Towards to a new radiation damage model for Synopsys TCAD

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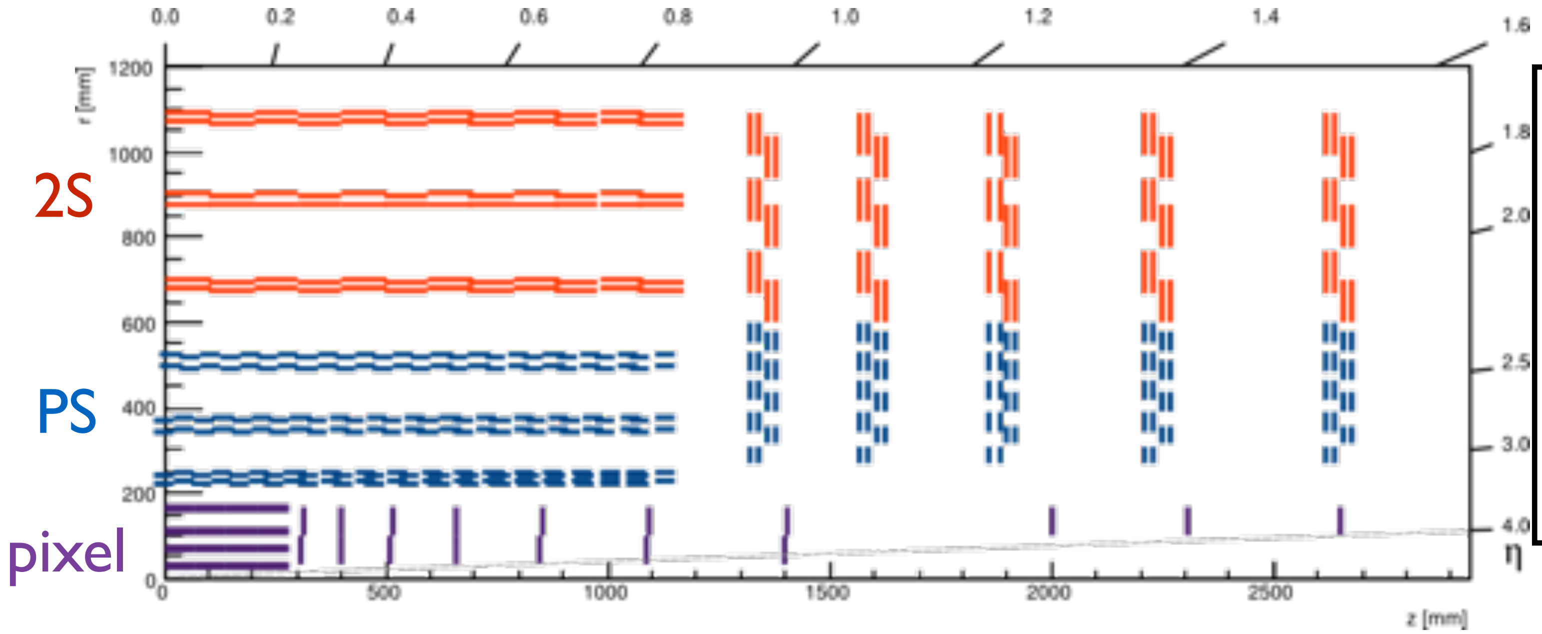
Introduction

High-Luminosity LHC (~ 2024):

- Luminosity of $5x10^{34}$ $cm^{-2}s^{-1}$, operate up to 200 events/crossing
- Maintain occupancy at ≈ 1% level and increase the resolution

➡ Pixel size ~ $25x100$ μm^2 or $50x50$ μm^2 (currently $100x150$ μm^2)

CMS Tracker baseline layout:



Outer tracker (R > 20 cm):

- 6 barrel layers and 5 endcap disks (with 2-strip and pixel-strip modules)

Inner tracker (20 cm > R > 4 cm):

- 4 barrel layers and 10 disks (with pixel modules, η up to 4)

Radiation tolerance for the 1th pixel layer after 3000 fb^{-1}:

- $\Phi_{eq} \approx 2x10^{16}$ cm^{-2}, Dose ≈ 5 MGy

Pixel sensors (3D or thin planar) which can withstand these radiation fluence are needed

Radiation damage

Optimization of the sensor → simulations

Simulations → device modeling (TCAD) + models for bulk & surf. damage

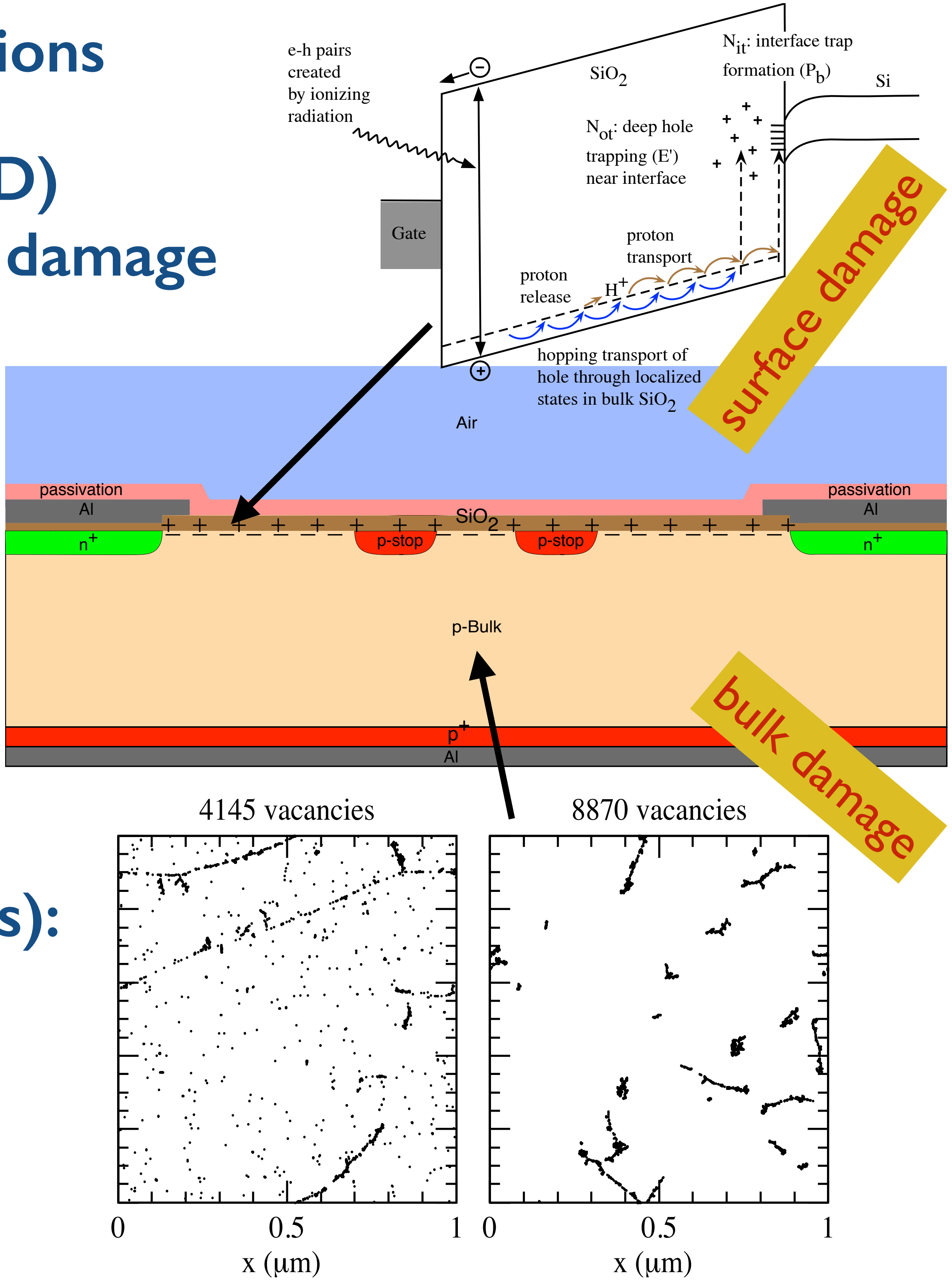
Bulk damage (NIEL):

