27th International Workshop on Vertex Detectors (VERTEX)
21-26 October 2018, Chennai - India.

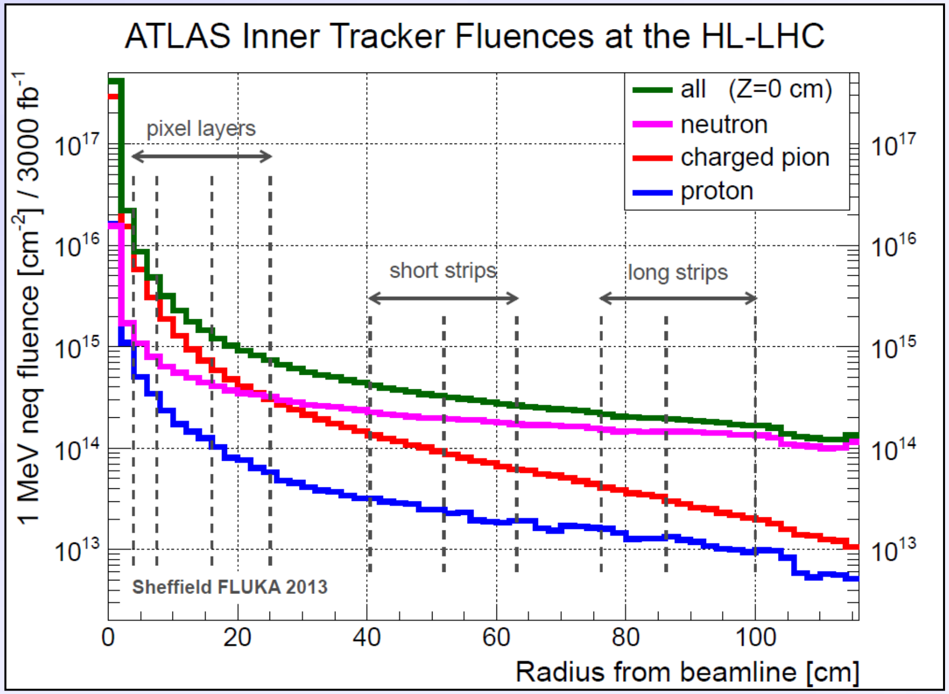
RD50 activities on radiation tolerant silicon detectors

Gianluigi Casse
University of Liverpool, UK
and
FBK, Italy

ON BEHALF of the RD50 COLLABORATION

The original Motivation (2002 - ….)

- **LHC upgrade**
  - **LHC upgrade towards High Luminosity LHC (HL-LHC)**
    *after LS3 (~2024-26); **expect*** **4000 fb^{-1}** *(x6 nominal LHC)*



[I. Dawson, P. S. Miyagawa, Sheffield University, Atlas Upgrade radiation background simulations]

Semiconductor detectors will be exposed to hadron fluences equivalent to
> 2 ·10^{16} n_{eq}/cm^2 (HL-LHC)

➔ detectors developed for running LHC cannot operate after such irradiation

RD50 : mandate to develop semiconductor sensors and characterisatoin methods for extreme fluence (where extreme is an ever increasing number).

The RD50 Collaboration

- **RD50: 56 *institutes and 358 members***

The RD50 community brings together solid state physicists; device physicists; experts of radiation-matter interactions; high energy physicists; electronics system designers; ASICs designers; sensor foundries. This community has learned to work towards common goals developing methods, tools and standards that are world reference for the domain. This vast expertise is an unsurpassed basis for continuing research towards sensor solution for future challenges.

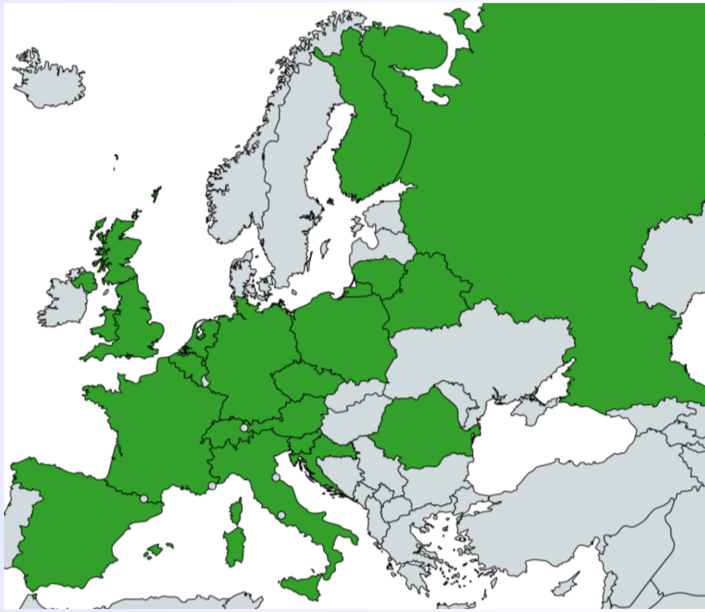
The R&D Collaboration “Radiation hard semiconductor devices for high luminosity colliders” was formed in 2001 and approved by the research board as RD50 in May 2002.

Main focuses:

- Studying and make choices about various semiconductor materials
- understanding the microscopic radiation damage mechanisms
- modelling the radiation damage on microscopic and macroscopic level
- **Radiation hardening by:**
  - ✓ **device engineering**
  - ✓ **material engineering optimization of operational conditions**

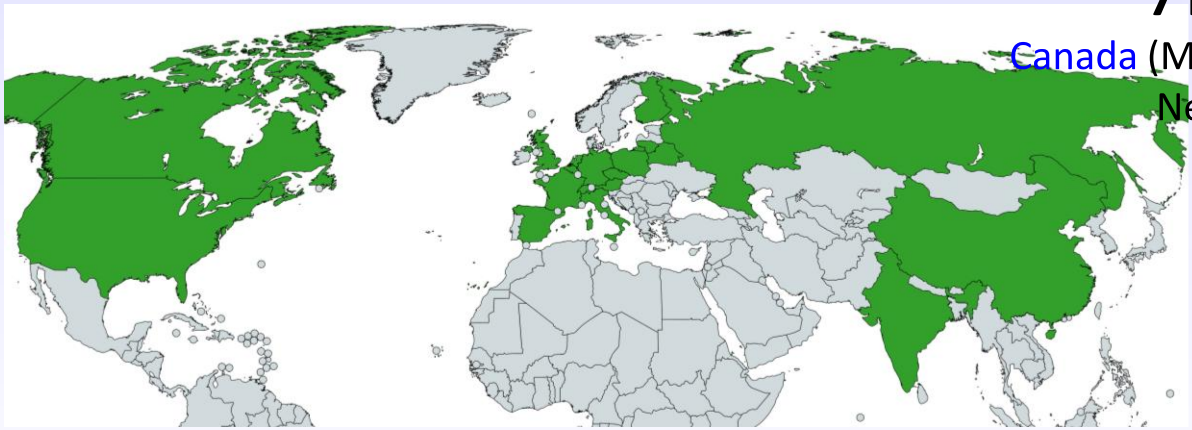
The RD50 Collaboration

- **RD50: 56 *institutes and 358 members***



49 European institutes

Austria (Wien), Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Orsay), Germany (Bonn, Goettingen, Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich(2x)), Italy (Bari, Perugia, Pisa, Trento, Torino), Kroatia (Zagreb) Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(3x), Santander, Valencia), Switzerland (CERN, PSI), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Oxford, RAL)



7 North-American institutes

Canada (Montreal), USA (BNL, Brown Uni, Fermilab, New Mexico, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

2 Asian institute

India (Delhi), China (Beijing)

Detailed member list: http://cern.ch/rd50

RD50 Organizational Structure

Co-Spokespersons

Gianluigi Casse and *Michael Moll*

(Liverpool University, UK
& FBK-CMM, Trento, Italy)

(CERN EP-DT)

Defect / Material Characterization

Ioana Pintilie
(NIMP Bucharest)

- **Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation**
- **DLTS, TSC, ….**
- **SIMS, SR, …**
- **NIEL (calculations)**
- **Cluster and Point defects**
- **Boron related defects**

Detector Characterization

Eckhart Fretwurst
(Hamburg University)

- **Characterization of test structures (IV, CV, CCE, TCT,.)**
- **Development and testing of defect engineered silicon devices**
- **EPI, MCZ and other materials**
- **NIEL (experimental)**
- **Device modeling**
- **Operational conditions**
- **Common irradiations**

- Wafer procurement (M.Moll)
- **Acceptor removal** (Kramberger)

New Structures

Giulio Pellegrini
(CNM Barcelona)

- **3D detectors**
- **Thin detectors**
- **Cost effective solutions**
- **Other new structures**
- **Detectors with internal gain**
- **LGAD: Low Gain Avalanche Det.**
- **Deep depleted Avalanche Det.**
- **Slim Edges**
- **HVCMOS**

- **LGAD (S.Hidalgo)**
- **HVCMOS (E. Vilella)**
- Slim Edges (V.Fadeyev)

Full Detector Systems

Gregor Kramberger
(Ljubljana University)

- **LHC-like tests**
- **Links to HEP(LHC upgrade, FCC)**
- **Links electronics R&D**
- **Low rho strips**
- **Sensor readout (Alibava)**
- **Comparison:**
  - **pad-mini-full detectors**
  - **different producers**
- **Radiation Damage in HEP detectors**
- **Timing detectors**
- Test beams
  (M.Bomben & G.Casse)

Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder & GLIMOS: M.Moll & M.Glaser (EP-DT)

RD50 so far …

Main achievements:

- development of the p-type silicon strip and pixel technology
- double column 3D detectors
- convincing demonstration of the performance of planar segmented sensors to the maximum fluences anticipated for the H-LHC ($3x10^{16}$ n_{eq} cm^{-2})
- extensive evaluation of defect engineered Silicon and other semiconductor materials
- observation and explanation of charge multiplication in highly irradiated sensors operated at high voltage
- design and production of LGAD (Low Gain Avalanche Detectors) for 4D tracking
- development of several unique characterization methods and systems for sensor and material analyses: Transient Current Technique (TCT), Edge-TCT, Two Photon Absorption (TPA)-TCT, Alivaba readout system and standardized measurement and analyses procedures, partly now marketed through spin-off companies
- defect characterization: identification of defects responsible for the degradation of various detectors parameters defining the state of the art in the corresponding solid state community
- data collection and development of damage parameters/models essential for sensor design (TCAD parameters) and for planning the running scenarios of LHC experiments and their upgrades (evolution of leakage current, CCE, power consumption, noise,….)
- close links to the LHC experiments (upgrades)

RD50 and running experiments

RD50 provides:

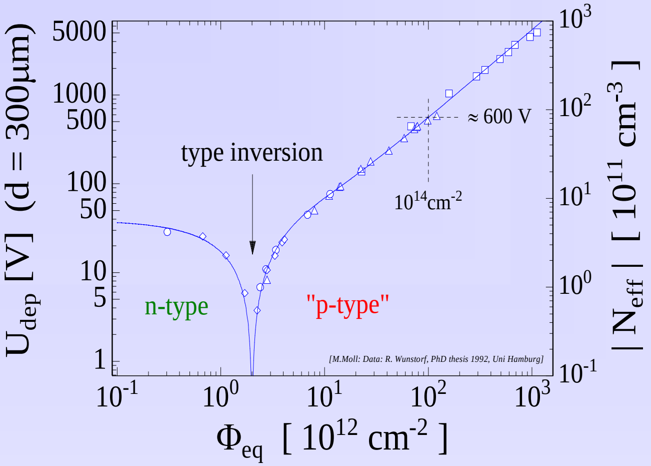
- large data sets for IV curves after irradiation and annealing.
- large data sets for CV curves after irradiation and annealing (up to fluences where this is still relevant).
- large data sets for Charge Collection curves after irradiation and annealing.

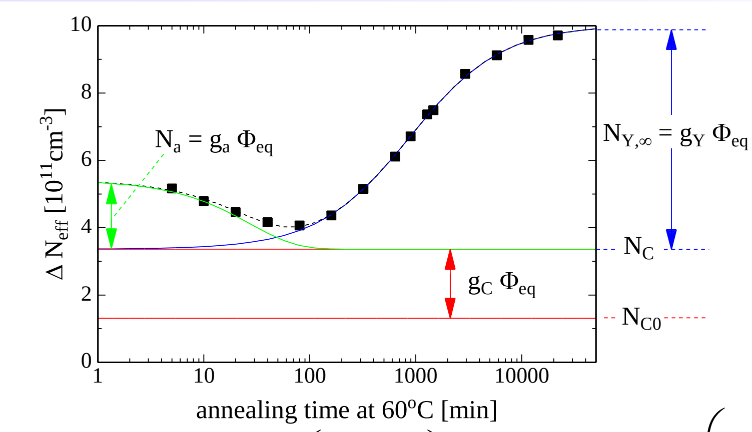
Parameterisations of the evolution of IV, CV and CCE-V.

Differences depending on material (O, C contents, CZ, FZ, Epi, …), thickness, electrode geometry, energy and type of irradiation, ….

Work on simulations to improve on existing irradiation/annealing/bulk/interface models for including all possible parameters. Use of efficient/real defect parameters for improving simulation (applicable to all cases above).

The macroscopic damage parameterisation (Hamburg model)

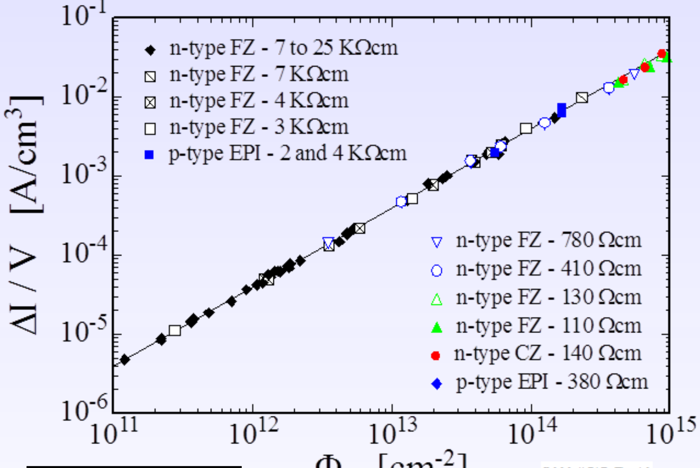




$$N_a = \Phi_{eq} \times \sum_i g_{ai} \times \exp\left(-\frac{t}{\tau_i}\right) \qquad N_Y = N_{Y,\infty}\cdot\left(1-\frac{1}{1+t/\tau_y}\right)$$

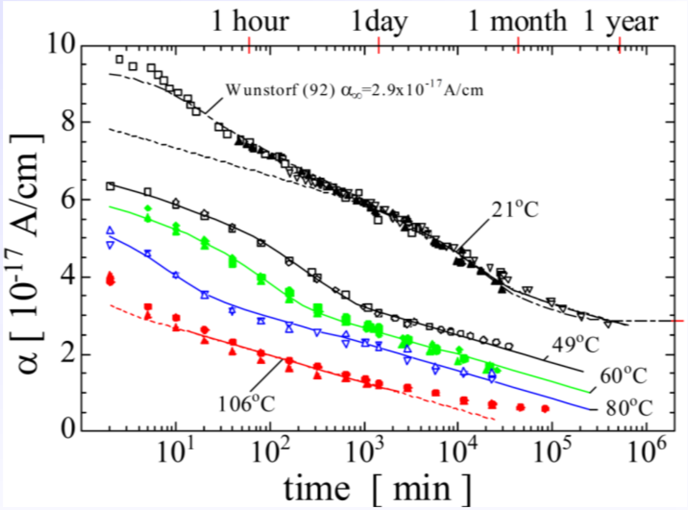
$$\boxed{\Delta N_{eff}(\Phi_{eq},t) = N_a(\Phi_{eq},t) + N_C(\Phi_{eq}) + N_Y(\Phi_{eq},t)}$$

$$N_C = N_{CO}\cdot\left(1-\exp\left(-c\cdot\Phi_{eq}\right)\right)+g_C\cdot\Phi_{eq}$$



[M.Moll PhD Thesis]

