Modeling neutron damage in silicon detectors for high energy physics experiments

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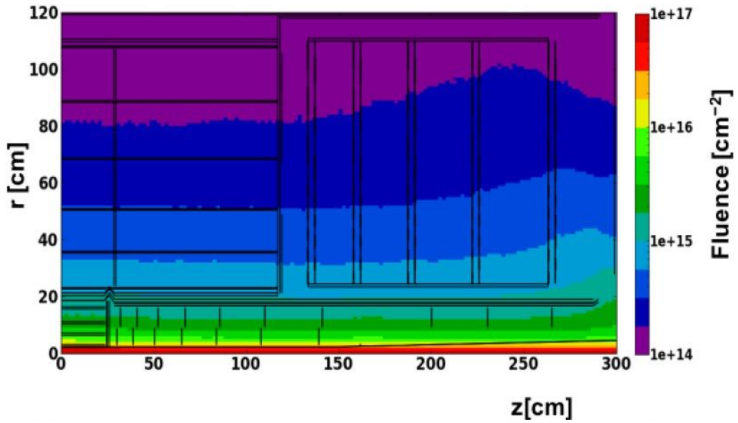
Outline

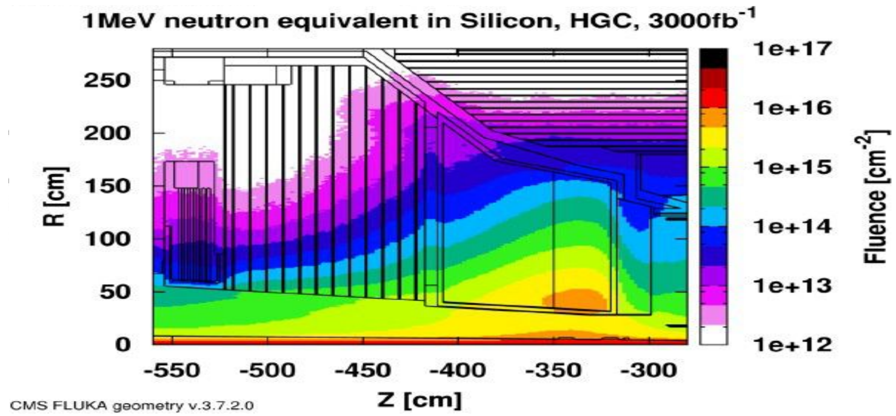
- *Introduction and Motivation*
- *Proton radiation damage Model*
- *Difference between proton and neutron damage*
- *Development of the neutron damage model*
- *Simulation Structure and parameters*
- *Results : Simulation vs Measurements*
  - V_{FD}, I_{LEAK}, CCE
- *Summary*

Introduction and Motivation

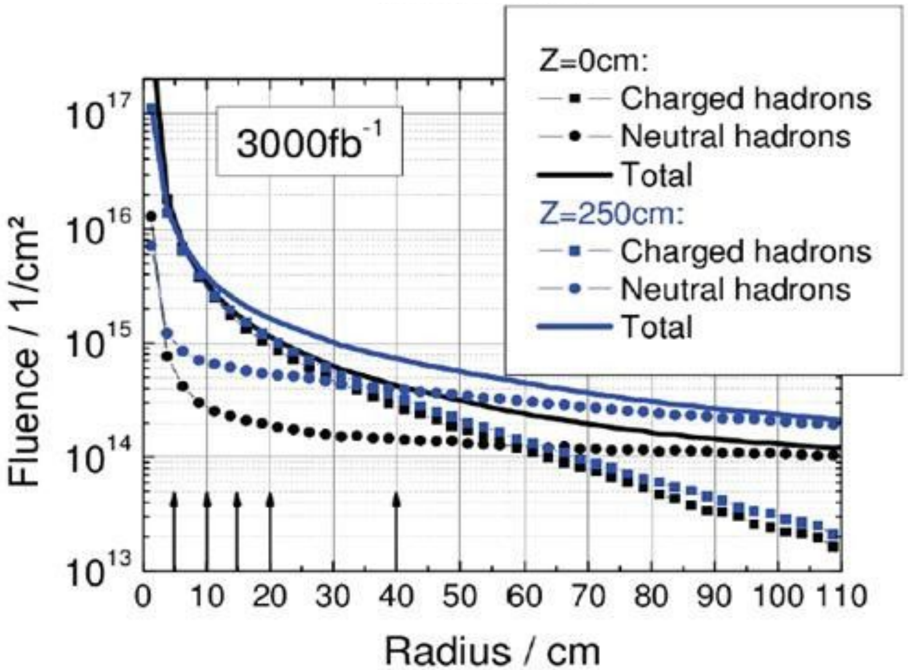
Predictions of the maximum 1MeV n_{eq} fluences normalized to 3000fb^{-1} of **HL-LHC**



Expected particle fluence in the ***Tracker volume***



Expected particle fluence in ***End cap calorimeter***



HL-LHC Phase

- Peak L ~ 5-7 x 10^{34} $cm^{-2}s^{-1}$
- Integrated L = 3000 fb^{-1} (10 yrs of operation)
- Pileup ~ 140-200
- Particle density: 5-10 times higher

Region	ϕ_{max} (1 MeV n_{eq} cm^{-2})
Outer tracker	1.1 x 10^{15}
Calorimeter	1.5 x 10^{16}

Simulations in TCAD Silvaco

Proton Radiation Damage Model

- Bulk Damage = 2 Trap Proton Damage Model* (Delhi Model)
- Surface Damage = Oxide charge density (Q_F) + 2 Interface traps

