Radiation Effects in Low-Gain Avalanche Detectors LGAD

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- LGAD
- Radiation Effects in Silicon
- Radiation Effects in LGAD
- Mitigation Program

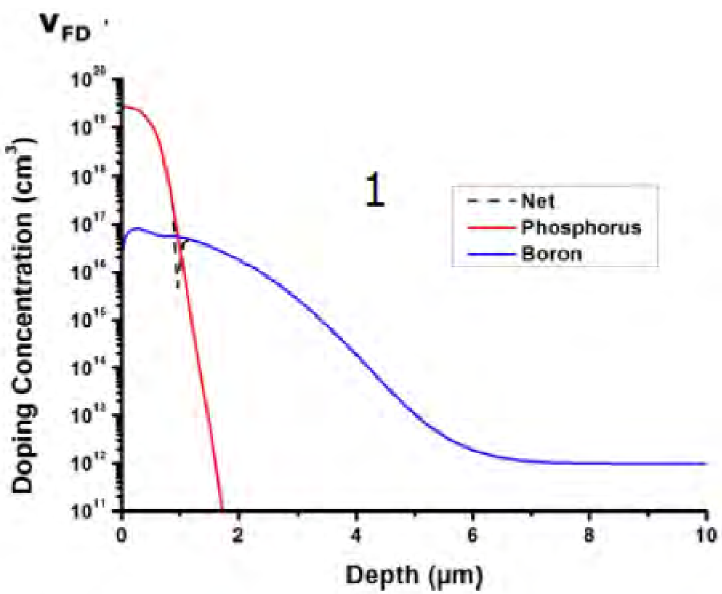
Part of this work was performed within the CERN RD50 Collaboration

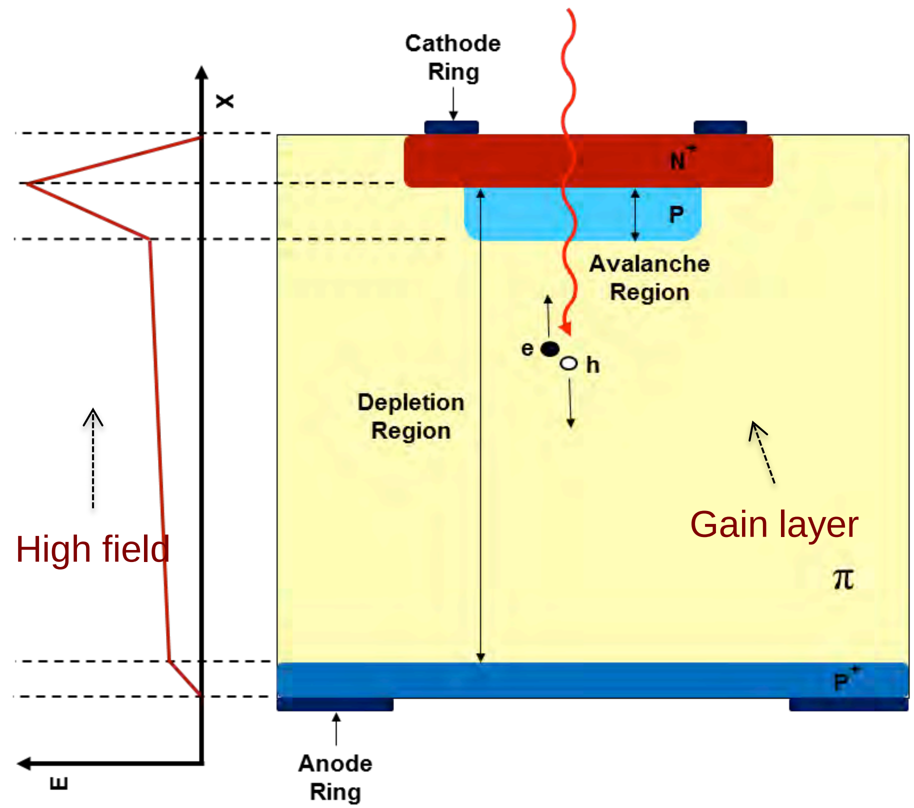
Low Gain Avalanche Detectors (LGADs)

The LGAD sensors, as proposed and manufactured by CNM & FBK

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage





Gain in Silicon detectors

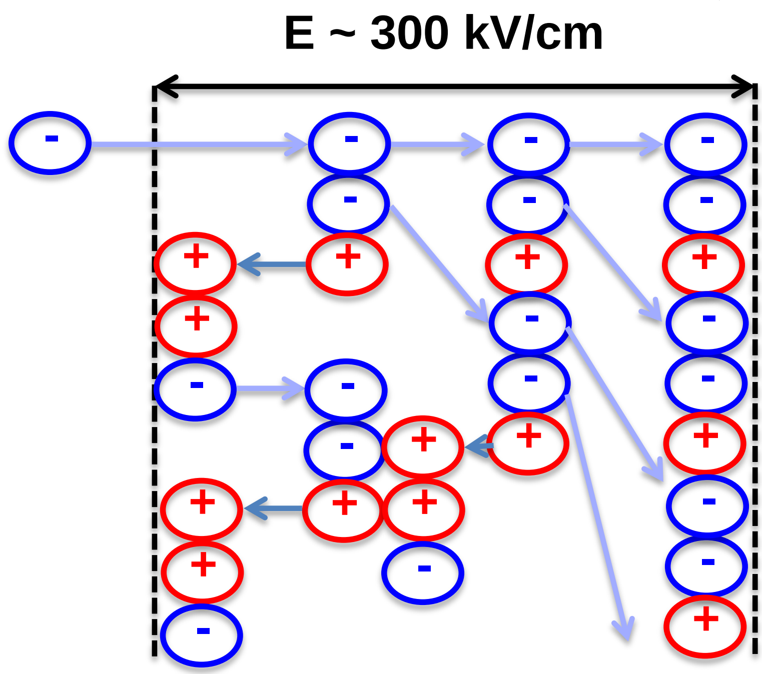
Gain in silicon detectors is commonly achieved in several types of sensors. It's based on the avalanche mechanism that starts in high electric fields: **E ~ 300 kV/cm**

Charge multiplication $N(l) = N_0 \cdot e^{\alpha \cdot l}$

Gain: $G = e^{\alpha\, l}$

$$\alpha_{e,h}(E) = \alpha_{e,h}(\infty) * \exp\left(-\frac{b_{e,h}}{|E|}\right)$$

α = strong E dependance
α ~ 0.7 pair/μm for electrons,
α ~ 0.1 for holes



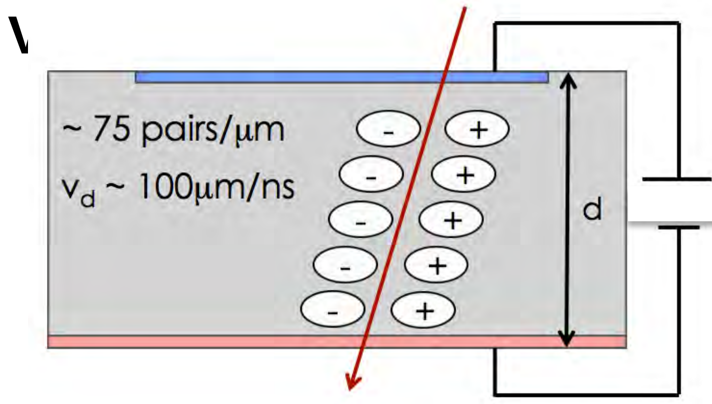
Concurrent multiplication of electrons and holes generate very high gain

Silicon devices with gain:

- **APD: gain 50-500**
- **SiPM: gain ~ 10^4**

How can we achieve E ~ 300kV/cm?

1) Use external bias: assuming a 300 micron silicon detector, we need

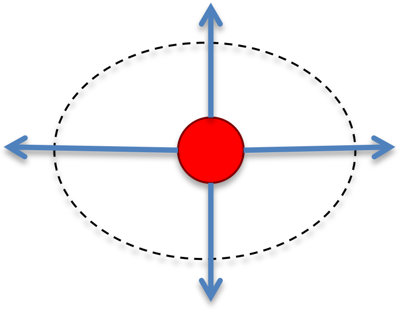


30 kV !!

Not possible

2) Use Gauss Theorem:

$$\sum q = 2\pi r * E$$



E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

Need to have 10^{16}/cm^3 charges !!

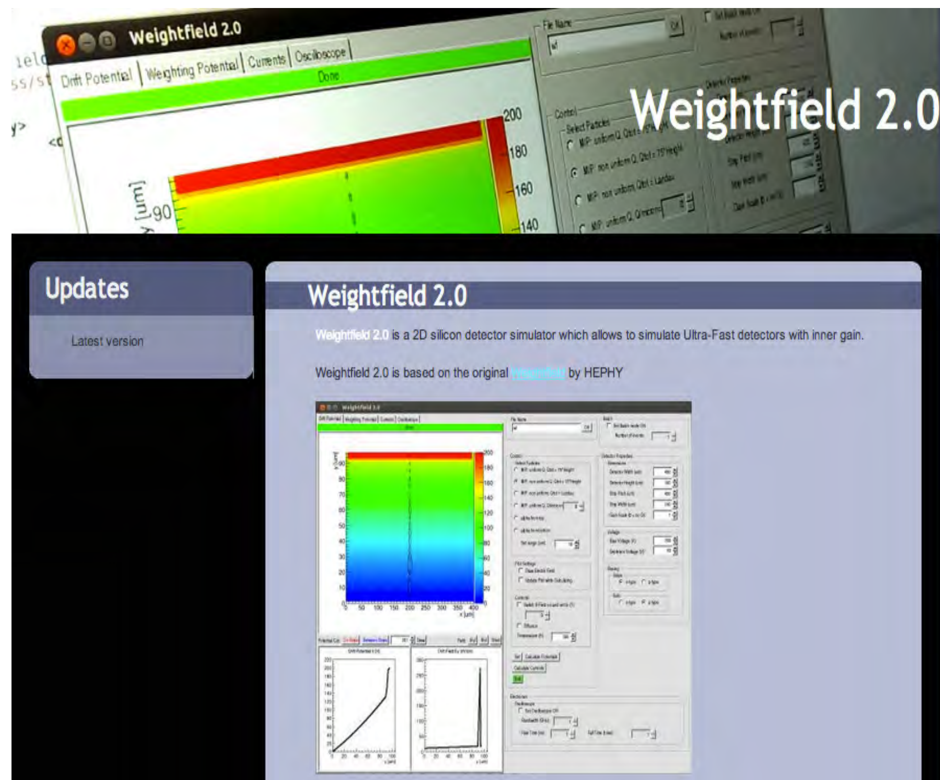
WeightField2: the Silicon Detector Simulator

Nicolo Cartiglia developed a full sensor simulation to optimize the sensor design

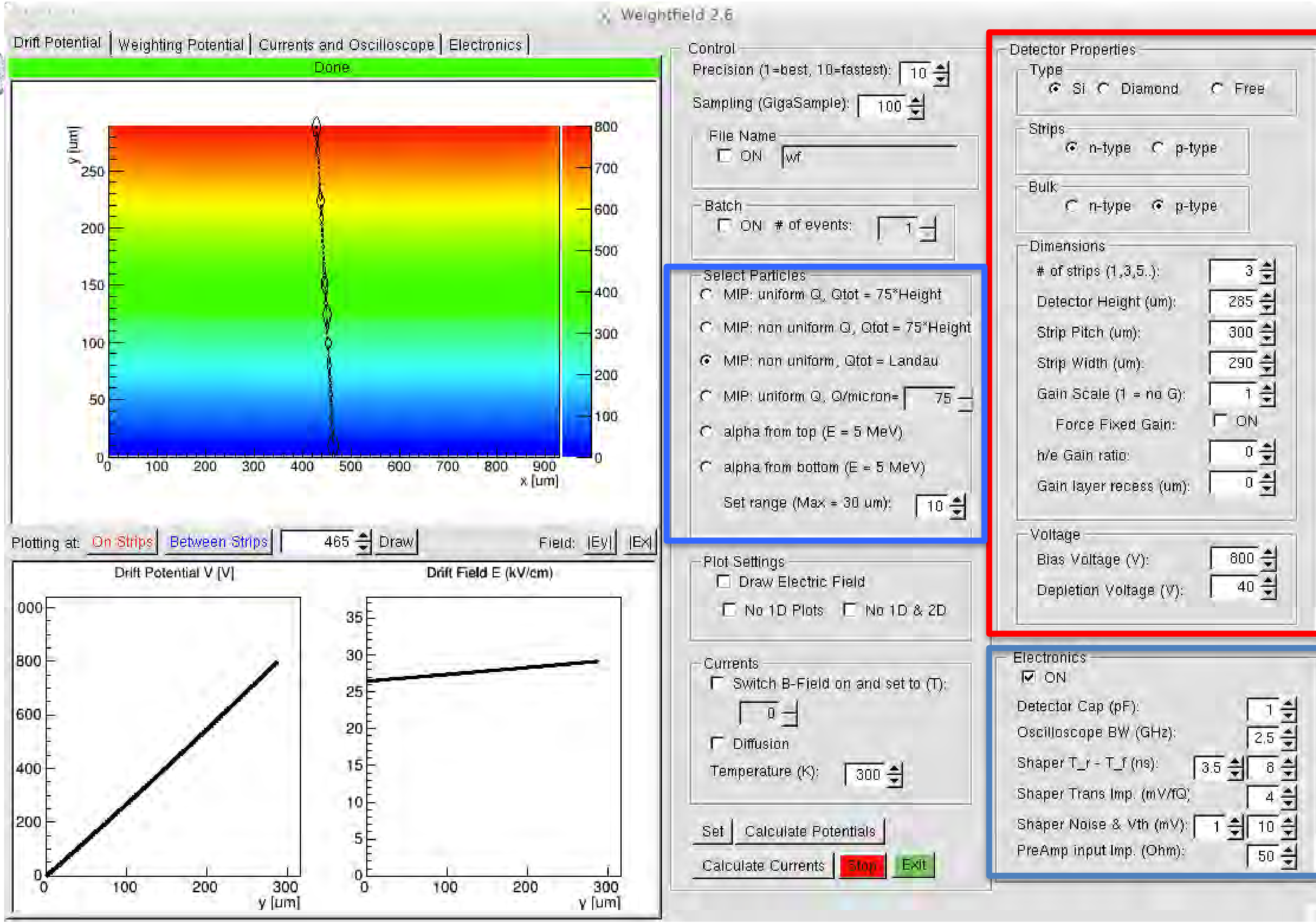
WeightField2, F. Cenna, N. Cartiglia 9th Trento workshop, Genova 2014

