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Radiation effects on charge collection in HV-CMOS detectors

HSTD11 & SOIPIX2017, Okinawa, Japan, 12.12.2017

Bojan Hiti (Jožef Stefan Institute, Ljubljana, Slovenia)

on behalf of

ATLAS Strip CMOS Collaboration

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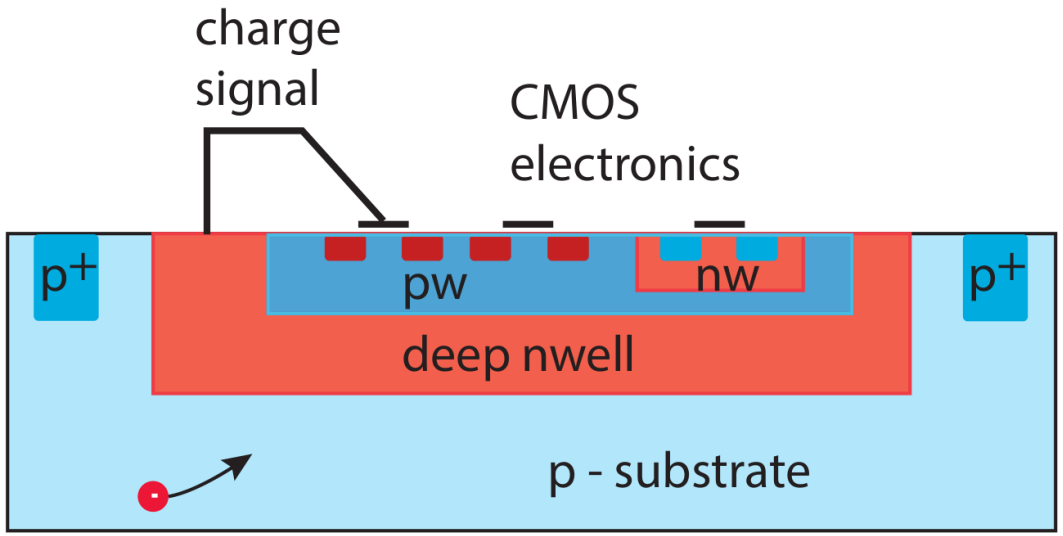
Motivation

- Depleted Monolithic Active Sensors with high voltage addons (HV-CMOS) have been investigated as an option for the ATLAS Phase II ITk upgrade (outermost pixel layer, strips)
- Large fill factor HV-CMOS produced on relatively low resistivity substrate (10 – few 1000 Ω·cm) → **partial depletion**
- Amount of collected charge depends on depletion depth
- Important to determine depletion depth after irradiation



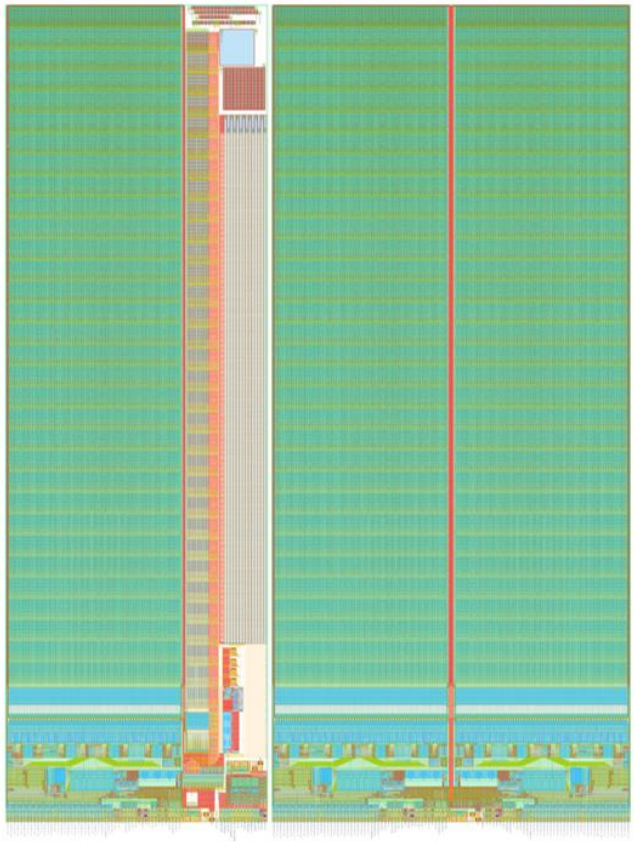
M. Garcia-Sciveres and N. Wermes, arXiv:1705.10150

