Study of depth-dependent charge collection profiles in irradiated pad diodes

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Introduction

- Luminosity in the CMS Phase-2 is up to $7.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$.
- This causes a neutron equivalent fluence of $3.5 \times 10^{16}\mathrm{cm^{-2}}$ (after 4000 $\mathrm{fb^{-1}}$)

in the first layer of the inner tracker.

- The radiation damage changes the electric field and trapping times of the sensors used

in the inner tracker.

The motivation of this talk

- Study the charge collection in highly irradiated silicon diodes which provides precise data for testing simulation of irradiated silicon sensors

The tool of study

- Edge-on measurement using electron beam with an energy of 5.2 GeV

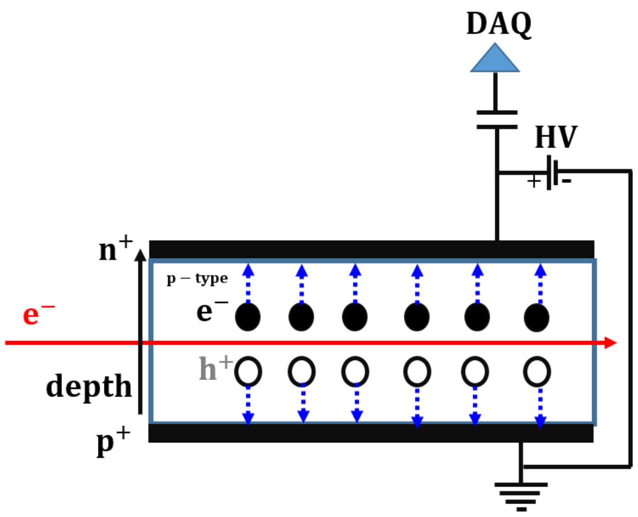
The performed measurements

- Charge profiles of non-irradiated and irradiated diodes at different bias voltages

Edge-on measurements with pad diodes

The method was introduced in previous RD50 workshop (37th RD50)

The measurement results were shown for four irradiated pad diodes (38th RD50)



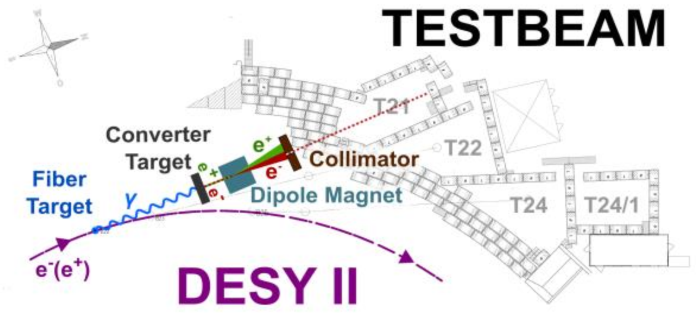
In this talk:

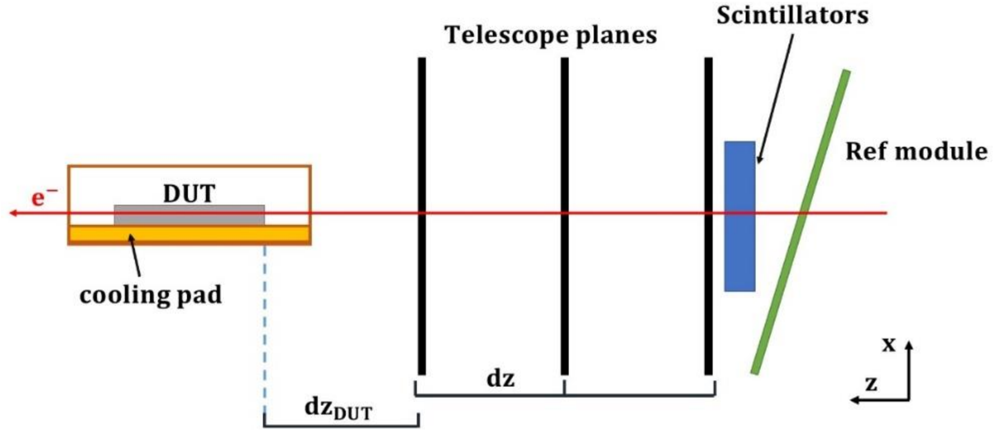
- The measurements results are compared with results of radiation damage models
- The data are unfolded to extract CCE profile as a function of depth.

Measurement setup

DESY II beam test facility:

- Electron/positron beam with energy of 1-6 GeV
- Beam energy of 5.2 GeV was chosen for the measurements
- Intrinsic resolution of each plane of telescope ≈ 3. 2 µm
- Timing reference module for reducing in-time pile up
- Scintillator for providing the readout trigger
- Rotation stage for the DUT with a precision of 0.10°(1.7 mrad)

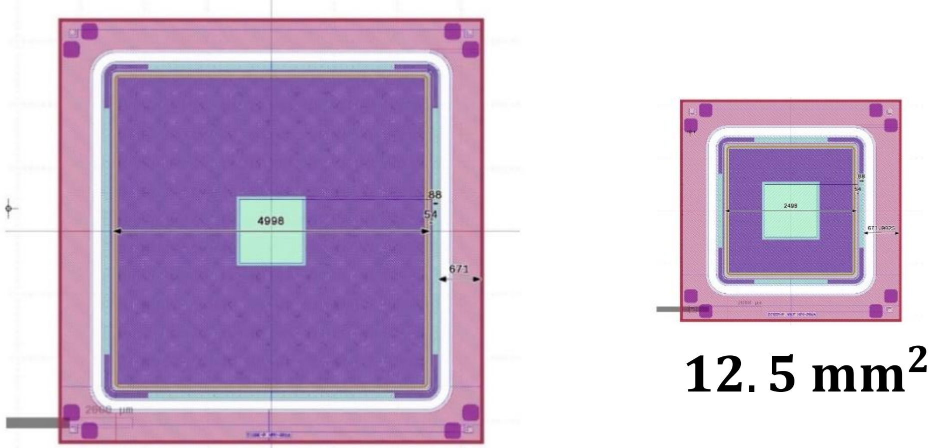




Specifications of the diodes

- Nominal thickness 150 μm
- Area ≈ 25 and 12.5 mm^2
- p-type (n^+pp^+ configuration)
- Doping concentration $\approx 4.5 \times 10^{12}\ cm^{-3}$
- Depletion voltage 75 V
- Manufactured by Hamamatsu Photonic K.K (HPK)
- Guard-ring is floating

Top view (dimensions are in micrometer)



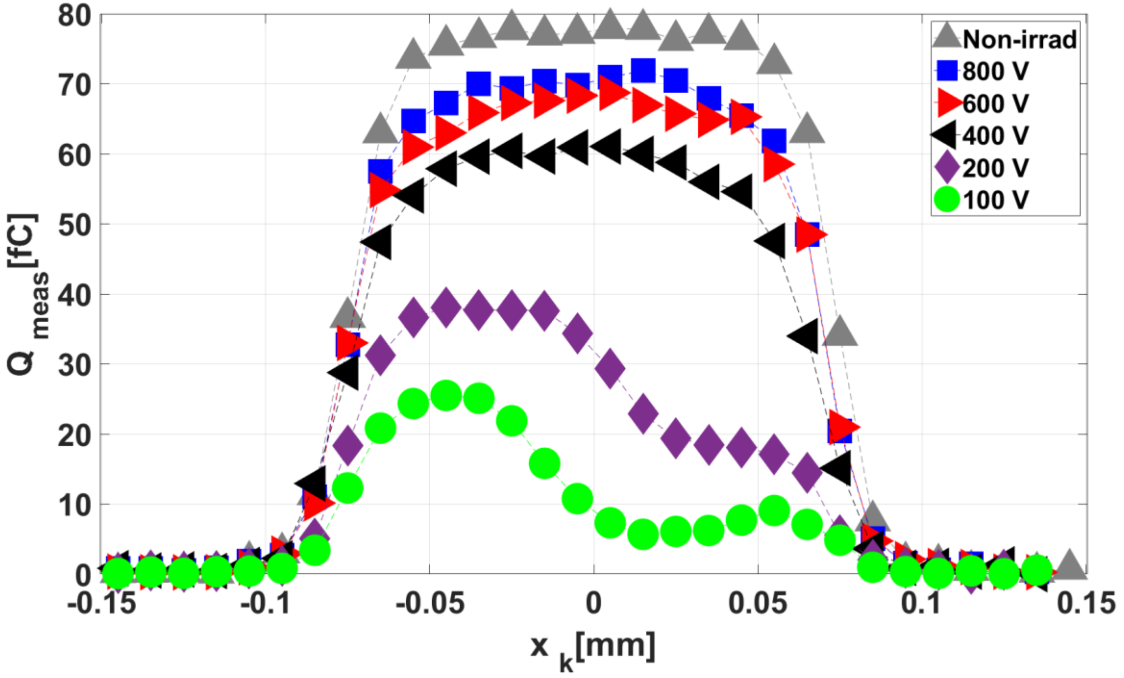
$25\ mm^2$ $\quad$ $12.5\ mm^2$

For irradiation study

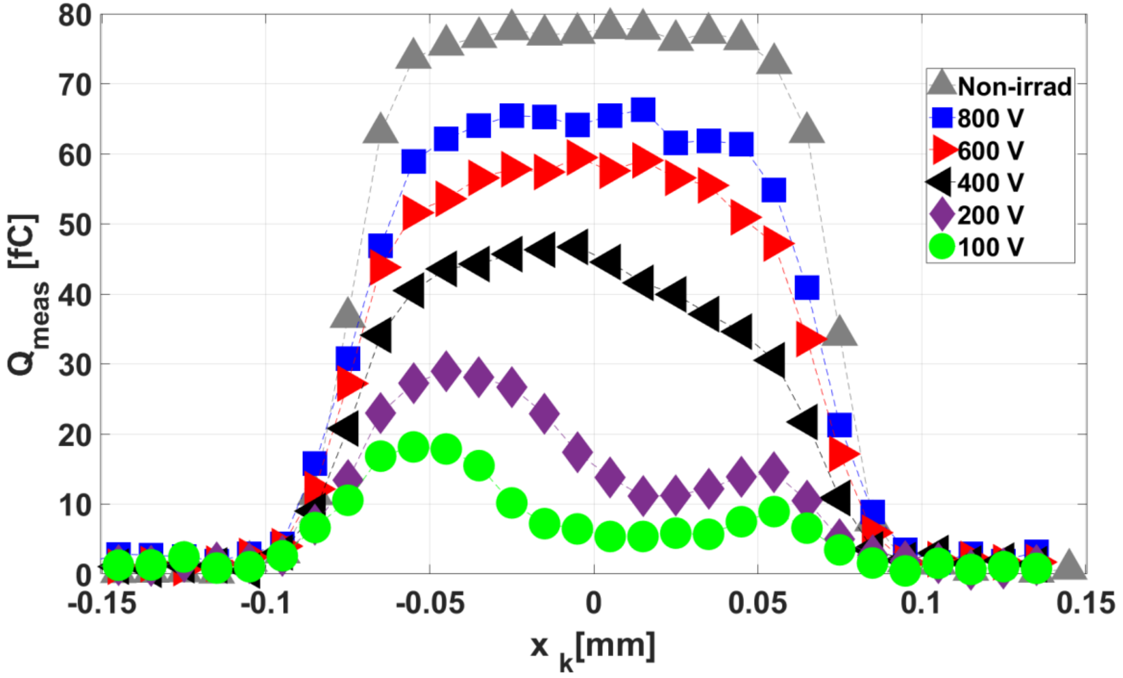
- Irradiation with 23 MeV protons at Karlsruhe Institute of Technology (KIT)
- Irradiation to 1 MeV equivalent fluence $\Phi_{eq} = 2, 4, 8$ and $12 \times 10^{15}\ cm^{-2}$ (hardness factor of $\kappa = 2.2$)