Bulk Damage Model

Trap Type	Energy Level (eV)	$g_{int}(cm^{-1})$	σ_e (cm2)	σ_h (cm2)
Acceptor	$E_c - 0.51$	4	2×10^{-14}	3.8×10^{-14}
Donor	$E_v + 0.48$	3	2×10^{-15}	2×10^{-15}

Surface Damage Model

Q_F ~ 3e11 to 1.5e12 cm^{-2} (Depending on the fluence)

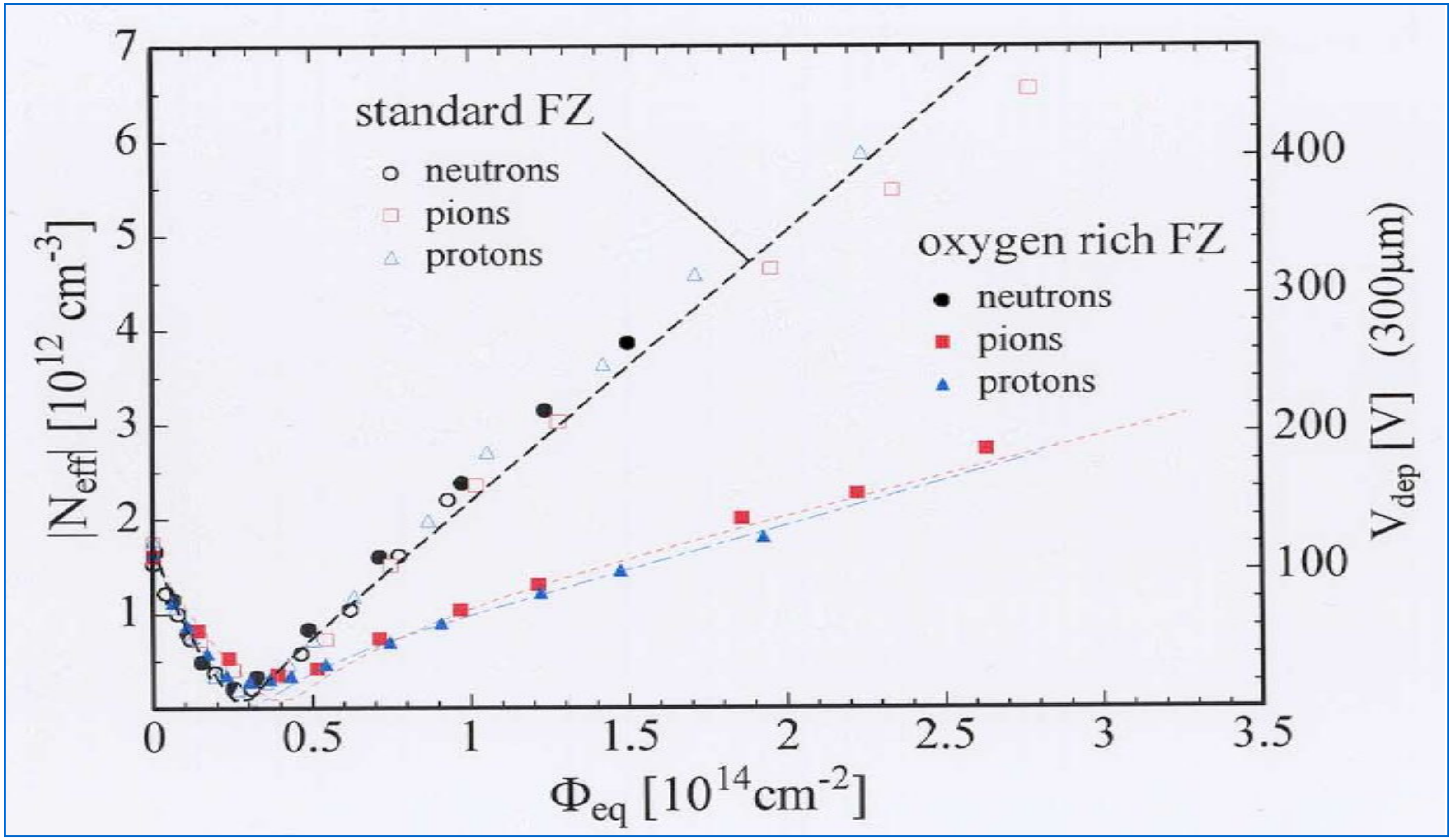
Trap Type	Energy Level (eV)	Trap density (cm^{-3})	σ_e (cm2)	σ_h (cm2)
Acceptor	$E_c - 0.60$	$0.6 \times N_{it}$	1×10^{-15}	1×10^{-15}
Acceptor	$E_c - 0.39$	$0.4 \times N_{it}$	1×10^{-15}	1×10^{-15}

where, N_{it} is the interface trap density which is similar in magnitude to the oxide charge denisty Q_F

No Neutron Radiation Damage Model yet for SIlvaco !!