Radiation hardness requirements for ATLAS pixel layer 4 (similar for strips):	
NIEL:	1e15 n_{eq} cm^{-2}
TID:	80 MRad

CHESS 2 chip

- CHESS 2 chip (large fill factor)
- Full reticle monolithic demonstrator chip of the ATLAS Strip CMOS project
- Designed at UCSC and SLAC, manufactured in the 350 nm technology by AMS
- 3 fully digital striplet arrays, 1 test field with analog test structures
- 4 substrate resistivities (20 – 1000 Ω·cm), *n* in *p*
- Same manufacturer also involved in ATLAS Pixel CMOS project (ATLASPix)

	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/

Sample irradiations

- CHESS 2 irradiations:
  - reactor neutrons (Ljubljana) – 4 resistivities, 5 fluences
  - 24 GeV protons (CERN PS) – 3 resistivities, 2 fluences
  - 800 MeV protons (Los Alamos LANSCE) – 4 resistivities, 3 fluences
- Highest fluences 2e15 n_{eq} cm^{-2} (neutrons) and 3.6e15 n_{eq} cm^{-2} (protons)
- Characterization of passive structures using Edge-TCT and ^{90}Sr
- Measurements before and after annealing (80 min at 60 °C)

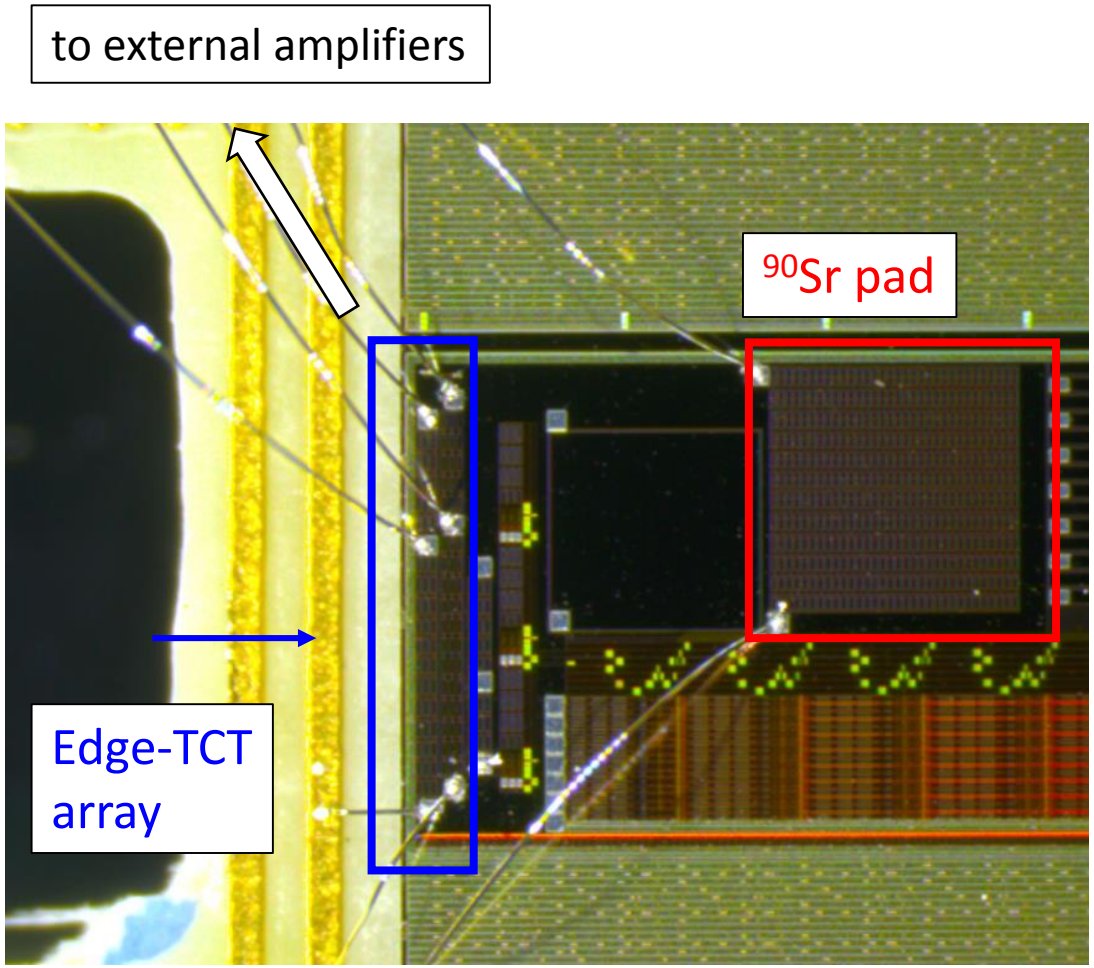
<table>
<tr><th>ϕ
(10^{14} n_{eq} cm^{-2})</th><th>unirrad.</th><th>1
(n)</th><th>3
(n)</th><th>5
(n)</th><th>10
(n)</th><th>20
(n)</th><th>4.2
(p)</th><th>7.8
(p)</th><th>8.7
(p)</th><th>14
(p)</th><th>36
(p)</th></tr>
<tr><td>20 Ω·cm</td><td></td><td colspan="5" rowspan="4">Ljubljana</td><td>CERN PS</td><td rowspan="4">LANSCE</td><td>CERN PS</td><td>n.a.</td><td>n.a.</td></tr>
<tr><td>50 Ω·cm</td><td></td><td>n.a.</td><td>n.a.</td><td colspan="2" rowspan="2">LANSCE</td></tr>
<tr><td>200 Ω·cm</td><td></td><td rowspan="2">CERN PS</td><td rowspan="2">CERN PS</td></tr>
<tr><td>1000 Ω·cm</td><td>breakdown</td><td>n.a.</td><td>n.a.</td></tr>
</table>

