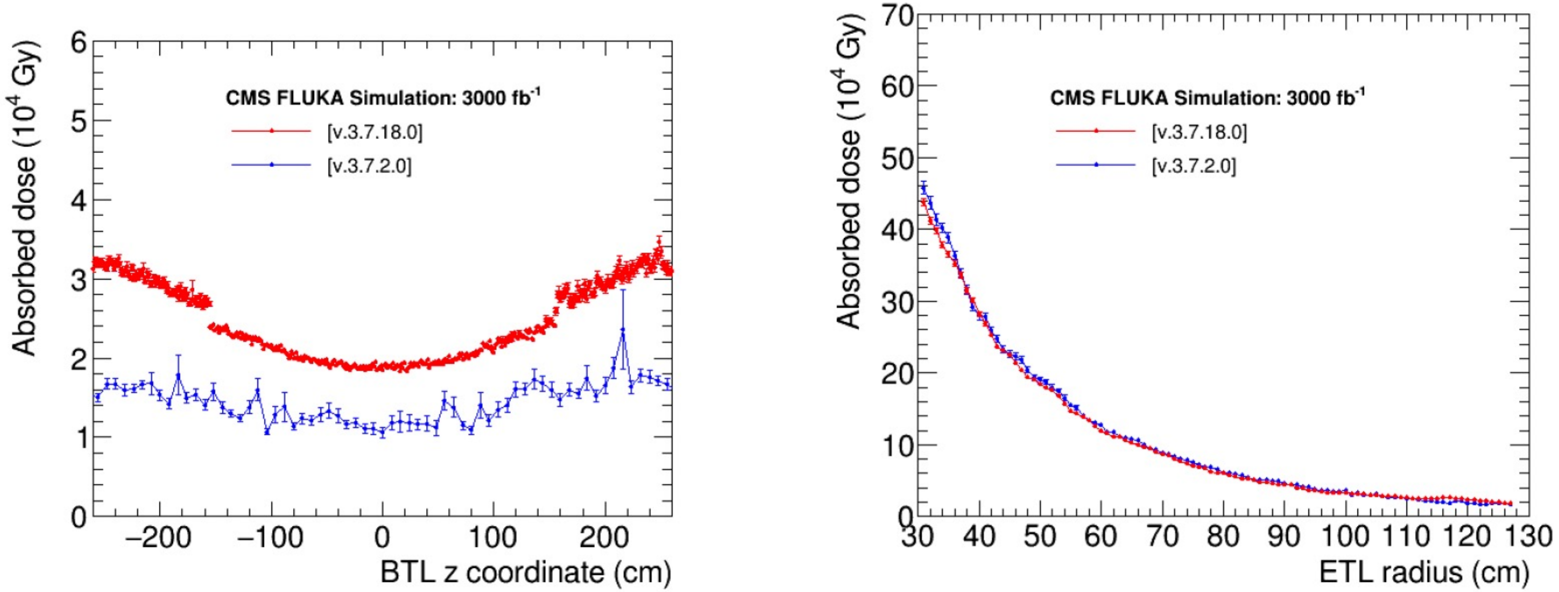


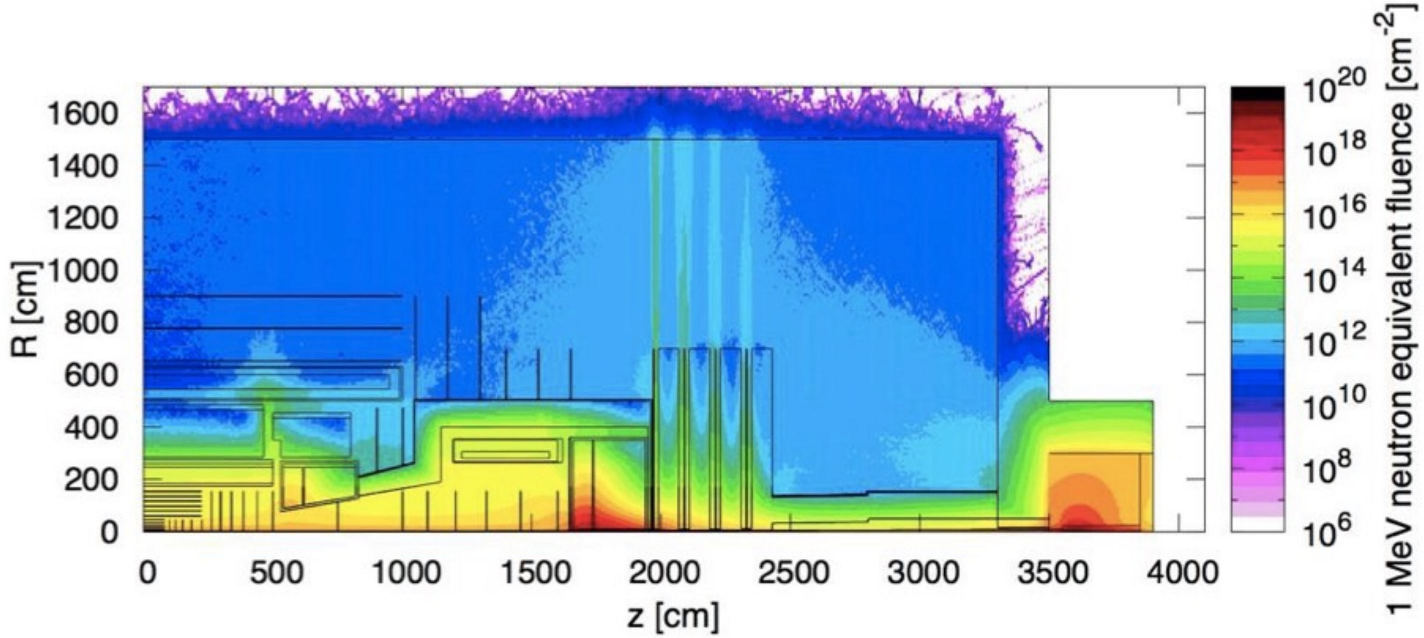
Figure A.3: Predicted doses in BTL (left) and ETL (right) using the updated FLUKA CMS simulation v.3.7.18.0 (red) and the preliminary geometry model of the FLUKA simulation run v.3.7.2.0 (blue).

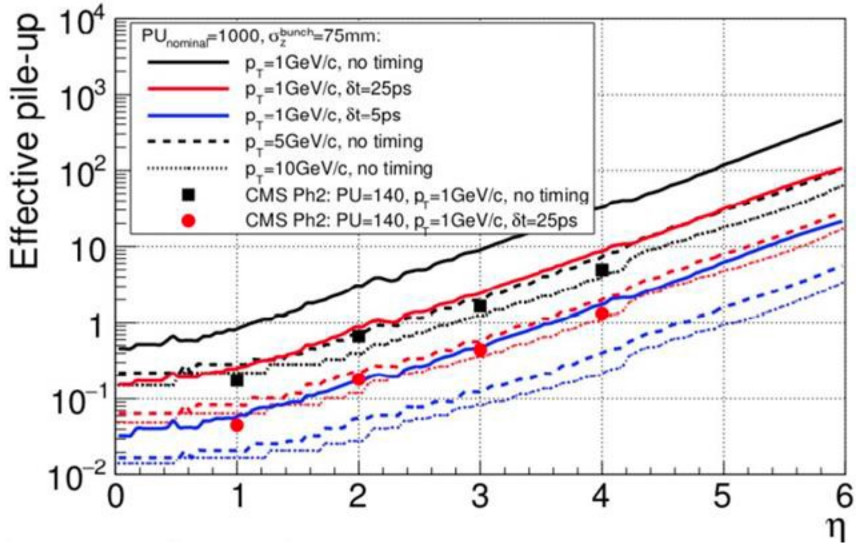
http://cds.cern.ch/record/2667167

Farther into the future,

➢ **FCC-hh**

- In the innermost tracking for integrated luminosity 30 ab^{-1} at 100 TeV,
  - 10^{18} n_{eq}/cm^2
  - 300 MGy TID
  - 10 GHz/cm^2 charged particles
- For the forward calorimeters
  - 5×10^{18} cm^{-2}
  - 5000 MGy
- Effective pile-up will put extreme pressure on timing detectors





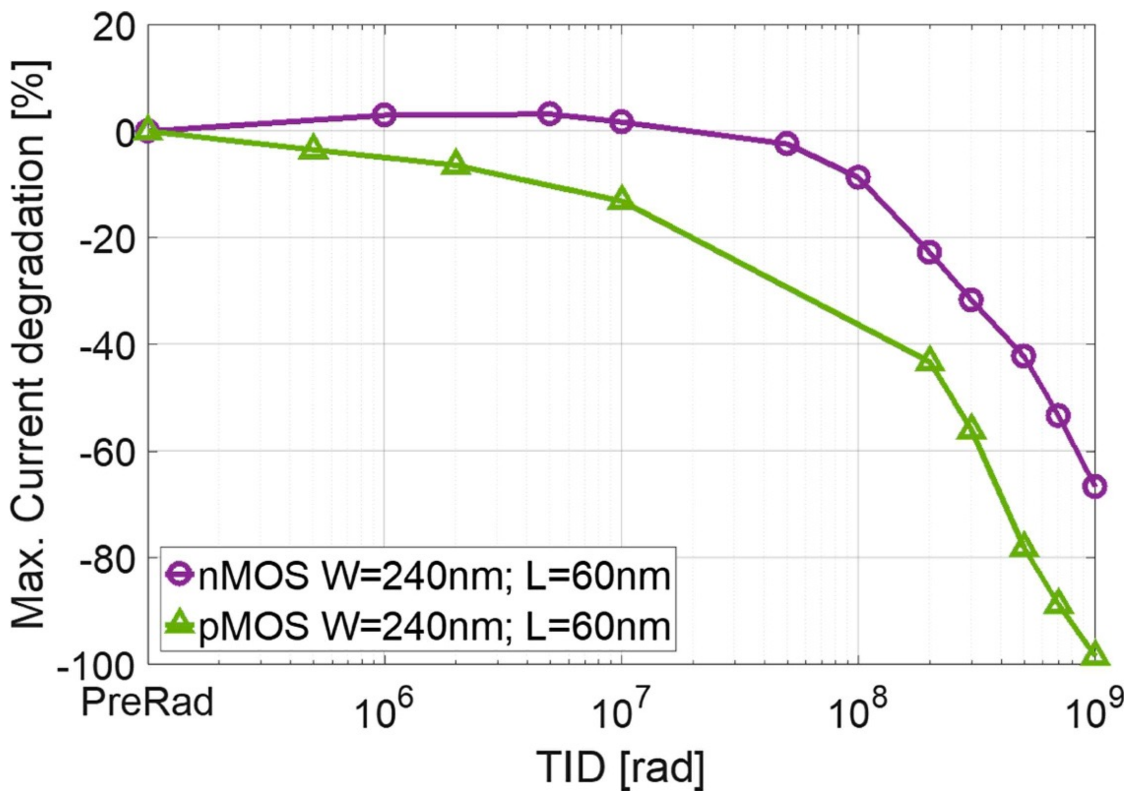
Effective pile-up is the number of vertices compatible with reconstructed tracks.

Here, effective pile-up = 1 means unambiguous primary vertex identification.

Some words from the FCC-hh CDR:
(https://fcc-cdr.web.cern.ch/#FCCHH)

- In CMOS 130 and 65 nm technologies, parasitic oxides used in the manufacturing processes are responsible for significant degradation. The 40 and 28 nm technologies' preliminary results show different phenomenology and slightly more promising radiation tolerance.

- It is unlikely that circuits designed with these technologies could survive the TID levels (100–5000 MGy) expected in the inner tracker layers and the forward calorimeters of FCC detectors.



- TID has traditionally limited the radiation tolerance of CMOS ASICs, however these technologies have not been tested for displacement damage at > 5×10^{17} neq/cm^2 and this might lead to additional failure mechanisms.

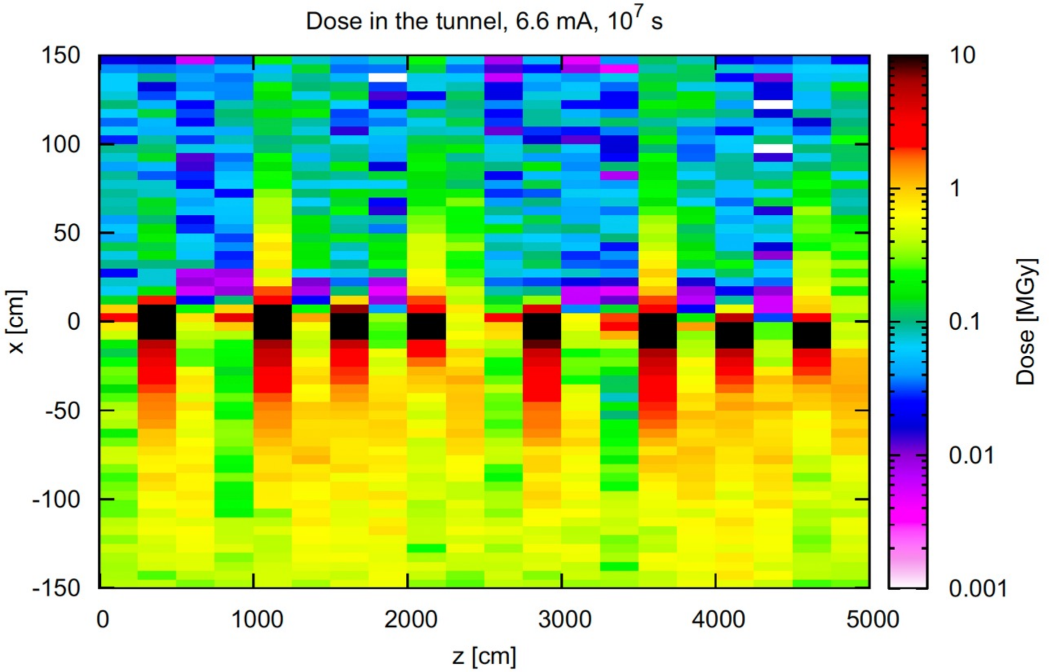
- CMOS technologies have been shifted from planar to bulk FINFETs starting from a nominal gate length of about 22 nm and have now reached the 7 nm pattern size. The literature* shows that TID tolerance has decreased with this miniaturisation due to radiation-induced leakage currents in the neck region of these devices, a characteristic that cannot be addressed by any design technique. This evidence shows that the construction of reliable electronics systems for FCC detectors cannot simply rely on the improved radiation performance which accompanies miniaturisation.

**M.P. King et al., IEEE Trans. Nucl. Sci. 64, 285 (2017)*

Vertex and timing detectors at future *lepton* machines will confront extremes of total ionizing dose and nonzero high energy hadron (HEH) effects.

