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Charge collection in proton irradiated HV-CMOS sensors

31st RD50 Workshop (CERN), 22.11.2017

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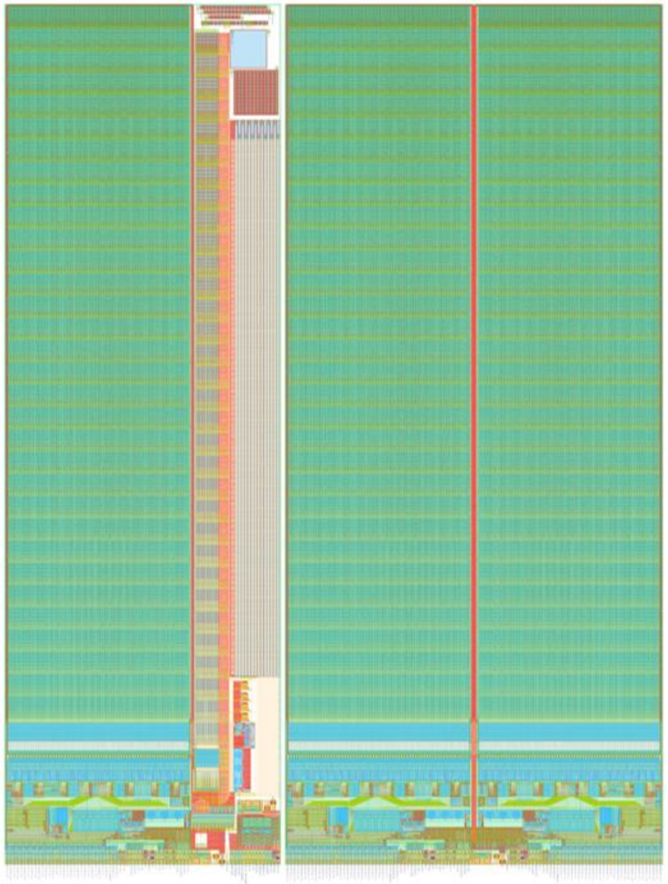
Sample

- CHESS 2 chip (designed at UCSC and SLAC, manufactured in the AMS-H35 technology by AMS)
- Full reticle monolithic demonstrator chip of the ATLAS Strip CMOS project
- 3 fully digital striplet arrays, 1 test field with analog test structures
- *n* in *p*
- 4 substrate resistivities (20 – 1000 Ω·cm)
- Same wafer material also used in production of the AtlasPix chip (monolithic pixel CMOS chip)

	Size
Height	18.6 mm
Width	24.3 mm
Thickness	250 µm
Standard resistivity	20 Ω·cm
Resistivity 2	50-100 Ω·cm
Resistivity 3	200-300 Ω·cm
Resistivity 4	600-2000 Ω·cm



H. Grabas, FEE 2016: https://indico.cern.ch/event/522485/

Irradiation campaigns

- Irradiation hardness studies with CHESS 2 carried out in Ljubljana:
  - reactor neutrons (Ljubljana) – 4 resistivities, 5 fluences (1e14 – 2e15 n_{eq}/cm^2)
  - 24 GeV protons (CERN PS) – 3 resistivities, 2 fluences
  - 800 MeV protons (Los Alamos LANSCE) – 4 resistivities, 3 fluences

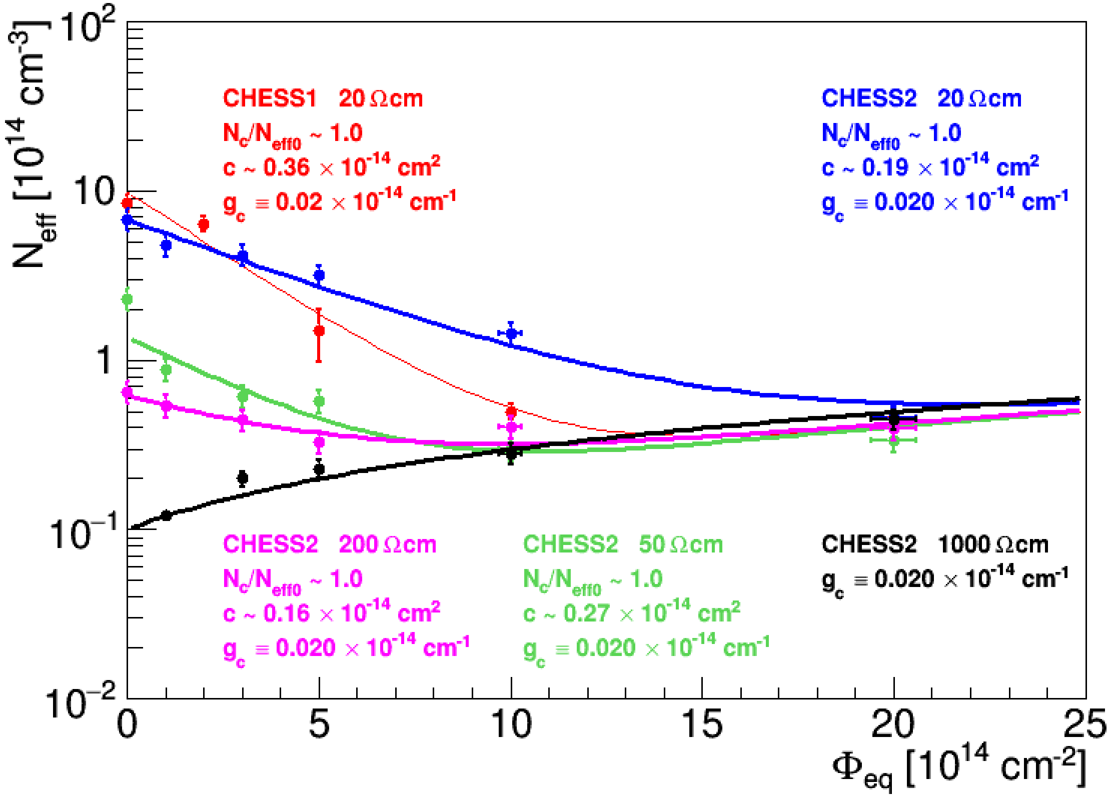
  } focus of this talk

- Characterization of passive structures using Edge-TCT and Sr^{90}
- Measurements before and after annealing (80 min at 60 °C)

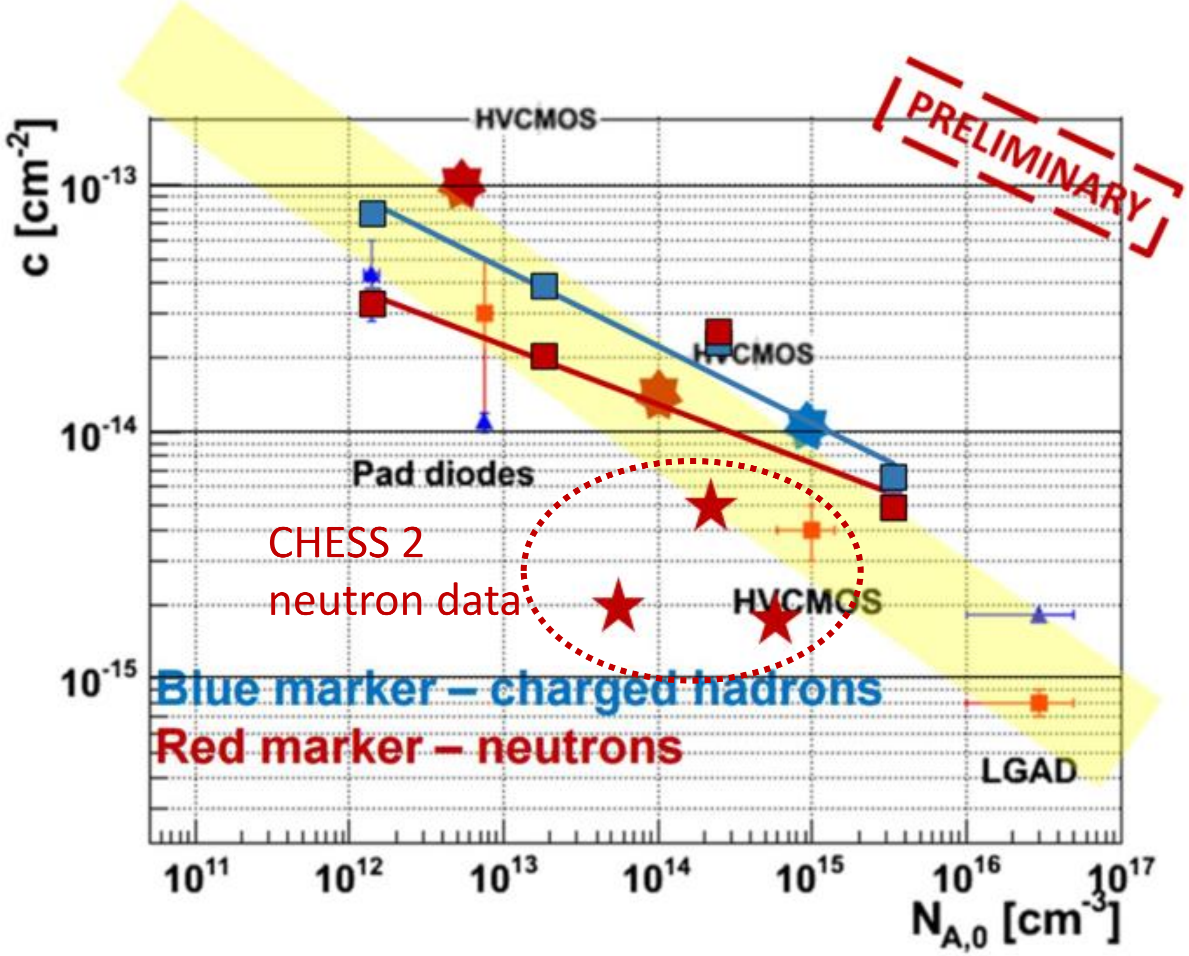
Table of proton irradiated samples/fluences

ϕ (10^{14} n_{eq} cm^{-2})	20 Ω·cm	50 Ω·cm	200 Ω·cm	1000 Ω·cm
0				breakdown
4.2	CERN PS	n.a.	CERN PS	CERN PS
7.7	Los Alamos	Los Alamos	Los Alamos	Los Alamos
8.7	CERN PS	n.a.	CERN PS	CERN PS
14	n.a.	Los Alamos	Los Alamos	n.a.
36	n.a.	Los Alamos	Los Alamos	n.a.