Available at http://personalpages.to.infn.it/~cartigli/weightfield2

It includes many "bells & whistles" required for the detailed description of the signals, i.e. charge generation, drift and collection.
It allows to separate the properties of the current source from the amplifier shaping.
Includes radiation damage.
(Perfect to teach and learn about silicon sensors)

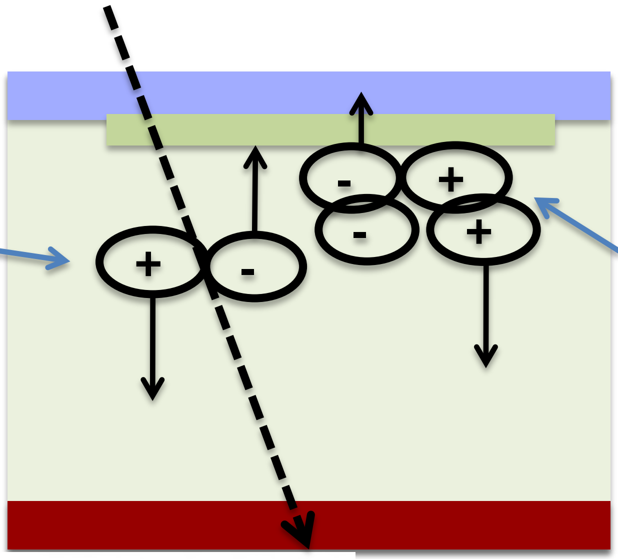


WeightField2: the Silicon Detector Simulator



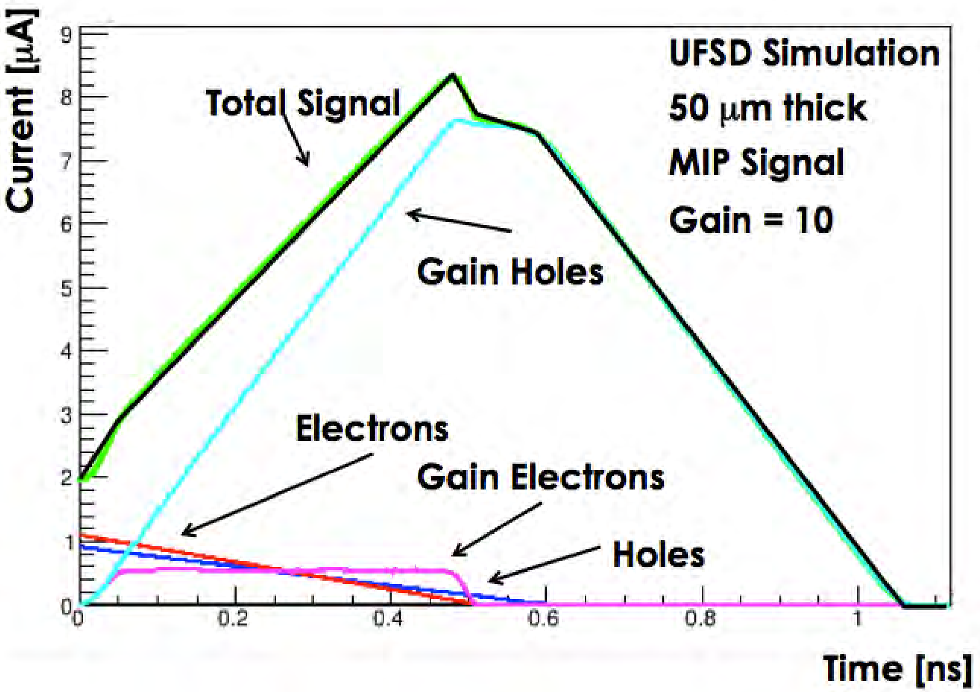
How gain shapes the signal

Initial electron, holes



Gain electron: absorbed immediately

Gain holes: long drift home



Electrons multiply and produce additional electrons and holes.

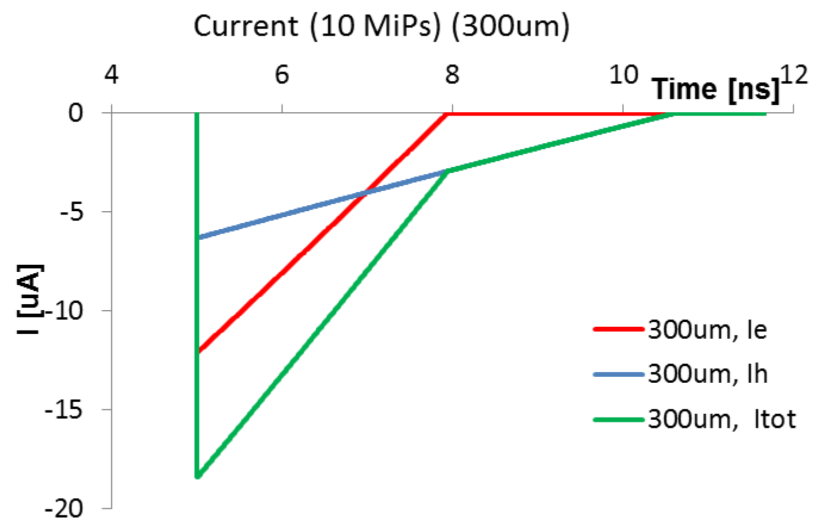
- **Gain electrons have almost no effect**
  - **Gain holes dominate the signal**

➔ No hole multiplication

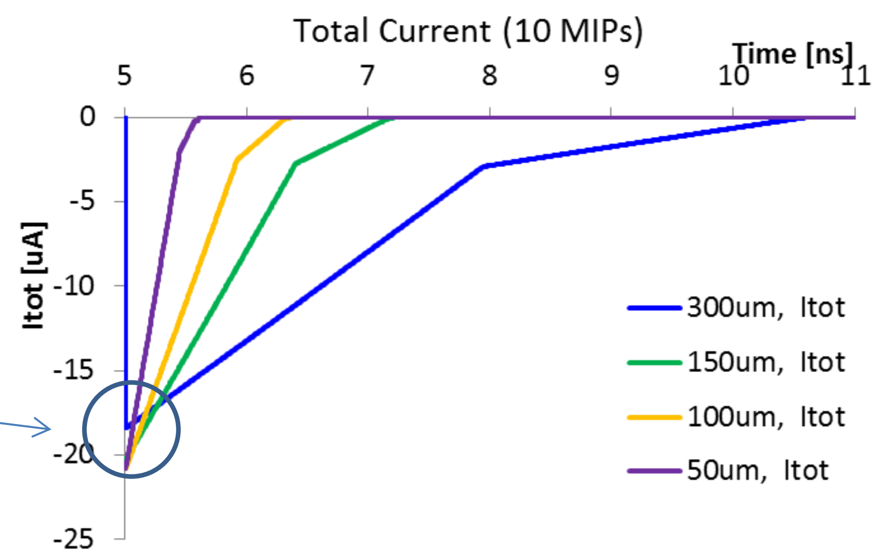
No-gain Silicon Pads: Current from 10 MIPs

Total current = electron current + hole current
Drift time difference electrons-holes clearly visible

Most importantly:
The current peaks at t=0 where we want to make the time measurement



The current signal of sensors with different thickness' show that the height of peak at t=0 is independent of the detector thickness!
Thick detectors contribute to the tail.
The 300µm sensor is not sufficiently over-depleted to reach saturation velocity, in contrast to the thinner ones.



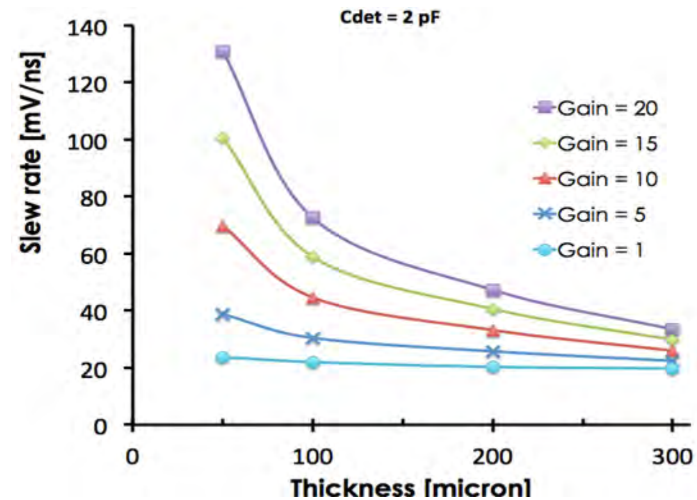
Simulations by Charilou Labitan

LGAD Timing Resolution

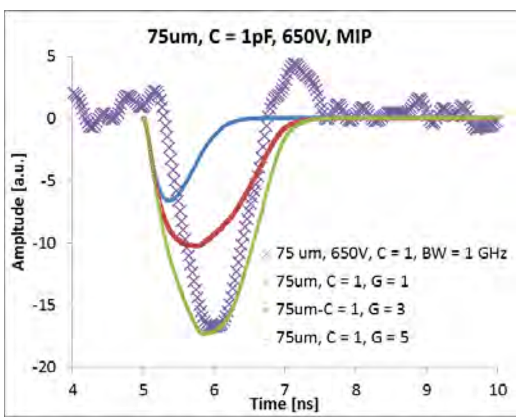
The timing resolution in silicon sensors can be expressed as the sum of four terms time walk σ_{TW}, time jitter σ_J, Landau fluctuations σ_L and TDC binning σ_{TDC}:

$$\sigma_t^2 = \sigma_{TW}^2 + \sigma_J^2 + \sigma_L^2 + \sigma_{TDC}^2$$

The first two terms are inversely proportional to the slope dV/dt
-> need fast (i.e. thin sensors) and large pulses (i.e. gain) .

