Hamburg Penta-Trap Model for radiation damage in silicon

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HIGH-D

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Introduction

High-Luminosity LHC radiation level for the 1st pixel layer after 3000 fb^{-1} :

- Neutron equivalent fluence $\Phi_{eq} \approx 2.3\times10^{16}$ cm^{-2}, dose ≈ 12 MGy

TCAD simulations of sensors give valuable input in:

- Understanding and predicting the performance of the sensor
- Optimisation for radiation hardness

Requirements:

- Accurate models + parameters describing **bulk** and **surface** radiation damage in TCAD
- Choice of correct boundary conditions

Motivation for this talk:

- Recently the **Hamburg Penta-Trap Model** (HPTM) with 5 effective traps has been introduced which gives a good and consistent description of **I-V**, **C-V** and **CCE_{IR}** of pad diodes irradiated with 24 GeV/c p in the fluence range of 3×10^{14} to 1.3×10^{16} cm^{-2}
- I-V, C-V and CCE_{IR} data have only limited sensitivity to the depth dependence of charge trapping, which is essential to predict the response of radiation-damaged segmented sensors, because of the highly non-uniform weighting field

➡Compare simulations to **edge-on** beam data

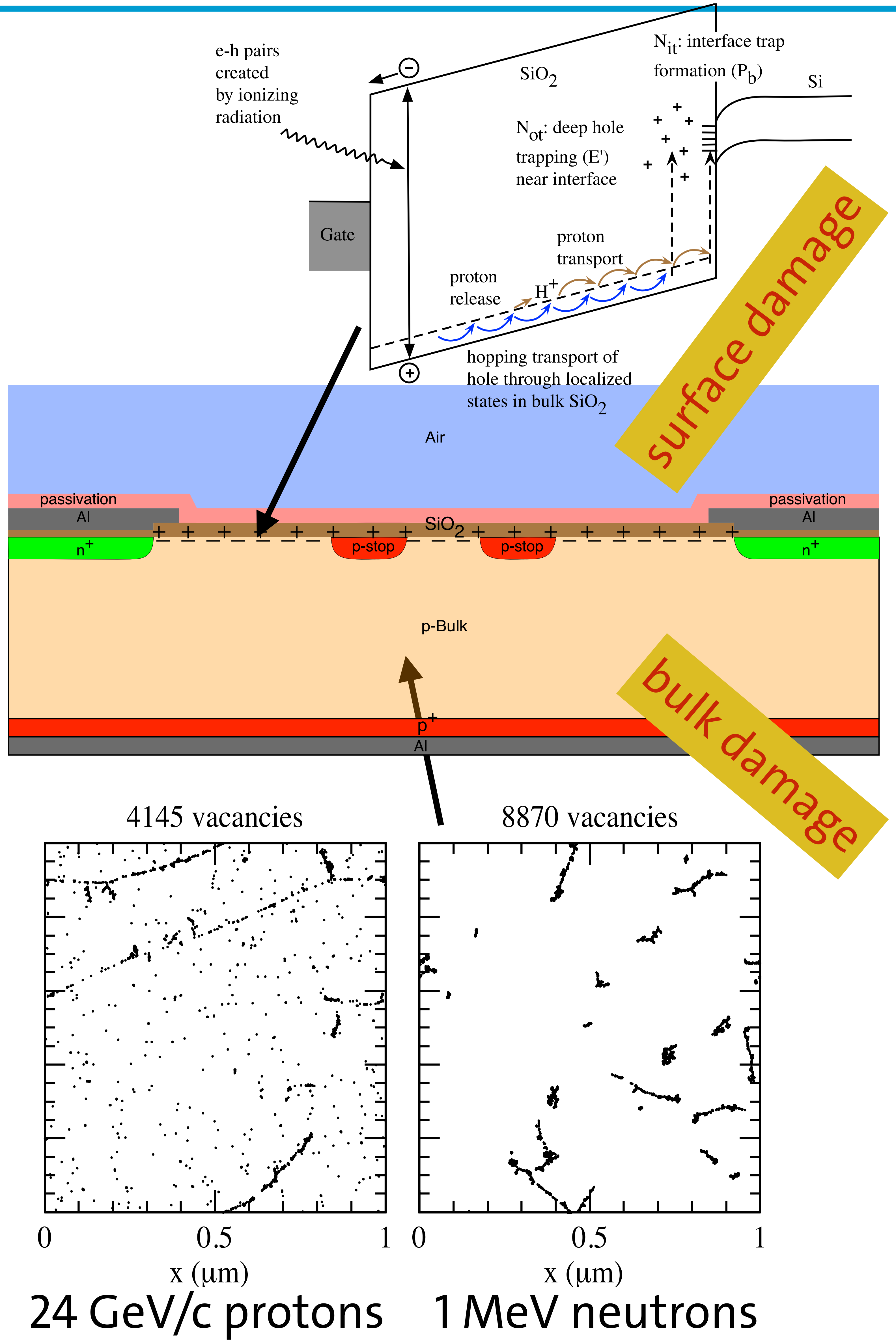
Radiation damage

Surface damage (Ionizing Energy Loss):

- Build up of oxide charges, border and interface traps
  - ➡ Increase of surface current
  - ➡ Change of electrical field near to the Si-SiO_2 interface
  - ➡ Trapping near to the Si-SiO_2 interface
- C-V/I-V on MOS capacitors, MOSFET and gate controlled diodes

Bulk damage (NIEL):

- Point and cluster defects in the silicon lattice
  - ➡ Increase of leakage current
  - ➡ Change of the space charge
    - Development of “double junction” with resistive region in between
  - ➡ Trapping of drifting charge
- I-V, C-V and CCE on pad diodes



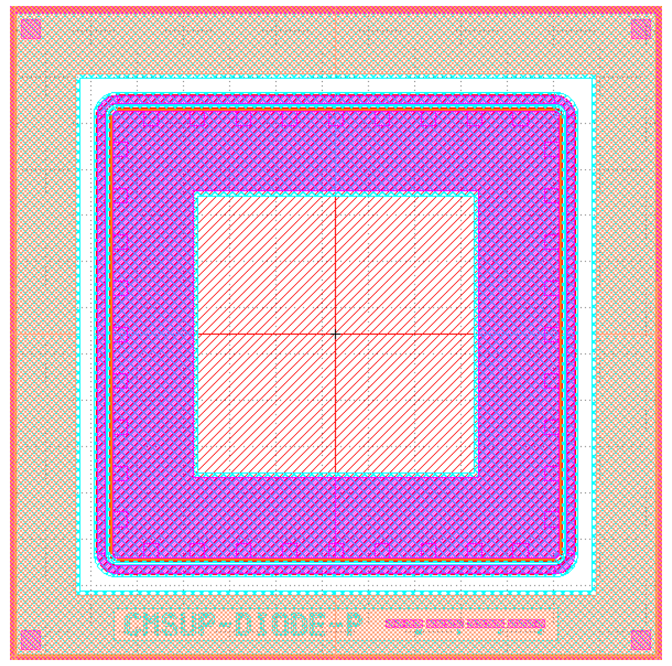
In the following only bulk damage from protons and no surface damage (1 D problem)

Diode measurements for HPTM

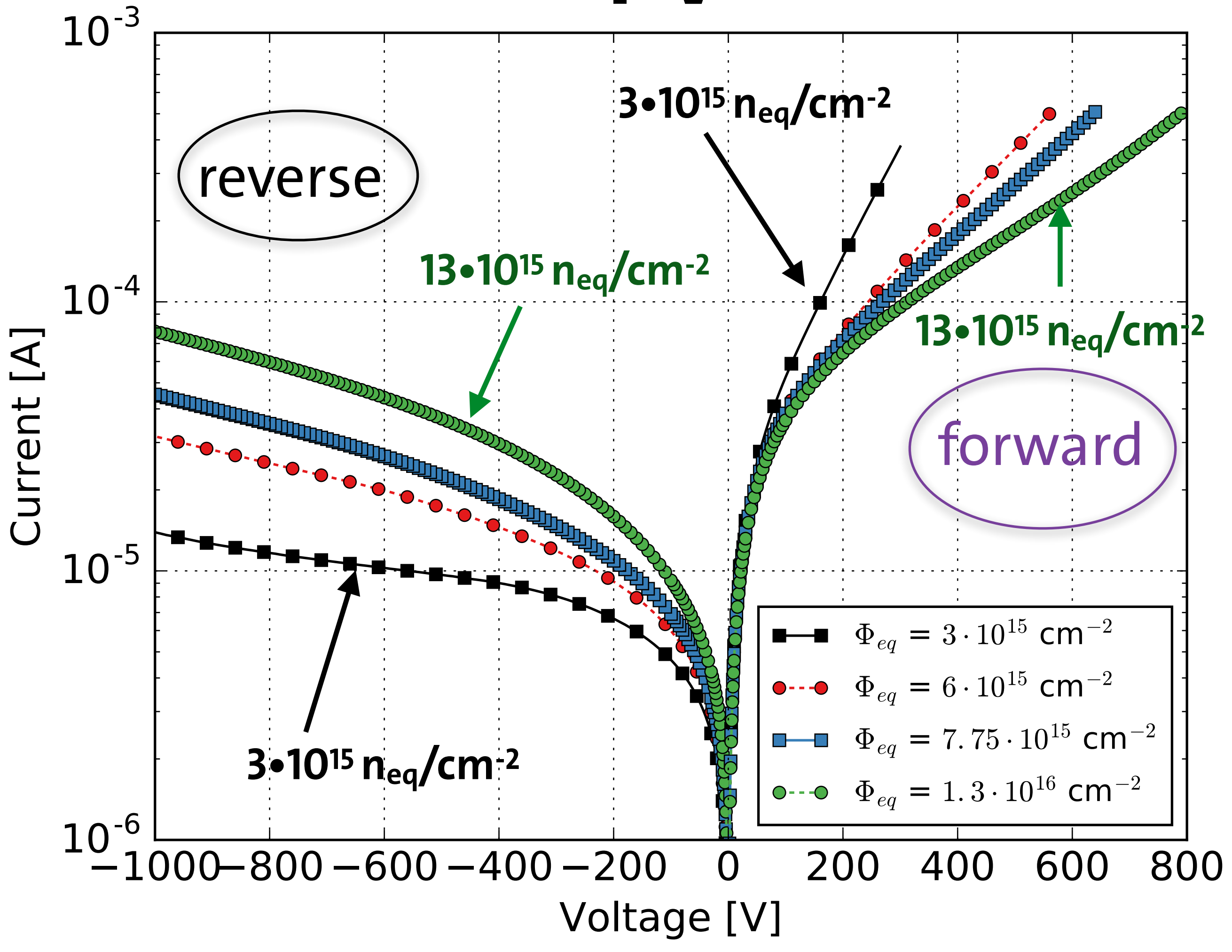
Diodes from the CMS HPK campaign:

- **p-type** (p-stop, p-spray, thinned **float zone** **FTH200** (200 µm thick)
- Irradiated with **24 GeV/c** protons at CERN IRRAD
  - Fluences: 0.3, 1, 1.5, 2.4, 3, 6, 7.75, 13•10[15] n_{eq}/cm^2
- Measurements after **80min@60°C** annealing (irrad. 2015) at **T= -20°C** and -30°C with reverse and forward bias applied
  - C/G-V with 100 Hz - 2 MHz, I-V up to 1000 V
  - TCT with 670 nm (red) and 1063 (IR) nm laser

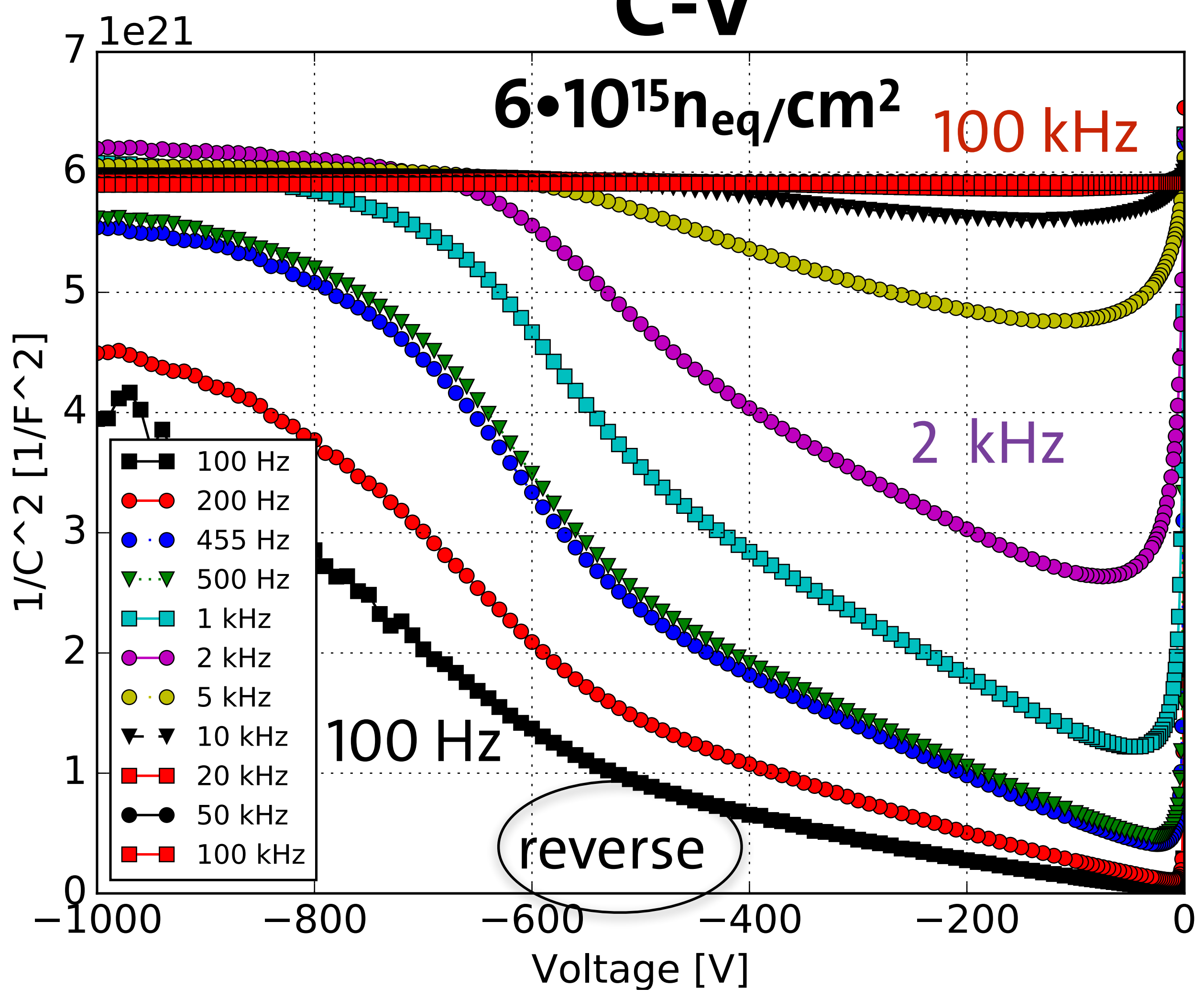
Diode 5mm x 5mm



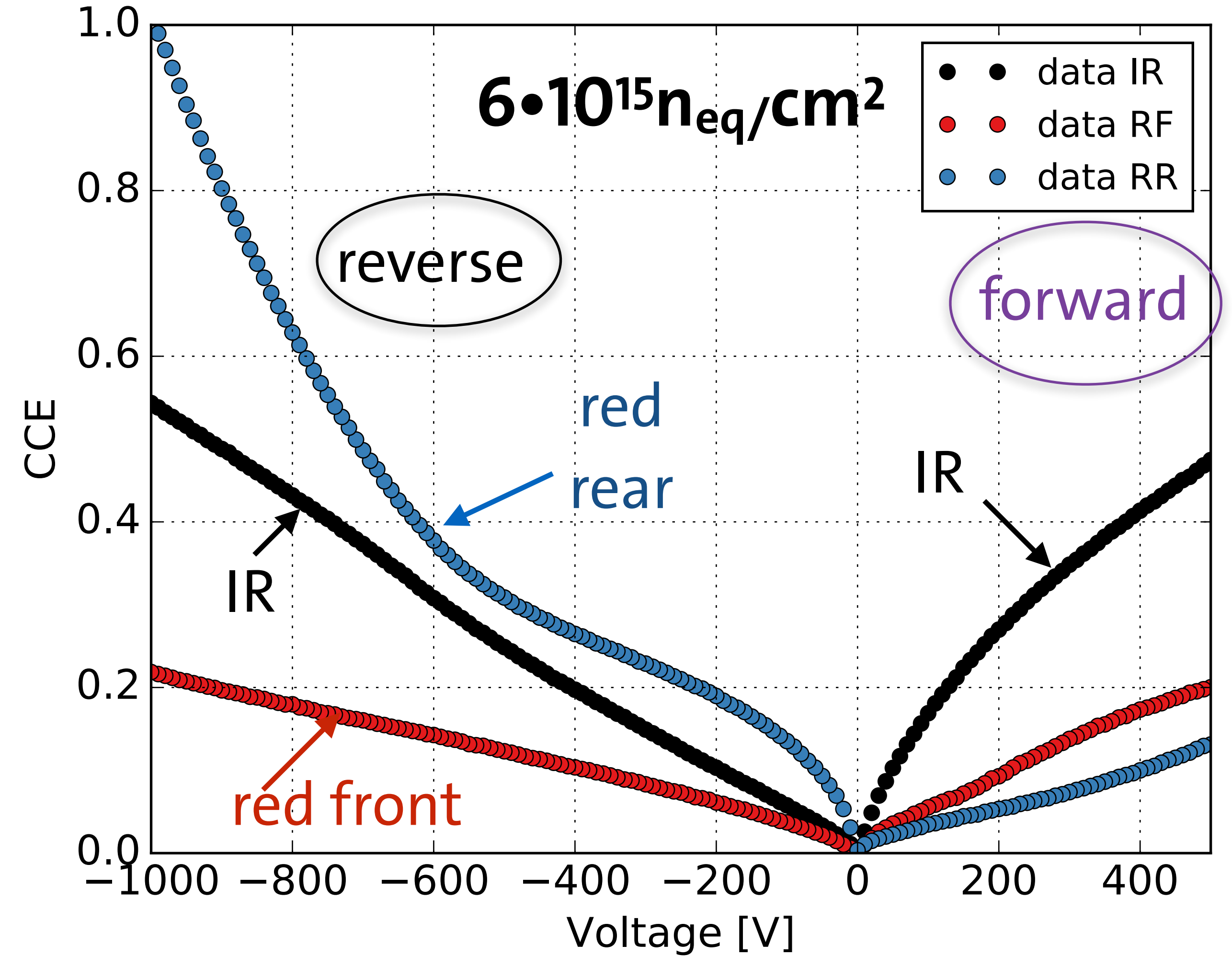
I-V



C-V



CCE



Are we able to reproduce all measurements with simulations?