R. Dalal. *Simulation of Irradiated Si Detectors.* PoS, Vertex-2014 030.

Difference between proton damage and neutron damage



***Introduction rate (g_{int}) of donor traps is 0.5 cm^{-1} for neutron irradiation, which is one sixth of the introduction rate of donortraps for protons irradiation.**

Measurements : Gunnar Lindstrom, University of Hamburg + CERN-RD48, PIXEL 2000 Genoa 05-09 June 2000

*Reference : I. Pintilie et al., Nuclear Instruments and Methods in Physics Research A 611 (2009) 52–68

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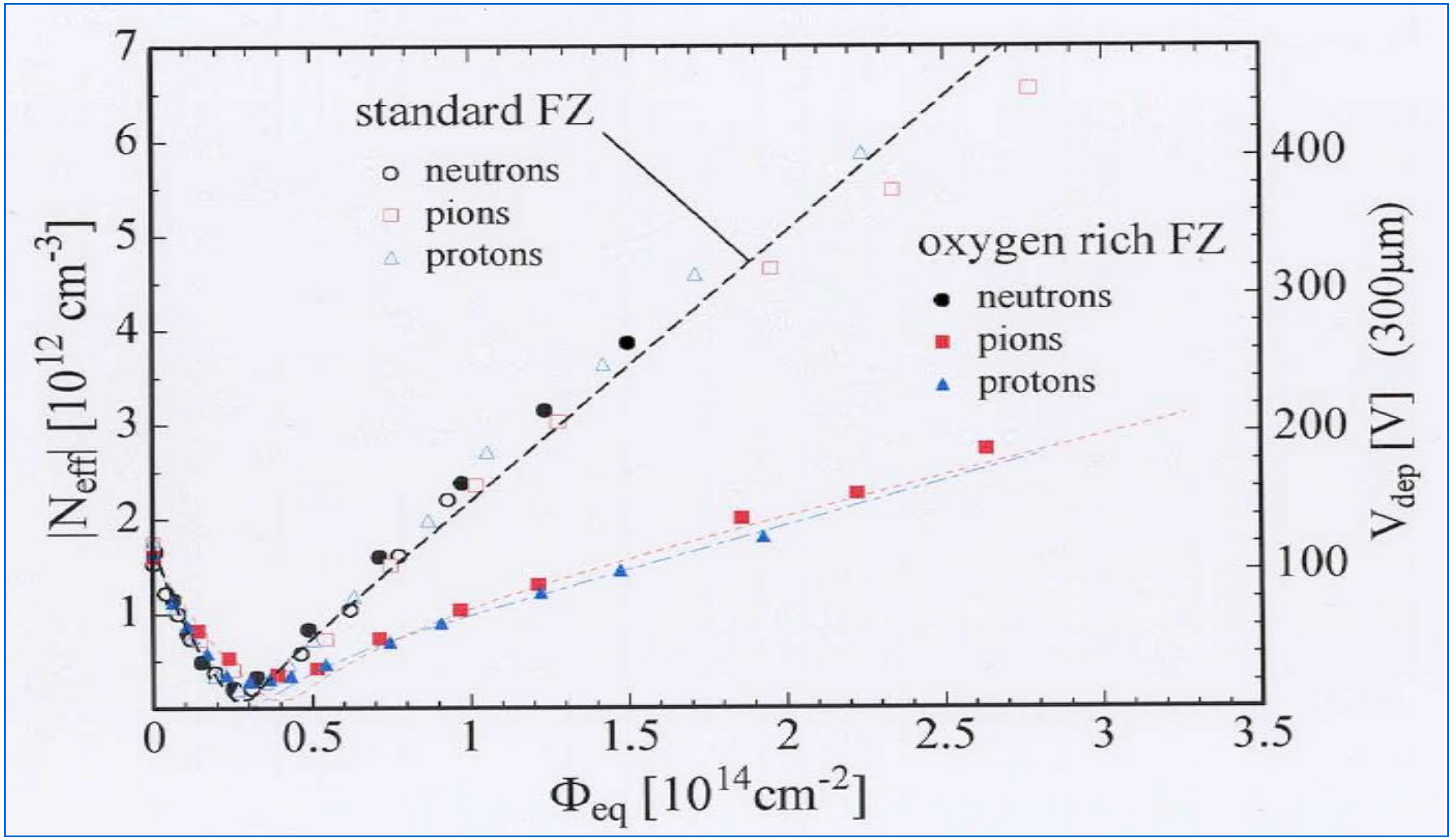

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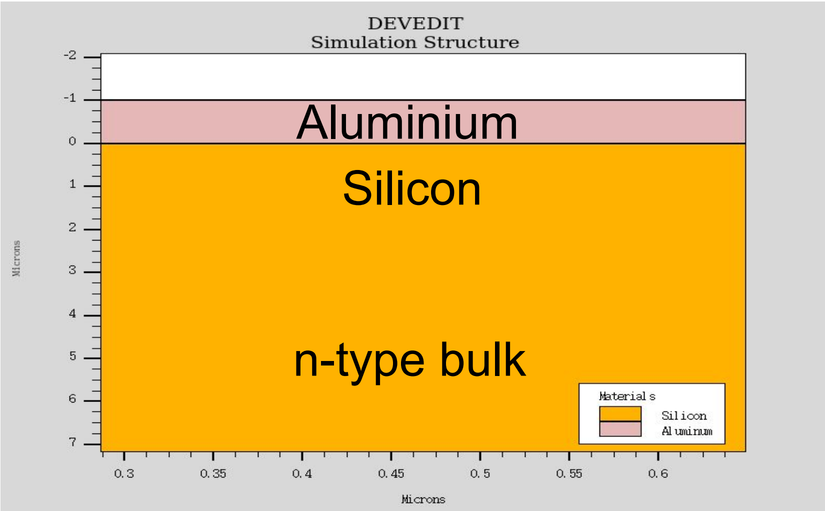
Development of the Neutron Damage Model