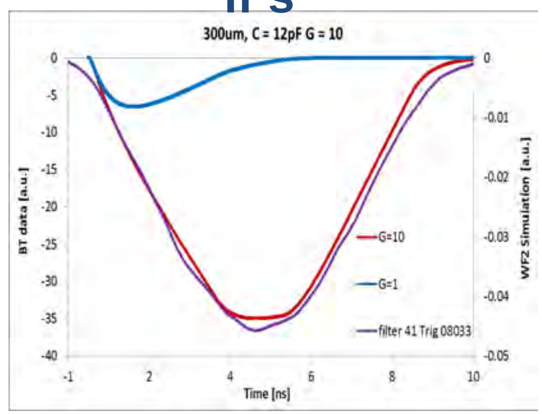


75 µm LGAD, β's



G ~ 5, τ_{Rise} = 500ps

300 µm LGAD, 120 GeV π's



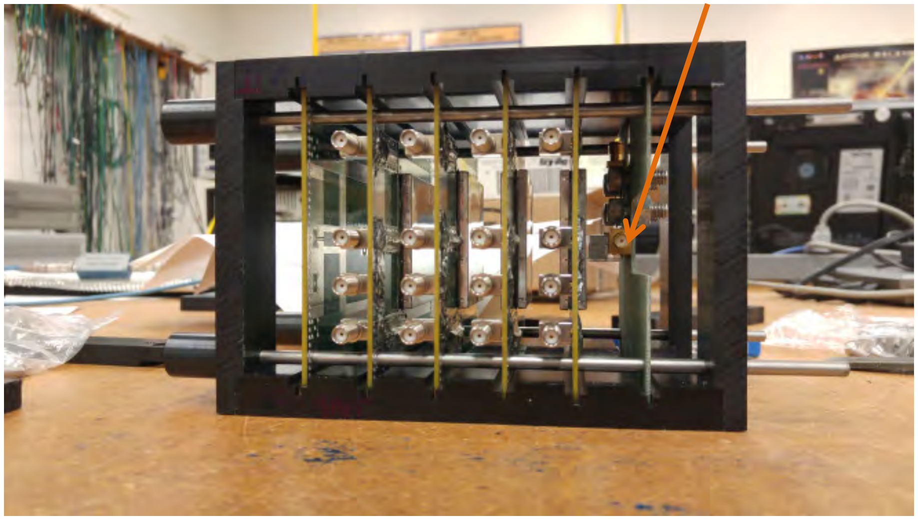
G ~ 10, τ_{Rise} = 5ns

WF2 simulations of 75 and 300µm LGAD reproduce the observed pulse shapes

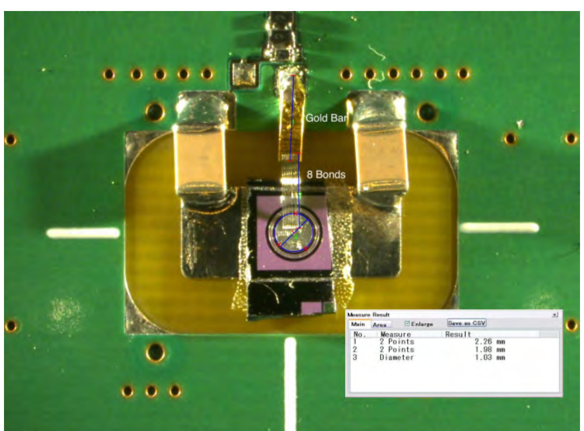
WF2: N. Cartiglia et al,

^{90}Sr β Telescope (A. Zatserklyaniy, Z. Galloway)

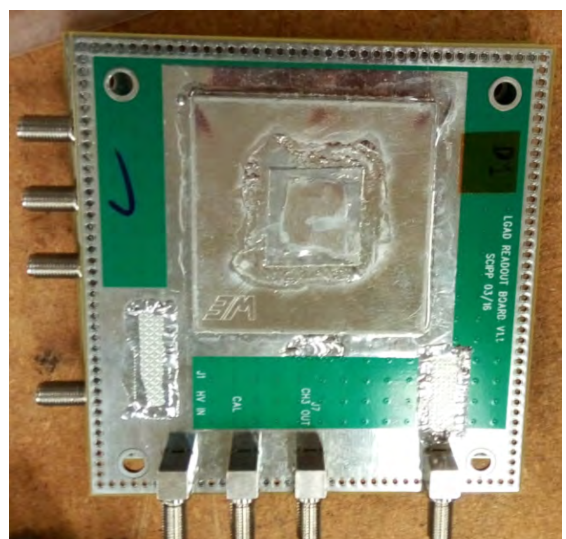
Stack of LGAD planes and the trigger plane



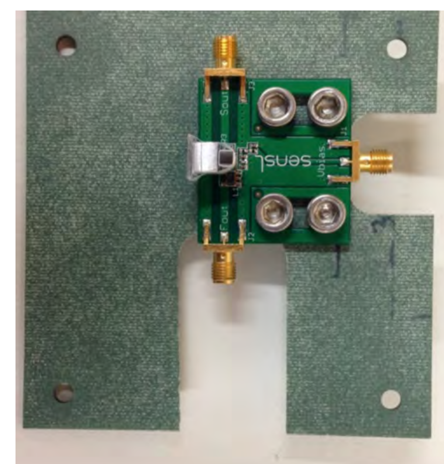
Reduced Inductance



Self-shielded LGAD



Quartz-SiPM Trigger

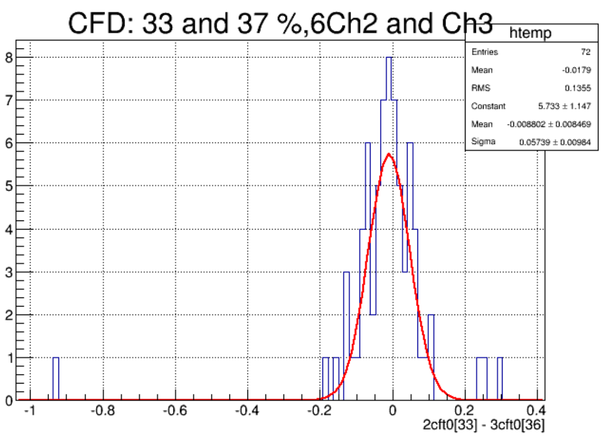


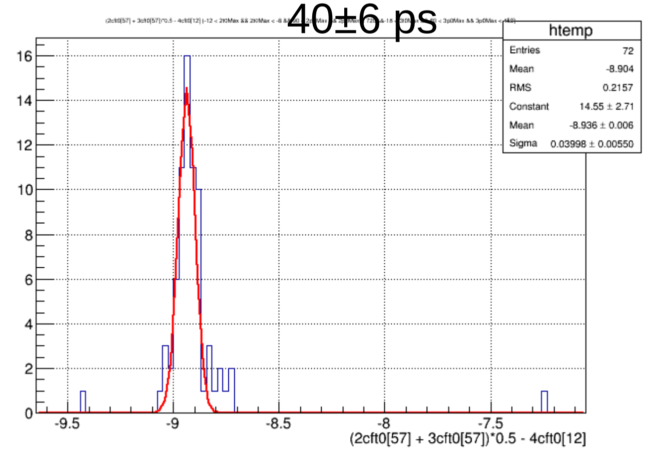
β Coincidence Data of 2 Thin LGAD

Plot time differences between:

1. between 2 LGADs average: 57±9ps

2. between average of 2 LGADs and trigger: 40±6 ps

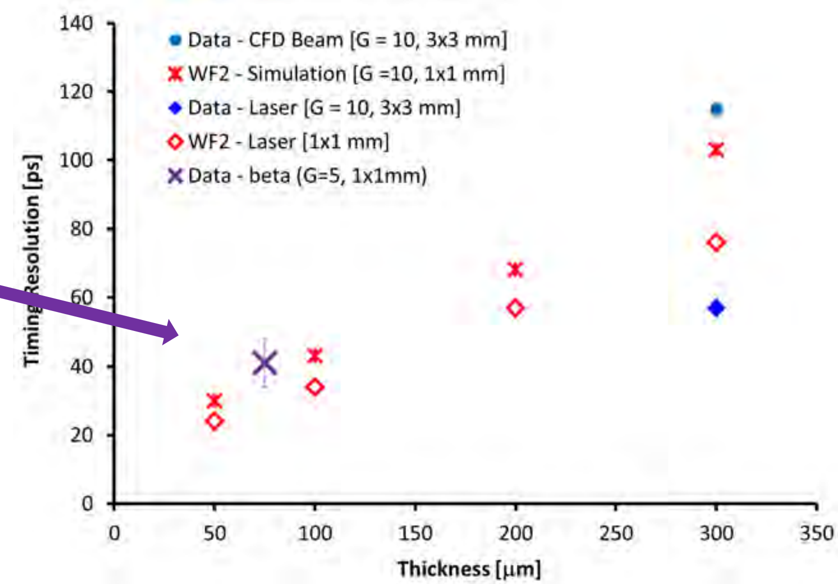




Timing Resolution (preliminary)
using Scope (sampling 20GS/s = 50ps) :
LGAD (75μ,G=5) , σ_{TIME}= 41±7ps

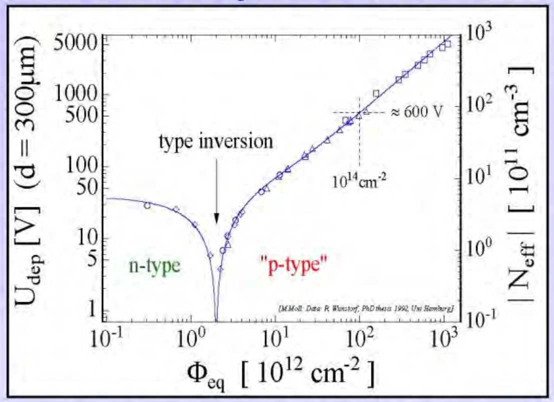
Quartz&SiPM Trigger:σ_{TIME}= 28ps

(Beam Test is being analyzed)

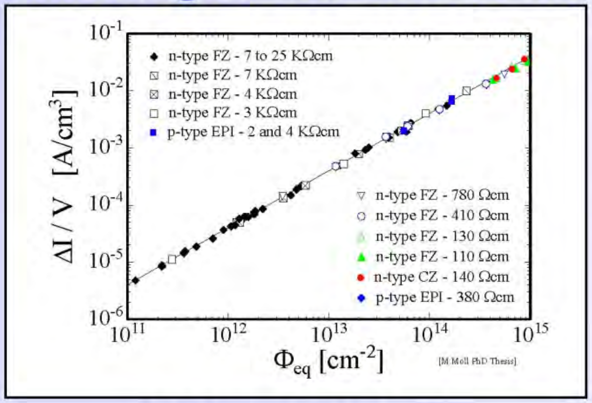


RD50 Radiation Damage (Reminder)

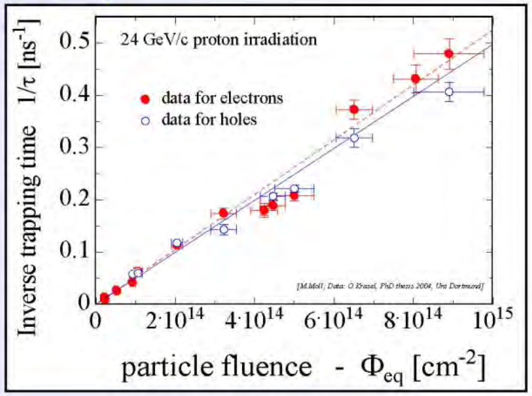
- Macroscopic bulk effects (annealing effects not shown here!) :



Depletion Voltage (N_{eff})

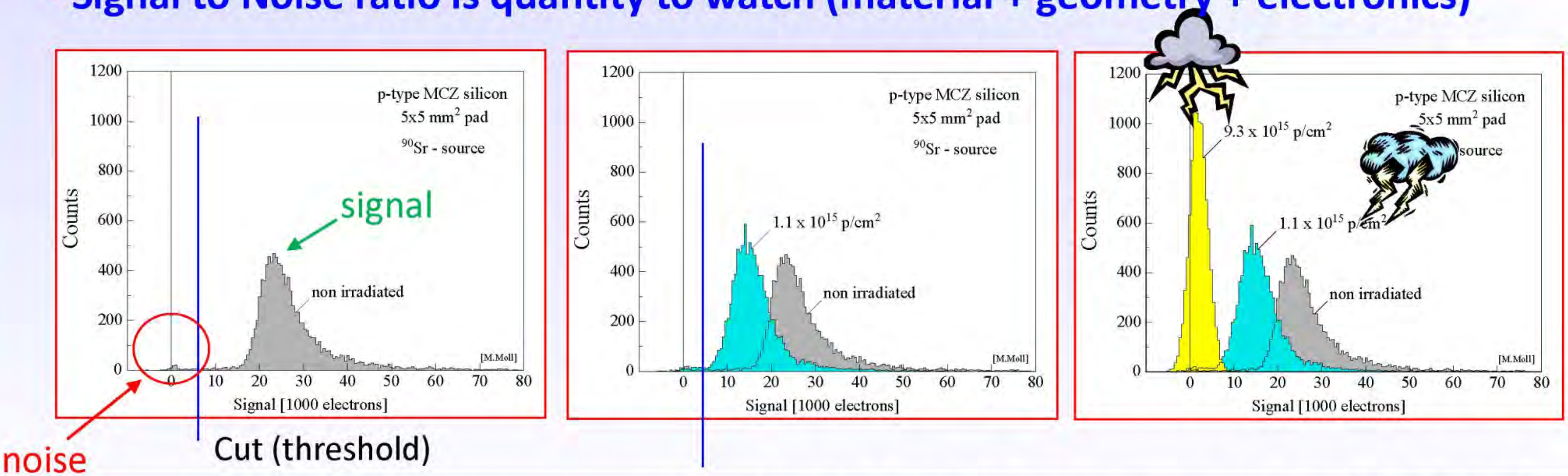


Leakage Current



Charge Trapping

- Signal to Noise ratio is quantity to watch (material + geometry + electronics)