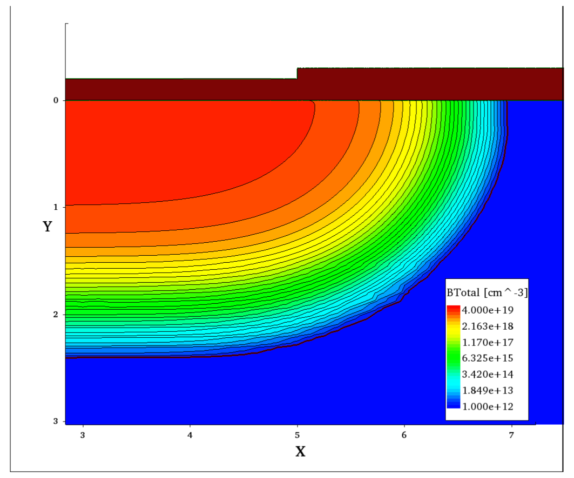
TCAD

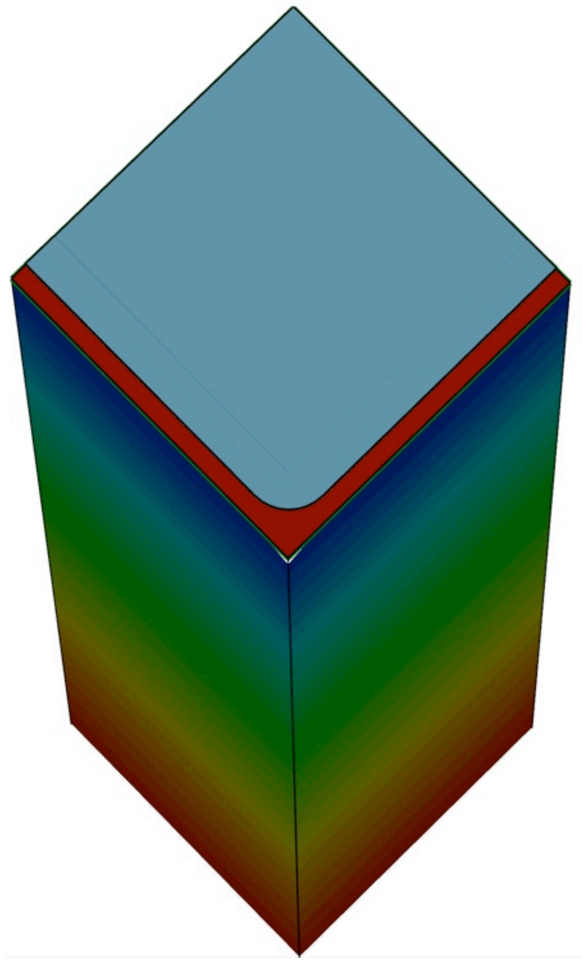
TCAD (Technology Computer Aided Design):

- Process simulation → doping profile
- Device simulation → electrical behaviour

  - Works by modelling electrostatic potential (Poisson's equation) and carrier continuity equations
  - Applies semiconductor equations + boundary conditions on mesh and solves

2D Boron profile





Poisson $$\nabla \cdot \epsilon \nabla \phi = -\rho_{eff} \quad \text{with} \quad \rho_{eff} = q[p - n + N_D - N_A] - \rho_{traps}$$

Electron continuity $$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot \mathbf{J}_n + R_{net} \quad \text{where } \mathbf{J}_n = qn\mu_n\mathbf{E} + qD_n\nabla n$$

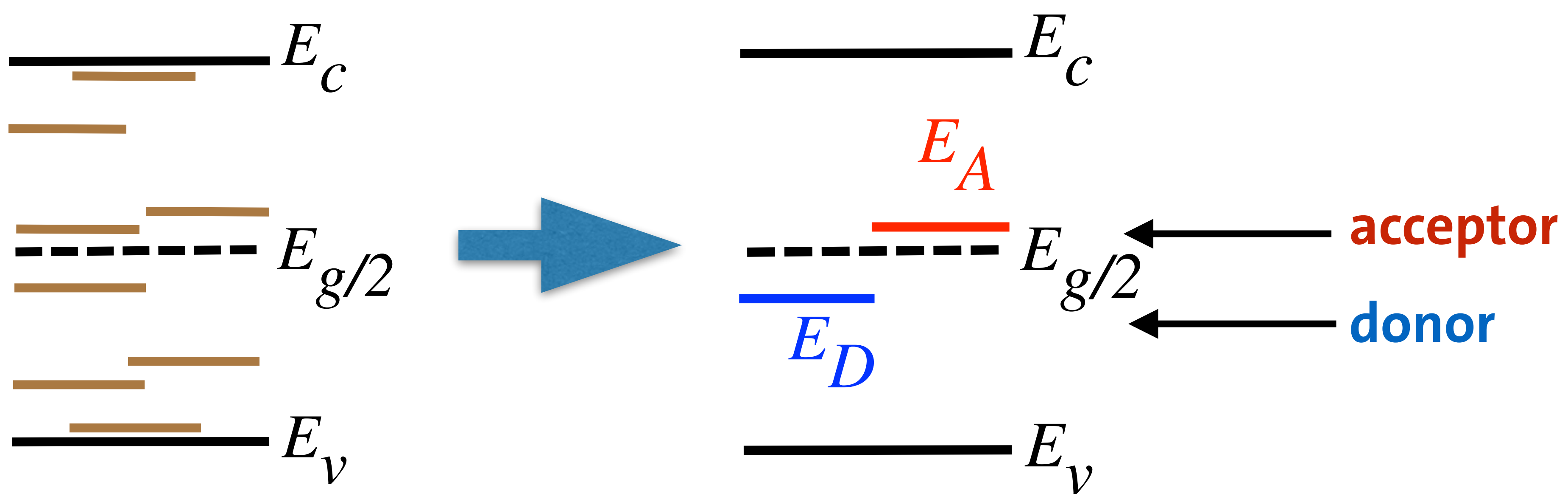
Hole continuity $$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot \mathbf{J}_p + R_{net} \quad \text{where } \mathbf{J}_p = qp\mu_p\mathbf{E} - qD_n\nabla p$$

- Different versions of physics models are available (mobility, avalanche, tunnelling etc)
- Radiation damage will change the net **recombination rate** R_{net} and the **charge density** due to ρ_{traps}

Radiation damage modelling

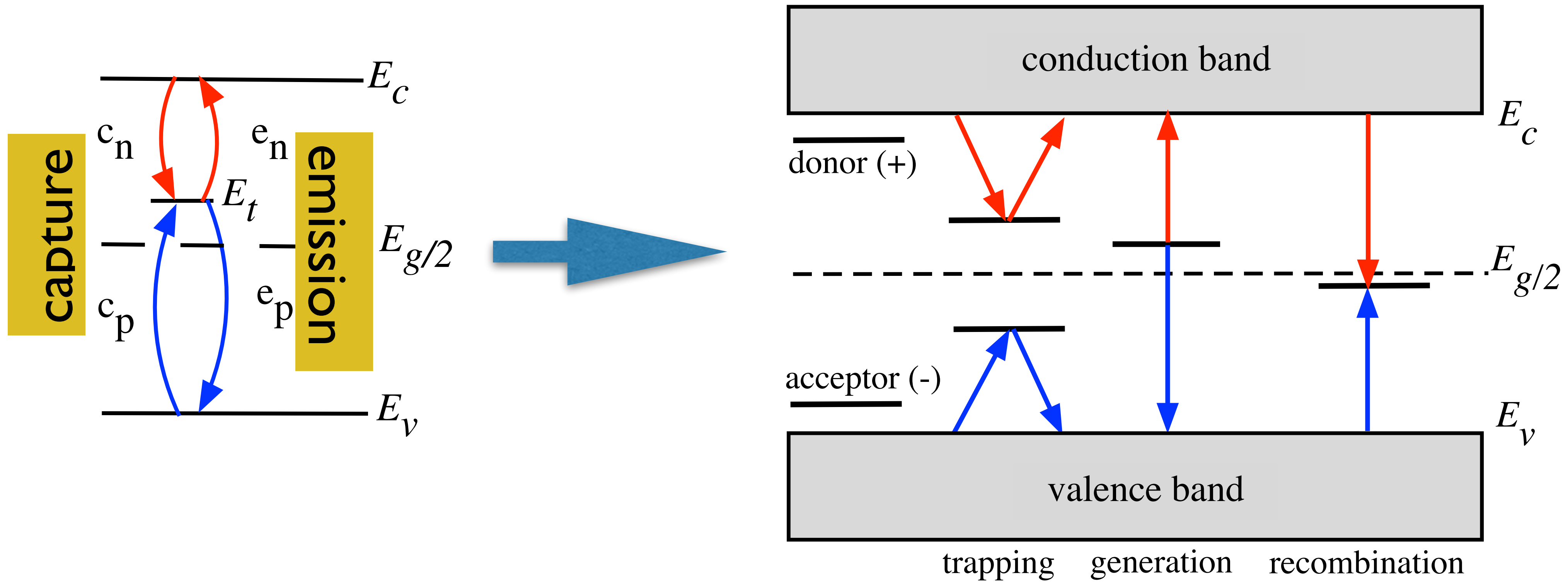
Radiation damage modelling:

- Usually effective trap levels modelling the measured identified point and cluster defects
- It is assumed that the traps obey SRH statistics



Example: 2 trap model → 6 free parameter

1. Energy levels + type: E_A , E_D fixed
2. **Concentrations**: N_A , N_D
3. **Cross sections:** σ^A_e , σ^A_h , σ^D_e , σ^D_h



$$\rho_{trap} = q[N_D f_D - N_A f_A]$$

with

$$f_D = \frac{v_h \sigma_h^D p + v_e \sigma_e^D n_i e^{E_D/kT}}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})}$$

$$f_A = \frac{v_e \sigma_e^A n + v_h \sigma_h^A n_i e^{-E_A/kT}}{v_e \sigma_e^A (n + n_i e^{E_A/kT}) + v_h \sigma_h^A (p + n_i e^{-E_A/kT})}$$

$$R_{net} = \frac{v_h v_e \sigma_h^D \sigma_e^D N_D (np - n_i^2)}{v_e \sigma_e^D (n + n_i e^{E_D/kT}) + v_h \sigma_h^D (p + n_i e^{-E_D/kT})} + \frac{v_h v_e \sigma_h^A \sigma_e^A N_A (np - n_i^2)}{v_e \sigma_e^A (n + n_i e^{E_A/kT}) + v_h \sigma_h^A (p + n_i e^{-E_A/kT})}$$

Trapping

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

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

Parameter Tuning

Applied parameter tuning procedure:

1. The **number** and **type** of defects is selected based on **microscopic** measurements
2. The **concentration** of the defects is assumed to be **proportional** to the **fluence**
3. The **I-V**, **C-V** at 455 Hz and 1 kHz and **CCE_{IR}** with infrared of diodes for the **fluences 3** , **6**, **13x10^{15} n_{eq}/cm^2** at -20 °C is simulated and the free parameters are determined using the Synopsys TCAD optimiser i.e. minimising the expression

$$F = \sum_{i,j} w_i^j \int_{V_{min}}^{V_{max}} \left(1 - \frac{Q_{i,sim}^j}{Q_{i,meas}^j}\right)^2 dV$$

where *i* runs over the different fluences and *j* over the different measurements where $Q_{i,sim}^j$ and $Q_{i,meas}^j$ are the simulated and measured quantities, respectively, V_{min} the minimum and V_{max} maximum voltage and w_i^j some weighting factors.

- **I-V** and **C-V** are simulated in **1D** (CPU time: ≈3 min)
- **CCE_{IR}** is simulated in **2D (r,ϕ)** at 5 voltages (CPU time: ≈50 min)

HPTM

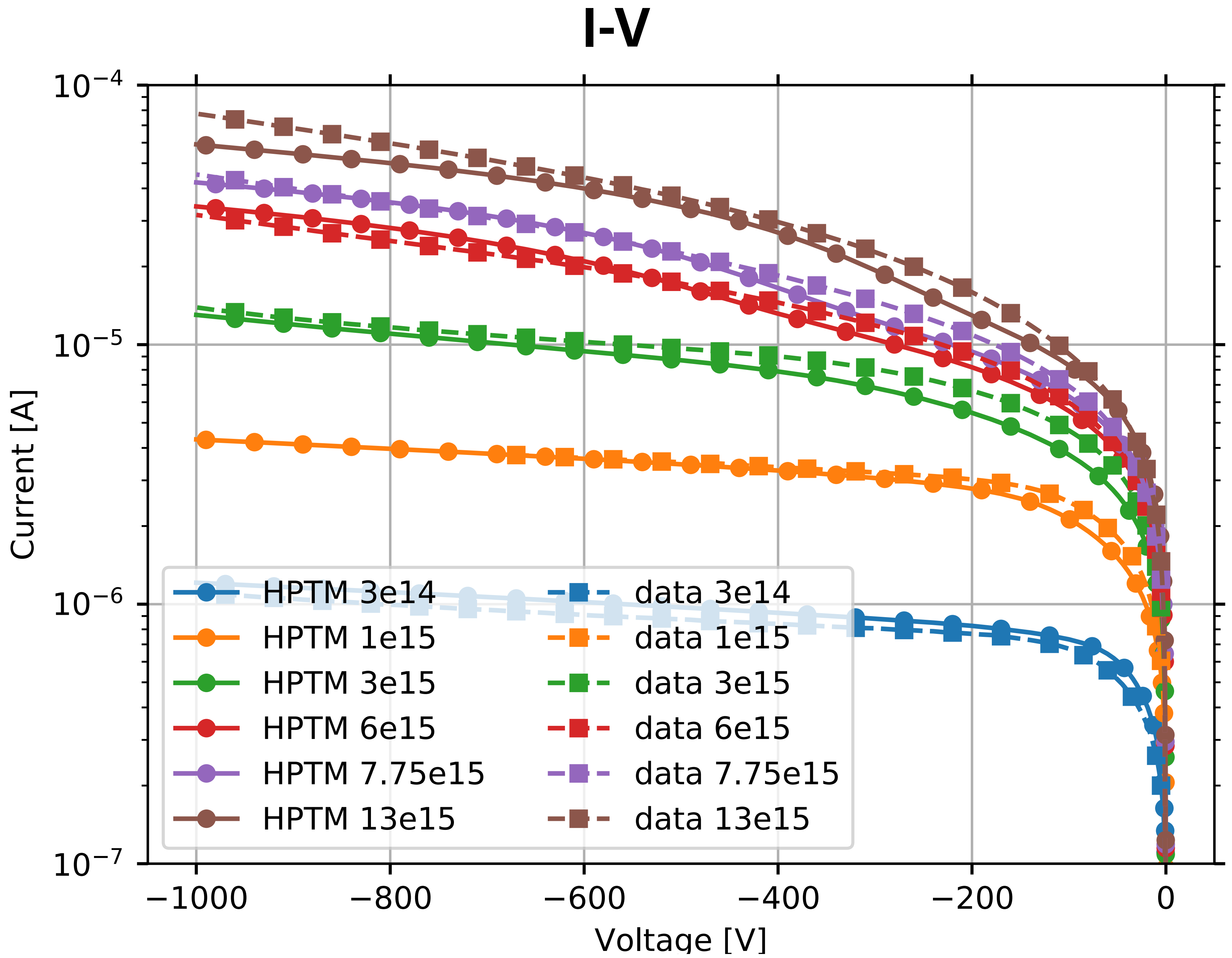
Result of tuning: Hamburg Penta Trap Model (HPTM)

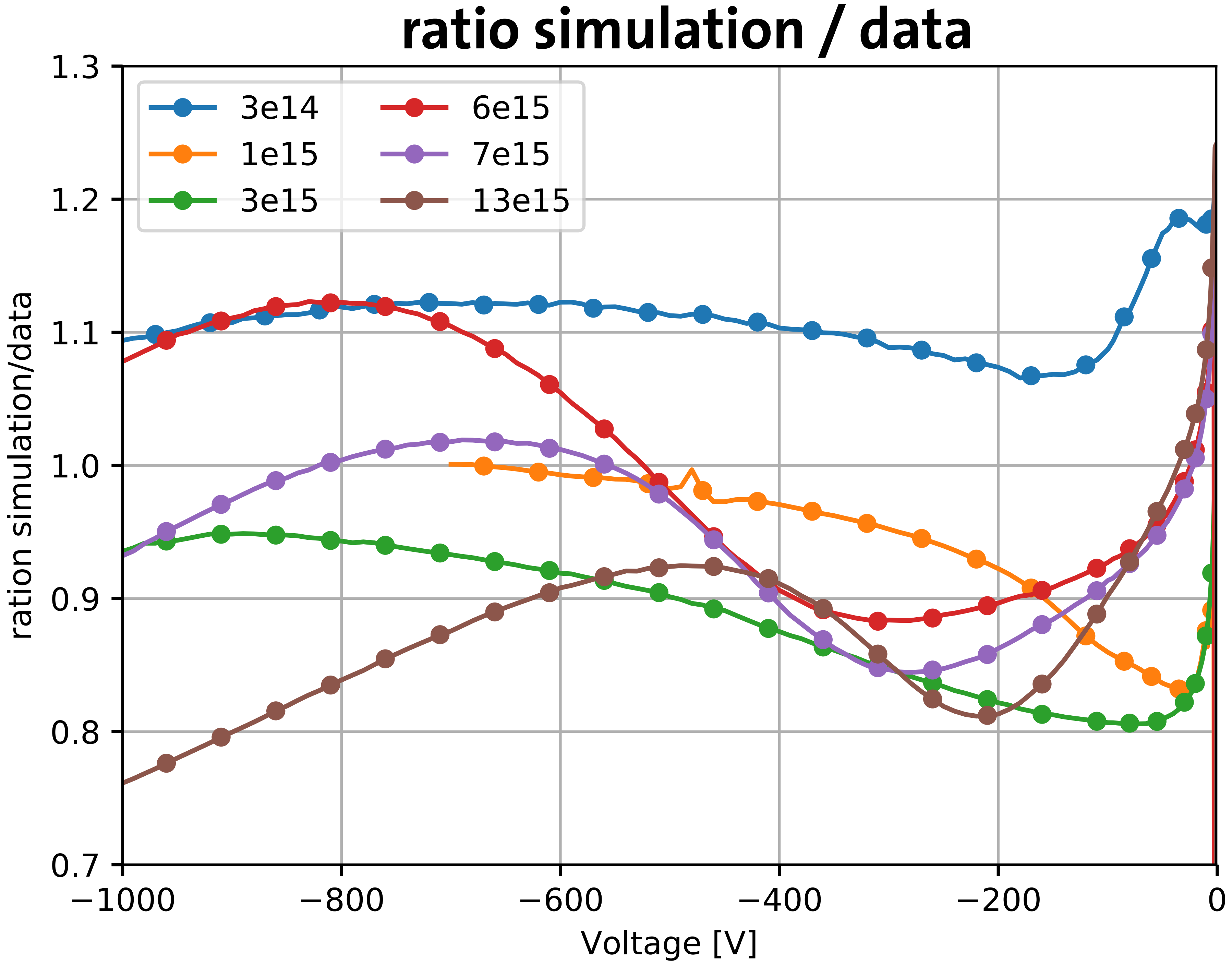
Defect	Type	Energy	g_{int} [cm^{-1}]	σ_e [cm^2]	σ_h [cm^2]
E30K	Donor	E_C-0.1 eV	0.0497	2.300E-14	2.920E-16
V_3	Acceptor	E_C-0.458 eV	0.6447	2.551E-14	1.511E-13
I_p	Acceptor	E_C-0.545 eV	0.4335	4.478E-15	6.709E-15
H220	Donor	E_V+0.48 eV	0.5978	4.166E-15	1.965E-16
C_iO_i	Donor	E_V+0.36 eV	0.3780	3.230E-17	2.036E-14

- Trap concentration of defects: $\mathbf{N = g_{int} \cdot \Phi_{neq}}$
- Simulations for the optimization have been performed at **T= -20 °C** with:
  1. Slotboom band gap narrowing
  2. Impact ionisation (van Overstaeten-de Man)
  3. **T**rap **A**ssisted **T**unneling Hurkx with tunnel mass = $\mathbf{0.25\ m_e}$ (default value: 0.5 m_e) in case of the I_p
  4. Relative permittivity of silicon = 11.9 (default value: 11.7)
- Both cross section for the E30K and the electron cross section for the C_iO_i were fixed ➔ 12 free parameter
- Optimization done with the nonlinear simplex method

I-V for different fluences

I-V for fluences from 0.3 - 13•10^{15} n_{eq}/cm^2 at T= -20 °C (for T= -30 °C see backup)



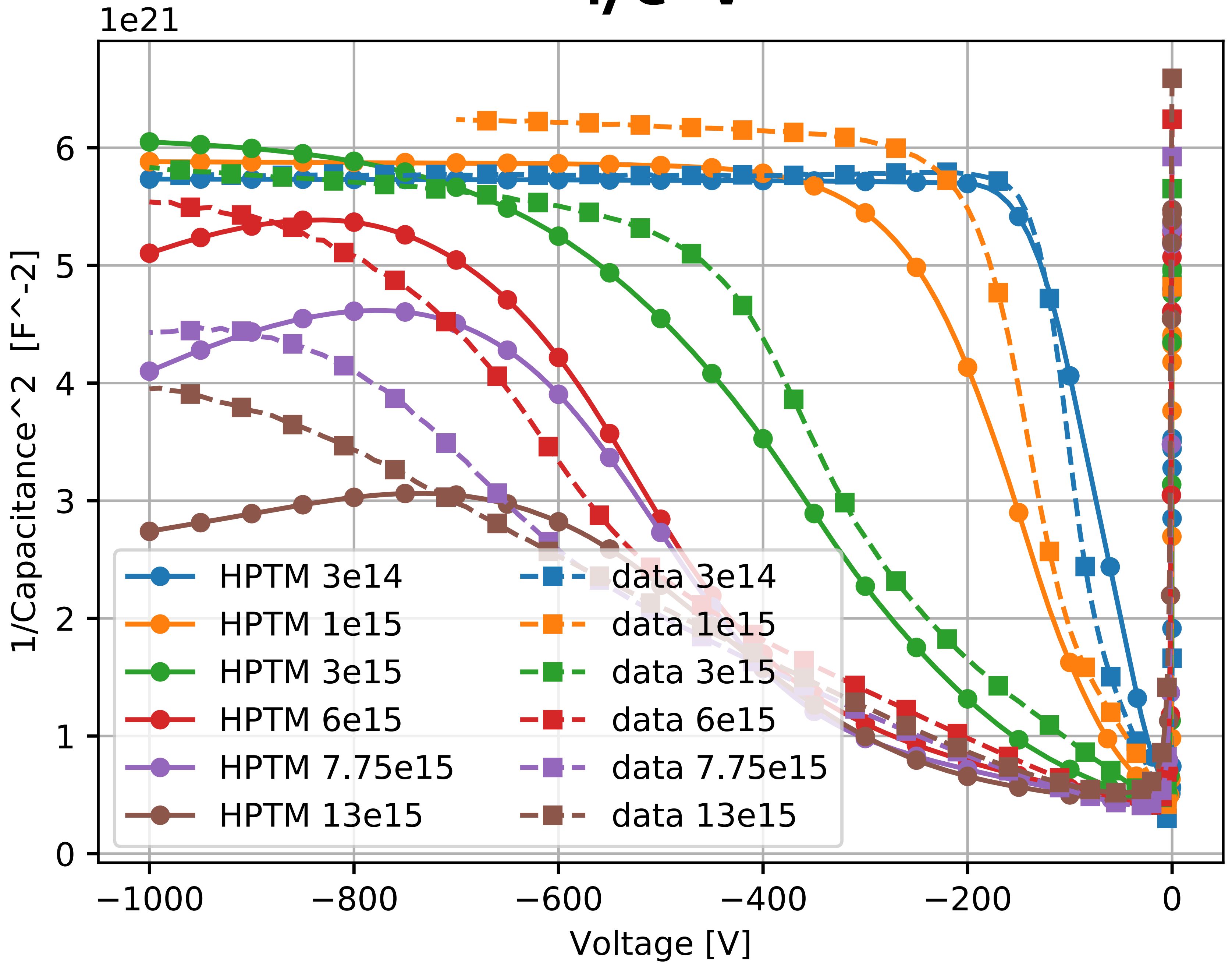


- The simulation for 0.3 and 1•10^{15} n_{eq}/cm^2 are extrapolations and the 7.75•10^{15} n_{eq}/cm^2 is a interpolation (not included in the optimization)
- The simulation agrees with the measurements within 20% for all fluences and voltages

