Radiation hardness studies of proton and neutron irradiated HVCMOS

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Overview

Introduction, setup and samples
TCT waveforms
Charge profiles
Collected charge
Depletion width
Effective space charge

- Neutron-only measurements (see: M. Fernandez et al., 26th RD50 meeting Santander) have been complemented by proton irradiated samples and additional analysis in this presentation

See also: M. Fernandez et al., "*Radiation hardness studies of neutron irradiated CMOS sensors fabricated in the ams H18 high voltage process*", **Nov. 2015**, submitted to JINST

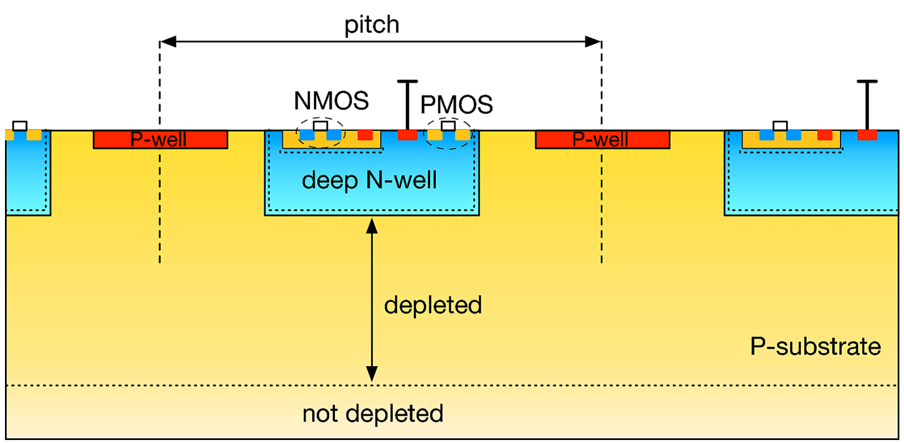
HVCMOS

• HVCMOS use **commercial** high-voltage CMOS technology as sensors on a **low resistivity substrate** (≤120V, ρ~10 Ω ·cm).

Expected **10 µm depletion at 100 V** → Charge can be collected **by drift.**
Expected **900 e-h pairs** → built-in **preamp** is needed.

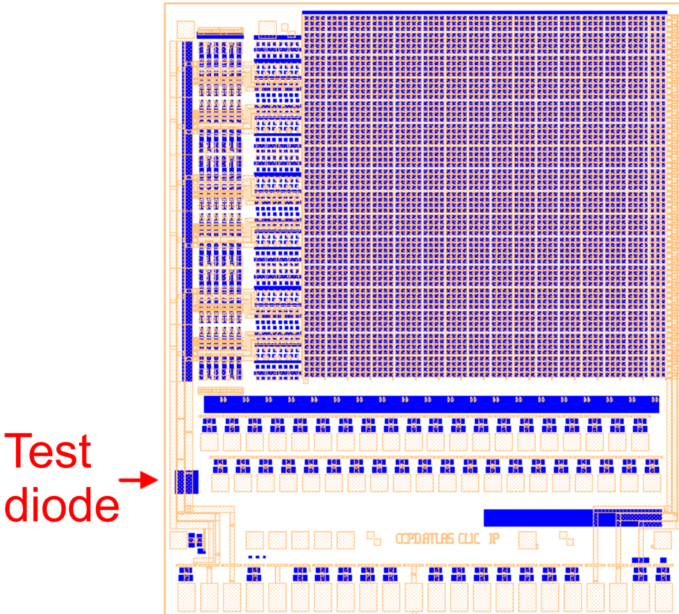
• To avoid damage to transistors both, **NMOS and PMOS** are **"embedded"** in a **Deep N Well (DNW)** . NMOS+PMOS ⇨ any complex signal processing can be implemented inside. The DNW works both as a substrate for transistors and as the signal collection region. **Nearly 100% fill factor:**

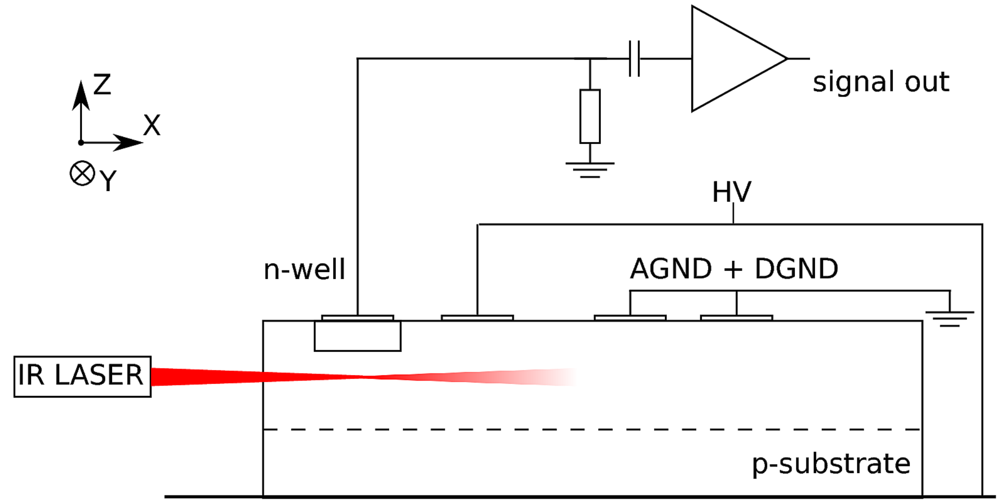
– Charge carriers do not have to travel long before being collected → **reduced trapping** impact.

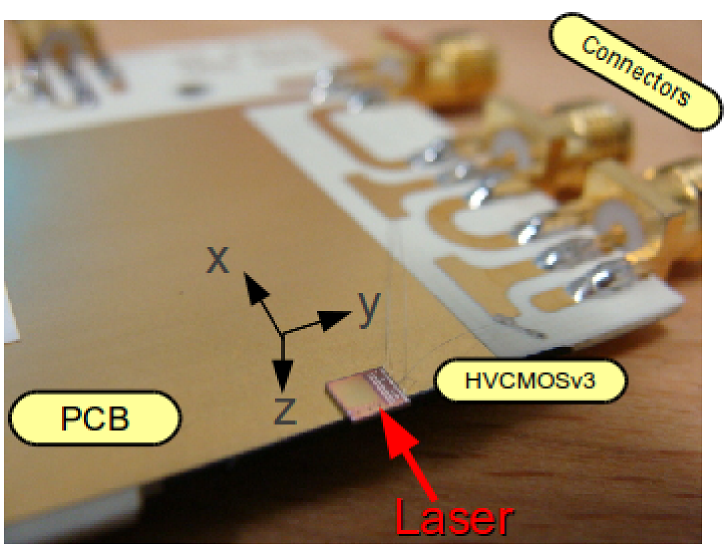


<u>In this presentation we study radiation hardness of test chips on the **ams H18 High Voltage CMOS** process.</u>

Setup and samples







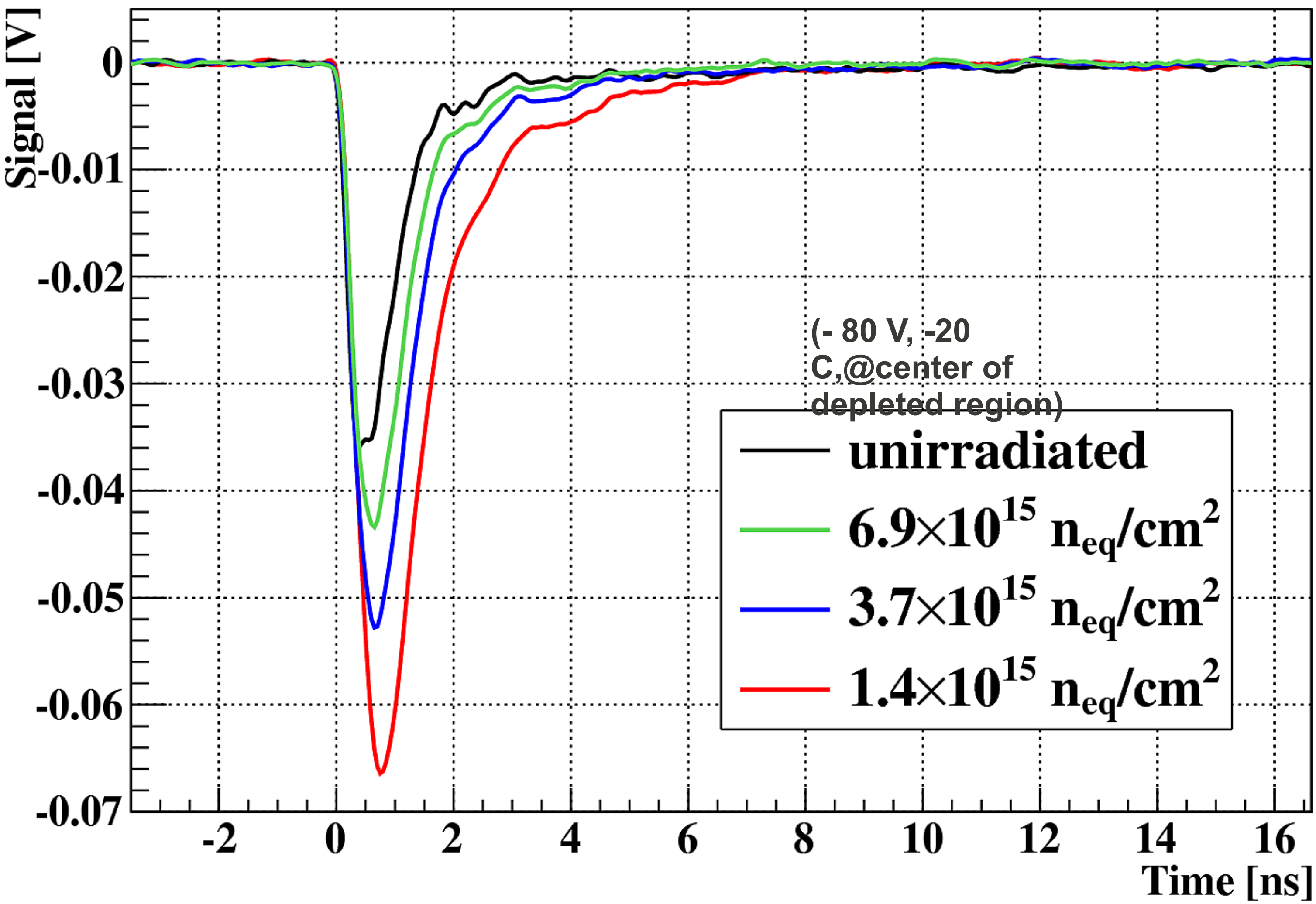
- Measurements at **CERN-SSD TCT+** setup. Edge-TCT configuration, 1064 nm (~200 ps), T = – 20 °C.
- Standalone **test diode** connected to amplifier (no NMOS or PMOS inside test diode).
- Detector glued to simple edge-TCT PCB using **conductive glue.**
- **1 detector per fluence**. **Three fluences** for neutrons, three for protons:

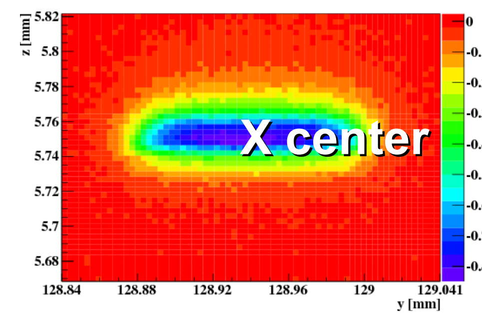
Neutron (Lbj)	1	7	20
Protons (PS)	1.4	3.7	6.9

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

Waveforms (protons)

- Higher **amplitude** and **collection time** (related to depletion depth) for **1.4 ×10^15 n_eq/cm^2**. Then decreasing for the 2 higher fluences.
- Both amplitude and t_{coll} are still **higher than the unirradiated** sample.
- **Charge** produced within space charge region is **collected** within **5 ns**.