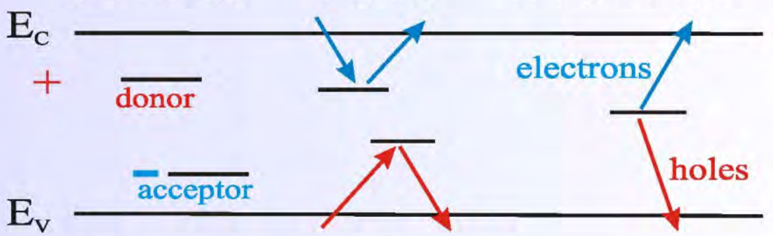


https://indico.cern.ch/event/468478/contributions/2135148/attachments/1290271/1921271/1600613-RD50-AIDA2020.pdf

RD50

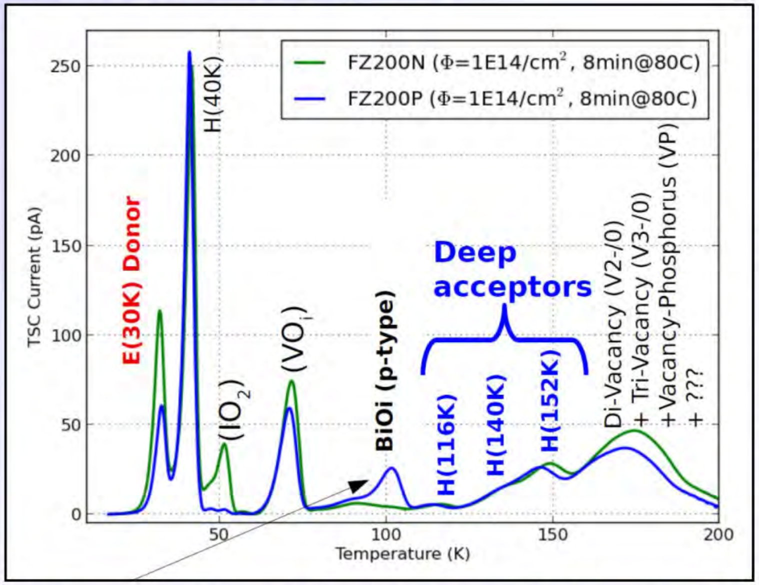
Defect Characterization

- **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)
  - *PC, RL, I-DLTS, TEM,... and simulation*
  - RD50: several hundred samples irradiated with protons, neutrons, electrons and ^{60}Co-γ

... significant progress on identifying defects responsible for sensor degradation over recent years!



Example: TSC measurement on defects produced by 23 MeV protons

[Elena Donegani et al, UniHH, RD50 Workshop, December 2015]

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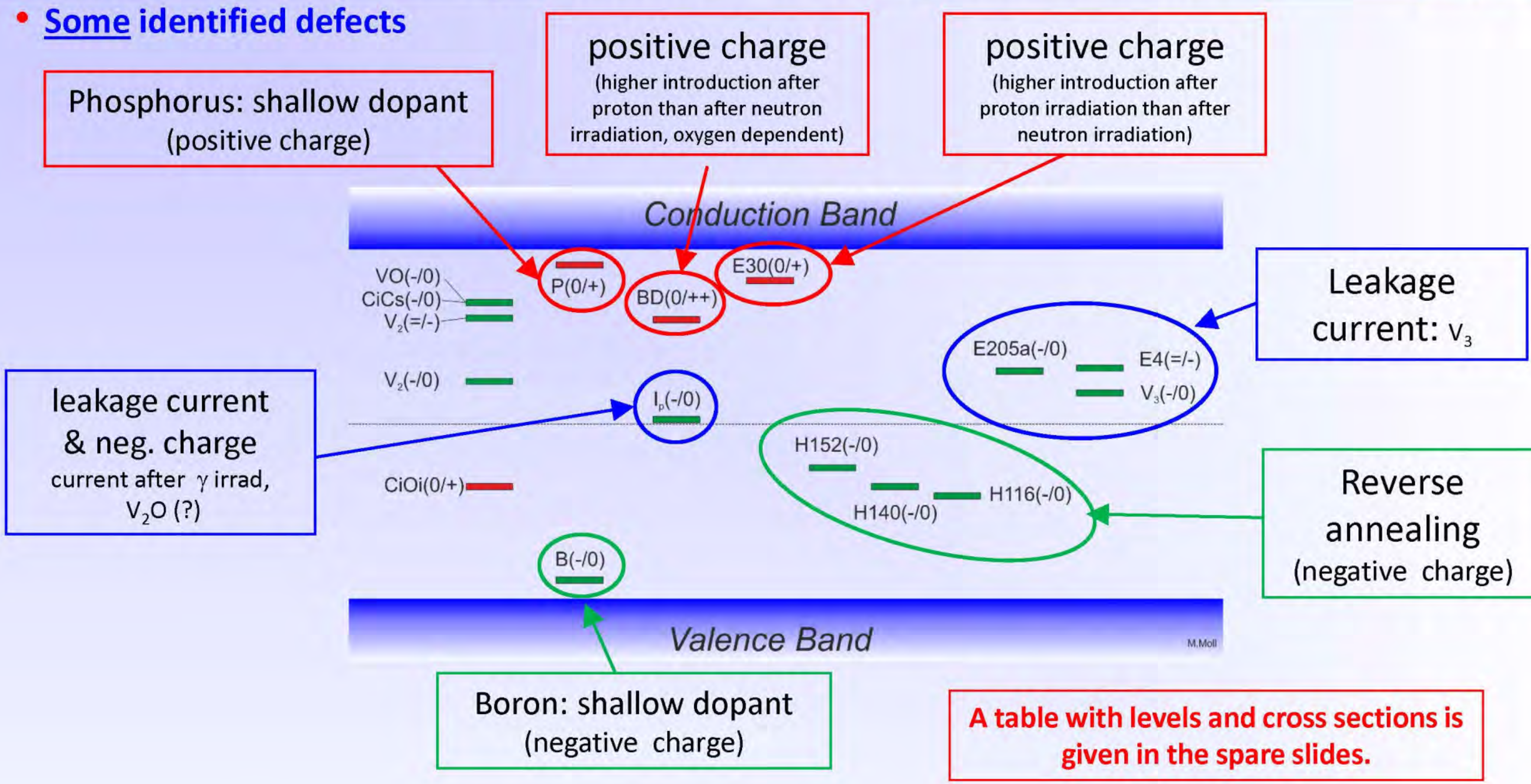
RD50

Summary on defects with strong impact on device performance after irradiation

- **Some identified defects**



- **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!

https://indico.cern.ch/event/468478/contributions/2135148/attachments/1290271/1921271/1600613-RD50-AIDA2020.pdf

Radiation Hardness of LGAD

The collected charge of LGAD detectors decreases with irradiation due to:

a. Increase of depletion voltage (same as in no-gain silicon sensors -> go thin)
b. Trapping of the drifting charges (same as in no-gain silicon sensors -> go thin)
c. Trapping of holes modifying the detector bulk (more than in no-gain silicon sensors -> go thin)
d. Removal of effective acceptors in the multiplication region

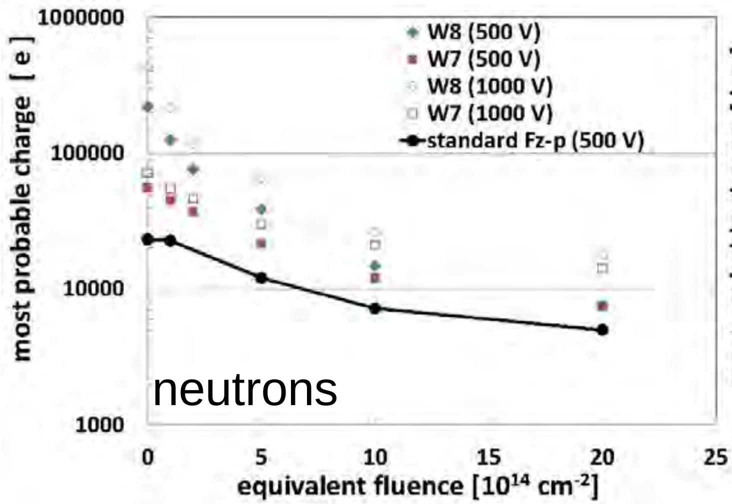
Point d. is slowly understood better and a few avenues of mitigation are being pursued by RD50.

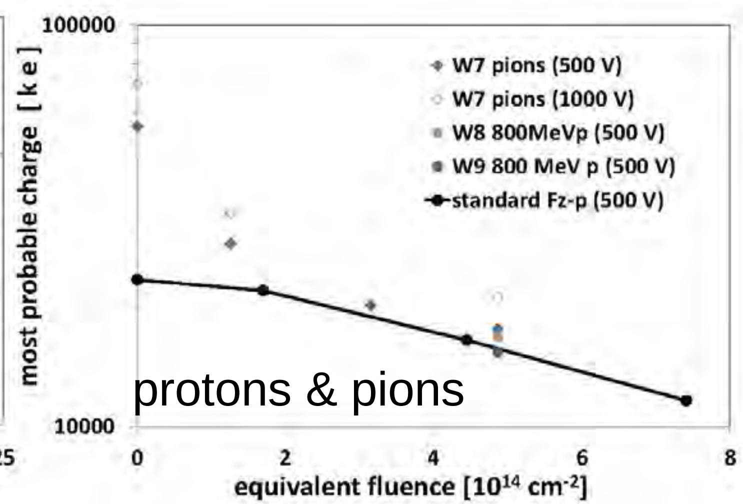
Level of a few 10^{15} neq are foreseen (e.g. HSTD in ATLAS).

Mitigation:
Replacing Boron with Gallium as dopant:
Carbon enriched Silicon wafers:
Balance gain from multiplication layer and bulk biasing

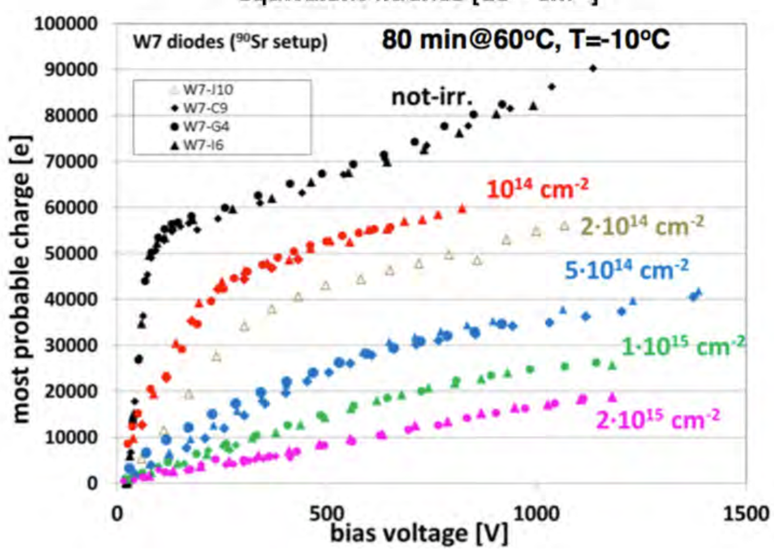
Radiation Damage in UFSD: Change in Gain

Measurement of collected charge (CCE) in 300 µm LGAD:
Gain = CCE(LGAD) / CCE(PiN)





G. Kramberger et al, 2015 JINST 10 P07006)



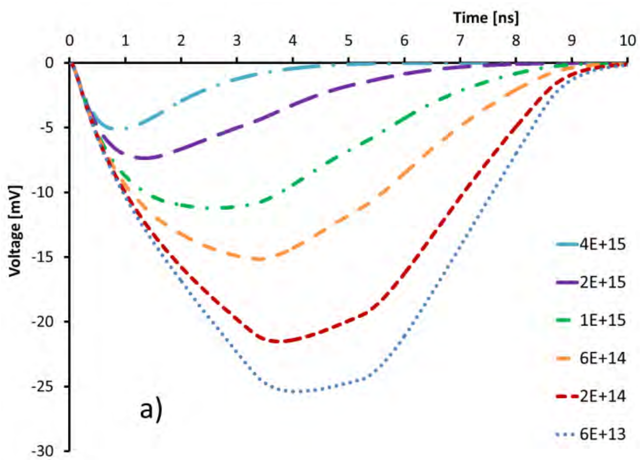
After 2e^{15} neq/cm^{2} gain > 3.6

Leveling-off of gain degradation at higher fluences:
Competition between initial acceptor removal and gradual acceptor creation.