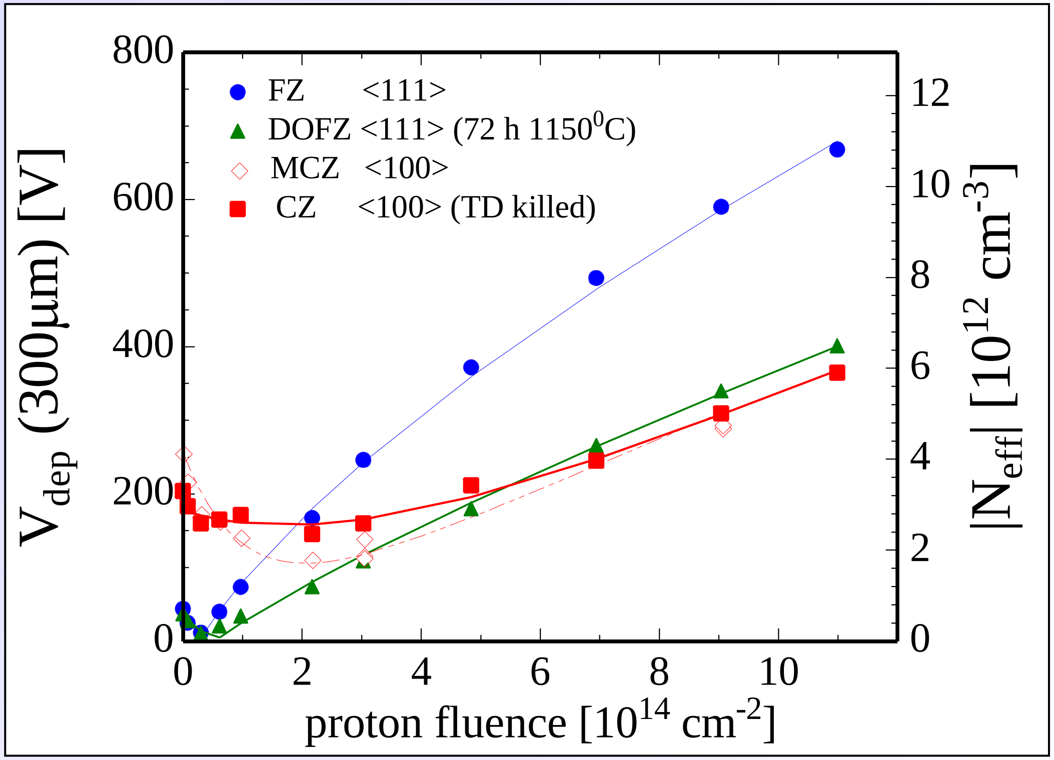
$$\boxed{\alpha = \frac{\Delta I}{V\cdot\Phi_{eq}}}$$



Current sensors in LHC, mainly n-type

The macroscopic damage parameterisation (Hamburg model)

- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence



- **CZ silicon and MCZ silicon**
  - "no type inversion" in the overall fluence range

(for experts: there is no "real" type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for: TCT, MCZ, double junction)

Change of charge collection efficiency

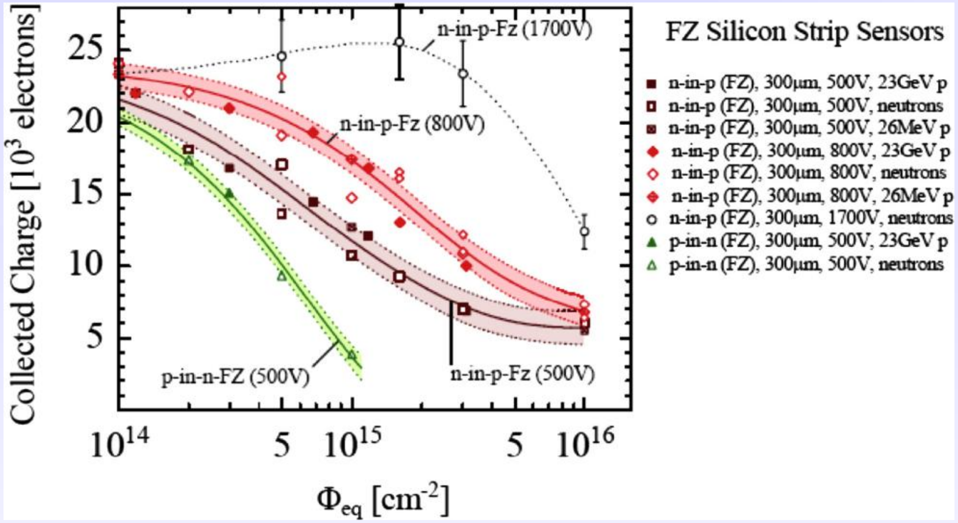
- **The irradiation introduces defects which act as trapping center for the charge generated by an ionizing particle**
- **This reduce the overall signal thus affecting the detector efficiency**

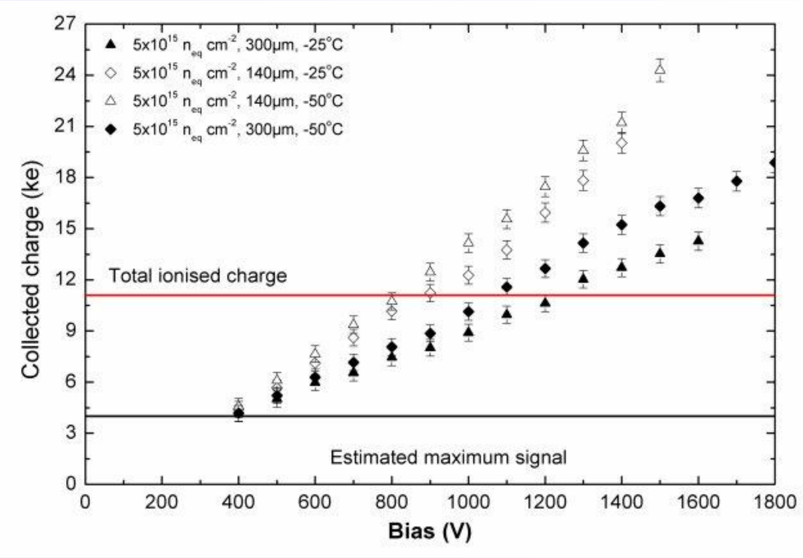
$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t \right) \qquad \frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(T,t)\,\Phi_{eq}$$

- When the effective trapping time becames of the order of the electron/hole drift time (5-20ns) the charge integrated at the electrodes by the front-end electronics is reduced

The degradation of the charge collection

Especially at high doses (HL-LHC regime) the V_{FD} is not a useful parameter. Use charge instead.

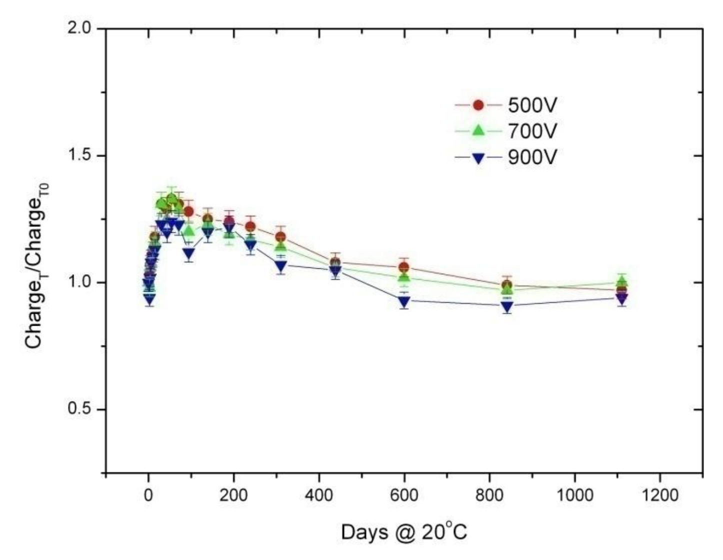


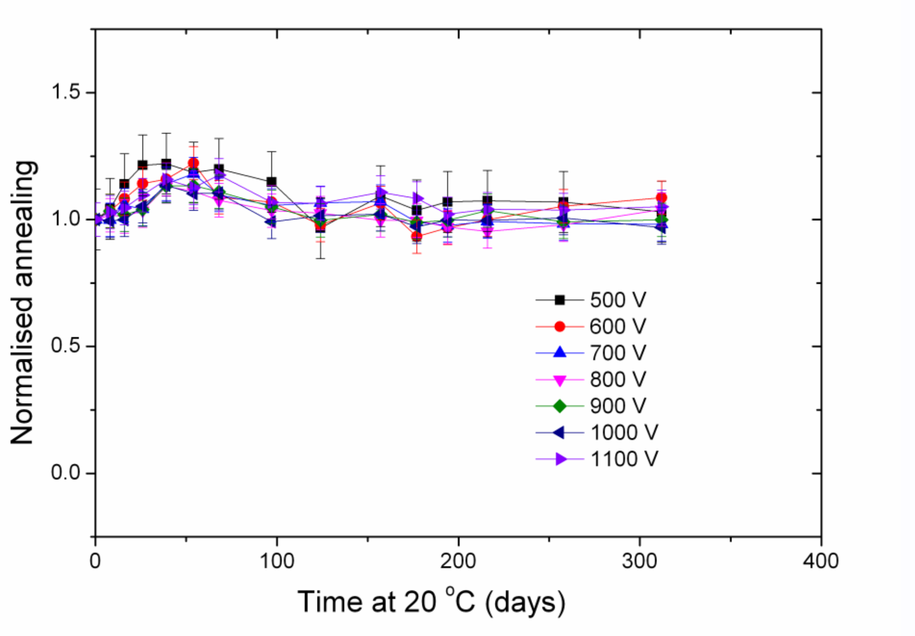


G. Casse et al., "Enhanced efficiency of segmented silicon detectors of different thicknesses after proton irradiations up to 1×10^{16} n_{eq} cm^{-2}, 624 (2010), 401-404.

Annealing of the CCE after irradiation

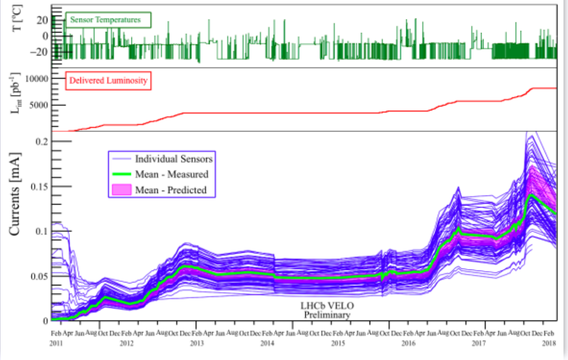
Normalised annealing of the collected charge in n-in-p microstrip sensors after 2 and 10 x 10^{16} n_{eq} cm^{-2} (26MeV p irradiation)

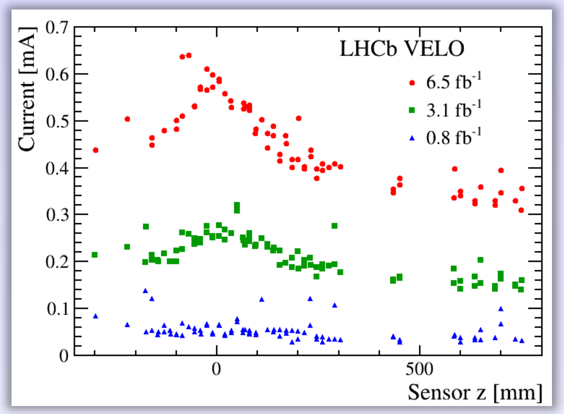


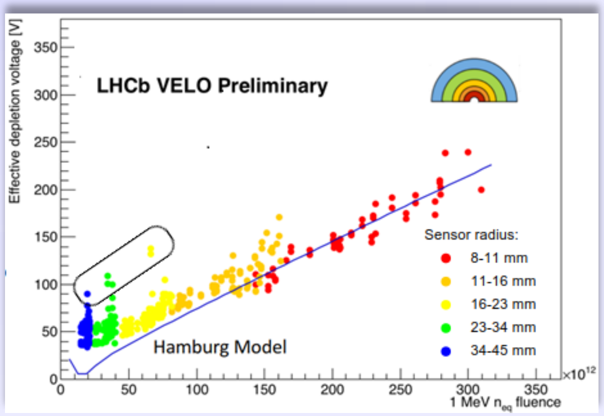


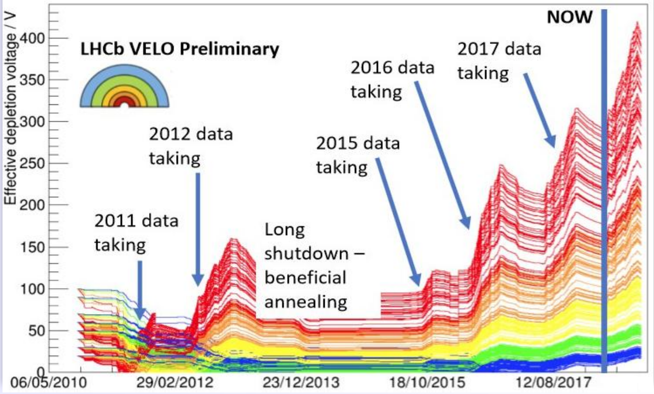
RD50 and running experiments

- The evolution of leakage current and effective depletion voltage are based on Hamburg model.
- Fluence is determined by Geant4 and FLUKA (comparison is ongoing),
  - the z-dependence of the fluence reflects the shape of the leakage current.

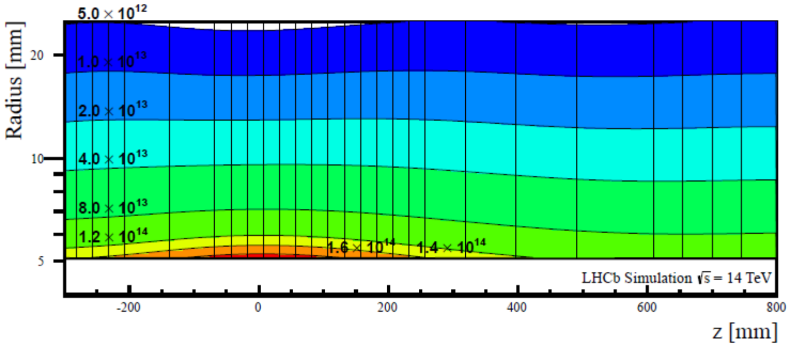






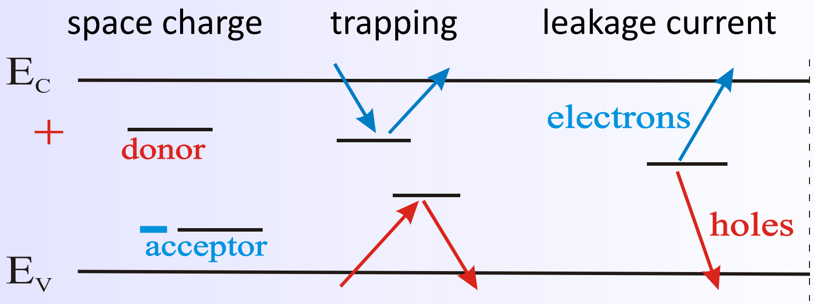


- Simulation for the VELO Upgrade shows that the inner tip of the sensors will be irradiated up to 7×10^{15} n_{eq} per 50 fb^{-1}.