Test structures

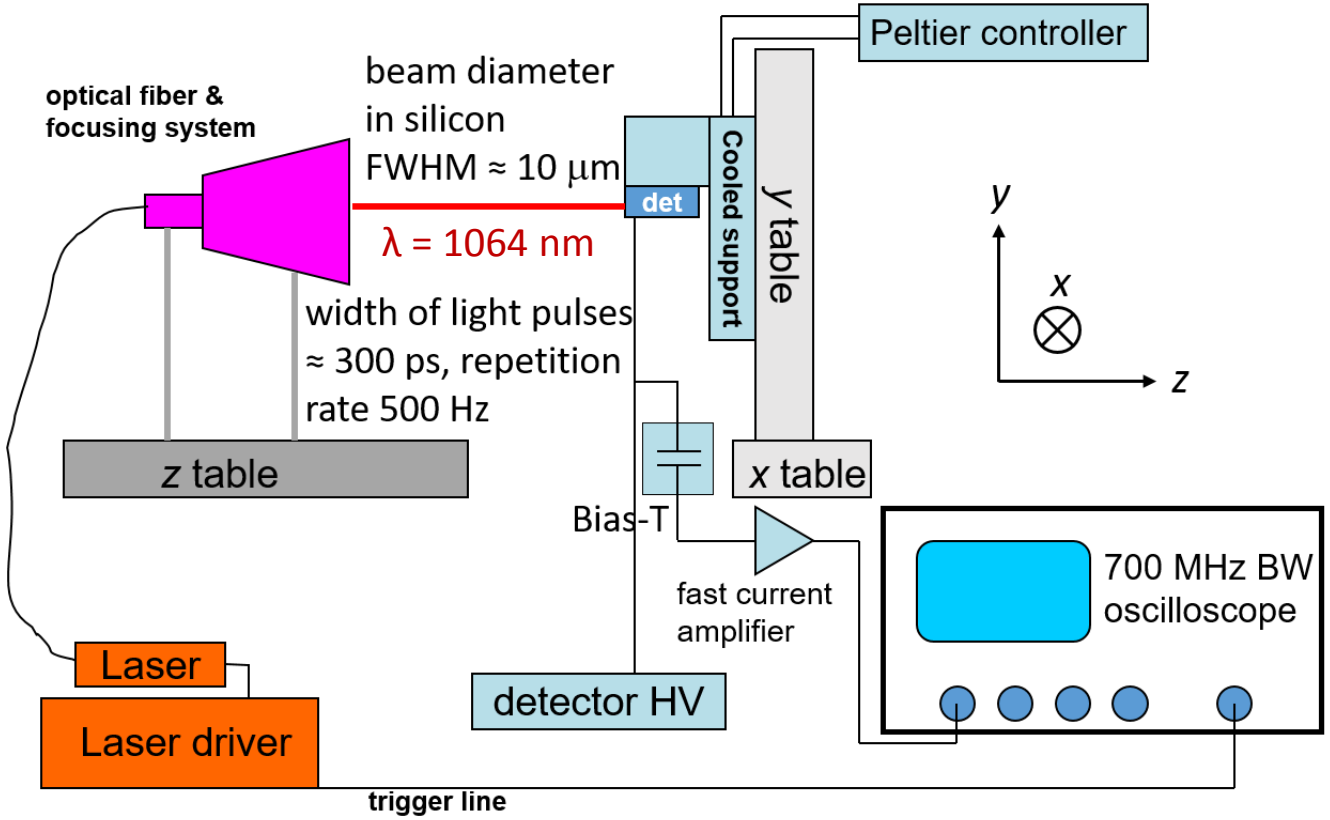
Passive test structures:

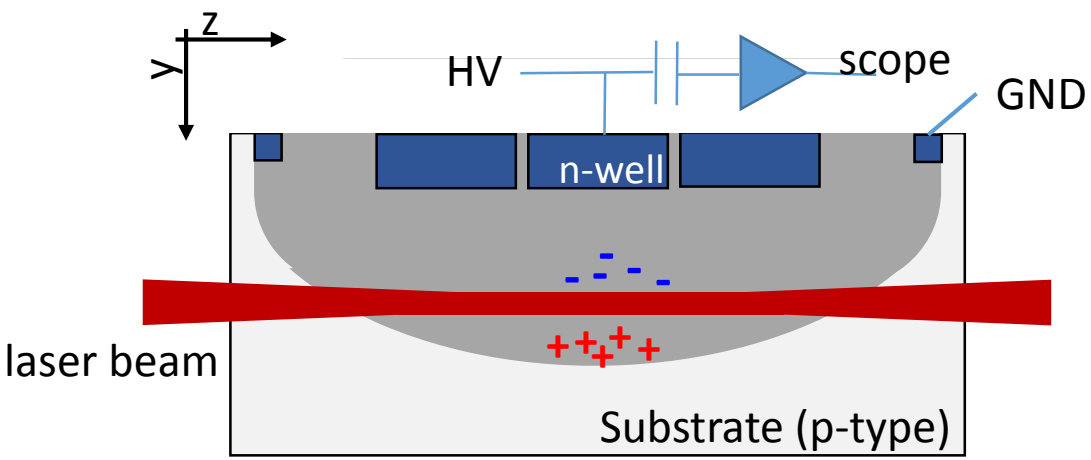
- 3 x 3 pixel array for Edge-TCT (pixel size 630 x 40 μm^2)
- Large pad for ^{90}Sr measurements (1.2 x 1.2 mm^2)