➢ For FCC-ee

(https://fcc-cdr.web.cern.ch/#FCCEE)

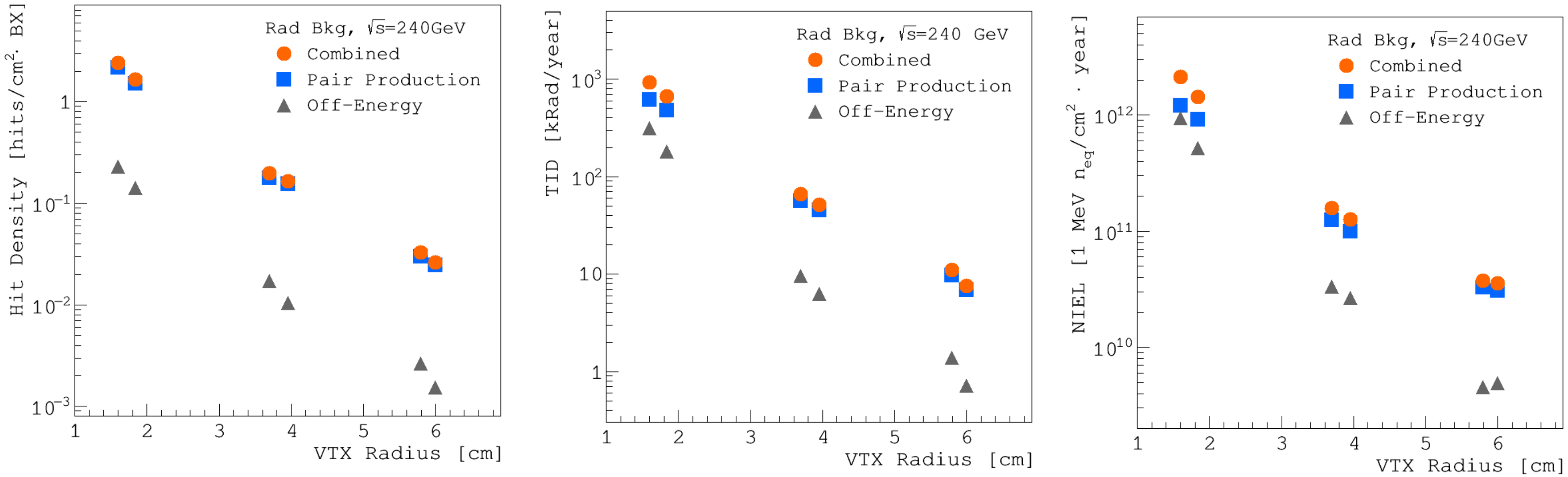


Dose distribution in an FCC-ee arc half-cell, normalized for 10^7 seconds of data and 6.6 mA beam current.

- Single event effects (SEE) are proportional to the high energy hadron fluence (HEH, i.e. hadrons with energies >20 MeV, produced by ionisation by a single particle).

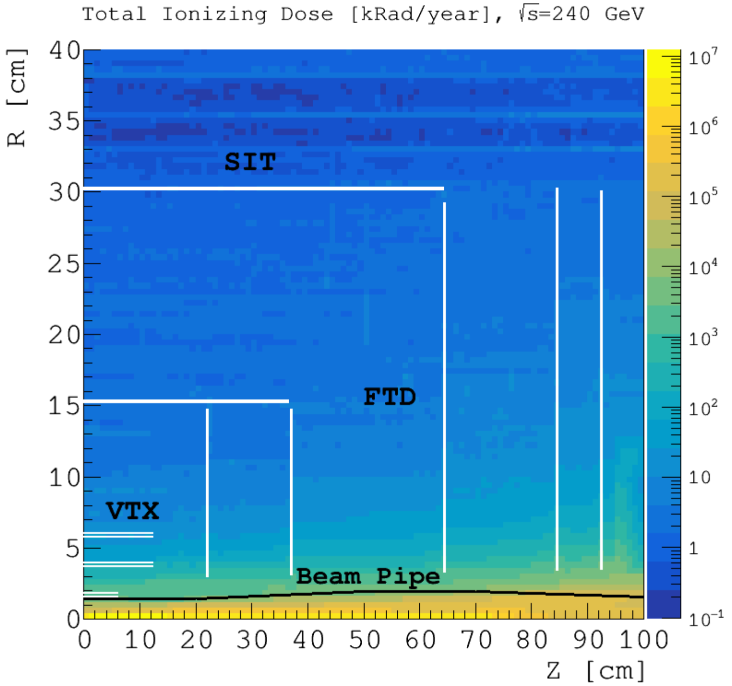
- SEE defined by their probability to occur. The effect depends on the device, the intensity and the kind of radiation field.

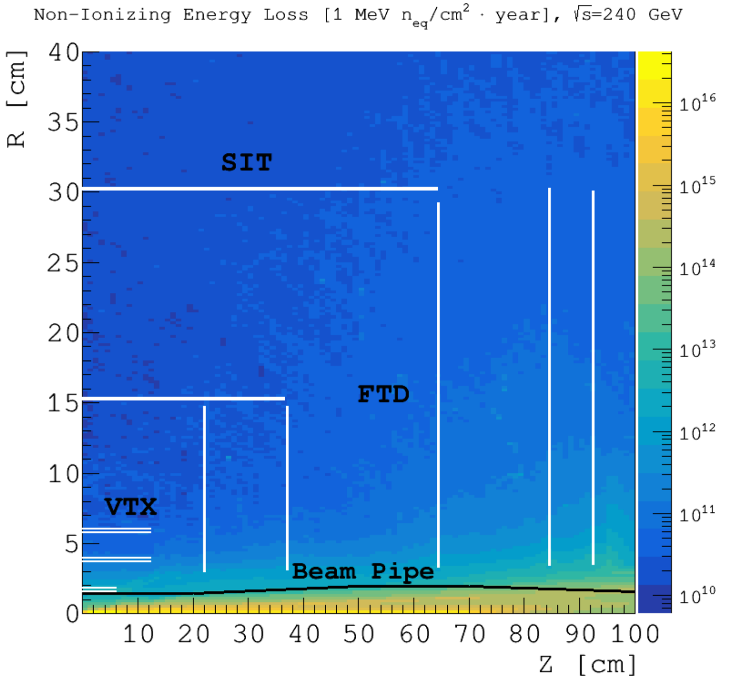
- For **CEPC**, when operating at the Z-pole energy, for the first vertex layer,
- maximum *annual* TID estimated at 3.4 MRad
- annual non-ionizing energy loss (NIEL) with safety factor 10 is ~6.2 x10^{12} 1-MeV n_{eq} cm^{-2}



Hit density, TID, and NIEL at different vertex detector layers due to pair production, off-energy beam particles and the two combined for the machine operation at √s = 240 GeV.

(Conceptual Design Report, https://arxiv.org/ftp/arxiv/papers/1811/1811.10545.pdf)





➢ **CLIC** – From the CDR, http://project-clic-cdr.web.cern.ch/ :

- Incoherent e^-e^+ pairs - dominant source for the total ionising dose.
- NIEL damage in the barrel - dominated by $\gamma\gamma \rightarrow$ hadrons.
- NIEL damage in the forward region, both $\gamma\gamma \rightarrow$ hadrons and incoherent e^-e^+ pairs contribute.
- Quoted numbers do not include safety factors for the simulation uncertainties.
- Assuming an overall safety factor of *two* for the $\gamma\gamma \rightarrow$ hadrons background and *five* for the incoherent e^-e^+ pairs, predict maximum flux in the inner vertex layers of ~4 x 10^{10} neq/cm^2/yr and up to 200 Gy/yr.

Table 4.2: Expected radiation damage (NIEL and TID) from incoherent pairs and $\gamma\gamma \rightarrow$ hadrons for the barrel pixel sensors (VXB 1–6) and for the lower end of the endcap pixel disks (VXEC 1–6) of the CLIC_ILD detector model. The numbers are quoted without safety factors for simulation uncertainties.

	Radius [mm]	Pairs NIEL [$10^9 n_{eq}/cm^2/yr$]	Hadr. NIEL [$10^9 n_{eq}/cm^2/yr$]	Pairs TID [Gy/yr]	Hadr. TID [Gy/yr]
VXB 1	31.0	3.87	11.51	39.43	4.57
VXB 2	33.0	2.88	8.57	27.83	4.01
VXB 3/4	44.0	0.99	4.60	8.01	2.46
VXB 5/6	58.0	0.45	2.92	3.30	1.66
VXEC 1/2	33.6	6.17	5.64	27.99	3.10
VXEC 3/4	33.6	6.72	5.79	29.25	2.96
VXEC 5/6	33.6	7.83	6.14	34.12	3.13

- Radiation simulations at the **ILC** show that the worst conditions are actually at the forward calorimeters.

However limiting our focus to the vertex detectors:

- beamstrahlung-induced background at the innermost layer leads to 1 kGy and 10^{11} neq/cm^2/yr. Components are disrupted primary beam, brem photons, e+e- pairs from beam interactions, radiative Bhabhas, and $\gamma\gamma \rightarrow$ hadrons. or muons.
- Assumes that neutrons backscattered from a beamdump are shielded.
- From the ILC TDR:

Sub-detector	Units	Layer	500 GeV	1000 GeV
VTX-DL	hits/cm^2/BX	1	6.320 ± 1.763	11.774 ± 0.992
		2	4.009 ± 1.176	7.479 ± 0.747
		3	0.250 ± 0.109	0.431 ± 0.128
		4	0.212 ± 0.094	0.360 ± 0.108
		5	0.048 ± 0.031	0.091 ± 0.044
		6	0.041 ± 0.026	0.082 ± 0.042

https://linearcollider.org/technical-design-report/

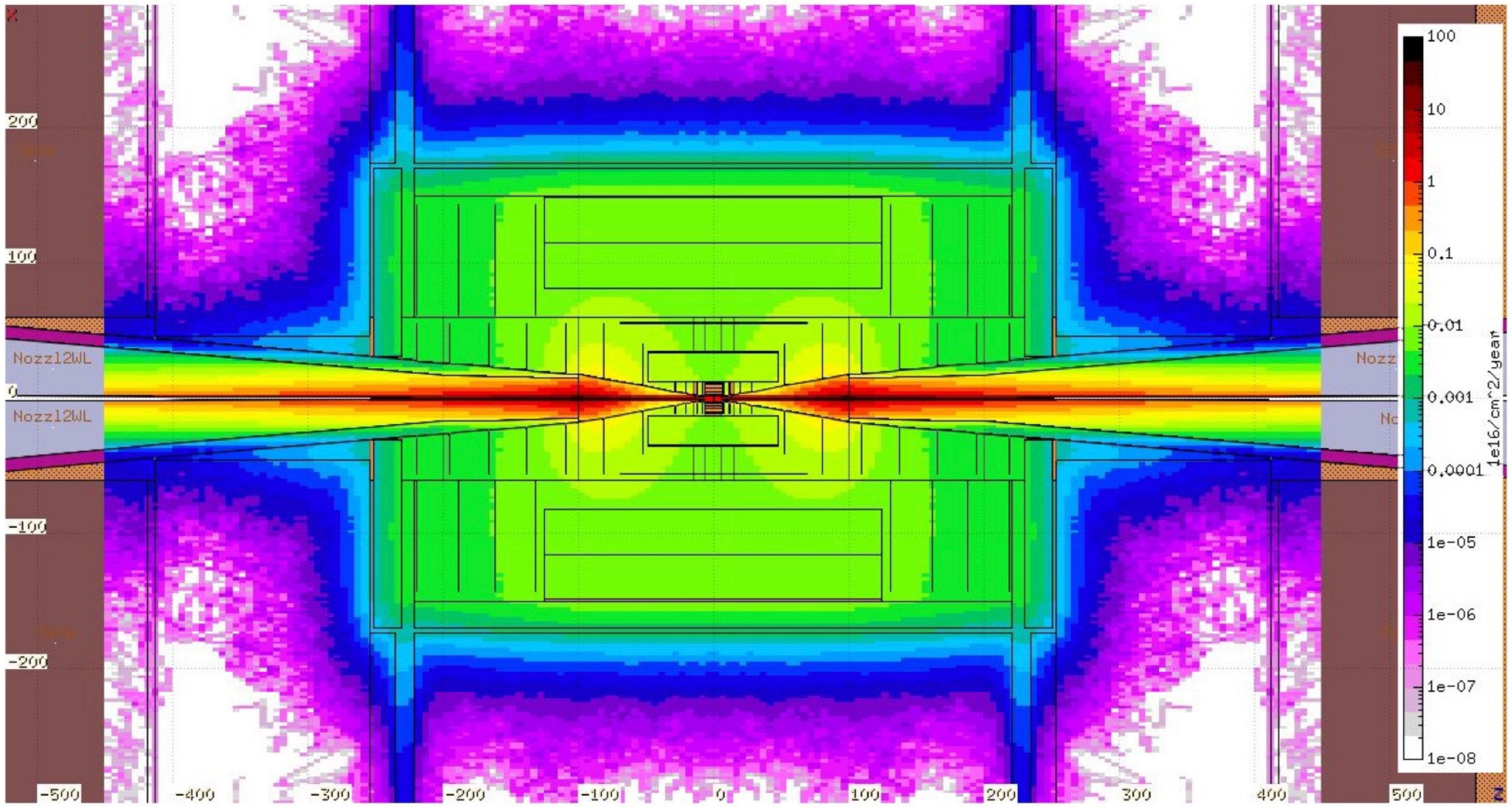
➢ Muon collider

Radiation levels at 3 TeV comparable to HL-LHC.

Expect (FLUKA simulation):

- $\sim 10^{14}$-10^{15}/cm^2/year in the tracker
- $\sim 10^{14}$/cm^2/year in the ECAL

1-MeV-neq fluence for one year of operation (200 days)



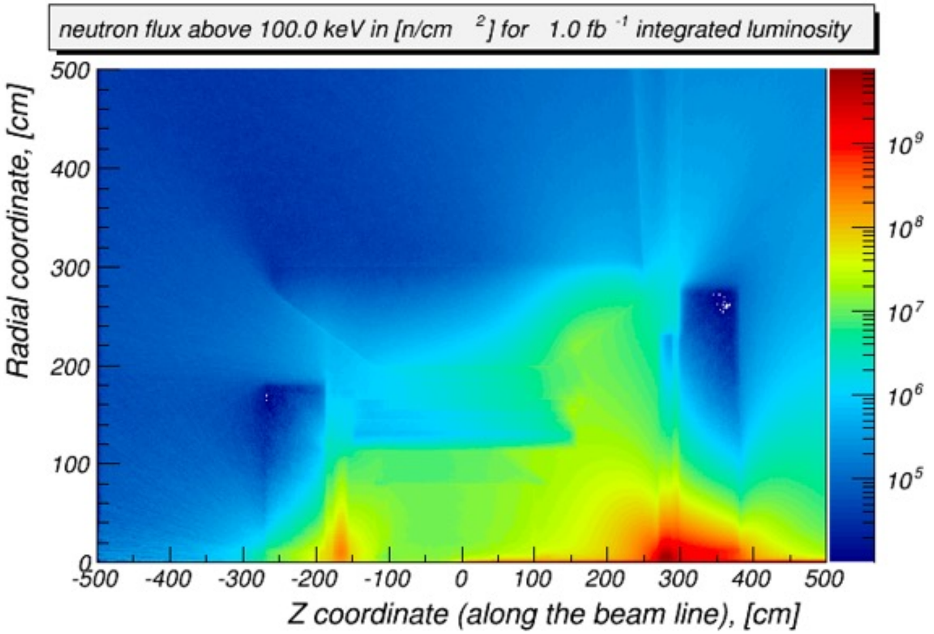
Expected (FLUKA simulation) to be approximately: $\sim 10^{14\text{-}15}$/cm^2/y in the tracker
$\sim 10^{14}$/cm^2/y in the ECAL

S. Jindiari, VCI 2022

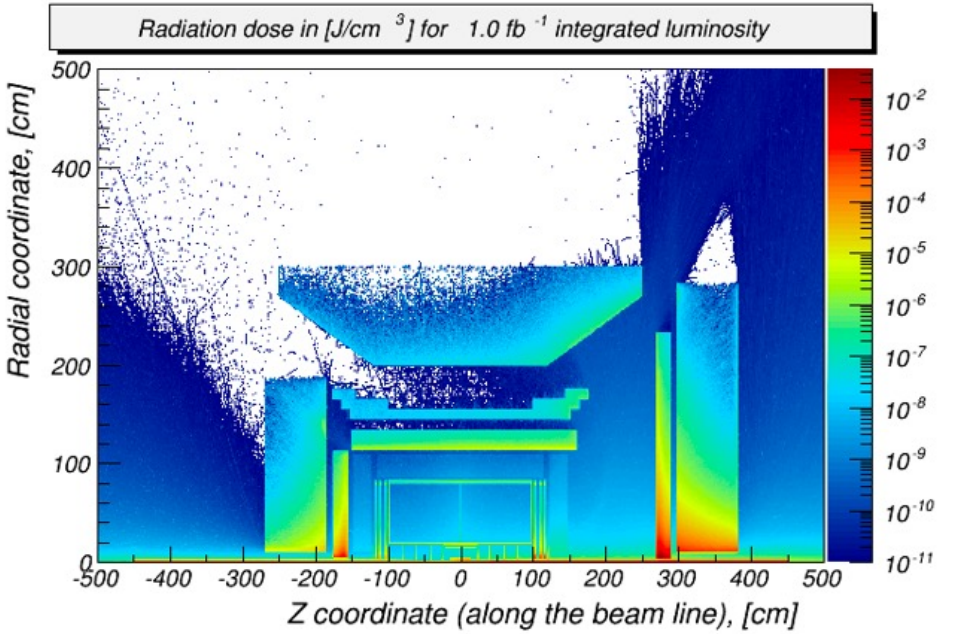
➢ EIC

Near-beamline regions' radiation has been simulated. At the top luminosity of 10^{34} $cm^{-2}s^{-1}$,

- Calorimeters in the backward arm show ~2.5 kRad/year max ionizing dose.
- Vertex tracker and the forward-backward calorimeters receive > 10^{10} neutrons/cm^2/year.
- Target radiation tolerance ~10^{15} neq/cm^2.