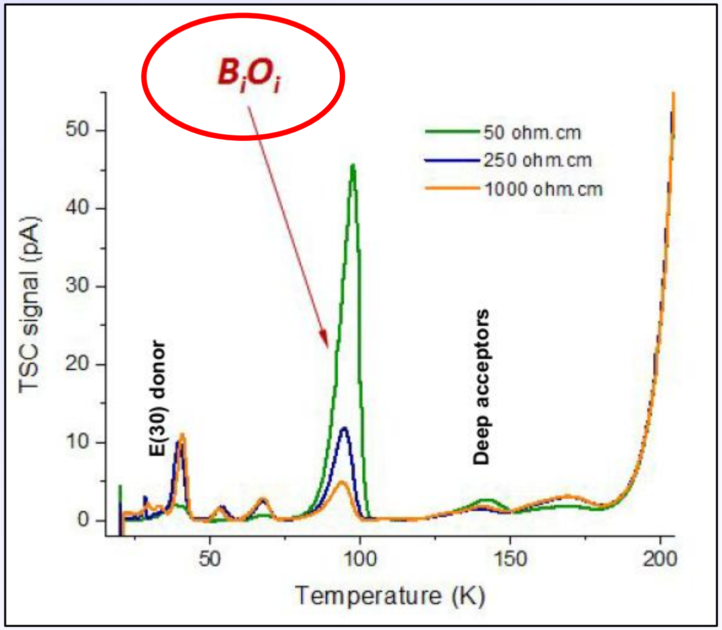


Defect Characterization

- **Aim of defect studies:**
  - **Identify defects responsible for Trapping, Leakage Current, Change of N_{eff}, Change of E-Field**
  - **Understand if this knowledge can be used to mitigate radiation damage (e.g. defect engineering)**
  - **Deliver input for device simulations to predict detector performance under various conditions**



- **Method:** Defect Analysis performed with various tools inside RD50:
  - **C-DLTS** (Capacitance Deep Level Transient Spectroscopy)
  - **TSC** (Thermally Stimulated Currents)
  - **PITS** (Photo Induced Transient Spectroscopy)
  - **FTIR** (Fourier Transform Infrared Spectroscopy)
  - **EPR** (Electron Paramagnetic Resonance)
  - **TCT** (Transient Current Technique)
  - **CV/IV** (Capacitance/Current-Voltage Measurement)
  - **MW-PC** (Microwave Probed Photo Conductivity)
  - *PC, RL, I-DLTS, TEM,… and simulation*
  - **RD50: several hundred samples irradiated with protons, neutrons, electrons and ^{60}Co-γ**

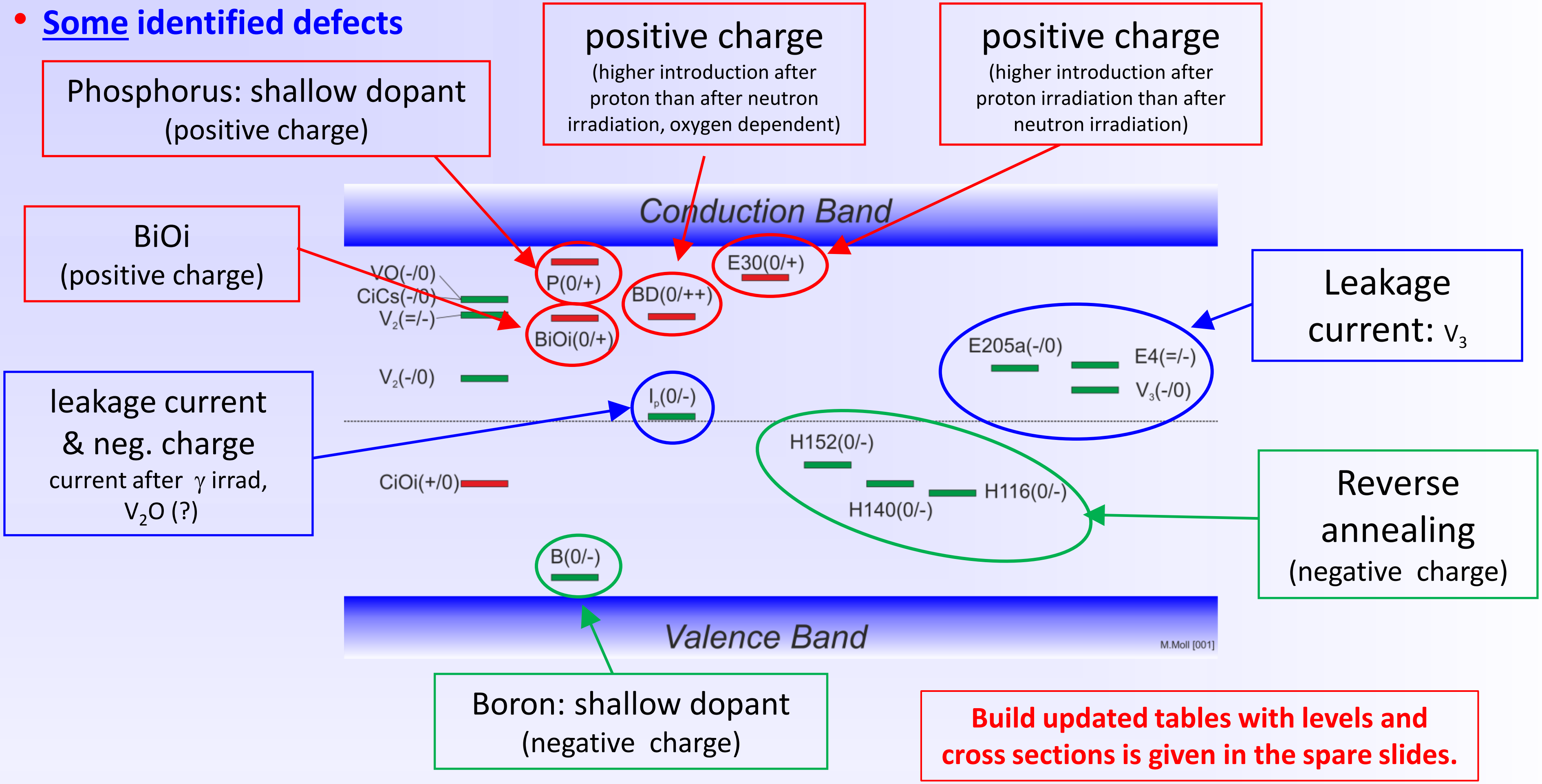


[Pedro Almeida, CERN, Trento Meeting, 2018]

Example: TSC measurement on defects produced by 23 GeV protons in p-type silicon of different resistivity

Summary on defects with strong impact on device performance after irradiation

- **Some identified defects**



Phosphorus: shallow dopant
(positive charge)

positive charge
(higher introduction after proton than after neutron irradiation, oxygen dependent)

positive charge
(higher introduction after proton irradiation than after neutron irradiation)

BiOi
(positive charge)

Leakage current: V_3

leakage current & neg. charge
current after γ irrad,
V_2O (?)

Reverse annealing
(negative charge)

Boron: shallow dopant
(negative charge)

Build updated tables with levels and cross sections is given in the spare slides.

- **Trapping: Indications that E205a and H152K are important** (further work needed)
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and particle energy and (for some) on material!

Defects with strong impact on device performance after irradiation

- **Most relevant defects with impact on device performance**

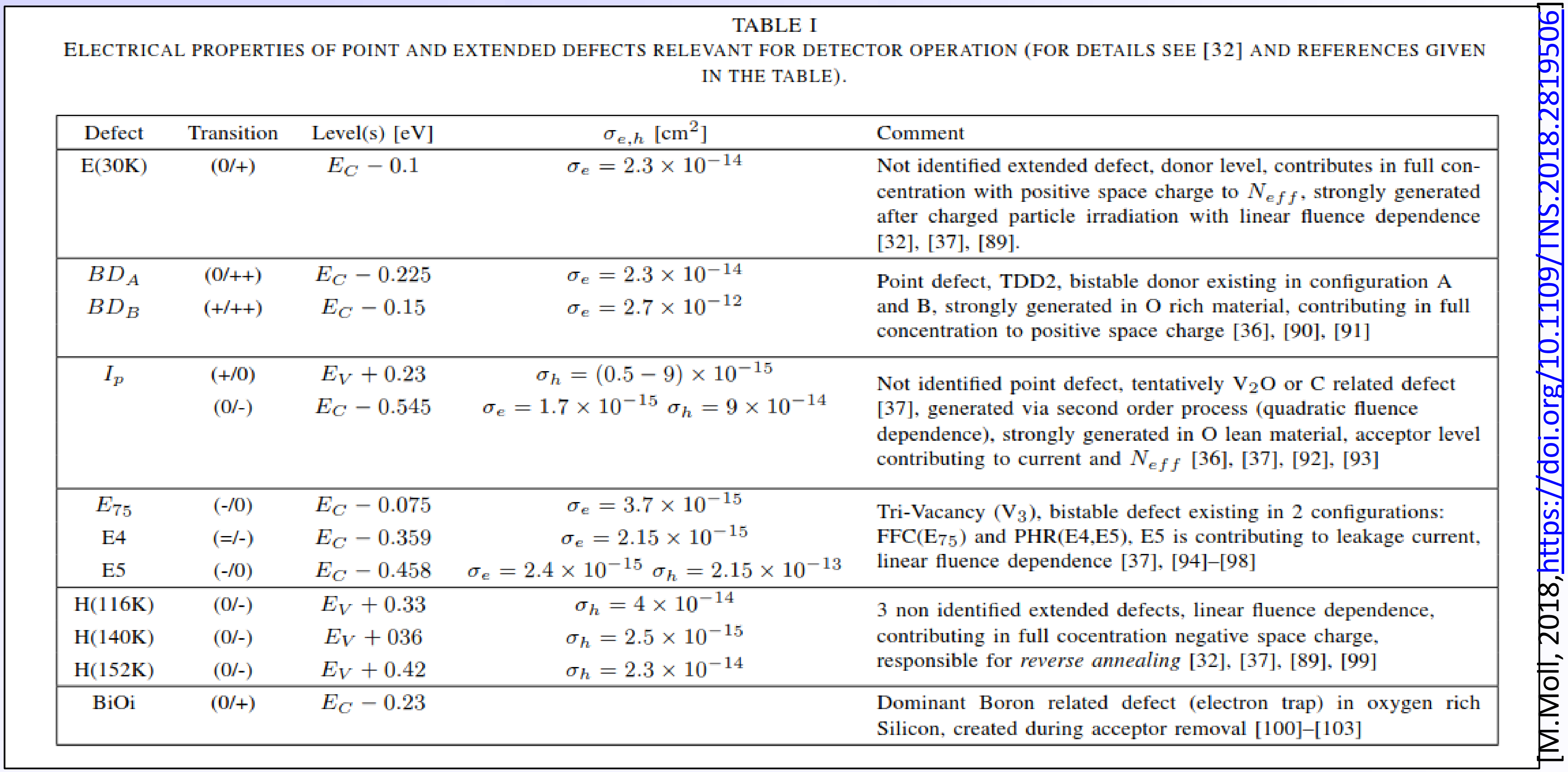
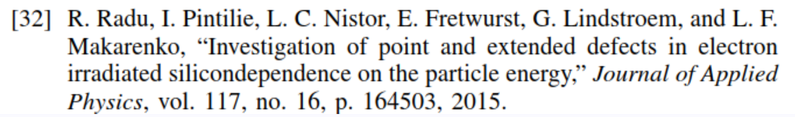


TABLE I

ELECTRICAL PROPERTIES OF POINT AND EXTENDED DEFECTS RELEVANT FOR DETECTOR OPERATION (FOR DETAILS SEE [32] AND REFERENCES GIVEN IN THE TABLE).

Defect	Transition	Level(s) [eV]	$\sigma_{e,h}$ [cm^2]	Comment
E(30K)	(0/+)	$E_C - 0.1$	$\sigma_e = 2.3 \times 10^{-14}$	Not identified extended defect, donor level, contributes in full concentration with positive space charge to N_{eff}, strongly generated after charged particle irradiation with linear fluence dependence [32], [37], [89].
BD_A	(0/++)	$E_C - 0.225$	$\sigma_e = 2.3 \times 10^{-14}$	Point defect, TDD2, bistable donor existing in configuration A and B, strongly generated in O rich material, contributing in full concentration to positive space charge [36], [90], [91]
BD_B	(+/++)	$E_C - 0.15$	$\sigma_e = 2.7 \times 10^{-12}$	
I_p	(+/0)	$E_V + 0.23$	$\sigma_h = (0.5 - 9) \times 10^{-15}$	Not identified point defect, tentatively V_2O or C related defect [37], generated via second order process (quadratic fluence dependence), strongly generated in O lean material, acceptor level contributing to current and N_{eff} [36], [37], [92], [93]
	(0/-)	$E_C - 0.545$	$\sigma_e = 1.7 \times 10^{-15}$ $\sigma_h = 9 \times 10^{-14}$	
E_{75}	(-/0)	$E_C - 0.075$	$\sigma_e = 3.7 \times 10^{-15}$	Tri-Vacancy (V_3), bistable defect existing in 2 configurations: FFC(E_{75}) and PHR(E4,E5), E5 is contributing to leakage current, linear fluence dependence [37], [94]–[98]
E4	(=/-)	$E_C - 0.359$	$\sigma_e = 2.15 \times 10^{-15}$	
E5	(-/0)	$E_C - 0.458$	$\sigma_e = 2.4 \times 10^{-15}$ $\sigma_h = 2.15 \times 10^{-13}$	
H(116K)	(0/-)	$E_V + 0.33$	$\sigma_h = 4 \times 10^{-14}$	3 non identified extended defects, linear fluence dependence, contributing in full cocentration negative space charge, responsible for *reverse annealing* [32], [37], [89], [99]
H(140K)	(0/-)	$E_V + 036$	$\sigma_h = 2.5 \times 10^{-15}$	
H(152K)	(0/-)	$E_V + 0.42$	$\sigma_h = 2.3 \times 10^{-14}$	
BiOi	(0/+)	$E_C - 0.23$		Dominant Boron related defect (electron trap) in oxygen rich Silicon, created during acceptor removal [100]–[103]

[M.Moll, 2018, https://doi.org/10.1109/TNS.2018.2819506]



[32] R. Radu, I. Pintilie, L. C. Nistor, E. Fretwurst, G. Lindstroem, and L. F. Makarenko, "Investigation of point and extended defects in electron irradiated silicondependence on the particle energy," *Journal of Applied Physics*, vol. 117, no. 16, p. 164503, 2015.

Radiation Damage Models
- Defect Parameters -

- **Several different models and tools are used within RD50 and other communities**