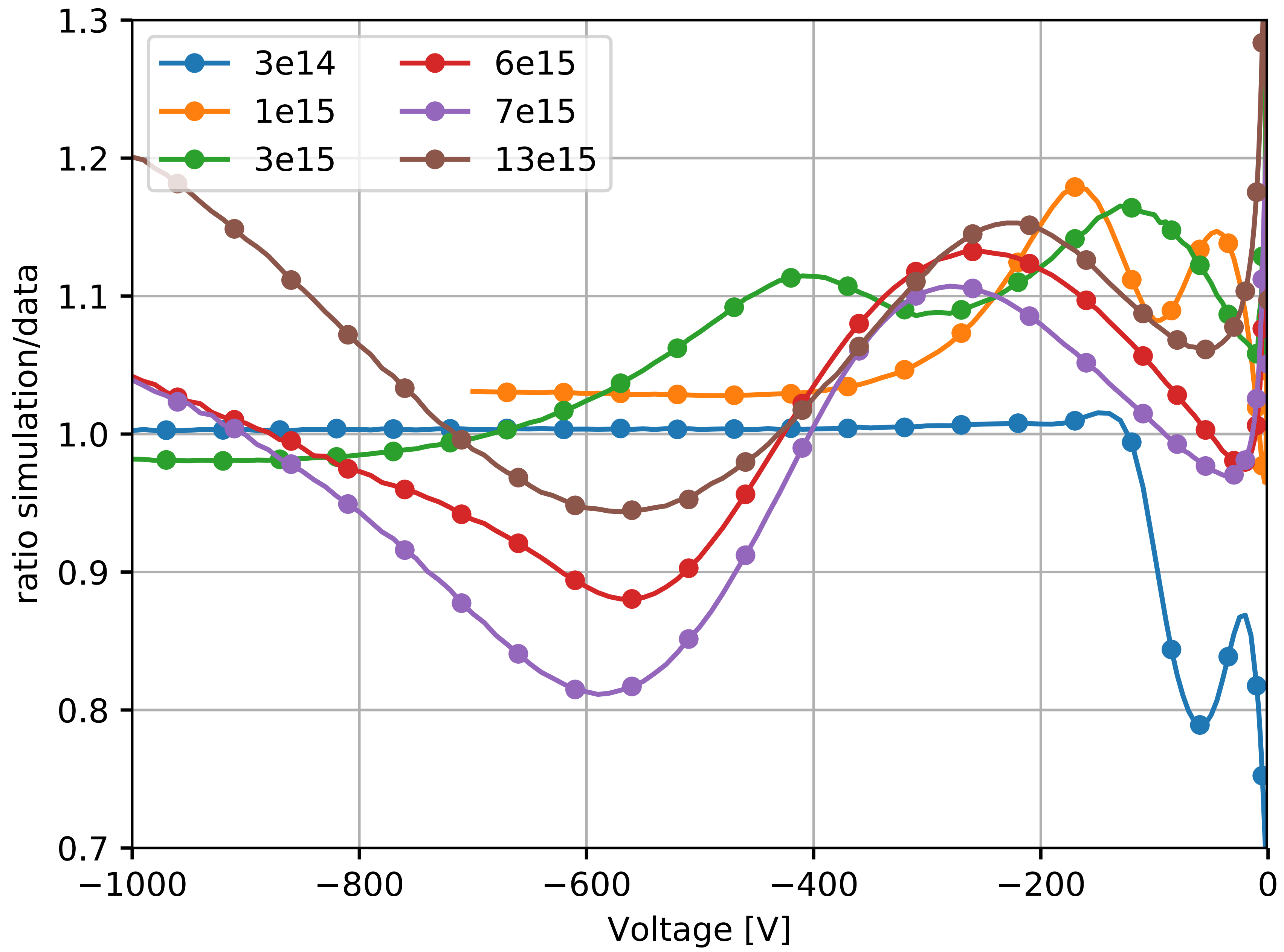
C-V for different fluences

C-V for fluences from 0.3 - 13•10^{15} n_{eq}/cm^2 at 455 Hz and T = -20 °C (for T= -30 °C see backup)

1/C²-V



ratio simulation / data

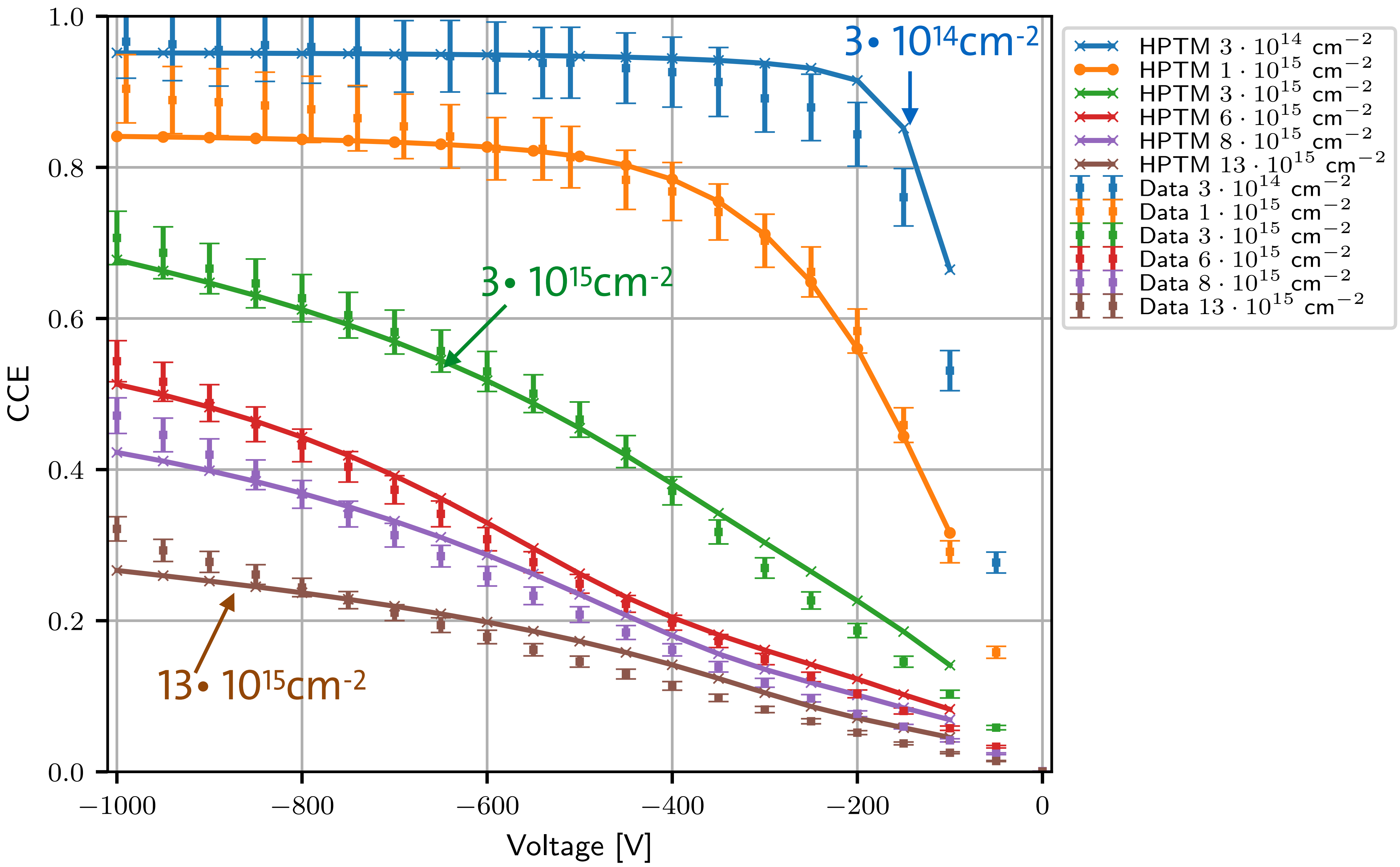


- The simulation for 0.3 and 1•10^{15} n_{eq}/cm^2 are extrapolations and the 7.75•10^{15} n_{eq}/cm^2 is a interpolation (not included in the optimization)
- The simulation agrees with the measurements within 20% for all fluences and voltages
- Deviation at highest fluence and voltage may be due to impact ionization
- A better agreement between simulations and measurements is achieved at 1 kHz

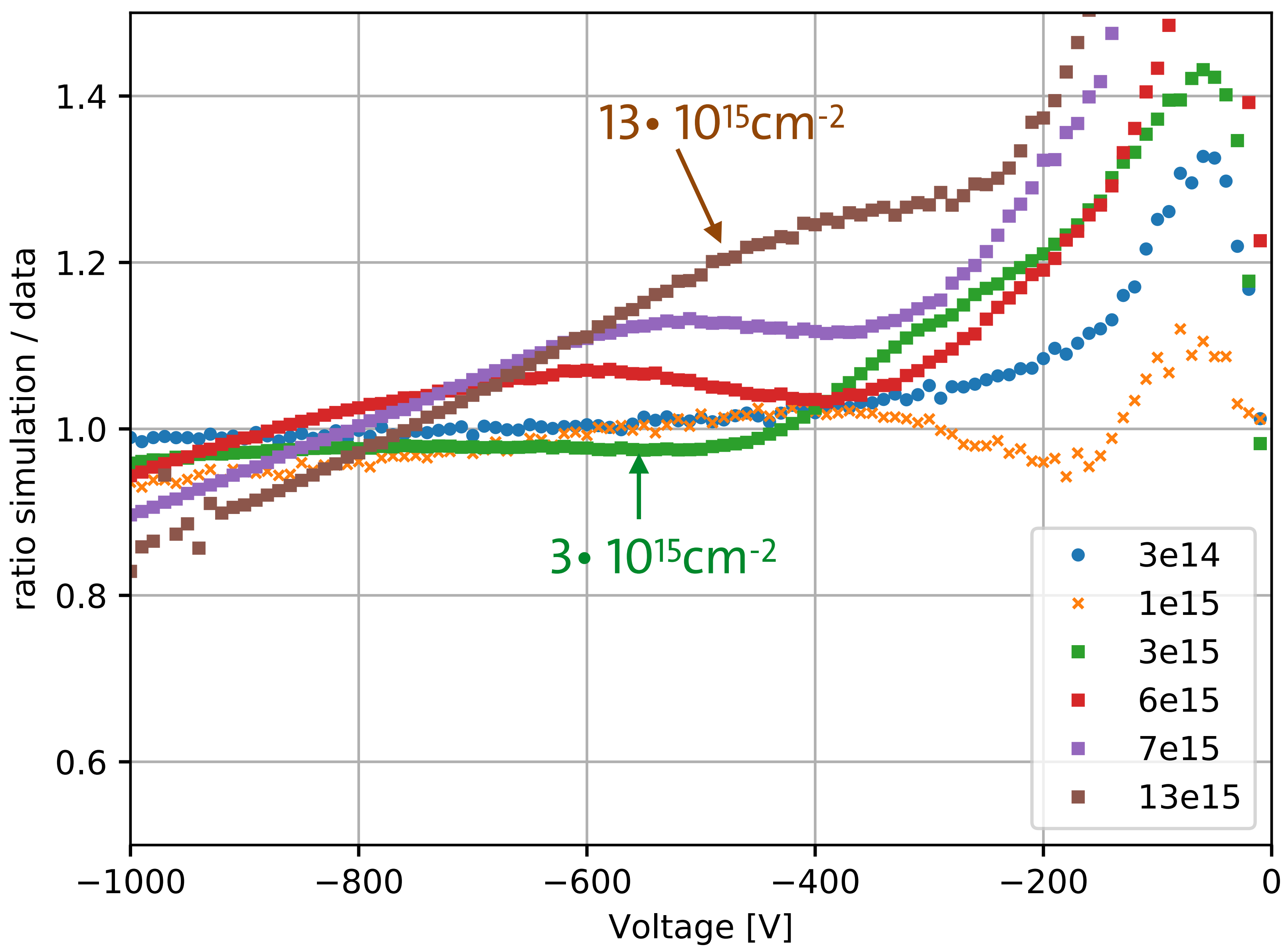
CCE vs. V (infrared)

CCE vs. V for fluences from 0.3 - 13•10^{15} n_{eq}/cm^2 with infrared laser and T = -20 °C (for T= -30 °C see backup)

CCE-V



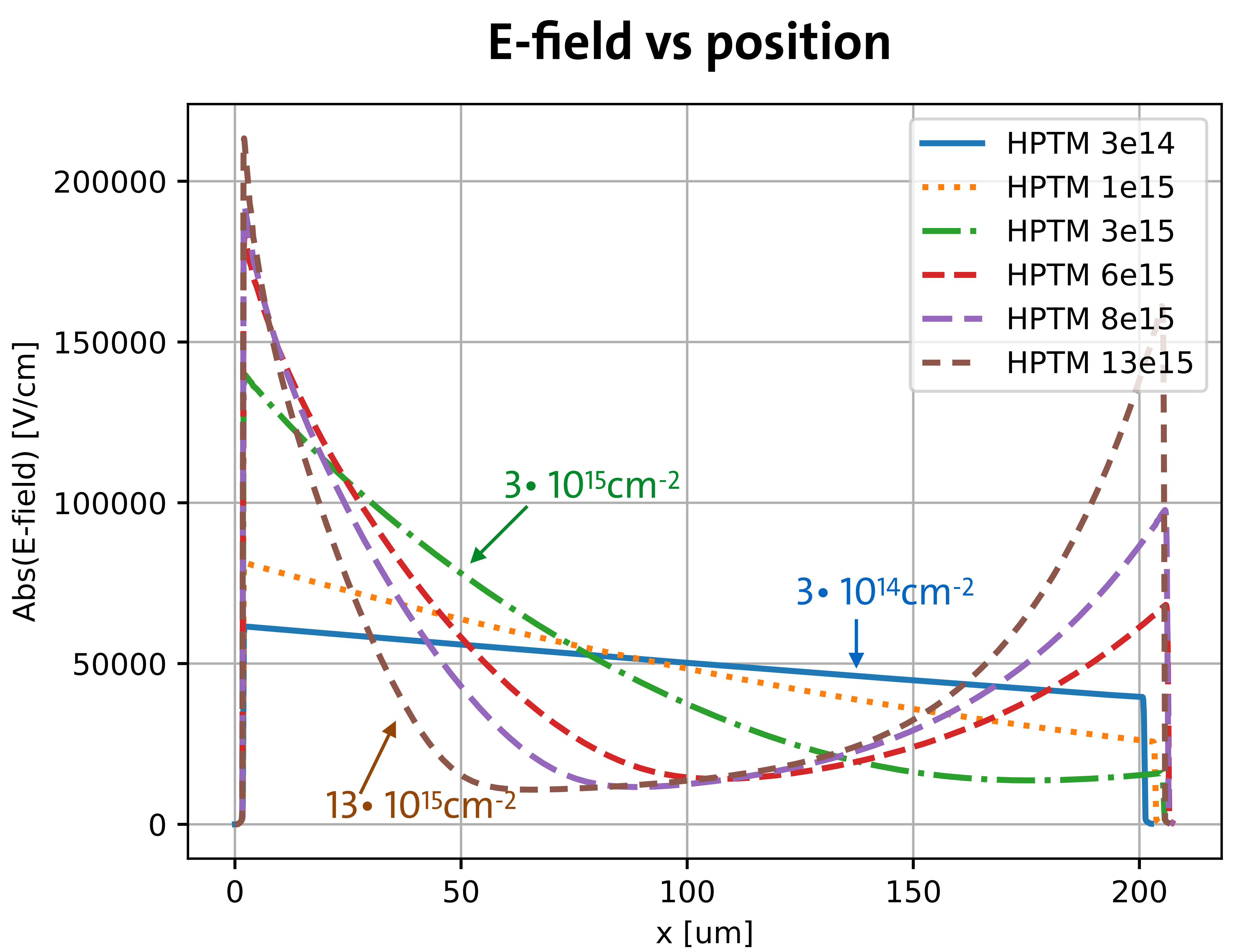
ratio simulation / data



- In the optimization only the voltages -200, -400, -600, -800 and -1000V were used
- For all fluences the voltage dependence is well reproduced
- At high voltages the simulation agrees with the measurements within 20% for all fluences

E-fields for different fluences

Simulated E-field as function of position for different fluences at 1000V



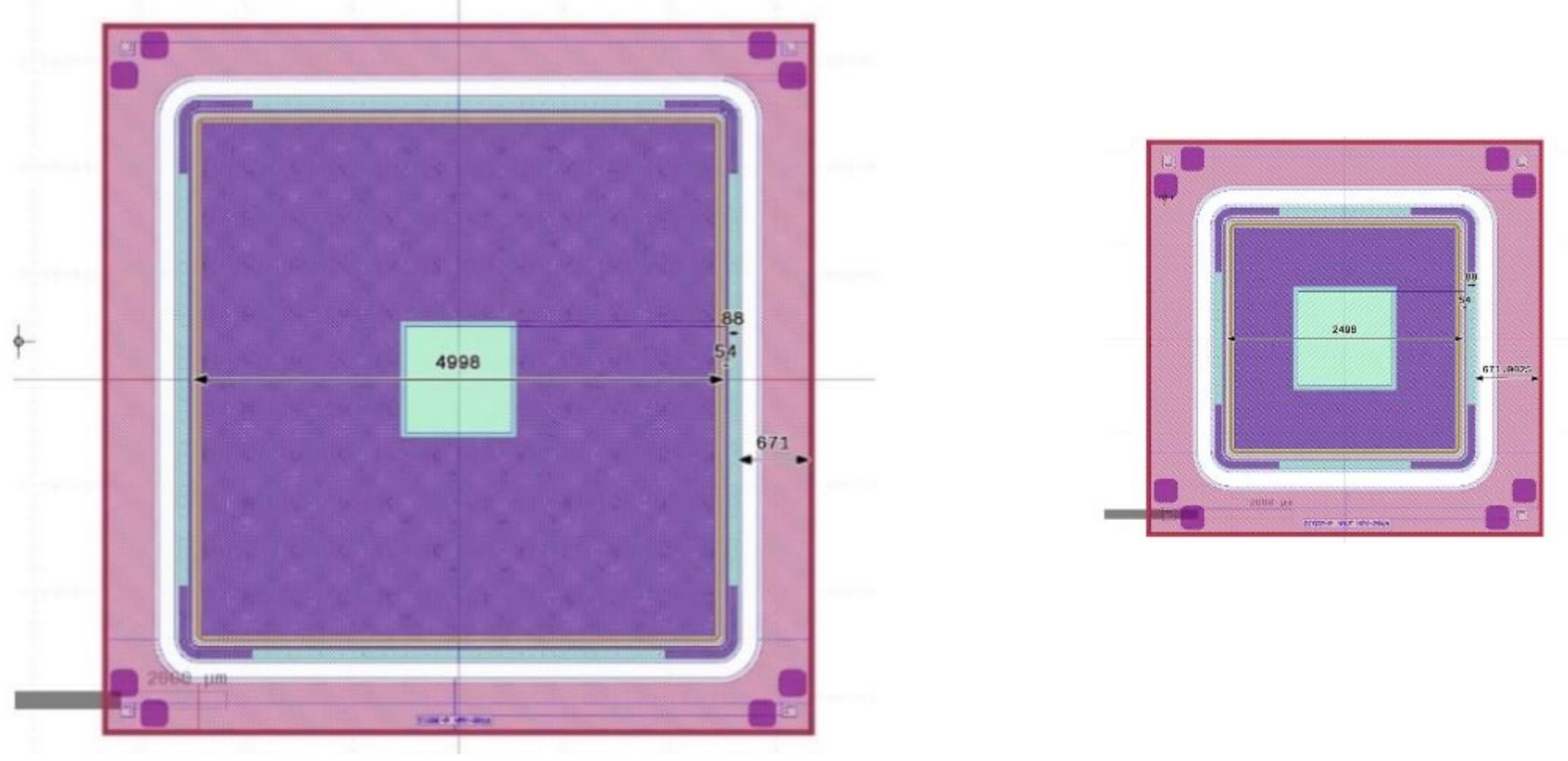
- Double peak structure for fluences $\geq 3 \cdot 10^{15}\ n_{eq}/cm^2$ clearly visible
- Peak field of $\approx 2 \cdot 10^5$ V/cm at the highest fluence ➔ impact ionisation