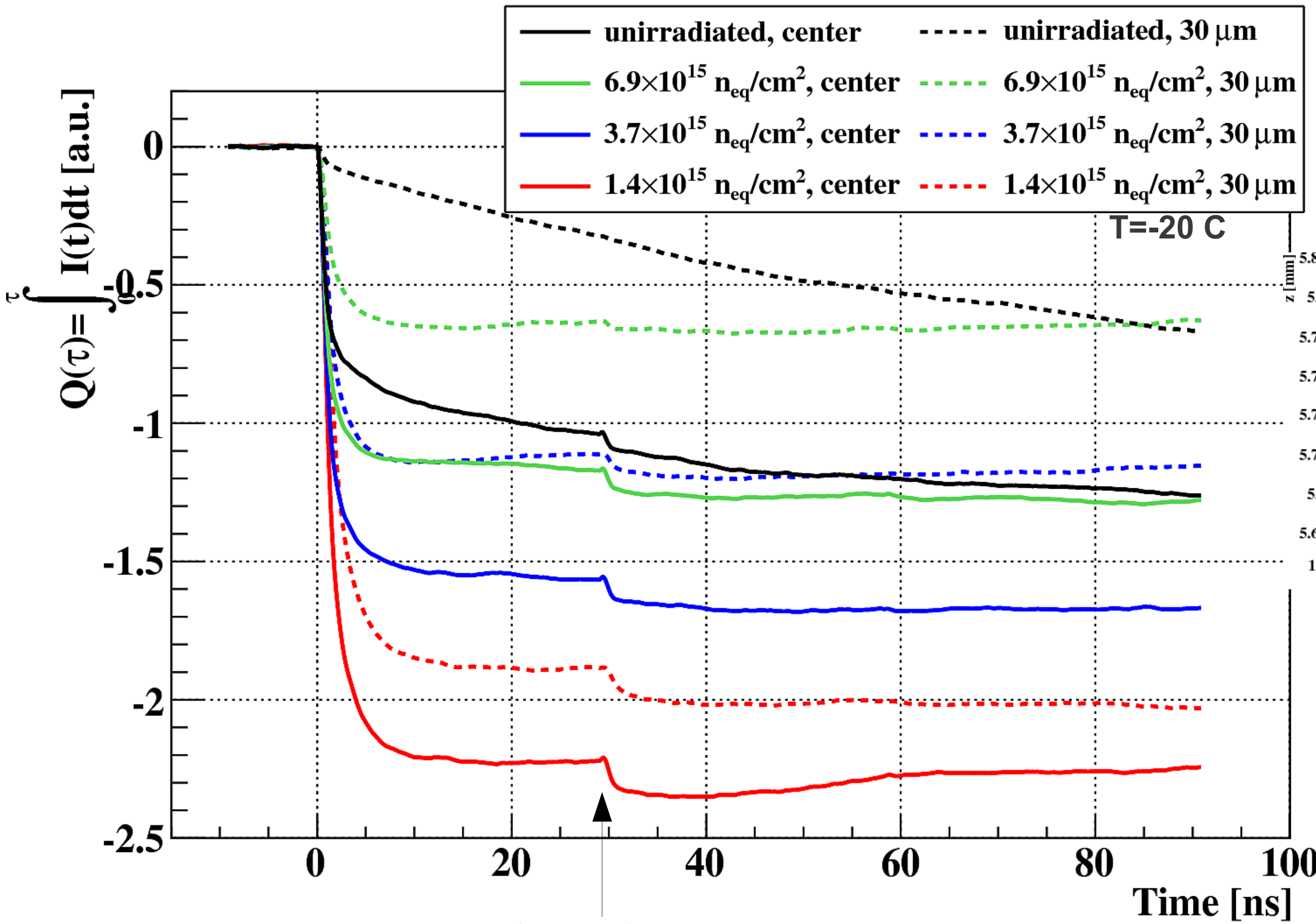


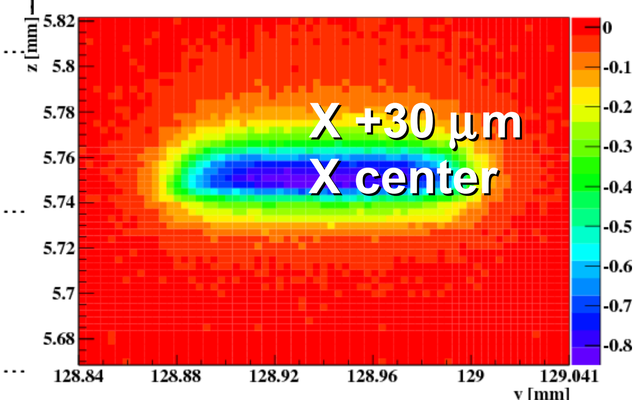


***2D scan** of the detector used to **locate** position of the diode*

Running charge: drift vs diffussion (protons)

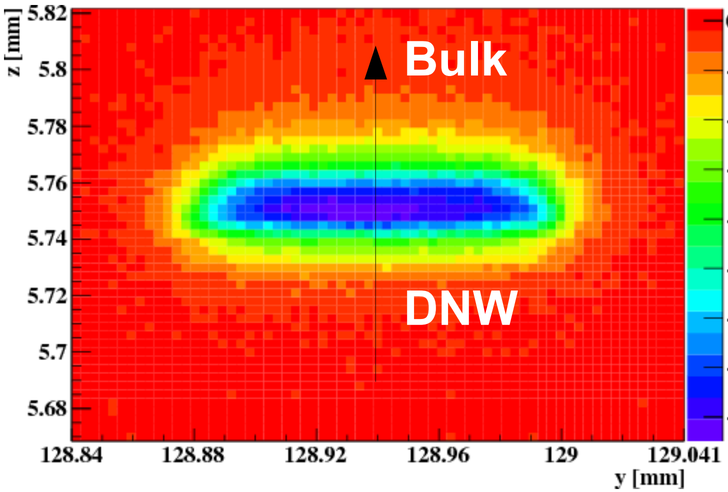
Unirradiated: quick "rise" (=**drift**), then slow accumulation (=**diffusion**)
Irradiated: quick rise, then constant. **No diffusion**



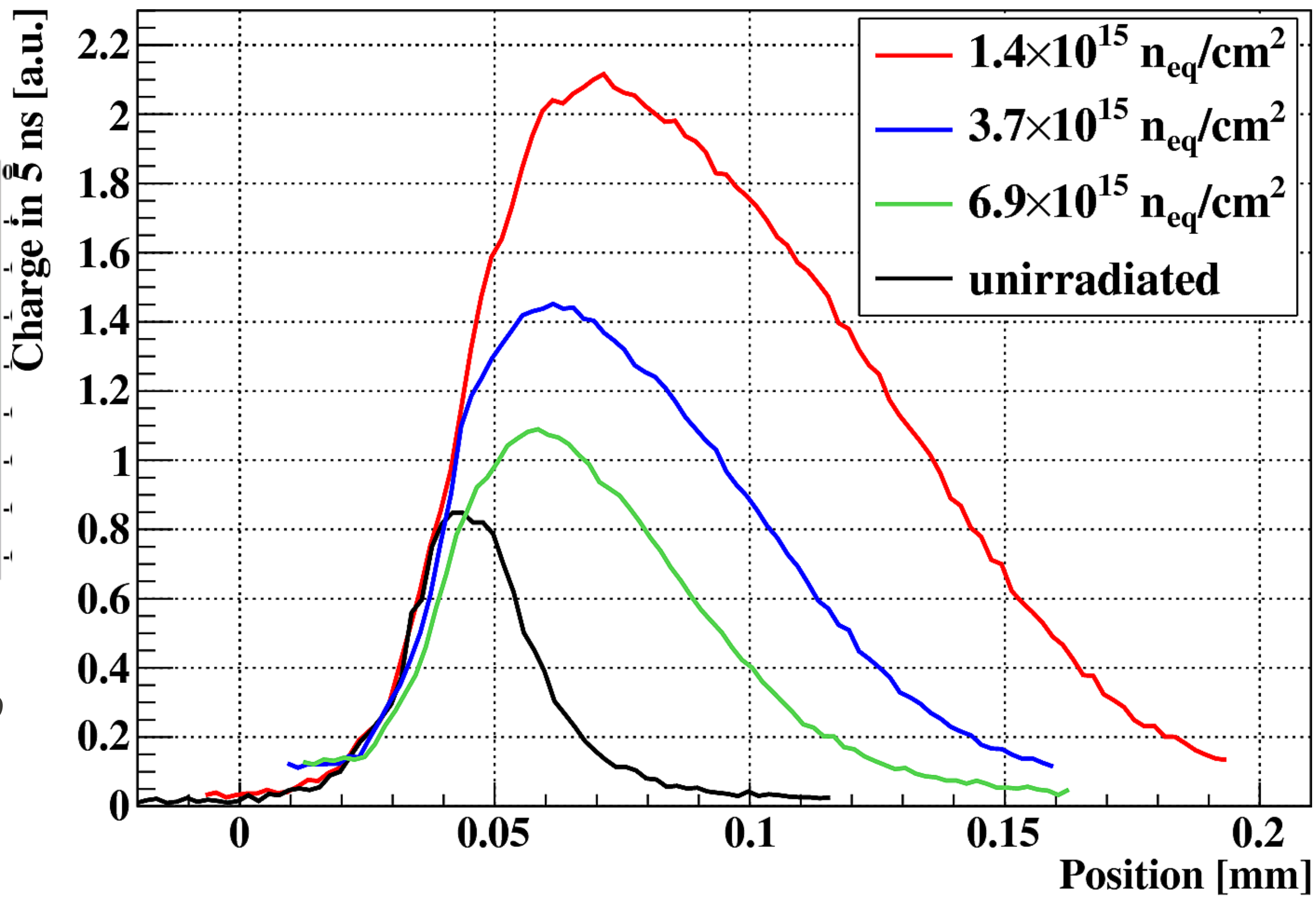


***2D scan** of the detector used to **locate** position of the diode*

Charge profiles Q(z) (protons)