Measurement results

$\Phi_{eq} = 2 \times 10^{15} \mathrm{cm}^{-2}$

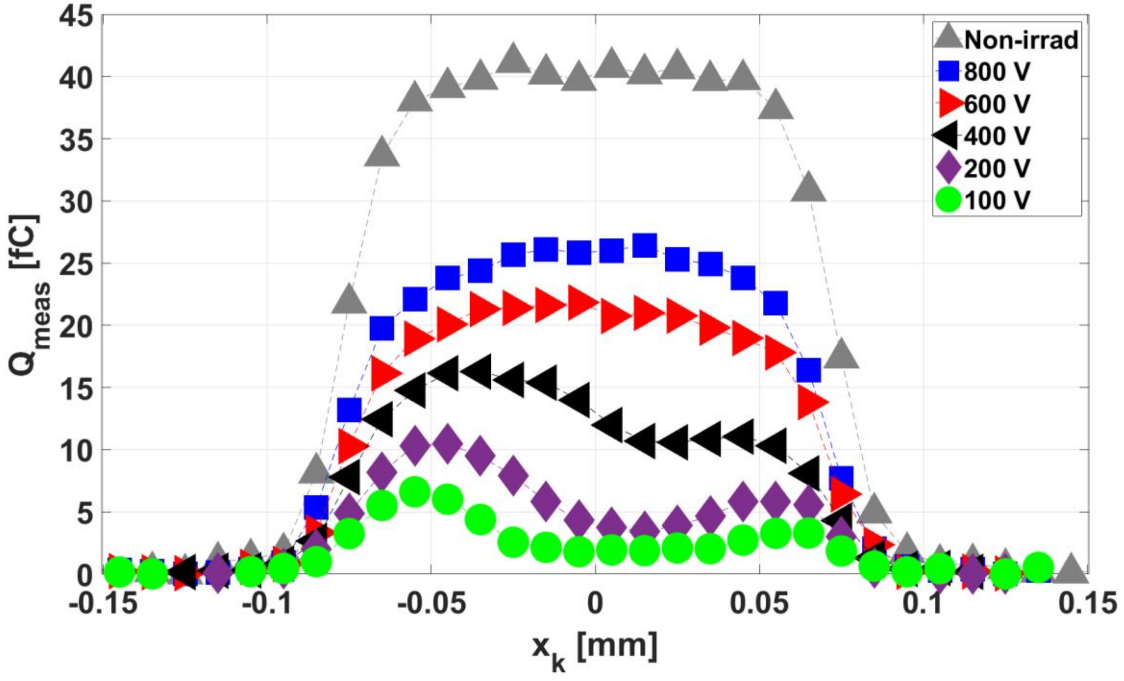


$\Phi_{eq} = 4 \times 10^{15} \mathrm{cm}^{-2}$

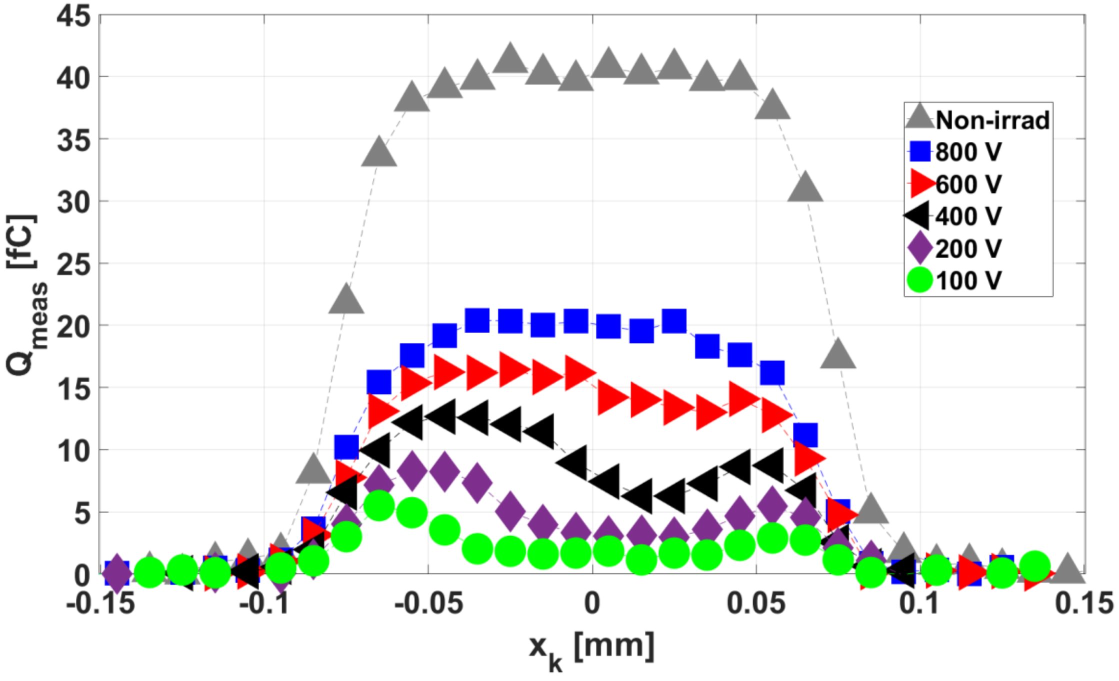


Measurement results

$\Phi_{eq} = 8 \times 10^{15} \mathrm{cm}^{-2}$



$\Phi_{eq} = 12 \times 10^{15} \mathrm{cm}^{-2}$



Hamburg Penta Trap Model

The model is optimized to describe the following experimental data:

- Capacitance versus Voltage (CV)
- Current versus Voltage (IV)
- Charge Collection Efficiency (CCE) versus Voltage

The data are taken for pad diodes:

- Active thickness: 200 µm
- Irradiation with 24 GeV protons at CERN PS facility
- Irradiation to equivalent fluence $\Phi_{eq} = 0.3, 1, 3, 6, 8, 13 \times 10^{15}\ \mathrm{cm}^{-2}$

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

i: measurement types
j: fluences

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

$g_{int}, \sigma_e, \sigma_h$: free parameters
g_{int}: introduction rate

The paper can be found Here

Perugia 2019 Model

The model is optimized to describe the following experimental data:

- Charge Collection Efficiency (CCE) with ^{90}Sr source

The data are taken for PiN diodes and strip sensors:

- Irradiation with 26 MeV protons
- Irradiation to equivalent fluence up to 2.2×10^{16} cm^{-2}

Trap Type	Energy (eV)	η (cm^{-1})	σ_e (cm^2)	σ_h (cm^2)
Donor	E_C-0.23	0.006	2.3×10^{-14}	2.3×10^{-15}
Acceptor	E_C-0.42	1.613	1.0×10^{-15}	1.0×10^{-14}
Acceptor	E_C-0.46	0.900	7.0×10^{-15}	7.0×10^{-14}

η: introduction rate

The paper can be found Here

Perugia 2022 Model

The model is optimized to describe the following experimental data:

- IV and CV measurements

The data are taken for Low Gain Avalanche Diodes (LGADs):

- Irradiation to equivalent fluence up to 1.0×10^{16} cm^{-2}

Defect number	Type	Energy level	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
1	Donor	$E_C - 0.23$ eV	2.3e-14	2.3e-15	0.015
2	Acceptor	$E_C - 0.42$ eV	1.0e-15	1.0e-14	10
3	Acceptor	$E_C - 0.46$ eV	4.0e-14	4.0e-13	1.2

η: introduction rate

The paper can be found Here

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Charge collection profiles

RD50

The charge collection profiles are convolution of:

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

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

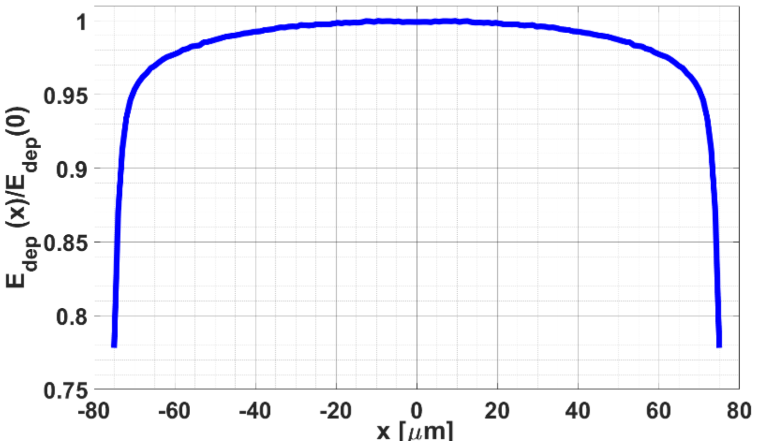
$$CCE_{tot}(x) = CCE_e(x) + CCE_h(x)$$

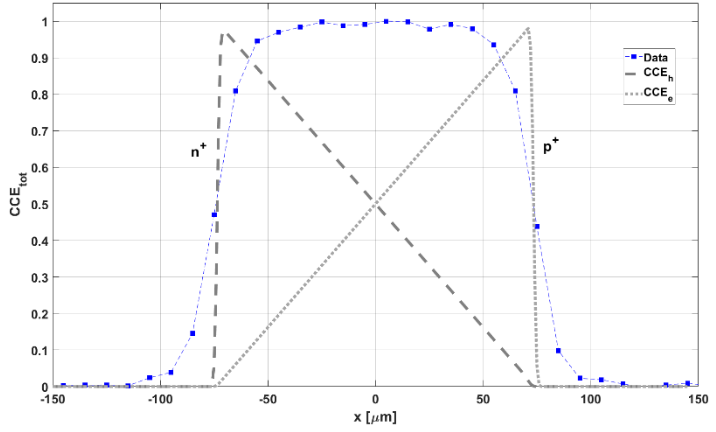
$$CCE_e(x) = \int_{-\frac{d}{2}}^{x} E_w(y) \cdot \exp\left(\int_{x}^{y} \frac{dy'}{\lambda_e(y')} \right) dy$$