Neutron flux from the e+p collisions at $\sqrt{s_{ep}}$ = 140 GeV studied using the BeAST detector concept with the assumed location in the RHIC, located/placed in the RHIC IP6 experimental hall, which also applies to the reference EIC detector.



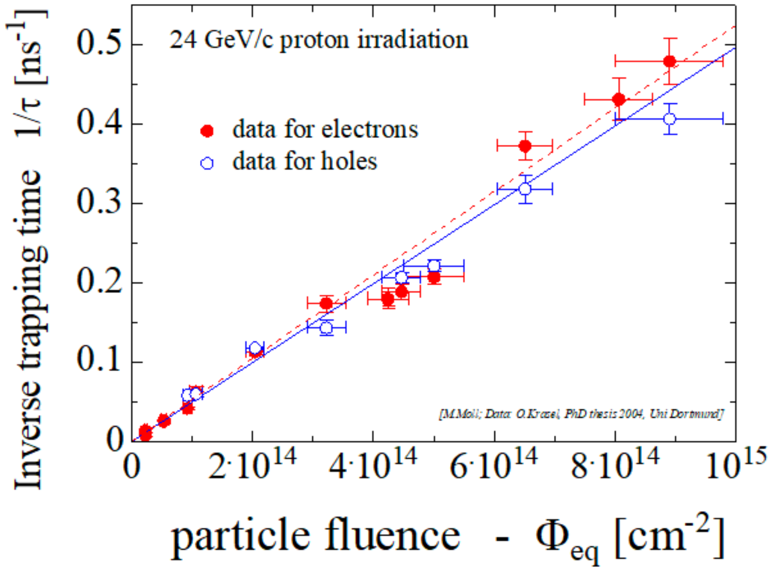
Ionizing radiation energy deposition from e+p collisions at $\sqrt{s_{ep}}$ = 140 GeV studied using the BeAST detector concept, which also applies to the reference EIC detector.

- Bunch crossing rate will be ≤ 10 ns, making fast timing detectors essential.

Some challenges

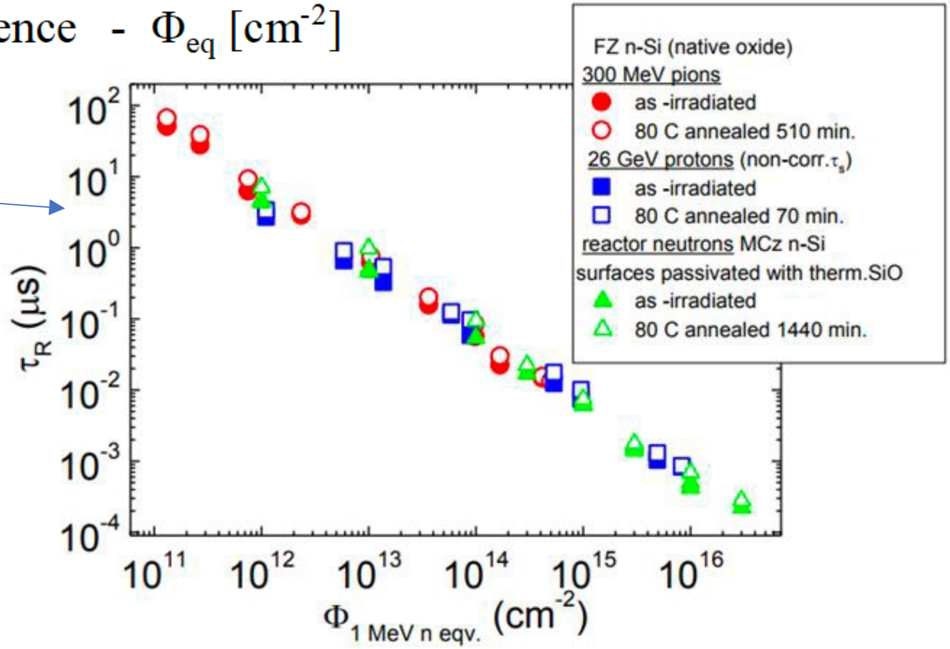
The detectors (vertex, timing, 4D) in the radiation environment of the experiment must be able to maintain:

- charge collection despite trapping.



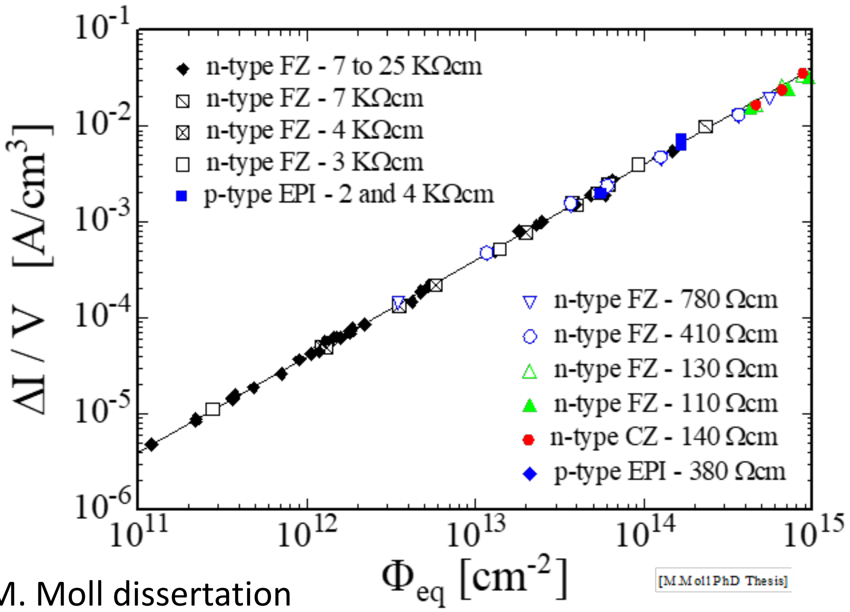
M. Moll using data from O. Krasel dissertation 2004

- adequate depletion volume. In under-depleted zones, the recombination time dives with fluence:



E. Gaubas et al., 27th RD50 Workshop

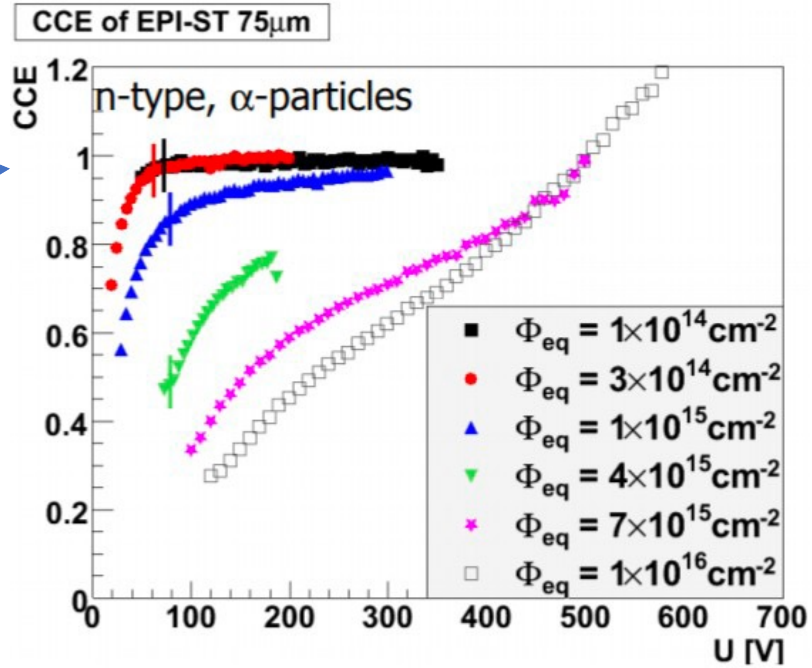
- S/N despite leakage current



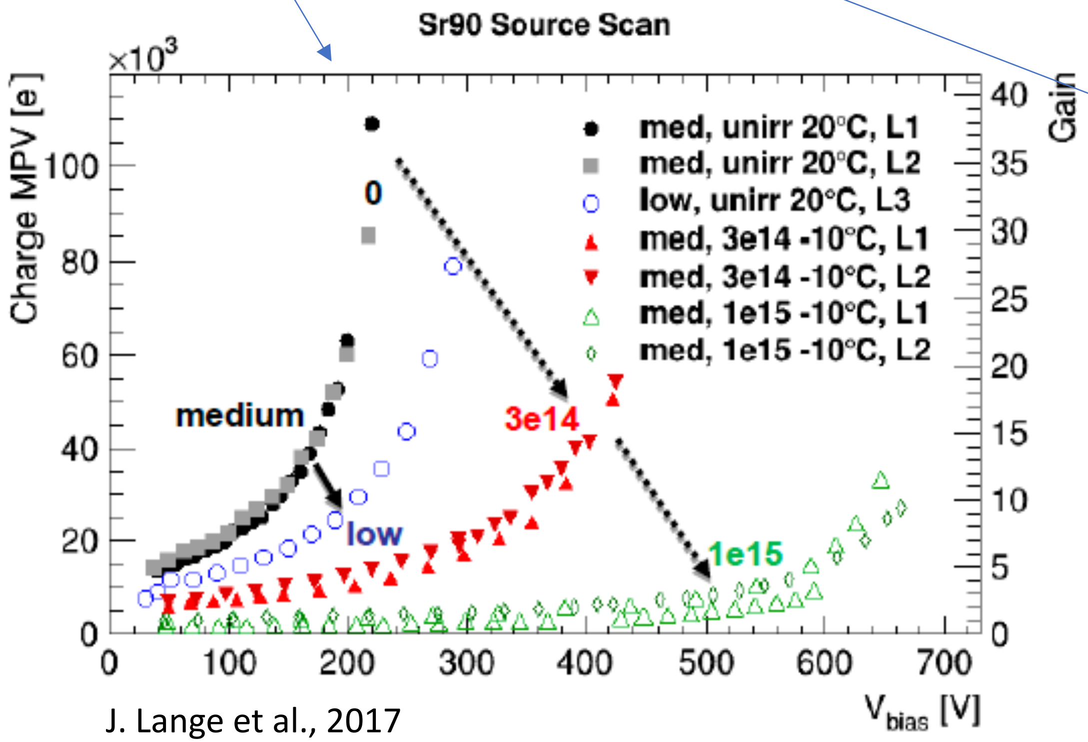
M. Moll dissertation

In the radiation field, detectors must maintain:

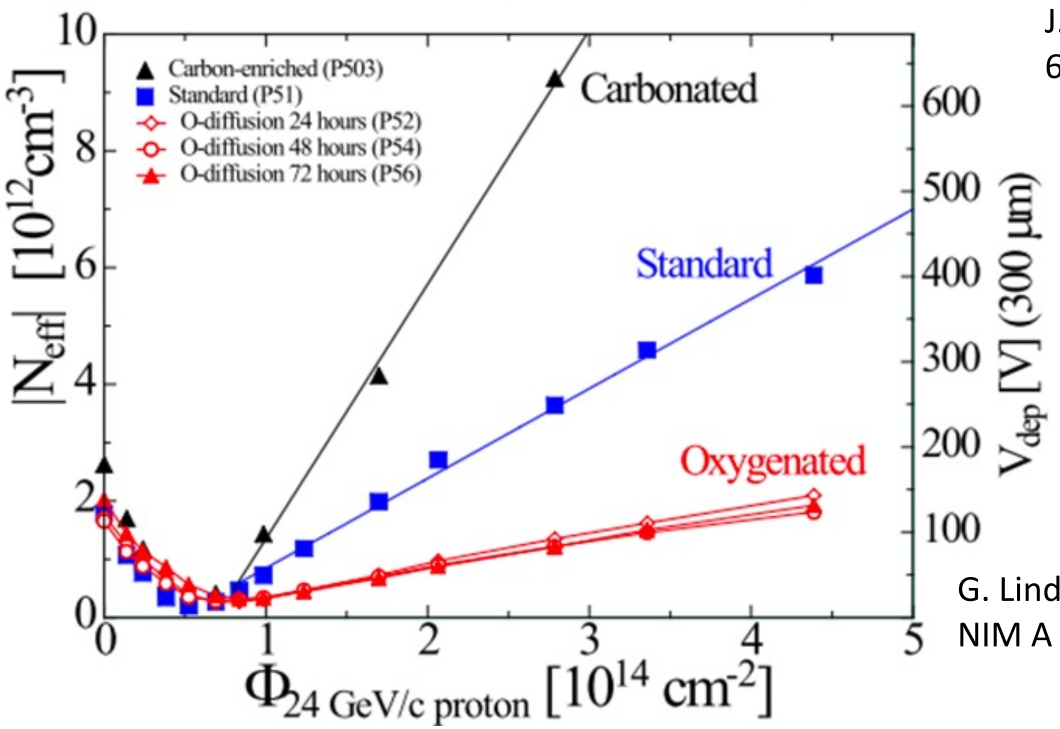
- charge collection efficiency, as defects modify space charge density – with implications on power
- gain, timing resolution despite radiation-induced acceptor removal



J. Lange et al., NIM A 622 (2010) 49.



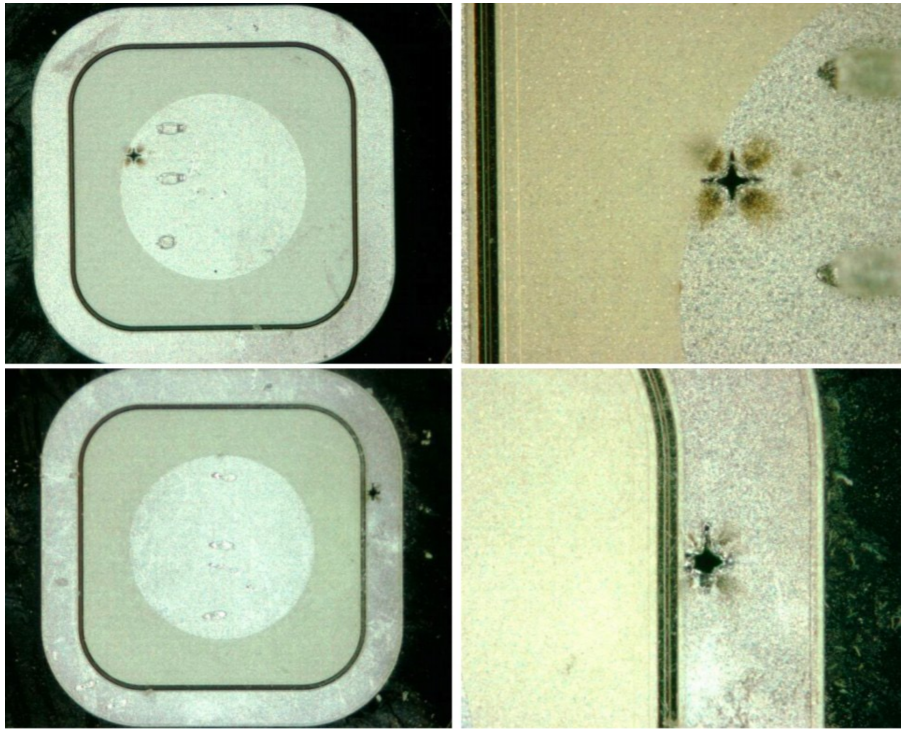
J. Lange et al., 2017 JINST 12 P05003.