Reminder: neutron irradiation



Neutron irradiation results presented in Trento 2017
Link



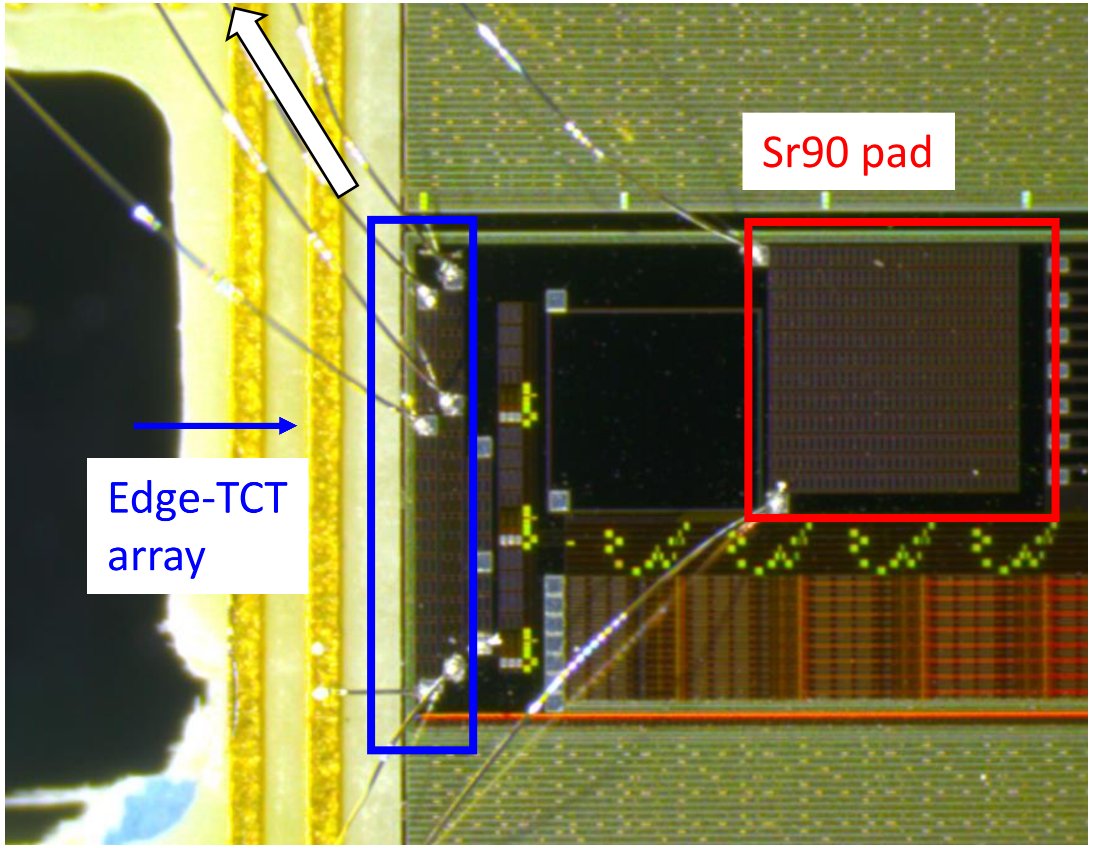
P. Dias de Almeida, 30th RD50 Workshop 2017

Test structures

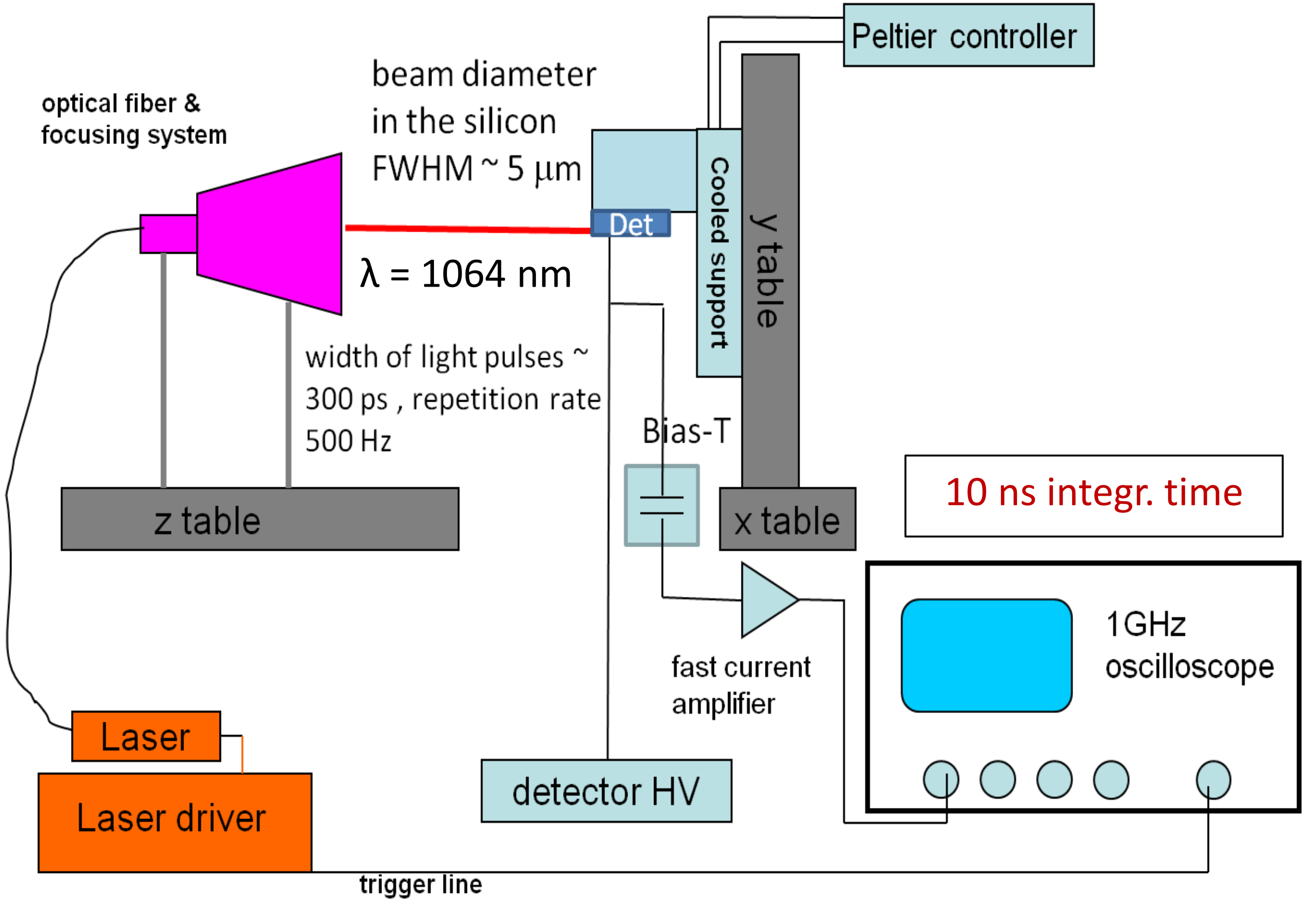
Passive test structures:
- 3 x 3 pixel array for Edge-TCT (pixel size 630 x 40 μm^2)
- Large pad for Sr90 measurements (1.2 x 1.2 mm^2)