- Point and cluster defects
  - ➡Increase of leakage current
  - ➡Change of the space charge in the depletion region, increase of full depletion voltage
  - ➡Charge trapping

Surface damage* (Ionizing Energy Loss):

- ↑ Oxide charge & ↑ interface trap

The models for bulk & surf. damage have to be correct (independently)



24 GeV/c protons 1 MeV neutrons

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[*] In this talk, not further discussed

Defect modeling approach

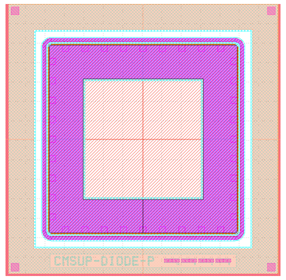
Radiation damage depends on

- particle type, energy, annealing, silicon material + vendor (surface)

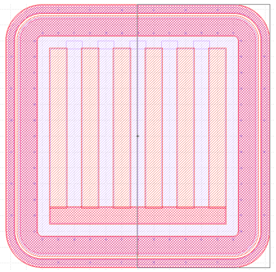
It is measured on

- diodes (bulk damage)
  - macroscopic (I-V, C-V, Transient Current Technique)
  - microscopic (Thermally Stimulated Current)
- special test structures (surface damage)
  - I-V, C/G-V and Thermally Dielectric Relaxation Current

Diode



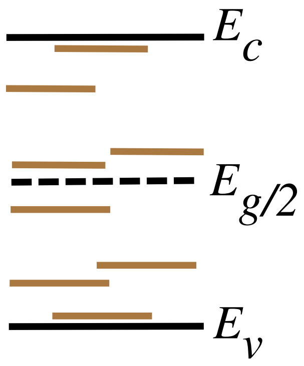
GCD



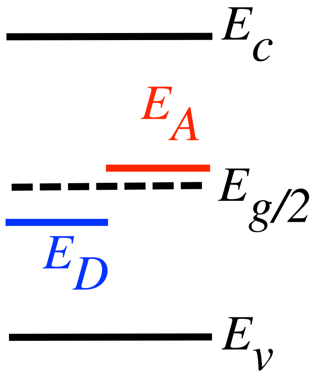
Validation of combined model on segmented sensor

Options for bulk damage modeling:

- Multi-trap model based on microscopic measurements



- Effective trap model tuned to macroscopic measurements e. g. Eremin 2-trap model



Acceptor (A) and donor (D) Energy levels fixed

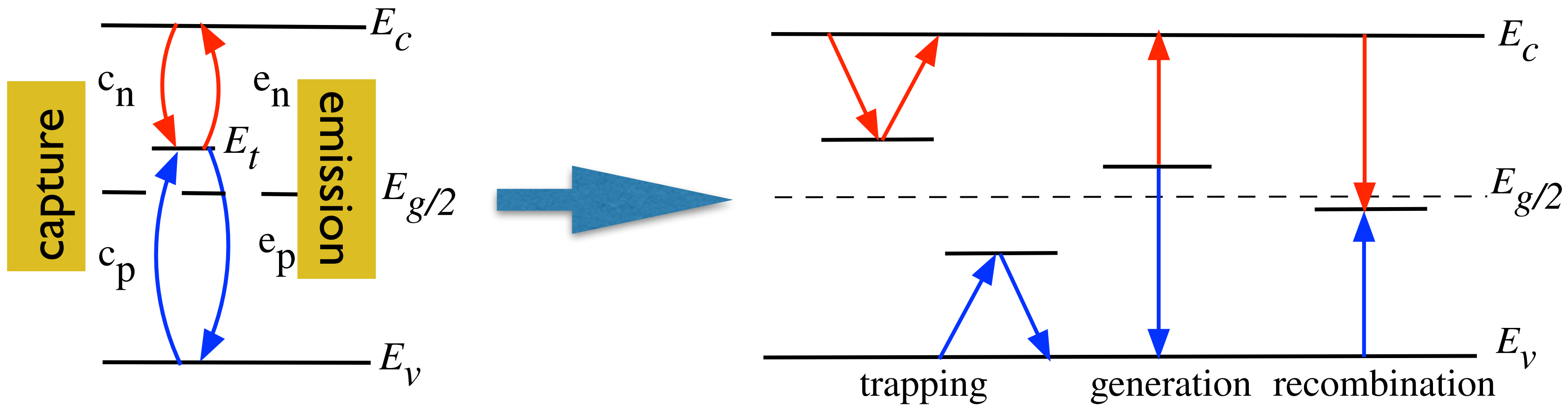
Basics of effective 2-trap models I

- One acceptor (A) and one donor (D)
- Energy levels fixed

E_A	E_D
E_C-0.525 eV	E_V+ 0.48 eV

(Eremin et al, NIMA 476 2002)

Traps obey Shockley-Read-Hall statistics:



2 trap model → 6 parameter

1. Concentrations : N_A , N_D
2. Cross sections : σ^A_e , σ^A_h , σ^D_e , σ^D_h

Basics of effective 2-trap models II

TCAD allows solving of device equations together with traps

1. Poisson: $\nabla \cdot \epsilon \nabla V = -\rho_{eff}$ with $\rho_{eff} = q[p - n + N_D f_D - N_A f_A] + \rho_{dopants}$

with f_D and f_A the occupied fractions given by SRH

2. Continuity equations: $\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot J_n + R_{net}$ with $J_n = q n \mu_n E + D_n \frac{dn}{dx}$

$\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot J_p + R_{net}$ with $J_p = q p \mu_p E - D_p \frac{dp}{dx}$

with R_{net} the net generation/recombination rate

Trapping is included and the effective trapping rates are given by the expressions:

$\Gamma_e = v_e[\sigma_e^A N_A(1 - f_A) + \sigma_e^D N_D f_D] \approx v_e \sigma_e^A N_A$ approx. if f_A and f_D negligible

$\Gamma_h = v_h[\sigma_h^D N_D(1 - f_D) + \sigma_h^A N_A f_A] \approx v_h \sigma_h^D N_D$

Aim:

- Simultaneous tuning of the 6 parameter to reproduce I-V, C-V and CCE with as simple as possible fluence dependence of parameters

Existing bulk damage models

Some available models:

1. 2-trap proton model (R. Eber Phd 2013): 23 MeV proton, 10min@60°C, ≤10^{15} n_{eq}/cm