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

$$E_w(x) = \frac{1}{d}$$

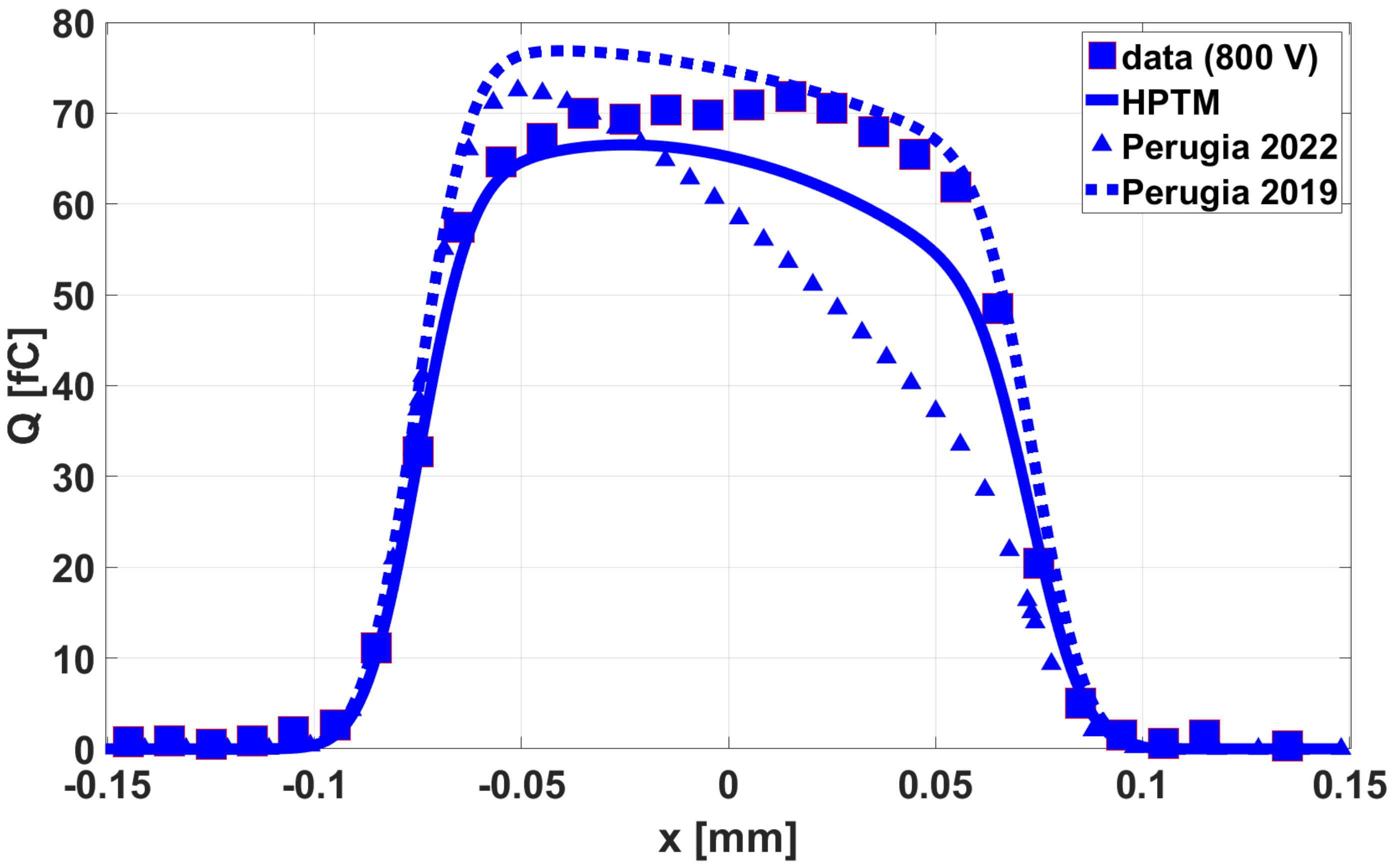
- $\lambda_{e,h}$ (x): charge collection length of electrons and holes from the models
- d: thickness of the diode (150 μm)
- A: scaling factor (76.8 for pad size of 25 mm^2 and 76.8 for pad size of 12.5 mm^2)
- σ_{res}: beam resolution (10 μm)





Comparison with simulation results

$$\Phi_{eq} = 2 \times 10^{15}\ \mathrm{cm}^{-2}$$



Comparison with simulation results

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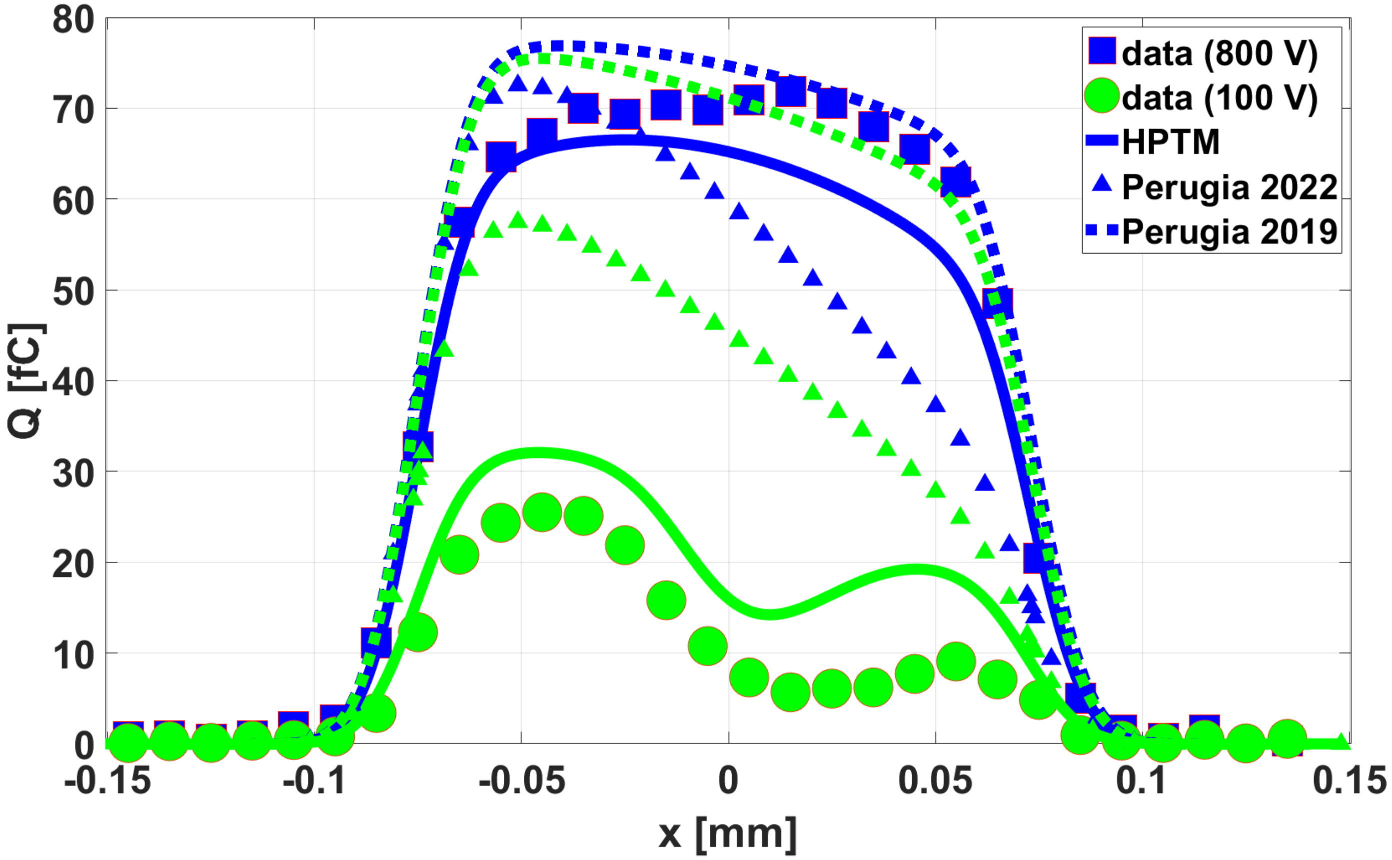
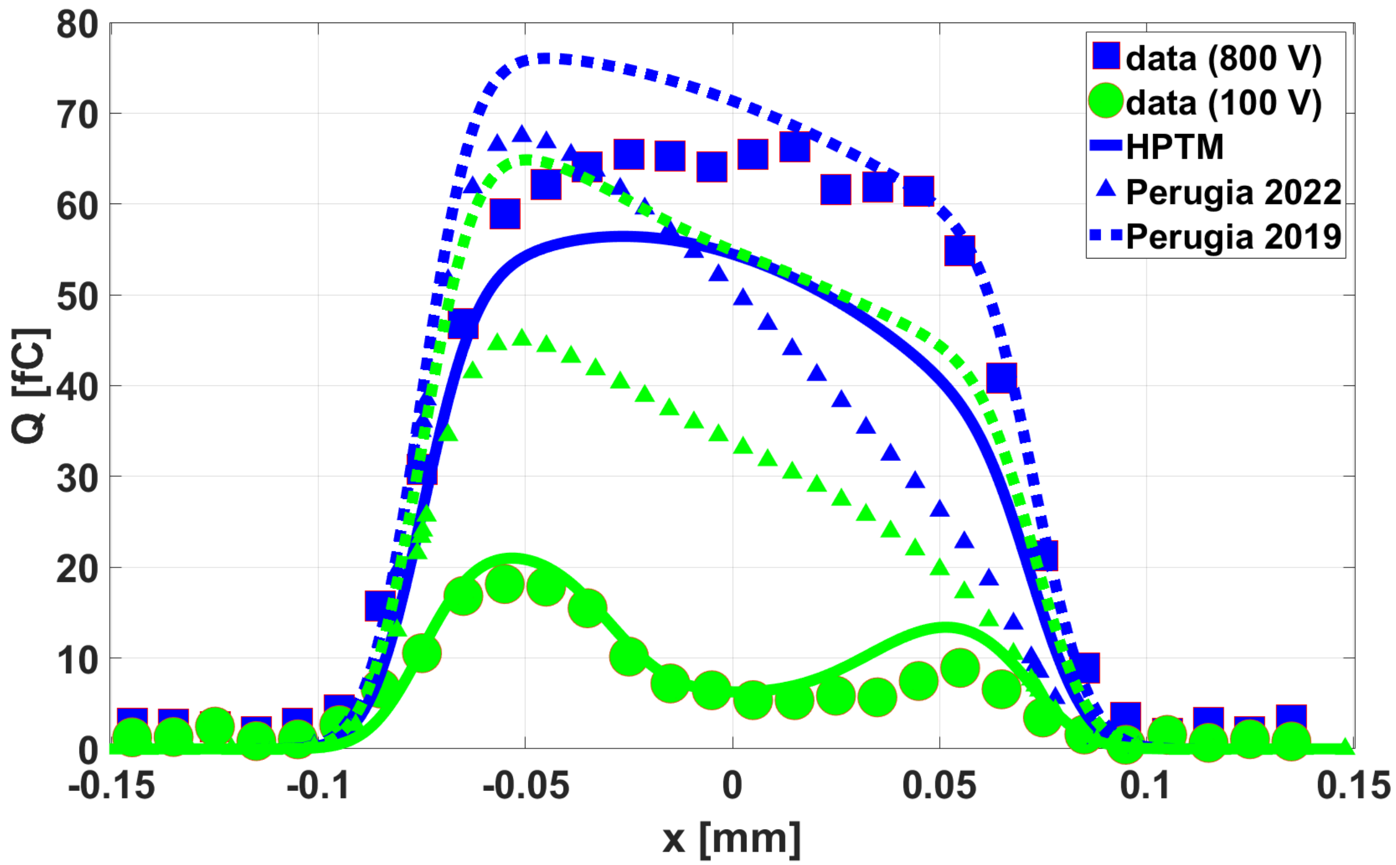