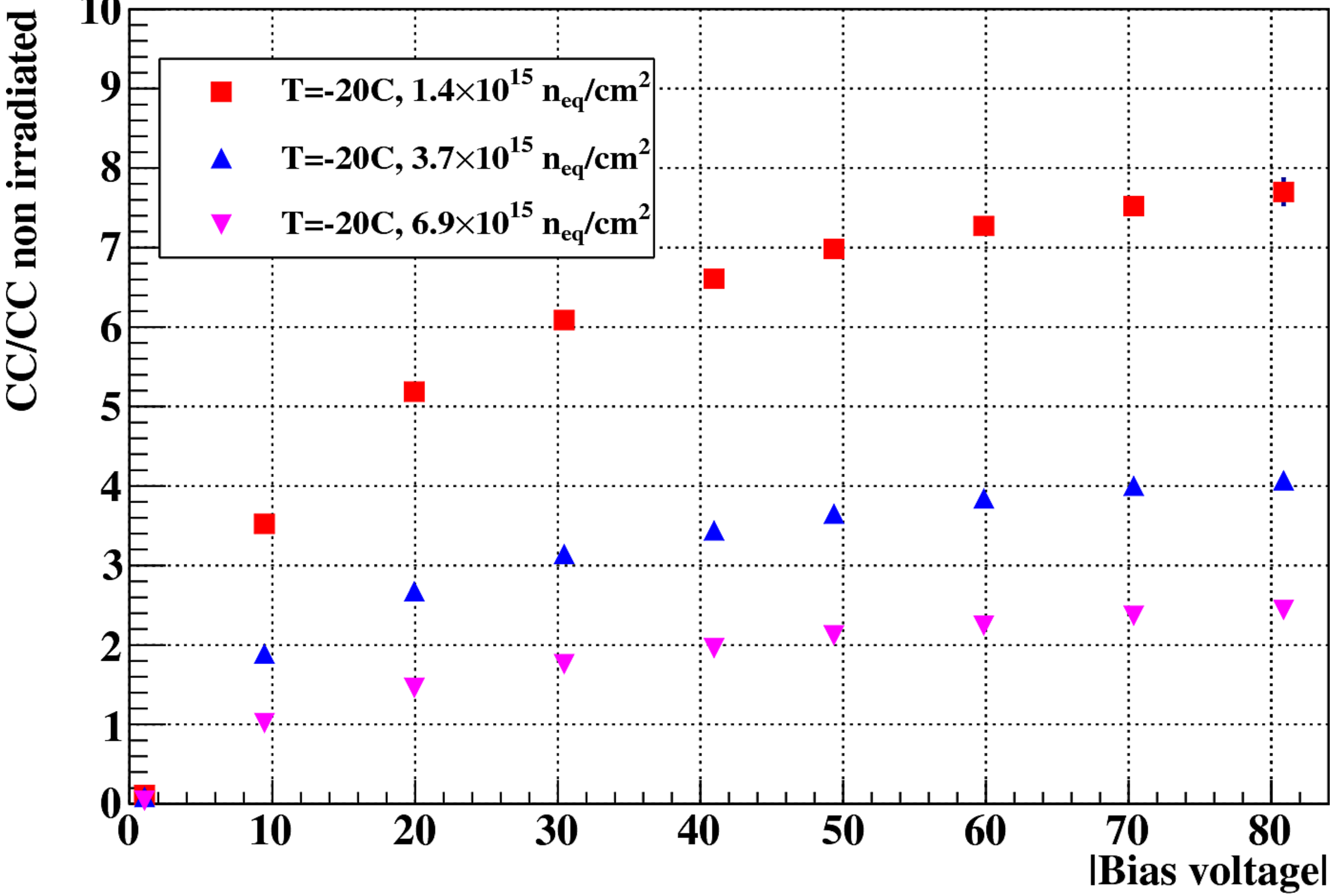


2D scan of the detector used to locate position of the diode



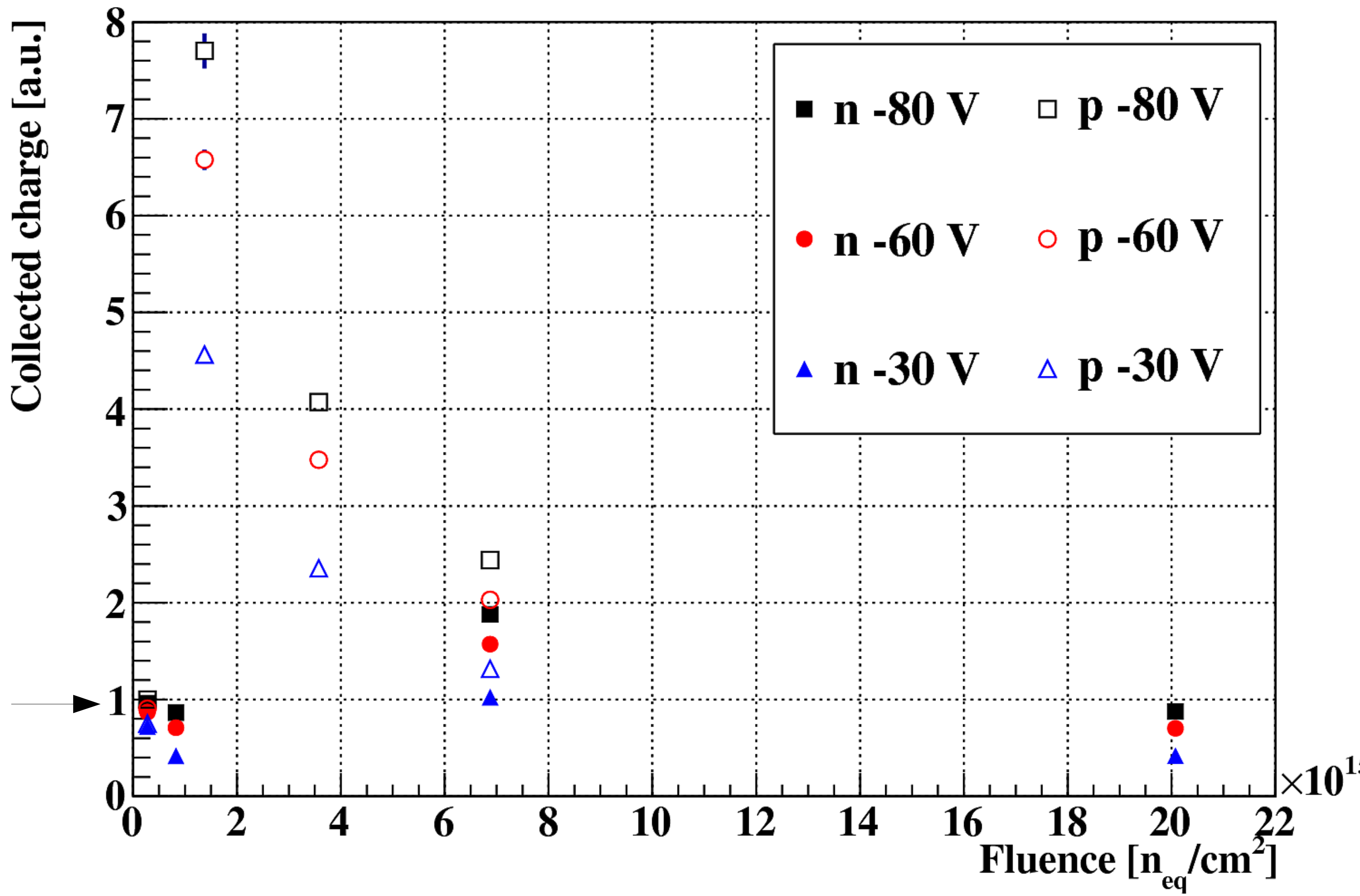
- Plotting **charge (collected in 5 ns)** as a **function of position**, towards the bulk of the detector. **Profiles** have been **shifted** such that raising edge coincides, for comparison purposes.
- For the measured fluences, more charge collected after **1.4×10^{15} n_{eq}/cm^2**, then decreases as fluence increases. At ~7×10^{15} n_{eq}/cm^2 it is still wider than the **unirradiated detector**.
- **Next**: **summing** all the charge in **200 µm** (*similar to MIP crossing the detector*)

Collected charge / unirradiated (protons)



- Collected charge (CC) calculated **over 5 ns** and summed **over 200 μm** along the "center line" of the detector. For each bias, CC is **referred to unirradiated detector.**
- CC for **1.4×10^{15} n_{eq}/cm^2** is **$\times 8$** the unirradiated !

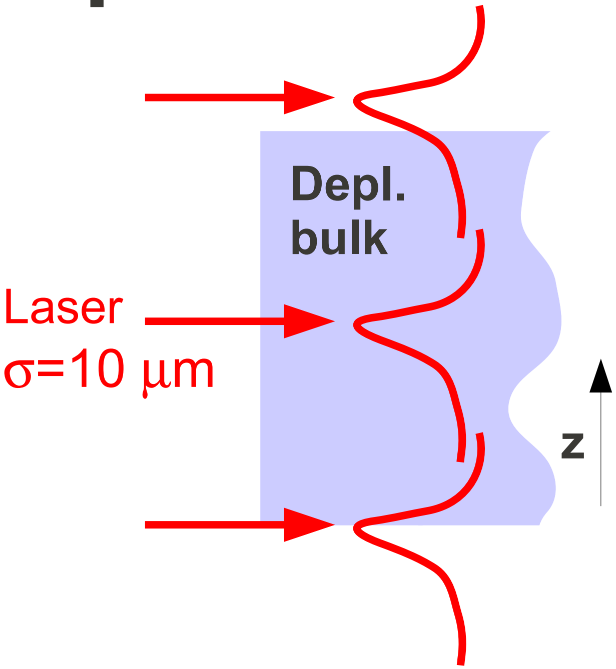
Collected charge (neutrons and protons)



Charge of unirradiated at 80 V is **defined** as **1**

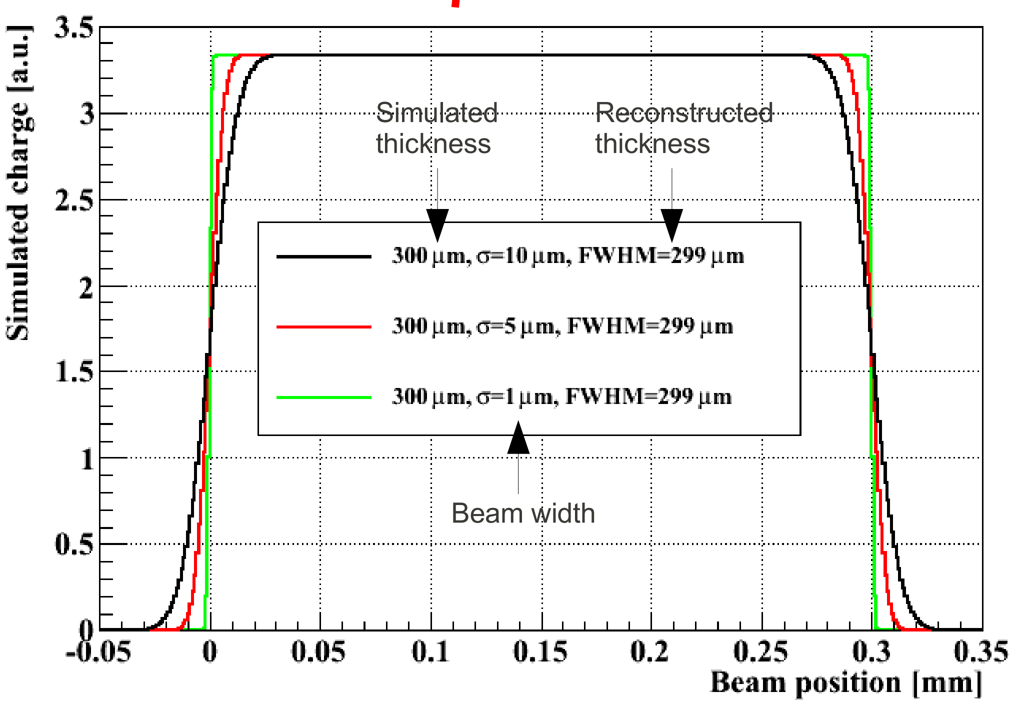
- Collected in **5 ns**, over **200 μm**. Showing 3 different voltages.
- **Fluence range 1-1.5 ×10^{15} n_{eq}/cm^2,** very fast increase of collected charge