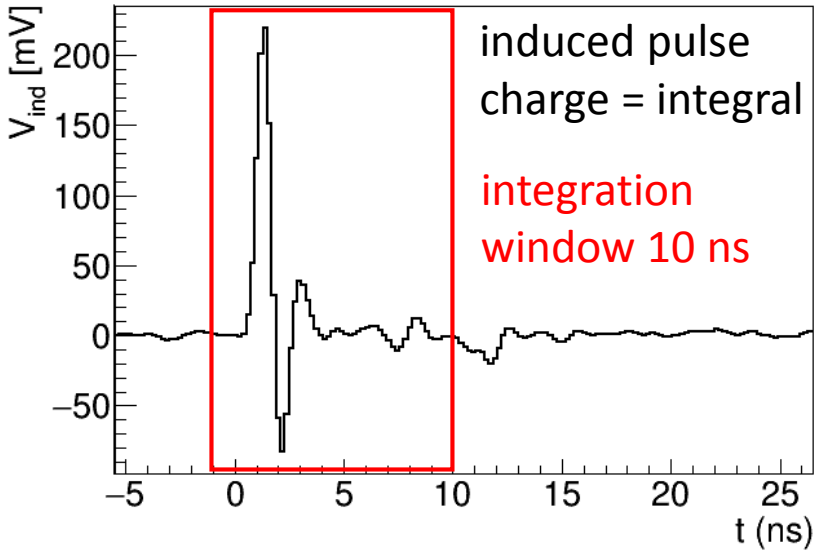
Bias voltage up to 120 V can be applied



Edge-TCT setup