Simulation structure and parameters

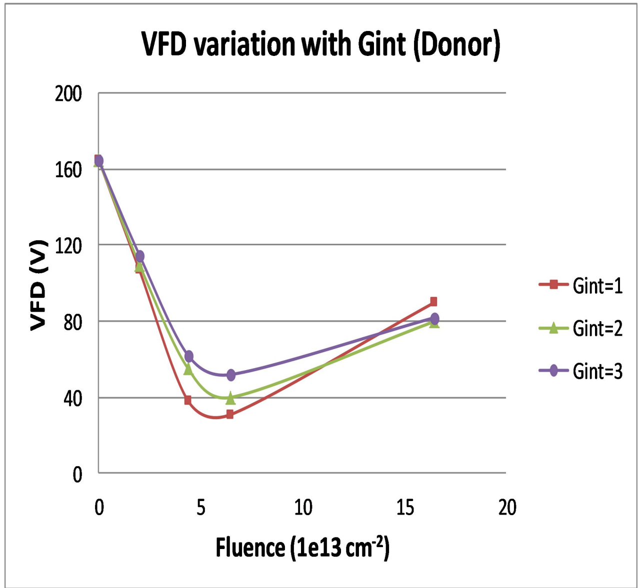


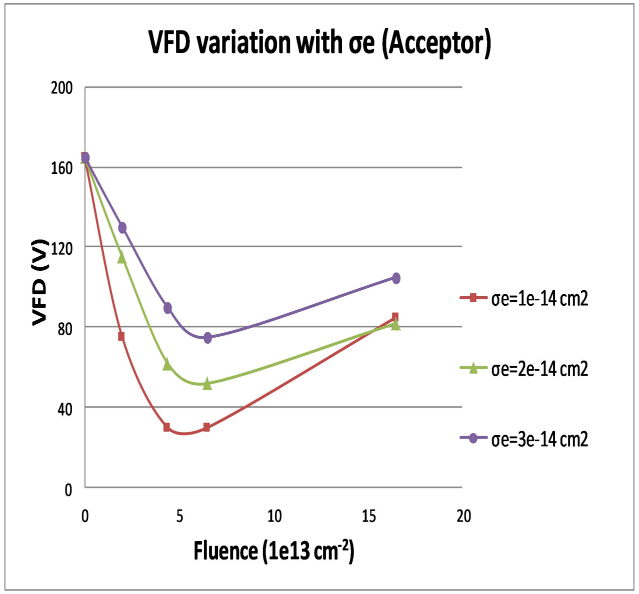
Optical Source	
Laser	Infrared
Wavelength	1060 nm
Mixed mode circuit	

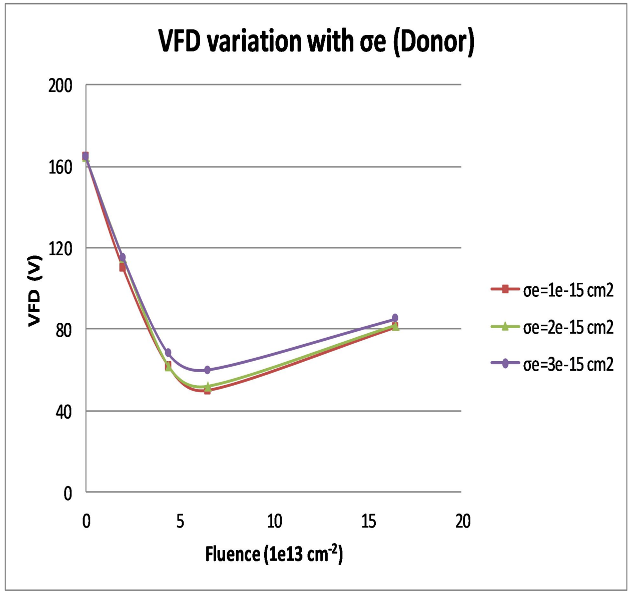
Simulation Parameters	
X Dimension	1 µm
Y Dimension	300 µm
Z Dimension	1 µm
n-bulk doping density	$2.37e12\ cm^{-3}$ $1e12\ cm^{-3}$
n^+/p^+ peak doping density	$1x10^{18}\ cm^{-3}$
Junction depth	1 µm
Temperature	263 K

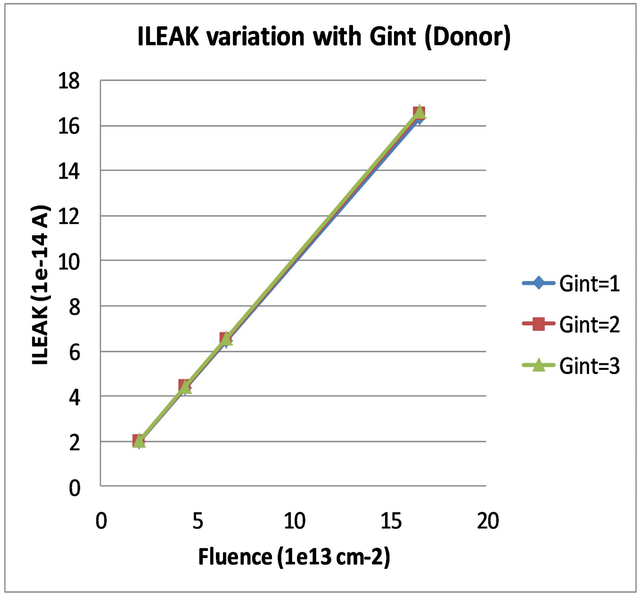
- V_{FD}, I_{LEAK} and CCE simulation have been carried out
- Fluence range : 0 to 9e14 1MeV $n_{eq}cm^{-2}$
- AC small signal frequency : 10^3 Hz for C_{diff} (diffusion capacitance)