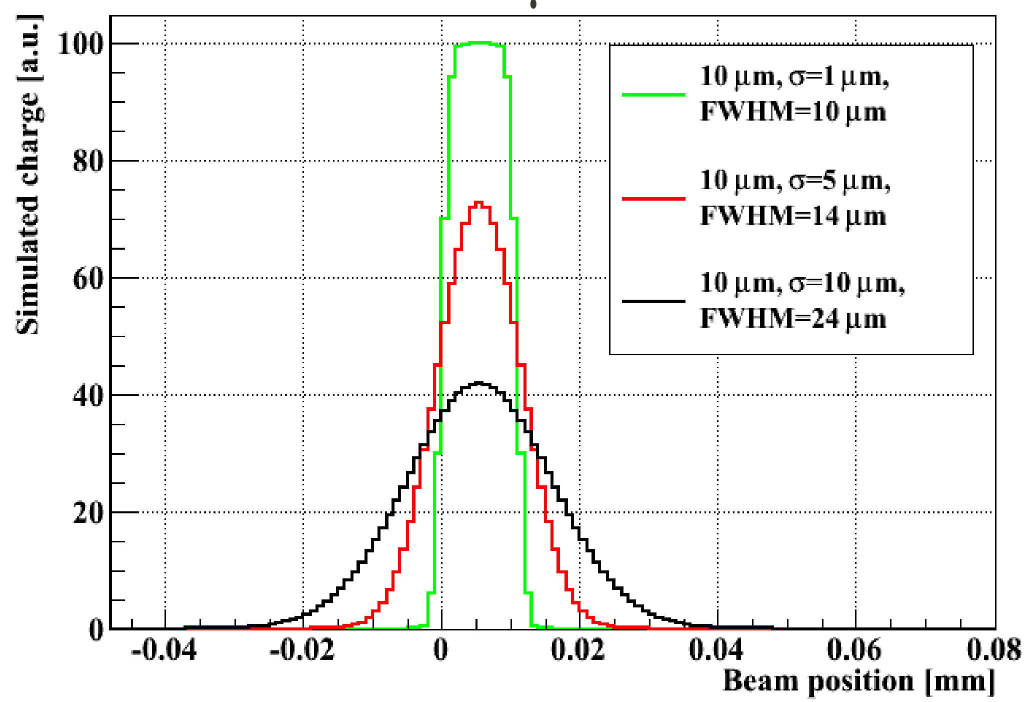
Spatial resolution in edge-TCT



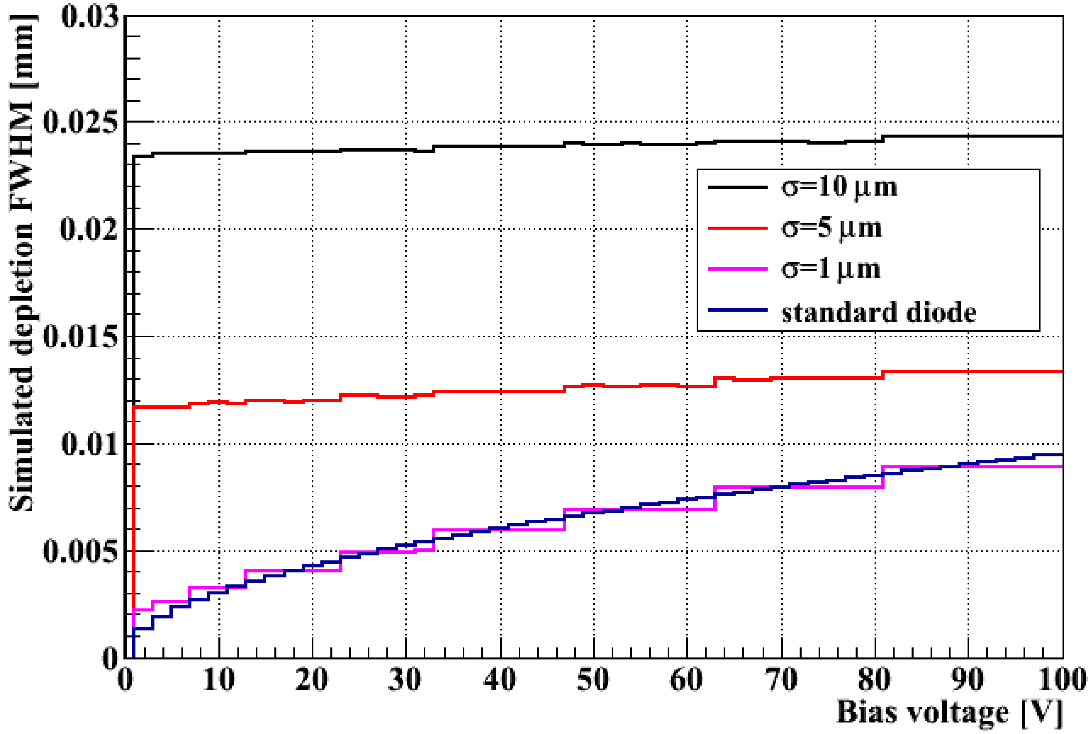
<u>Geometrical simulation:</u>

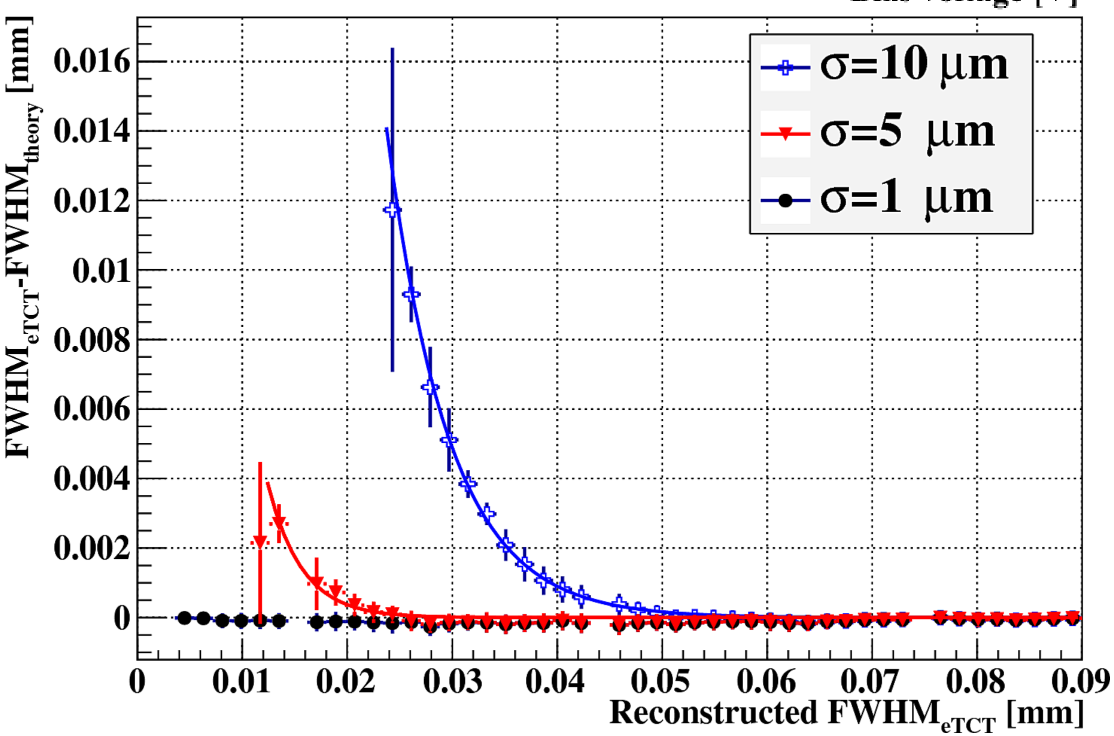
- The depleted volume of the detector is modeled as a **box** with a width representing the depth of the depleted region.
- Across the **box** detector is **fully efficient** for charge collection
  Outside the box **no charge** is collected.
- **Charge collected** = **convolution** of gaussian with box.
  Depleted depth = **FWHM** of charge profiles.
- Our laser for these measurements: **σ=10 μm**





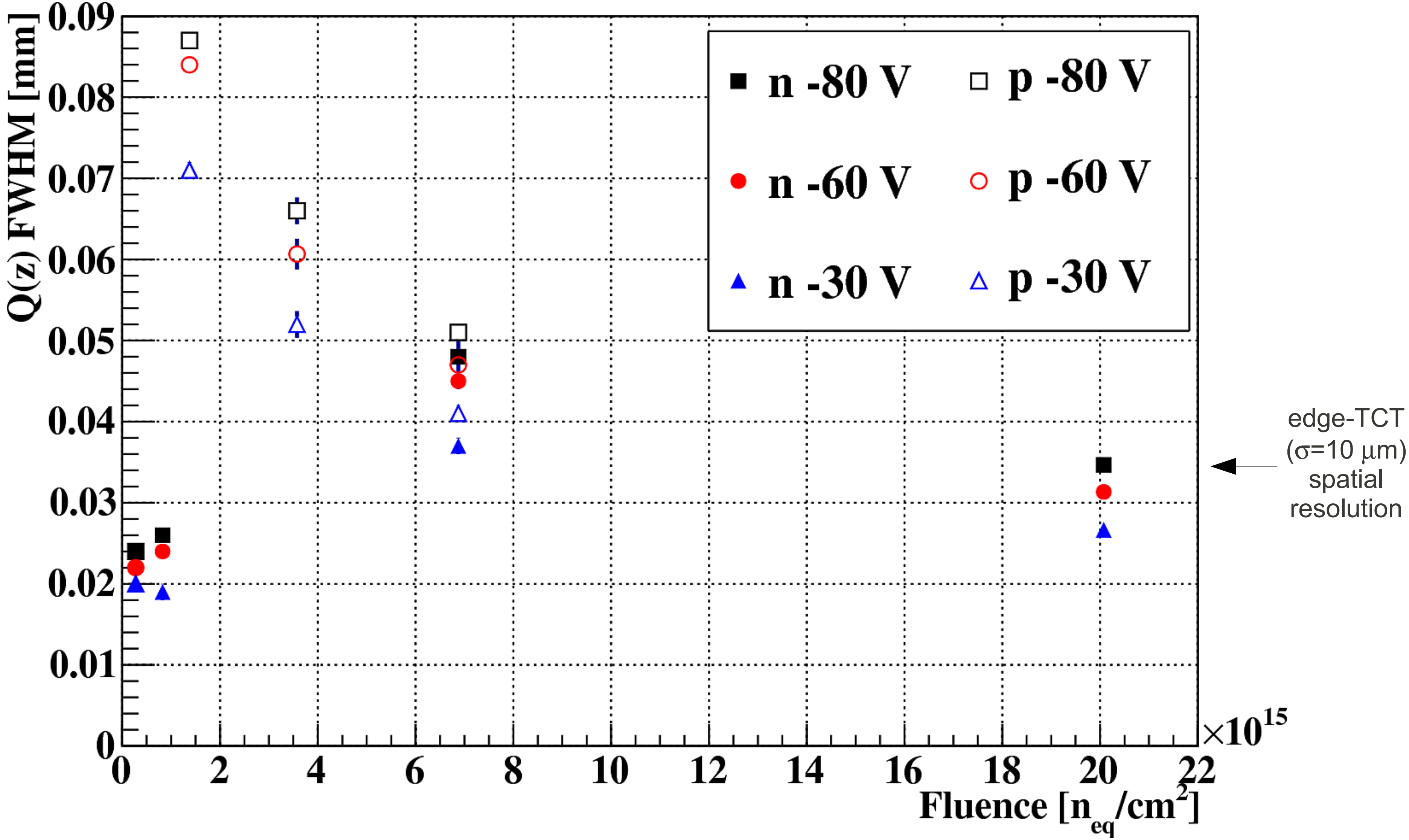
Spatial resolution in edge-TCT





- Simulated **FWHM** (10 Ω·cm bulk) **versus** bias **voltage**, for different laser beam widths (σ).
- **FWHM(~0V)** is **not zero** [no diffusion or built in voltage were simulated here, only geometry!]
- Very narrow beam (**σ~1 μm**) **needed** to accurately resolve depletion depth in low resistivity bulk (→ Advantage of Two Photon Absorption-TCT)
- **Difference** between the **simulated** and **theoretical** depletion thickness, as a function of the simulated (that is, observed) value.
- For **σ=10 μm**, real depletion width must be above ~35 μm if we want to take FWHM from edge-TCT as the size of the depletion region.

Depleted width (neutrons and protons)



- FWHM of Q(z ; 5ns) distributions (T=-20C) in a **vertical scan** along the center of the detector
- Depleted width is **maximum** at **1.5** $\times$**10**^{15} **n**$_{eq}$**/cm**^{2} **(p)**.