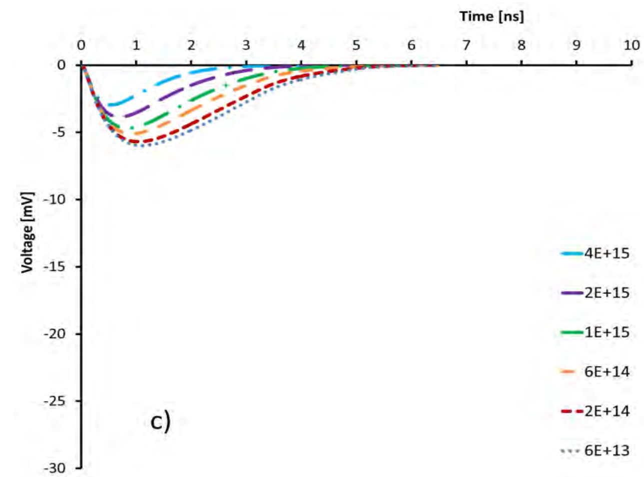
Radiation Damage in UFSD: Trapping only

Pulse shapes in LGAD vs. Fluence [neq/cm^2]

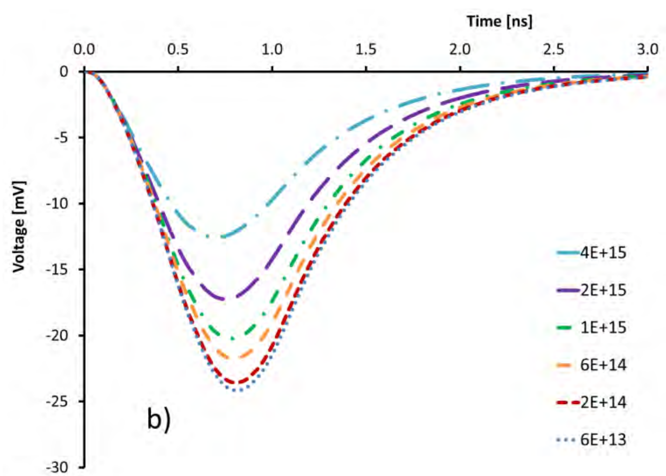
LGAD 300µm, Gain = 10



PiN 300µm, Gain = 1

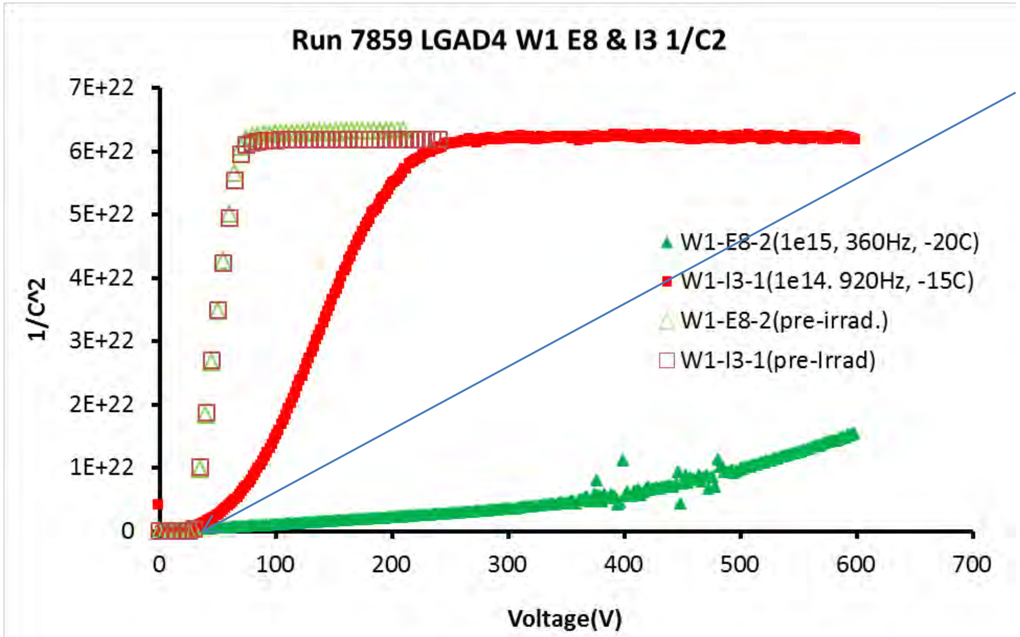


50µm, Gain = 10



Trapping mainly effects the late holes, but not the fast front edge which is important for timing..

C-V with 300 um FZ LGAD (W1 Run 7859)



Pre-rad

“Foot” of 30V: gain ~ 5

Depletion Voltage: 75V

Post-rad

n fluence 10^{14} neq/cm^2:

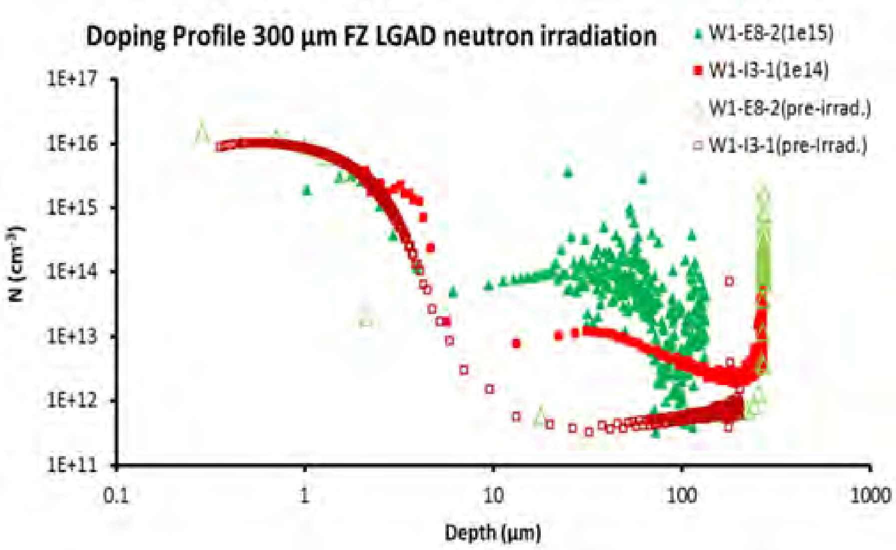
Foot of ~30V

Depletion Voltage: 230V

n fluence 10^{15} neq/cm^2:

Foot of ?V

Depletion Voltage: > 1000V as expected



Measured doping profile extracted from C-V data on 300µm LGAD for 0, 1e14 and 1e15 neq/cm^2

Bulk increases, multiplication decreases

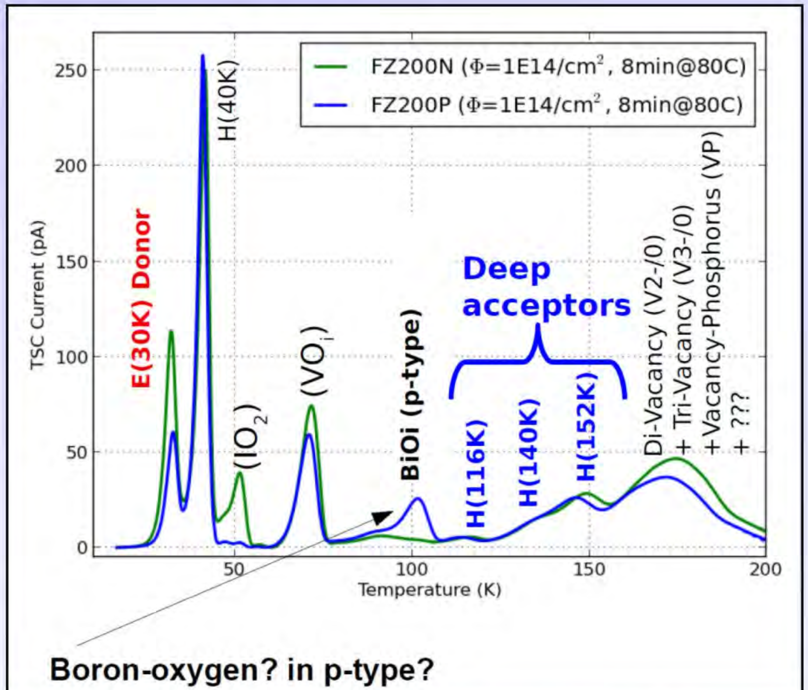
RD50

Acceptor removal - Boron related defects?

CERN

• Microscopic study of defects

- TSC (Thermally Stimulated Current) comparing n- and p-type sensors



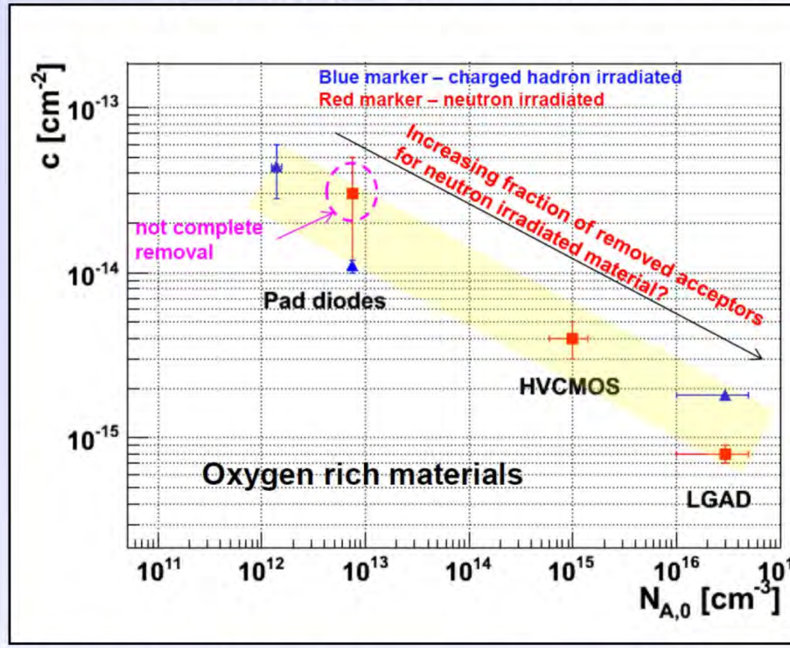
[Elena Donegani et al, UniHH, RD50 Workshop, December 2015]

- Reminder: Deep acceptors (H(116K)..) and shallow donors (E30K) alter space charge
- Some defect only seen in p-type (Boron containing) material; indication for "Boron removal" by defect kinetics (e.g. $B_i \rightarrow B_iO_i$)

• Macroscopic observation (Neff)

- p-type sensors of different resistivity show acceptor removal:

$$\Delta N_{eff} = |N_{Boron}| \cdot exp(-c \cdot \Phi) + ... \text{ [simplified]}$$

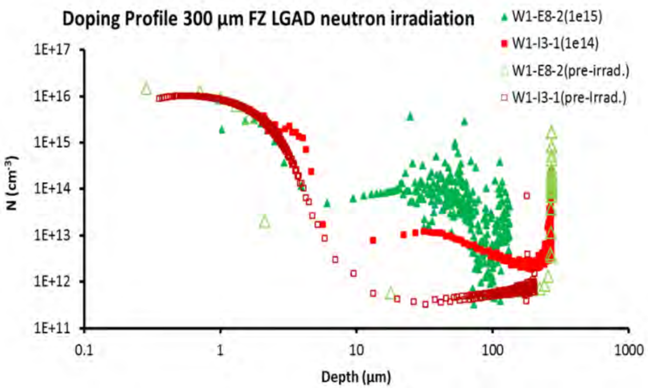


[Gregor Kramberger et al, Ljubljana, RD50 Workshop, June 2016]

- So-called *"acceptor removal"* responsible for:
  - Gain degradation in sensors with intrinsic gain
  - Good performance of low resistivity CMOS sensors after high irradiation.
- **Why not studied more intensively before?**
  - Focus was on high resistivity and on n-type!