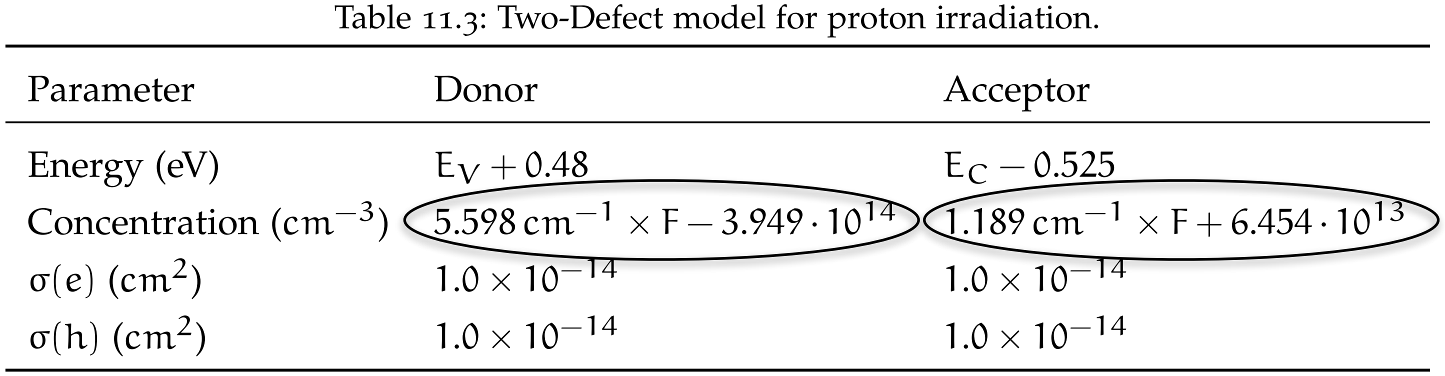
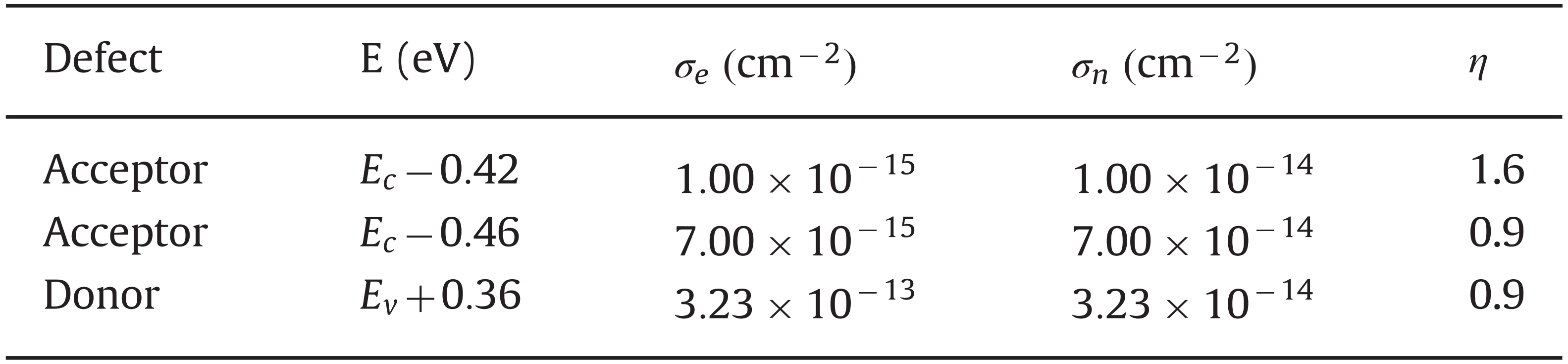


Table 11.3: Two-Defect model for proton irradiation.

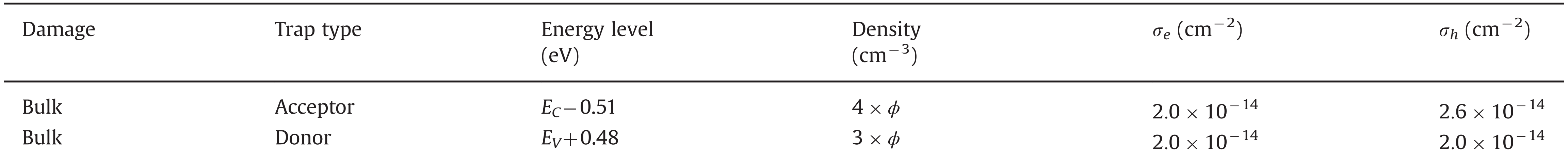
Parameter	Donor	Acceptor
Energy (eV)	$E_V + 0.48$	$E_C - 0.525$
Concentration (cm^{-3})	$5.598\,cm^{-1} \times F - 3.949 \cdot 10^{14}$	$1.189\,cm^{-1} \times F + 6.454 \cdot 10^{13}$
$\sigma(e)$ (cm^2)	1.0×10^{-14}	1.0×10^{-14}
$\sigma(h)$ (cm^2)	1.0×10^{-14}	1.0×10^{-14}

2. 3-trap Perugia model (D. Passeri IEEE TNS 2006): ≤10^{15} n_{eq}/cm^2



Defect	E (eV)	σ_e (cm^{-2})	σ_n (cm^{-2})	η
Acceptor	$E_c - 0.42$	1.00×10^{-15}	1.00×10^{-14}	1.6
Acceptor	$E_c - 0.46$	7.00×10^{-15}	7.00×10^{-14}	0.9
Donor	$E_v + 0.36$	3.23×10^{-13}	3.23×10^{-14}	0.9

3. 2-trap proton model (Delhi, G. Jain NIMA 2015): 23 MeV proton, model for Silvaco TCAD



Damage	Trap type	Energy level (eV)	Density (cm^{-3})	σ_e (cm^{-2})	σ_h (cm^{-2})
Bulk	Acceptor	$E_C - 0.51$	$4 \times \phi$	2.0×10^{-14}	2.6×10^{-14}
Bulk	Donor	$E_V + 0.48$	$3 \times \phi$	2.0×10^{-14}	2.0×10^{-14}

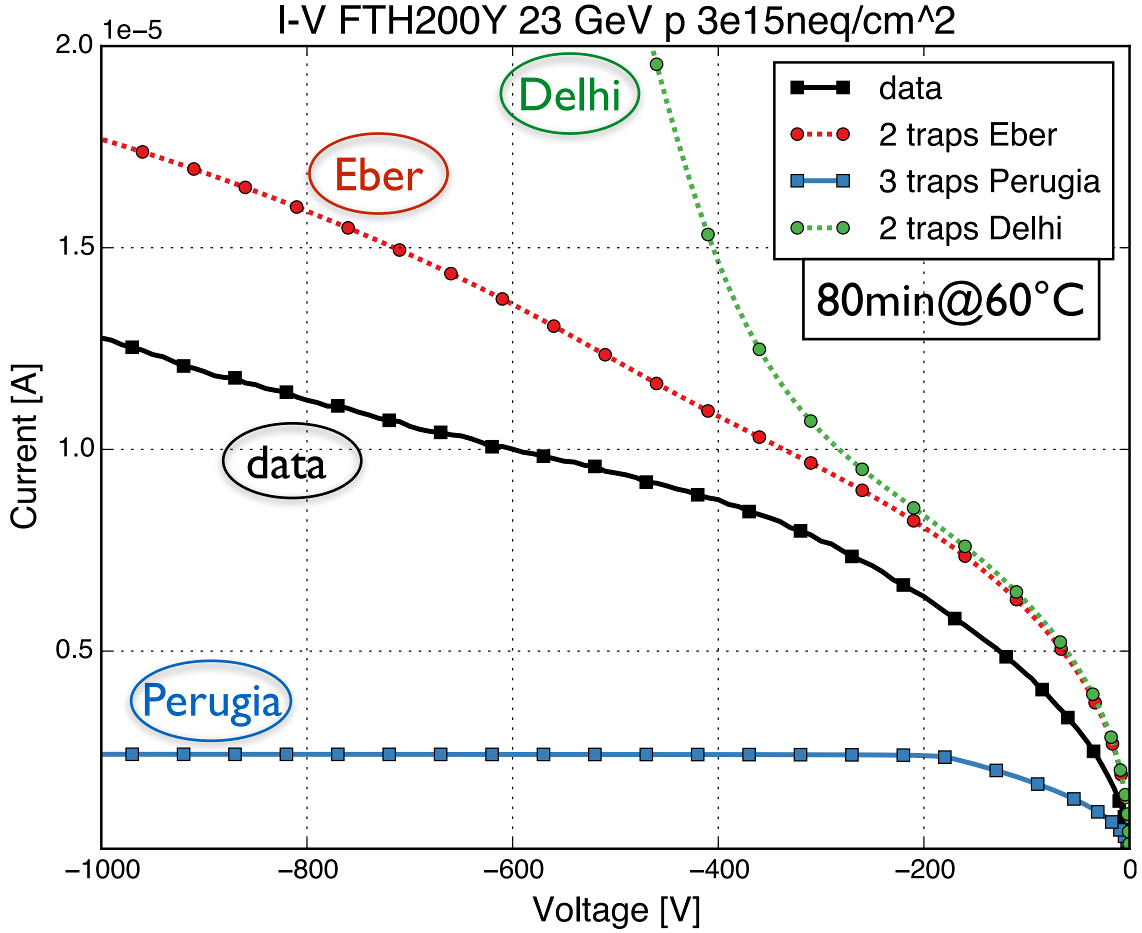
Where do we stand?