Edge-on measurements I

Sensors:

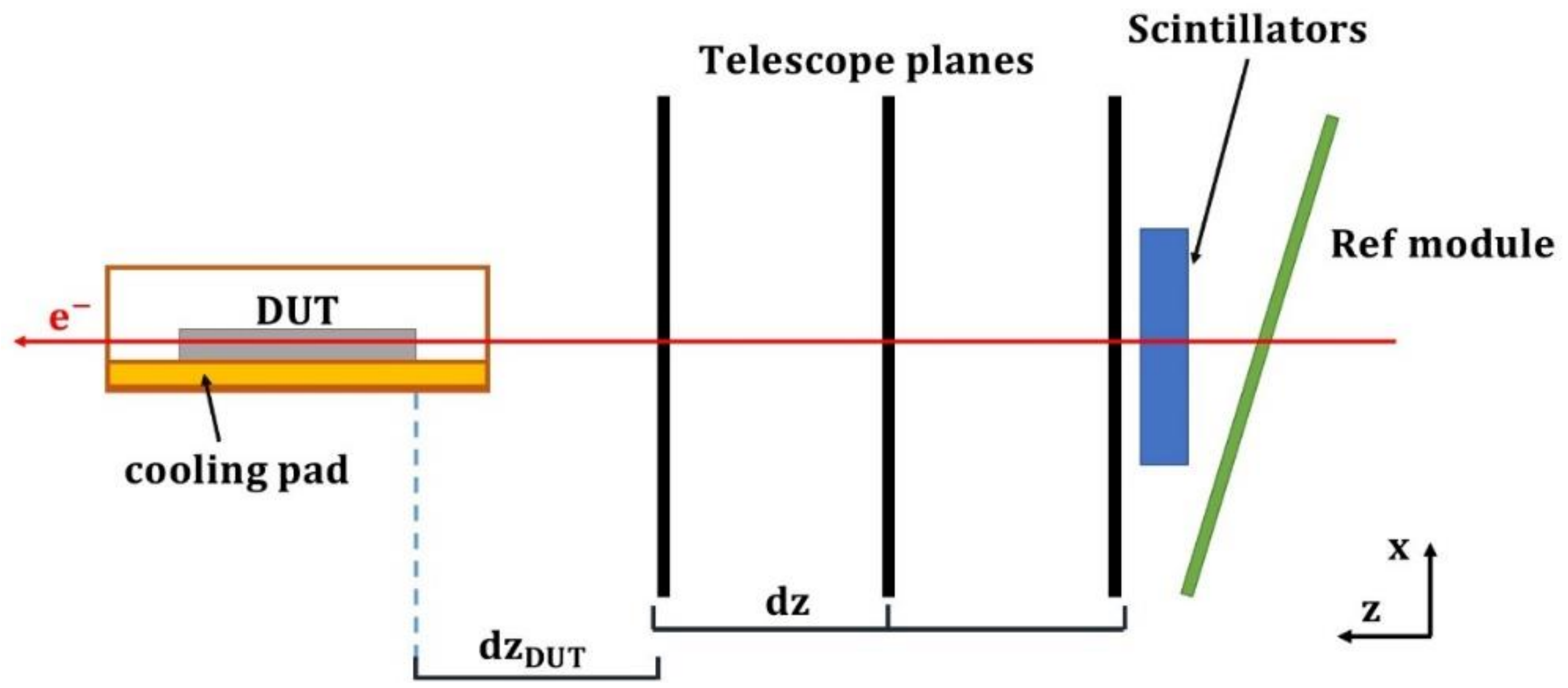
- HPK n^+p pad diodes, area 5.0x5.0 and 2.5x2.5 mm^2
- p-stop isolation
- FTH **150 µm thick**
- Depletion voltage: 75 V ($4.5x10^{12}$ cm^{-3})
- Irradiations:
  - 23 MeV protons (KIT), hardness factor 2.2
  - Φ_{eq} = 2, 4, 8, $12x10^{15}$ cm^{-2}

Diode 5mm x 5mm | Diode 2.5mm x 2.5mm



Beam test:

- At DESY II beam test facility using the DATURA telescope
- Electron beam with 5.2 GeV
- Intrinsic resolution for each plane of telescope ≈ 3.2 µm
- Track reconstruction using **upstream** triplet and **time reference module**
- Rotation stage for the DUT with precision of 0.1° (1.7 mrad)

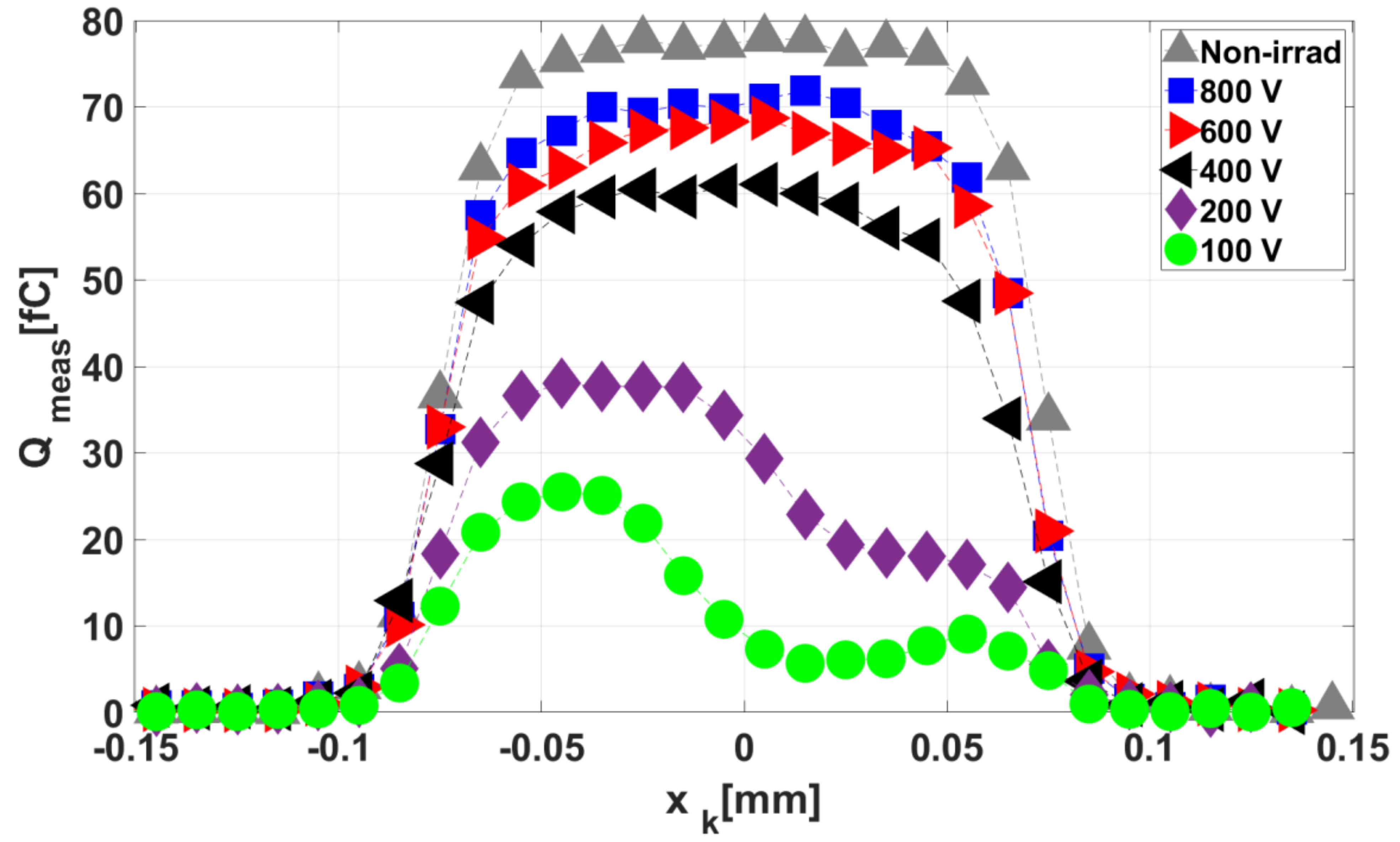


For details see: M. Hajheidari et al., https://doi.org/10.1016/j.nima.2021.166177

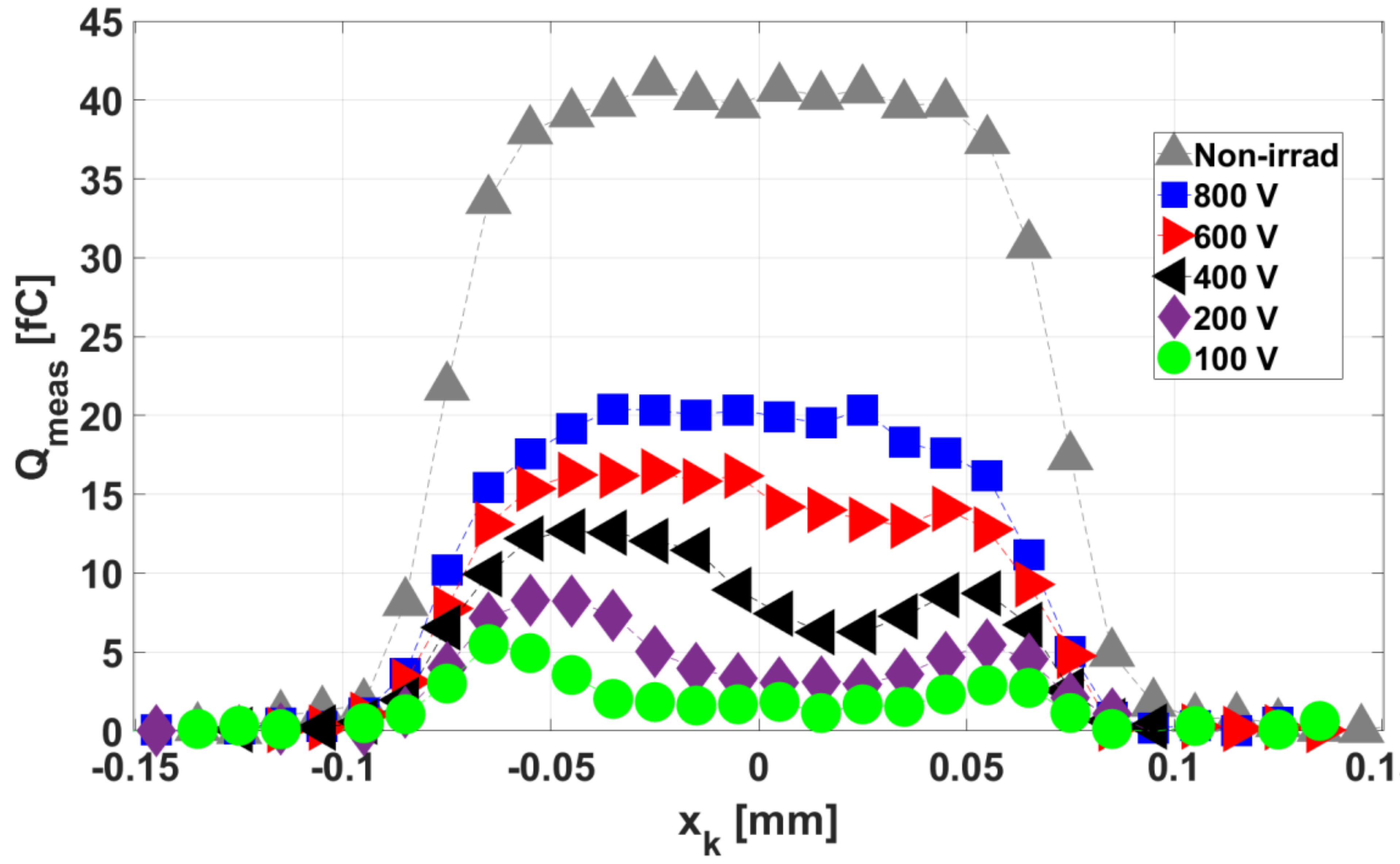
Edge-on measurements II

Examples of charge collection profiles as function of voltages:

Φ_{eq} = 2x10^{15} cm^{-2}



Φ_{eq} = 12x10^{15} cm^{-2}



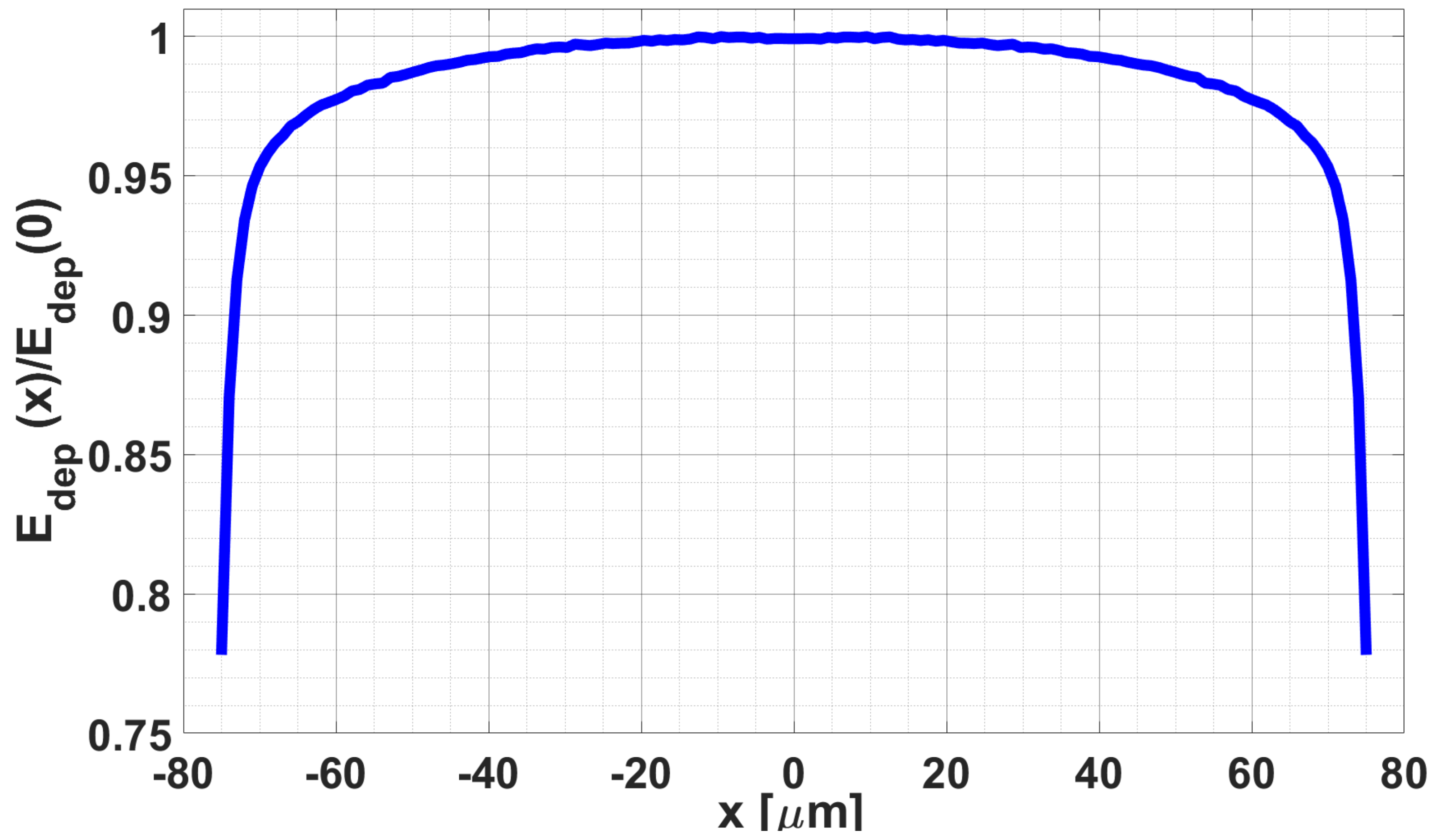
- Double peak structure at low voltages
- Uniform at high voltages
- Reduced charge collection as function of fluence

Simulation of Charge Collection profiles

The charge collection profiles are a convolution of:

- the CCE profile
- the smearing caused by the limited spatial resolution of the track position
- the energy deposition of the electron beam as function of depth in the diode

GEANT4 simulation



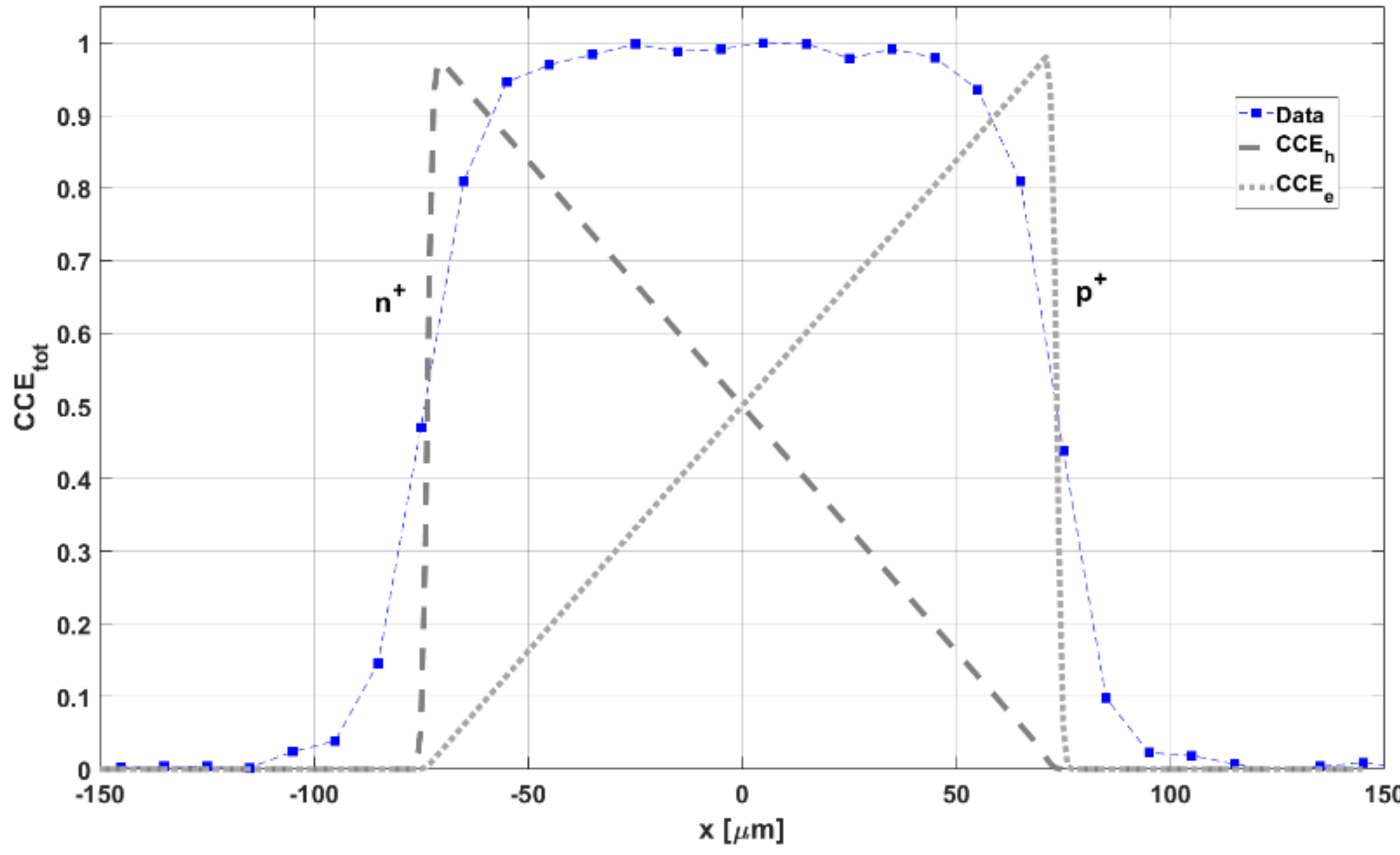
$$Q_{sim}(x) = A \cdot \left(CCE_{tot}(x) \cdot \frac{E_{dep}(x)}{E_{dep}(0} \right) * Gauss(x,0,\sigma_{res})$$

with $CCE_{tot}(x) = CCE_e(x) + CCE_h(x)$

and $$CCE_e(x) = \int_{-d/2}^{x} E_w(y) \cdot \exp\left(\int_x^y \frac{dy'}{\lambda_e(y')} \right) dy$$

$$CCE_h(x) = \int_x^{d/2} E_w(y) \cdot \exp\left(- \int_x^y \frac{dy'}{\lambda_h(y')} \right) dy$$