G. Lindstroem et al., NIM A 466 (2001)

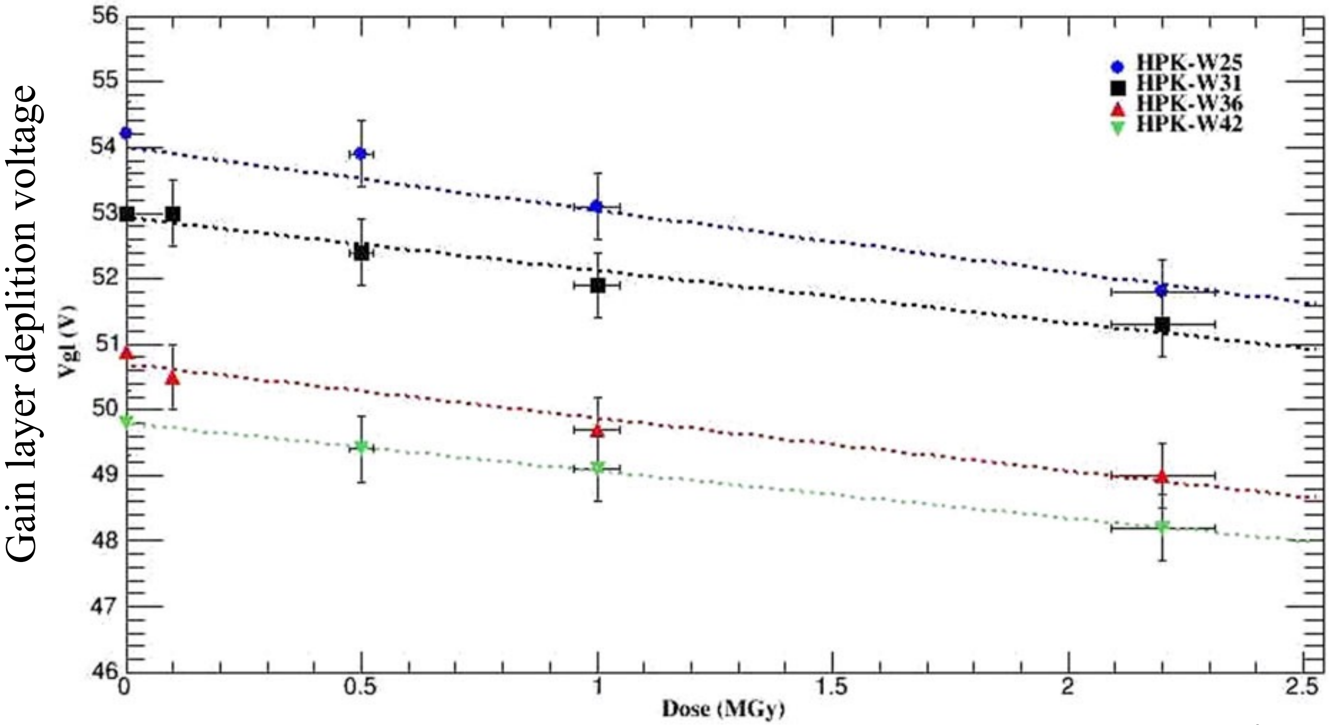
Risks as the radiation environment intensifies:

- Achieving depletion raises operating voltages, increasing risk of irreversible breakdown, “single event burnout”



S. Hidalgo, CNM

- For devices with internal gain (see LGADs, next slides), as signal diminishes with fluence, must either increase the gain (defect engineering) or decrease the noise – without losing speed



M.R. Hoeferkamp et al., Front. Phys 10 (2022)

The **Hamburg Model*** for predicting silicon response to radiation damage, has been essential for detector studies since it was released in 1999.

- The model needs to be updated for the fluences foreseen today. This is underway now in LHC experiment working groups using data from inner tracking detectors.

- A general model that starts from defect levels to describe macroscopic properties of silicon is needed. This is a goal of the DRD3 collaboration.

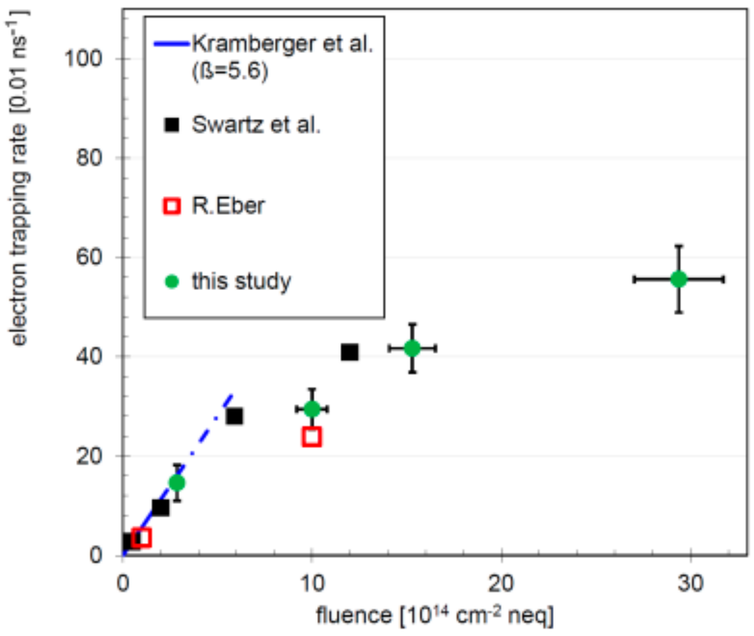
- Fundamental properties of the carriers – mobility, lifetime – must be quantified at the highest fluences.

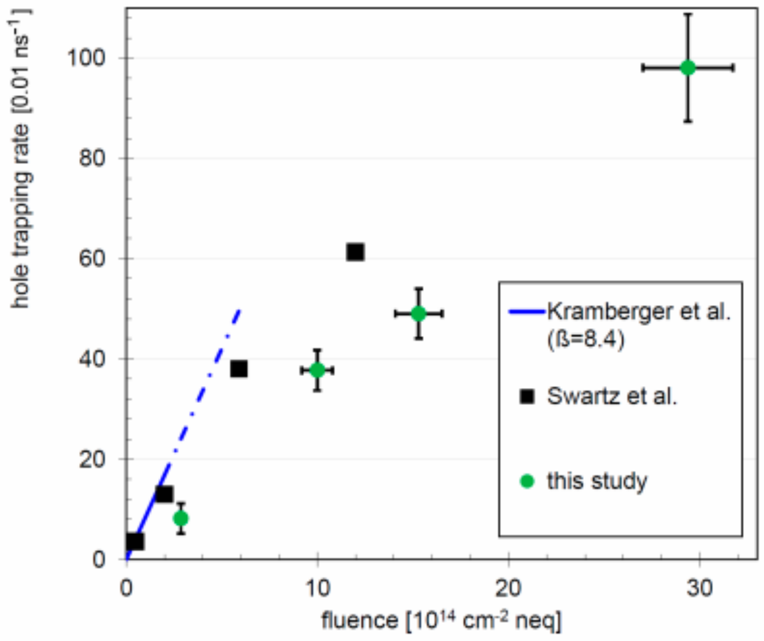
* https://mmoll.web.cern.ch/thesis/

Effects at the highest fluences

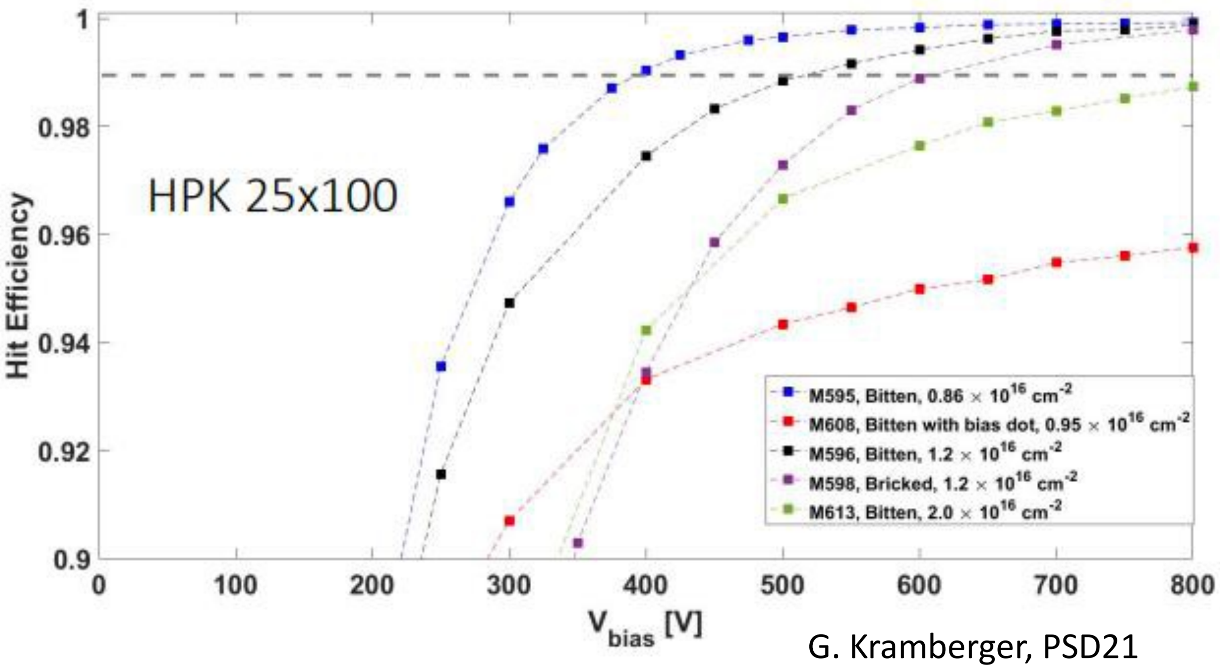
Some damage effects observed at LHC fluences are not extrapolating as badly as was feared.

- Trapping probability saturates.
- A double junction structure produces deeper active volume.
- Controlled charge multiplication is achievable.





W. Adam et al. (CMS) 2016 JINST 11 P04023



G. Kramberger, PSD21

Approaches and opportunities

Trapping, i.e. signal loss, turns out to be the issue for the vertex detector. And acceptor removal is the challenge for the active gain devices.

Approaches being explored:

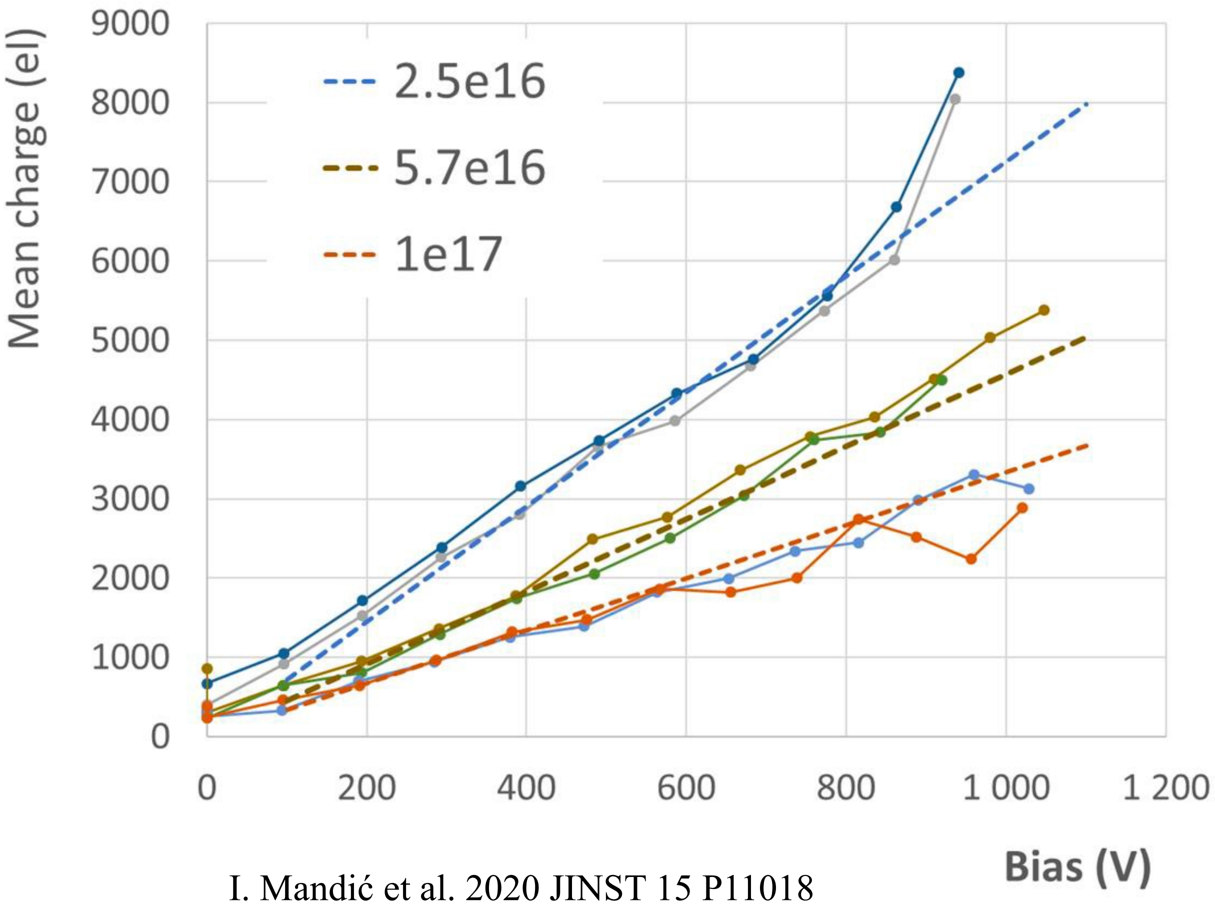
- Reduce the distance between electrodes
- Incorporate a gain structure – low gain avalanche detectors (LGADs)
- Apply defect engineering

These are introduced in the slides that follow.