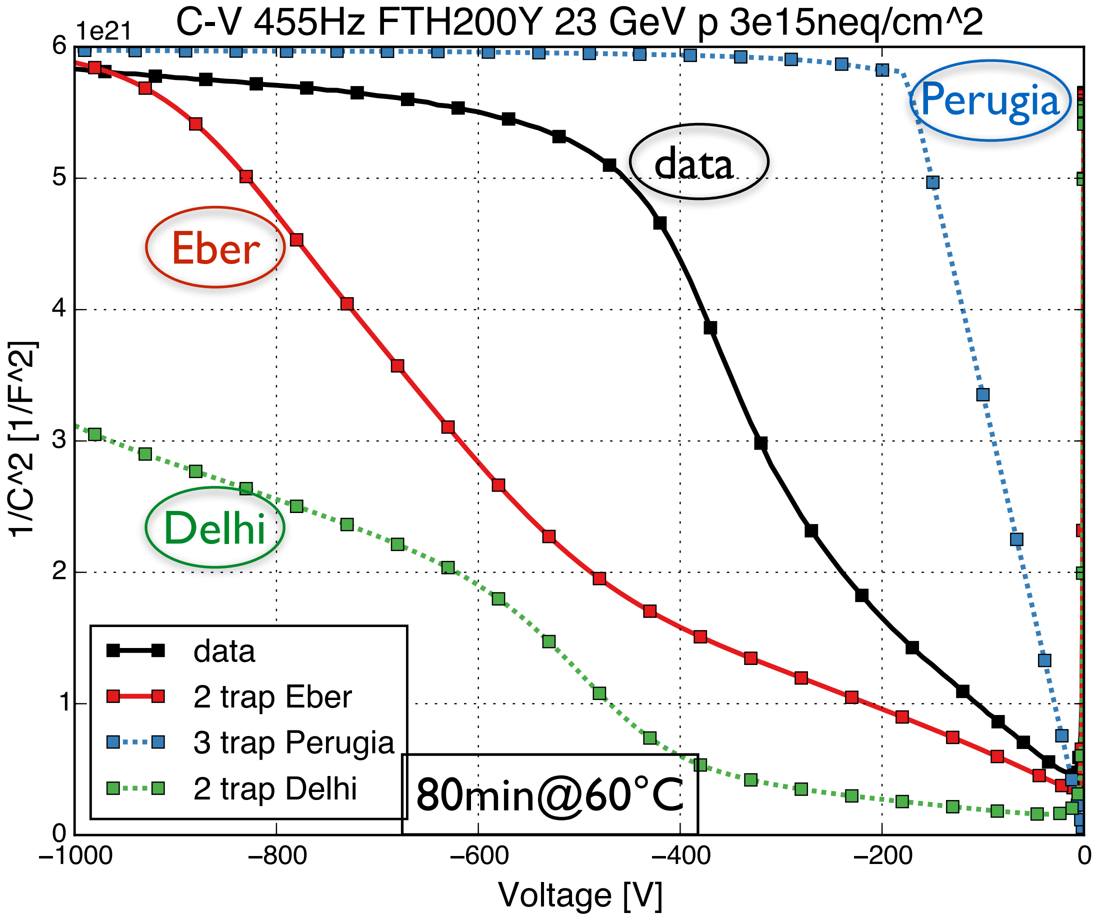
Why another bulk damage model?

- The current bulk models are limited in fluence (< $3 \cdot 10^{15}$ n_{eq}/cm^2)
- Do not include annealing effects
- Are tuned to one specific material type & irradiation

Examples:

- HPK diode, p-type, 200 um thick, T = -20 °C





None of existing models matches 23 GeV p $3 \cdot 10^{15}$ n_{eq}/cm^2

Toward to a new model

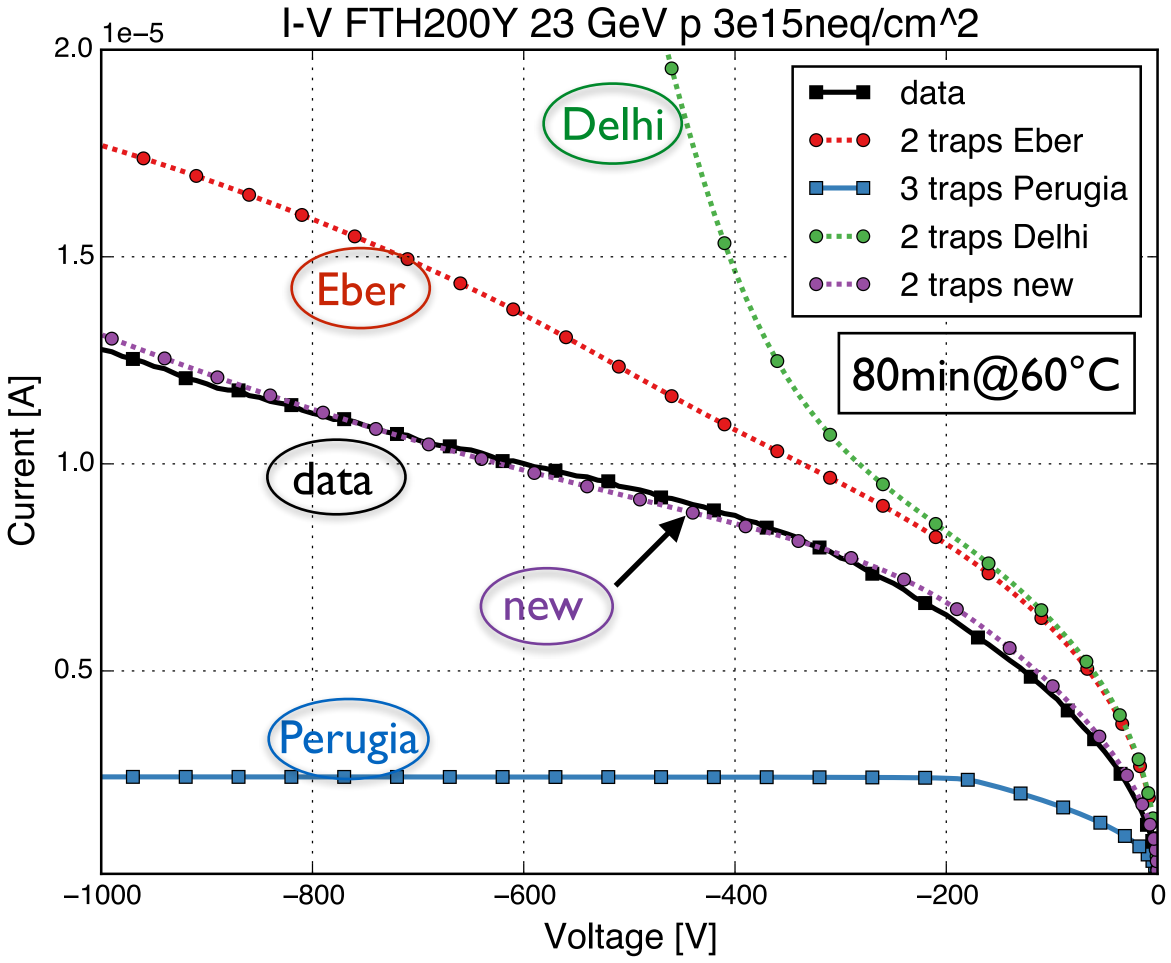
First attempts for new effective damage model:

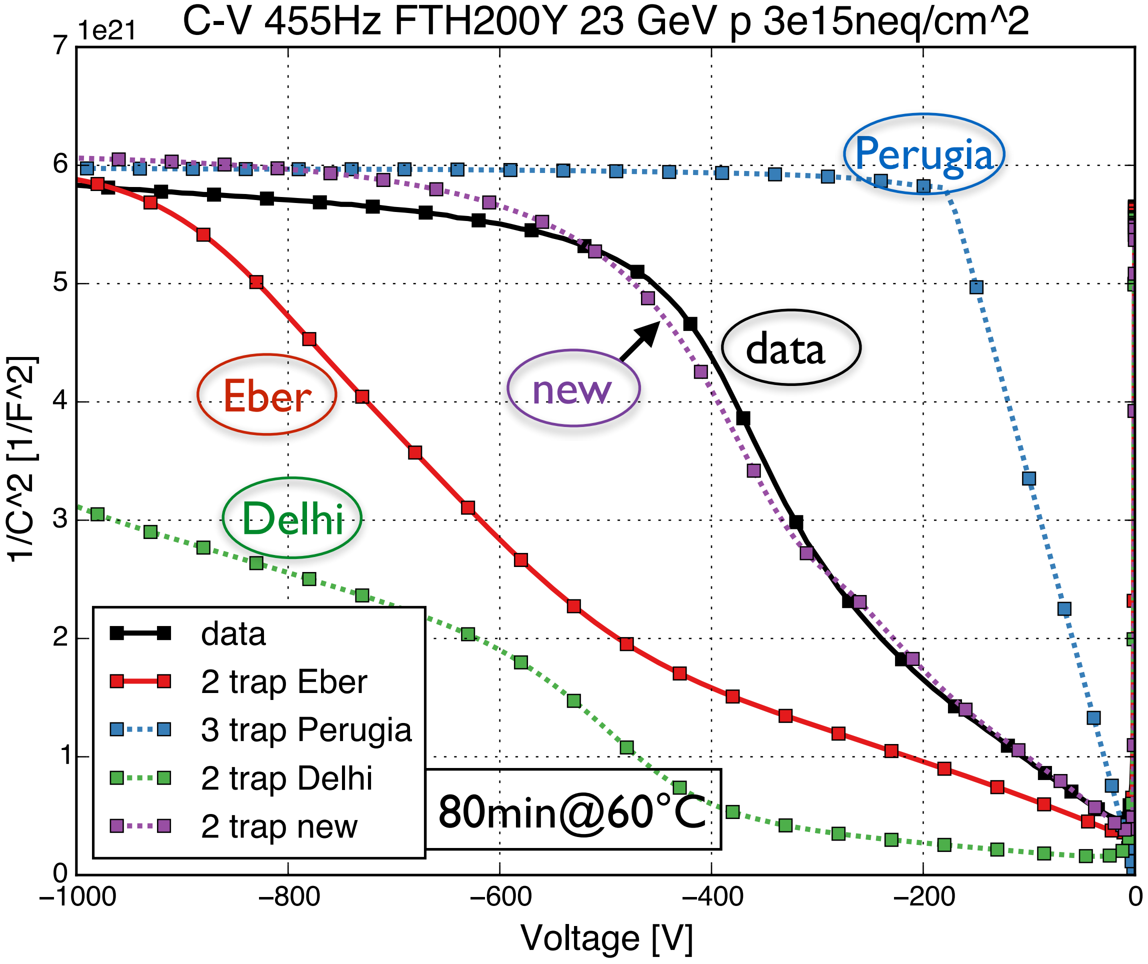
- Simulation of I-V and C-V of diodes for different fluences (HPK campaign) using the optimizer of TCAD for the determination of the 6 free parameters (≈ 3 min/sim.) i.e. minimize the relative deviation between the simulations and measurements over a large voltage range or more precise: Minimize

$$F = w_1 \int_{V_{min}}^{V_{max}} (1 - \frac{I_{sim}}{I_{mes}})^2 \, dV + w_2 \int_{V_{min}}^{V_{max}} (1 - \frac{C_{sim}}{C_{mes}})^2 \, dV$$

with I_{sim} simulated current, I_{mes} measured current
C_{sim} simulated capacitance, C_{mes} measured capacitance
V_{min} ,V_{max} min. and max of voltage range
w_1, w_2 weighting factors
using for example an quasi-Newton methods.

First optimization results

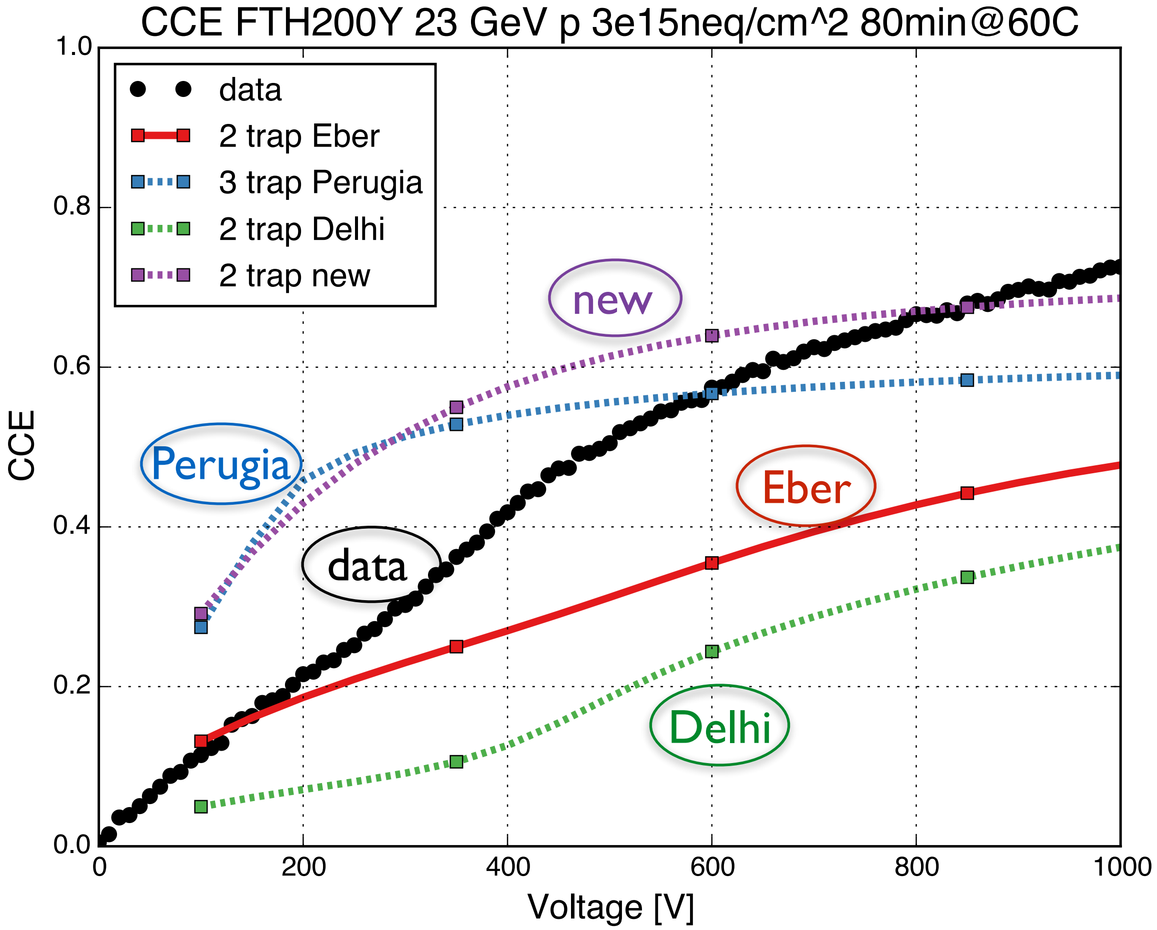




Good match of I-V & C-V simultaneously

TCT simulations (CCE)