Example of CCE



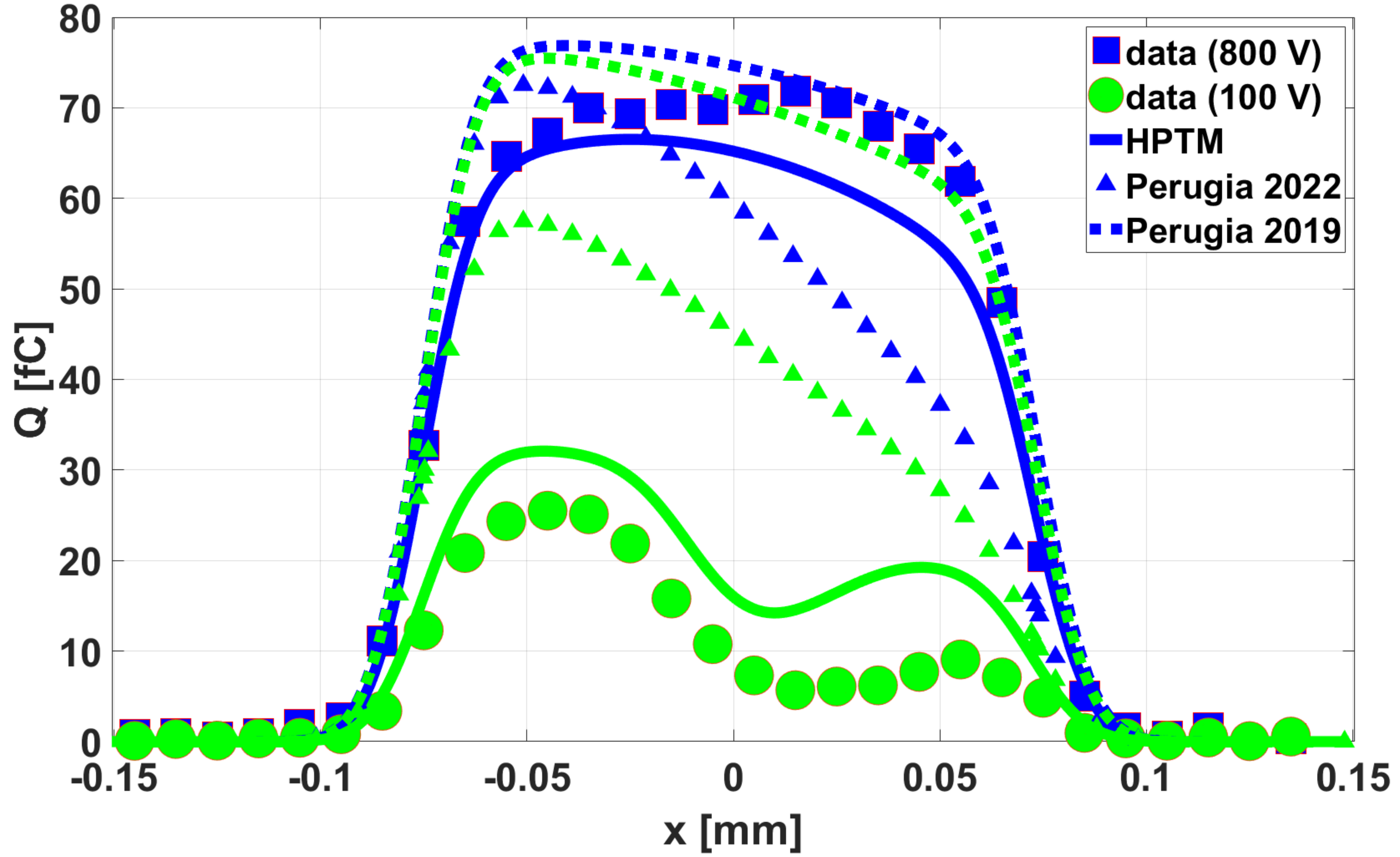
- d: thickness of diode, E_w weighting field
- $\lambda_{e,h}(x)$: charge collection length of electrons and holes of the model
- A: scaling factor and σ_{res} beam resolution (10 µm)

Comparison of simulation and data I

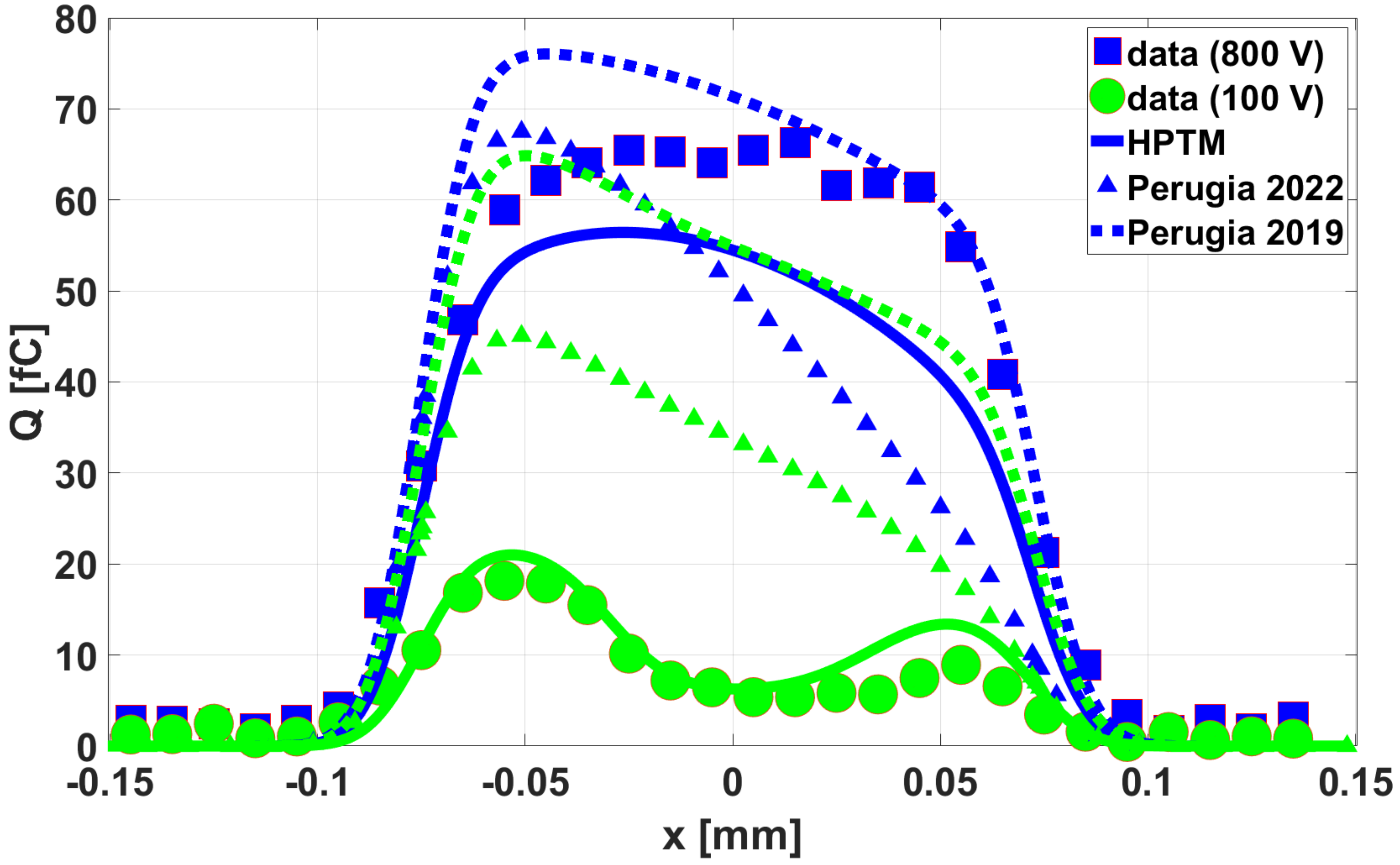
Models used:

- Hamburg Penta Trap Model (HPTM)
- Perugia (2022): 3 traps (B_iO_i, V_2, V_3) cane be found: Here
- Perugia (2019): 3 traps (B_iO_i, V_2, V_3) can be found: Here

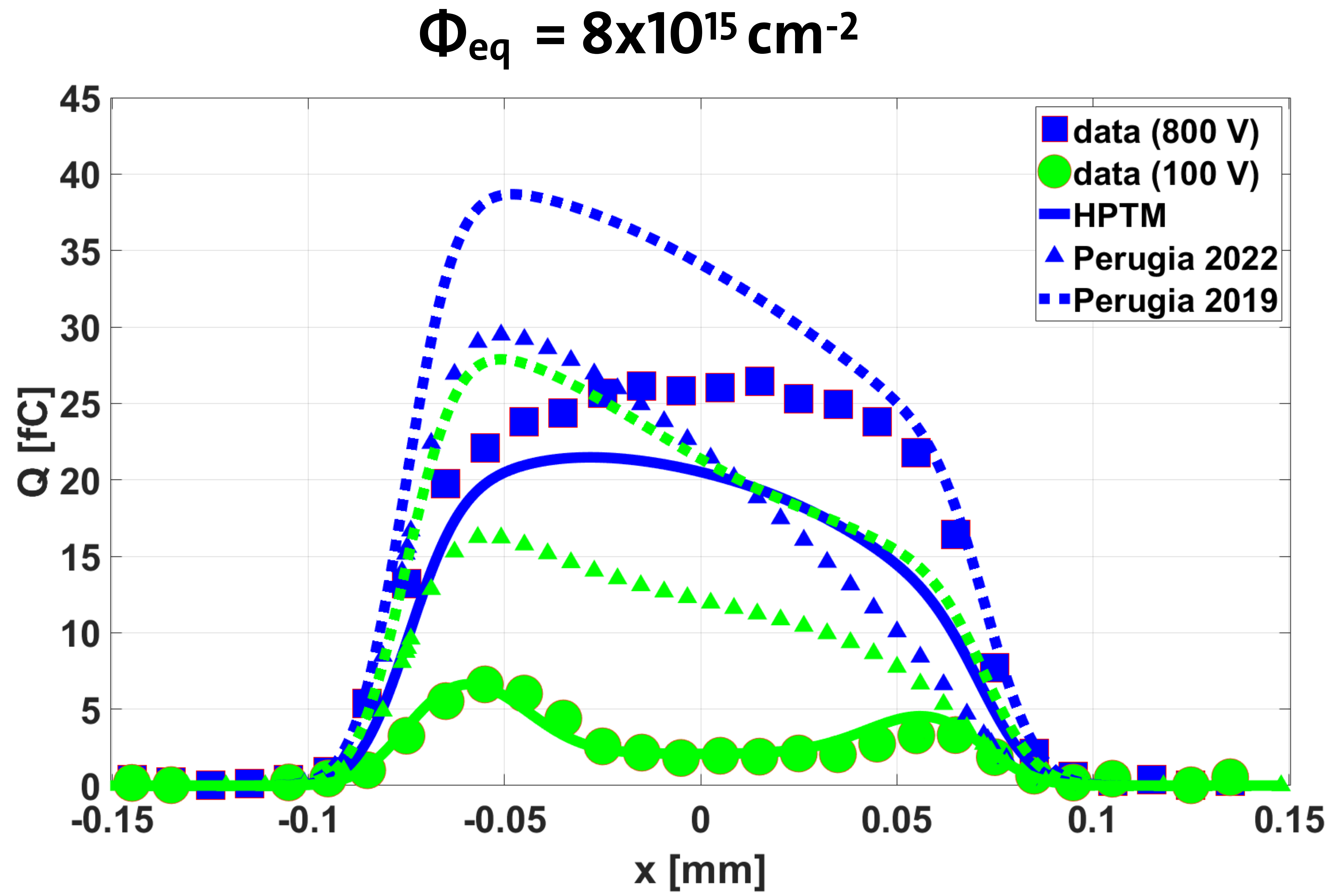
Φ_{eq} = 2x10^{15} cm^{-2}

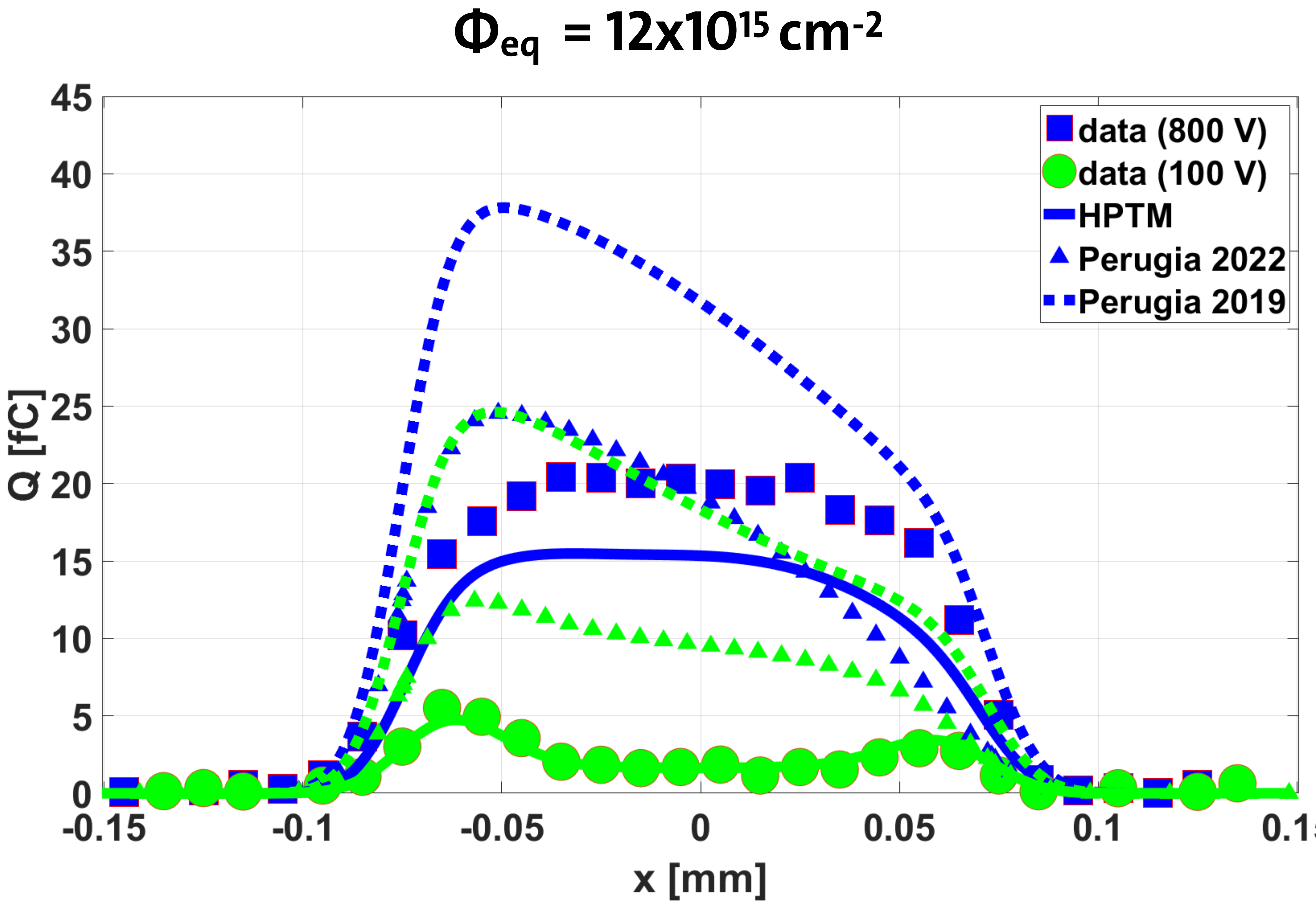


Φ_{eq} = 4x10^{15} cm^{-2}



Comparison of simulation and data II





Summary

- The HPTM gives a good and consistent description of **I-V**, **C-V** and **CCE$_{IR}$** of pad diodes
- A method was developed which allows the direct comparison of TCAD simulations with edge-on beam test measurements
- Using the HPTM the simulated charge collection as function of voltage shows a depth dependence even though such an information was not explicitly used in the optimisation
- At low voltages the simulated charge collection is similar to the measured one, but at higher voltages there is a disagreement

➡ Consideration of edge-on measurements during optimization

➡ Rethinking the choice of defects?

➡ ...

Thank you for your attention!

BACKUP

Up to now state of the art

3-trap Perugia parameters (F. Moscatelli et al IEEE Trans Nucl Sci 2017) for Synopsys TCAD

RADIATION DAMAGE MODEL FOR P-TYPE SUBSTRATES
(UP TO 7×10^{15} N/CM^2)

Type	Energy (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η (cm^{-1})
Acceptor (V_2)	Ec-0.42	1×10^{-15}	1×10^{-14}	1.613
Acceptor (V_3)	Ec-0.46	7×10^{-15}	7×10^{-14}	0.9
Donor (C_iO_i)	Ev+0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

RADIATION DAMAGE MODEL FOR P-TYPE SUBSTRATES
(IN THE RANGE 7×10^{15}–1.5×10^{16} N/CM^2)

Type	Energy (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η (cm^{-1})
Acceptor	Ec-0.42	1×10^{-15}	1×10^{-14}	1.613
Acceptor	Ec-0.46	3×10^{-15}	3×10^{-14}	0.9
Donor	Ev+0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

RADIATION DAMAGE MODEL FOR P-TYPE SUBSTRATES
(IN THE RANGE 1.6×10^{16}–2.2×10^{16} N/CM^2)

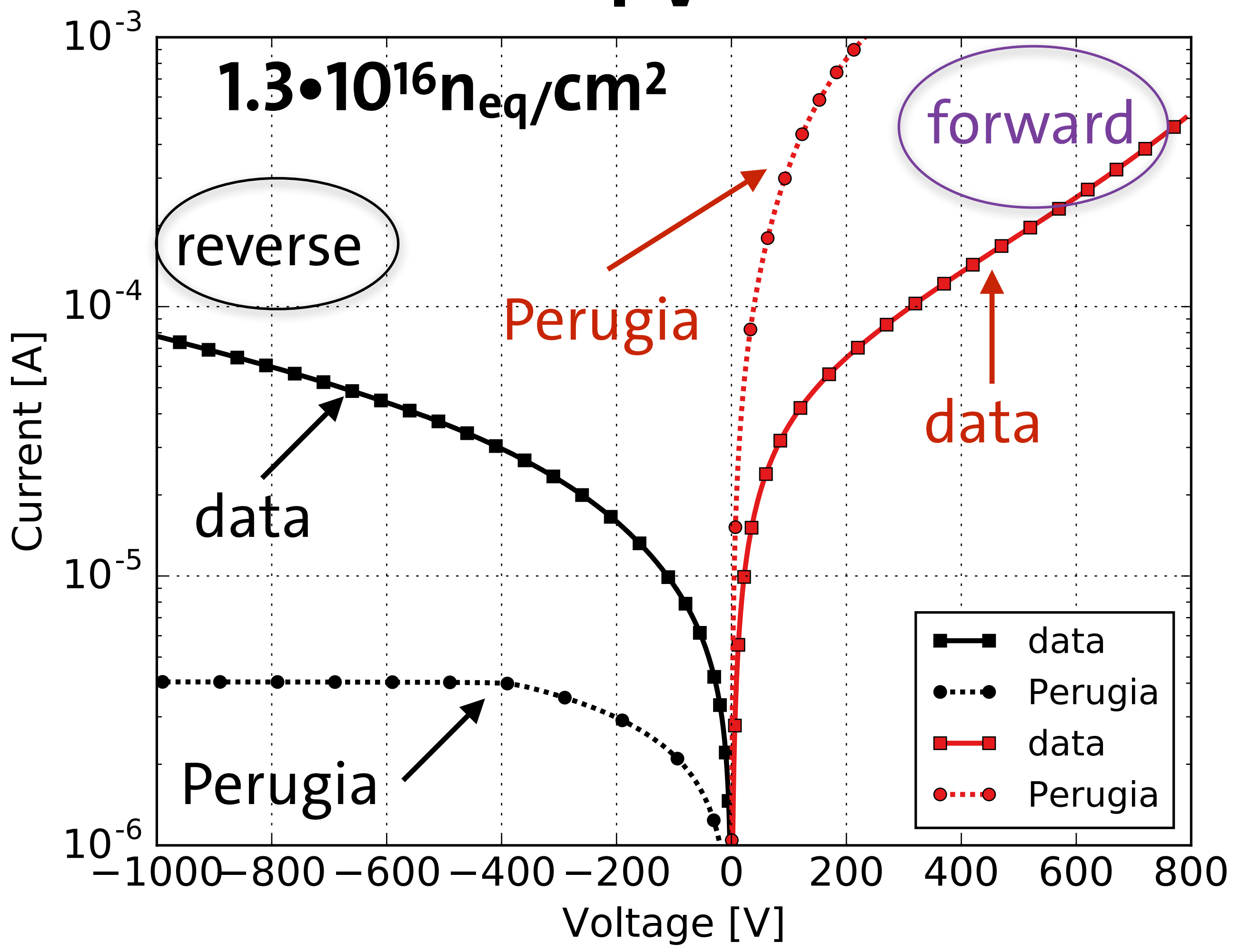
Type	Energy (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η (cm^{-1})
Acceptor	Ec-0.42	1×10^{-15}	1×10^{-14}	1.613
Acceptor	Ec-0.46	1.5×10^{-15}	1.5×10^{-14}	0.9
Donor	Ev+0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

Fluence depending cross sections!!!