Reducing the drift distance

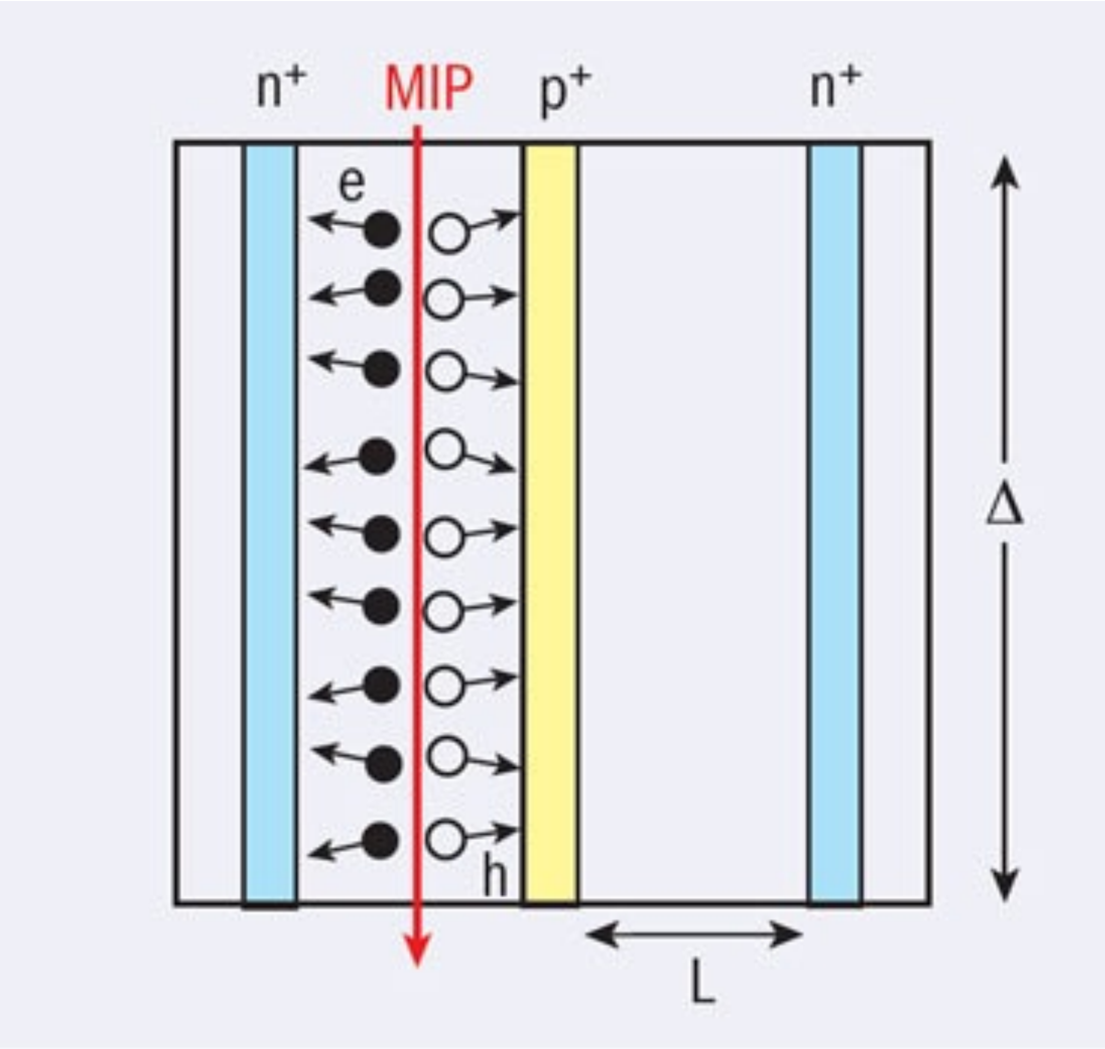
In planar devices, thin substrates inhibit trapping, maintaining charge collection even after 1e17 neutrons

- 75 µm epitaxial diode
- More charge collected under forward bias, but S/N is better under reverse bias.

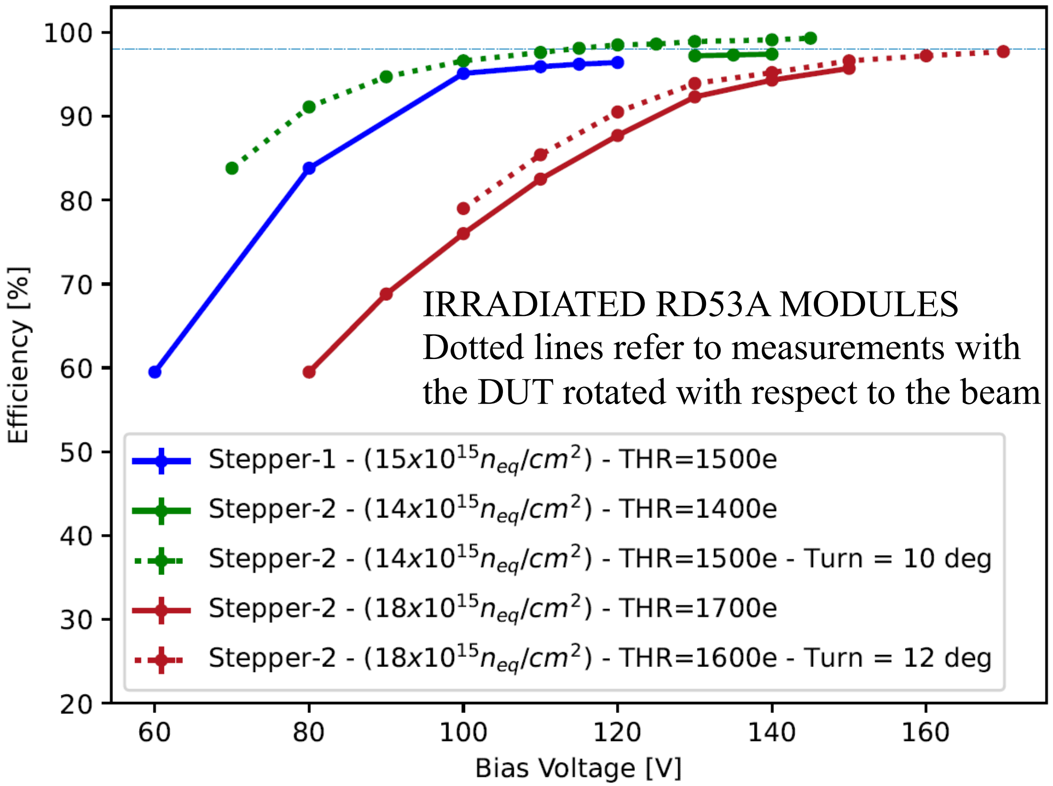


I. Mandić et al. 2020 JINST 15 P11018

3D sensors – trapping is inhibited by the short distances achievable between electrodes.



Testbeam indications of very good efficiency...

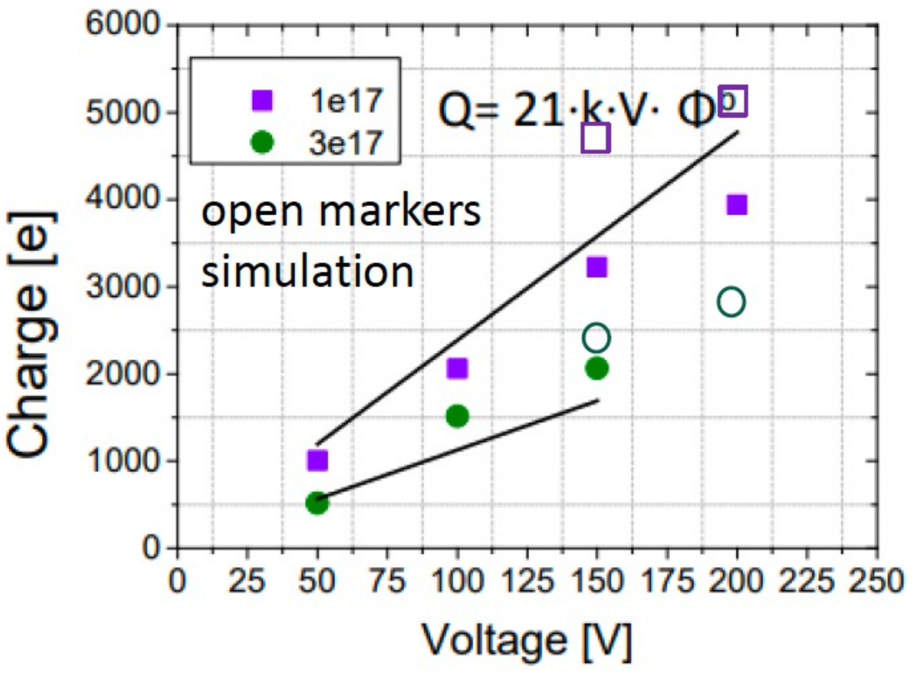


R. Ceccarelli, PIXEL2022

Charge collection modeled and observed in 3D strip sensors exposed to ~10^{17} n_{eq} neutrons

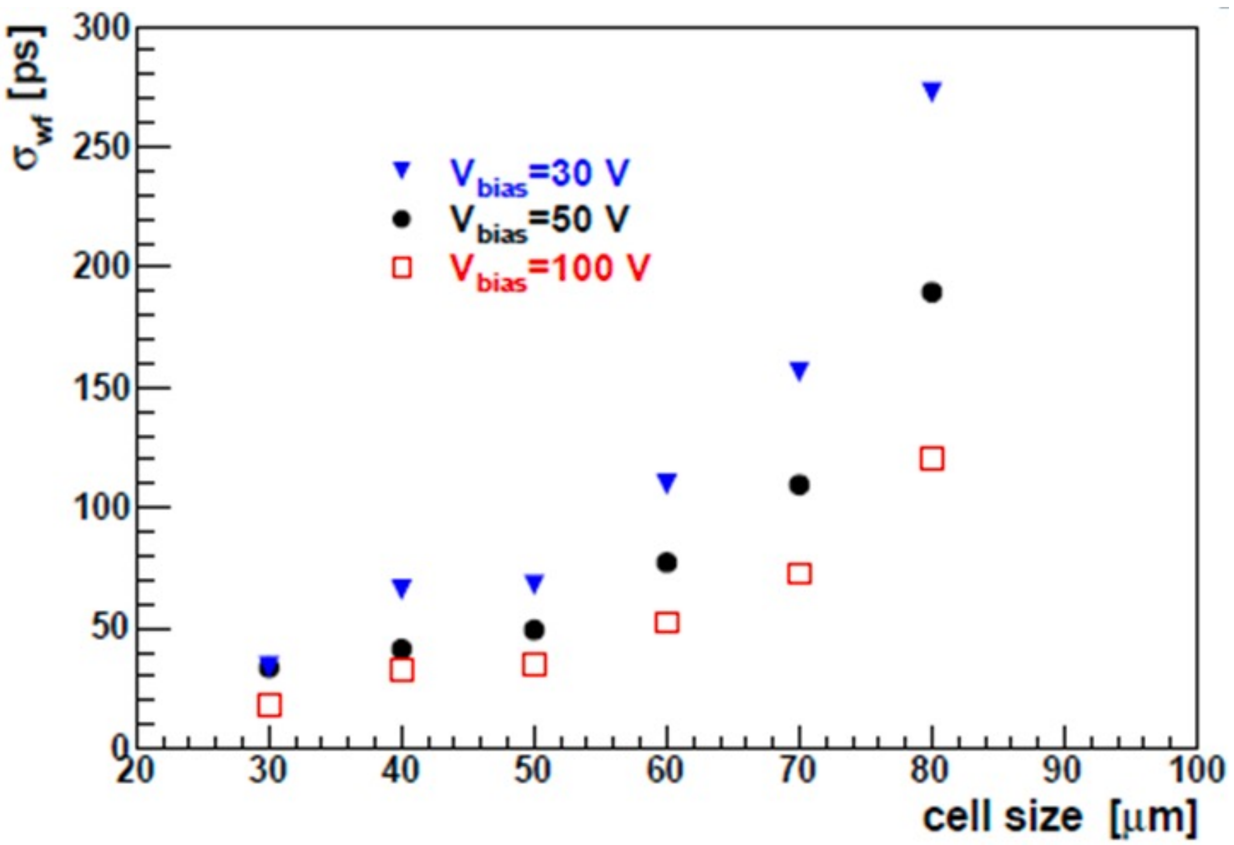
Measurements of 3D - Strip sensors irradiated to FCC-hh fluences using TCT/Alibava/CCE setups

M. Manna et al., NIMA 979 (2020) 164458.
M. Manna et al., 35th RD50 workshop,2019



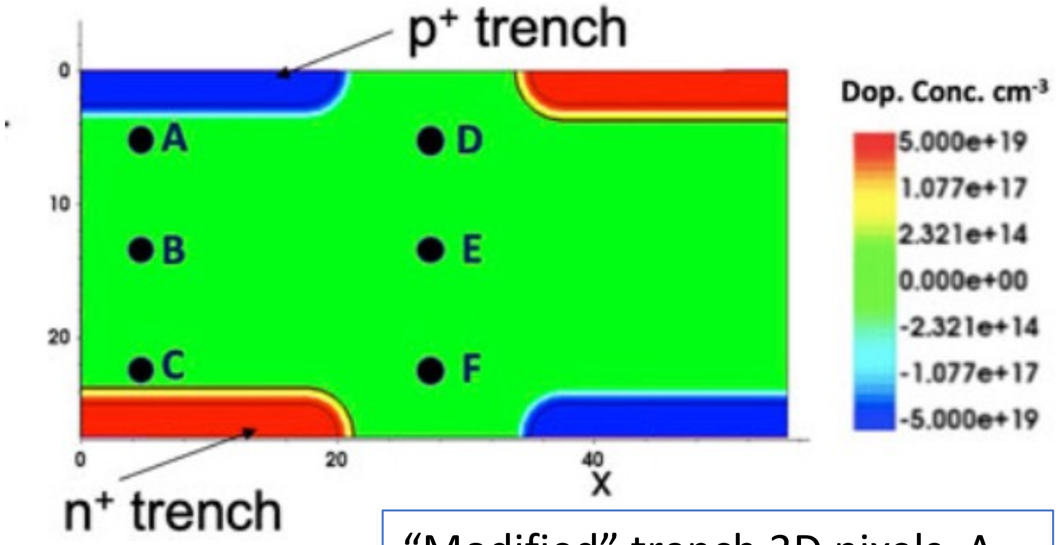
Signals around few 1000 e !