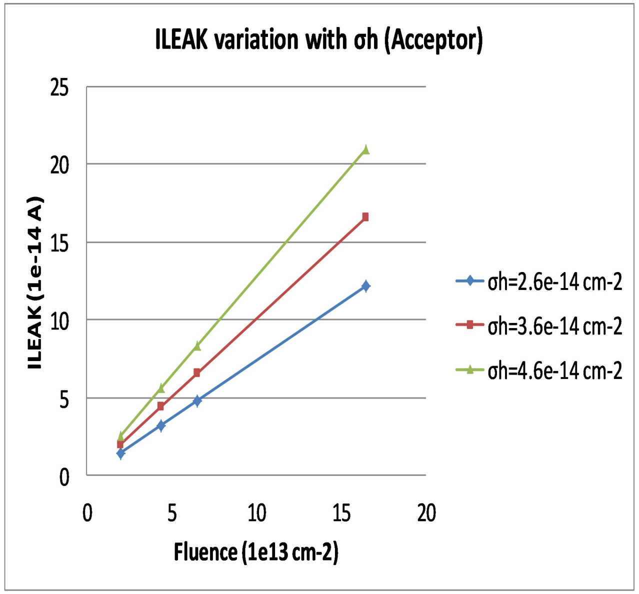
Sensitivity of Macroscopic parameters of the detector with respect to trap parameters (1/2)