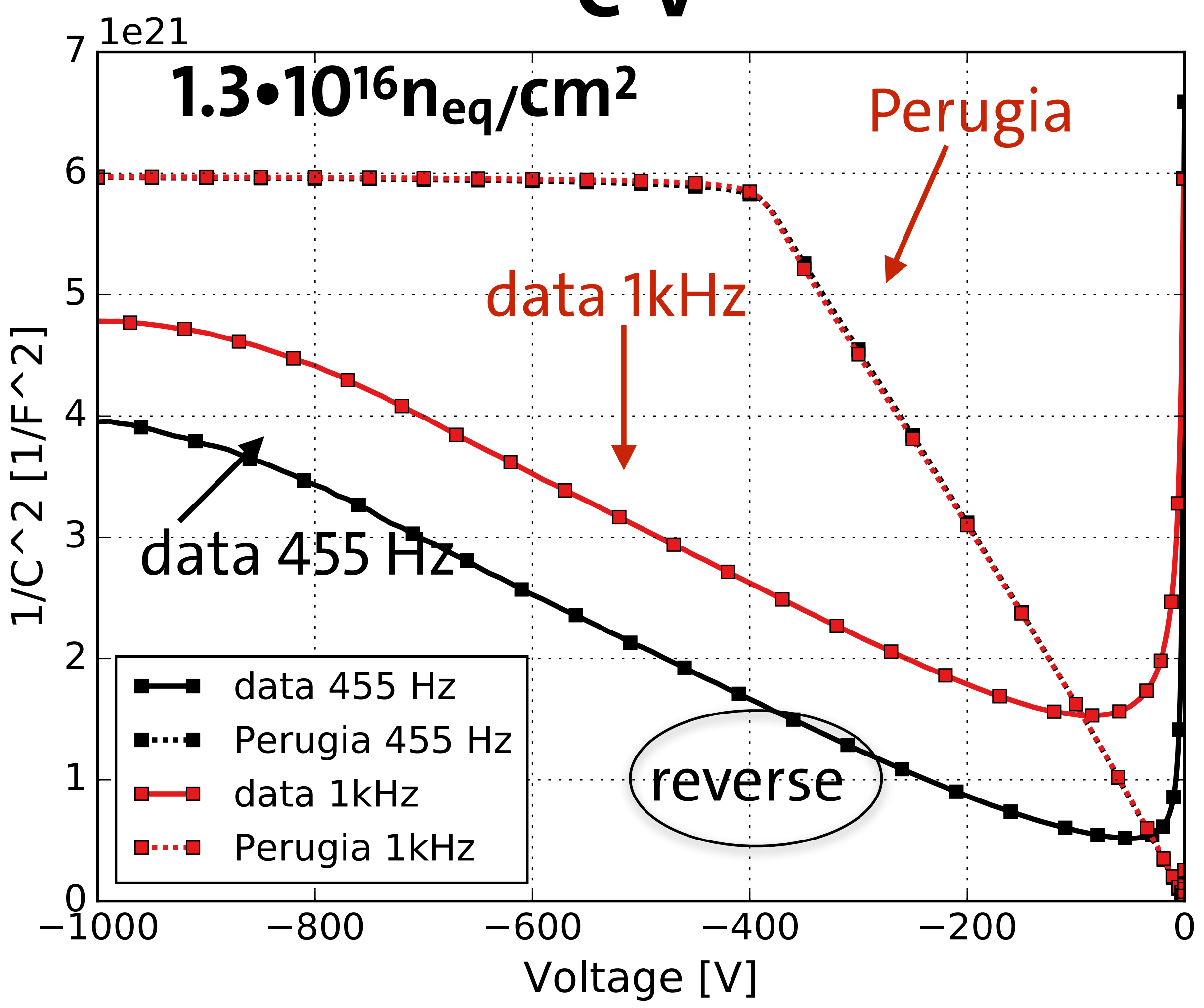
Up to now state of the art

Does it describe our data?

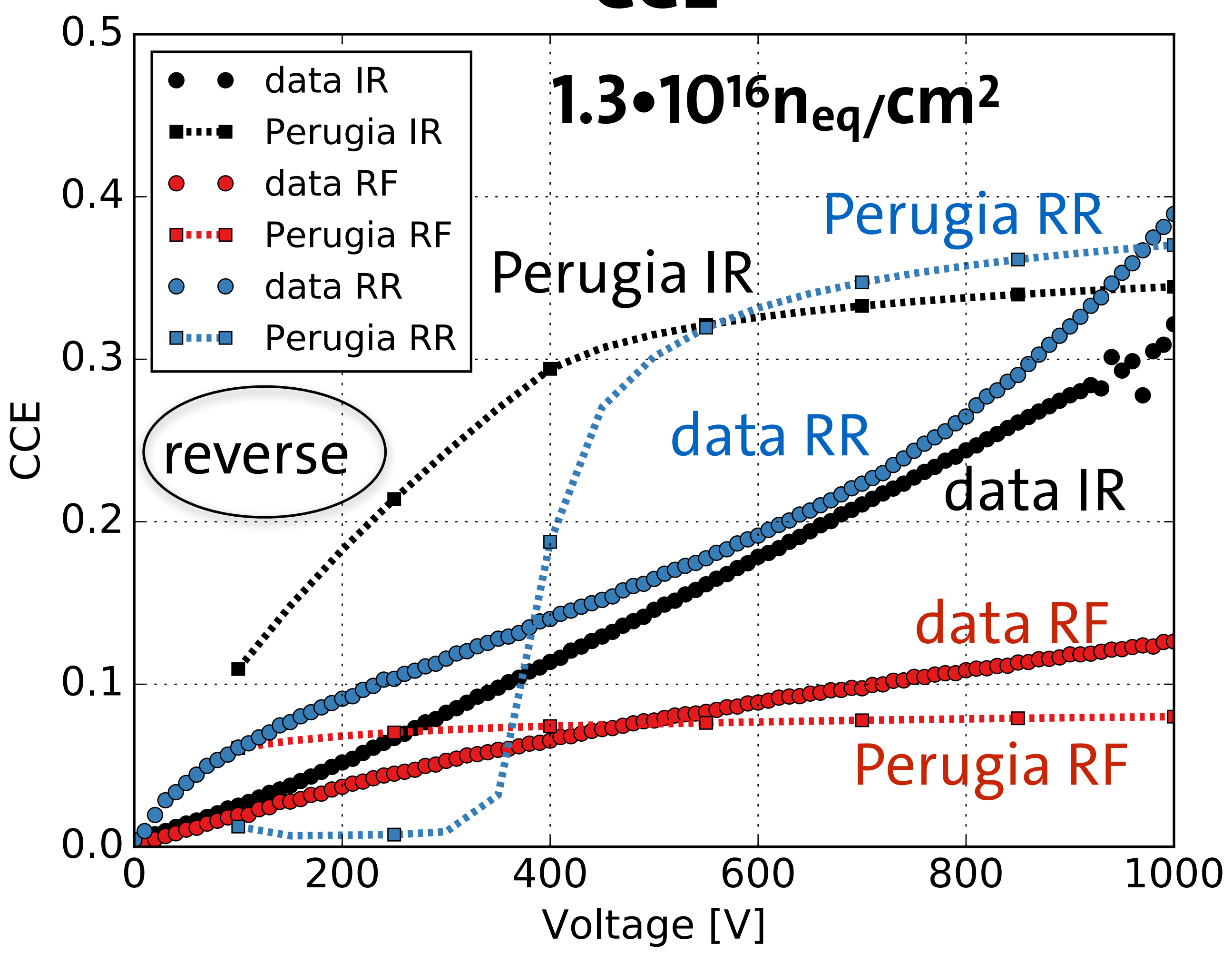
I-V



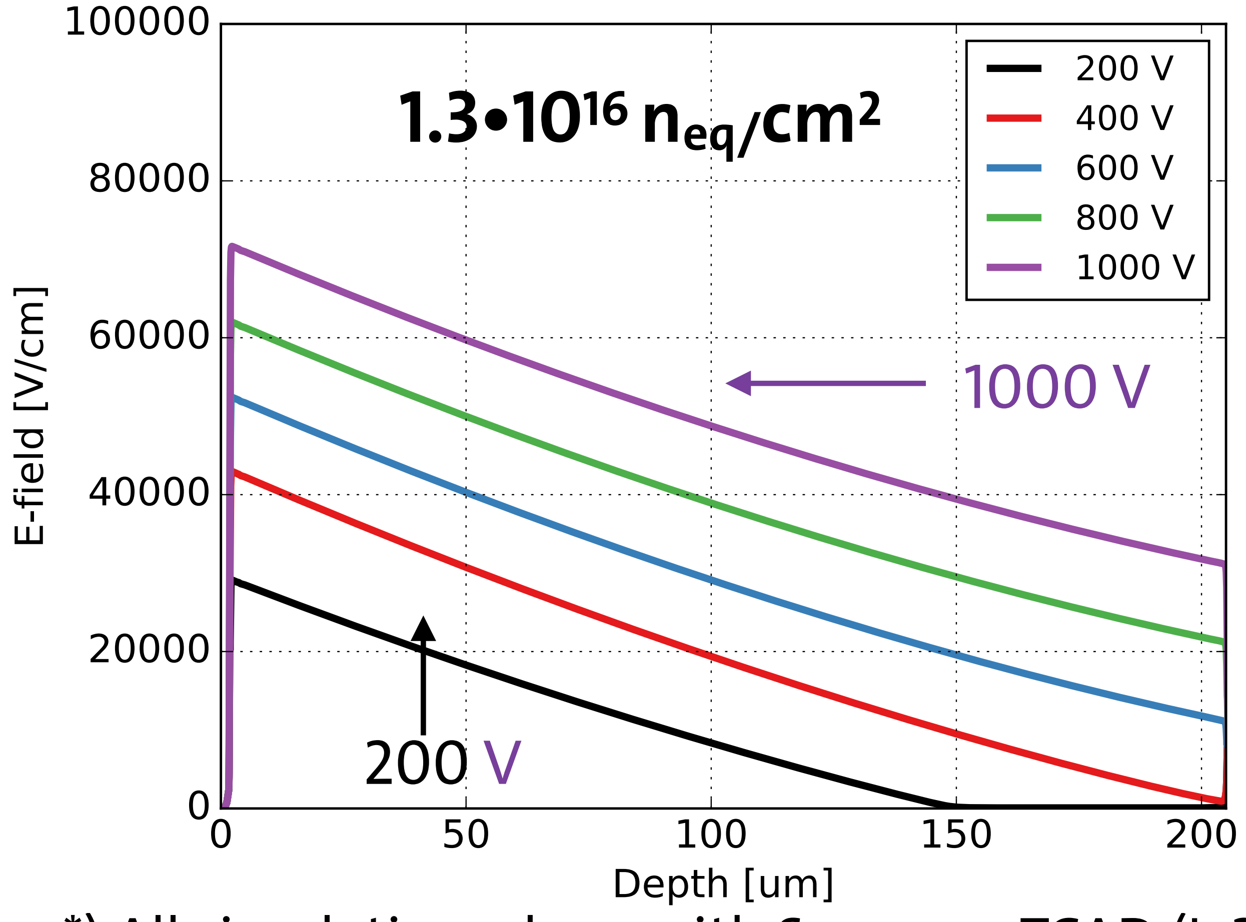
C-V



CCE

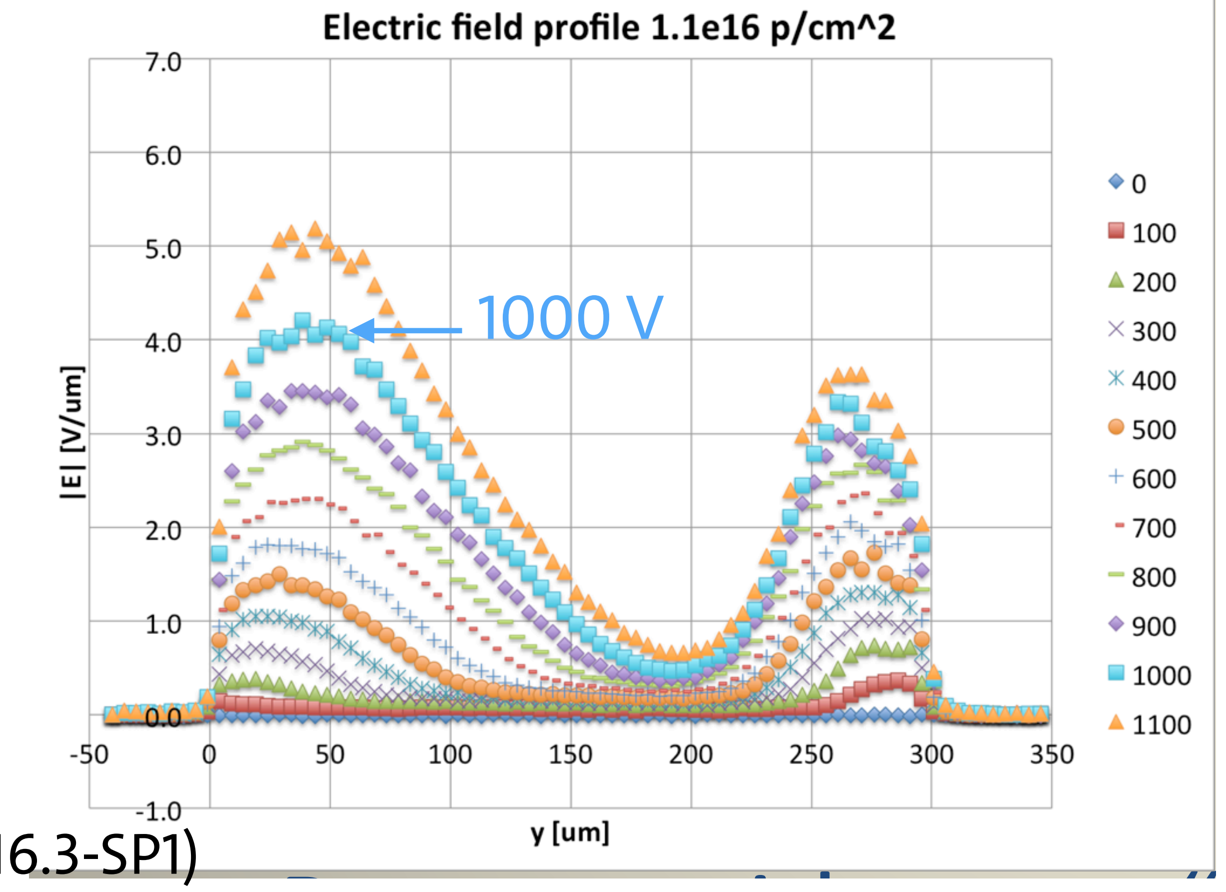


Electric field



Edge-TCT measurements

(M. Mikuž: Tredi,Paris, FEB 2016)



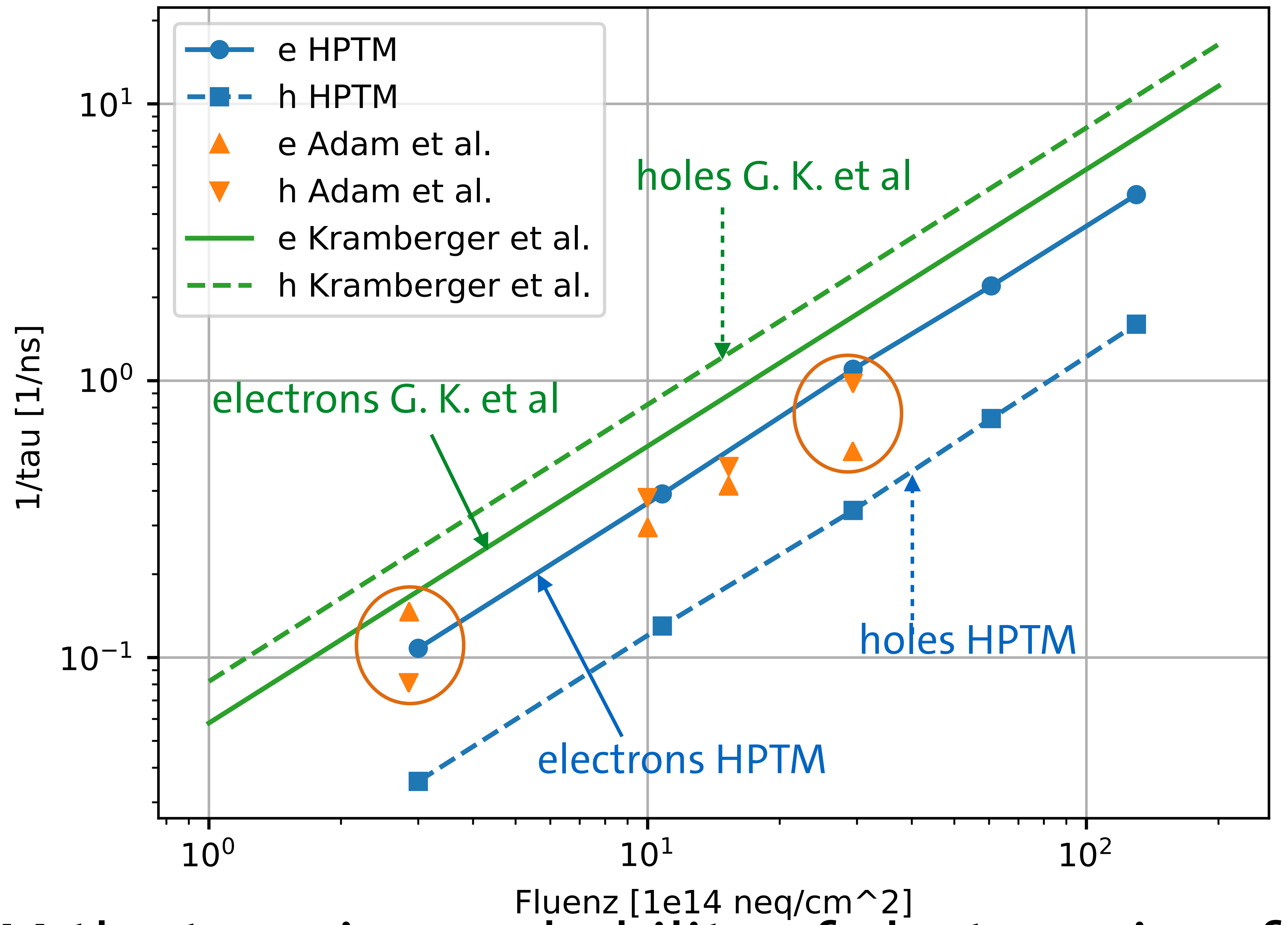
*) All simulations done with Synopsys TCAD (L-2016.3-SP1)

- Reverse current too low
- CV shows no frequency dependence
- CCE has not the correct voltage dependence
- No double peak

Trapping

Trapping rates:

$$\frac{1}{\tau_e} = \sum_{defects} v_e \sigma_{t,p} (1 - f_t) N_t \qquad \frac{1}{\tau_h} = \sum_{defects} v_h \sigma_{t,p} f_t N_t$$