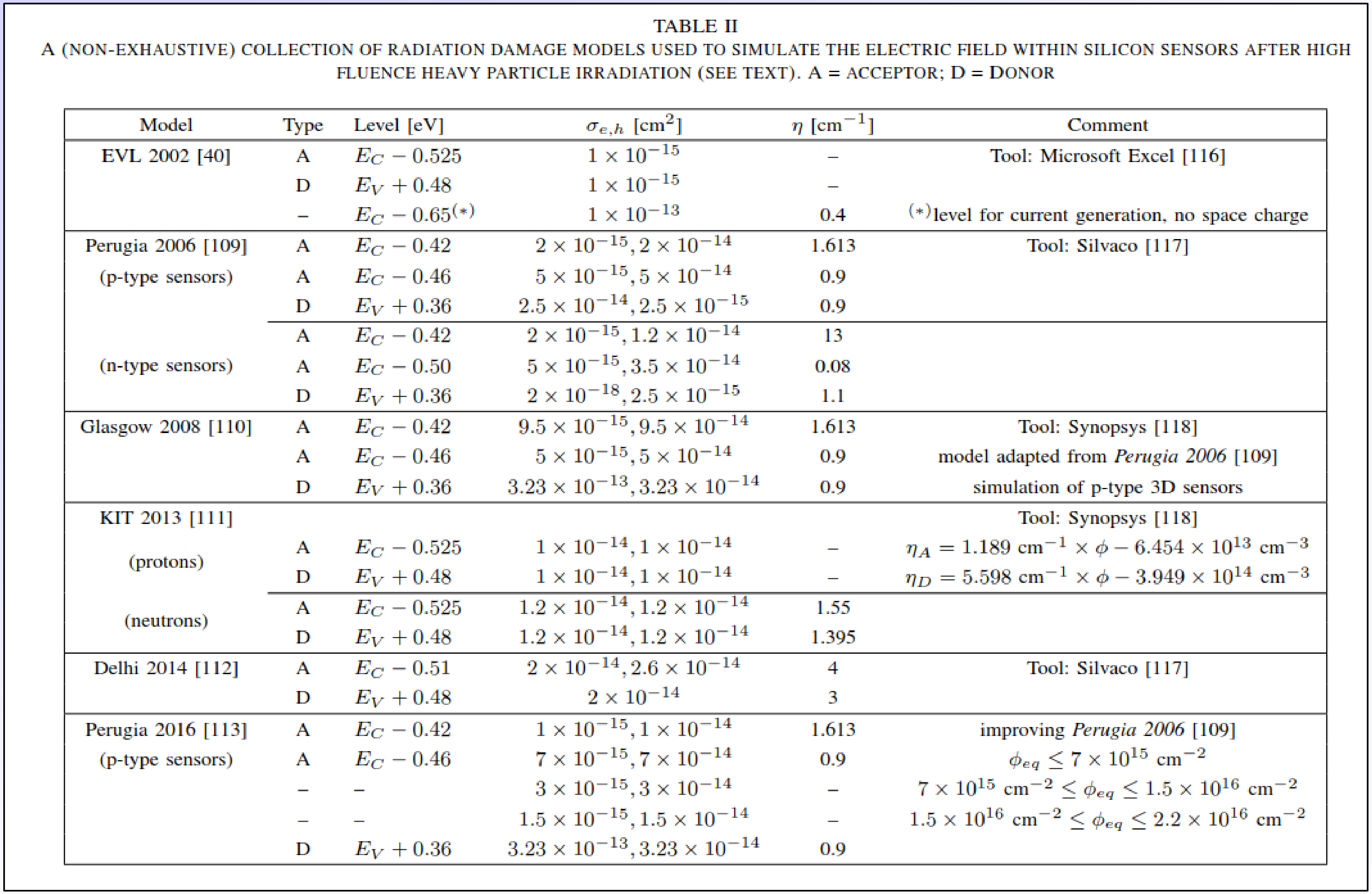


TABLE II

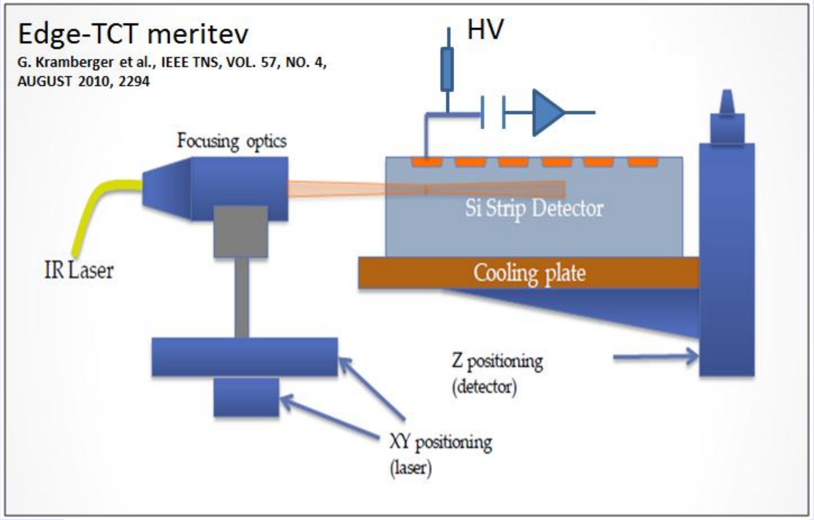
A (NON-EXHAUSTIVE) COLLECTION OF RADIATION DAMAGE MODELS USED TO SIMULATE THE ELECTRIC FIELD WITHIN SILICON SENSORS AFTER HIGH FLUENCE HEAVY PARTICLE IRRADIATION (SEE TEXT). A = ACCEPTOR; D = DONOR

Model	Type	Level [eV]	$\sigma_{e,h}$ [cm^2]	η [cm^{-1}]	Comment
EVL 2002 [40]	A	$E_C - 0.525$	1×10^{-15}	–	Tool: Microsoft Excel [116]
	D	$E_V + 0.48$	1×10^{-15}	–	
	–	$E_C - 0.65^{(*)}$	1×10^{-13}	0.4	$^{(*)}$level for current generation, no space charge
Perugia 2006 [109]	A	$E_C - 0.42$	$2 \times 10^{-15}, 2 \times 10^{-14}$	1.613	Tool: Silvaco [117]
(p-type sensors)	A	$E_C - 0.46$	$5 \times 10^{-15}, 5 \times 10^{-14}$	0.9	
	D	$E_V + 0.36$	$2.5 \times 10^{-14}, 2.5 \times 10^{-15}$	0.9	
(n-type sensors)	A	$E_C - 0.42$	$2 \times 10^{-15}, 1.2 \times 10^{-14}$	13	
	A	$E_C - 0.50$	$5 \times 10^{-15}, 3.5 \times 10^{-14}$	0.08	
	D	$E_V + 0.36$	$2 \times 10^{-18}, 2.5 \times 10^{-15}$	1.1	
Glasgow 2008 [110]	A	$E_C - 0.42$	$9.5 \times 10^{-15}, 9.5 \times 10^{-14}$	1.613	Tool: Synopsys [118]
	A	$E_C - 0.46$	$5 \times 10^{-15}, 5 \times 10^{-14}$	0.9	model adapted from *Perugia 2006* [109]
	D	$E_V + 0.36$	$3.23 \times 10^{-13}, 3.23 \times 10^{-14}$	0.9	simulation of p-type 3D sensors
KIT 2013 [111]					Tool: Synopsys [118]
(protons)	A	$E_C - 0.525$	$1 \times 10^{-14}, 1 \times 10^{-14}$	–	$\eta_A = 1.189$ cm$^{-1} \times \phi - 6.454 \times 10^{13}$ cm^{-3}
	D	$E_V + 0.48$	$1 \times 10^{-14}, 1 \times 10^{-14}$	–	$\eta_D = 5.598$ cm$^{-1} \times \phi - 3.949 \times 10^{14}$ cm^{-3}
(neutrons)	A	$E_C - 0.525$	$1.2 \times 10^{-14}, 1.2 \times 10^{-14}$	1.55	
	D	$E_V + 0.48$	$1.2 \times 10^{-14}, 1.2 \times 10^{-14}$	1.395	
Delhi 2014 [112]	A	$E_C - 0.51$	$2 \times 10^{-14}, 2.6 \times 10^{-14}$	4	Tool: Silvaco [117]
	D	$E_V + 0.48$	2×10^{-14}	3	
Perugia 2016 [113]	A	$E_C - 0.42$	$1 \times 10^{-15}, 1 \times 10^{-14}$	1.613	improving *Perugia 2006* [109]
(p-type sensors)	A	$E_C - 0.46$	$7 \times 10^{-15}, 7 \times 10^{-14}$	0.9	$\phi_{eq} \leq 7 \times 10^{15}$ cm^{-2}
	–	–	$3 \times 10^{-15}, 3 \times 10^{-14}$	–	7×10^{15} cm$^{-2} \leq \phi_{eq} \leq 1.5 \times 10^{16}$ cm^{-2}
	–	–	$1.5 \times 10^{-15}, 1.5 \times 10^{-14}$	–	1.5×10^{16} cm$^{-2} \leq \phi_{eq} \leq 2.2 \times 10^{16}$ cm^{-2}
	D	$E_V + 0.36$	$3.23 \times 10^{-13}, 3.23 \times 10^{-14}$	0.9	

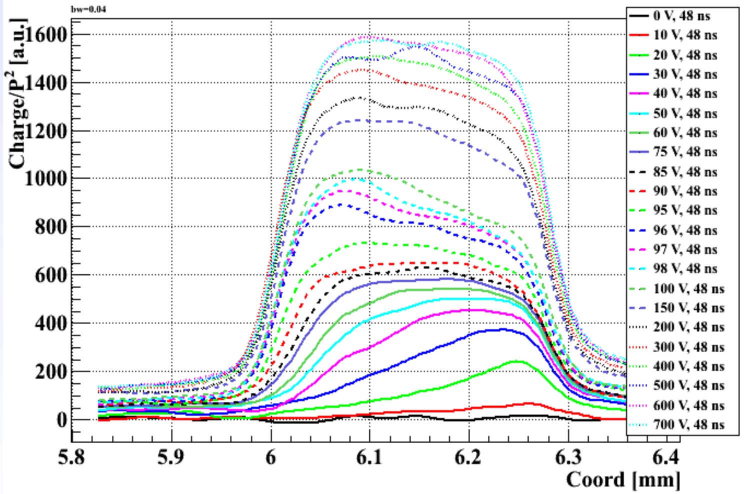
[M.Moll, 2018,https://doi.org/10.1109/TNS.2018.2819506]

Studying the electric field

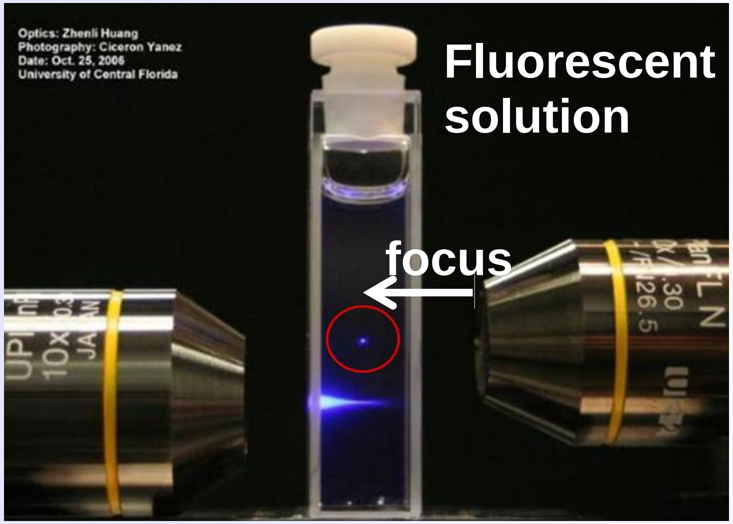
RD50 investigation methods: Edge TCT. Charge generation, charge velocity and electric field profile.


Edge-TCT meritev

G. Kramberger et al., IEEE TNS, VOL. 57, NO. 4, AUGUST 2010, 2294

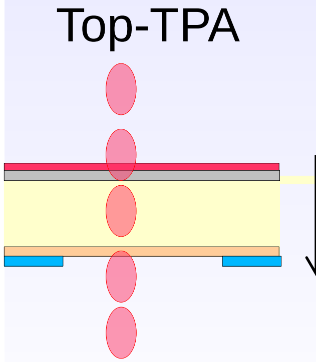


TPA: Two Photon Absorption

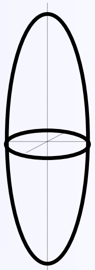


Single Photon Absorption

Two Photon Absorption



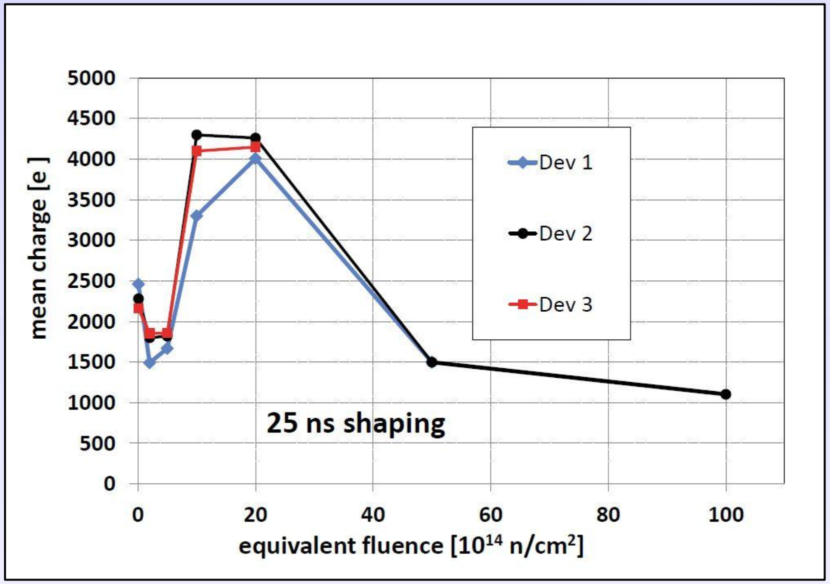
Two Photons must be **coincident in time** (pulsed **mode-locked** lasers) and in **space** (**microfocusing**)

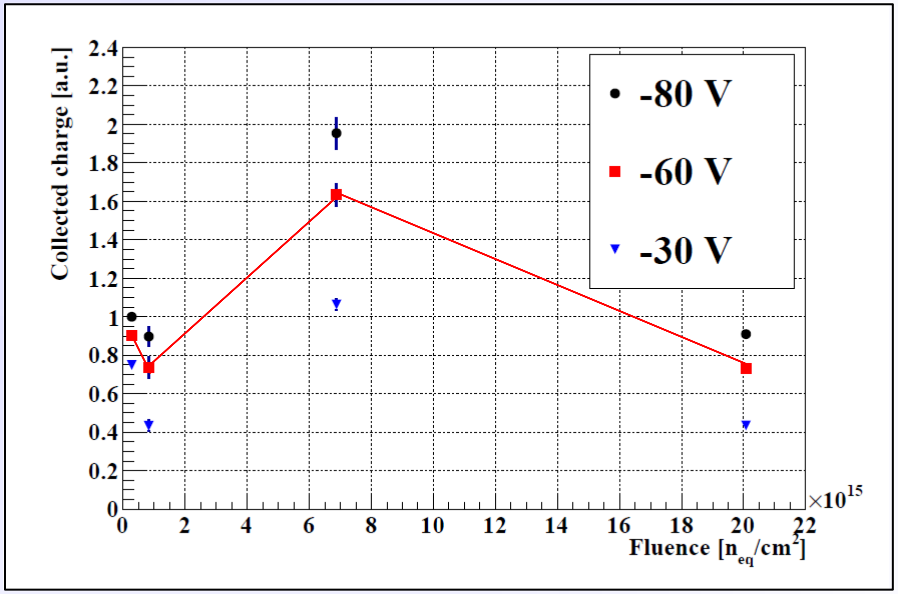


×**100** objective

HVCMOS – CCE as function of fluence

- **350nm – neutron irradiation**
  - AMS, 350nm, CHESS-1, 20 Ωcm ($7 \cdot 10^{14}$cm^{-3})
  - 2mm x 2mm passive sensor (400 pixel)
  - Sr^{90}, 25 ns shaping, 120 V
- **180nm – neutron irradiation**
  - AMS, 180nm, HV2FEI4, 10 Ωcm ($1.4 \cdot 10^{15}$cm^{-3})
  - 100μm x 100 μm passive pixel
  - IR-laser, 5 ns integration



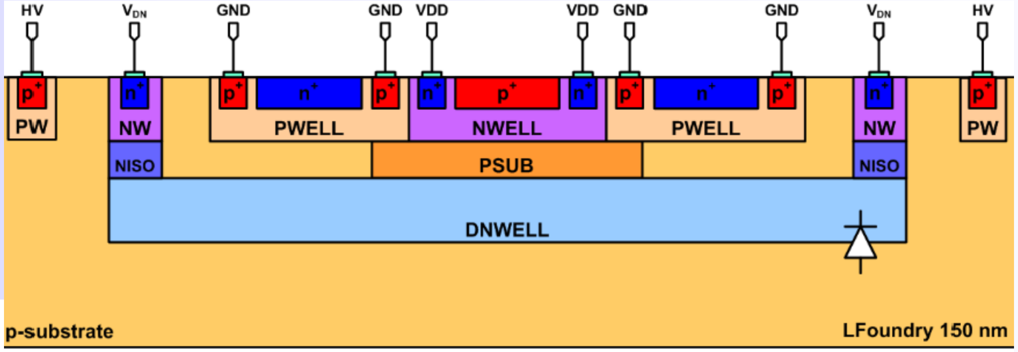


[M.Fernandez-Garcia et al, 2016 JINST 11 P02016]

- **CCE rising above initial value for fluences in order of some 10^{15} n_{eq}/cm^2**
  - Up to about 10^{15} n_{eq}/cm^2 CCE decreases [diffusing charge gets trapped]
  - Above about 10^{15} n_{eq}/cm^2 CCE rises above initial value [reduction of N_{eff}, "acceptor removal"]
  - Above some 10^{15} n_{eq}/cm^2 CCE finally degrading [trapping, increase of space charge N_{eff}]

RD50 and HV-CMOS

HV-CMOS: key technology for the future of experiments



RD50-ENGRUN1

Aims

- Improve the current time resolution of HV-CMOS sensors (by a factor 10)
- Implement different sensor cross-sections
- Study options to increase the device area beyond the reticle size limitation
- Measure the sensors performance after a wide range of fluences