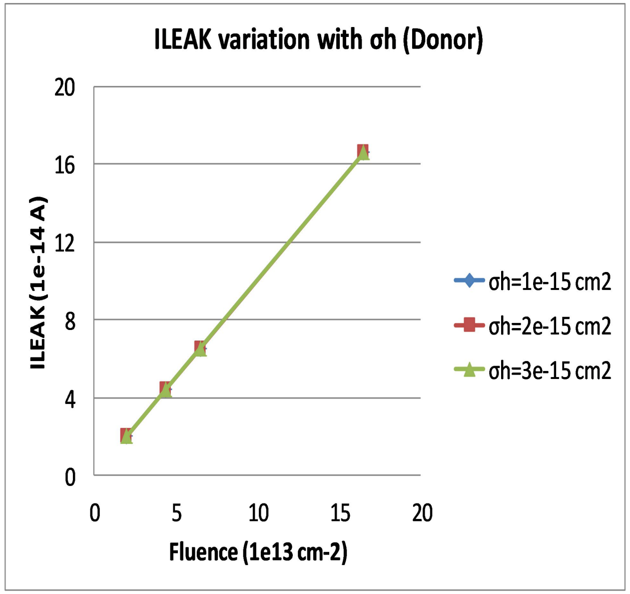




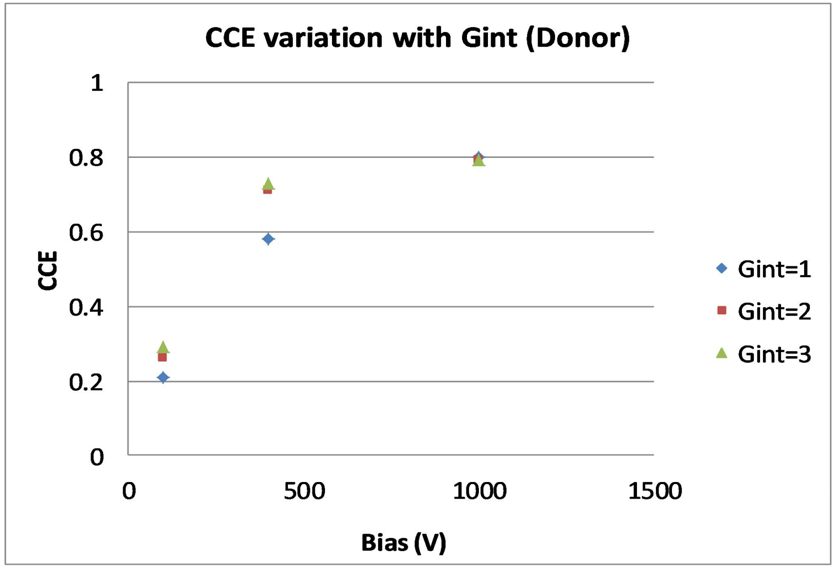


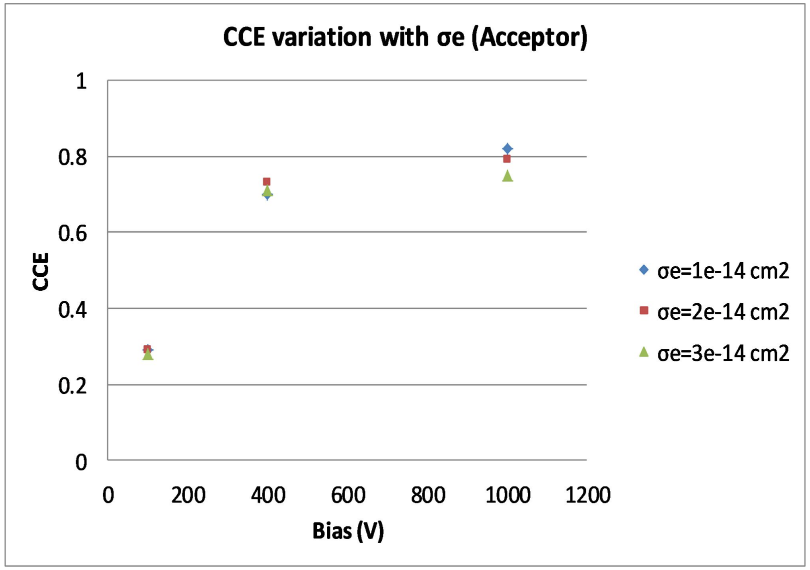


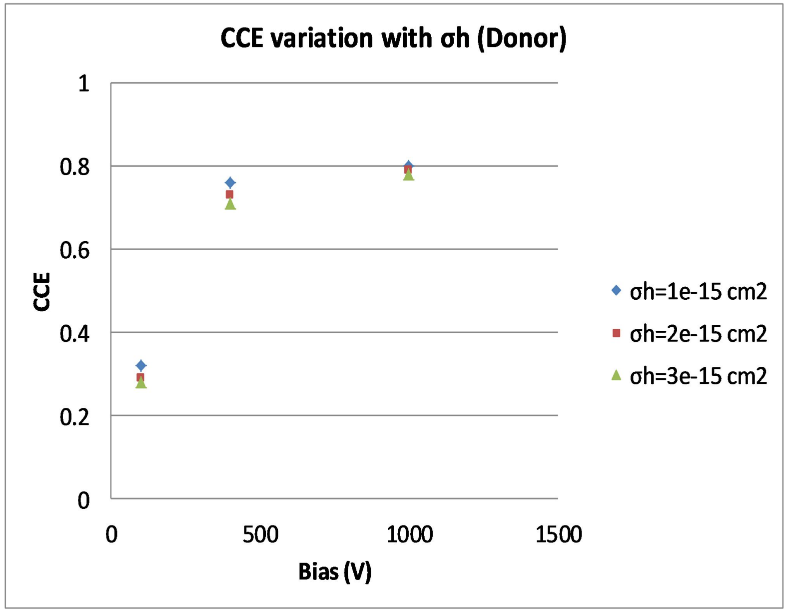




Sensitivity of Macroscopic parameters of the detector with respect to trap parameters (2/2)







Neutron damage model

Results of the sensitivity study of V_{FD}, I_{LEAK} and CCE towrds various trap parameters

- V_{FD} has a strong dependecy on g_{int} (donor trap) and σ_e, σ_h (Acceptor traps)
- I_{LEAK} depends mainly on σ_h (Acceptor).
- CCE depends mainly on g_{int} (donor trap) and slightly on other parameters.

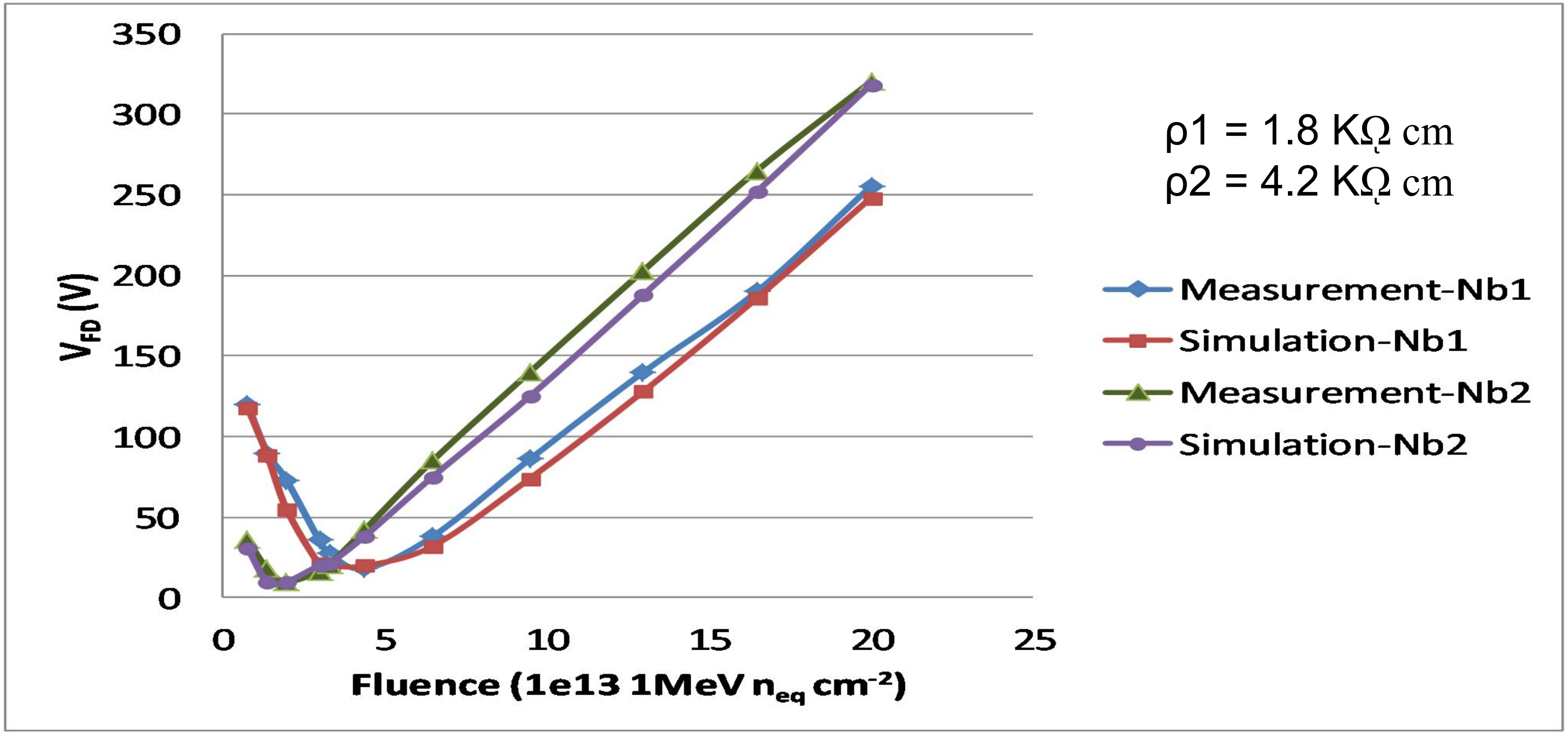
- Two bulk traps : 1 Acceptor + 1 Donor
- Trap parameters : Trap type, Energy level, g_{int}, σ_e, σ_h