Indications for excellent timing potential in 3D geometry:

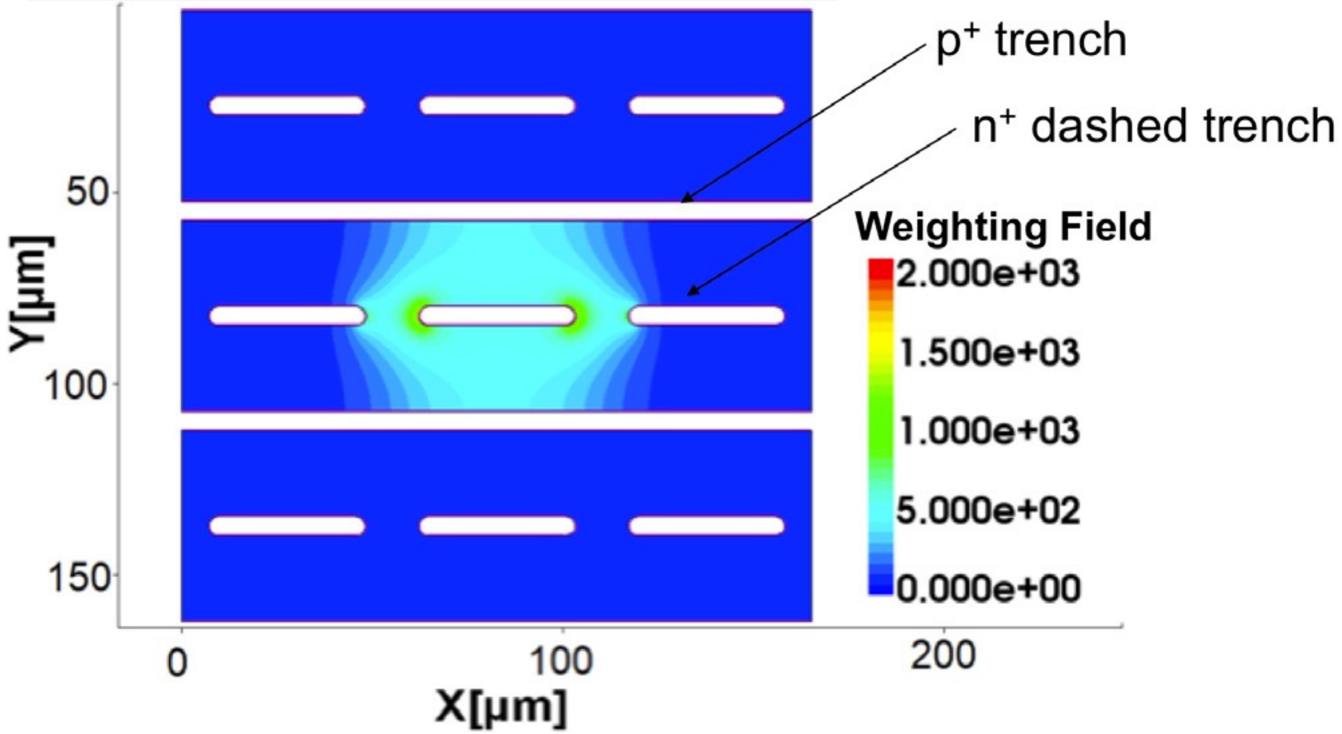


G. Kramberger, PSD2021

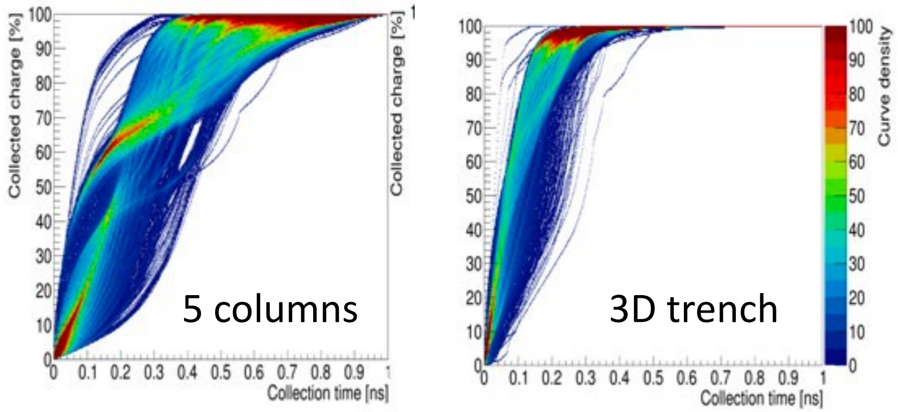
Trench geometry can smooth the electric field in 3D devices, preserving the radiation tolerance while improving speed of collection: the motivation for the Timespot project.



“classic” trench 3D pixels: R. Mendicino et al., NIM A 927 (2019) 24.



“Modified” trench 3D pixels, A. Boughedda et al., Front. Phys., 07 July 2022



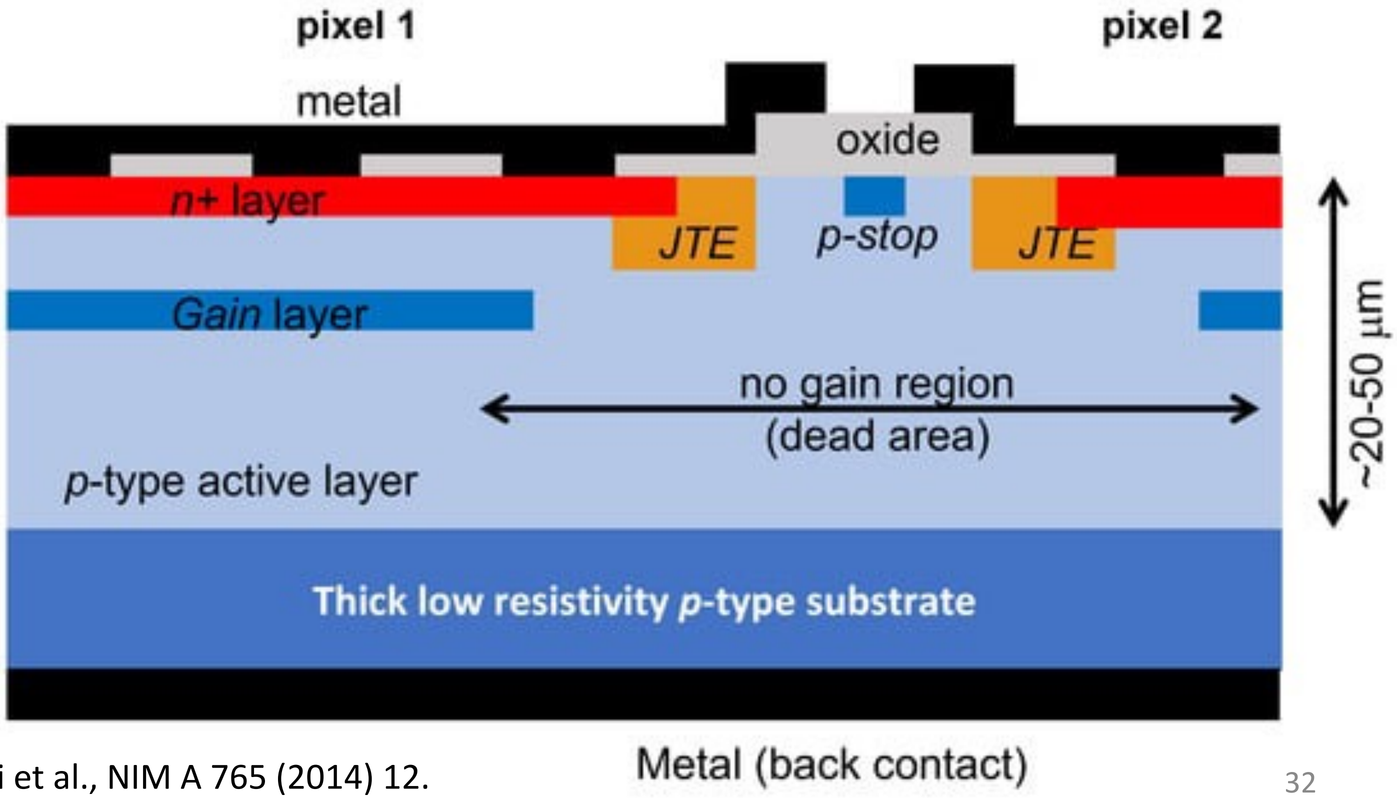
Simulated **charge collection curves** for MIPs uniformly crossing a pixel over its active area.
M. Garau, TREDI 2023

Incorporate internal gain: LGADs

The traditional LGAD design includes a gain layer below the surface, with a goal to obtain gain for electrons but not holes, with:

- gain field ~ 300 kV/cm across ~1 micron near the junction
- bulk field ~20 kV/cm, for saturated electron drift velocity ~10^7 cm/s.

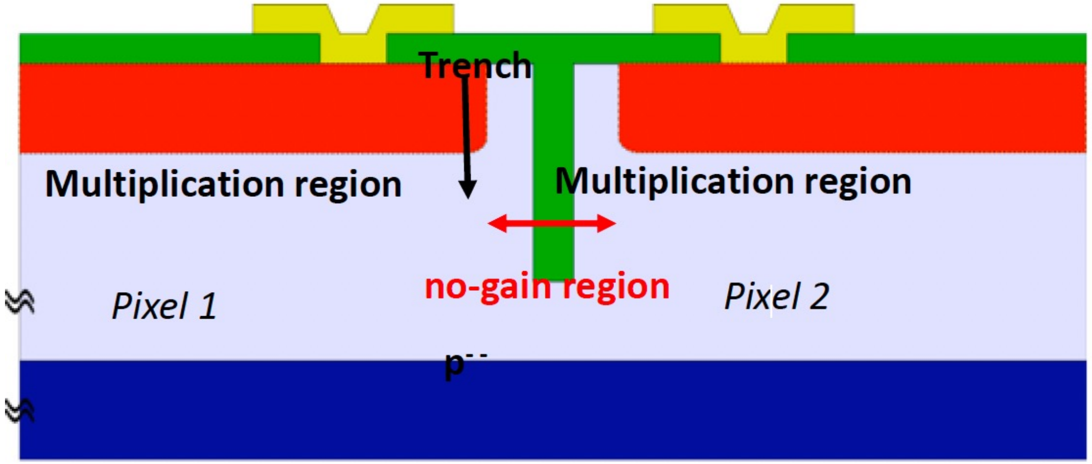
Initial designs isolate the electrodes with p-stops combined with junction termination extensions to reduce the electric field at the electrode edges for breakdown suppression. This succeeds but reduces the fill factor.



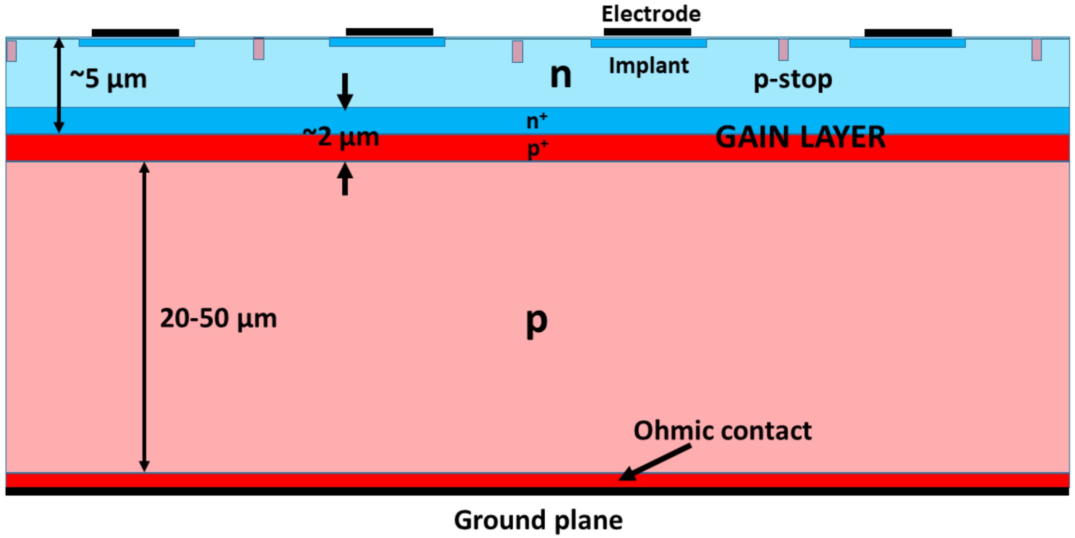
G. Pellegrini et al., NIM A 765 (2014) 12.
H.F.W. Sadrozinski et al., NIM A 730 (2013) 226.

Many solutions proposed to increase the fill factor are now being explored...

Trench-isolated (TI) LGAD replaces JTE with a silicon oxide-filled trench of width < 1 micron and depth ~few microns



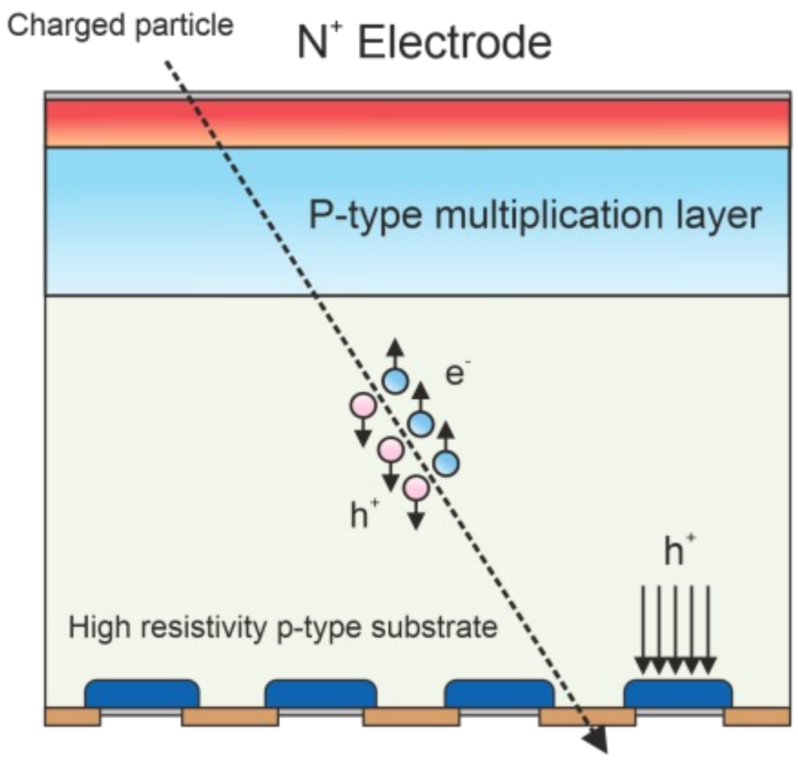
G. Paternoster et al., IEEE Elect. Dev. Lett. 41, no. 6, June 2020.



Deep junction (DJ) LGAD eliminates JTE, pairs p++ gain layer with an n++ layer to lower the field, buries the junction (~5 micron) so that fields are low at the surface. Sufficient gain maintained although field outside electrodes is low.

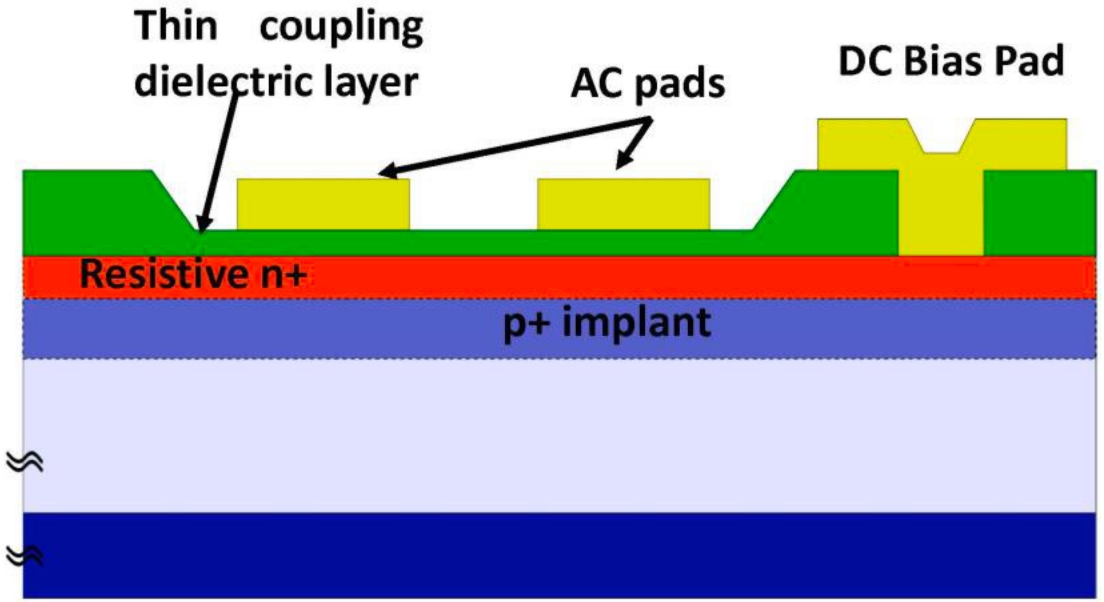
S. Ayyoub et al., arXiv:2101.00511

Fill factor solutions, continued....