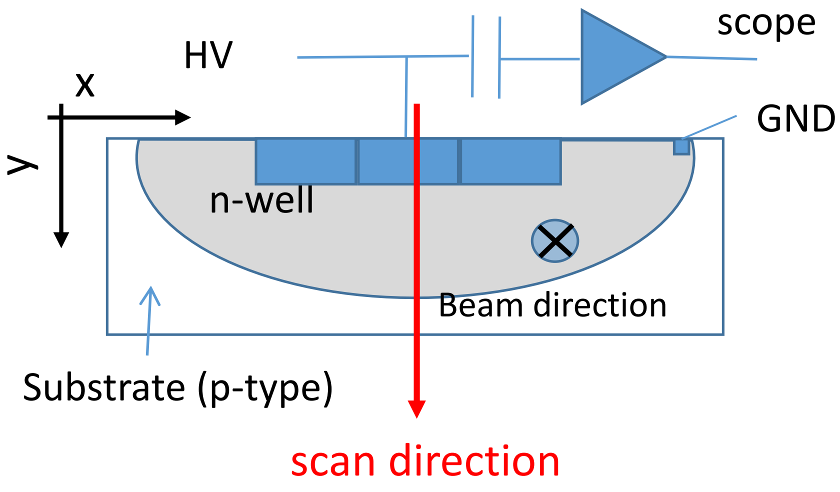
Bias voltage up to 120 V can be applied

to external amplifiers



Edge-TCT setup

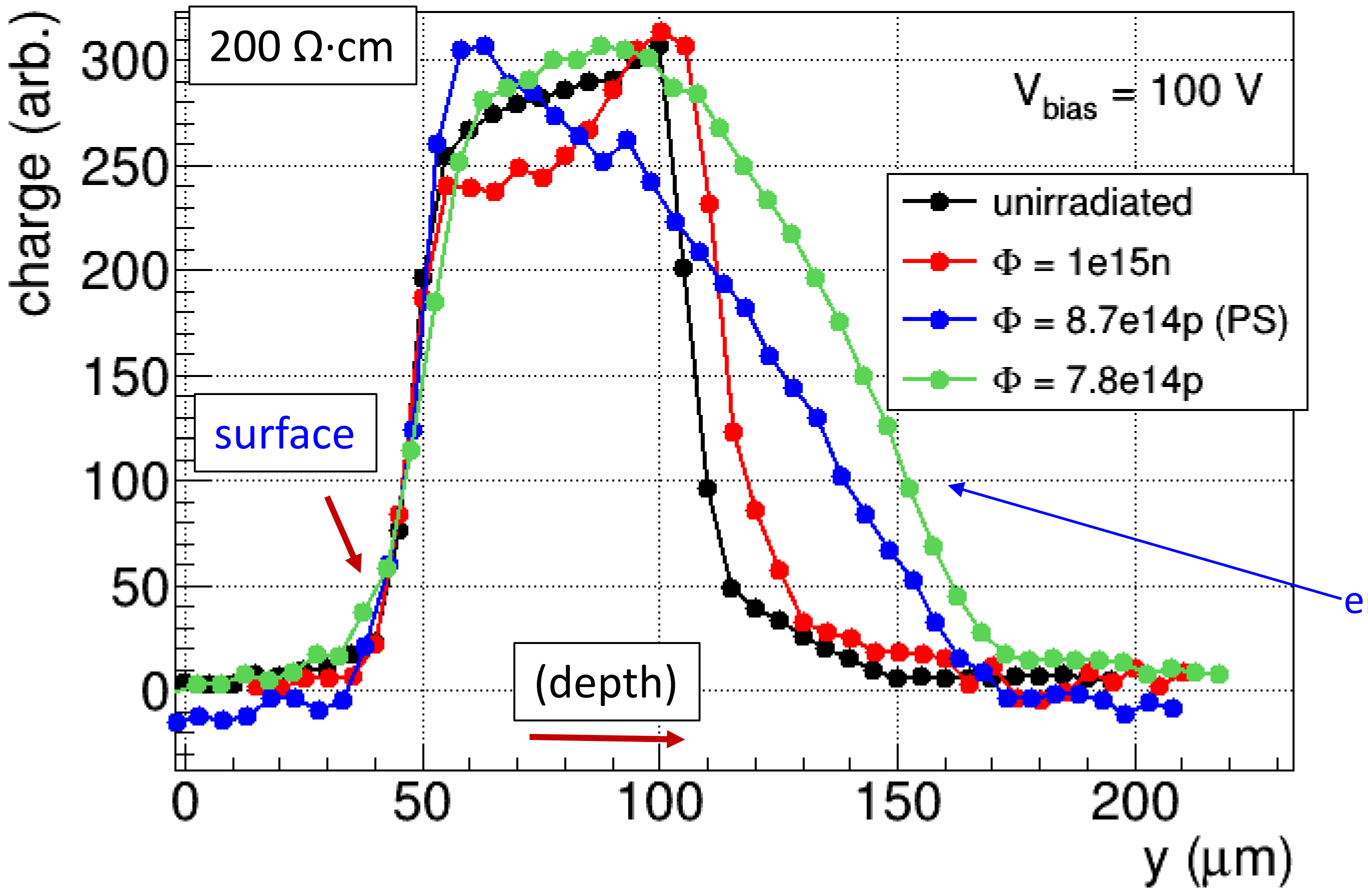


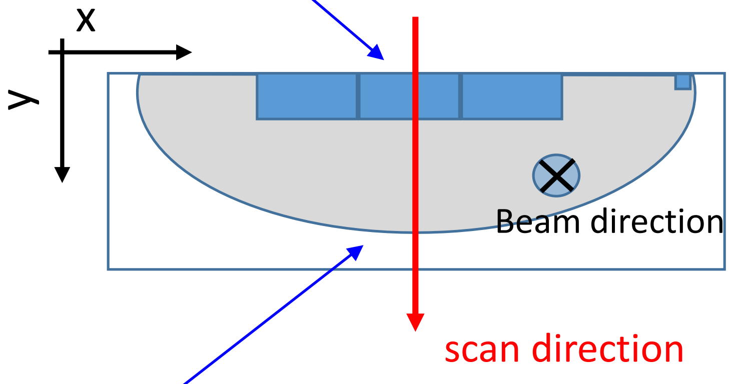


- Standard Edge-TCT measurements (Particulars setup)
- Scan along the middle of the central pixel

(more details: www.particulars.si)

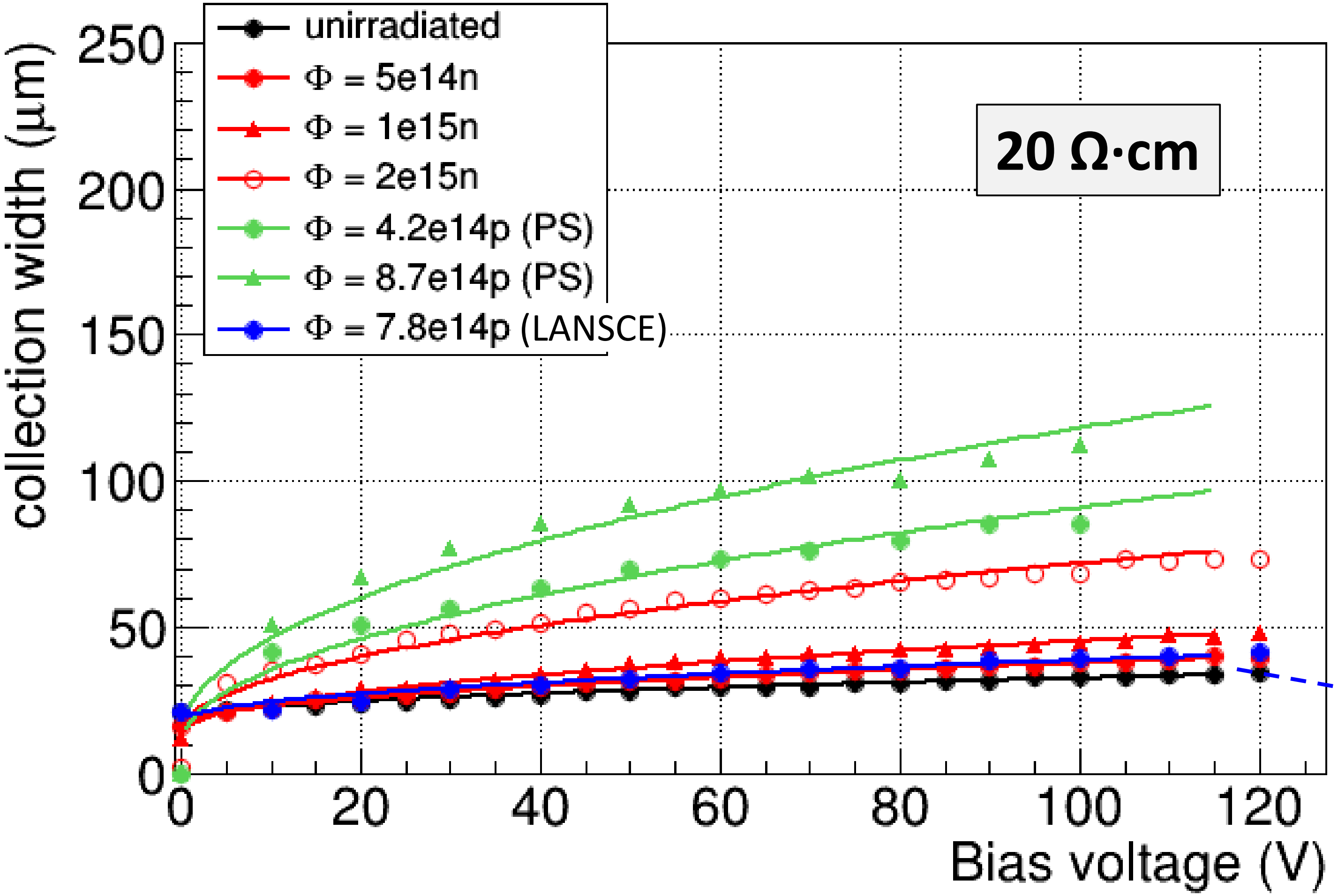
Charge collection profiles





- After proton irradiation significant increase in charge collection width is observed (even compared to neutrons)
- Depleted depth is evaluated as width of the charge collection profile

Depletion vs. bias voltage (20 Ω·cm)



N_{eff} is extracted from voltage dependence by fitting:

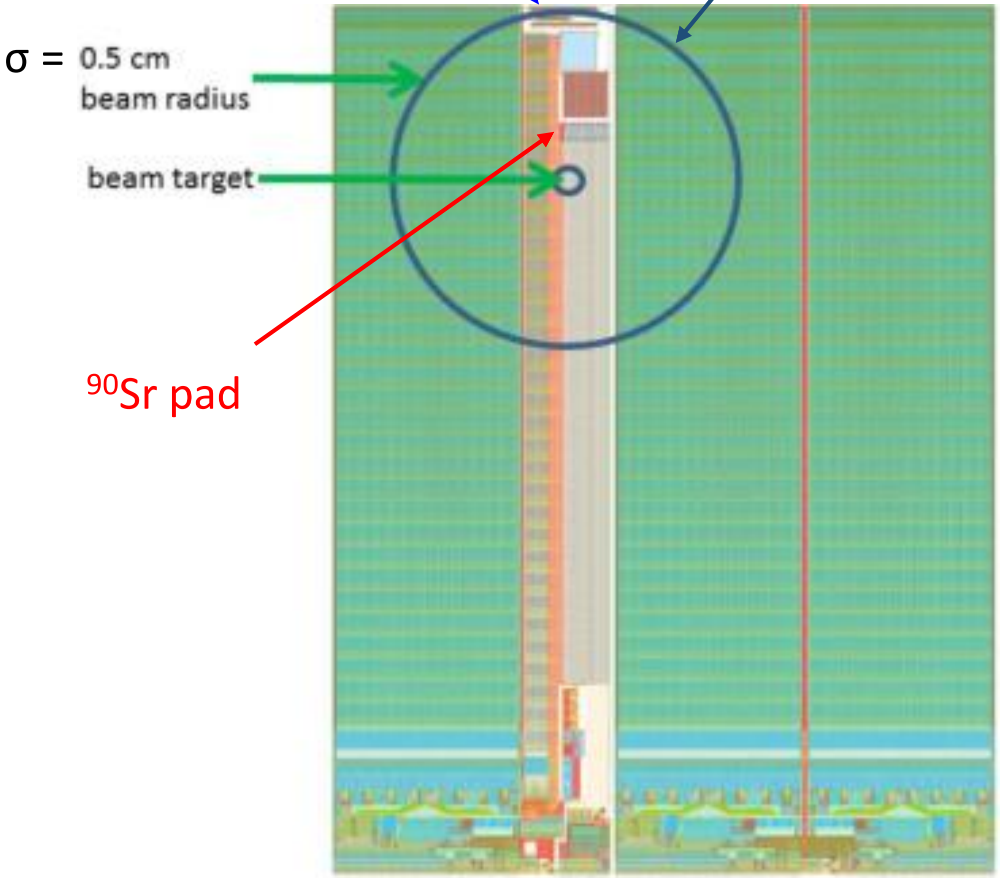
$$\mathrm{Width}(V_{bias}) = w_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} V_{bias}}$$