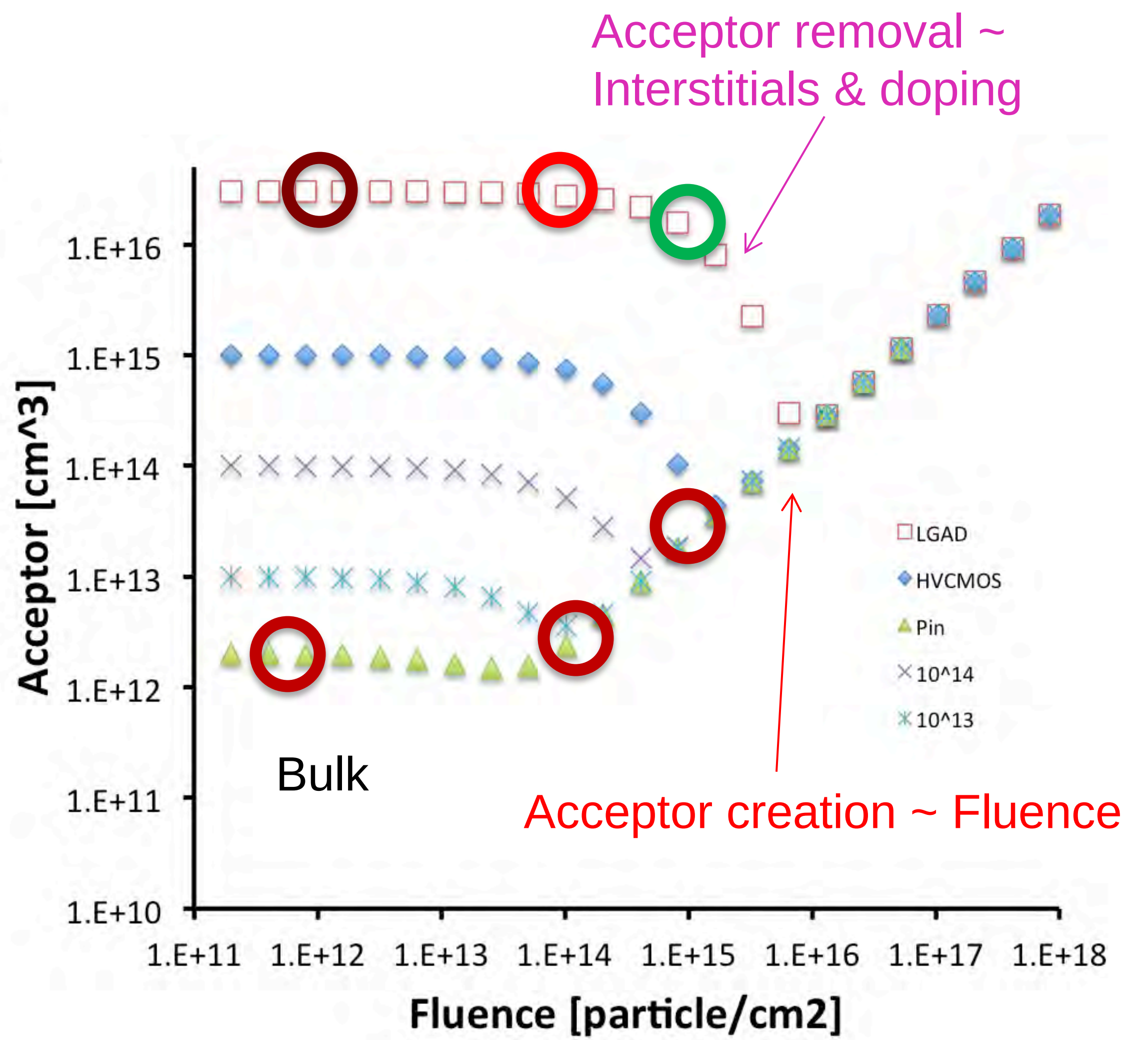
https://indico.cern.ch/event/468478/contributions/2135148/attachments/1290271/1921271/1600613-RD50-AIDA2020.pdf

WF2 Model: FZ Bulk & gain good agreement



WF2 Model **(preliminary)** based on Gregor Kramberger's data on 300µm LGAD, being revisited with thin sensors.

FZ p gain-layer and bulk follow quite closely the prediction.

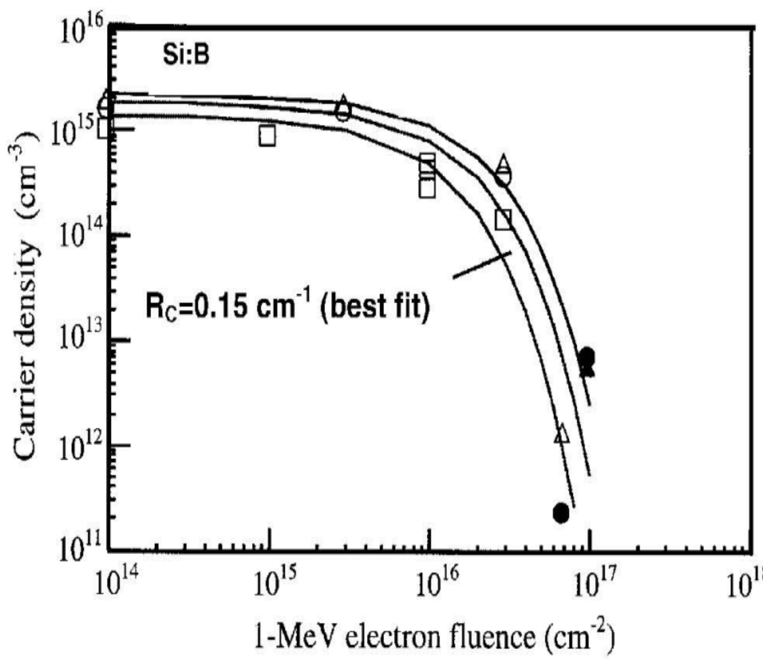


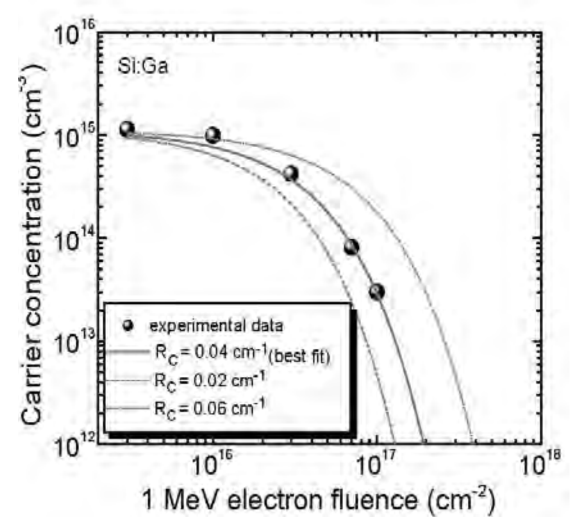
Improving Radiation Hardness of LGAD I

Replacing Boron with Gallium as dopant:
Ga or Al form complexes with radiation-induced defects (“interstitials”), which may have less impact on device performance, when compared to the boron related defect (Bi-Oi) complex.
Using Ga as dopant in Si instead of B can reduce the acceptor removal effect.
In fabrication at CNM

A. Khan et al.,
Solar Energy Materials & Solar Cells
75 (2003) 271–276

Carrier density removal @ 10^{17}:
Boron: 2e15 -> 1e12
Gallium: 1e15 -> 3e13

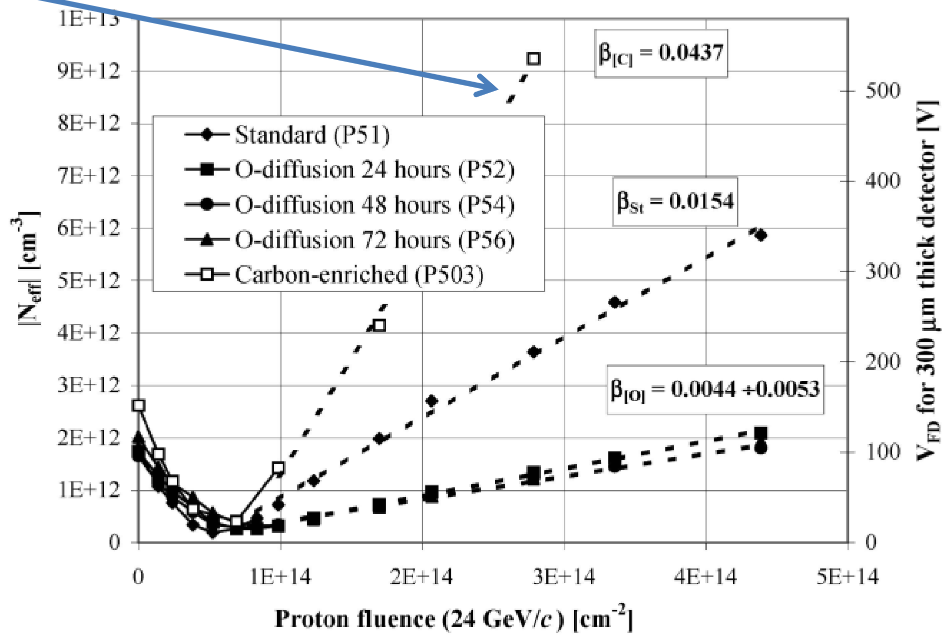




Improving Radiation Hardness of LGAD II

.**Carbon enriched Silicon wafers**:
RD48 collaboration observed that a high carbon concentration can reduce the formation of inactive Bi-Oi defects, as a result of the formation of more energetically favorable carbon-oxygen (C-O) complexes. Diffusing or implanting Carbon in the multiplication layer would suppress the acceptor removal during irradiation. *Two fabrication runs* are already in progress at CNM Barcelona in the framework of the RD50 collaboration.

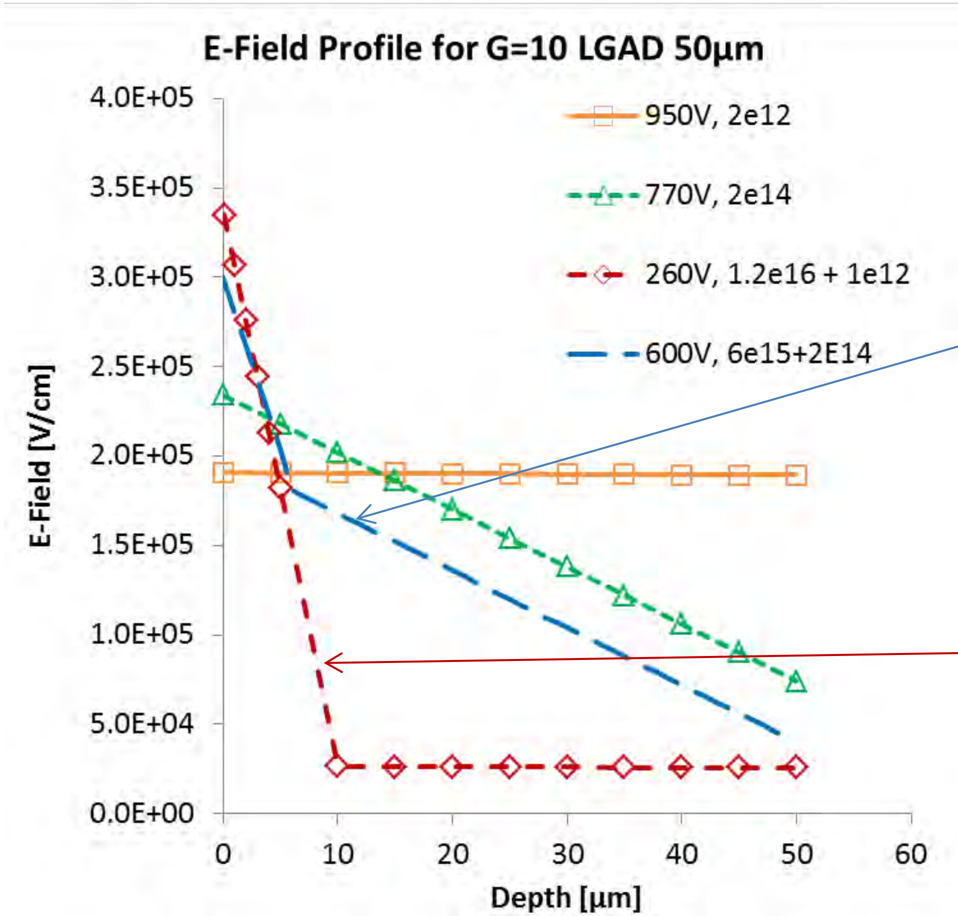
Rose Collaboration, *NIMA 466 (2001) 308–326*
Carbon-enriched silicon retains more than twice the number of acceptors than FZ.



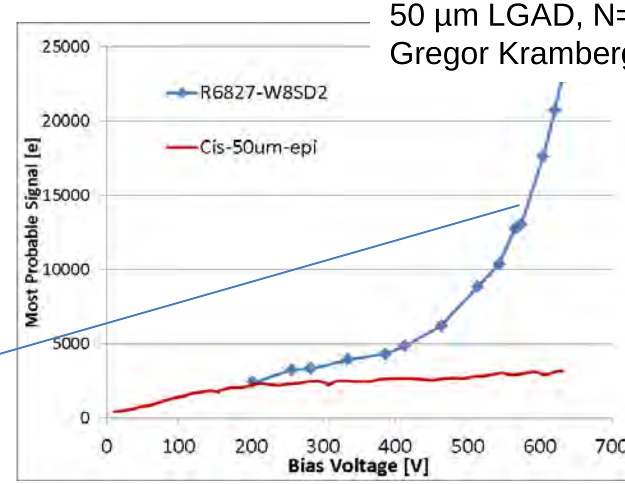
E-field in LGAD: bulk and “gain” field

LGAD’s are characterized by the highly-doped thin p-layer which supplies the large field to satisfy the condition for charge multiplication.
The E-field needed for charge multiplication can be supplied by the bulk (high voltage operation needed!) or a combination of bulk and multiplication layer.