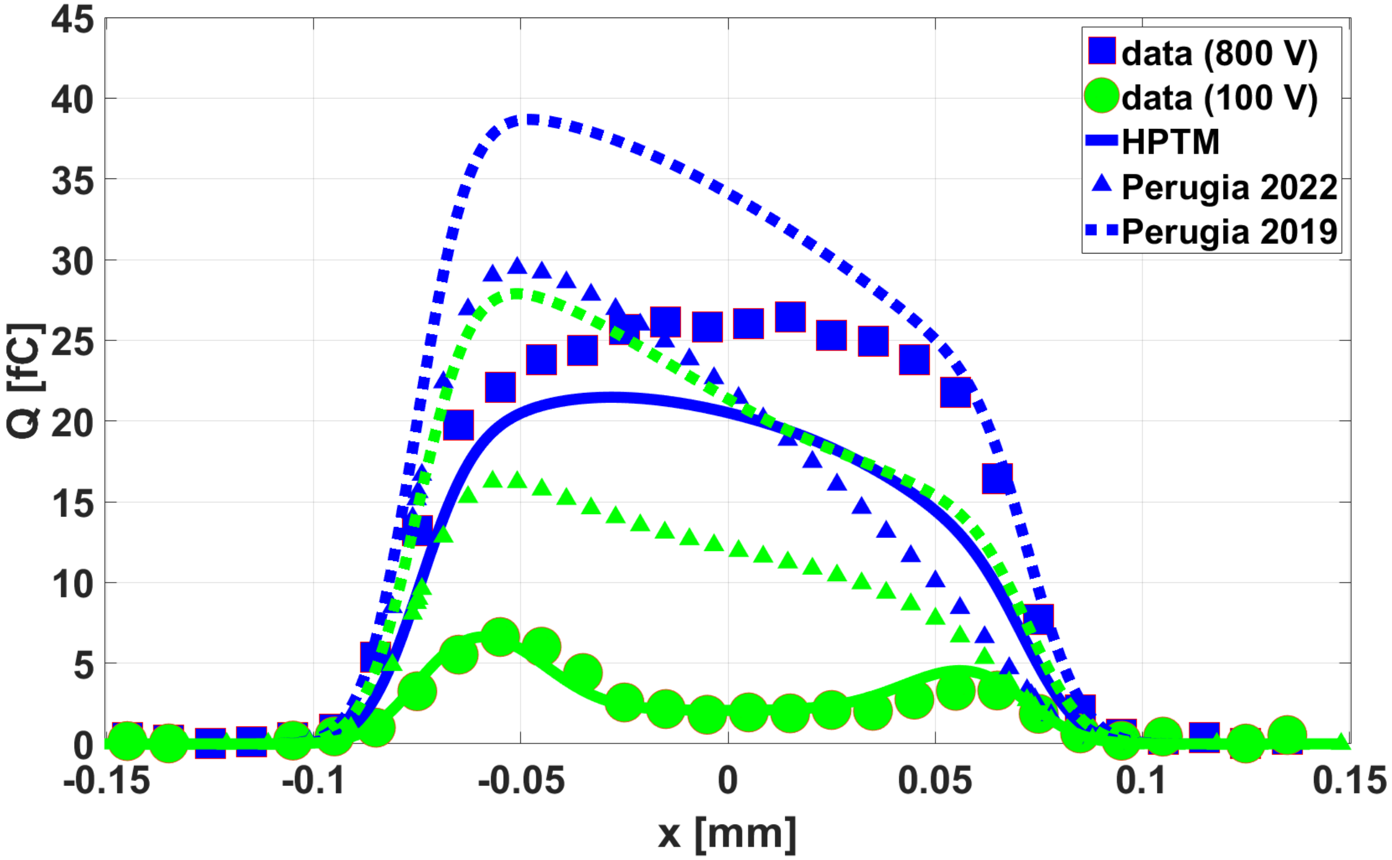
Comparison with simulation results

$$\Phi_{eq} = 4 \times 10^{15}\ \text{cm}^{-2}$$



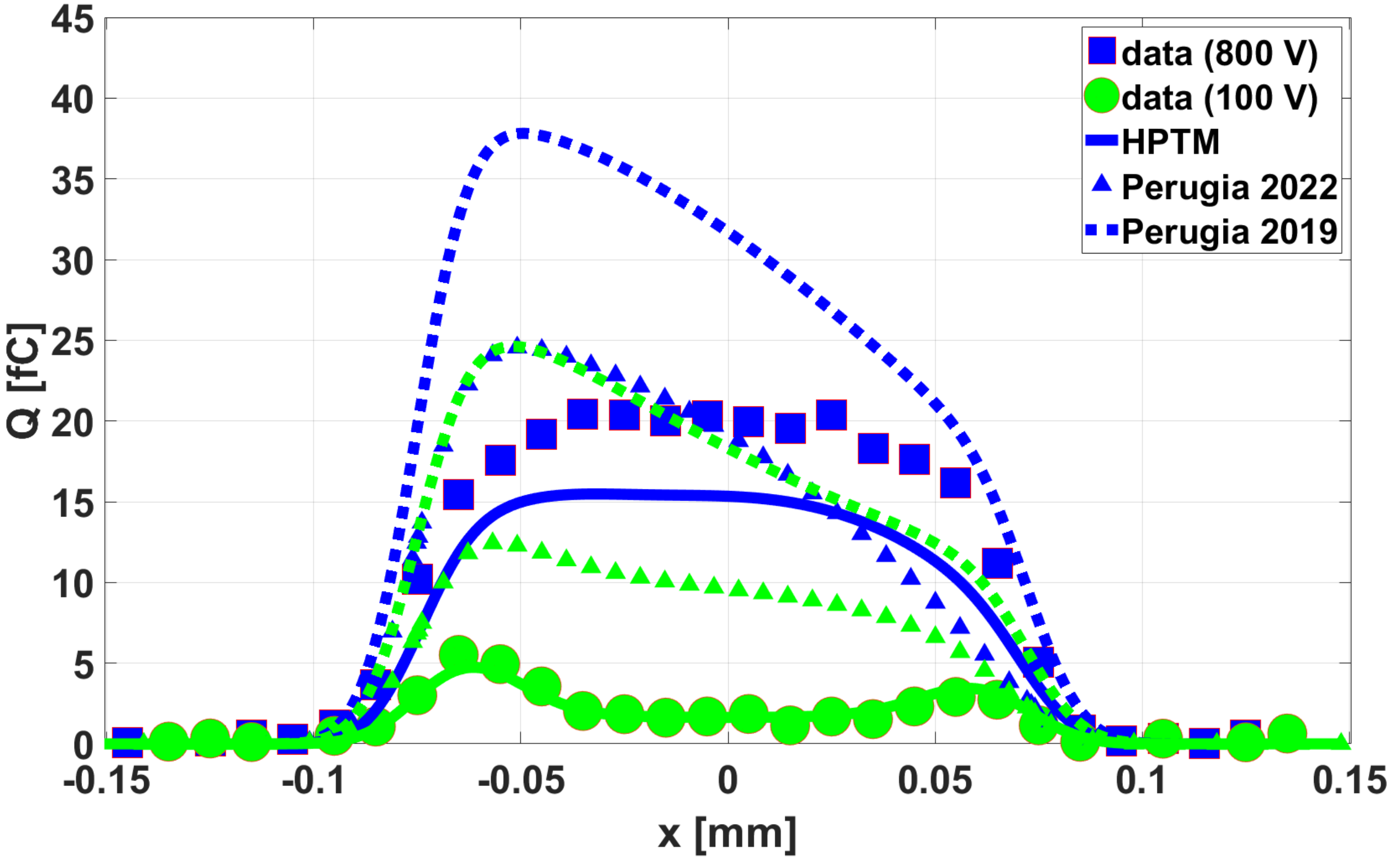
Comparison with simulation results

$$\Phi_{eq} = 8 \times 10^{15}\ \mathrm{cm}^{-2}$$



Comparison with simulation results

$$\Phi_{eq} = 12 \times 10^{15}\ \mathrm{cm}^{-2}$$



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Unfolding of charge collection profiles

Unfolding the measurements with respect to experimental effects:

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

$$CCE_{spl}(x) = spline\left(CCE_{x_i}\right), x_i = -65, -45, -25, -5, +15, +35, +55\ \mu m$$