Check with CCE vs voltage for IR (1063nm) laser



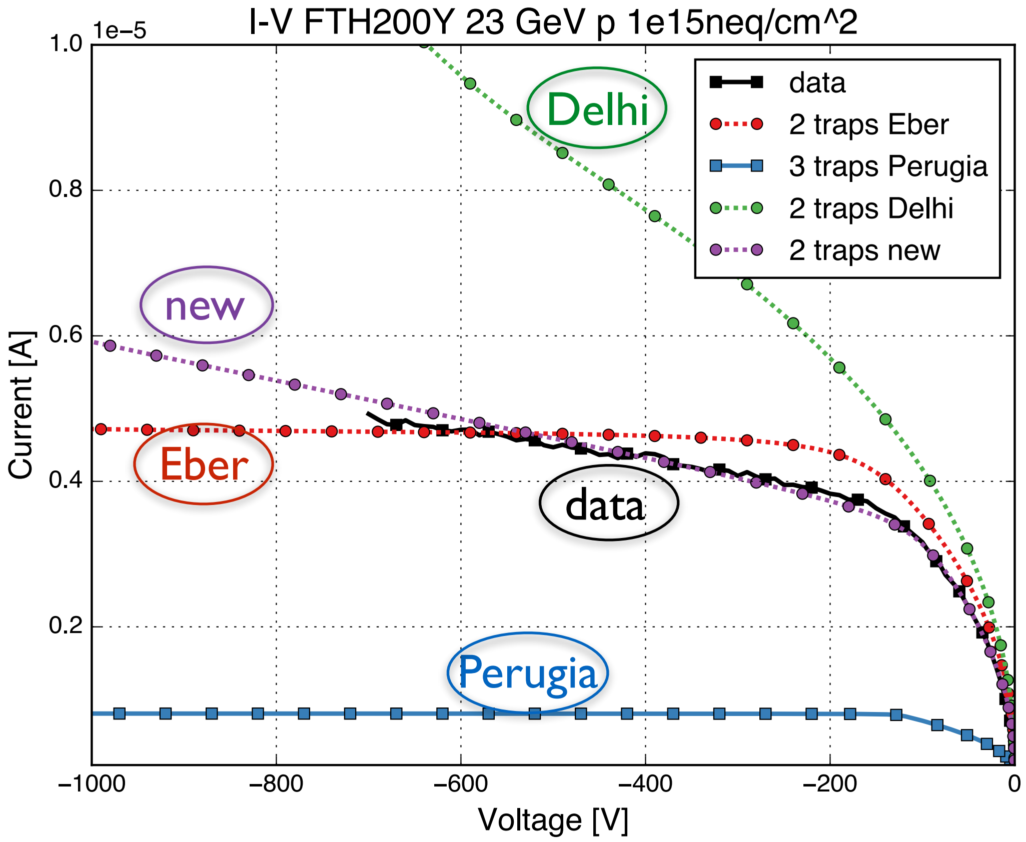
CCE simulation takes too long to be included in optimization procedure 180 min/sim

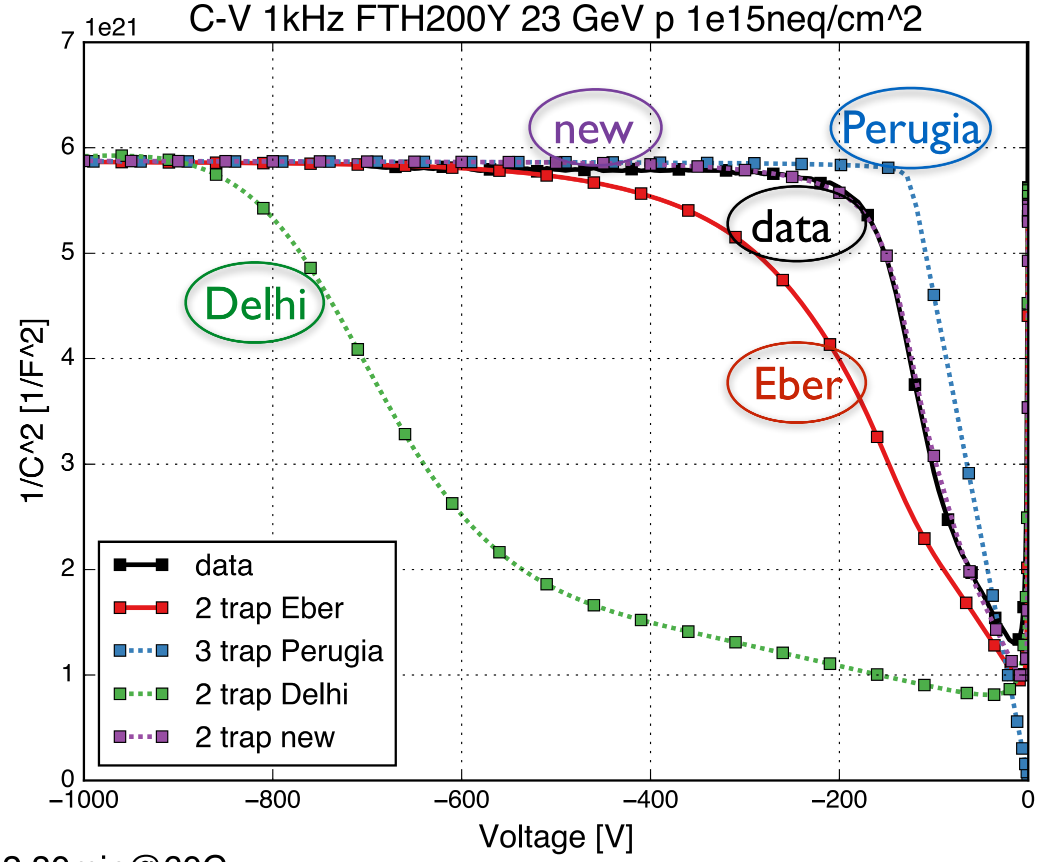
- Models from Eber and Delhi results in too low CCE
- New fit gives too high CCE at low voltages