  Then decreases but always bigger than the unirradiated sample

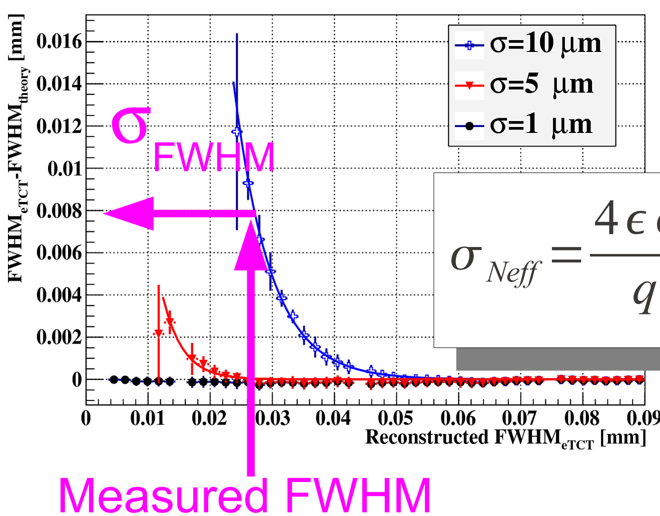
Methods for space charge calculation

Correction by laser width

- Assuming abrupt junction. N_{eff} calculated for each bias using measured FWHM.

$$N_{eff} = \frac{2\epsilon\epsilon_0}{q \cdot FWHM^2} V$$

- Measured FWHM also used to estimate error in depleted thickness:



$$\sigma_{Neff} = \frac{4\epsilon\epsilon_0}{q} \cdot \frac{V+V_b}{FWHM^3} \sigma_{FWHM}$$

- **Two** options:

1) No correction: use σ_{Neff} as uncertainty for N_{eff}
2) Use σ_{FWHM} to correct measured data:

$FWHM_{corr} = FWHM_{meas} - \sigma_{FWHM}$

Fit method

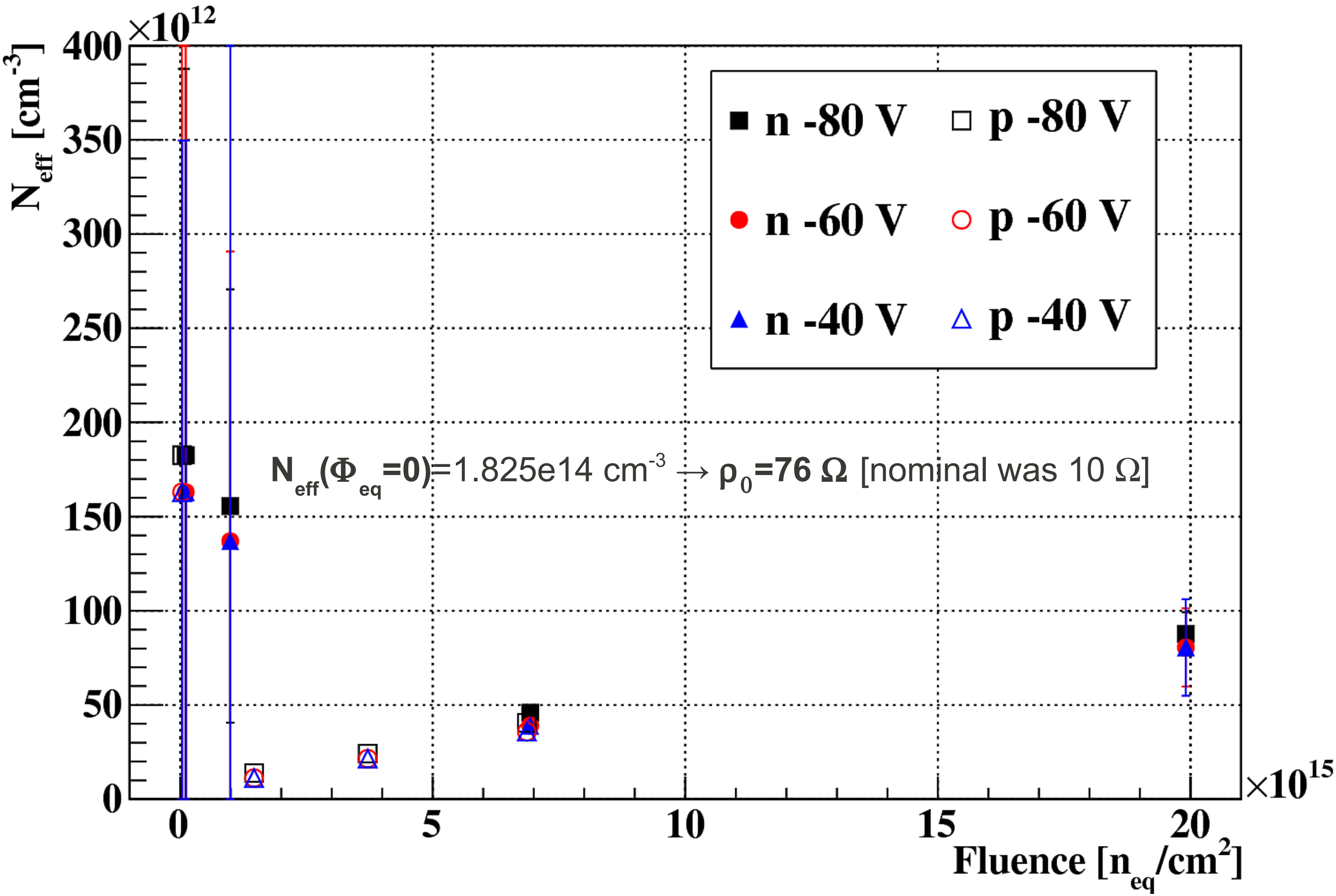
$$FWHM(V) = d_0 + \sqrt{\frac{2\epsilon\epsilon_0}{qN_{eff}} V}$$

- As proposed by Ljubljana group [G.Kramberger, I. Mandic, 26th RD50 meeting, Santander]
- N_{eff} calculated from a fit of measured FWHM versus voltage.
- Parameter d_0 introduced to account for FWHM(0)≠0. Reasons being: width of laser, built-in voltage, contribution of diffusion.
- Note that calculated $\mathbf{N_{eff}}$ values will have the value of w_0 already discounted: FWHM' ≈ FWHM - d_0

Method 1: using simulation

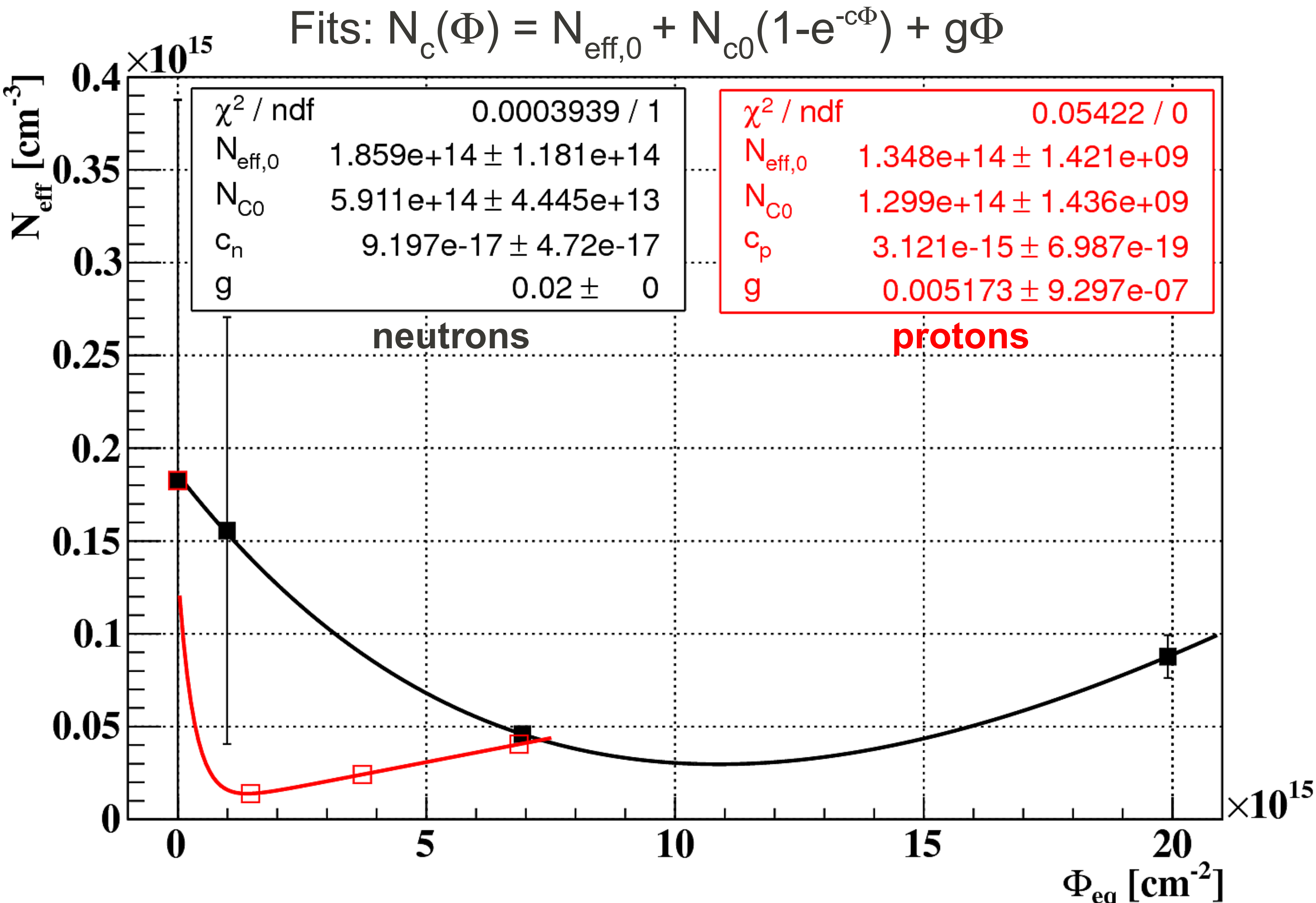
$$N_{eff} = \frac{2\epsilon\epsilon_0}{q \cdot FWHM^2} V \qquad \sigma_{Neff} = \frac{4\epsilon\epsilon_0}{q} \cdot \frac{V+V_b}{FWHM^3} \sigma_{FWHM}$$

1.1) Effective space charge (data not corrected)