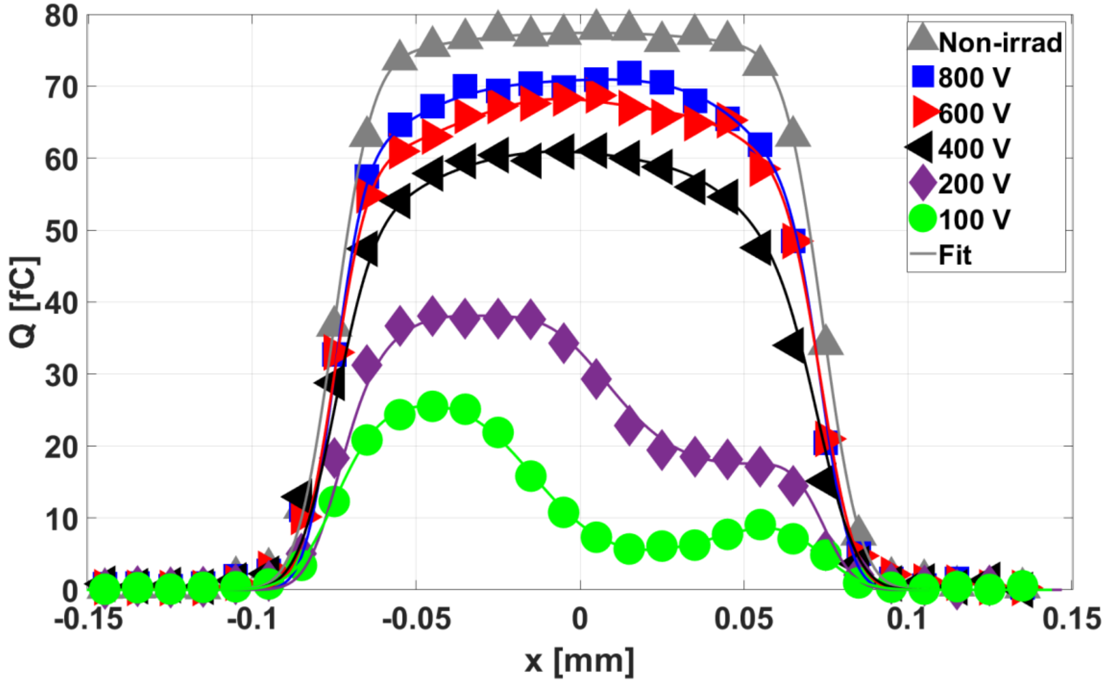
Minimizing the following function by taking CCE_{x_i} as free parameters:

$$D^2 = \sum_k \left(Q_{meas}(x_k) - Q_{sm}(x_k + \Delta x_{tr})\right)^2 + w_{pen} \sum_{i=2}^{6} \left(\frac{0.5\left(CCE_{x_{i+1}} + CCE_{x_{i-1}}\right) - CCE_{x_i}}{\Delta x} \right)^2$$

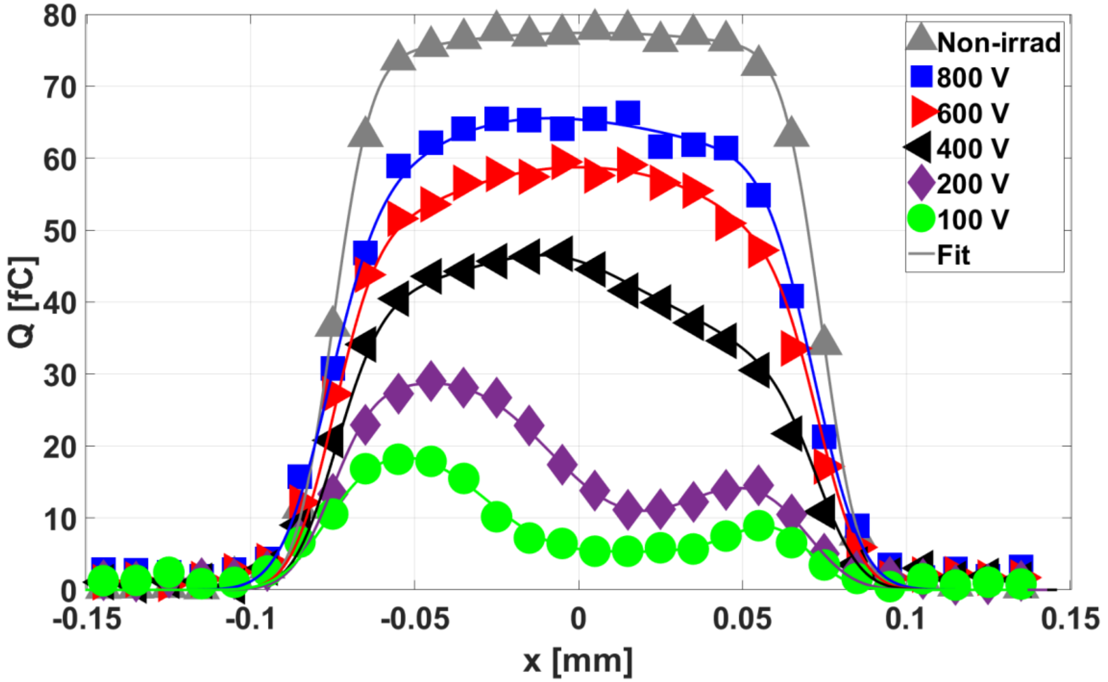
- A: scaling factor (76.8 for pad size of 25 mm^2 and 76.8 for pad size of 12.5 mm^2)
- Δx: distance between two adjacent points: 20 µm
- Δx_{tr}: shift due the transformation from test-beam coordinate to the sensor coordinate system