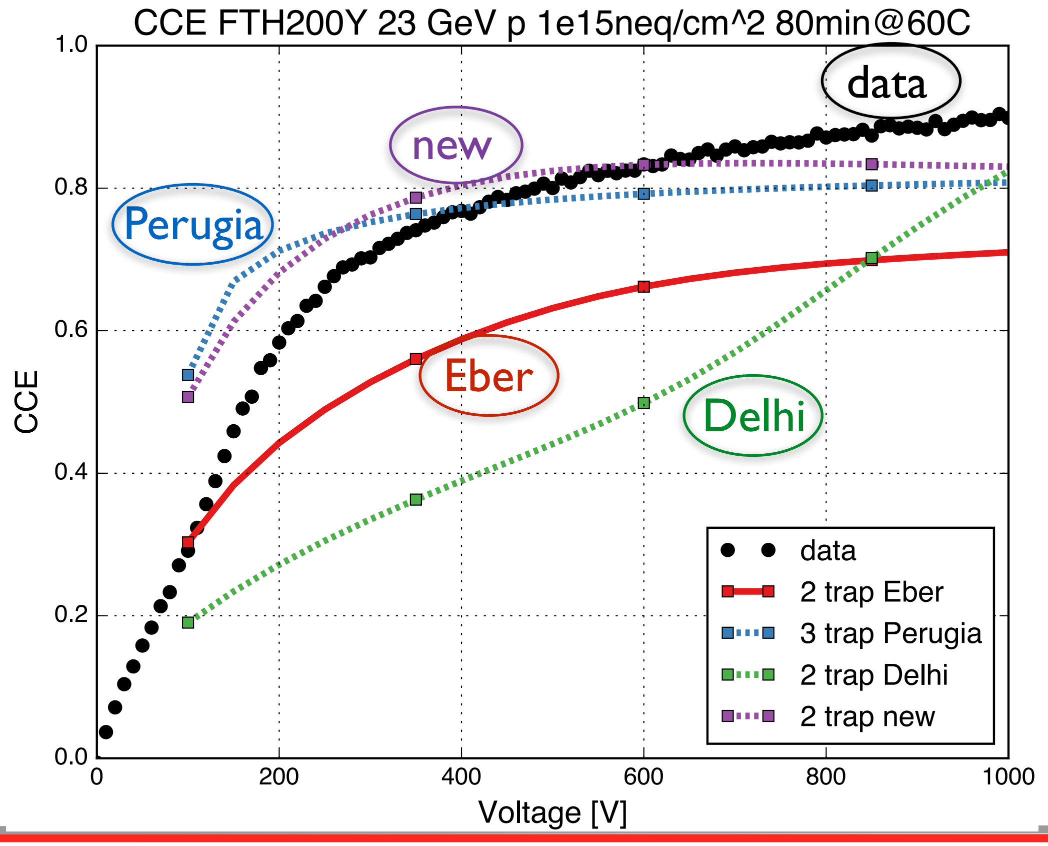
Next step:

- Possibly include forward I-V to get constrain on recombination
- Are 2-traps sufficient for a consistent description at high fluences?

Case: 23 GeV p $1 \cdot 10^{15}$ n_{eq}/cm^2



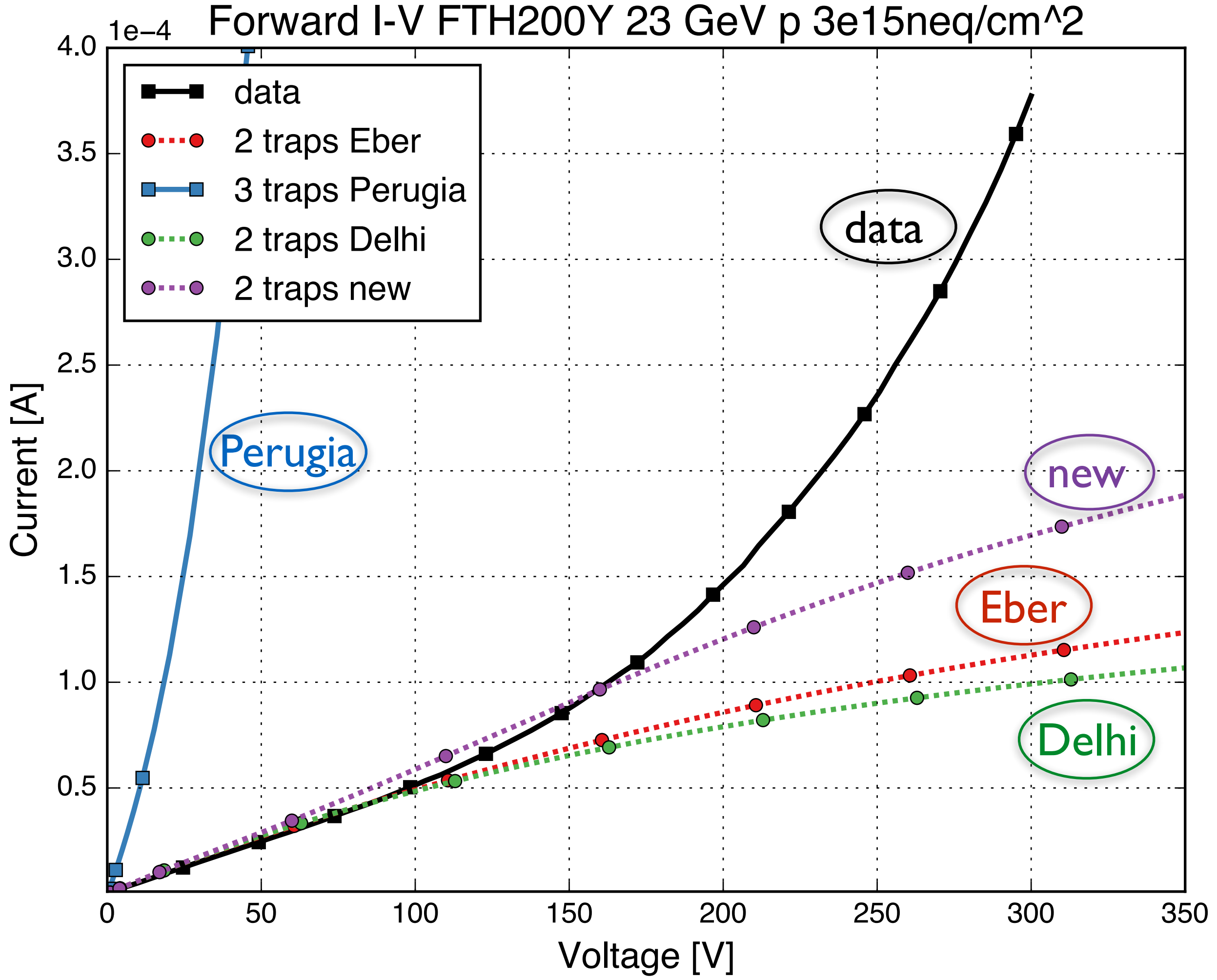




Disagreement smaller in the case of $1 \cdot 10^{15}$ n_{eq}/cm^2

Forward I-V for 23 GeV p $3 \cdot 10^{15}\ n_{eq}/cm^2$

Forward I-V measurement compared to simulations



None of the models reproduce the measured forward I-V

- Fit with I-V, C-V and forward I-V using the EVL 2-trap model doesn't converge ☹

Next steps to test:

  - Let the energy levels in the 2-trap model free (8 parameter) ☹
  - 3-trap models (9 parameter or 12 parameter)