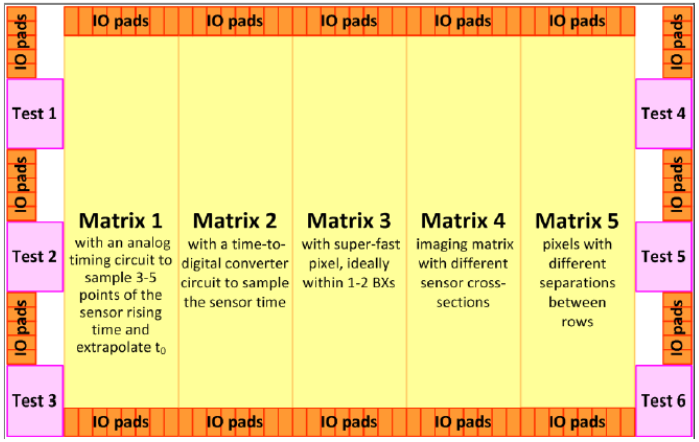
Technology

- 150 nm HV-CMOS from LFoundry
- Large area submission (2 cm x 2 cm, engineering run)

Design effort

- FBK (N. Massari, M. Perenzoni and C. Zhang)
- IFAE (R. Casanova)
- Uni. Barcelona (O. Alonso, +1)
- Uni. Liverpool (S. Powell, E. Vilella and C. Zhang)
- Uni. Seville (F. Muñoz and R. Palomo)

TCAD simulations + DAQ development



Matrix 1 with an analog timing circuit to sample 3-5 points of the sensor rising time and extrapolate t_0

Matrix 2 with a time-to-digital converter circuit to sample the sensor time

Matrix 3 with super-fast pixel, ideally within 1-2 BXs

Matrix 4 imaging matrix with different sensor cross-sections

Matrix 5 pixels with different separations between rows

Test structure 1	Simple CMOS capacitors to study oxide thickness
Test structure 2	10 x 10 matrix of very small pixels with passive RO
Test structure 3	10 x 10 matrix of very small pixels with 3T-like RO
Test structure 4	Small matrix of pixels for TCT, e-TCT and TPA-TCT
Test structure 5	Single pixels for sensor capacitance measurements
Test structure 6	…

UNIVERSITY OF LIVERPOOL

8/16 Eva Vilella – 32nd RD50 Workshop – Hamburg, 4-6 Jun. 2018

4D Tracking

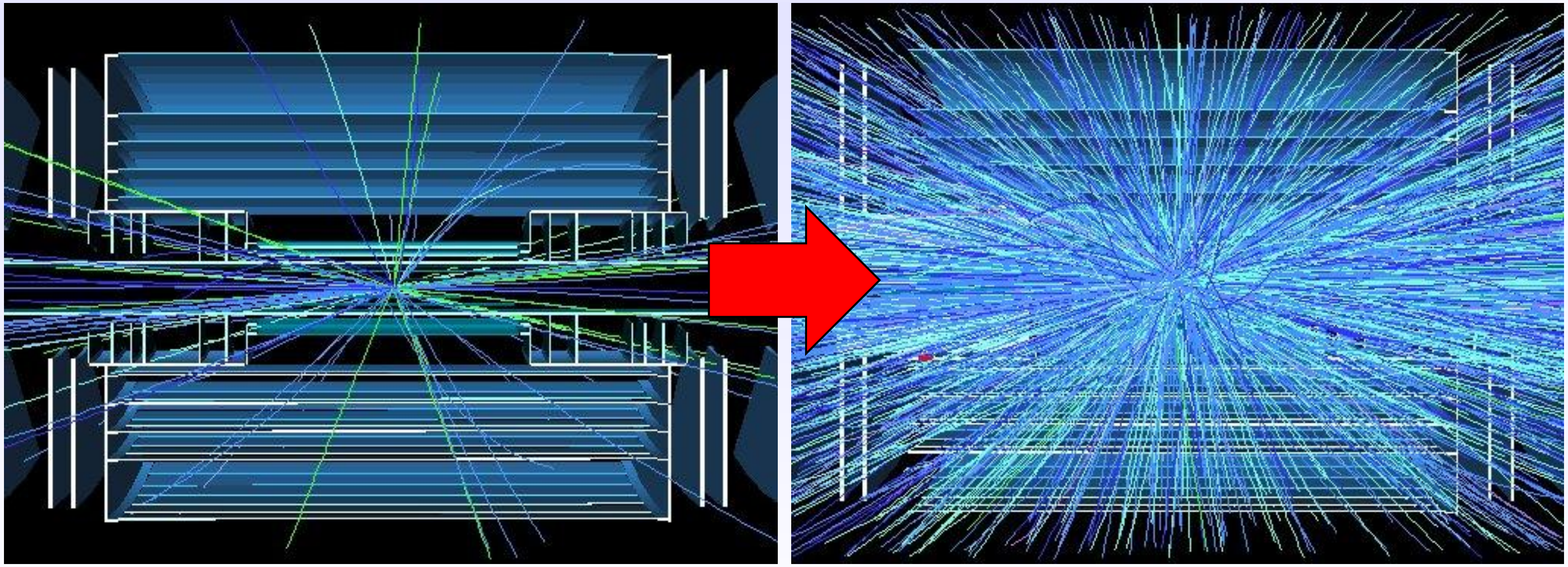
RD50 development for 4D tracking: LGAD (Low Gain Avalanche Diodes) or UFSD (Ultra Fast Silicon Detectors).

Inspired by the Charge Multiplication effect.

Stimulated attention of HL-LHC experiments:

Pile-up mitigation. Performance required: $t_{res} < 50$ ps

Limitation to overcome: radiation tolerance to some 10^{15} n_{eq} cm^{-2}. Improving the fill factor.

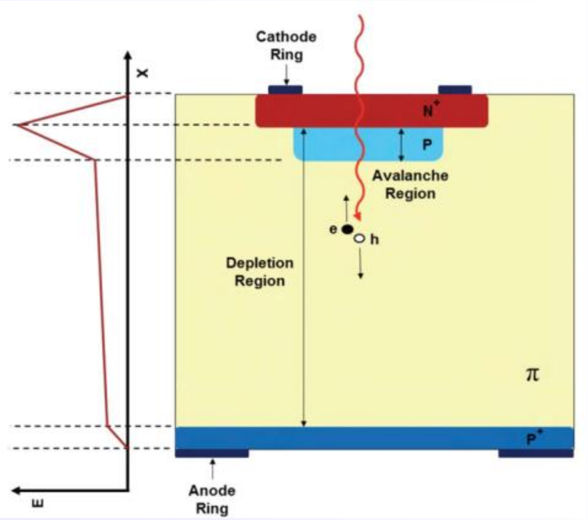


4D Tracking

Idea suggested by charge multiplication in silicon.
Low gain (<< 100) silicon detectors (LGAD) have been proposed for 4D tracking: combine the high spatial resolution of segmented silicon sensors with avalanche multiplication for producing high S/N devices.
This can achieve time resolutions < 100 ps. Several application possible, also Timing Layers for primary vertices disentanglement at the HL-LHC.
Pioneered within RD50, first devices fabricated by foundries within RD50: CNM, FBK.

Principle:

Add to n-on-p Silicon sensor an extra thin p-layer below th junction which increases the E-field so that charge multiplication with **moderate gain** of 10-50 occurs without breakdown.



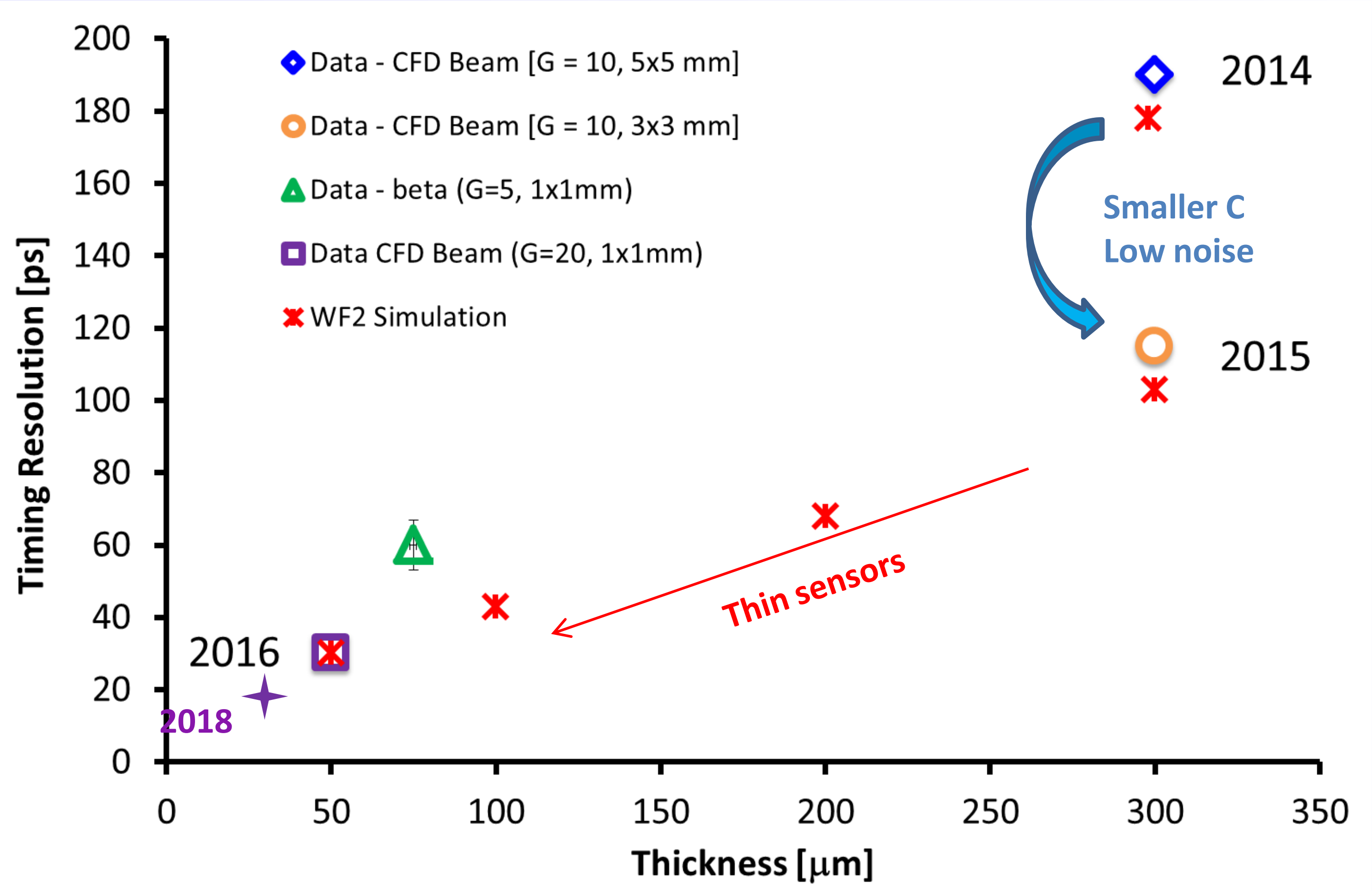
Timing resolution:

$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$

$$\sigma_{TimeWalk} = [\frac{V_{th}}{S/t_{rise}}]_{RMS} \propto \left[\frac{N}{\frac{dV}{dt}}\right]_{RMS} , \quad \sigma_{Jitter} = \frac{N}{dV/dt} \approx \frac{t_{rise}}{S/N}$$

- Maximize slope dV/dt (i.e. large and fast signals)
- Signal ~ gain, expect jitter ~ 1/G
- Minimize noise N

4D tracking



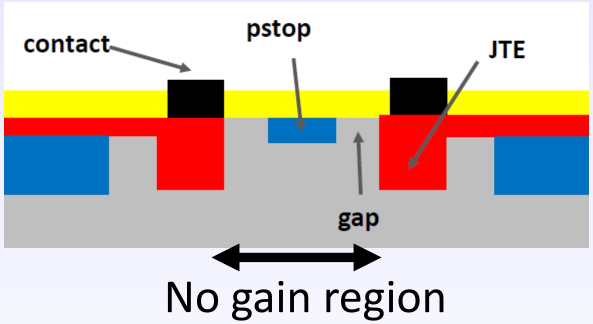
Hartmut F.-W. Sadrozinski, "UFSD Timing", RD50 June 2018

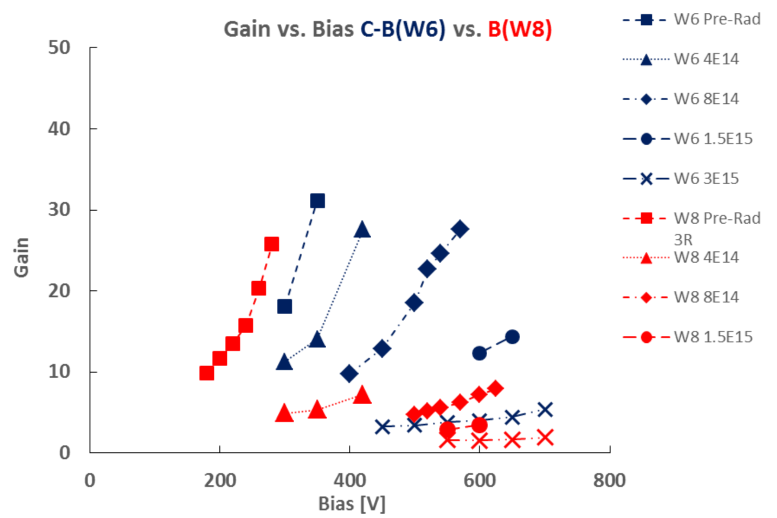
4D tracking

Improvements on LGAD's:

Radiation tolerance: in HL-LHC the timing layer sensors would need to operate up to 1-2 x 10^{15} n_{eq} cm^{-2}.

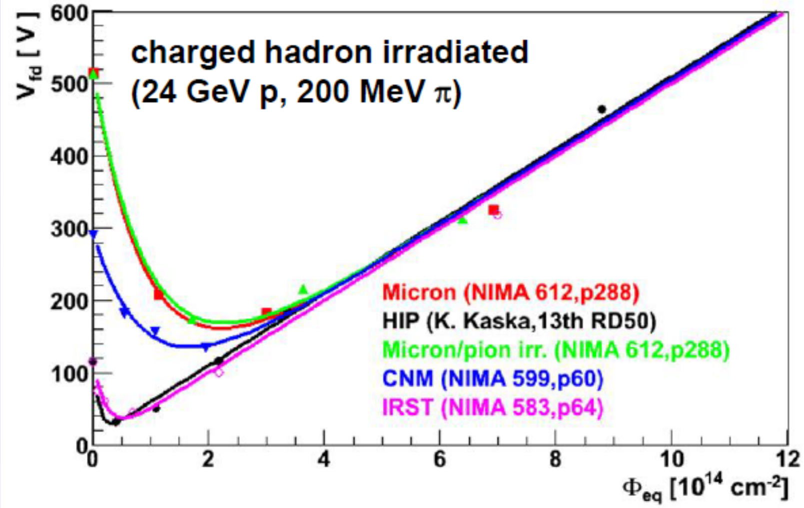
Fill factor: the shaping of the electric field at the edge of the multiplication region introduces no-Gain areas in the detector.