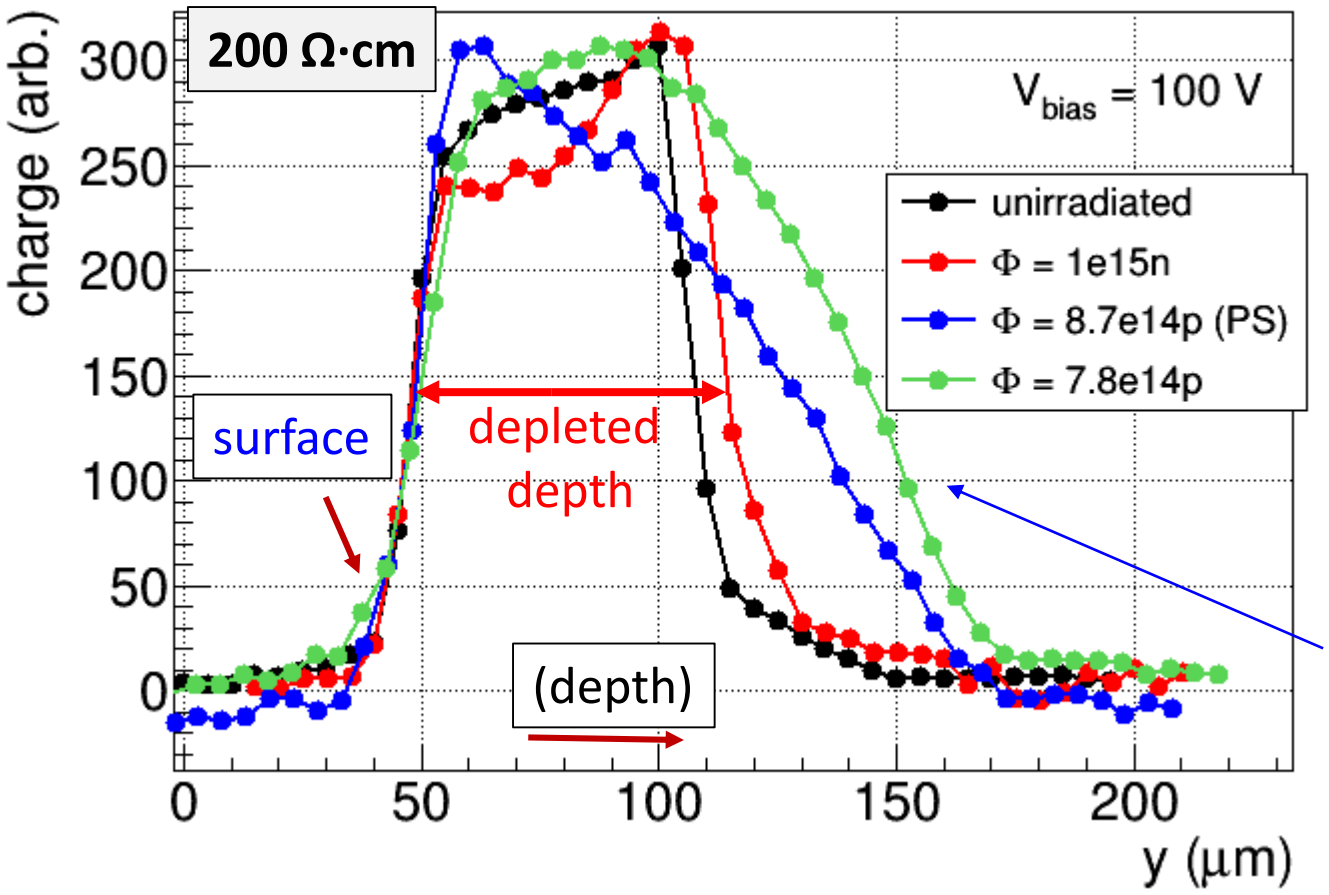


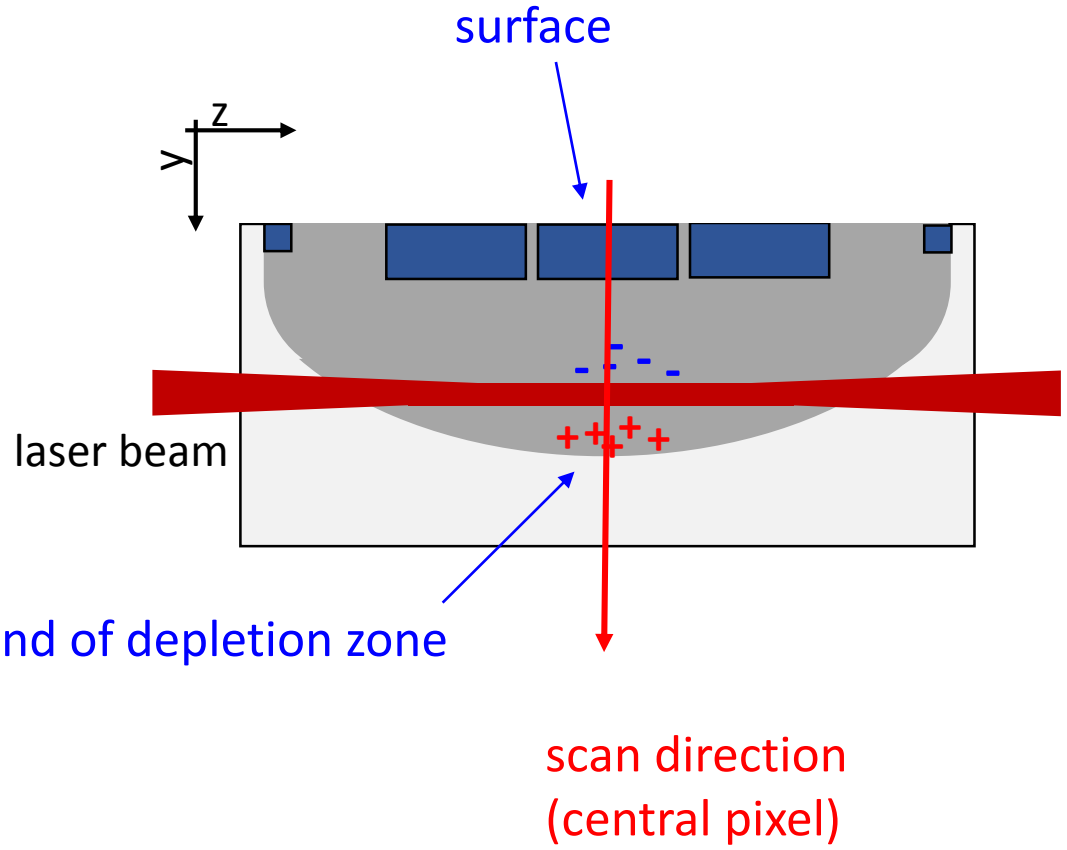




(more details: www.particulars.si)