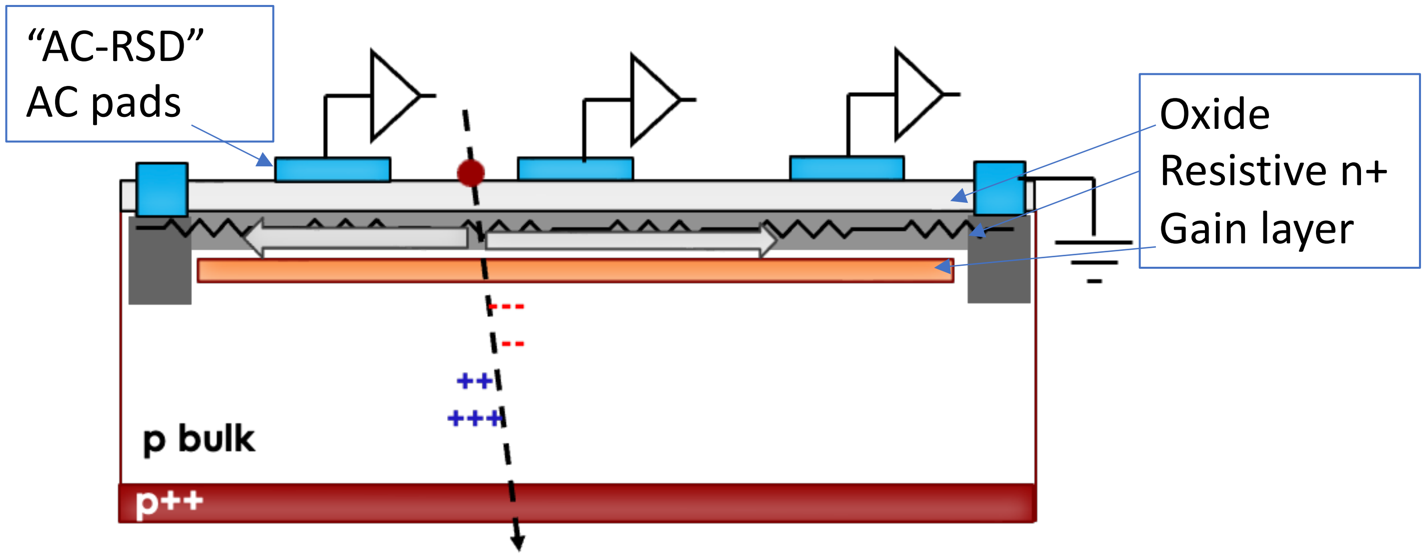
Inverse LGAD (iLGAD): The p^+ electrode is segmented on the ohmic side, collecting holes.

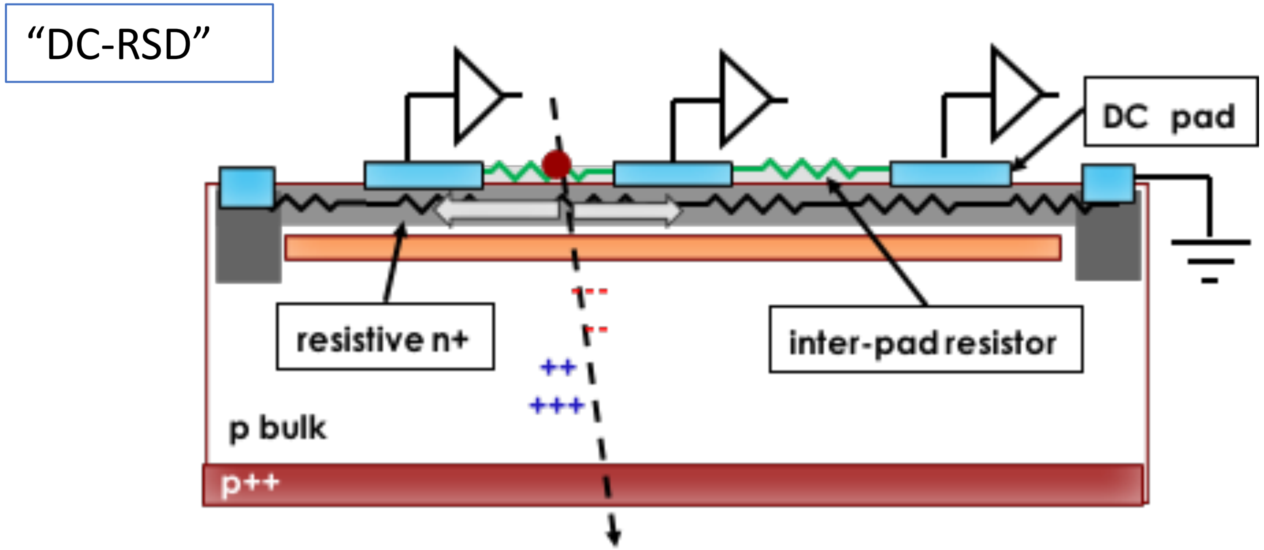
E. Curras et al., NIM A 958 (202) 162545.



AC-LGAD: physical pixelation of the LGAD disappears. The n^{++} implant at the junction is highly resistive and extends in a continuous sheet over the gain layer across the whole sensor. Add dielectric layer and AC coupling to readout.

G. Giacomini et al., 2019 JINST 14 P09004.





Resistive Silicon Detectors (RSD)

- Thin LGAD with a resistive read-out. Initial design AC-coupled.
- Signal sharing of charge induced in the resistive layer, fast signal in the nearby AC pads. Slow charge flows to ground.
- spatial resolution better than 0.5 x pitch/√12

- Now developing DC-RSD: Remove oxide layer, add interpad-resistors to confine the signal regions. Avoids collection of leakage current only at the periphery; improves control of signal sharing.

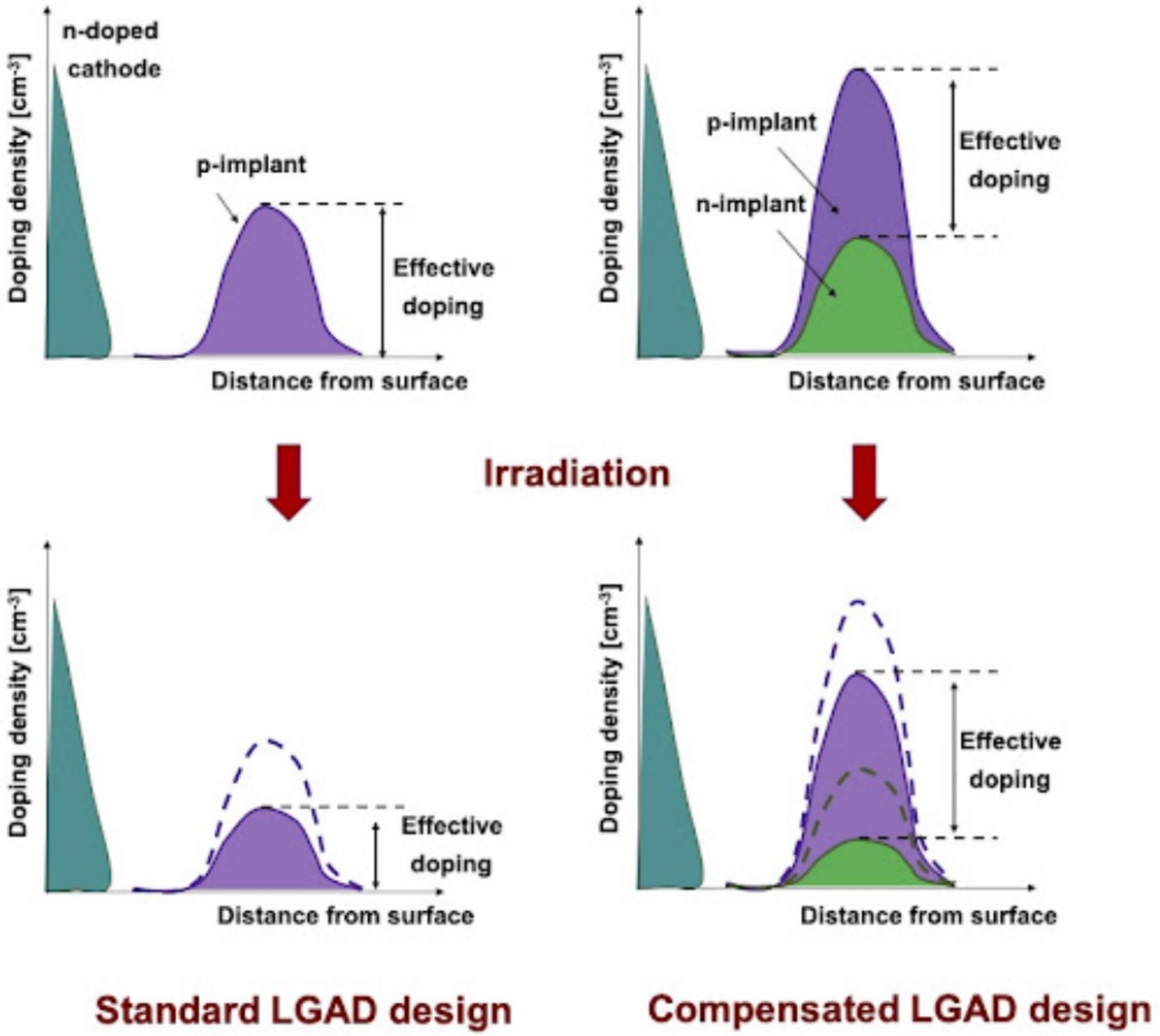
R. Arcidiacono, 22nd RD50 Workshop

Thinning the LGADs: the eXFlu project

Goal: extend silicon LGAD operation up to 5E17, by exploiting observed saturation of damage effects beyond 5E15.

- Sensor thickness limited to 20-30 microns.
- Thinner sensors provide higher gain after irradiation.
- New gain layer design, "compensated LGAD" – with p and n doping combination in the gain layer.

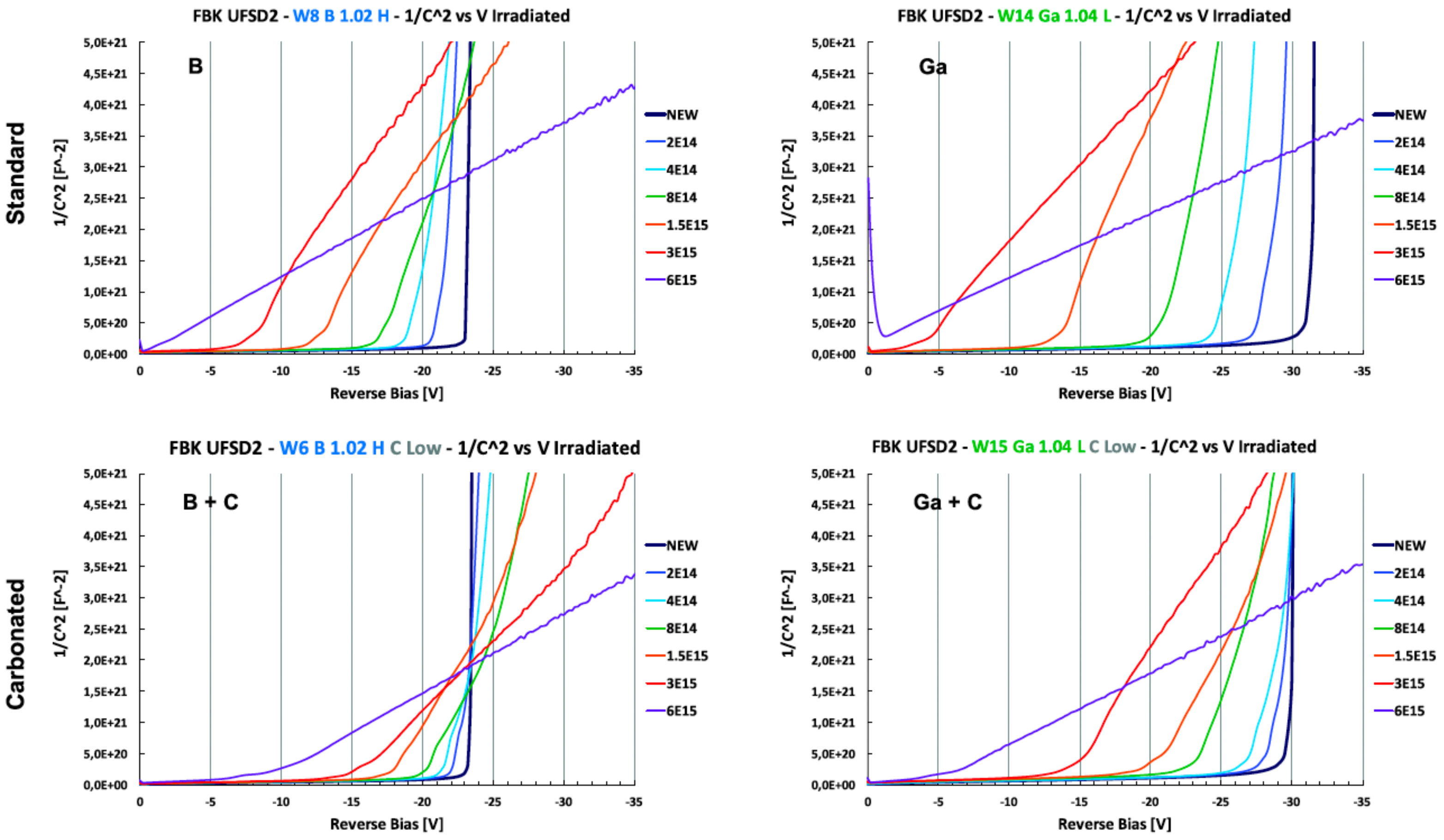
- pre-irradiation, internal signal multiplication from the gain layer
- with radiation, signal multiplication progressively moves from gain layer to bulk region



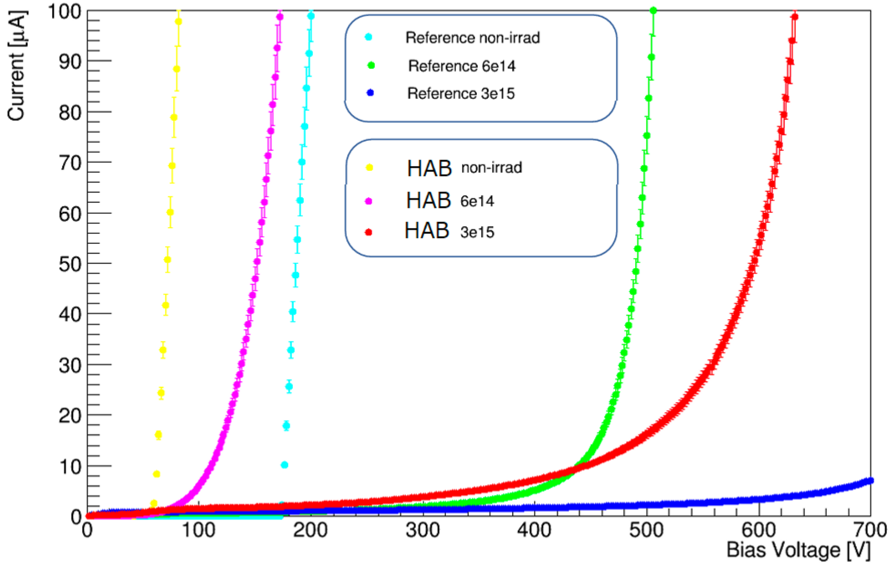
https://aidainnova.web.cern.ch/thin-silicon-sensors-extreme-fluences

A next step for LGADs involves defect engineering to control acceptor removal:

- carbon infusion?
- Alternatives to boron?
- Fine-tune the depth and geometry?