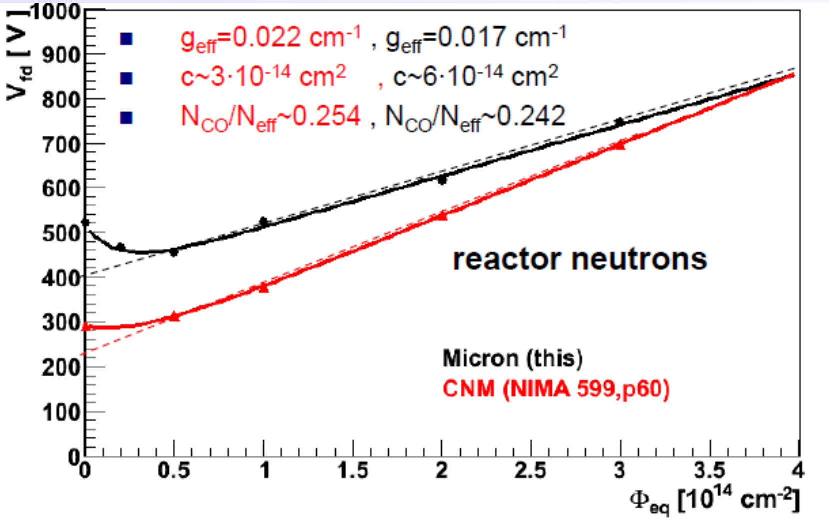


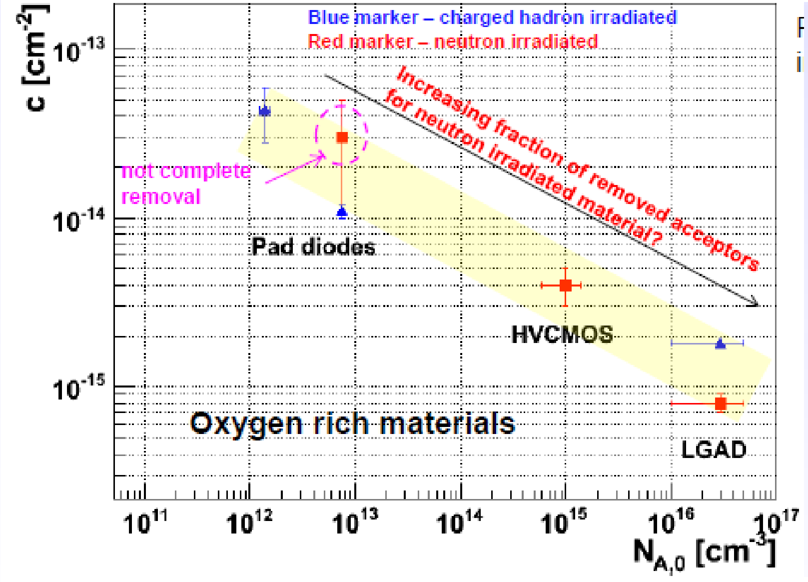


Radiation hardness studies of LGADs

Gain reduction caused by acceptor removal.







$$V_{mr} = V_{mr,0} \cdot \exp(-c \cdot \Phi_{eq})$$

G. Kramberger, Initial acceptor removal in p-type silicon, 10th Trento Workshop, 2015, Trento

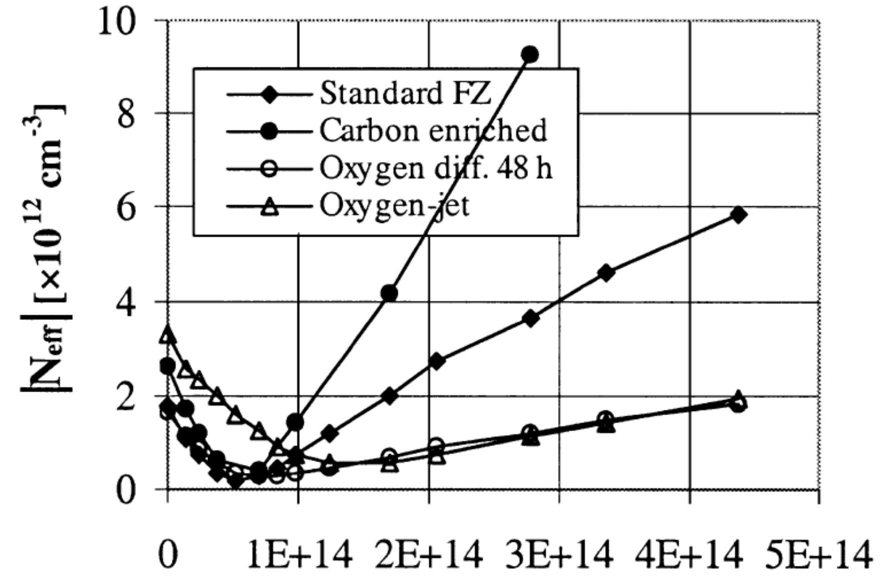
Radiation hardness studies of LGADs

Mitigating acceptor removal.

Changes of the p-doping layer: Ga instead of B?

Old results can also help (crystal engineering)

Proton irradiated Carbon enriched Si FZ diodes exhibit faster acceptor introduction rates. This can be used for compensating for the acceptor removal (C layer should much the depth profile of the multiplication p-ayer).



A. Ruzin et a., "Radiation effects in silicon detectors processed on carbon and oxygen-rich substrates", Mat. Science in Sem. Processing 3, pp. 257-261 (2000)

Radiation hardness studies of LGADs

Changes of the p-doping layer: Ga instead of B?

Old results can also help (crystal engineering)

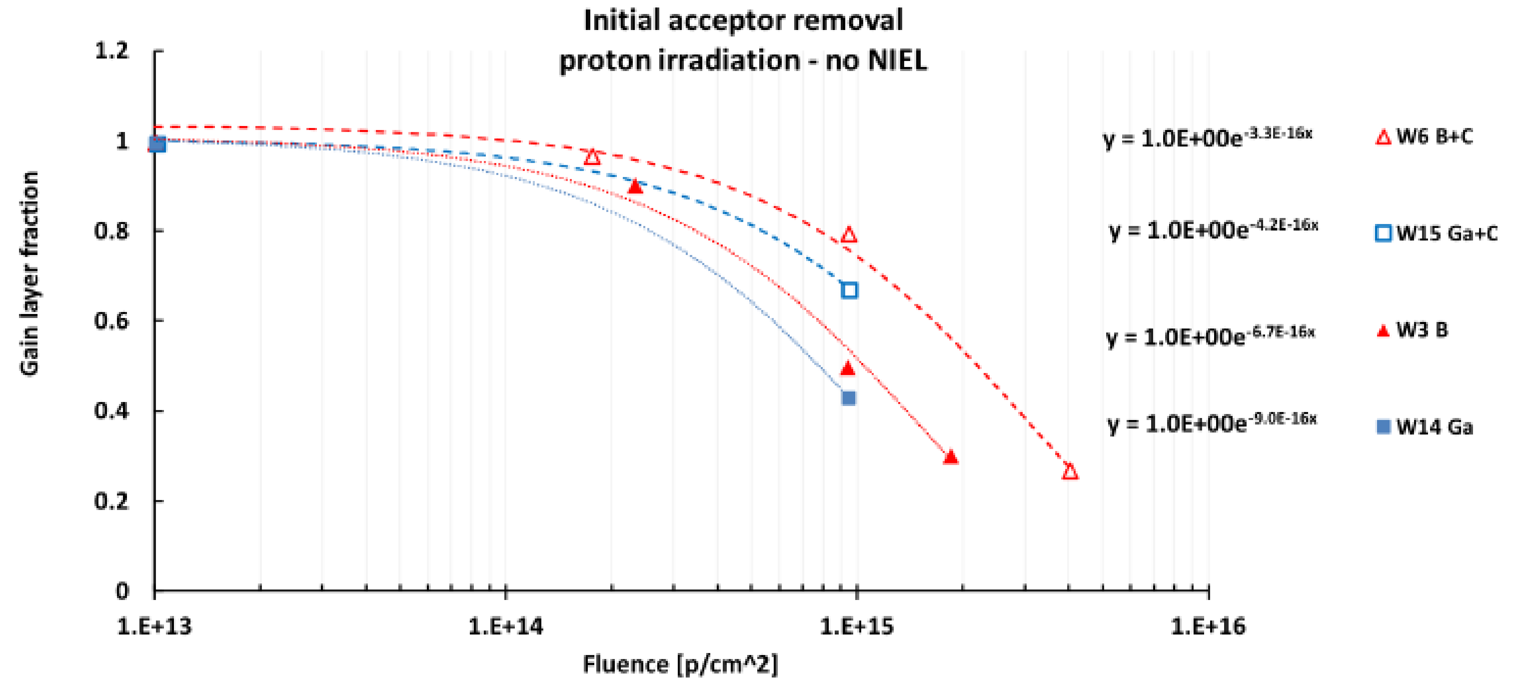
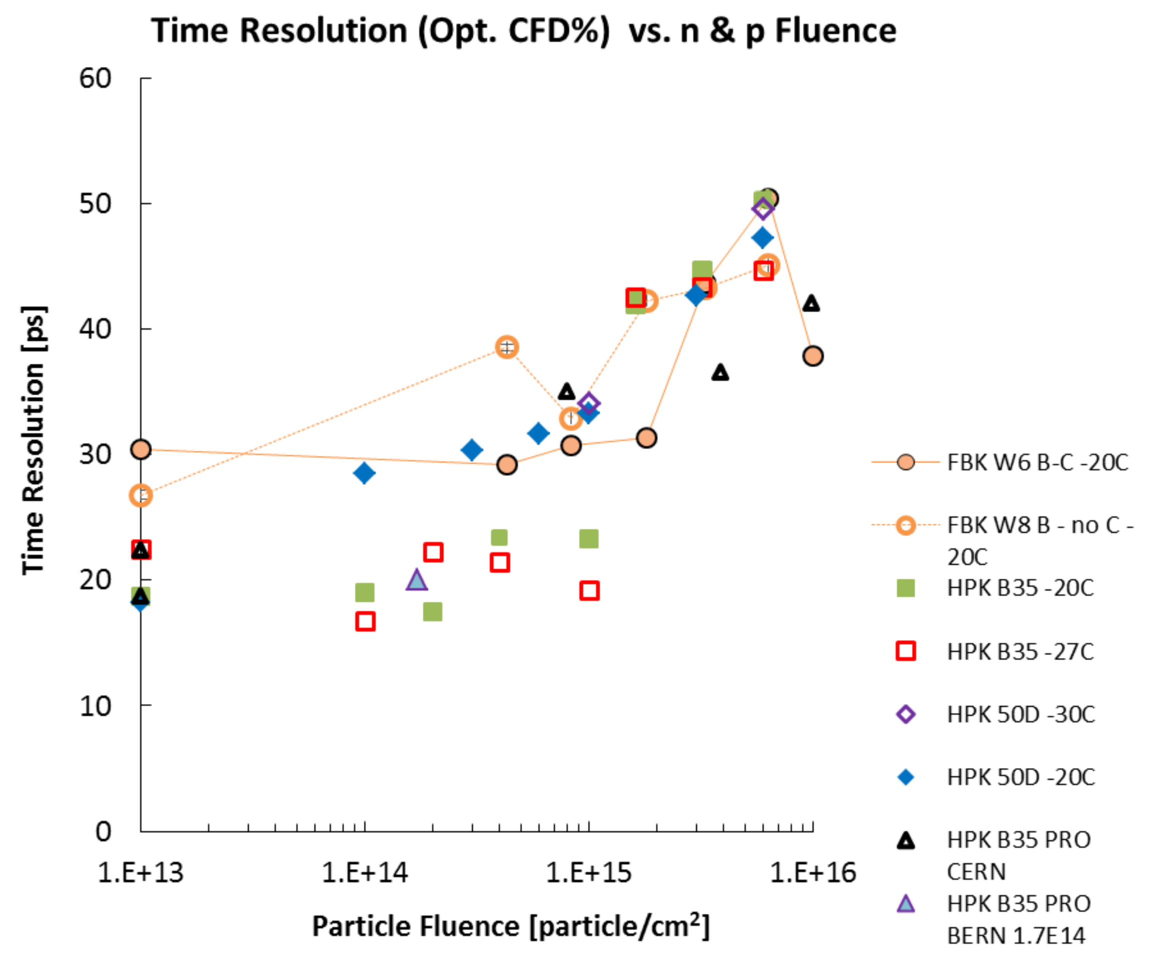


Figure 13: Fraction of gain layer still active as a function of proton irradiation.

Radiation hardness studies of LGADs



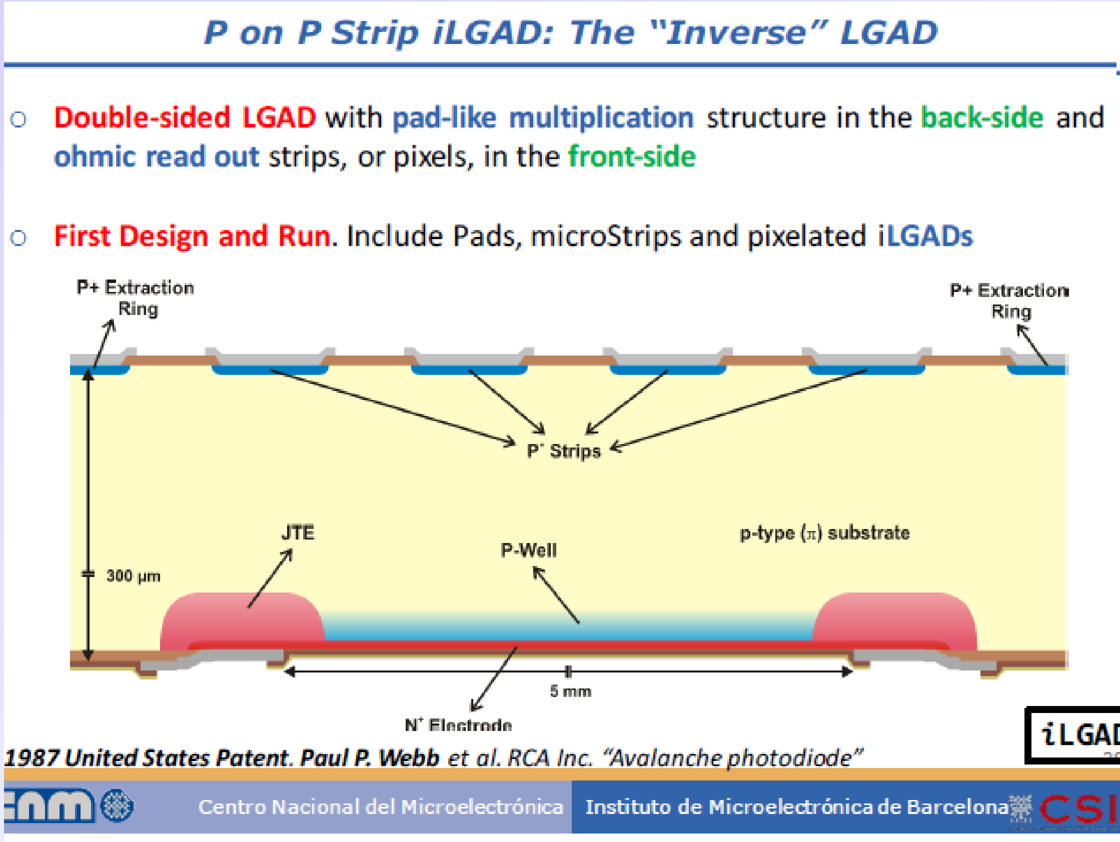
Measurements were done with the UC Santa Cruz β-telescope

Protons seem to damage less
Thickness matters at fluences up to 1E15 neq/cm^2 since Jitter is small, Landau fluctuations dominate
Carbon Infusion helps up to 3E15 neq/cm^2

HPK 50µm: Z. Galloway et al, https://arxiv.org/abs/1707.04961
Comparison HPK 35 & 50µm: Z. Zhao et al, https://arxiv.org/abs/1803.02690
FBK Gallium and Carbon S. Mazza et al, https://arxiv.org/abs/1804.05449

Hartmut F.-W. Sadrozinski, "UFSD Timing", RD50 June 2018

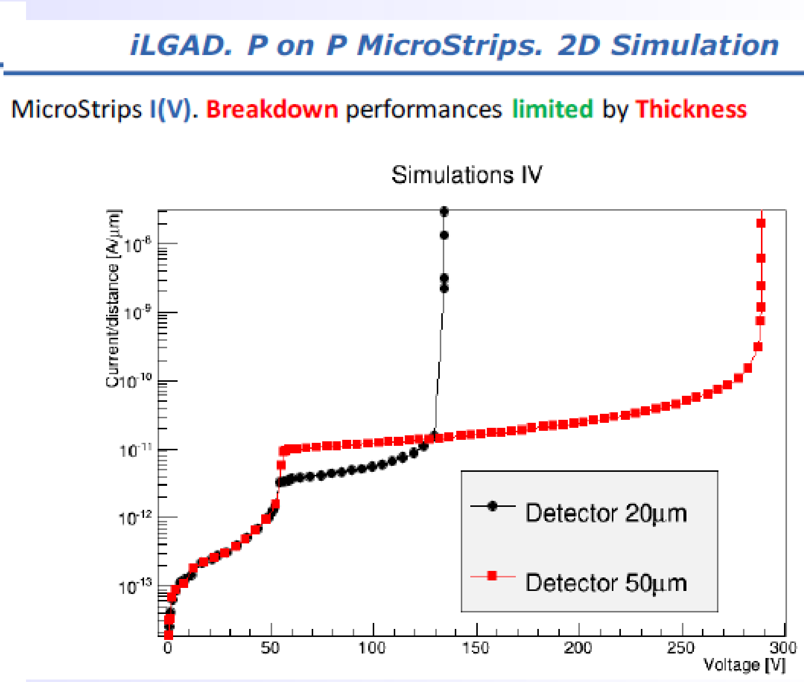
Improving the fill factor of LGADs



P on P Strip iLGAD: The "Inverse" LGAD

- **Double-sided LGAD** with **pad-like multiplication** structure in the **back-side** and **ohmic read out** strips, or pixels, in the **front-side**
- **First Design and Run**. Include Pads, microStrips and pixelated **iLGADs**