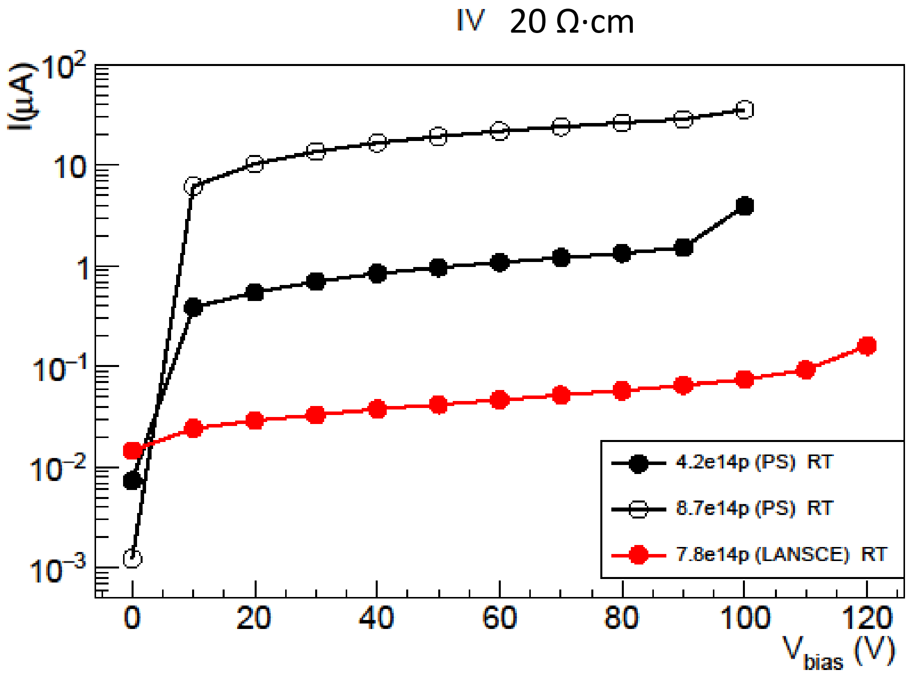
LANSCE sample different from PS samples

Edge-TCT received fluence at LANSCE

Edge-TCT structure
local fluence probably
less than nominal

proton beam
position at LANSCE

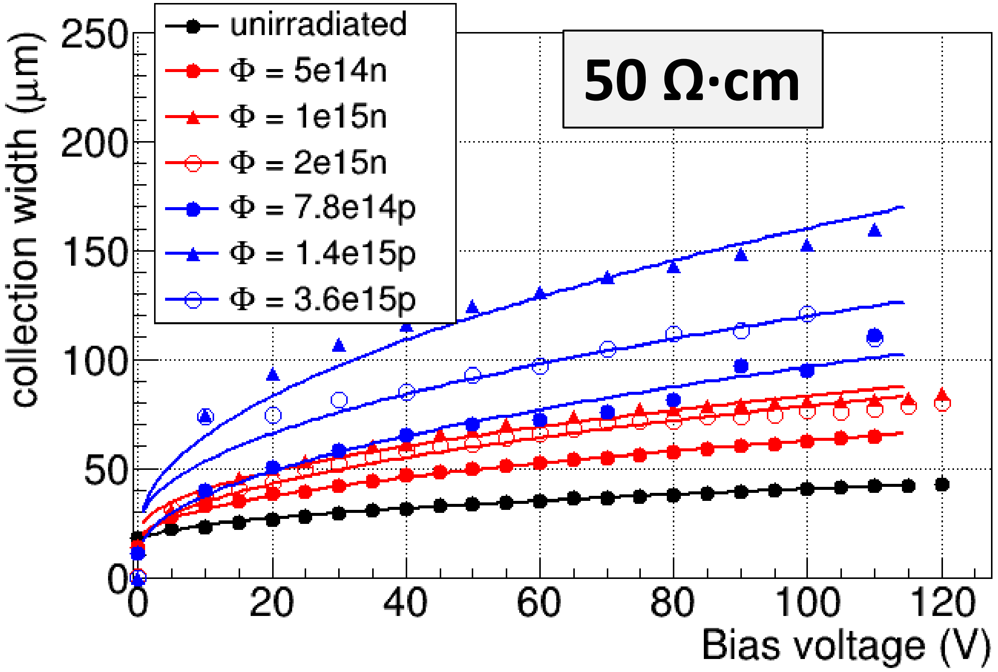


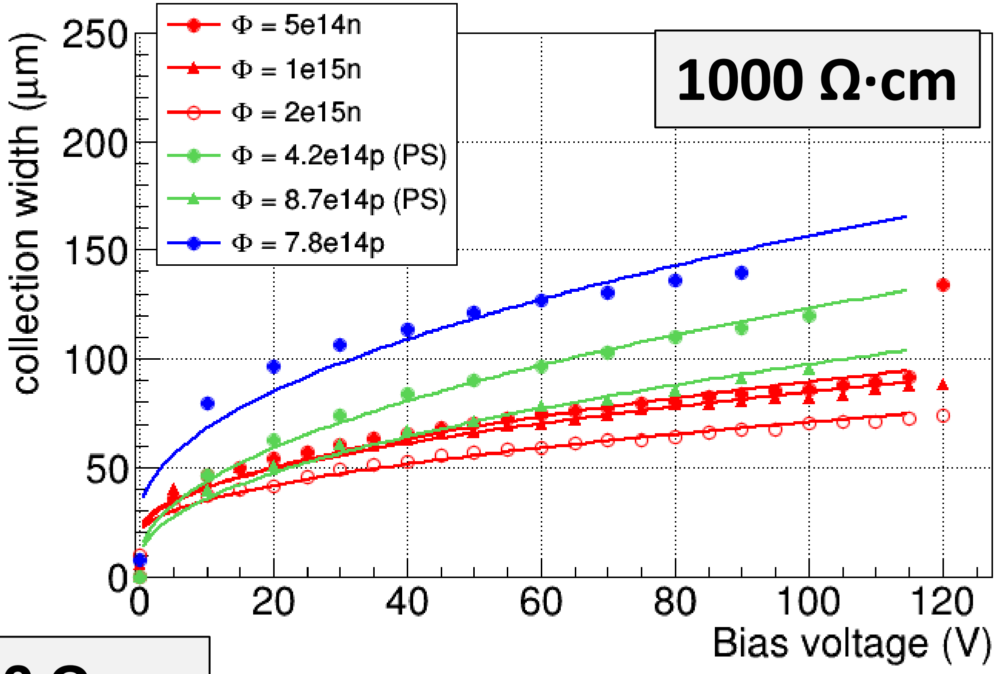


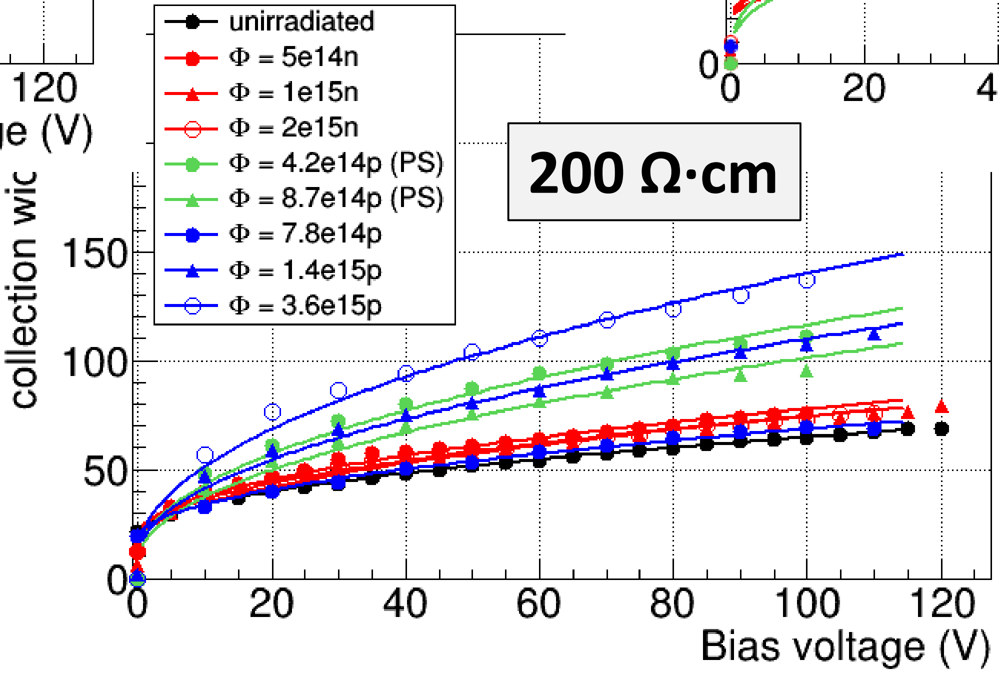
Due to the beam position at LANSCE the received fluence in the Edge-TCT structure is relatively sensitive to placement precision.

Large error margins on fluence have to be assumed.

Depletion depth at remaining resistivities

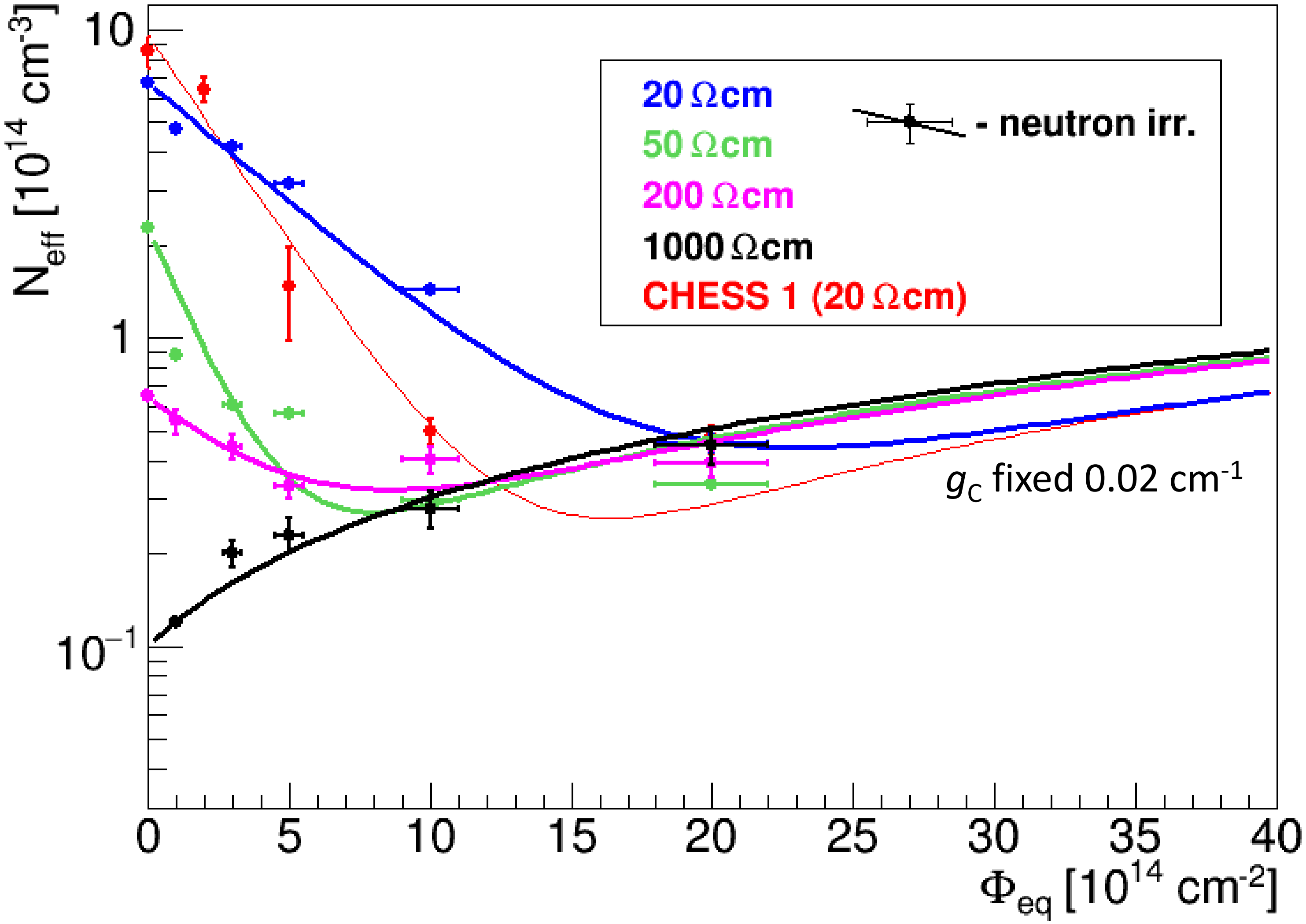






Proton irradiated samples have in general a larger depletion depth than neutron irradiated ones