Trap Type	Energy Level (eV)	$g_{int}(cm^{-1})$	$\sigma_e\ (cm^2)$	$\sigma_h\ (cm^2)$
Acceptor	$E_c - 0.51$	4	**7.2×10^{-15}**	**2.8×10^{-14}**
Donor	$E_v + 0.48$	**1**	2×10^{-15}	2×10^{-15}

No Surface Damage Model has been used !!

Results and comparisons
Simulations and Measurements

V_{FD} Variation with Neutron Fluence (n-type)

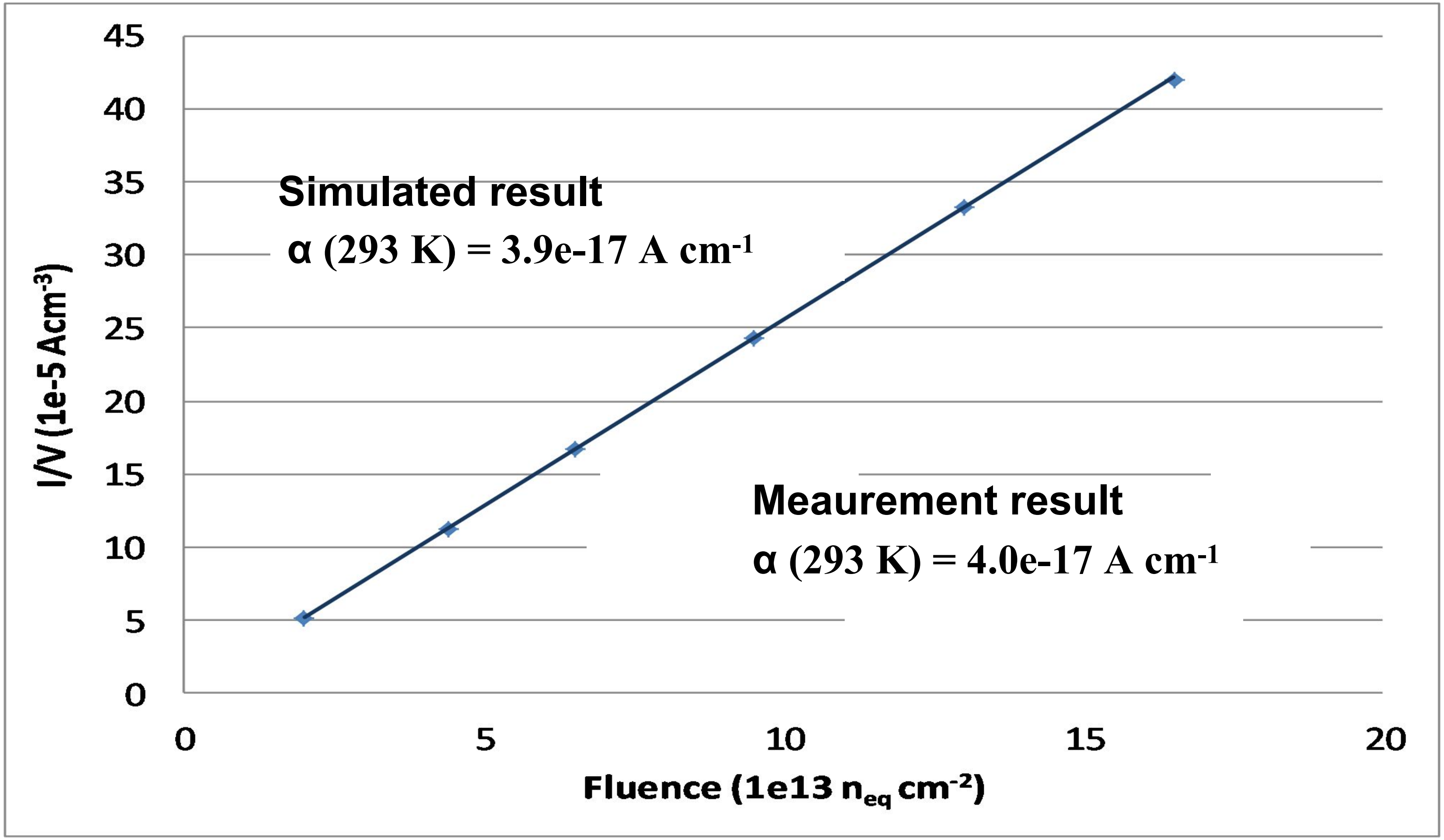


- For n-type sensor, V_{FD} first decreases, reaches minima and thereafter it increases with increasing neutron fluence.
- As fluence increases the effective doping concentration decreases because of the creation of mainly acceptor traps following by the ***type inversion**** of the bulk material.