1987 United States Patent. Paul P. Webb et al. RCA Inc. "Avalanche photodiode"



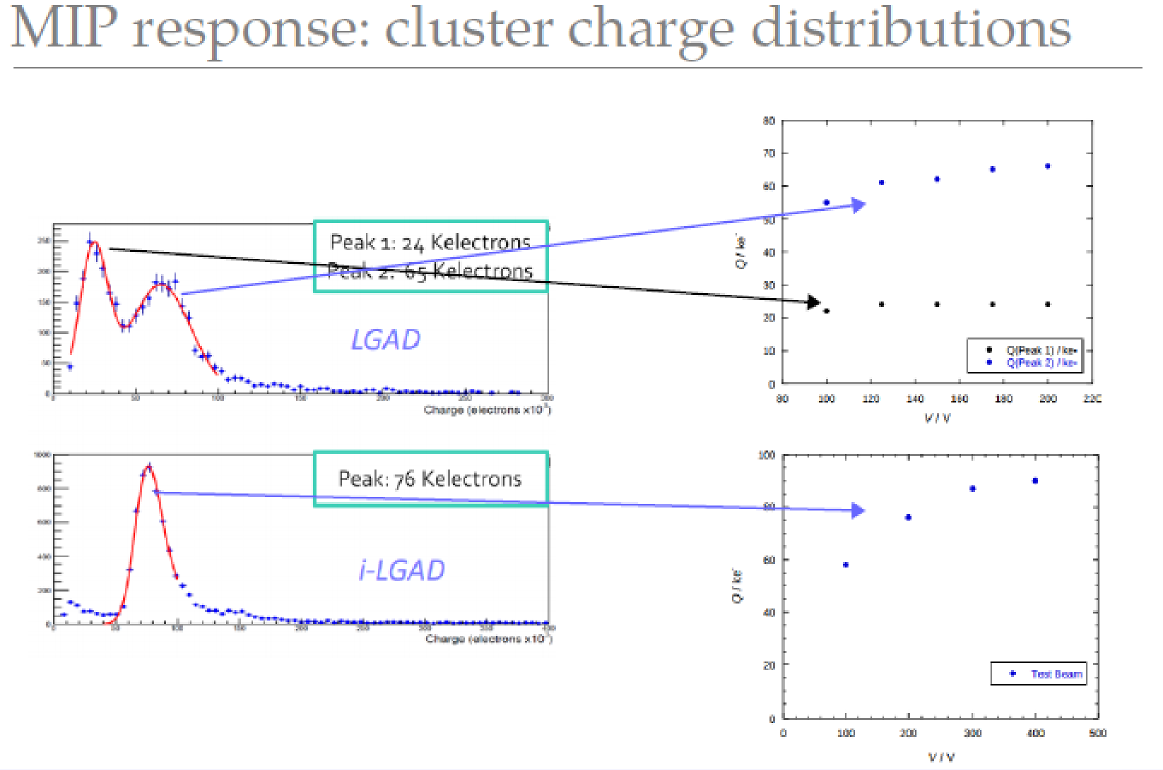
iLGAD. P on P MicroStrips. 2D Simulation

MicroStrips I(V). **Breakdown** performances **limited** by **Thickness**

Simulations IV

S. Hidalgo et al., 27th RD50 meeting, 3/12/2015, CERN

Improving the fill factor of LGADs



MIP response: cluster charge distributions

Peak 1: 24 Kelectrons
Peak 2: 65 Kelectrons

LGAD

Peak: 76 Kelectrons

i-LGAD

J. Duarte-Campderrós 31st RD50 Workshop (CERN) Geneve, Nov. 21st 2017

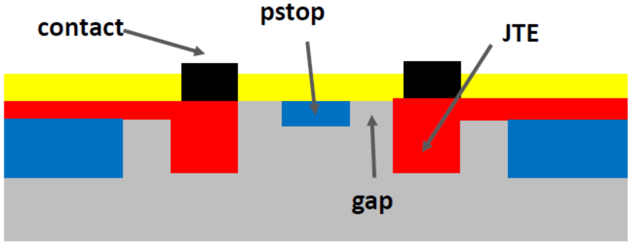
Improving the fill factor of LGADs

Current technology (FBK UFSD2)

- Detectors with internal gain are typically affected by Fill Factor reduction.
- Two regions are present :
  - i) GAIN region (pixel core)
  - ii) NO-GAIN region (pixel border)

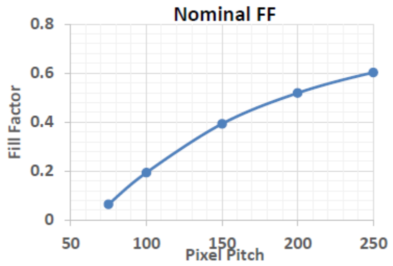
$$\text{Fill Factor} = \frac{\text{gain area}}{\text{total area}}$$

- The pixel border is a dead-region. The carriers generated in this area are not multiplied.



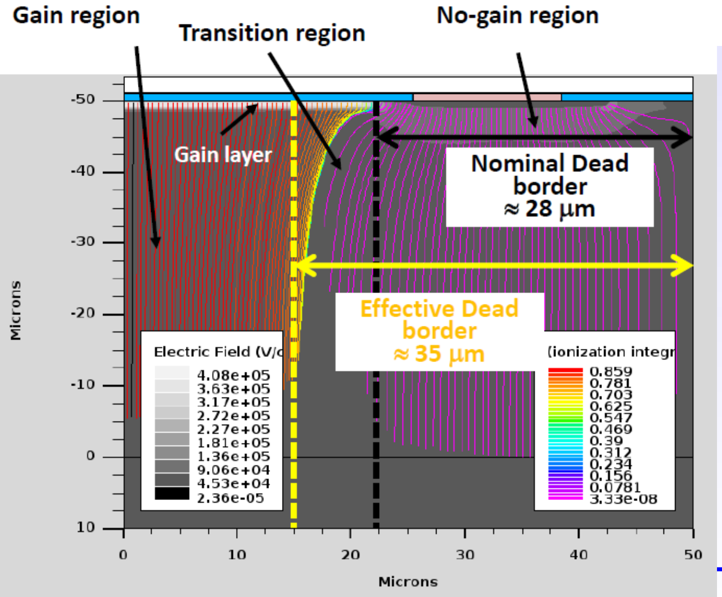
- The pixel border region is necessary to host all the structures to control the E field (JTE, p-stop, etc..). Its dimensions are due to design and technology constraints

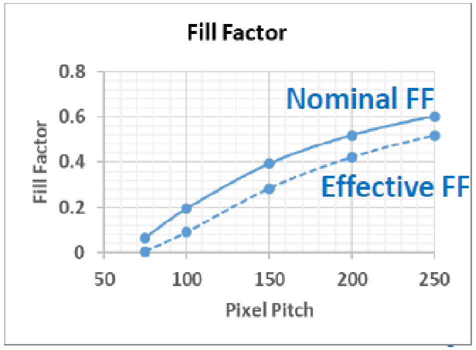
The minimum pixel (strip) dimension are dominated by the Fill Factor. Small pixels are not feasible.



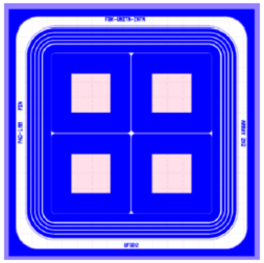
Measured no-gain area width:

- HPK: 100 µm
- FBK: 70 µm
- CNM: 70 µm

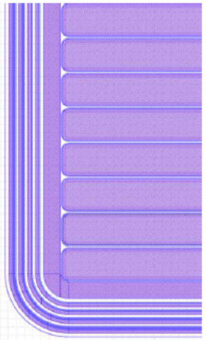




1x1 mm² pixels
- > FF = 87%

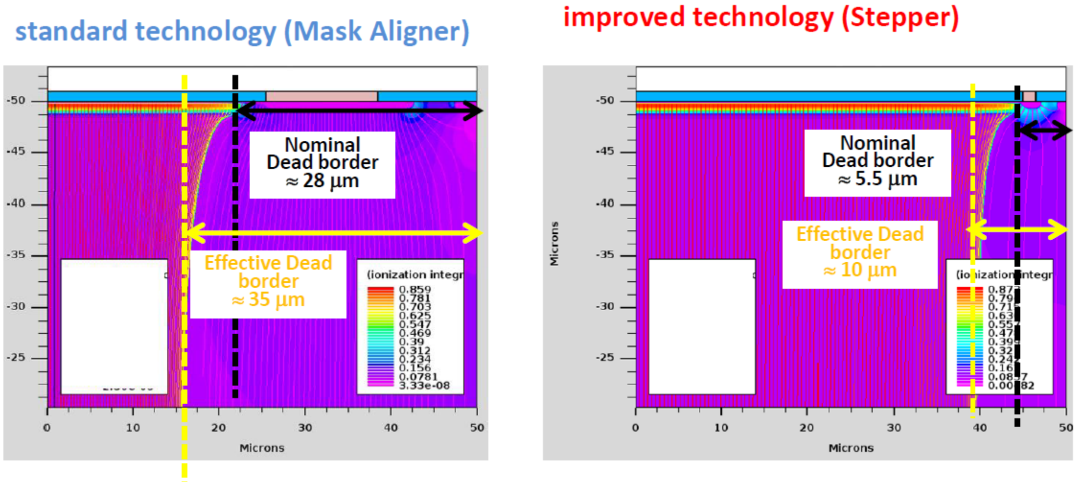


200 µm Strips
- > FF = 66%



CMM
CENTRE FOR MATERIALS AND MICROSYSTEM

Improving the fill factor of LGADs

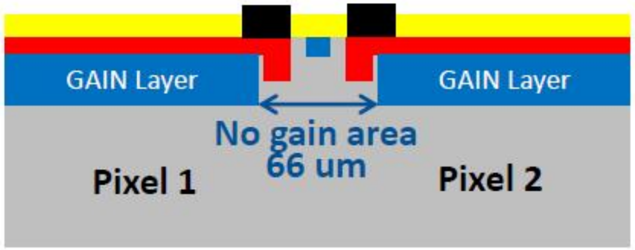

standard technology (Mask Aligner)

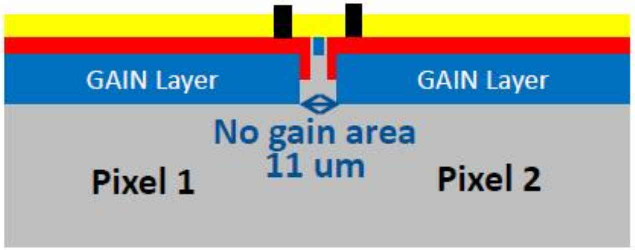
improved technology (Stepper)

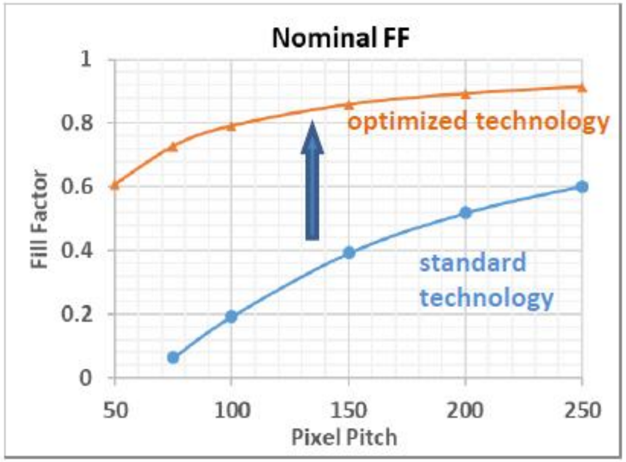
x6 reduction in nominal dead border region

but only a x3 reduction in the effective dead boarder Region. The transition region width is an intrinsic limit of this design

CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS







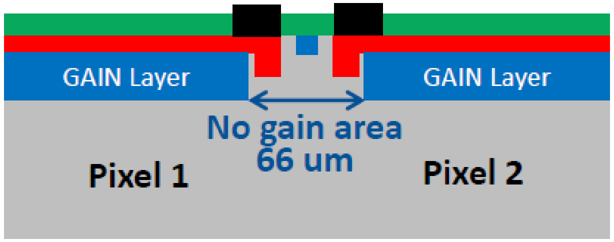
Improving the fill factor of LGADs

FONDAZIONE BRUNO KESSLER

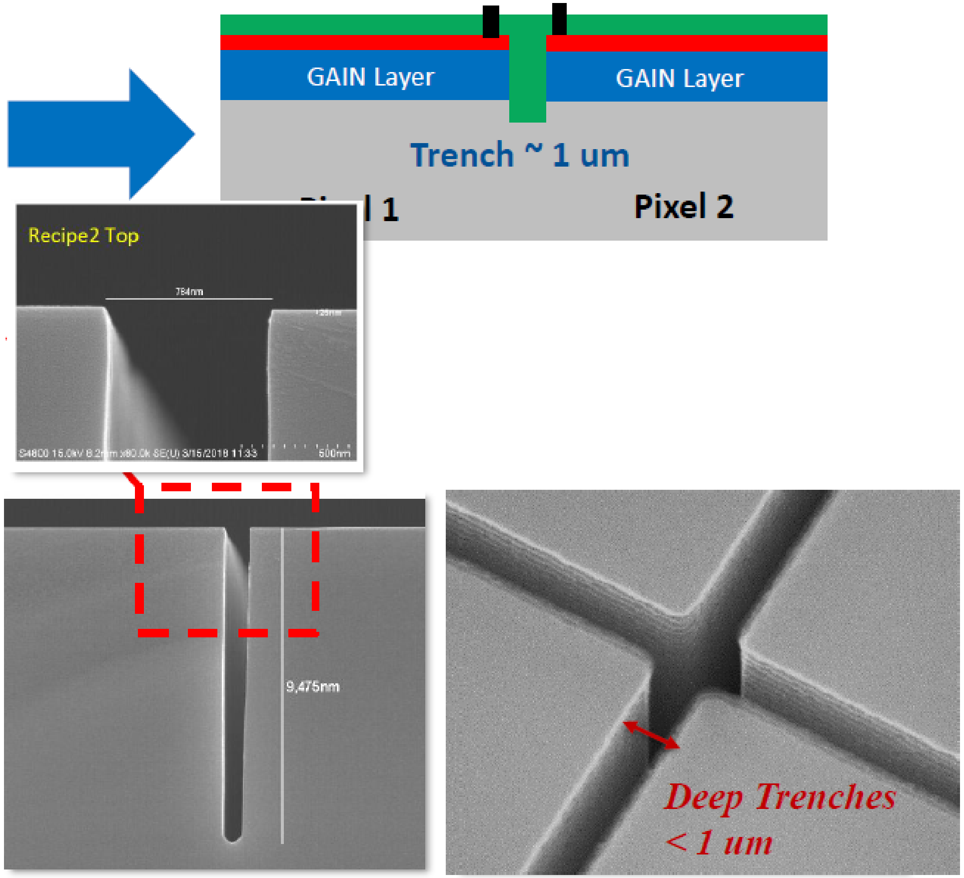
New strategies to improve FF

2nd Option: Trench isolation LGAD

Standard JTE + p-stop isolation



Trench Isolation



- Trench isolation could drastically reduce the inter-pixel border region down to few microns

Trench isolation technology

- Typical trench width < 1 um
- Max Aspect ratio: 1:20
- Trench filling with: SiO_2, Si_3N_4, PolySi