Effective space charge concentration – neutron irradiated samples

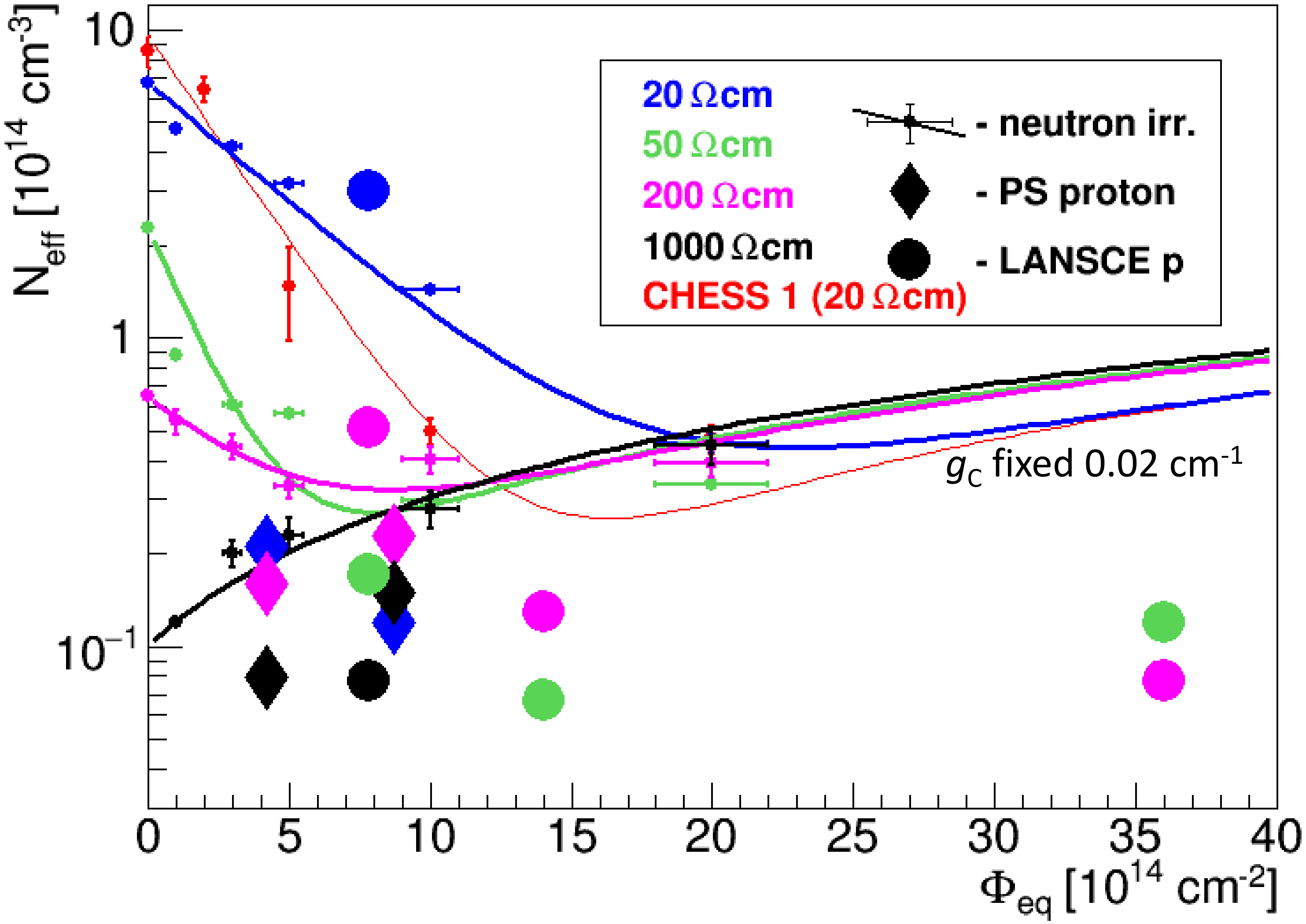


$$N_{eff} = N_{eff0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq})) + g_C \cdot \Phi_{eq}$$

acceptor removal acceptor introduction

Neutrons only

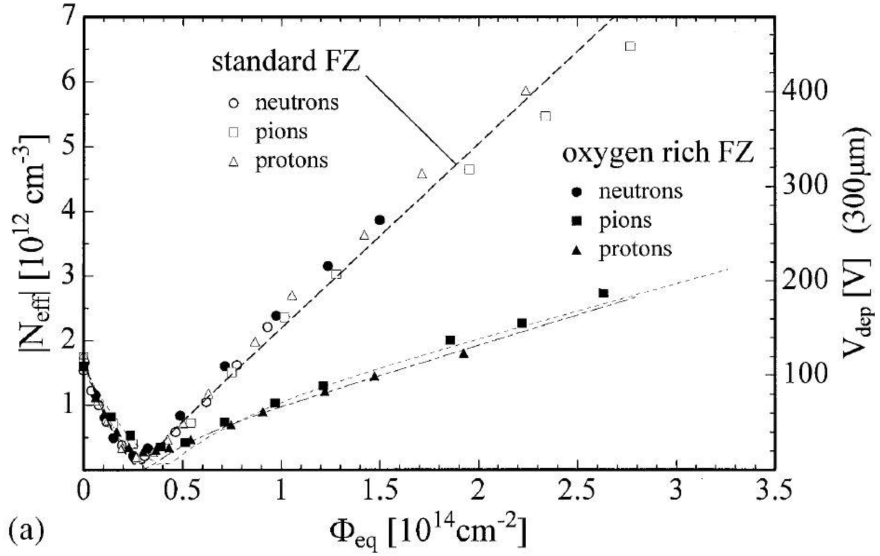
Effective space charge concentration



$$N_{eff} = N_{eff0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq})) + g_C \cdot \Phi_{eq}$$

- Acceptor introduction rate lower with protons than with neutrons

  Common in oxygenated silicon

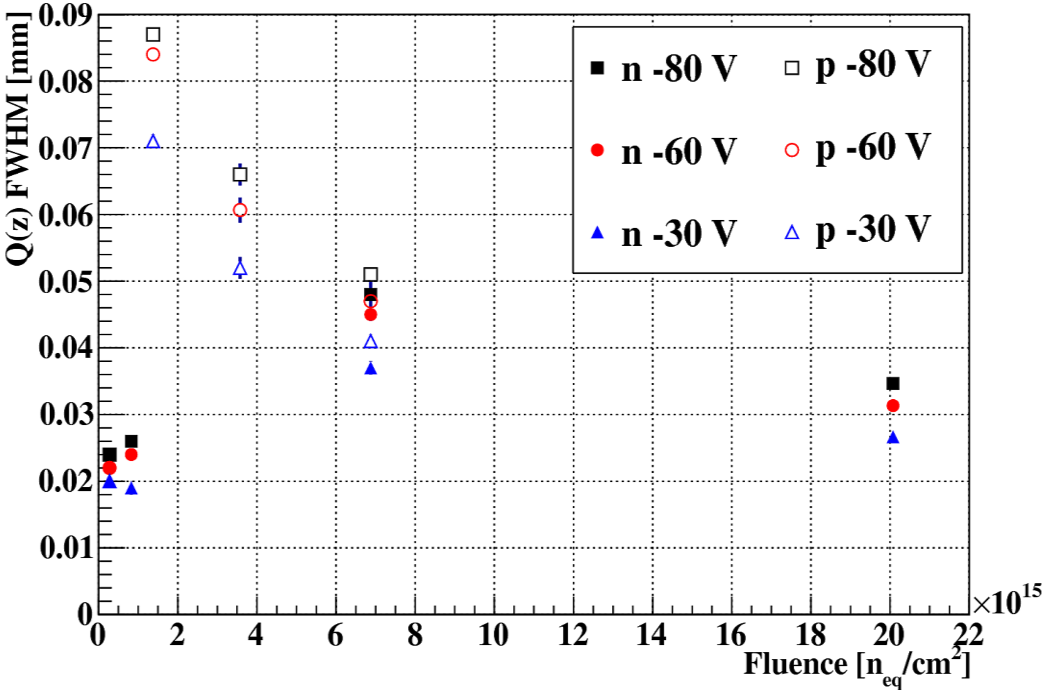


- Possibly large errors on received proton fluence
- Acceptor removal parameters for protons cannot be determined due to a small number of measurement points