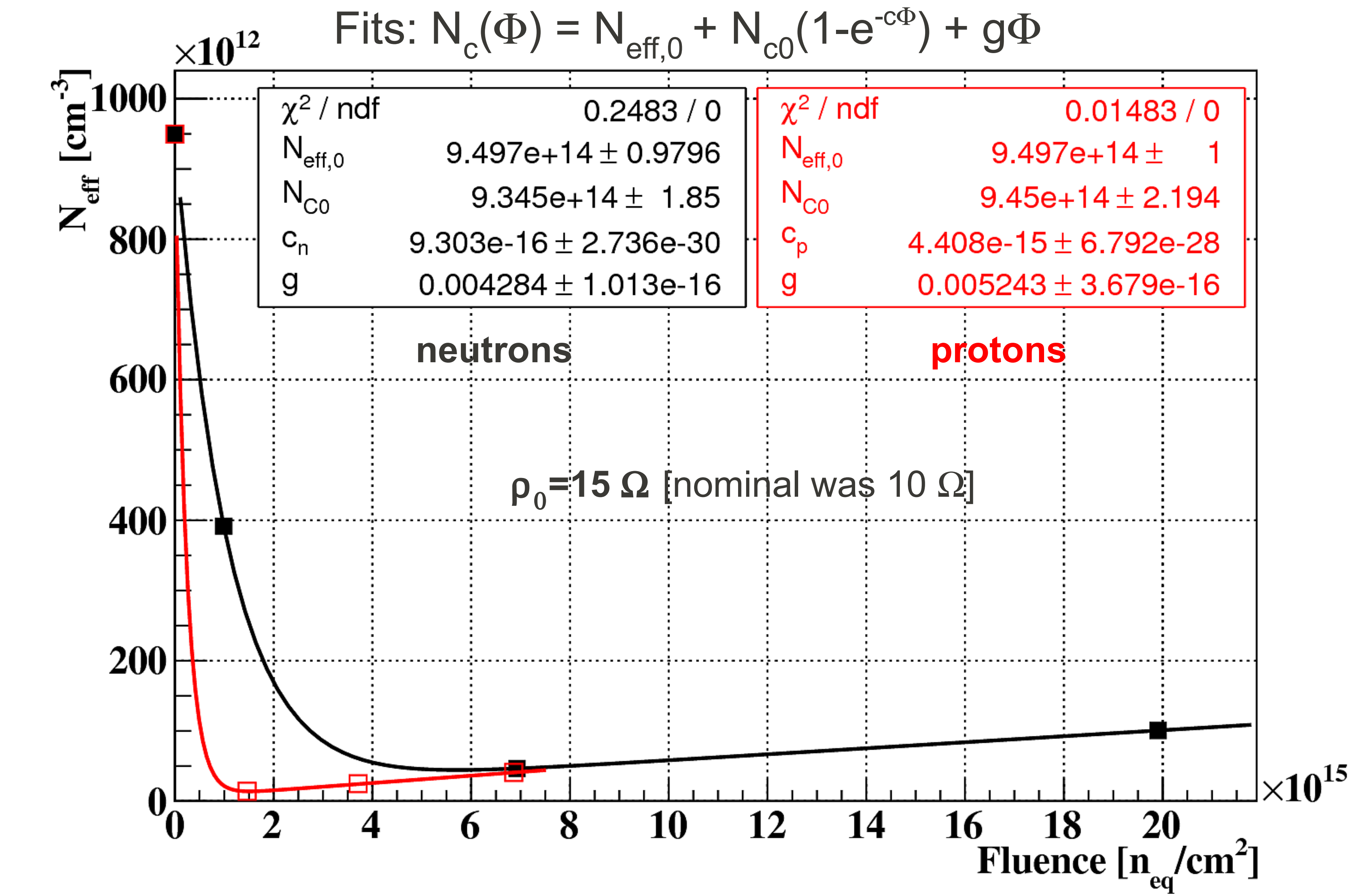
- N_{eff} calculated from FWHM. Simulation used to estimate error bars σ_{Neff}

1.1) Space charge change with fluence (not corrected)



- g_p: Introduction rate for protons needs to be left free
- Due to the low number of measurements, the minimum of acceptor removal for **neutrons** seems to happen much later in fluence

1.2) Space charge change with fluence (corrected data)

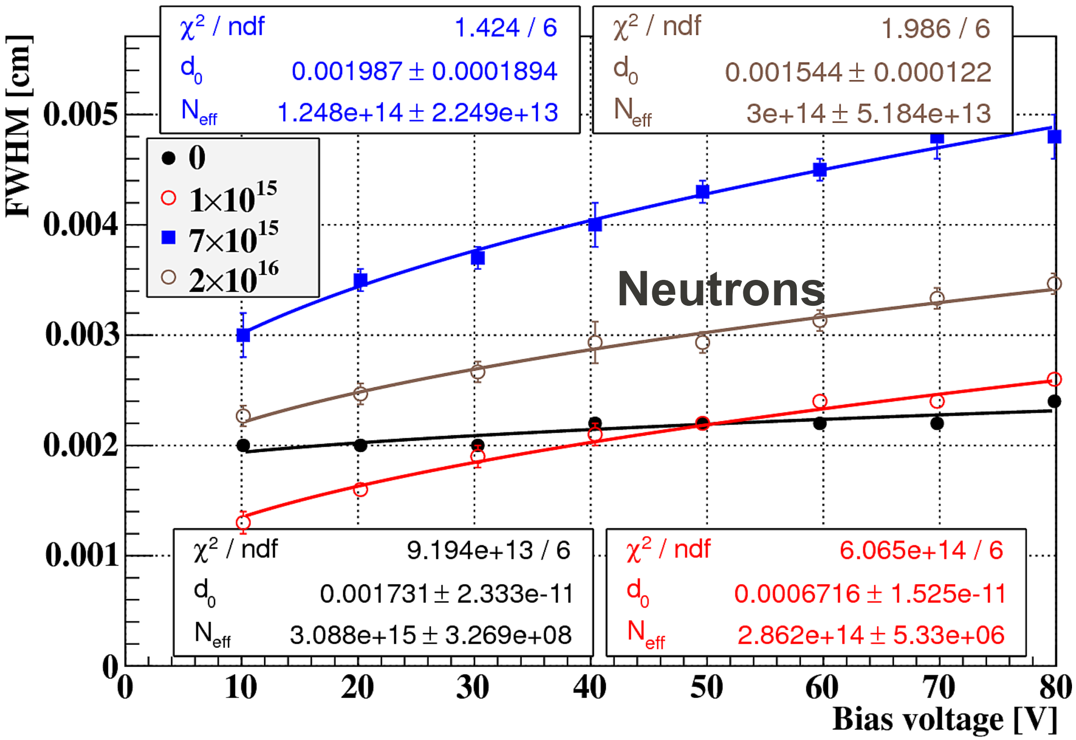


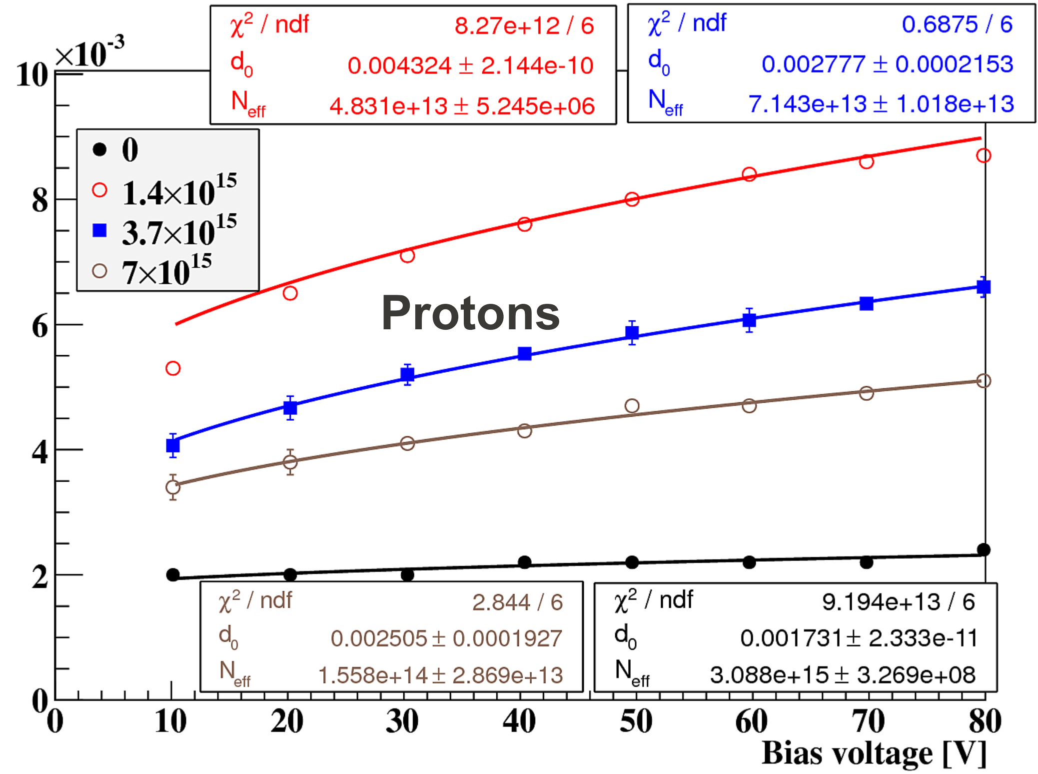
- Measured FWHM was corrected by simulation: $FWHM_{corr} = FWHM_{meas} - \sigma_{FWHM}$
- g_p and g_n need to be left free
- Calculated initial resisitivity ~15 Ω ·cm (nominal was ~10 Ω ·cm). Neff calculated at 80 V

Method 2: N_{eff} from fit

$$FWHM(V) = w_0 + \sqrt{\frac{2\epsilon\epsilon_0}{qN_{eff}} V}$$

FWHM fits

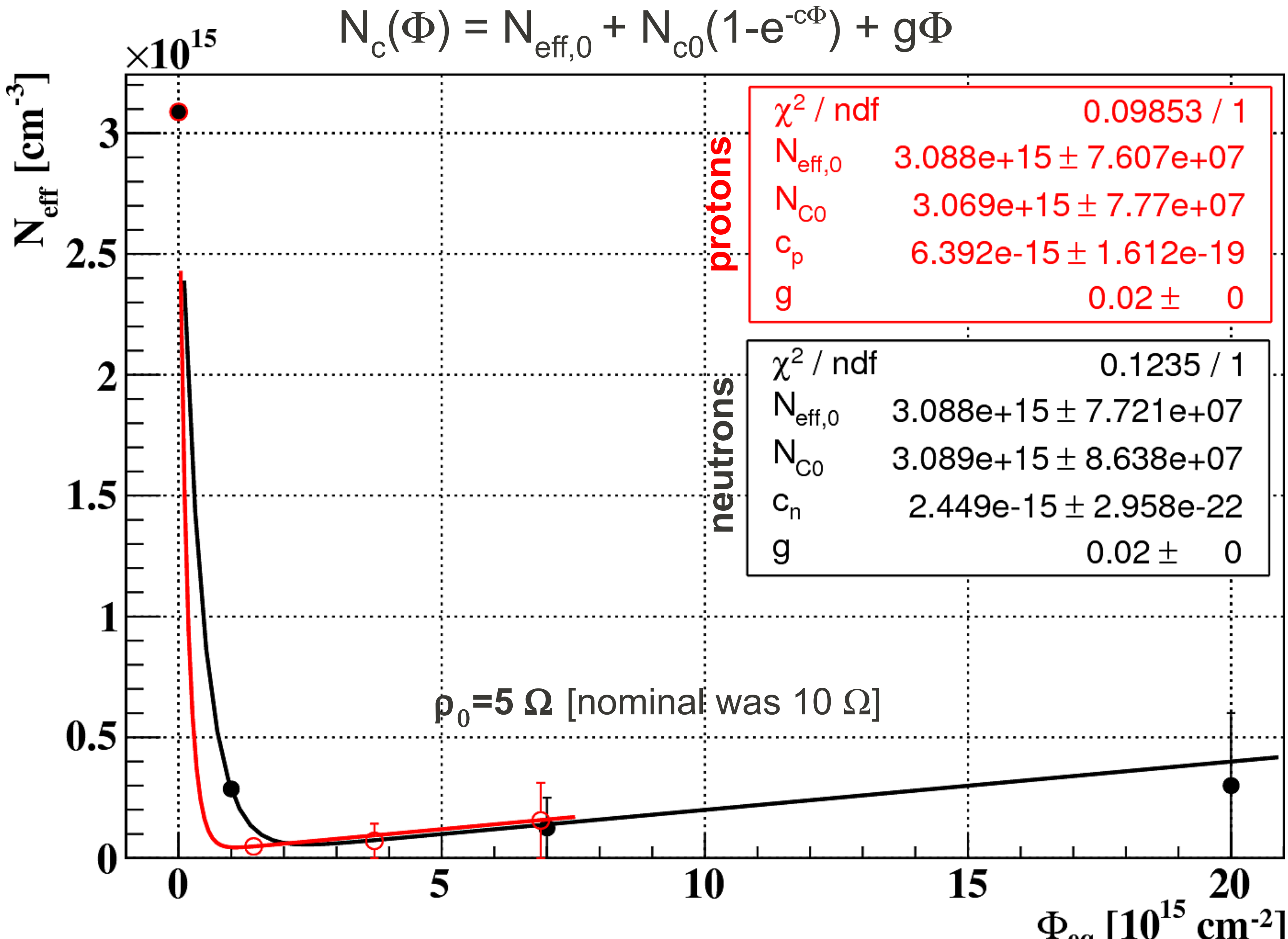




- The term $\mathbf{d_0}$ in the fits ranges between 7-30 μm (neutrons) and 25-50 μm (protons)