*Reference : F. Hartmann, Evolution of Silicon Sensor Technology in Particle Physics, Springer, 2009.

Measurements : Gunnar Lindstrom, University of Hamburg + CERN-RD48, PIXEL 2000 Genoa 05-09 June 2000

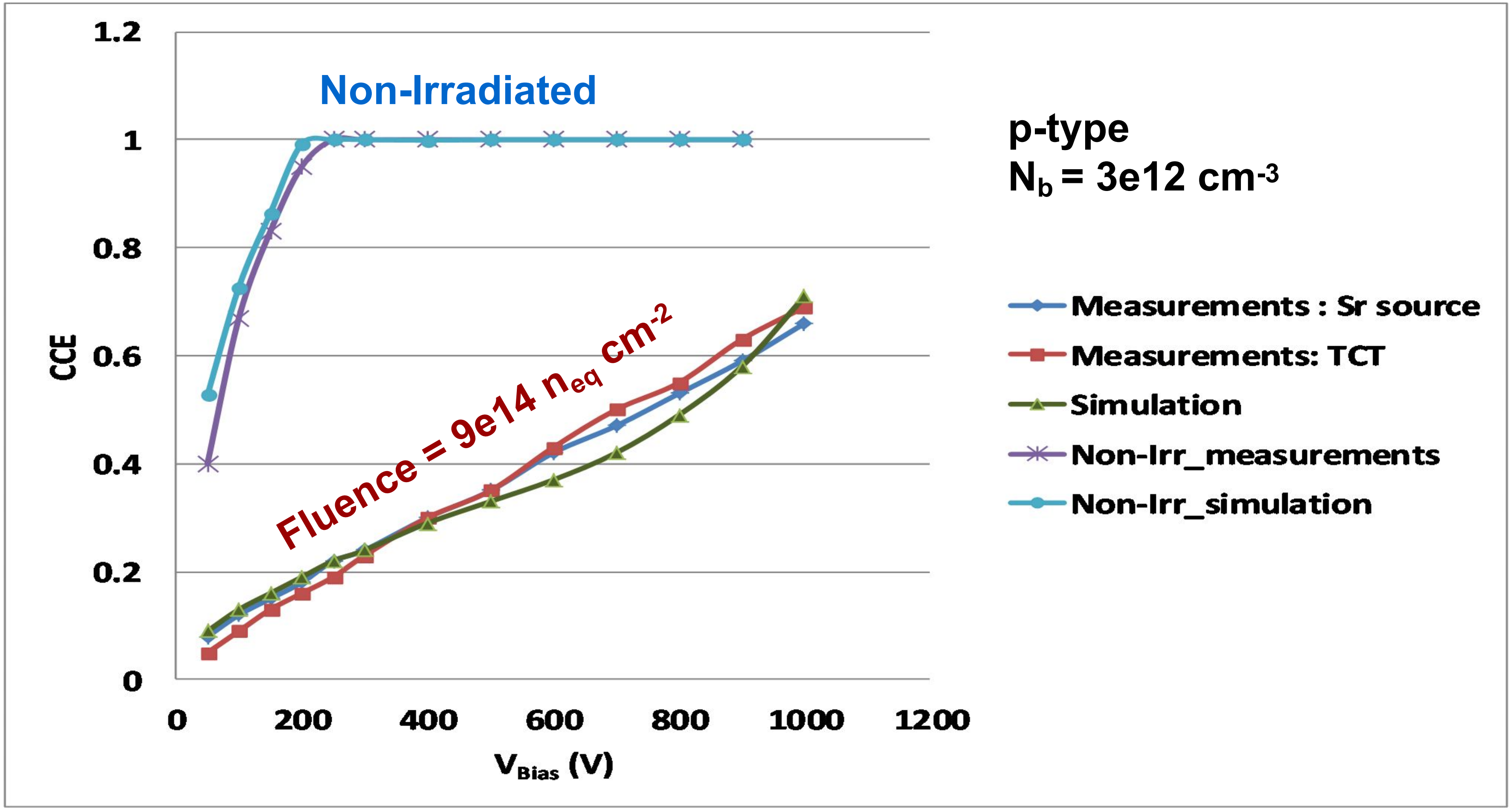
I_{LEAK} Variation with Neutron Fluence (n-type)



where, α is the current related damage paramter given by $\alpha = \frac{I / V}{\phi}$

- The saturation value of the leakage current increases with increase in fluence.

CCE variation with V_{Bias}



- **For any bias voltage CCE is found to decrease with increase in neutron fluence.**
- **For any fluence CCE is found to increase with increase in applied bias.**

Measurements : E. Curras. Nuclear Instruments and Methods in Physics Research A, Proceeding 2016

Summary and future outlook

- Sensitivity studies have been performed by varying trap parameters to investigate macroscopic properties like V_{FD}, I_{LEAK} and CCE.
- The effective two traps neutron damage model has been proposed.
- Good agreement has been observed for V_{FD} against measuremenst up to a fluence of 1.65e14 1MeV n_{eq} cm^{-2} .
- α value is found to be very close to the value published in literature.
- CCE simulations were performed both for non-irradiated and irradited devices and they are found to be in good agreement with measurements.

- More simulations need to be performed at different temperatures.
- Simulations for p-type bulk need to be performed as well.
- More TCT Simulations would be done to find out effective trapping probability of charge carriers in different bulk type substrates.

Thanks for your attention !