Kraner et al NIMA 1993

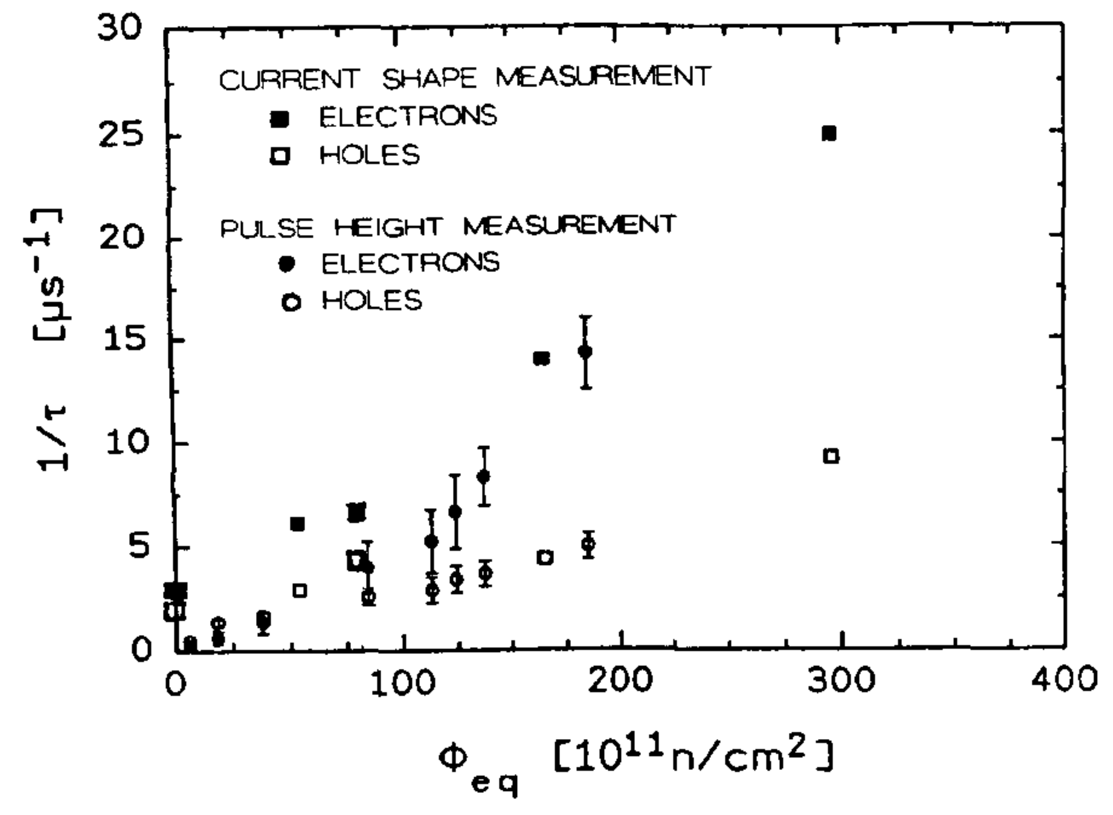
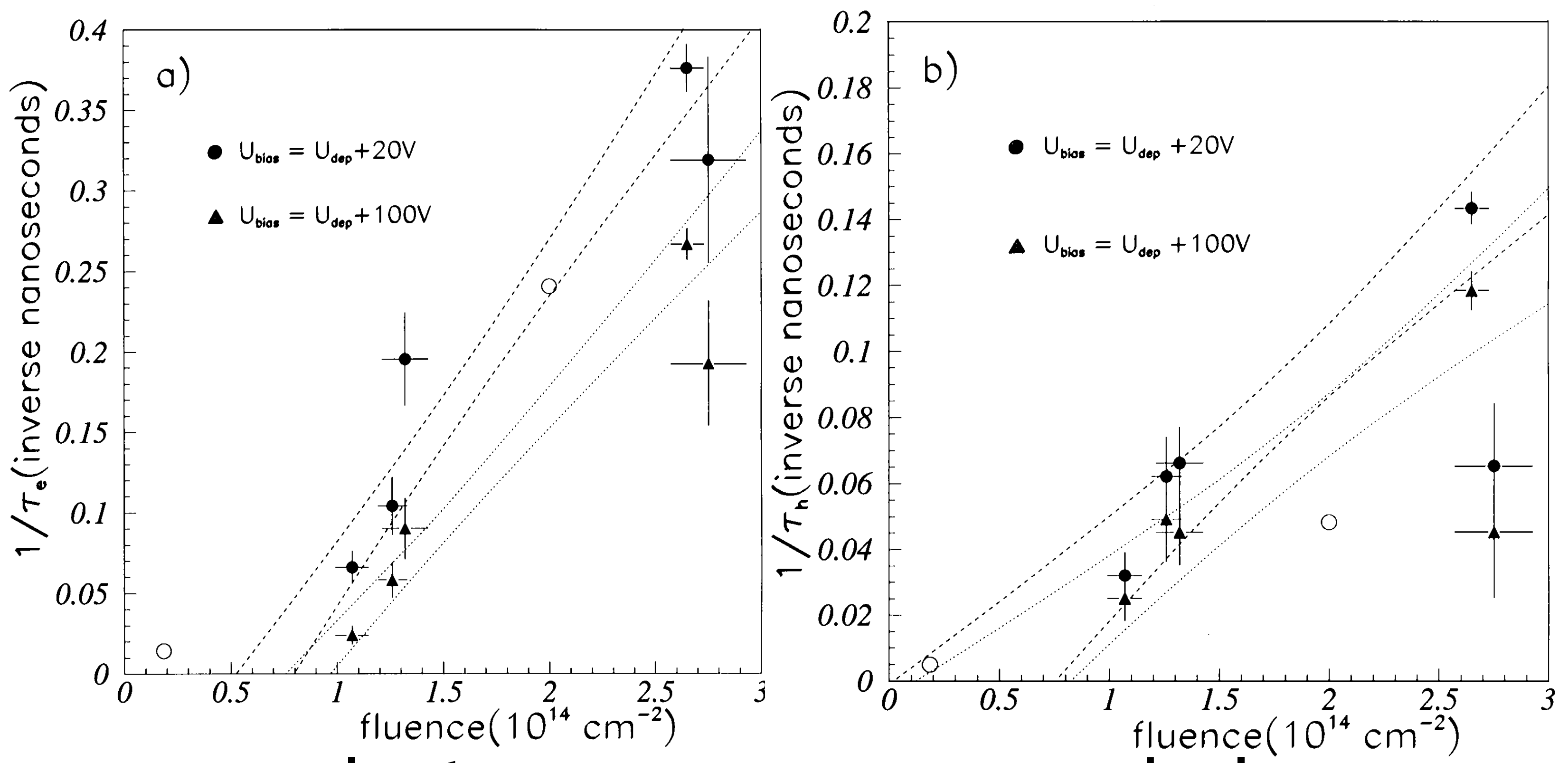


Fig. 9. Trapping probabilities, $1/\tau$, for both holes and electrons as a function of fast neutron fluence as measured by the observed pulse width (squares) and the calculated charge collection time (circles).

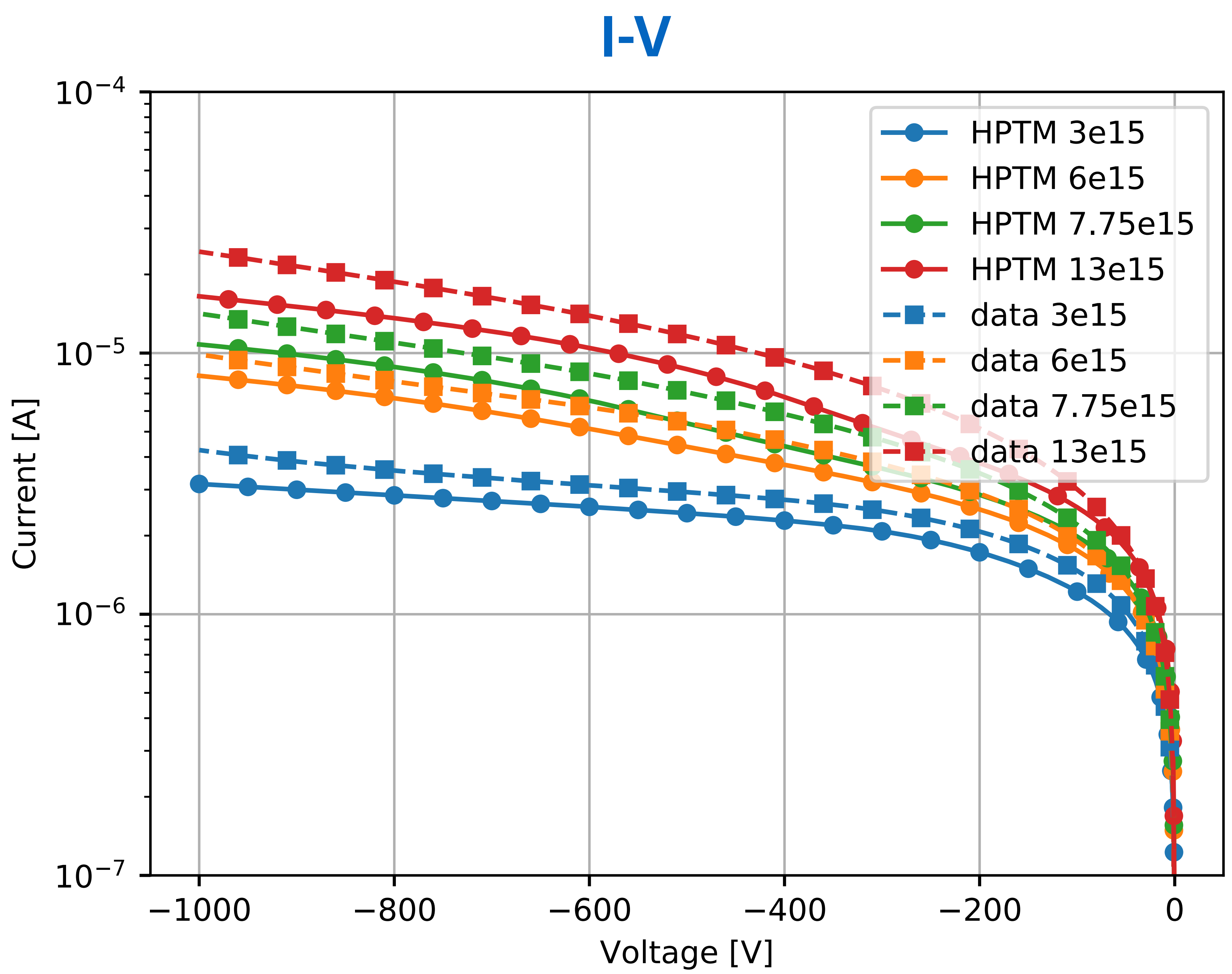
Beatie et al NIMA 1999

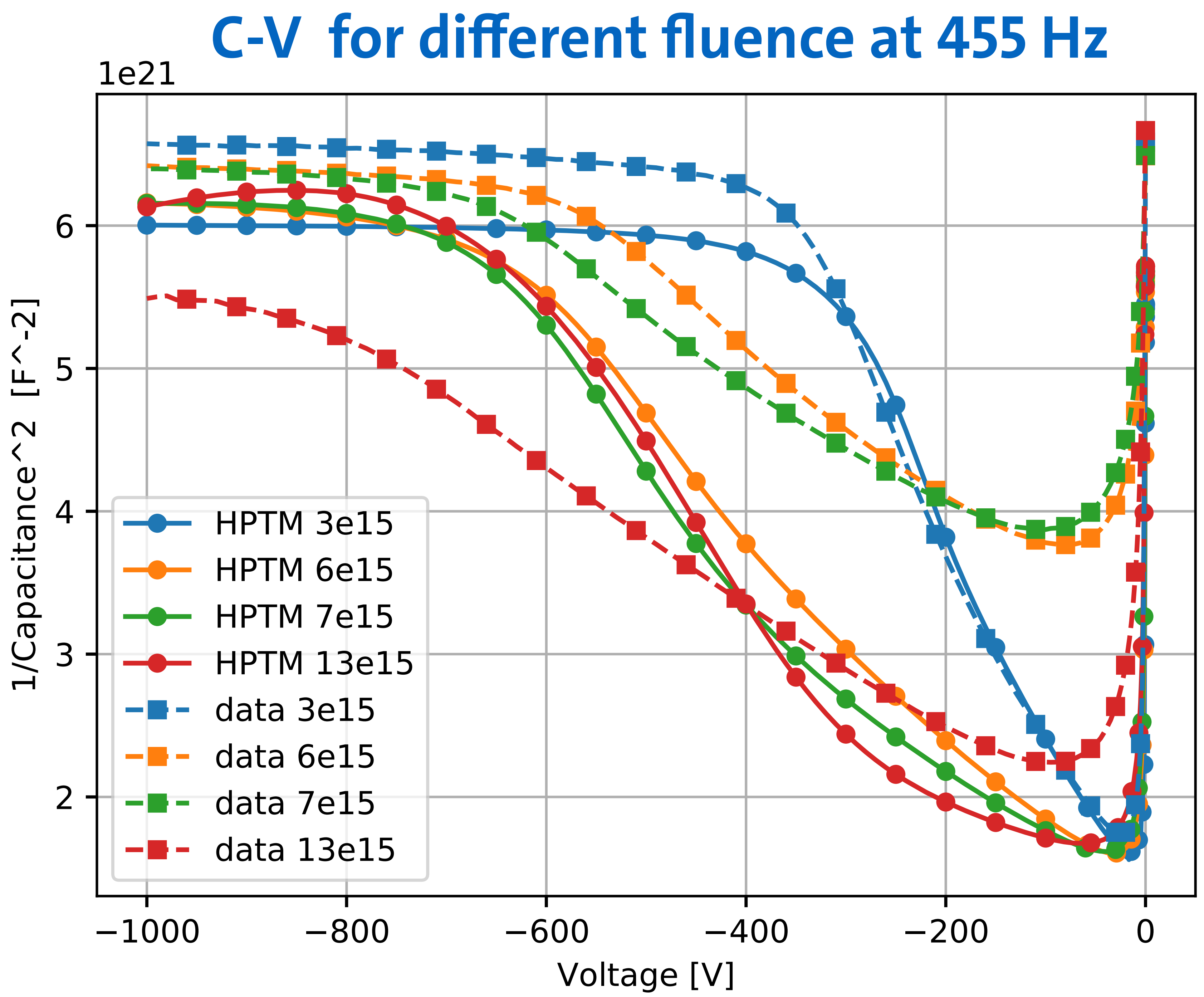


electrons holes

- For HPTM the trapping probability of electrons is a factor 3 higher than for holes
- Similar to old alpha TCT measurements (1993, 1999) but different to new red laser TCT measurements
- Effect know since Brodbeck et al. NIMA 2000, but not investigated further

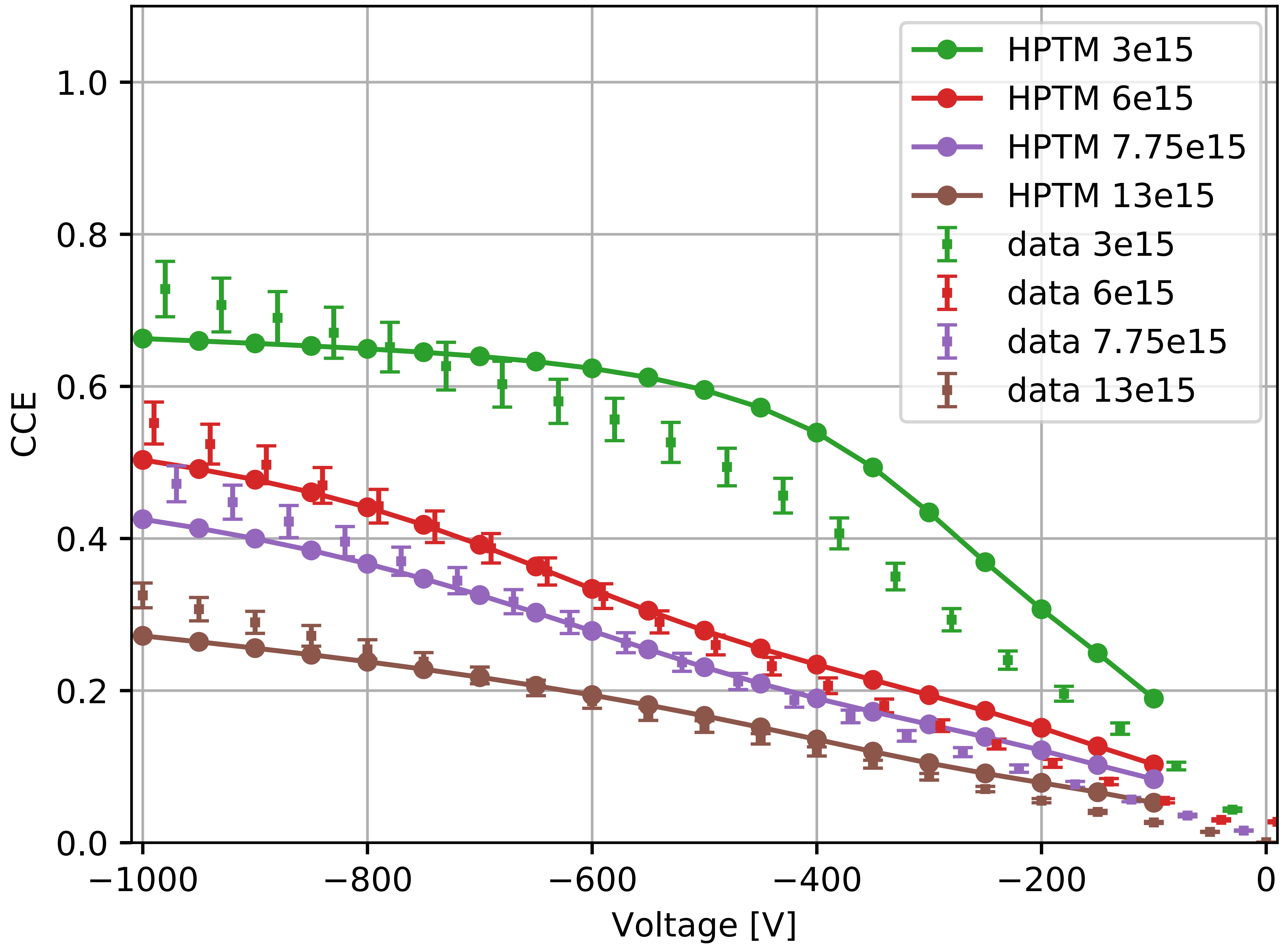
I-V and C-V at T=-30°C





CCE at T=-30°C

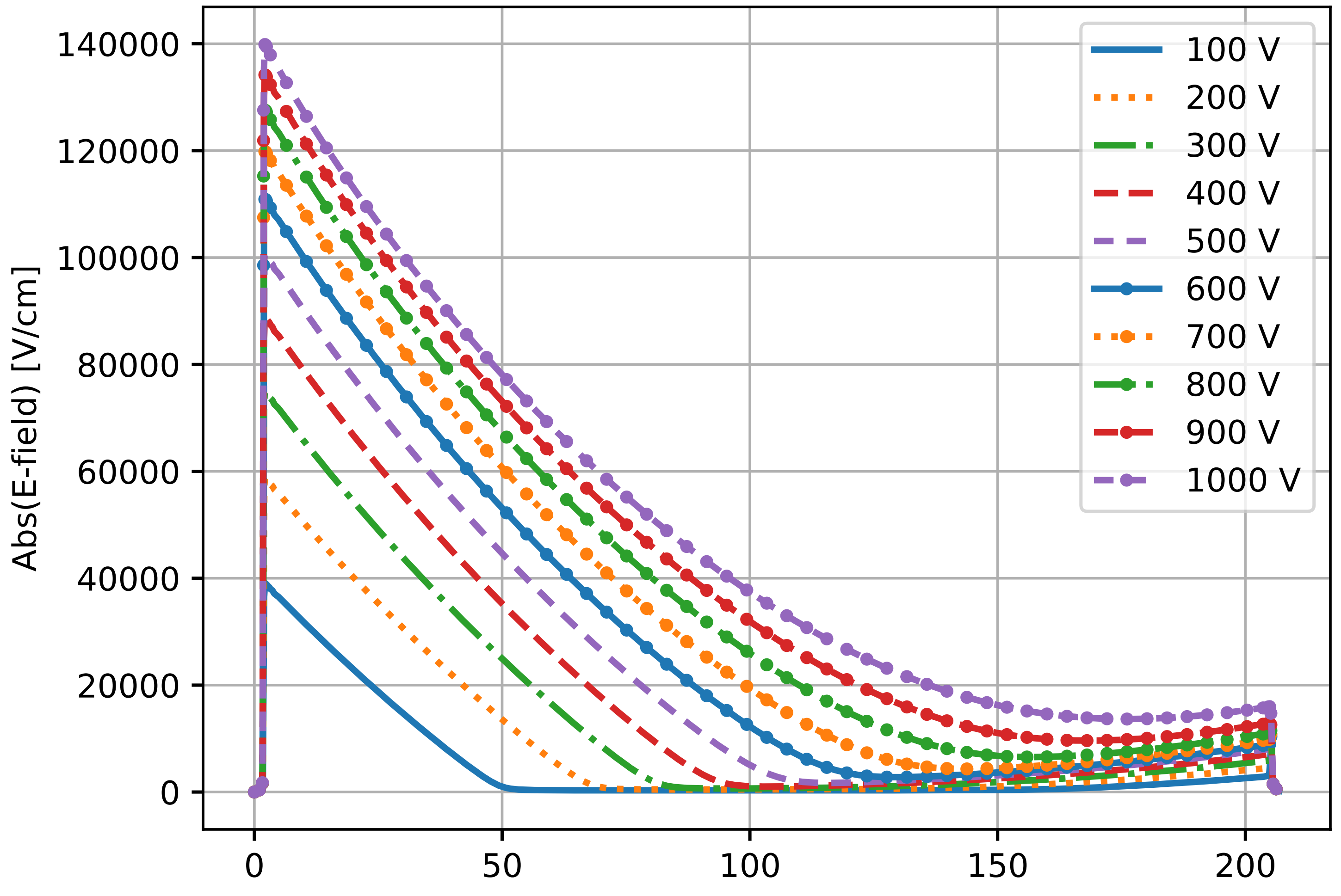
CCE-V for different fluence (infrared) at T = -30 °C