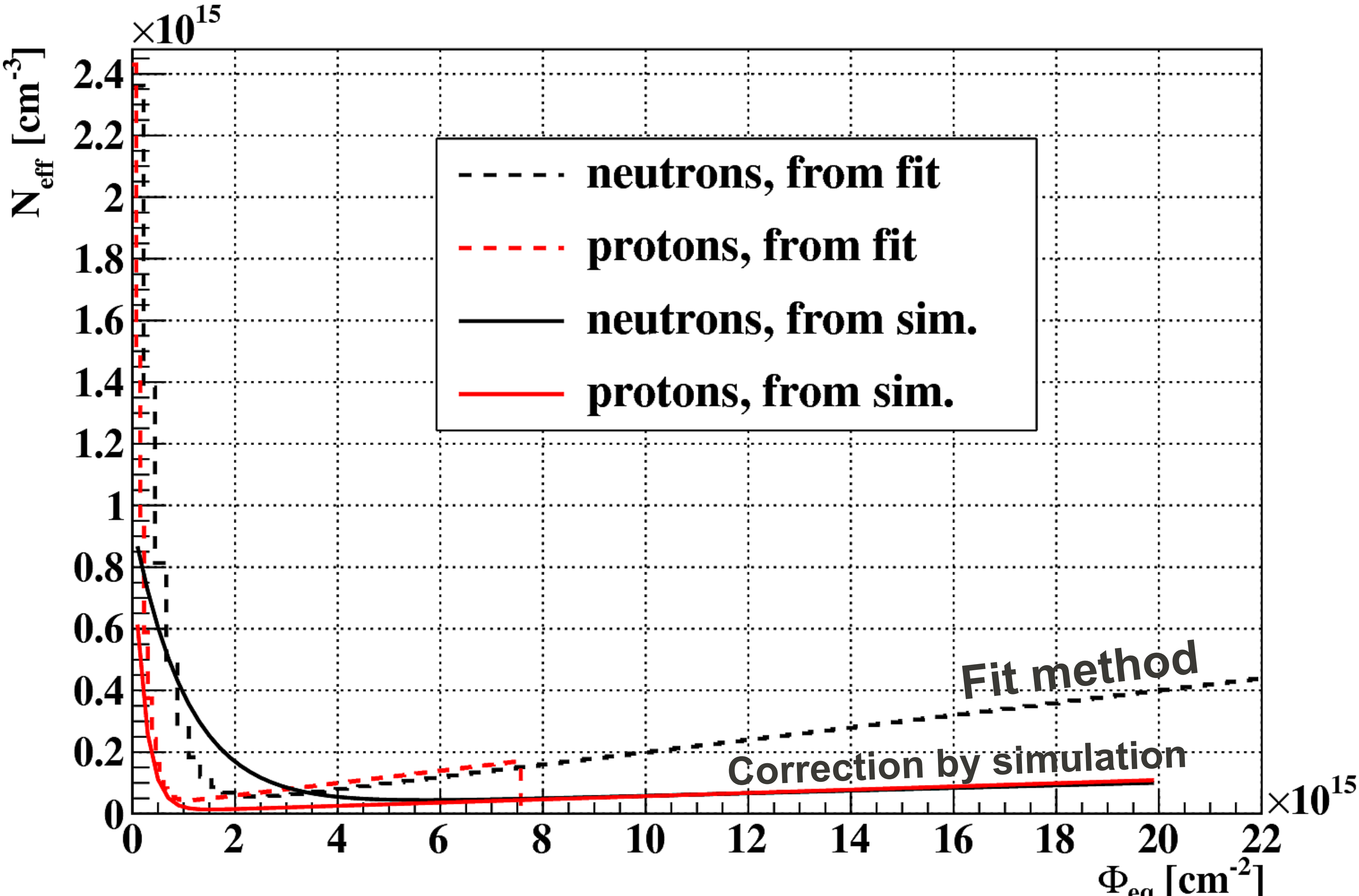
- This method is **more robust** than method 1, since it uses data from all bias to calculate N_{eff}.

Space charge change with fluence (fit method)



- Lowest value of space charge happens after **~10^{15}** (**2×10^{15}**) n_{eq}/cm^2 for **protons** (**neutrons**)
- Initial resisitivity ~5 Ω ·cm (nominal was ~10 Ω ·cm)

Comparison of calculated Neff



- Corrected N_{eff} using simulation leads to lower space charge than Neff extracted from fit

Conclusions

- Measured 7 different HVCMOS test diodes realized as deep N-wells on low resistivity Si. One detector not irradiated. Three were irradiated to (1, 7, 20) $\times 10^{15}$ n_{eq}/cm^2 (neutrons), the other three to (1.4, 3.7, 6.9) $\times 10^{15}$ n_{eq}/cm^2 (protons).

- In HVCMOS the amount of collected charge is increasing with radiation!
  For **neutron** irradiated 7×10^{15} n_{eq}/cm^2 the **collected charge doubles**.
  For **protons** 1.5×10^{15} n_{eq}/cm^2 collected charge is **8 times bigger** !!!!
  After 2×10^{16} n_{eq}/cm^2 collected charge is similar to unirradiated (trapping, too many defects)
  Fast changes with fluence. Carefully choose position of sensor in experiment.

- To sample the fast rise of charge with fluence, measurements with neutrons and protons at lower fluence are needed!!!

- Space charge was calculated using 2 different methods

  1) Using a geometrical simulation, measured FWHM is corrected by the width of the laser.
  2) From a fit of measured FWHM vs voltage, where the FWHM(V=0) is substracted from the data.

  Both methods yield an initial resistivity compatible with nominal and show a deactivation of doping with fluence.

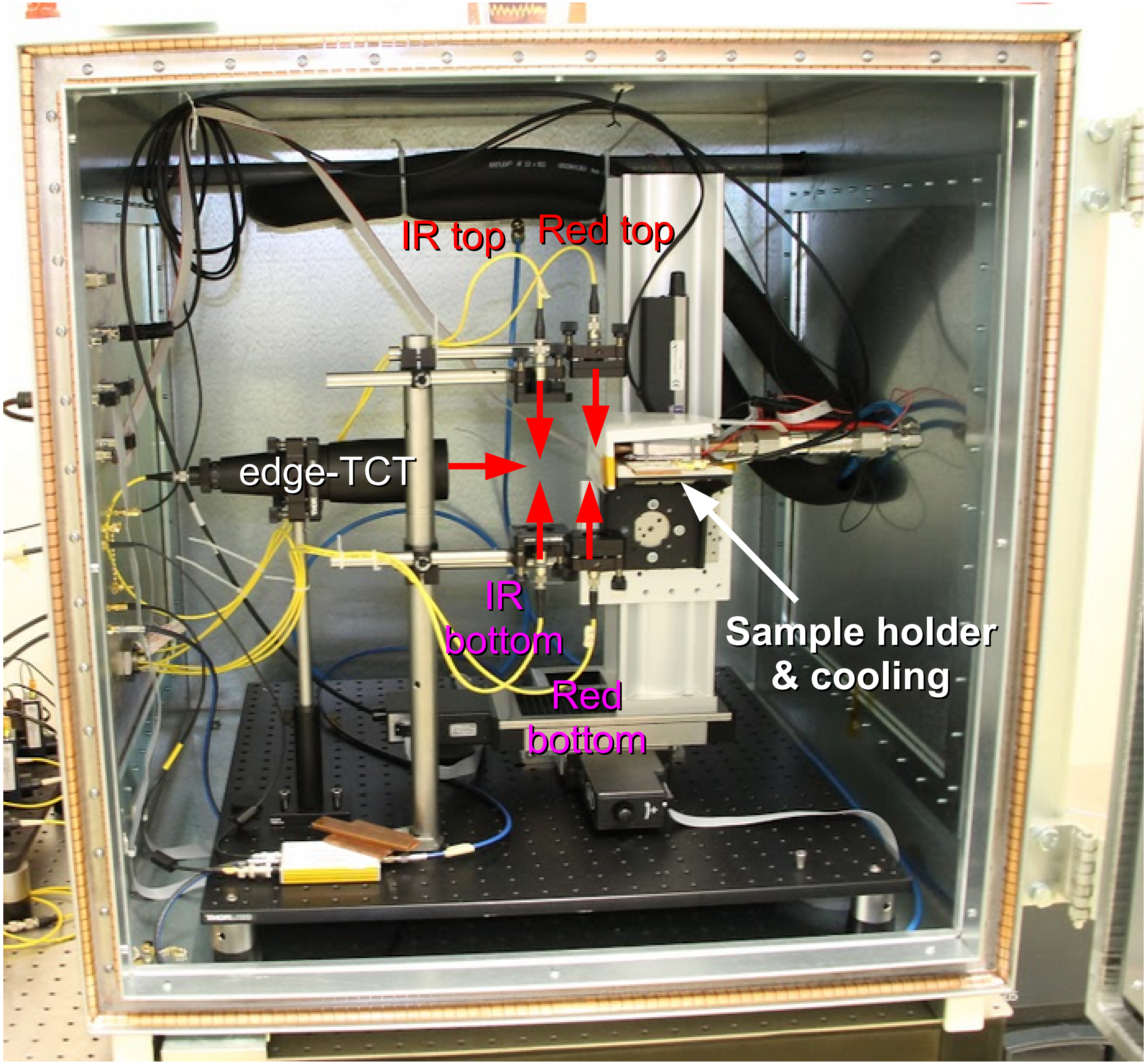
“I don't want to achieve immortality through my work; I want to achieve immortality through not dying” (Woody Allen)

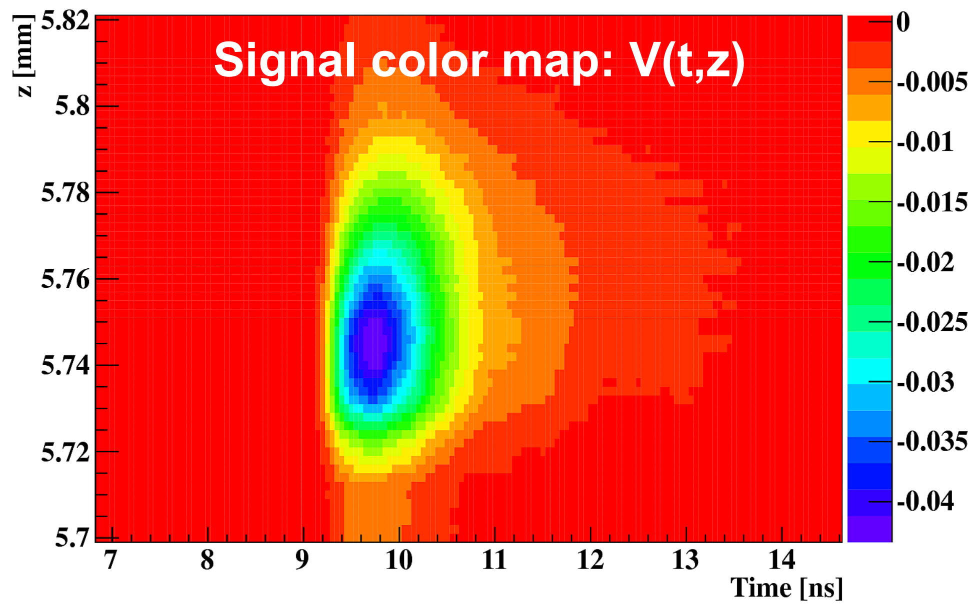
and more...

Christian&Joaquin: we hope your setups and DAQ stay immortal, so we don't need to fix them...