G. Lindstroem et al., NIMA 466 (2001) 308–326

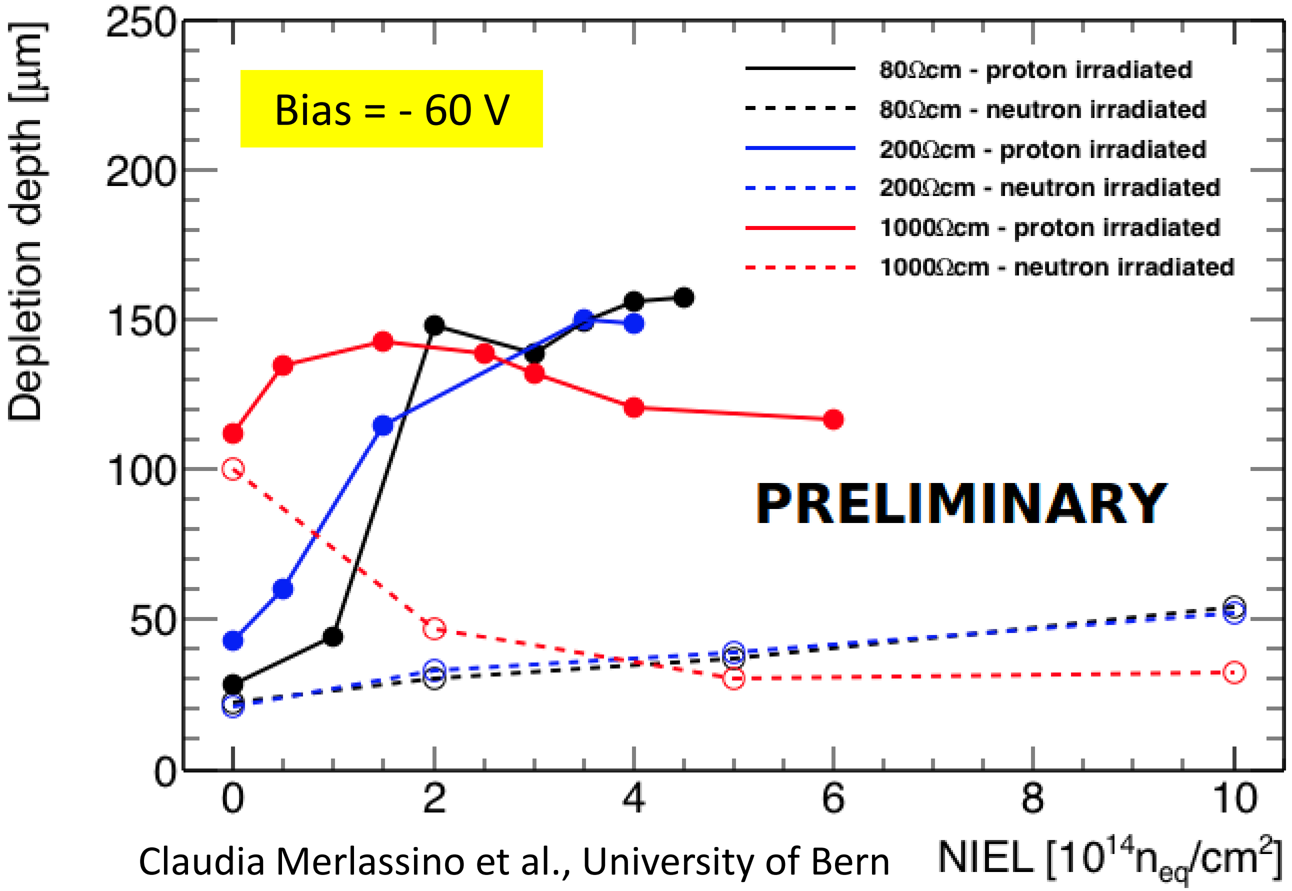
Other measurements with proton irradiated samples

AMS H18 10 Ωcm (CCPDv3)
Depleted depth vs fluence:



M. Fernández, 27th RD50 workshop, December 2015

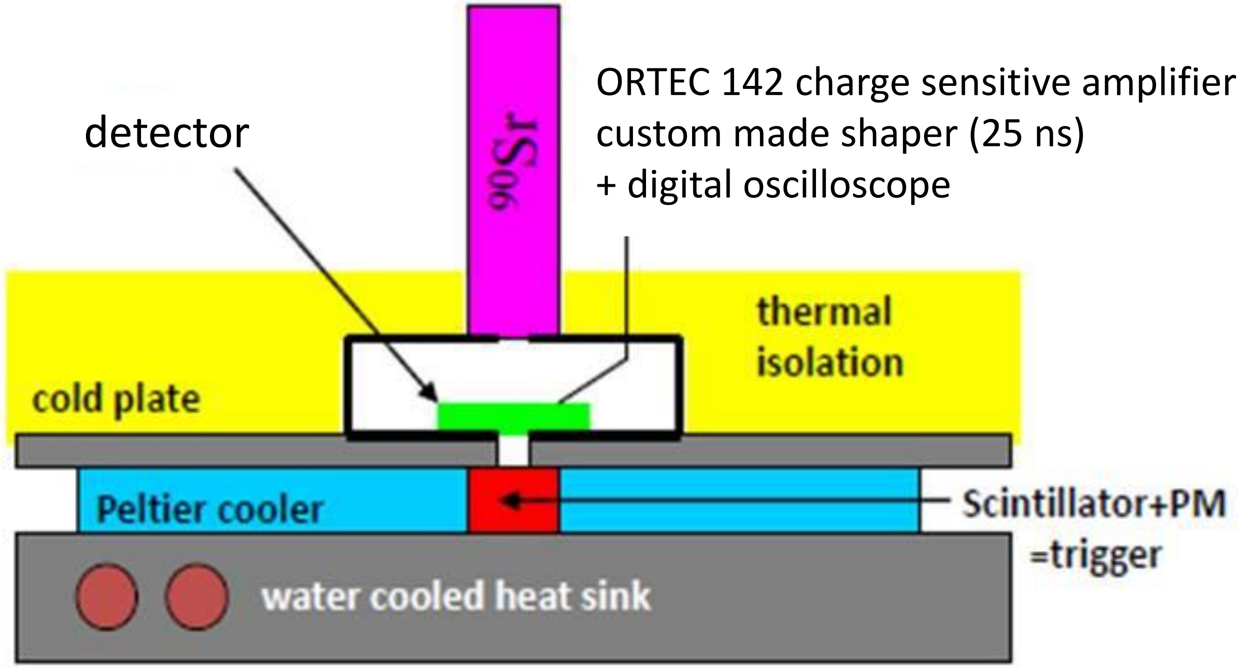
AMS H35 DEMO
Proton irradiation at Bern (18 MeV p)

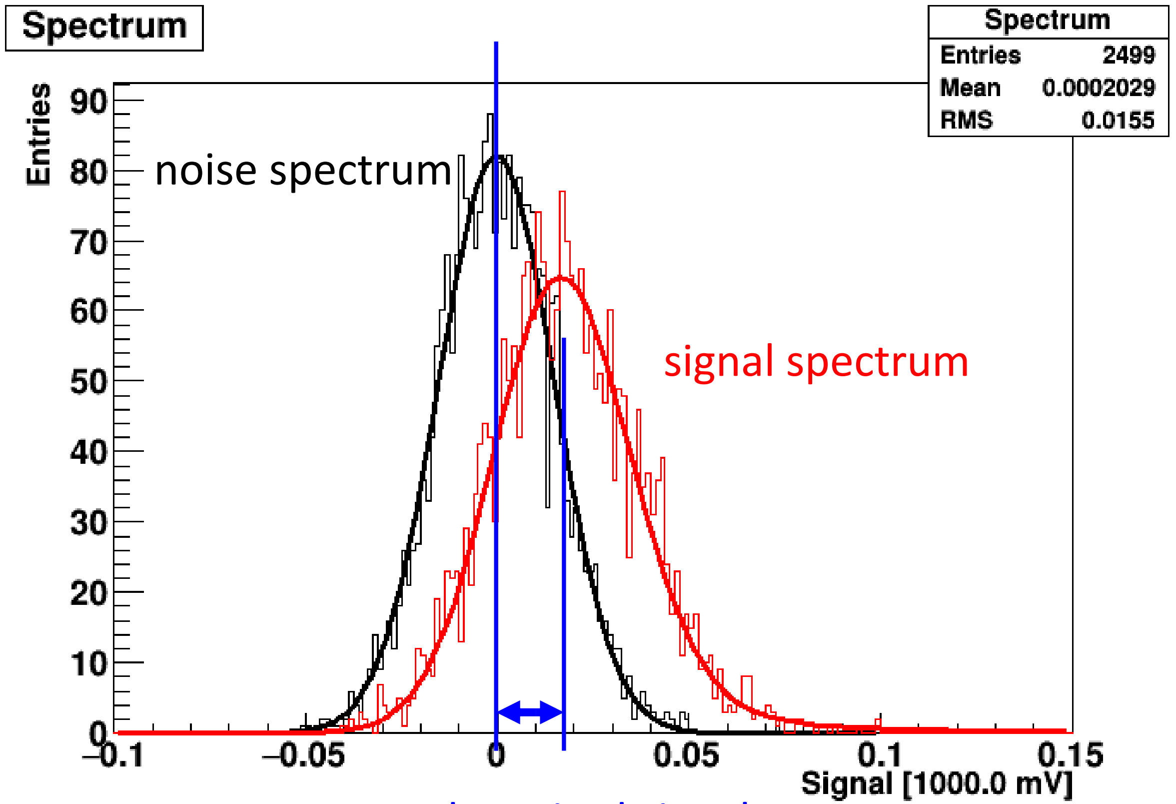


Claudia Merlassino et al., University of Bern

All measurements show very large depletion depth compared to neutron irradiated samples