CMM
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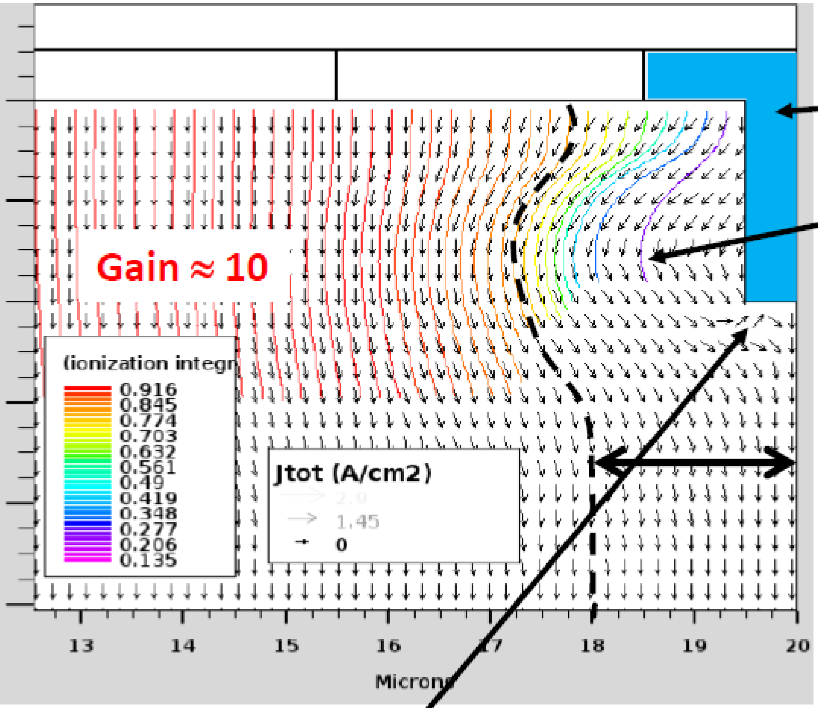
Improving the fill factor of LGADs



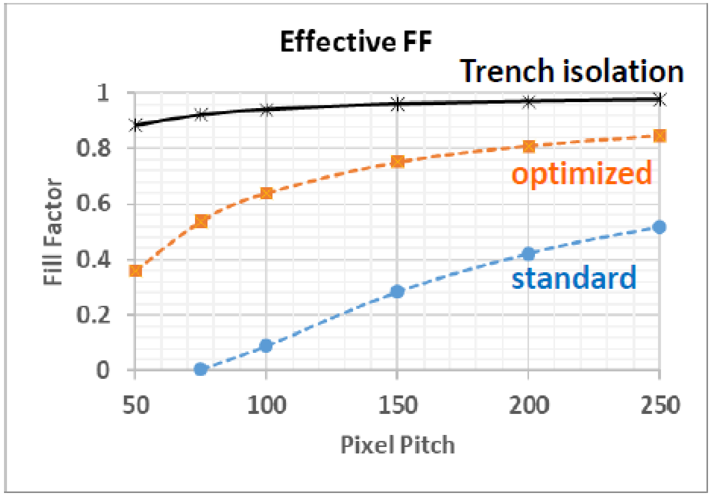
Isolation trench

The Electric field lines wrap up the trench. → the charges are collected and pushed through the multiplication region

Dead border ≈ 2-3 μm

Possible risk:

Charge Collection from trenches surface (high defectiveness), even if no multiplication occurs at trenches interface



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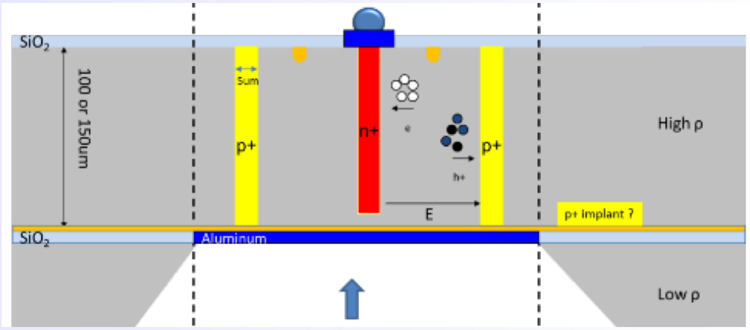
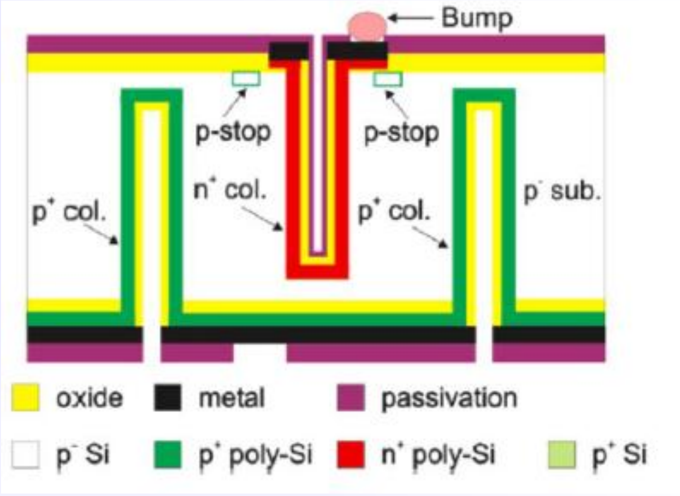
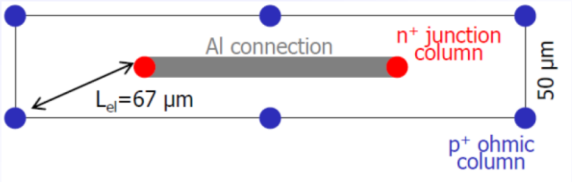
Ultra-high radiation tolerance

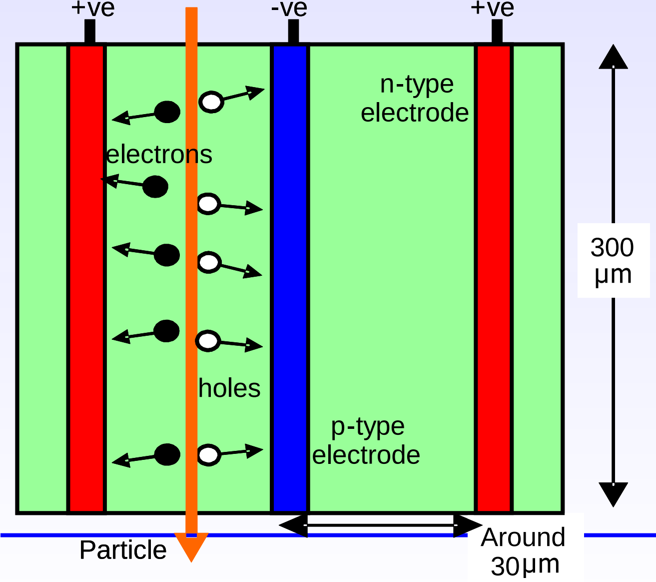
- Array of electrode columns passing through substrate
- Electrode spacing << wafer thickness (e.g. 30µm:300µm)
- Benefits
  - $V_{depletion}$ (Electrode spacing)^2
  - Collection time Electrode spacing
  - Reduced charge sharing
- More complicated fabrication - micromachining

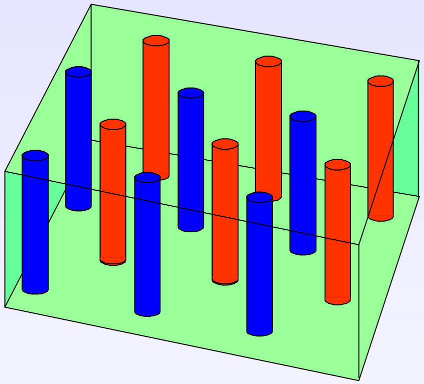






Proposed by S. Parker and C. Kenney in 1995.

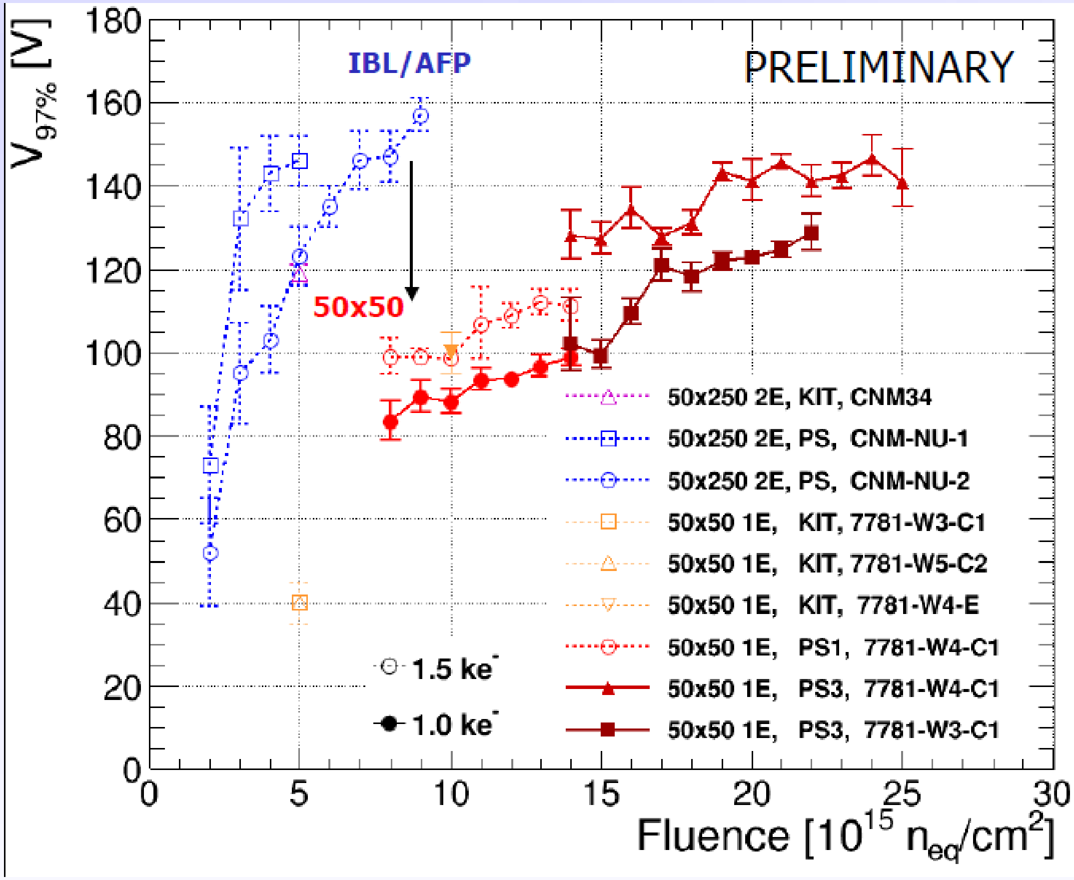




Ultra-high radiation tolerance

3D sensors efficient after 3×10^{16} n_{eq} cm^{-2}!

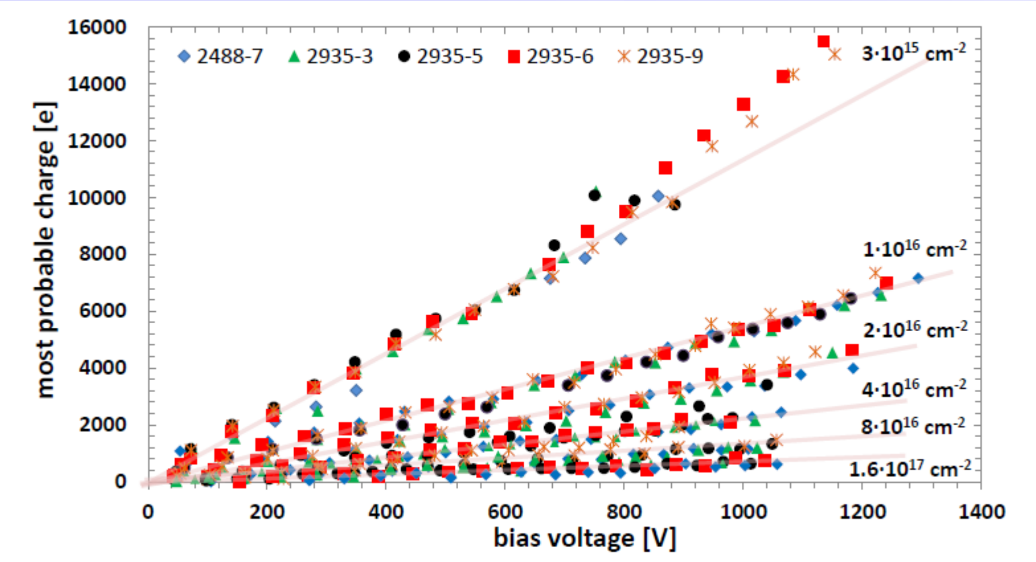
J. Lange, 3D detectors for the LHC, 31/11/17, 31st RD50 meeting, CERN.

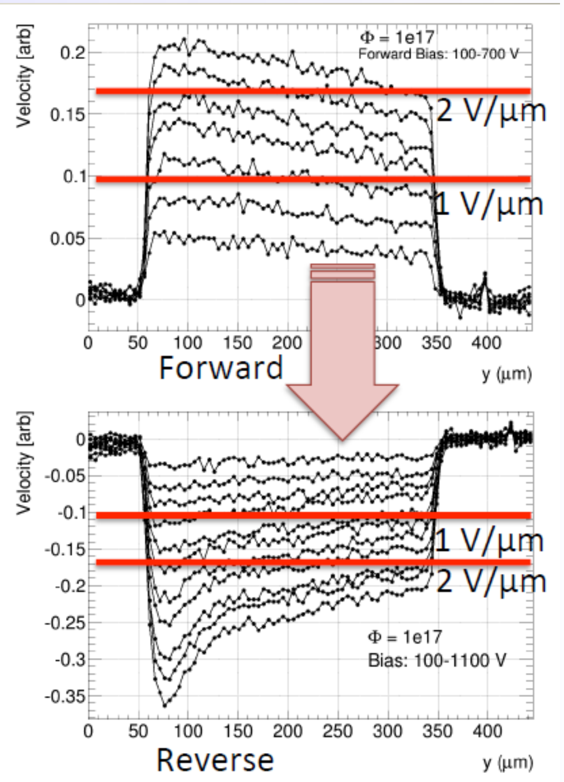


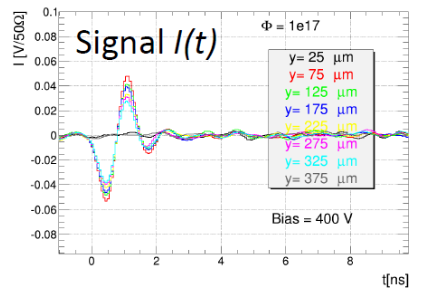
- Take $V_{97\%}$ as estimate of operation voltage
- Highly improved operation voltage for 50x50 µm² 3D compared to IBL/AFP generation
- At ITk baseline fluence of 1.3e16 n_{eq}/cm^2 only 100 V needed
  - Thin planar needs >=500 V
    N. Savic et al., 28th RD50 Workshop, Torino, Italy, 6-8 June 2016
- **Even at 2.5e16 n_{eq}/cm^2: $V_{97\%}$ < 150 V**

Ultra-high radiation tolerance

Exploring final limit: 10^{17} n_{eq} cm^{-2}, still alive?







M. Mikuz, 28th RD50 meeting,
Torino, 8/06/2016

G. Kramberger et al. JINST 8,
PO8004, 2013

RD50 in the future …

Sensors for various applications are ongoing a transition : successful and well mature hybrid sensors (micro-strip in particular but also pixelated hybrid sensors) could be phased out in many domains.

- Applications are going to be ever more demanding on sensors, beyond current technology capabilities. High energy physics in particular sets extreme challenges:
- radiation survival up to $7x10^{17}$ n_{eq} cm^{-2} is a challenge for future applications
- tight resolution requirements (1 μm point resolution)
- Very light and low power sensors (< 1% X_0)

RD50 is ideally positioned for carrying out the research program towards:

- Sensing up to extreme radiation fluences (10^{17} n_{eq} cm^{-2} and above):
    - ✓Characterization of sensor behavior (current, temperature dependence, annealing effects, signal measurements)
    - ✓Microscopic defects investigation to the new damage regime
- Extended models for describing sensor performances up to these extreme fluences
    - ✓Insertion of extreme damage effects in TCAD semiconductor simulation software
    - ✓Parametric description of operation parameters (signal, trapping, current) as a function of fluence and temperature.
- Investigation of new structures and enhancement of their potential (LGAD, small area 3D, HV-CMOS).

And, just as it happens to R&D endeavours and as the history of RD50 testifies, be the forum where new ideas develop.