Comparison with fit results

$\Phi_{eq} = 2 \times 10^{15} \mathrm{cm}^{-2}$

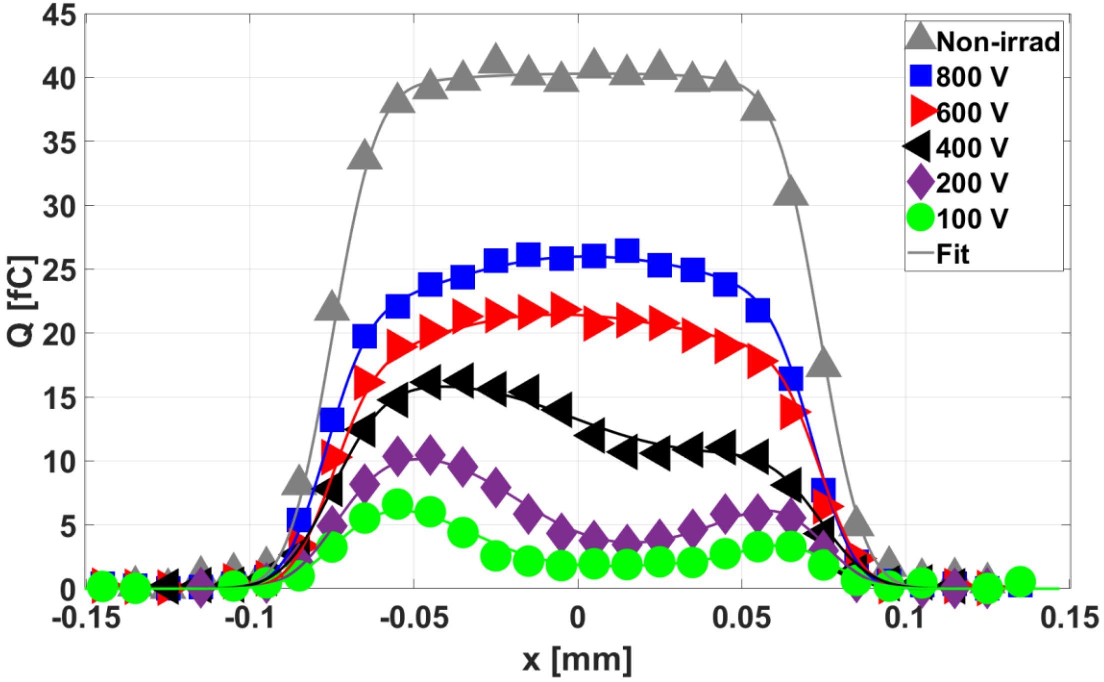


$\Phi_{eq} = 4 \times 10^{15} \mathrm{cm}^{-2}$

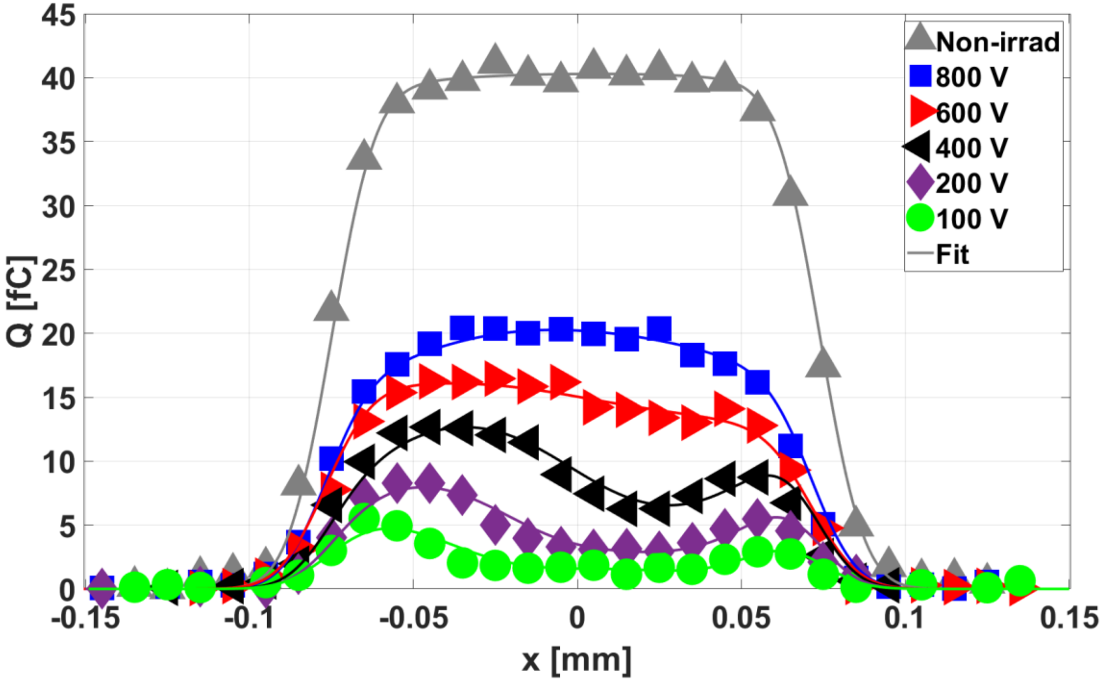


Comparison with fit results

$\Phi_{eq} = 8 \times 10^{15} cm^{-2}$

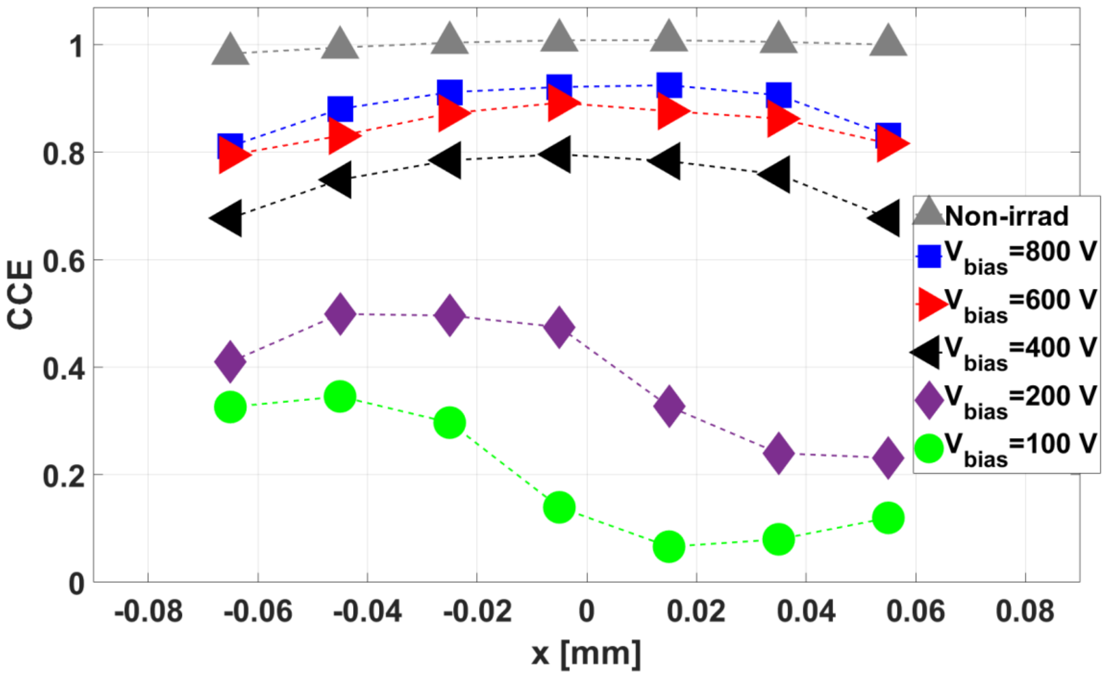


$\Phi_{eq} = 12 \times 10^{15} cm^{-2}$

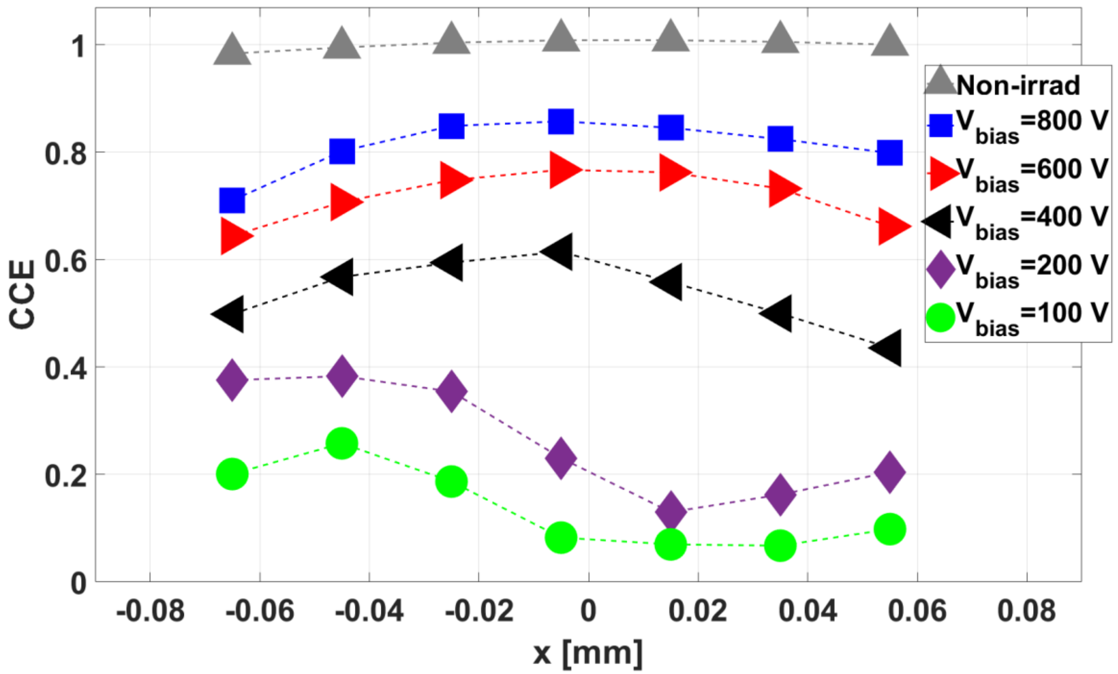


CCE as a function of depth

$\Phi_{eq} = 2 \times 10^{15} \text{cm}^{-2}$



$\Phi_{eq} = 4 \times 10^{15} \text{cm}^{-2}$



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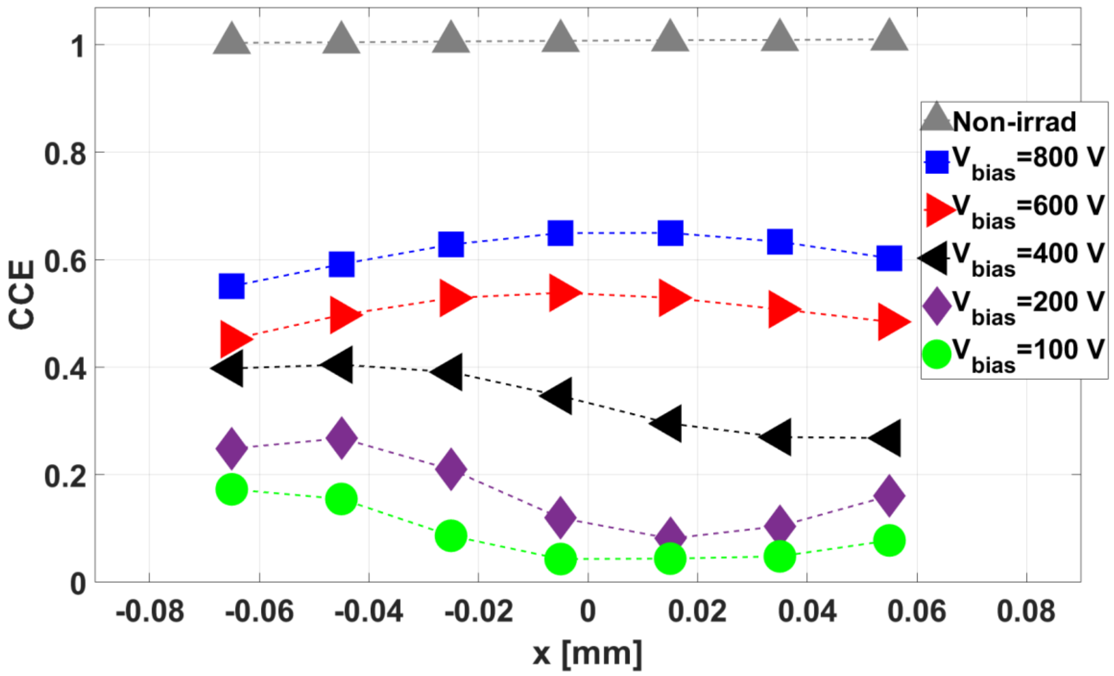
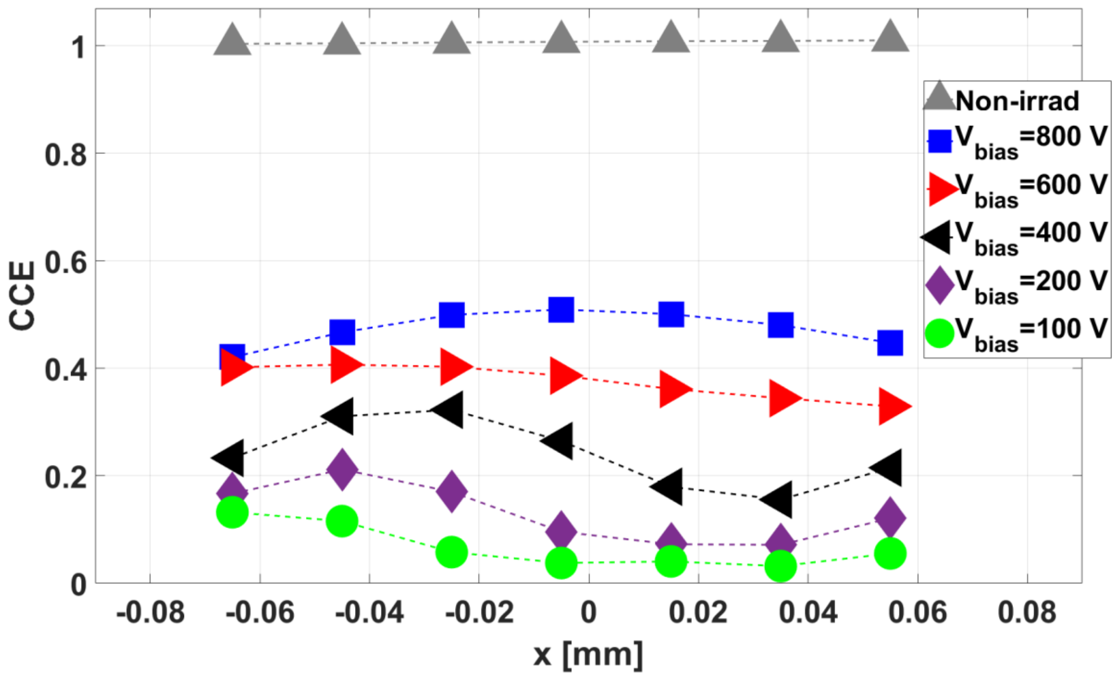
CCE as a function of depth

$\Phi_{eq} = 8 \times 10^{15} cm^{-2}$



$\Phi_{eq} = 12 \times 10^{15} cm^{-2}$



Summary and Conclusions

- Charge collection profiles of irradiated and non-irradiated diodes were measured.
- The data have been corrected for experimental effects: finite beam resolution and transverse energy leakage.
- These results provide a precise determination of the position dependence of the charge collection in radiation-damaged diodes.
- The precise CCE data can be used to tune and test radiation damage models.
- The procedure of comparing data to radiation damage models has been demonstrated for 3 models: HPTM and two Perugia models.