BACKUP

CERN-SSD TCT+

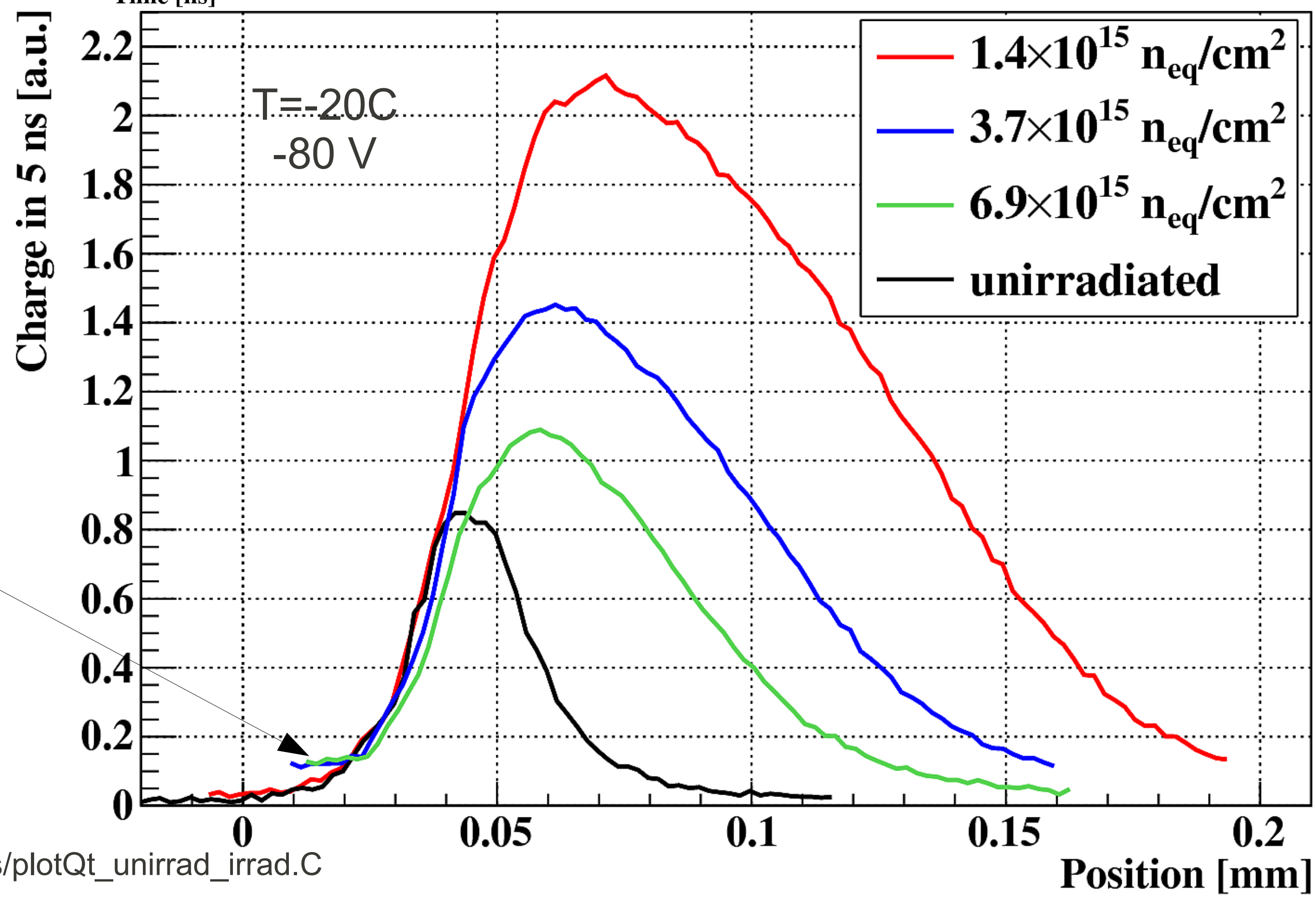

IR top
Red top
edge-TCT
IR
bottom
Red
bottom
Sample holder
& cooling



Problem: Collected charge Q(z) for 2 highest fluences (**4e15** and **7e15** neq/cm2) does not start at 0. This "pedestal" extends for ~10 um. However **1.5e15** starts from Q(z)~0.
Strange: redo these measurements.

[seen as well for 0 C]

Charge does not decrease



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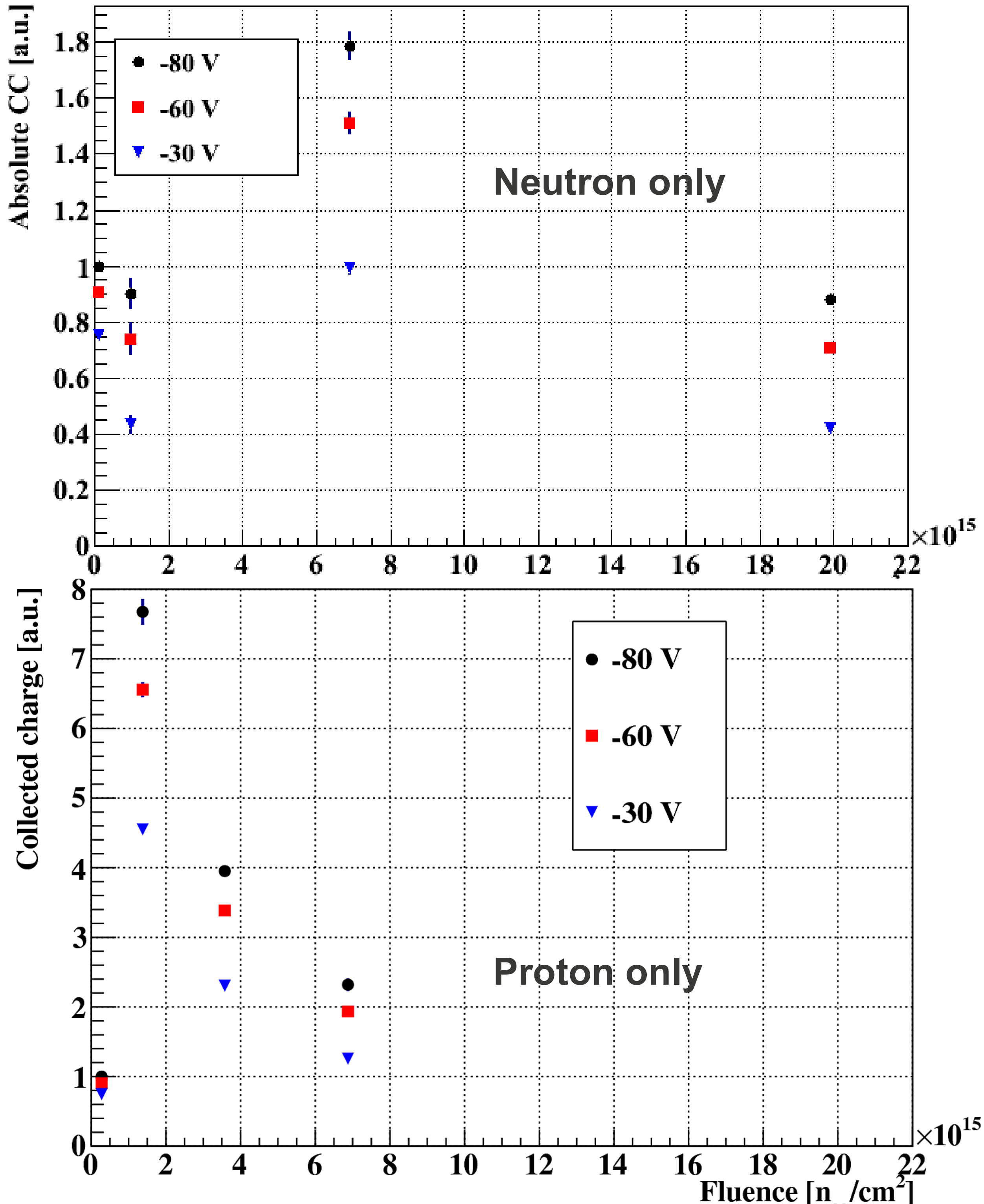
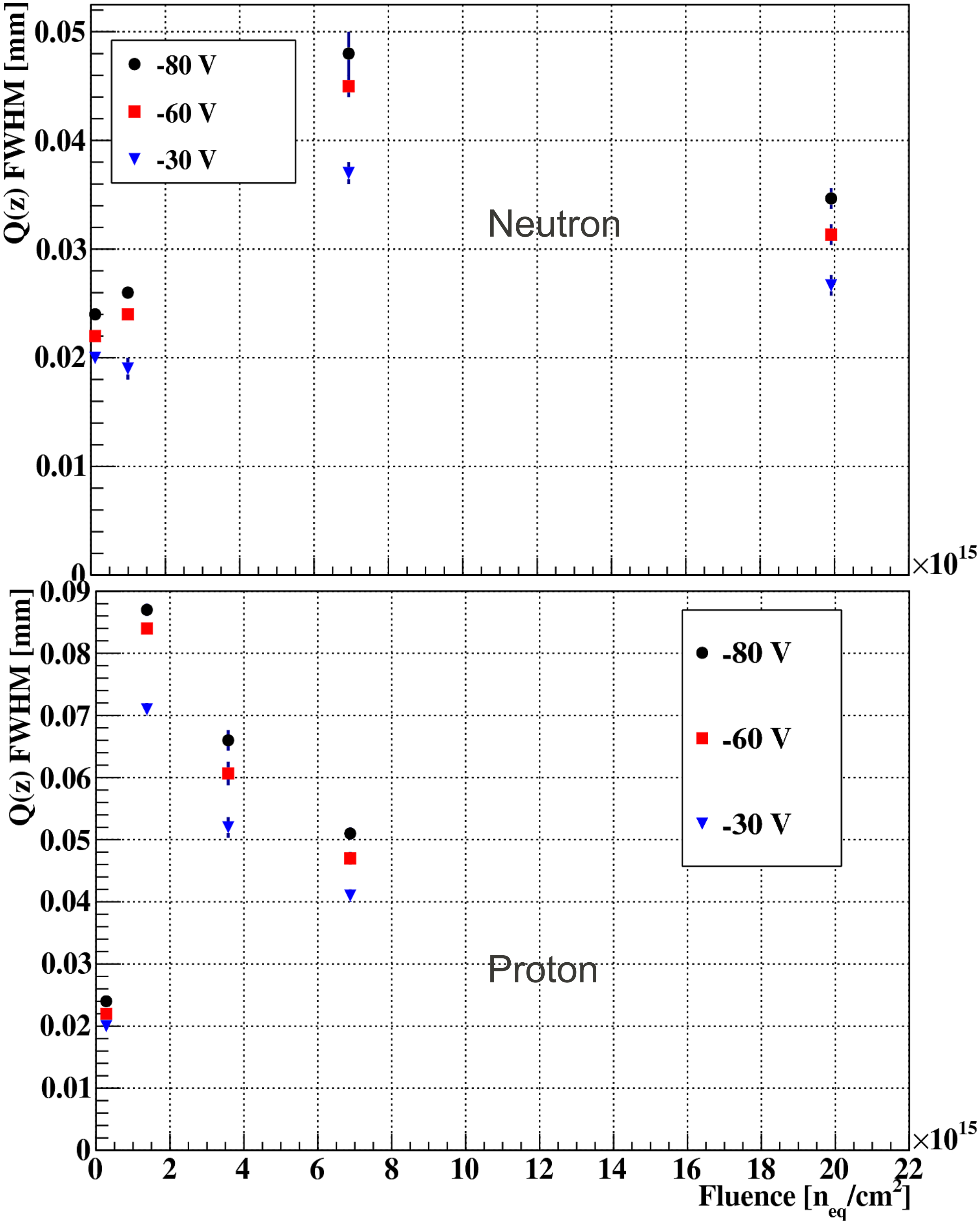


CCE_vs_Fluence.C



CCE_vs_Fluence.C

Estimation of Neff error