^{90}Sr setup

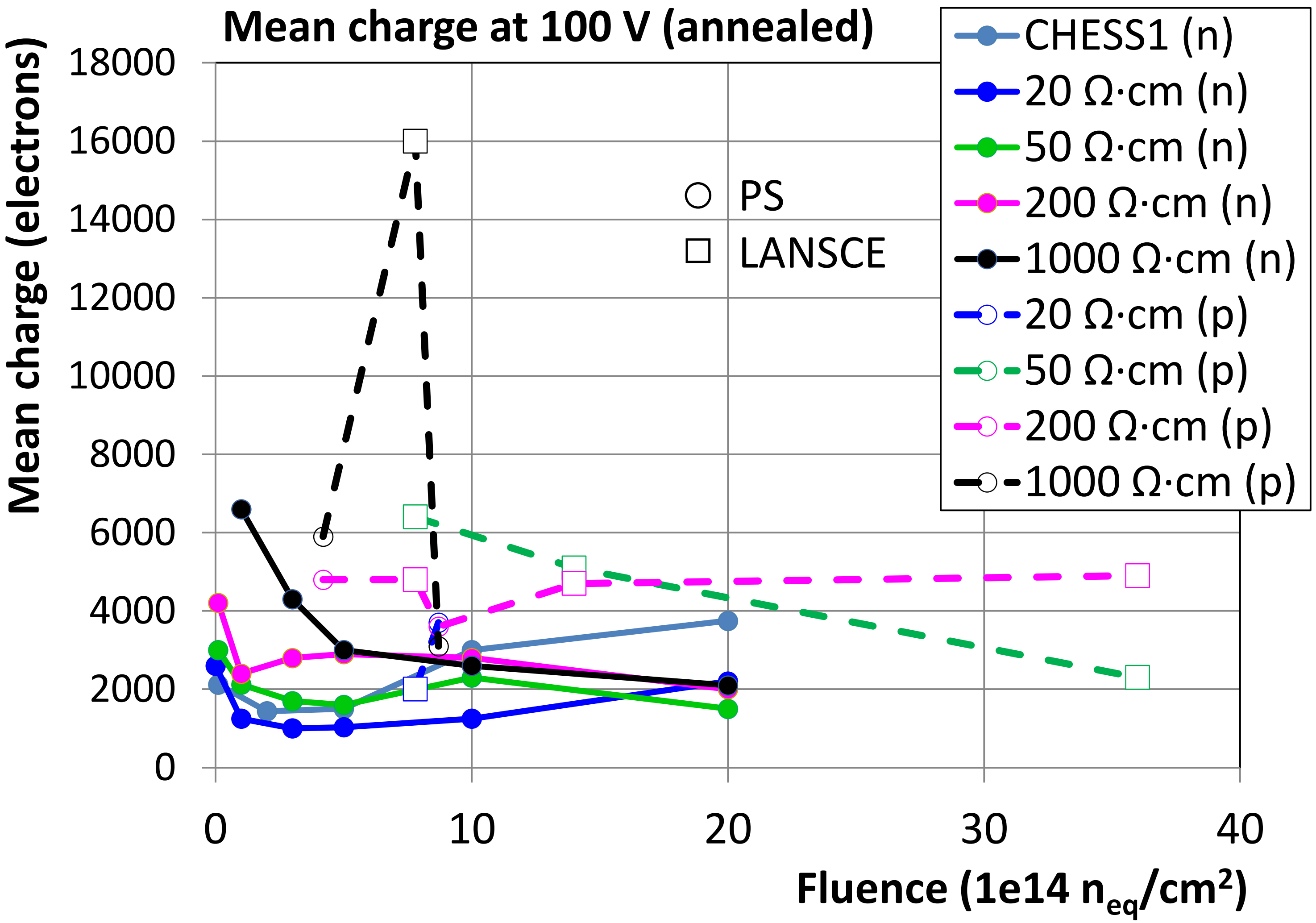




- Measurement:
  - 1) Record *N* (= 2500) waveforms
  - 2) Determine peaking time from the average waveform
  - 3) Sample waveforms at the peak and fill the spectrum
  - 4) Fit the spectrum with a convoluted landau + gauss function

- HV-CMOS: small signals, large noise → S/N low
- Signal strength determined from the shift between triggered and noise spectrum
- System calibrated with epi-diodes of known size

^{90}Sr collected charge



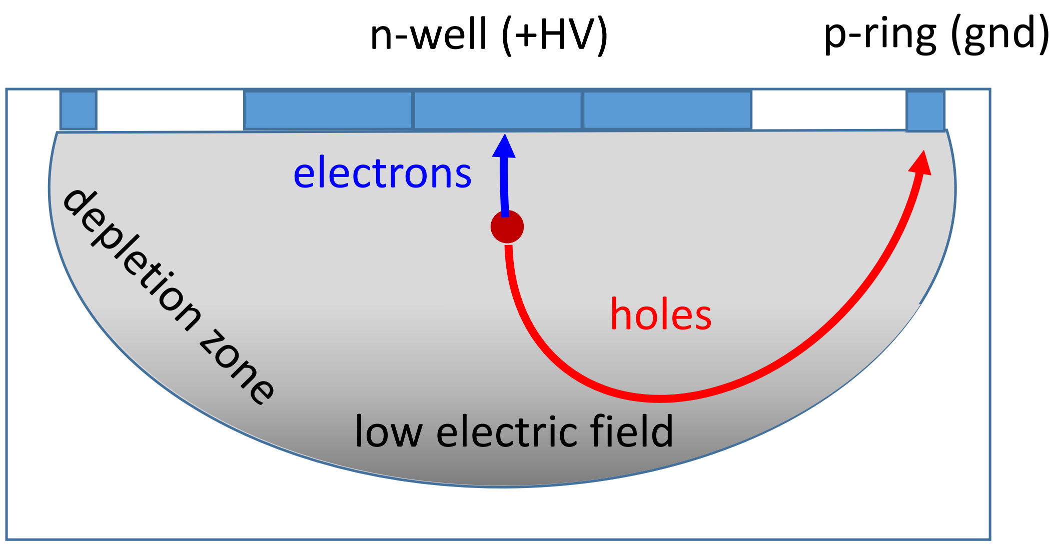
- More charge collected in proton irradiated than in neutron irradiated sample at any fluence/resistivity
- Acceptor removal:

  at certain fluences collected charge is more than before irradiation
- Annealing (not shown)

  10 % more charge after 80 min at 60 °C
- Very constant response of 200 Ω·cm sample with respect to fluence (both n and p)
- In 50 Ω·cm and 200 Ω·cm depletion depth of > 100 μm measured with Edge-TCT
  - Expected mean charge > 10000 e^-
  - Observed charge < 5000 e^-

^{90}Sr collected charge

- In irradiated samples ≈ 50 % less charge collected (^{90}Sr) than expected from Edge-TCT
- The reason for low CCE is due to sensor biasing from the top
  - Drift of both types of charge carriers ends on the chip surface
  - Holes have to drift through a low *E* region, where trapping is high
  - Trapped charge carriers only pass a part of the weighting field
  - The effect is strongly mitigated by thinning and back plane metalization
  - Observed in LFoundry CMOS chips with and without processed back plane

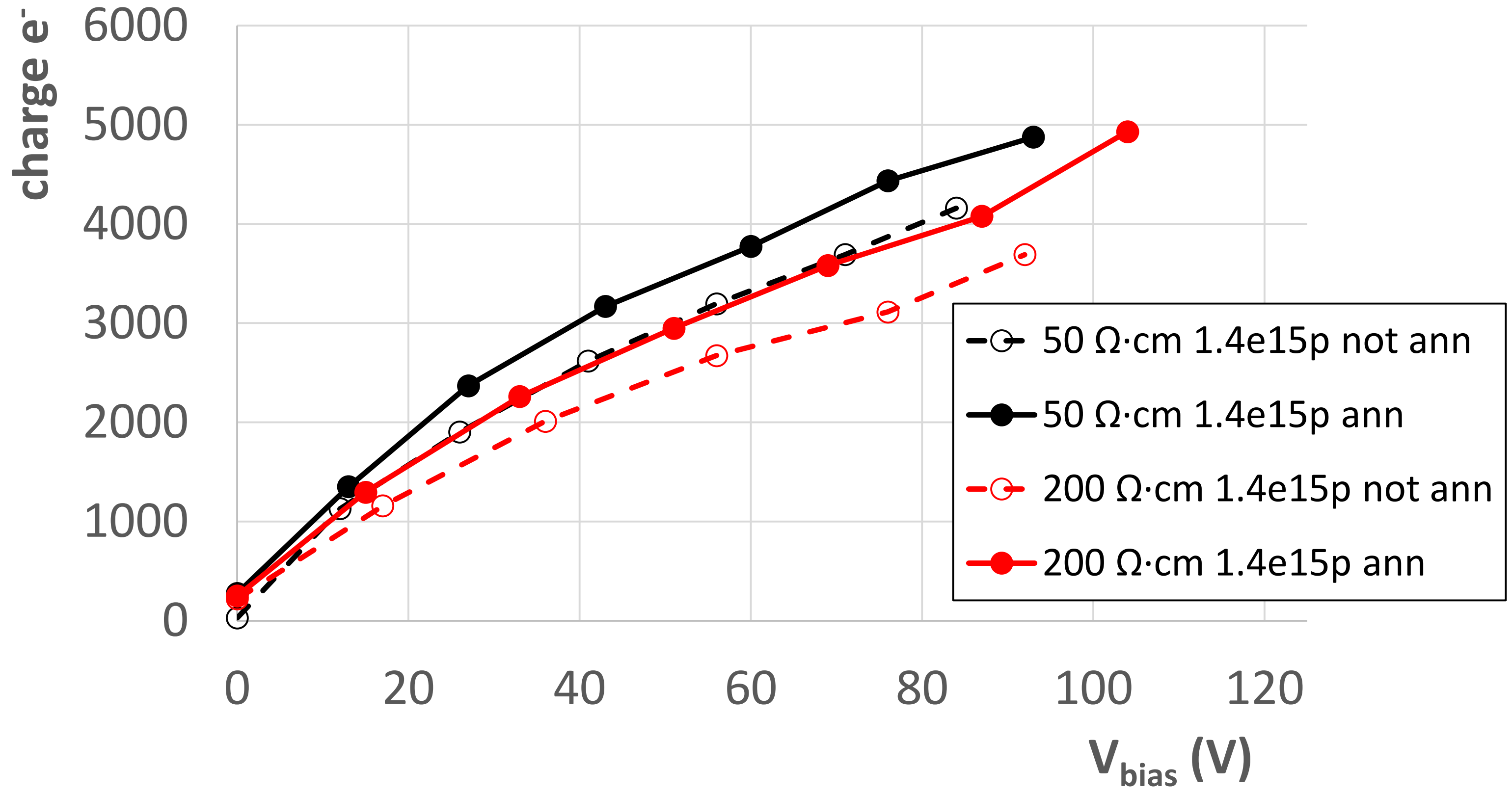


Summary and conclusions

- Extensive sensor radiation hardness study conducted with AMS CHESS 2 samples of different resistivities
  - Proton irradiated, compared to an earlier neutron irradiation
  - Edge-TCT, ^{90}Sr measurements
- Acceptor removal observed in proton irradiated samples
  - Larger depletion depth and greater charge collected than with neutron irradiated samples at all fluences and resistivities
  - Lower acceptor introduction rate than with neutrons
  - Insufficient number of measurement points to determine acceptor removal parameters
- Less charge collected than expected for a measured depletion depth
  - Metalized backplane and back biasing is required
- Large uncertainty on received proton fluence
  - Small dedicated detectors or scanning beam better suited to achieve uniform irradiation level