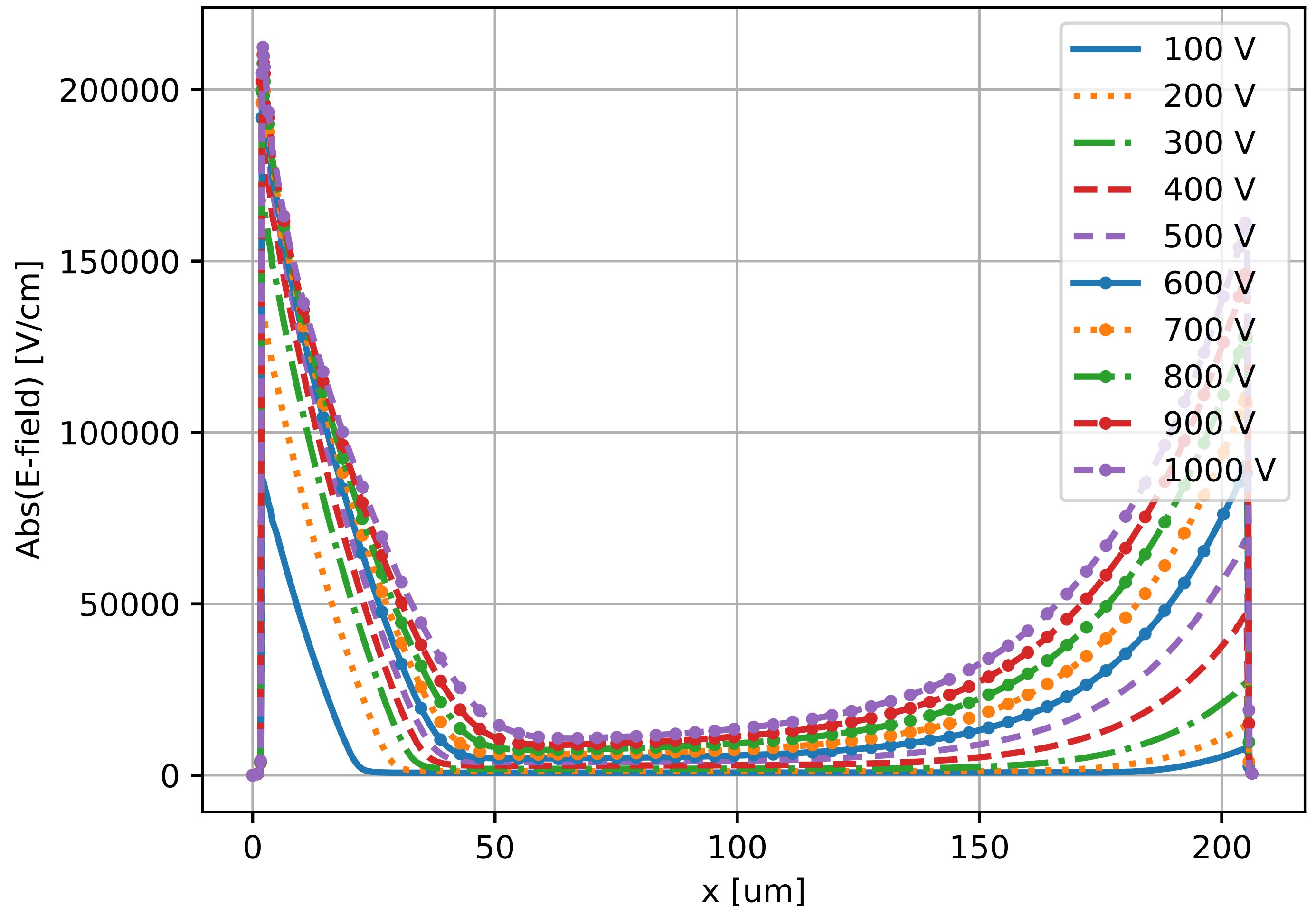
E-fields vs. voltage

E-field vs. voltage

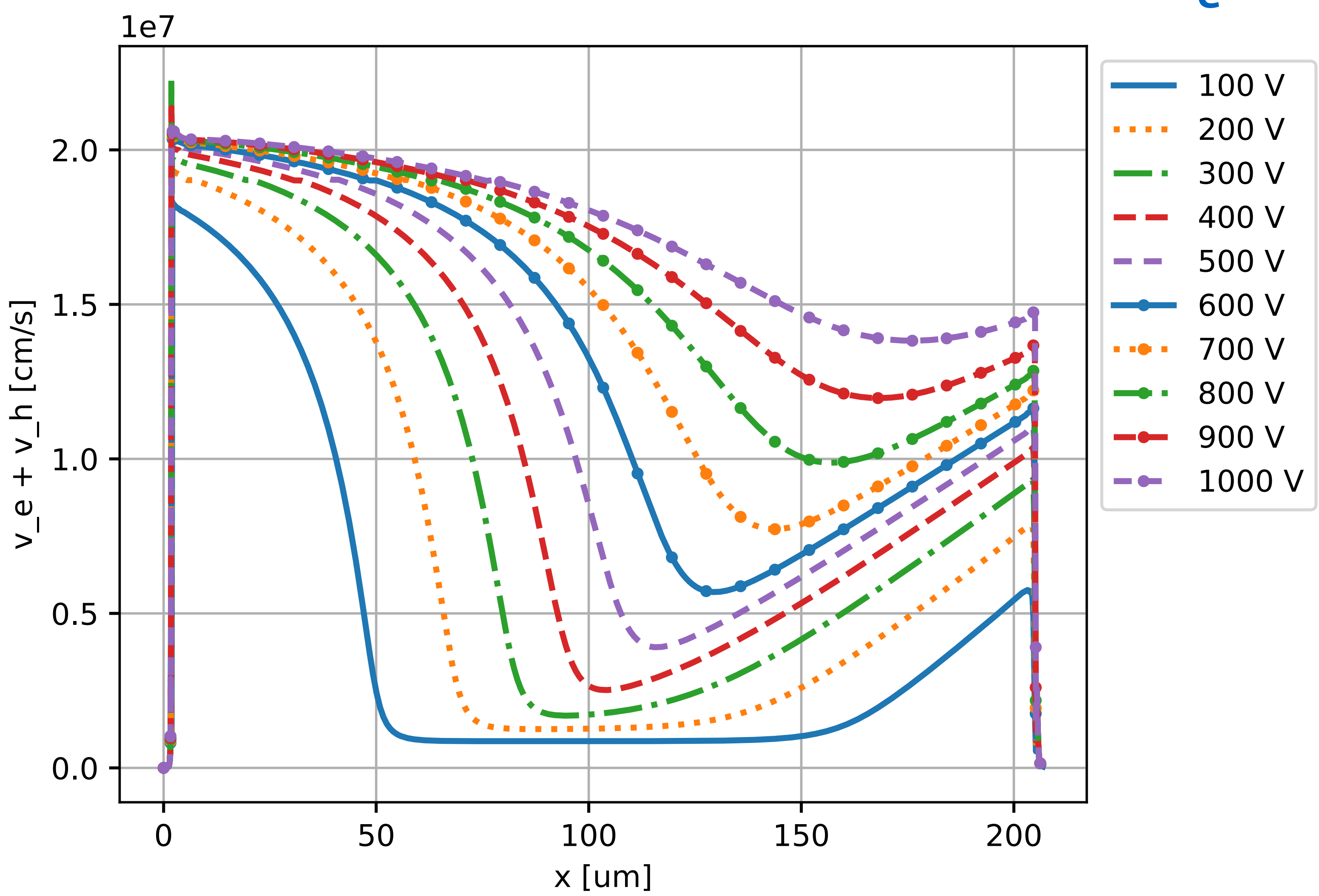
$3 \cdot 10^{15} n_{eq}/cm^2$

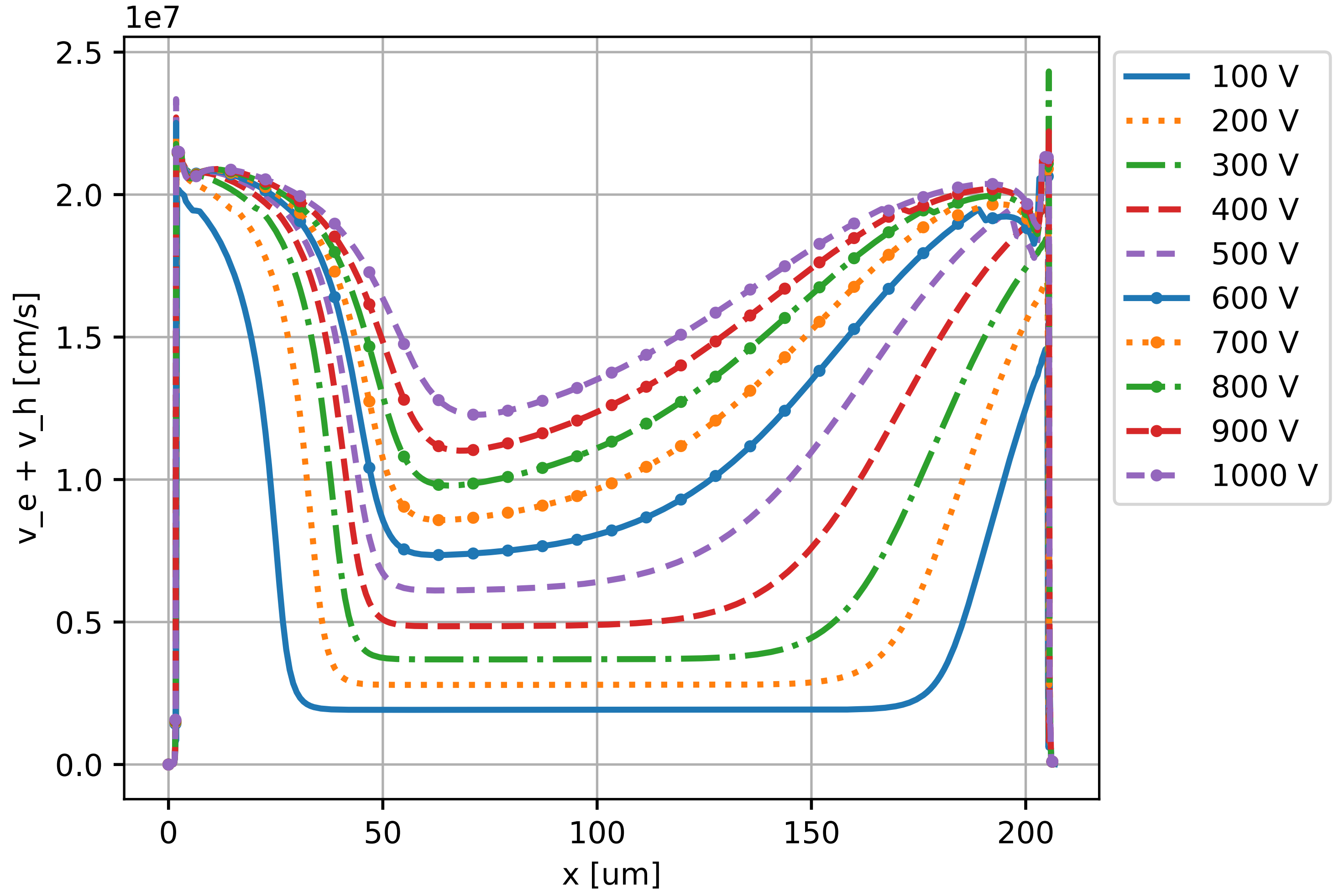


$1.3 \cdot 10^{16} n_{eq}/cm^2$



$v_e + v_h$ vs. voltage

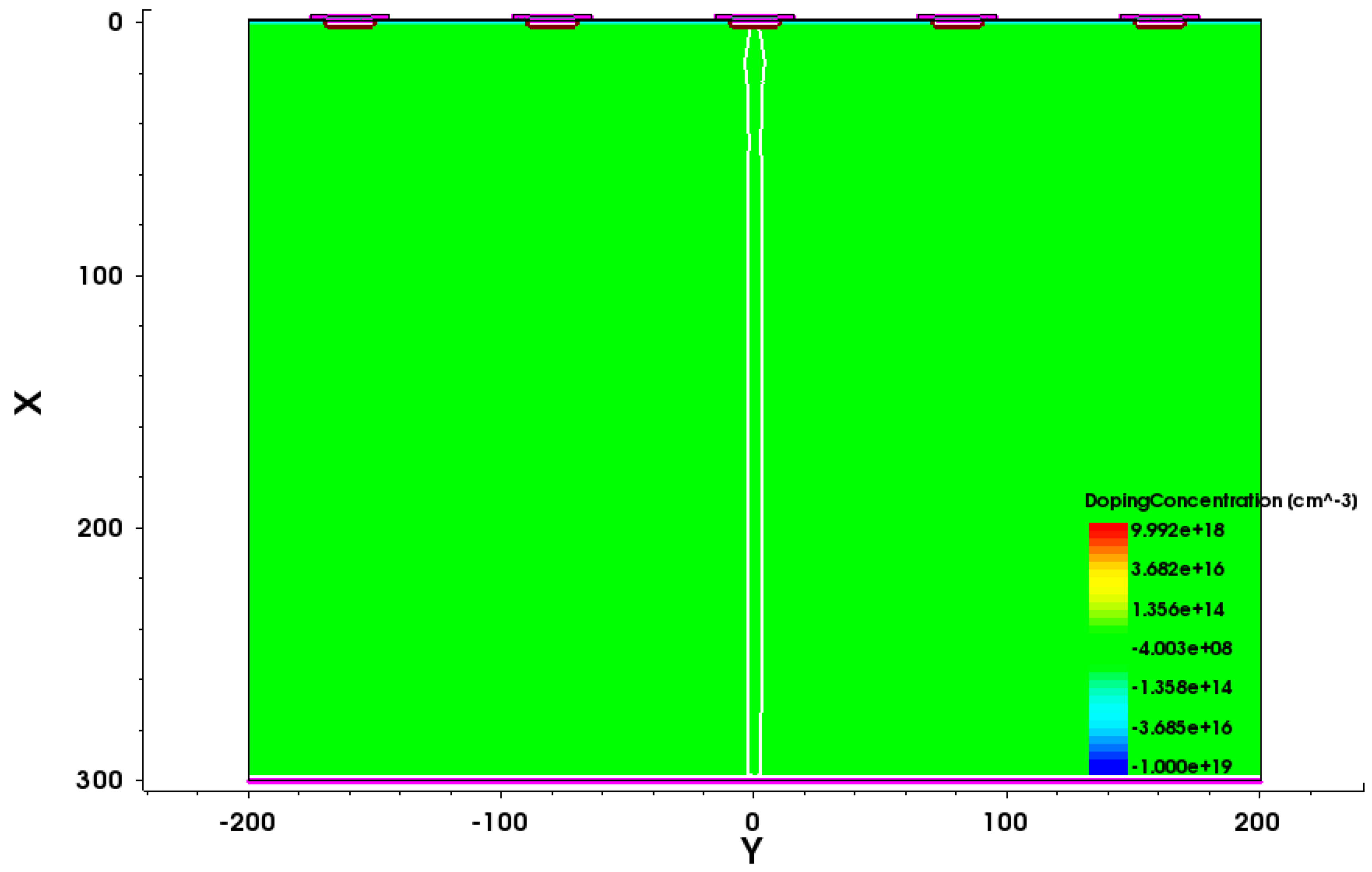




Comparison with strips

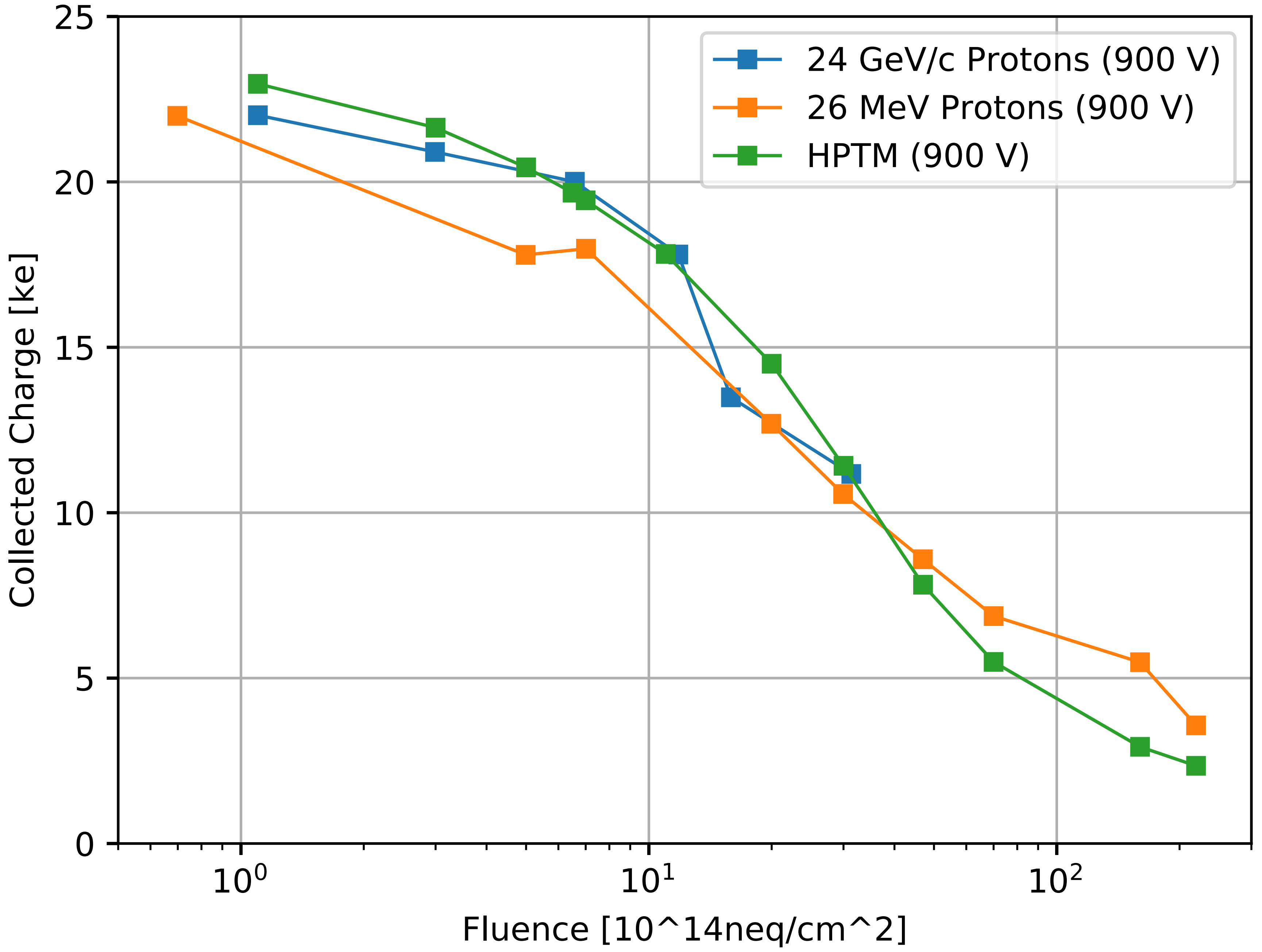
Charge collection measured with strip sensors (data from Affolder et al NIMA 2010)

Simulated structure



- 5 AC coupled strips simulated
- 80 e-h/um generated

Collected charge vs. fluence



- Float zone silicon
- 300 um thick sensors
- 80 um pitch
- T = -25 °C
- ^{90}Sr source

Simulation of charge collection I

Procedure to determine the charge collection as function of depth:

1. Perform **1D** TCAD simulation with HPTM for protons as function of voltage
2. Calculate trap **occupancies** f_t as function of depth (y)
3. Calculate **trapping rates** as function of depth for electron and holes

$$\frac{1}{\tau_e} = \sum_{defects} v_e^{th}\sigma_{t,n}(1-f_t)N_t$$

$$\frac{1}{\tau_h} = \sum_{defects} v_h^{th}\sigma_{t,p}f_t N_t$$

➡ **Charge collection lengths as function of depth and voltage**:

- $\lambda_e(y) = \tau_e(y) \cdot v_e(y)$ and $\lambda_h(y) = \tau_h(y) \cdot v_h(y)$ with drift velocities v_e and v_h from the simulation