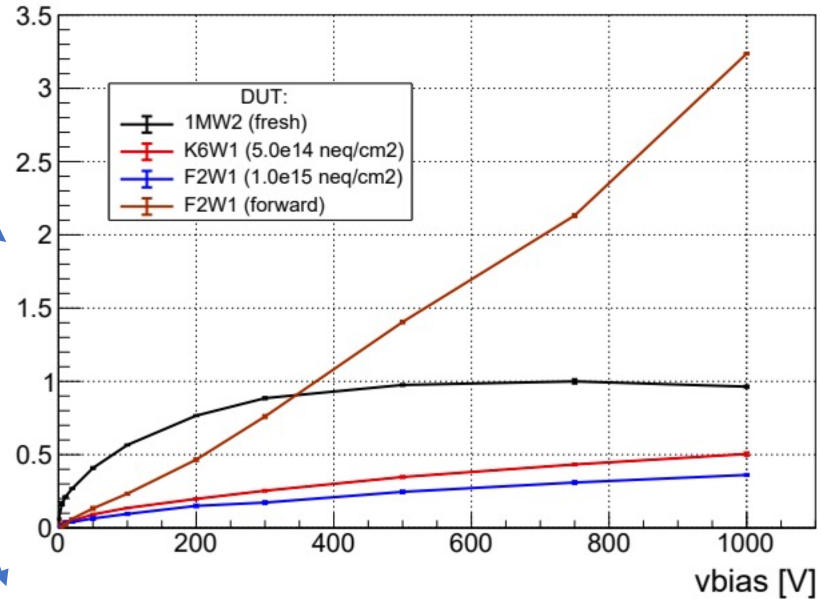
Response of various gain layer dopings to neutron irradiation.
M. Ferrero et al., NIM A 919 (2019) 16.



"Half-activated boron": dope with more boron than required - atoms not in the Si lattice capture oxygen to suppress acceptor removal.
K. Hara et al., TREDI 2023

Some goals and progress beyond silicon and beyond traditional hybrid technology – and certainly this is only a partial list

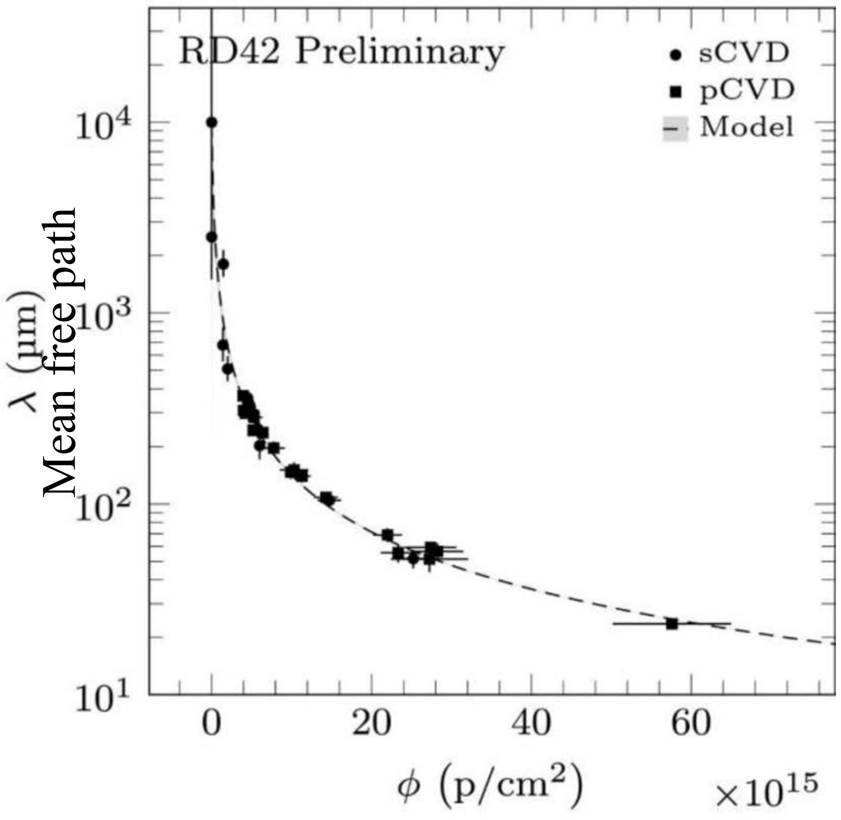
- New explorations of **wide band gap semiconductors** are a priority. High carrier saturation velocity predicts good operation in timing applications. Band gap predicts operability without cooling.
- Continued efforts in **diamond**, especially in the 3D geometry with graphite electrodes

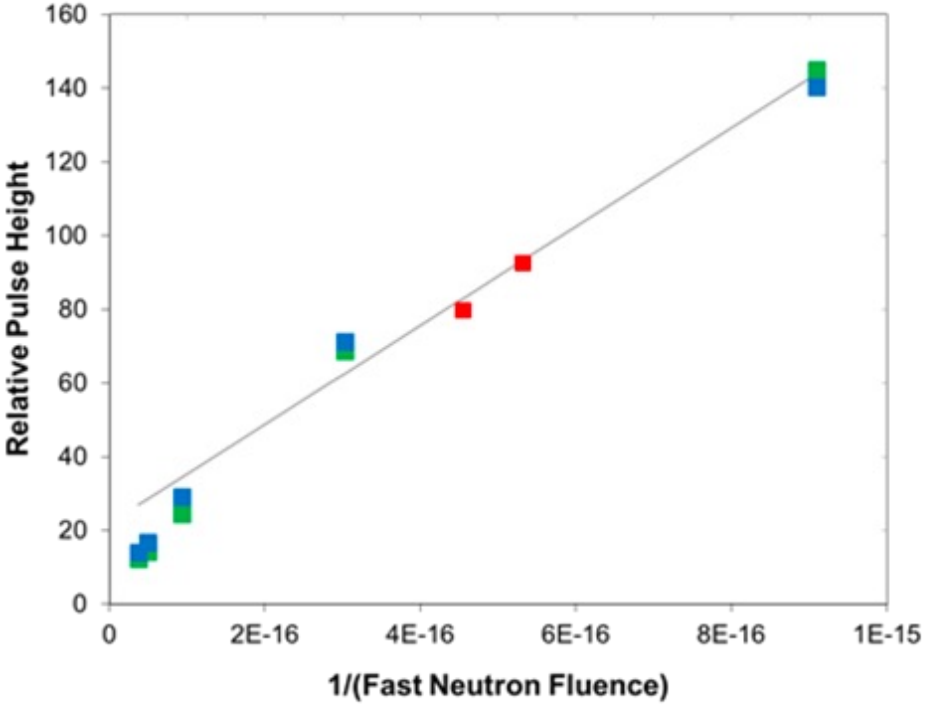


In this SiC sample, forward bias yields almost a factor of 10 increase of the signal at 1e15 neq/cm^2

E. Curras et al., TREDI 2023

N. Venturi et al., NIM A 924 (2019) 241.





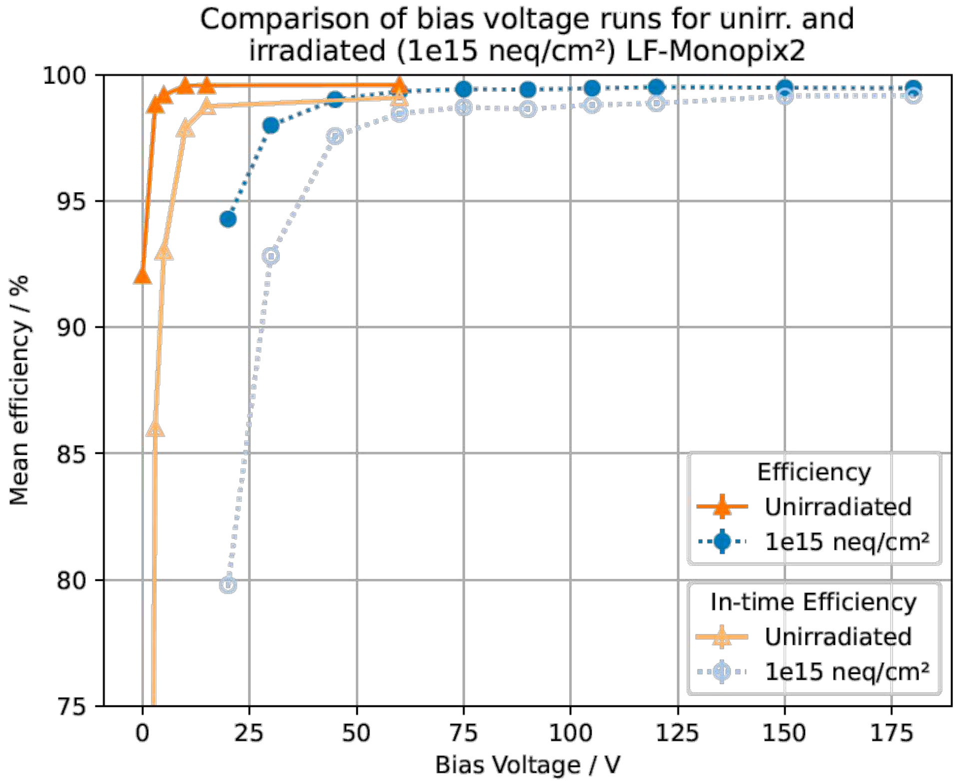
In this SiC sample, the fast-neutron fluence corresponding to the lowest observed pulse height is 1.1 x 10^{17} n cm^{-2}.

F.H. Ruddy et al., Trans. Am. Nucl Soc. 90 (2004) 348.

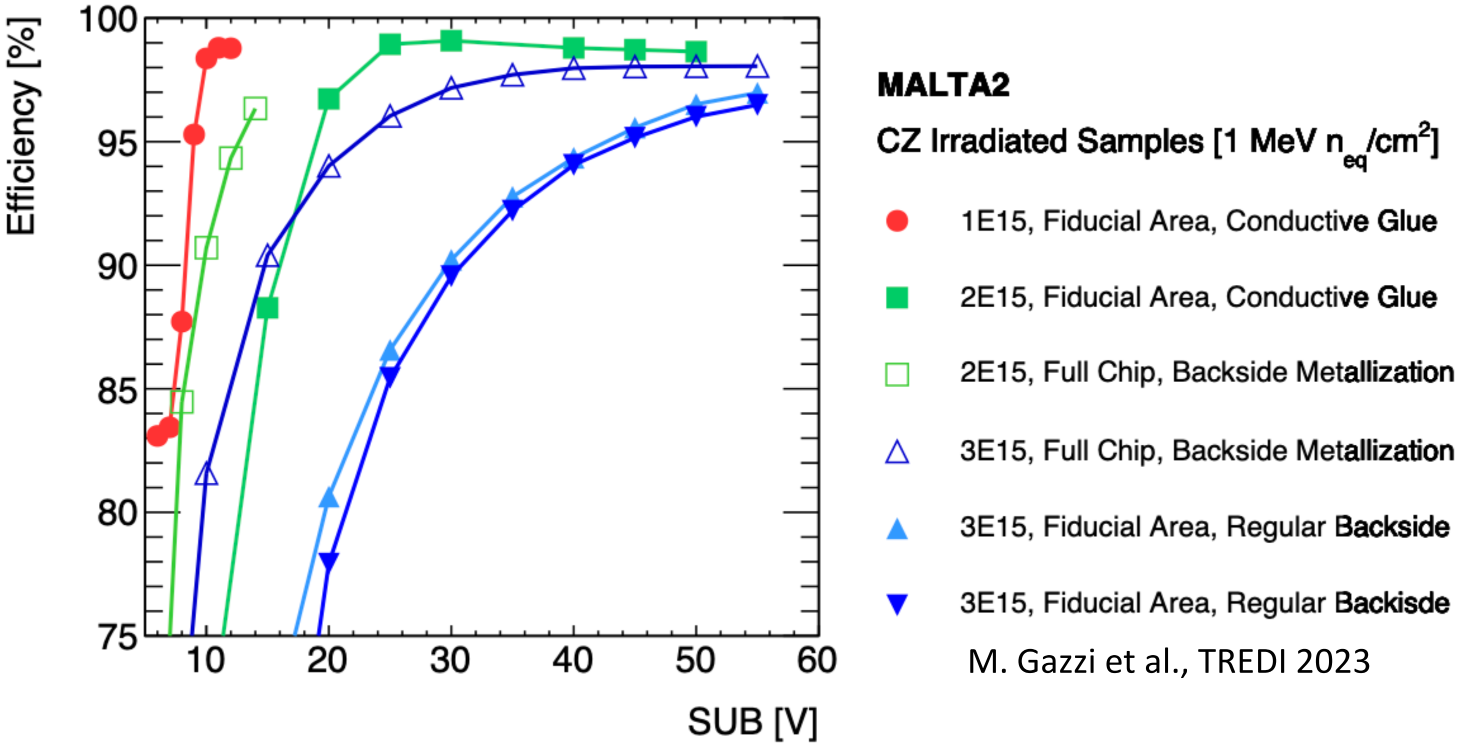
Radiation hardness in MAPS continues to improve

LF-Monopix2 DMAPS

Efficiencies before & after irradiation



I. Caicedo, 42nd RD50 Workshop



M. Gazzi et al., TREDI 2023

Comparable evaluation needs to be made on interconnects, mechanical supports, services.

- Much work is underway but publications are relatively few.
- Candidate materials are regularly evaluated directly in radiation environments but less often modeled.
- Some guidance can come from modelers in the space sciences.

- Some interesting takeaway reading:
  - Readout Technologies for Future Detectors, M. Begel et al., arXiv:2203.14894 [physics.ins-det]

  "Modern fiber-optical transceivers are not sufficiently radiation tolerant to be placed inside the tracking detector....so the transmitters receiving the data via long electrical cables...limit the readout bandwidth. [Development of] radiation tolerant fiber-optical links is one way to solve the problem. The other approach is...on-detector compression, reduction, aggregation. [The compression] electronics need comparable radiation tolerance as the fiber-optical links. Silicon-photonic technology...found to be highly radiation tolerant."[1,2]

  - Radiation-tolerant, low-mass, high bandwidth, flexible printed circuit cables for particle physics experiments, N.C. McFadden et al., NIM A 830 (2016) 461-465.
  - Modeling Radiation Damage in Materials Relevant for Exploration and Settlement on the Moon, N.E. Koval et al., https://www.intechopen.com/chapters/81141

[1]A. Kraxner et al., TWEPP2018
[2]T. Prousalidi et al., TWEPP 2021.

Conclusions

- Radiation environments are being carefully simulated for all future facilities
- Saturation and non-linear effects are becoming apparent at the highest fluences
- Trapping i.e. signal loss is the primary challenge
- Many ingenious technologies are being explored