Diodes: Irradiation plan

Data between 3e15 and 1.3e16 n_{eq}/cm^2 for model building needed

🟩 irradiation done 🟨 planned 🟪 NO SAMPLES

	24GeV protons											
R/cm	**10**									**5**		
Φ/1e15	**3**	**Large**	**Small**	**6**	**Large**	**Small**	**9**	**Large**	**Small**	**13**	**Large**	**Small**
Epi100N		Epi100N_02_DiodeL_11	Epi100N_03_DiodeS_13		Epi100N_03_DiodeL_2	NO SAMPLES		Epi100N_02_DiodeL_3	NO SAMPLES		Epi100N_03_Diode_1	Epi100N_02_DiodeS_13
		Epi100N_03_DiodeL_11									Epi100N_03_Diode_2	Epi100N_03_DiodeS_14
Epi100Y		Epi100Y_02_Diode_1	Epi100Y_02_DiodeS_15		Epi100Y_02_DiodeL_3	Epi100Y_03_DiodeS_13		Epi100Y_04_DiodeL_3	Epi100Y_05_DiodeS_15		Epi100Y_03_Diode_1	Epi100Y_03_DiodeS_15
		Epi100Y_05_Diode_1									Epi100Y_03_Diode_2	
FZ120N		FZ120N_05_Diode_2	NO SAMPLES		FZ120N_05_DiodeL_9	NO SAMPLES		FZ120N_07_Diode_1	FZ120N_05_DiodeS_16		FZ120N_06_Diode_1	FZ120N_06_DiodeS_16
FZ120Y		FZ120Y_07_DiodeL_2	FZ120Y_03_DiodeS_16		FZ120Y_07_DiodeL_3	FZ120Y_06_DiodeS_16		FZ120Y_07_DiodeL_8	FZ120Y_07_DiodeS_13		FZ120Y_07_DiodeL_9	FZ120Y_07_DiodeS_14
FTH200N		FTH200N_24_Diode_2			FTH200N_04_Diode_2	FTH200N_02_DiodeS_14		FTH200N_06_Diode_1	FTH200N_02_DiodeS_16		FTH200N_25_Diode_2	FTH200N_04_DiodeS_14
FTH200P					FTH200P_03_DiodeL_5	FTH200P_01_DiodeS_14		FTH200P_03_DiodeL_9	FTH200P_01_DiodeS_16			
FTH200Y		FTH200Y_01_DiodeL_5	FTH200Y_02_DiodeS_16		NO SAMPLES	NO SAMPLES		NO SAMPLES	NO SAMPLES		FTH200Y_01_Diode_1	FTH200Y_03_DiodeS_16
MCZ200N		MCZ200N_04_DiodeL_8			NO SAMPLES	NO SAMPLES		NO SAMPLES	NO SAMPLES		MCZ200N_06_DiodeL_11	MCZ200N_06_DiodeS_14
											MCZ200N_09_DiodeL_11	
M200P			NO SAMPLES		MCZ200P_01_DiodeL_8	MCZ200P_03_DiodeS_13		MCZ200P_02_DiodeL_8	MCZ200P_02_DiodeS_13			
M200Y		MCZ200Y_04_Diode_2	MCZ200Y_03_DiodeS_13		NO SAMPLES	NO SAMPLES		NO SAMPLES	NO SAMPLES		MCZ200Y_04_DiodeL_9	MCZ200Y_05_DiodeS_15
FZ200N		NO SAMPLES	NO SAMPLES		NO SAMPLES	NO SAMPLES		NO SAMPLES	NO SAMPLES		NO SAMPLES	NO SAMPLES
FZ200Y		FZ200Y_02_DiodeL_11	FZ200Y_03_DiodeS_13		FZ200Y_03_Diode_1	FZ200Y_04_DiodeS_13		FZ200Y_05_DiodeL_11	FZ200Y_05_DiodeS_13		FZ200Y_06_DiodeL_11	FZ200Y_06_DiodeS_13
FZ320N		FZ320N_07_DiodeL_3	FZ320N_01_DiodeS_16		FZ320N_07_DiodeL_5	FZ320N_07_DiodeS_13		NO SAMPLES	FZ320N_07_DiodeS_14		NO SAMPLES	FZ320N_07_DiodeS_16
FZ320Y		FZ320Y_05_DiodeL_9	FZ320Y_04_DiodeS_13		FZ320Y_05_DiodeL_11	FZ320Y_05_DiodeS_16		FZ320Y_06_DiodeL_8	FZ320Y_06_DiodeS_13		FZ320Y_06_DiodeL_9	FZ320Y_06_DiodeS_16

Irradiation with 24 GeV/c p at the PS on the way

Summary

1. It was shown that the available bulk damage models do not reproduce the data for high fluences
2. An attempt is made to develop a new model by fitting I-V and C-V measurements using the optimizer of TCAD
3. It seems that a 2-trap model is not able to describe I-V, C-V and CCE simultaneously
4. Diode irradiations with fluences $3 \cdot 10^{15}$ n_{eq}/cm^2, $6 \cdot 10^{15}$ n_{eq}/cm^2, $9 \cdot 10^{15}$ n_{eq}/cm^2 and $1.3 \cdot 10^{15}$ n_{eq}/cm^2

Backup

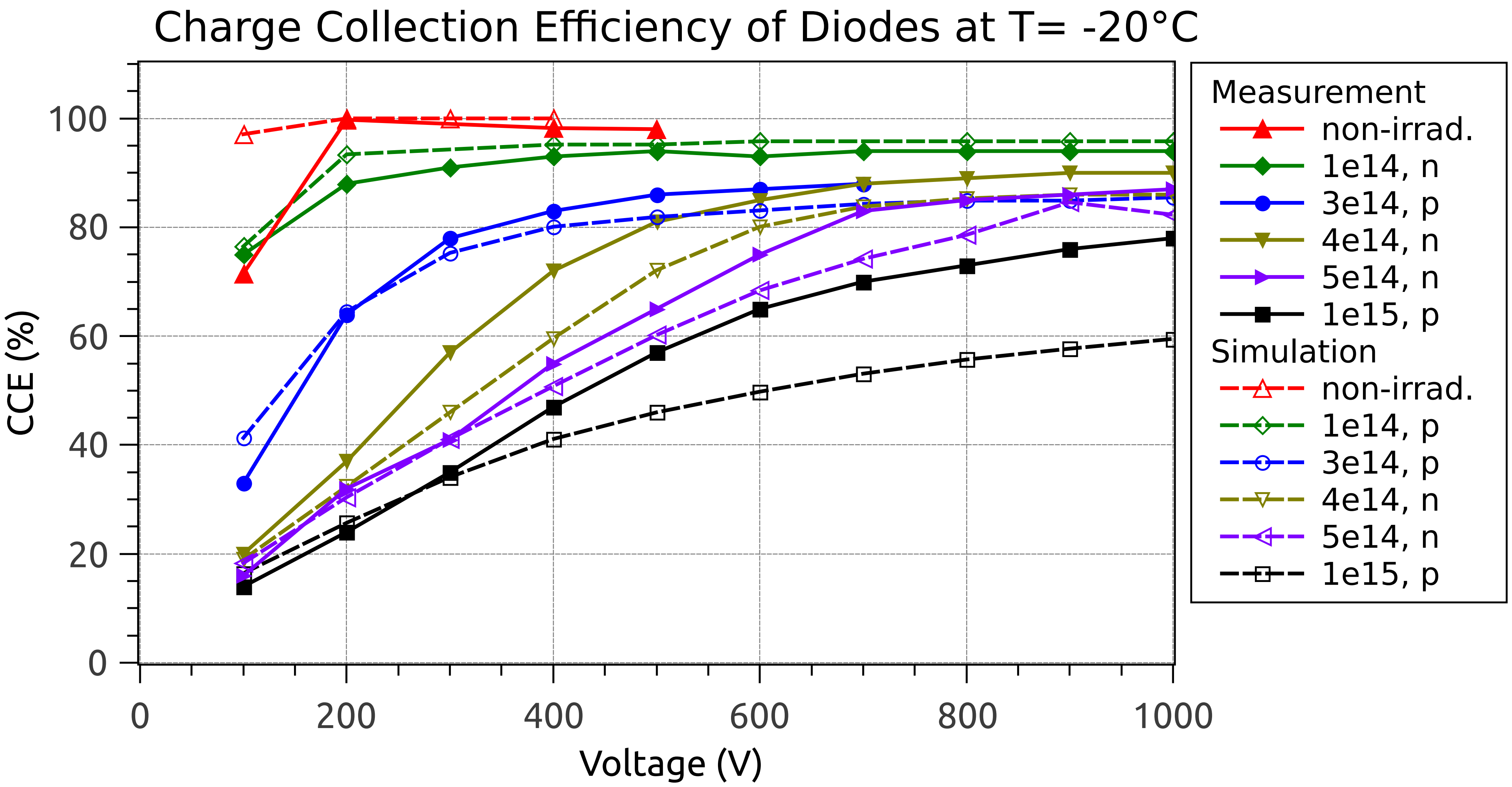


Figure 11.24: Charge collection efficiency of FZ320N diodes at $T = -20\,^{\circ}C$ and several fluences (proton and neutron irradiation):
The CCE is simulated quite well, only at $F = 10^{15}\,n_{eq}cm^{-2}$ *the measured CCE values are higher.*
Data partly from [Poe13].