Back up
Charge distribution, non-irradiated diode

Measurement conditions:

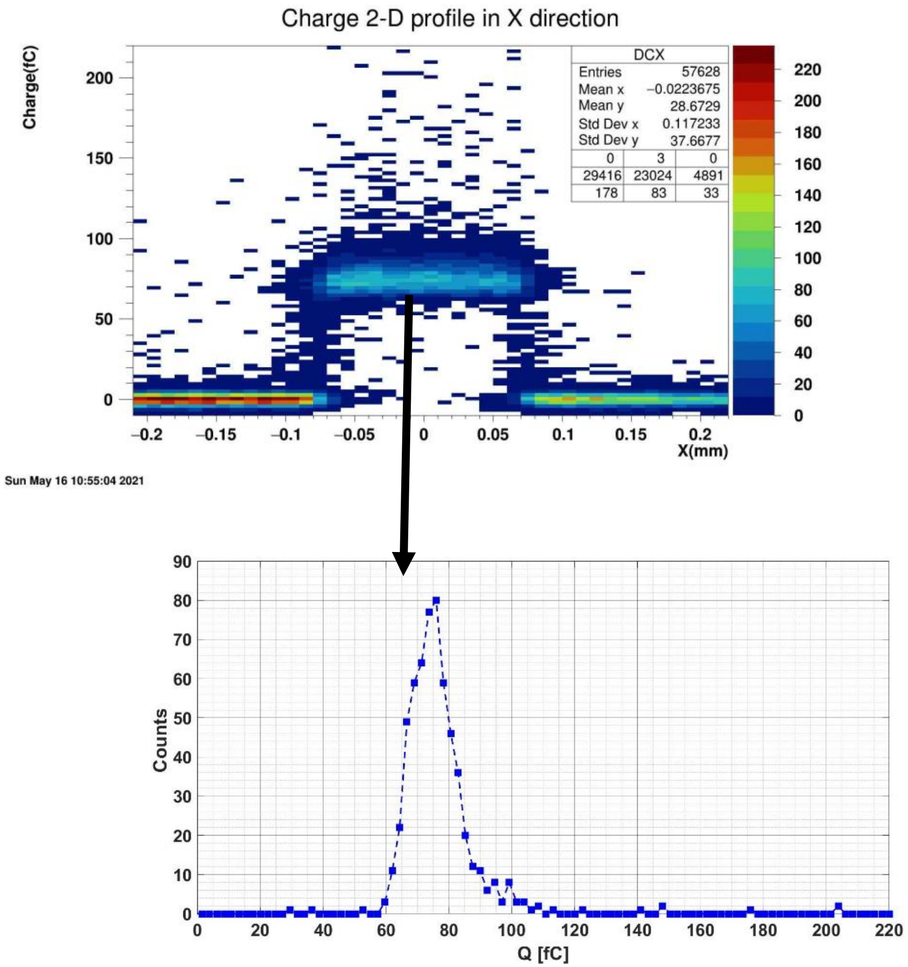
- Room temperature
- $V_{bias} = 120$ V
- θ : 0°
- $E_{beam} = 5.2$ GeV
- Beam divergence: ±1 mrad

Observations:

- In the central region of the diode (i.e. 0.07 mm < X < 0.07 mm)

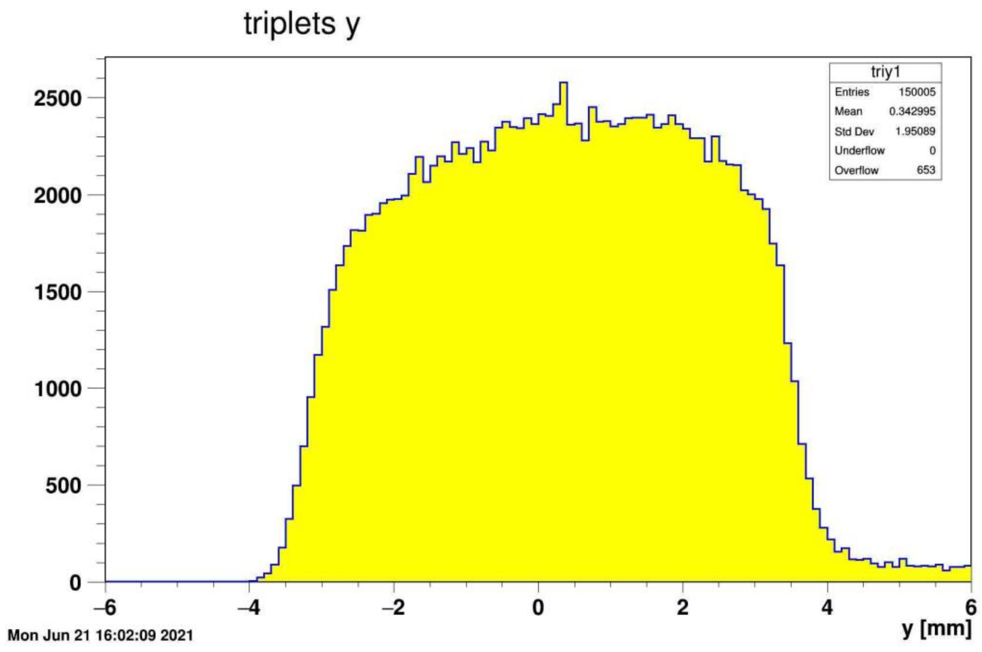
the collected charge is well above the noise level

- Data taking without zero suppression enables us measuring very low charges (relevant for irradiated diodes)