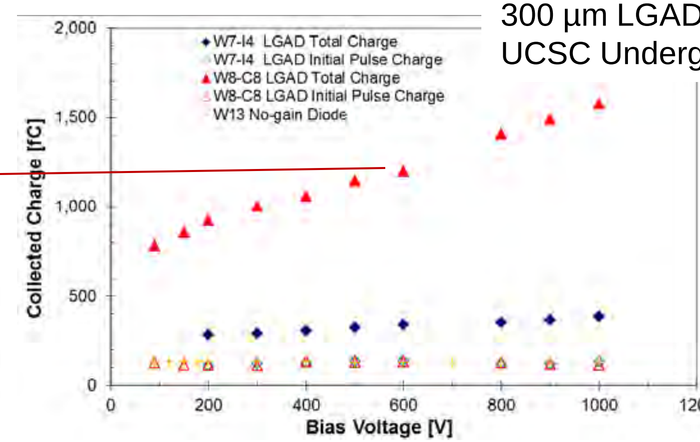
Bias dependence of the gain depends on the relative contribution of the two.



50 µm LGAD, N=2e14
Gregor Kramberger, JSI



300 µm LGAD, N=1e12
UCSC Undergrads



Mitigating Radiation Effects in LGAD III

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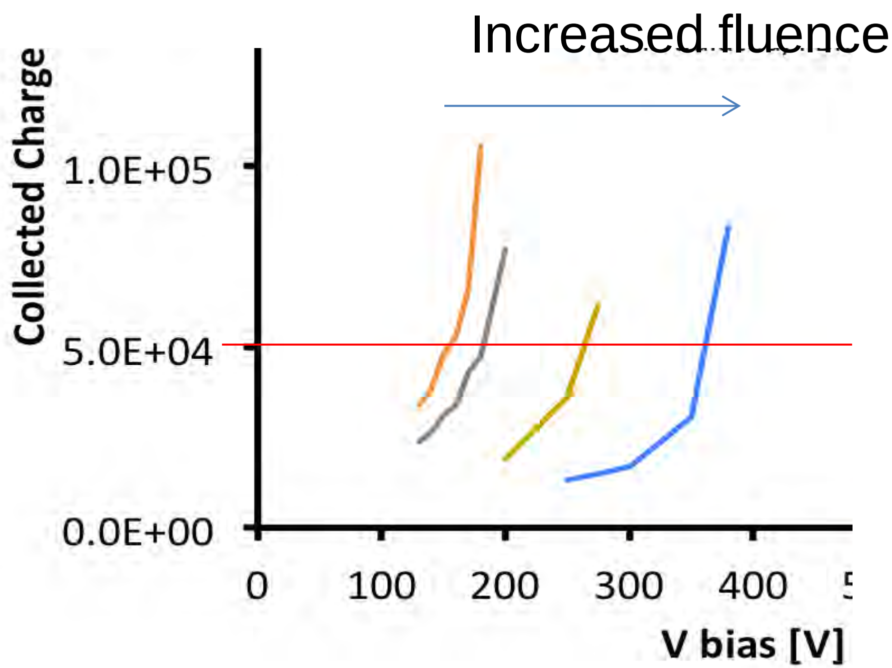
Balance gain from multiplication layer and bulk biasing

Start with high concentration of multiplication layer and low bias and increase bias when acceptor removal changes gain layer effectiveness.

This will keep the number of collected charges constant even when trapping dominates (in contrast to no-gain sensors).

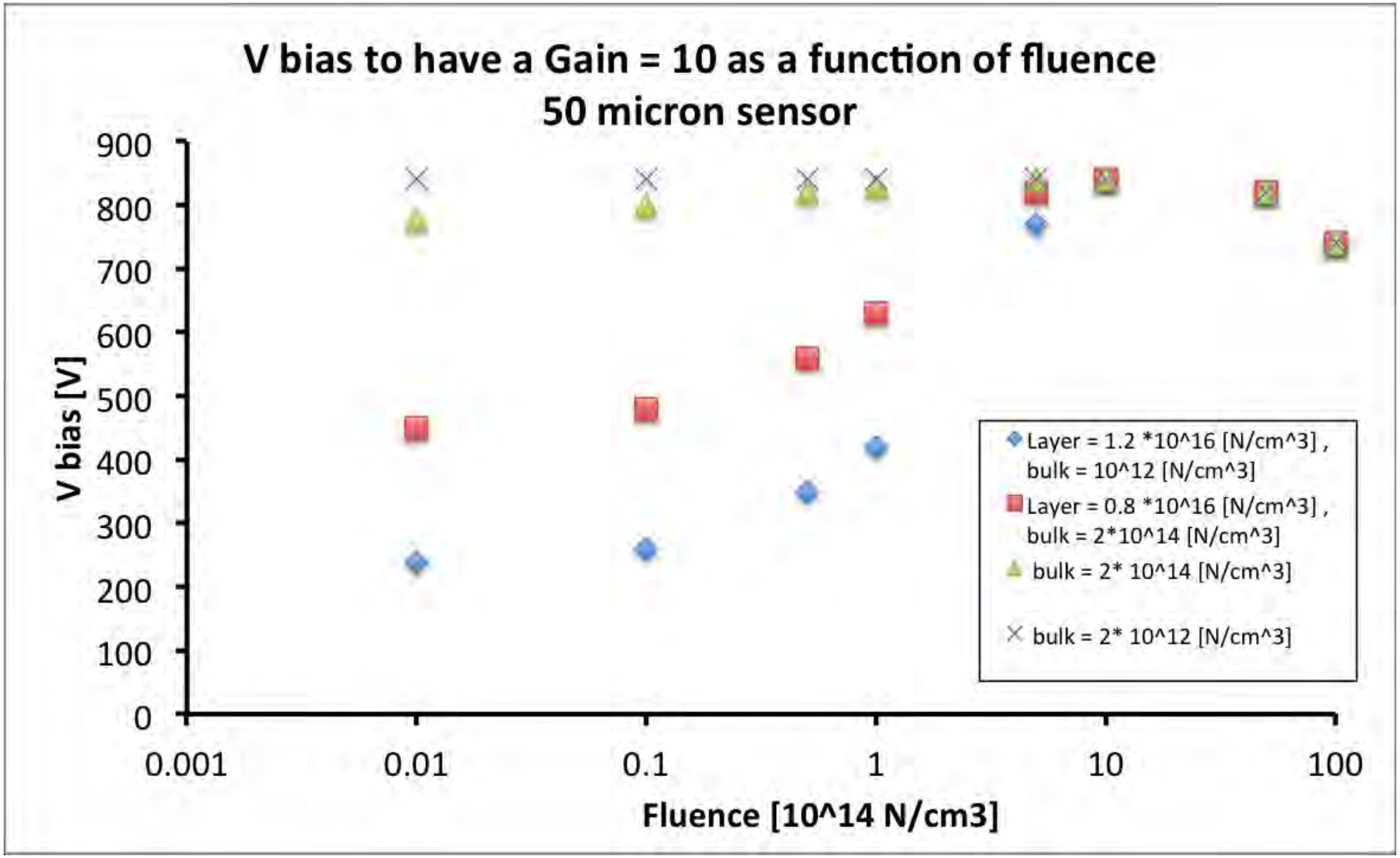
Good timing resolution requires a collected charge of ~ 50ke-

The collected charge can be held constant with increasing the bias voltage when the multiplication layer decreases.



E-field in LGAD bulk adds to the “gain field”

Internal gain reduces operating voltages required to reach multiplication



Model courtesy Nicolo Cartiglia

Preliminary, subject to refinement of acceptor removal model.

Conclusions

- Low-Gain Avalanche Detectors (LGAD) with gain of ~10 promise to give very good timing resolution when they are made thin.
- We are achieving about 50 ps timing resolution in the laboratory with 75um thick LGAD using a ^{90}Sr source and a fast trigger counter.
- The gain layer in the detectors adds additional radiation sensitivity beyond the one for no-gain silicon detector
- There is a program in place to reduce the radiation sensitivity by using
  thin sensors,
  changing the dopant and wafer type to reduce "acceptor removal"
  devise an operational strategy to keep the collected charge constant

Contributors

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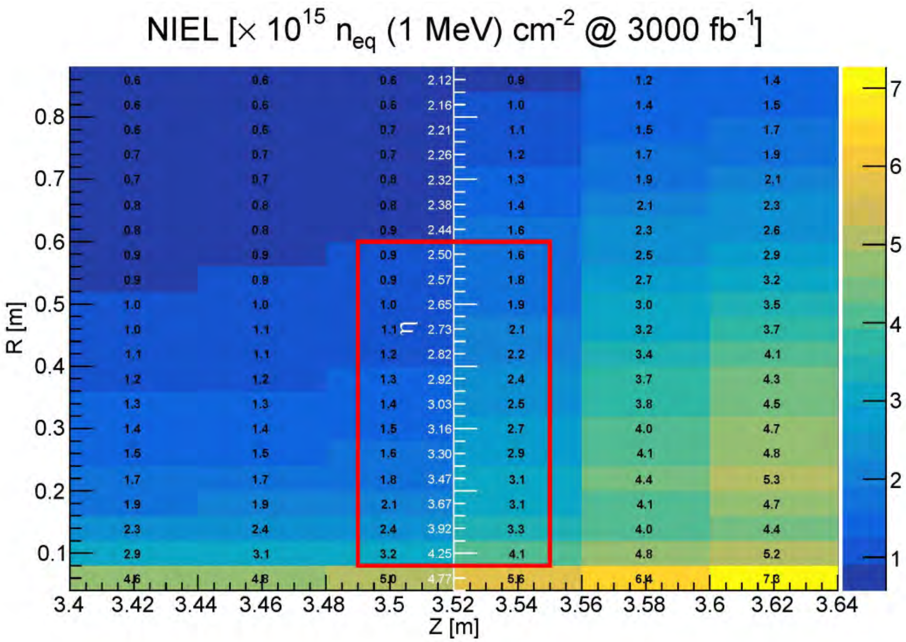
R-Z dependence of Fluence @ HGTD