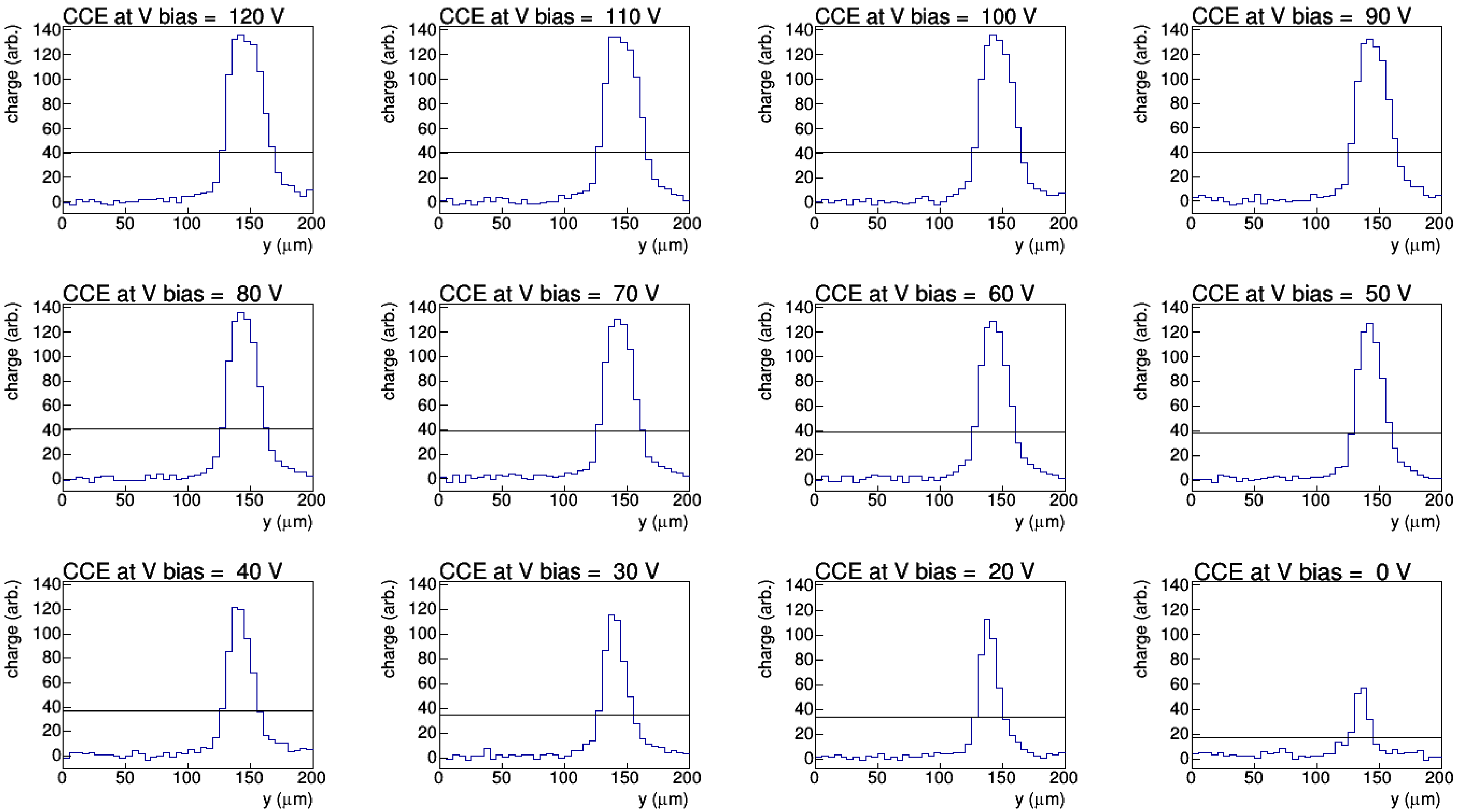
BACKUP

Annealing

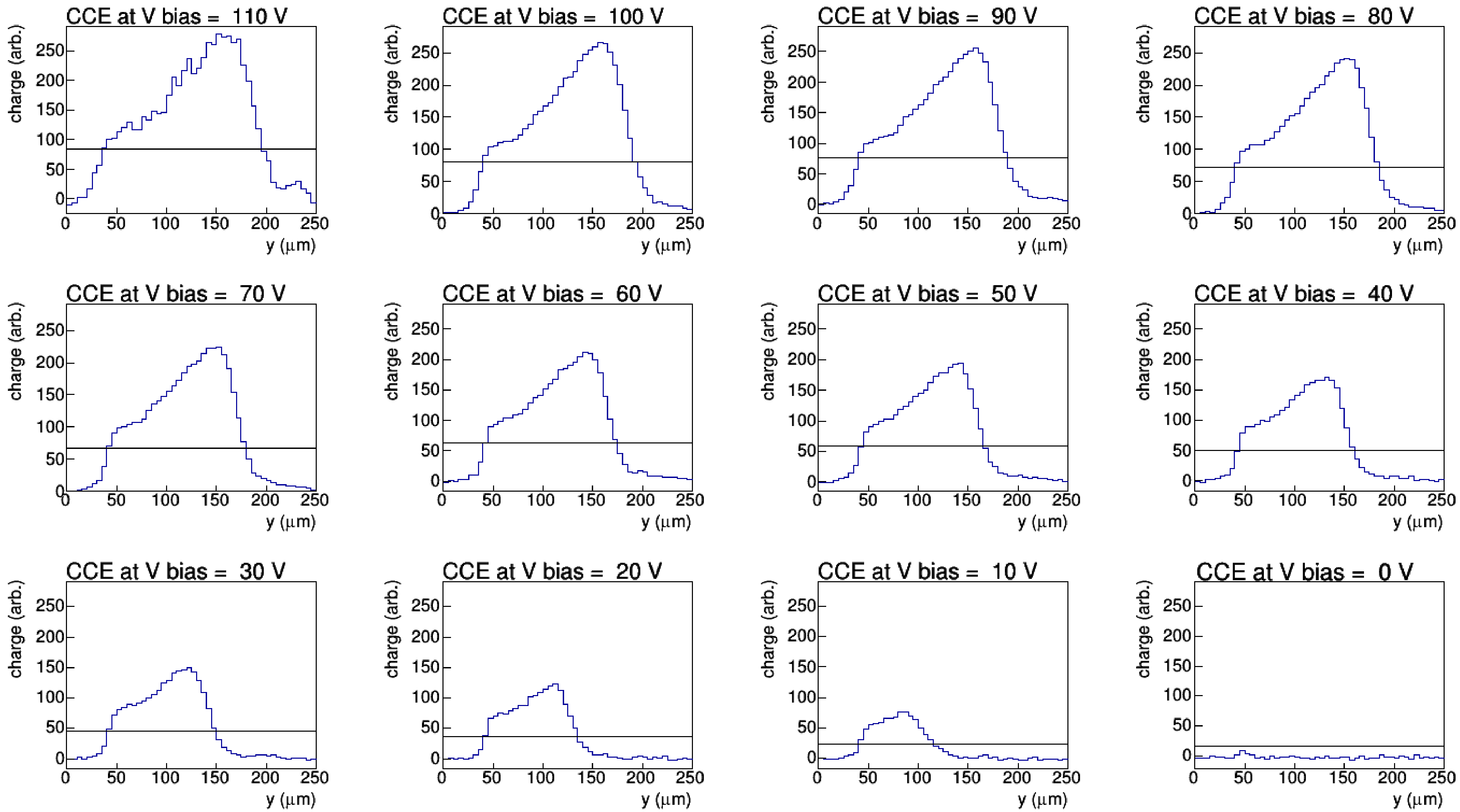


- Collected charge before and after annealing (80 min at 60 °C)
- After annealing about 10 % increase in charge
- Later electrical breakdown in annealed samples

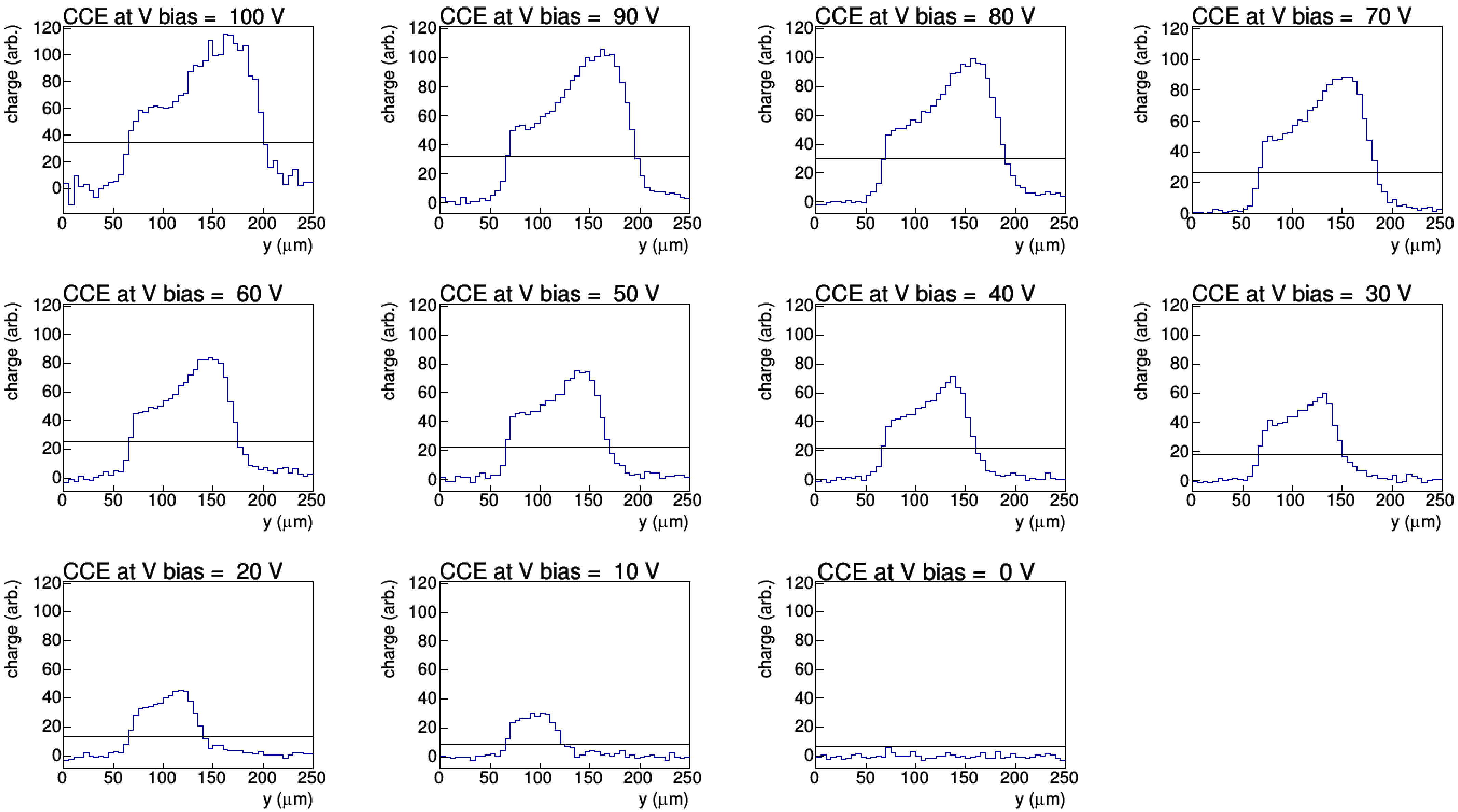
Charge collection profiles 20 Ω·cm (7.8e14p)



Charge collection profiles 50 Ω·cm (1.4e15p)



Charge collection profiles 200 Ω·cm (3.6e15p)



Charge collection profiles 1000 Ω·cm (7.8e14p)