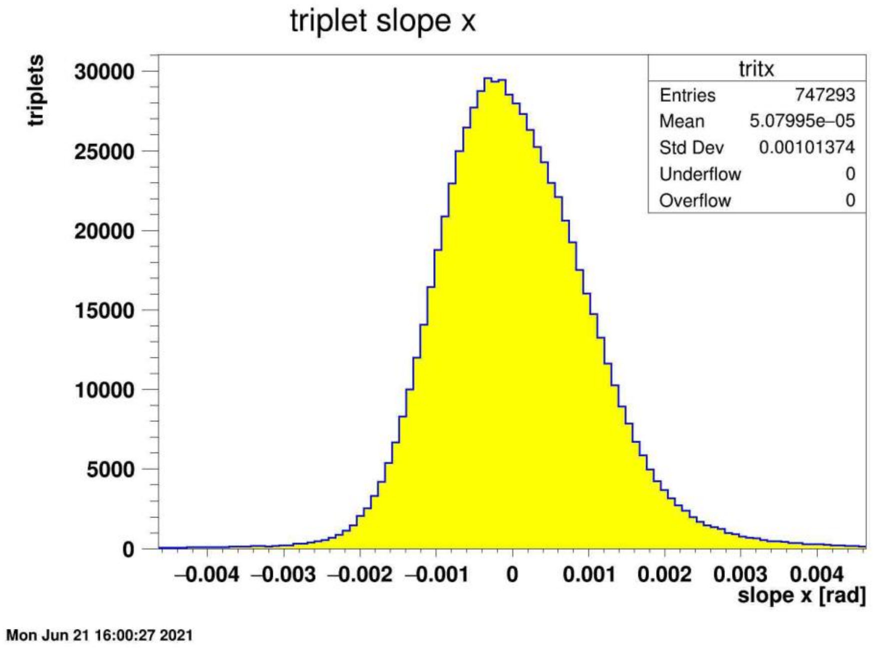


Back up
Geometrical cuts

$|y_{dut}| < 2.0$ mm

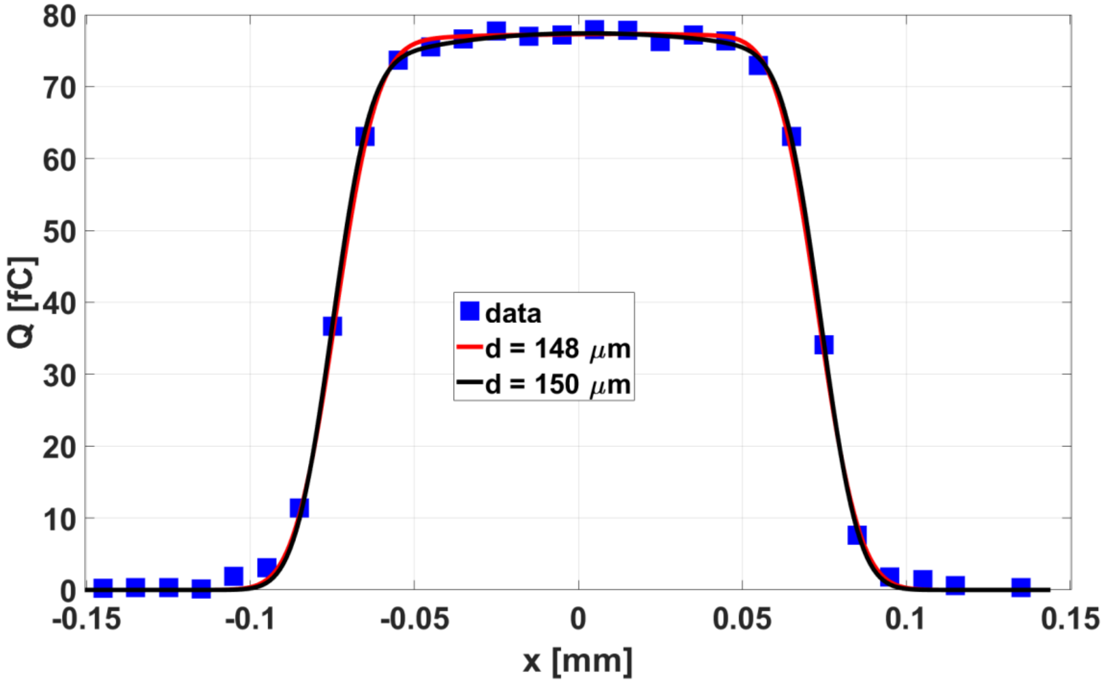


$|\theta_x| < 1$ mrad

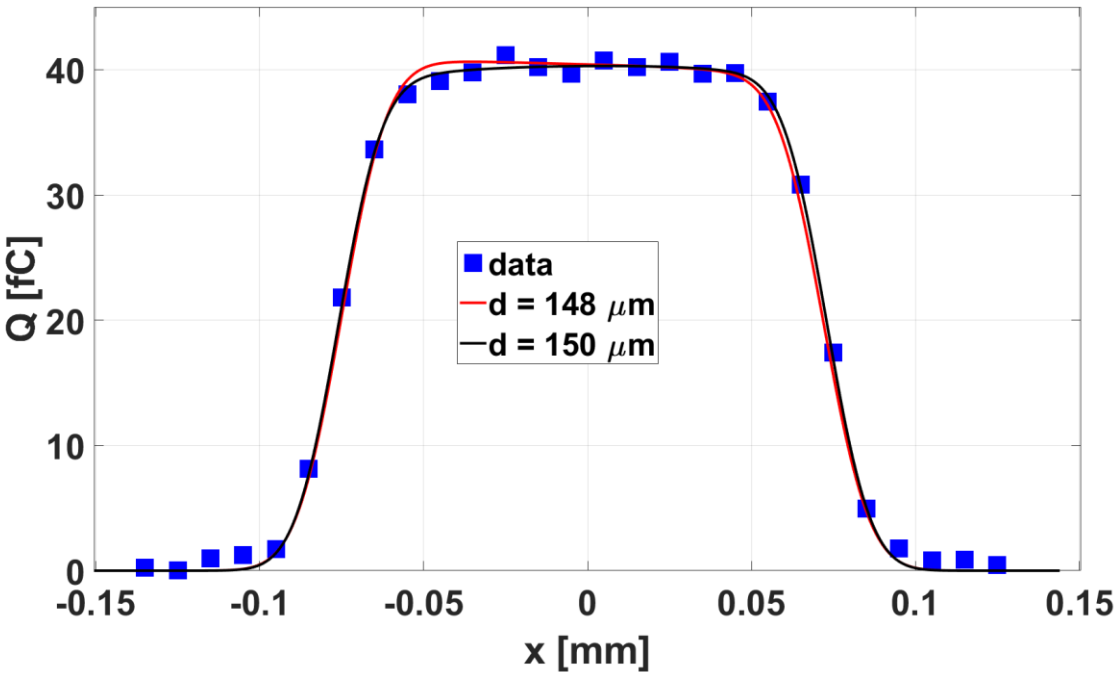


Back up
Extracted CCE for different thicknesses

$5 \times 5\ mm^2$



$2.5 \times 2.5\ mm^2$



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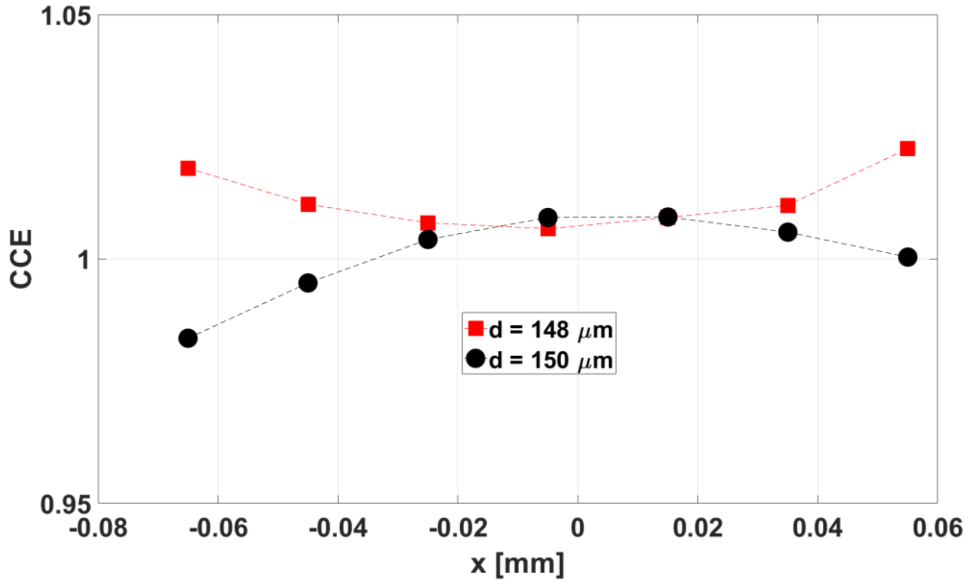

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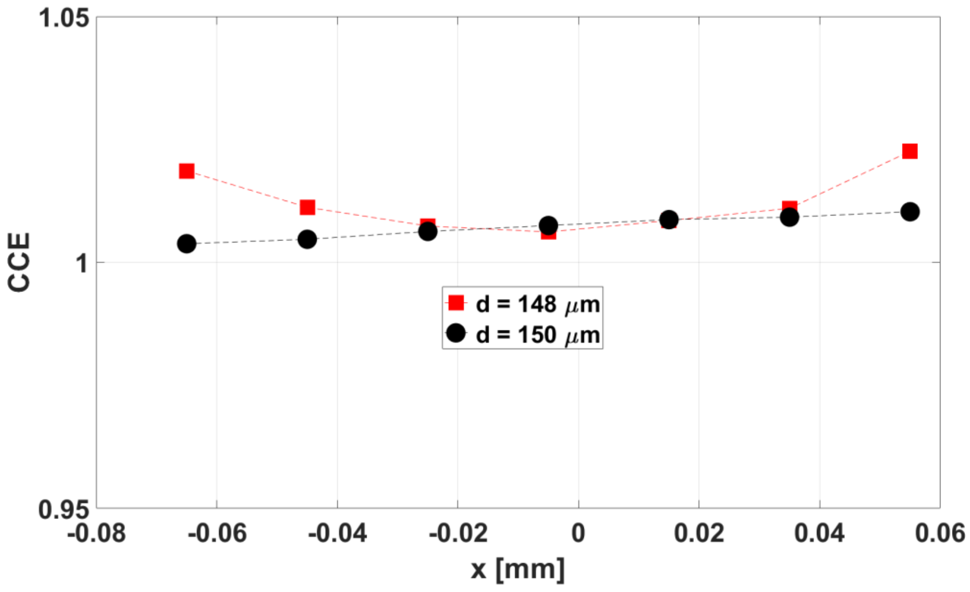
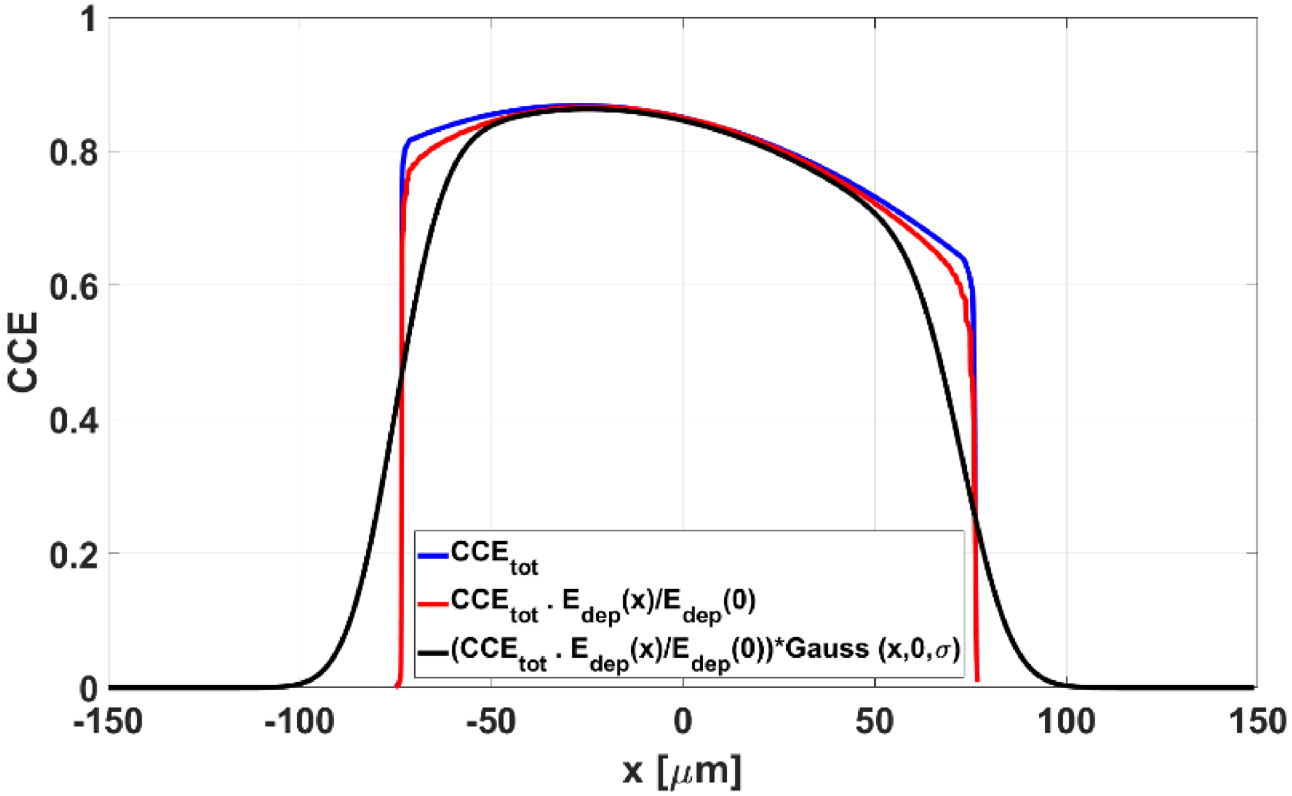


Back up
GEANT4 simulation result



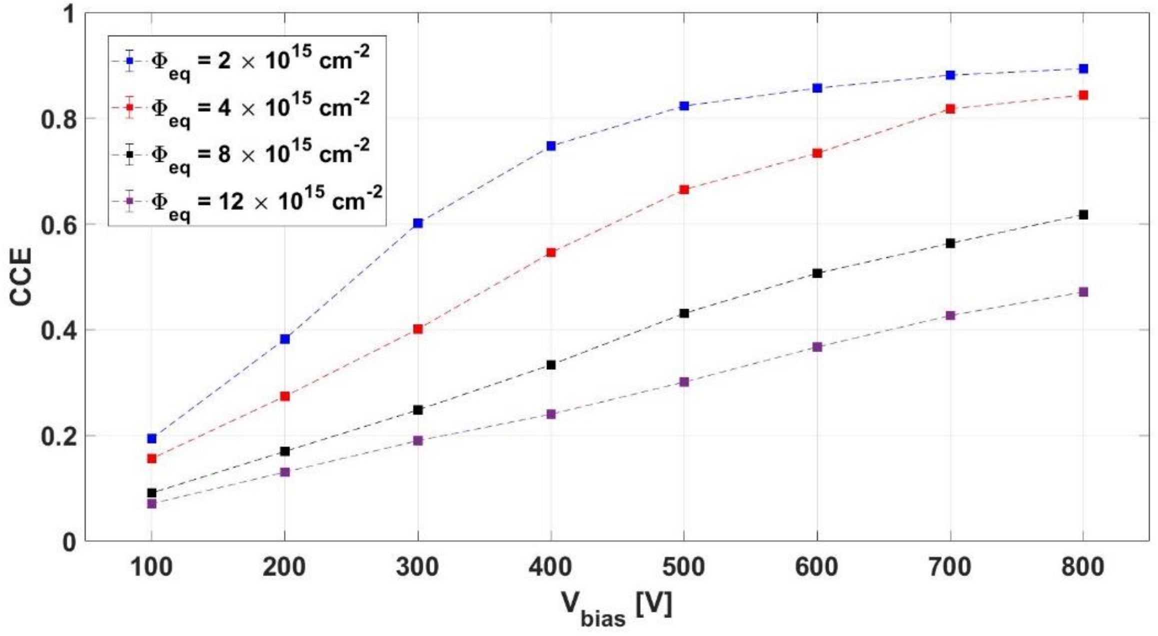
Back up
CCE as a function of bias voltage

Measurement conditions:

- Temperature: -20 C
- $V_{bias} = 100 - 800$ V

DUTs:

- Proton irradiated at $\Phi_{eq} = 2, 4, 8, 12 \times 10^{15}$ cm^{-2}



CCE is calculated as:

$$\mathrm{CCE}(V_{bias}) = \frac{\sum_{x=-150\ \mu m}^{+150\ \mu m} Q_{x,irradaited}(V_{bias})}{\sum_{x=-150\ \mu m}^{+150\ \mu m} Q_{x,non-irradaited}}$$