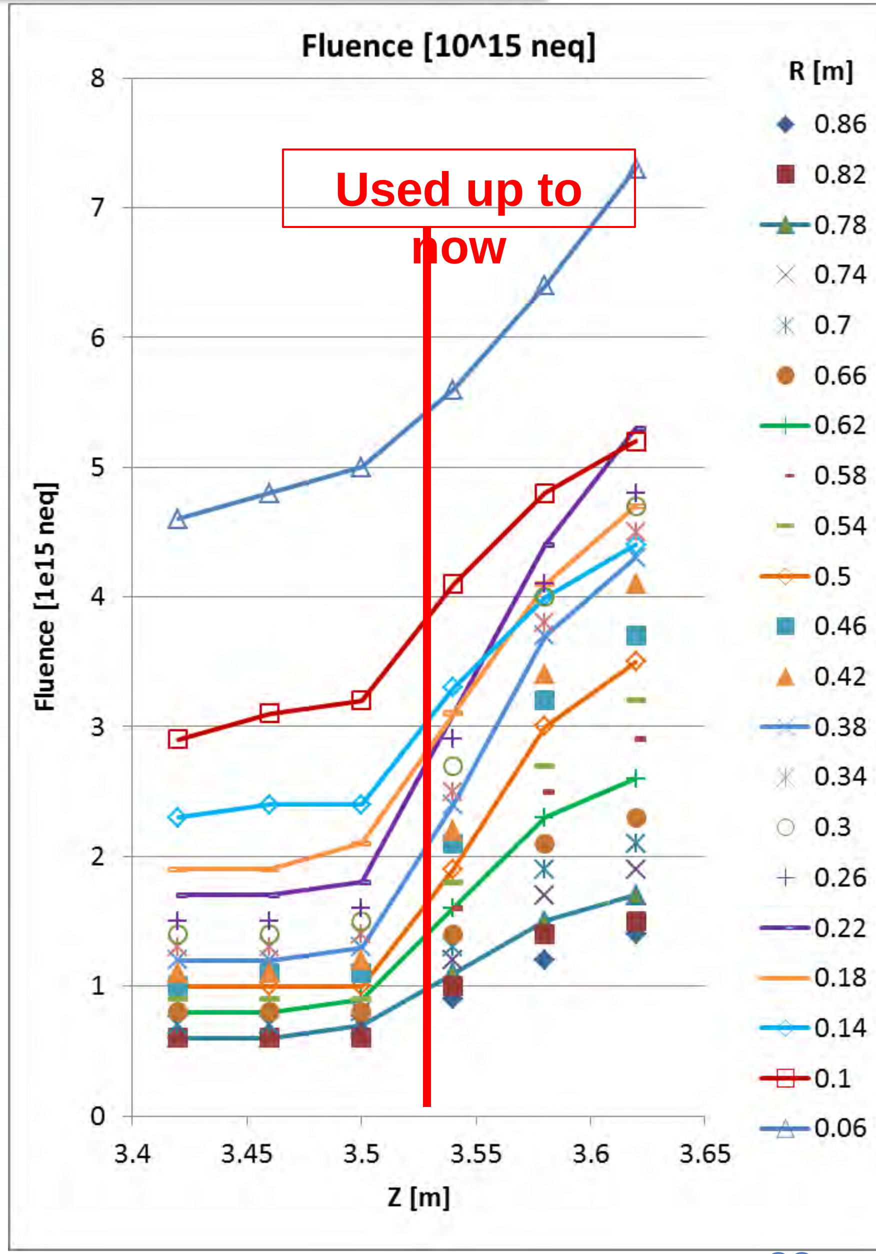
Data from F. Lanni: NIEL

based on M. Shupe's HGTD presentations

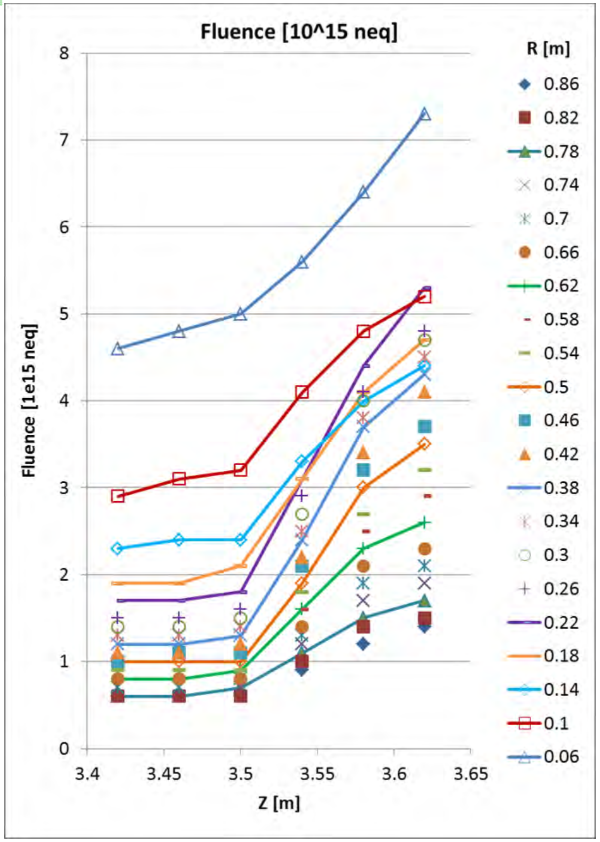


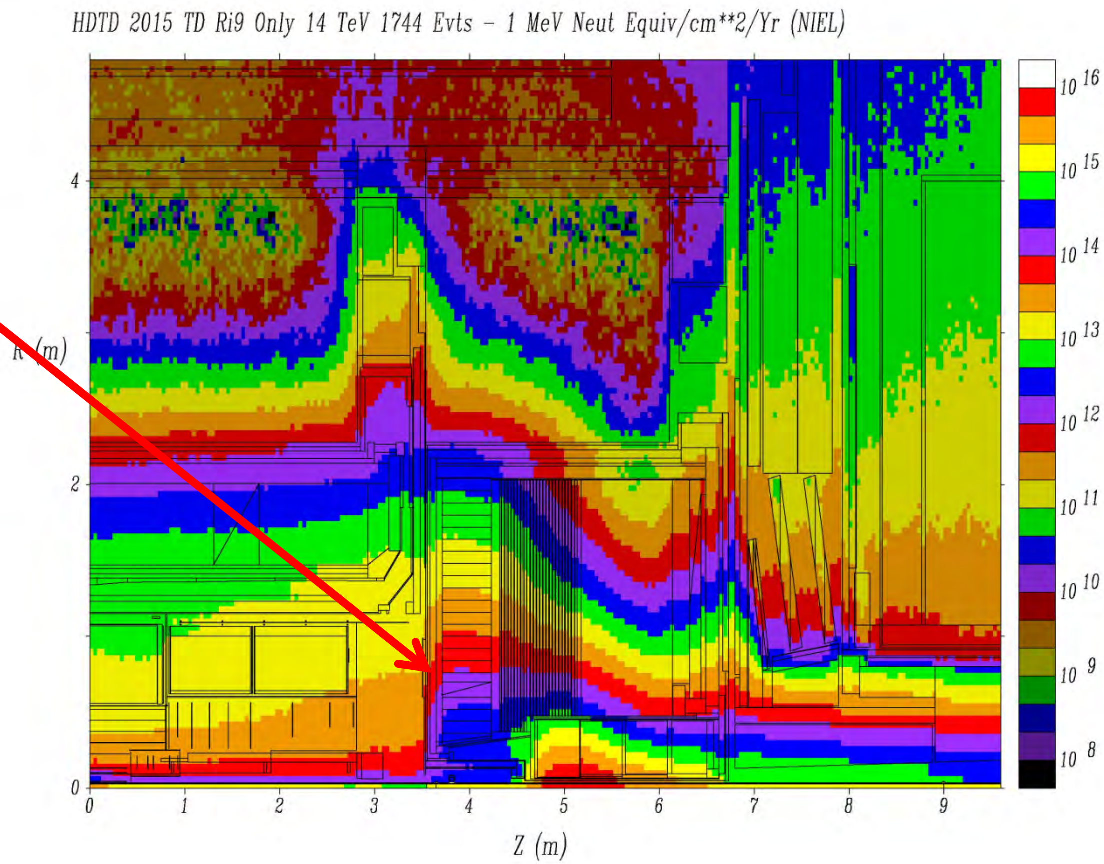
The R-Z plot shows a strong increase in the z-dependence of the fluence in the HGTD region.

Presently use fluence values at z = 3.53 cm.
At z = 3.4 fluence ~ 10 - 20% lower
At z = 3.6 fluence ~ 30% higher



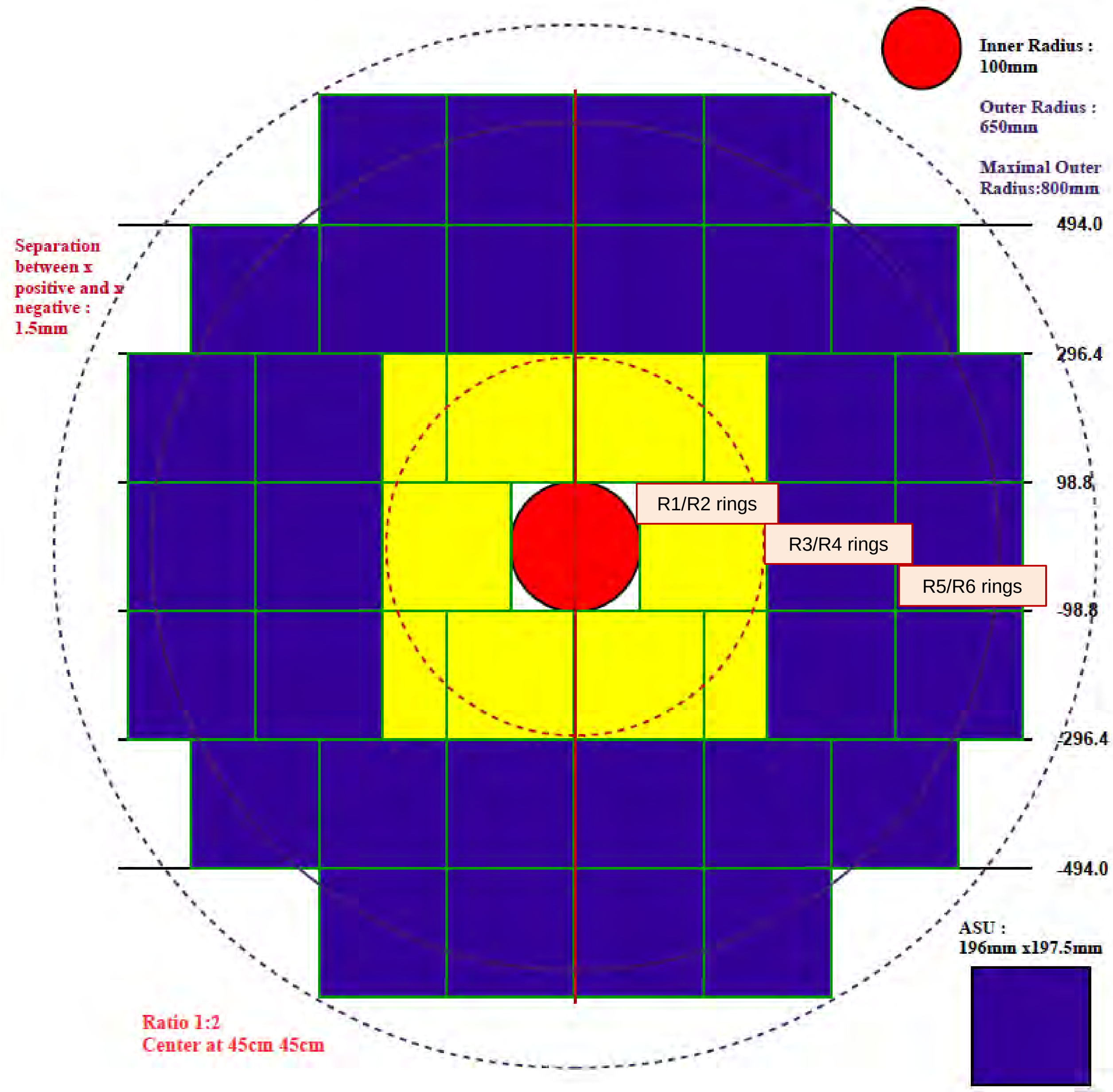
R-Z dependence of Fluence @ HGTD





The z-dependence in the HGTD region is part of a larger-scale trend in front of the FCAL.
Albedo?

HGTD at End Cap side/ End View from Simulation studies

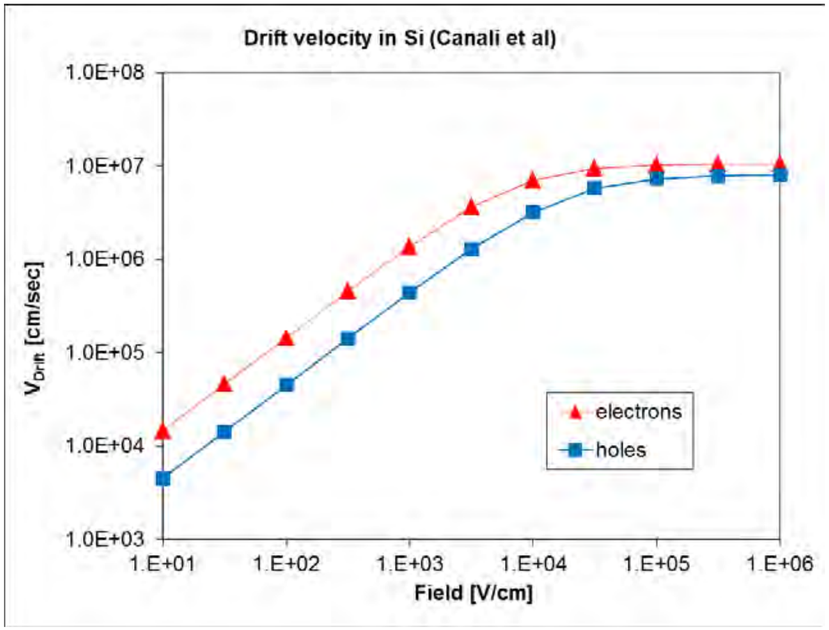


Basic Sensor unit: 96.0x96.0mm2 active (thickness=150 micron)

Number of Sensors per Plane: 4x46=184 (~16960cm2 active)

Number of Sensors per HGTD-disk: 4x184=736 (~67830cm2 active)

Charge Collection Time in Si Sensors



Drift velocity saturates for both electrons and holes!

-> need thin sensors or large over-depletion for fast charge collection

Collection time is close to minimum when
E-Field ≥ 20 kV/cm

For 300um Si
Collection time ~ 4 ns (h), ~ 3 ns (e)
For 50um Si
Collection time ~ 0.7 ns (h), ~ 0.5 ns (e)