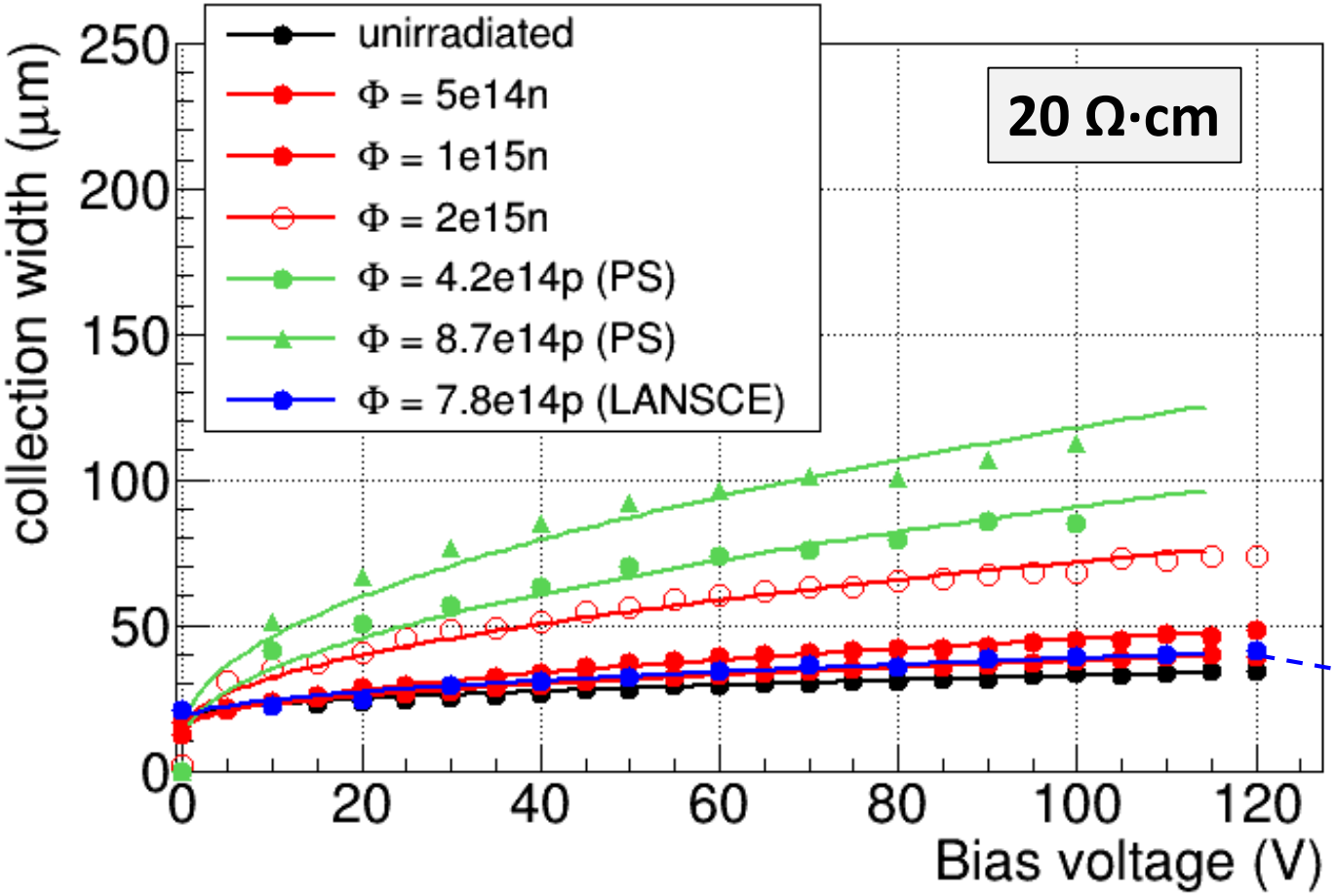
Charge collection profiles





Depleted depth = width of the charge collection profile

Depletion vs. bias voltage (20 Ω·cm)



From voltage dependence effective space charge concentration N_{eff} is extracted by fitting:

$$\mathrm{Width}(V_{bias}) = \underbrace{w_0}_{\text{0 V offset}} + \underbrace{\sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} V_{bias}}}_{\text{constant space charge approximation}}$$

LANSCE sample different from PS samples (received local fluence less than nominal)

Depletion depth increases after irradiation (acceptor removal – later)
Depletion depth is larger after irradiation with protons than with neutrons

Received proton fluence at LANSCE

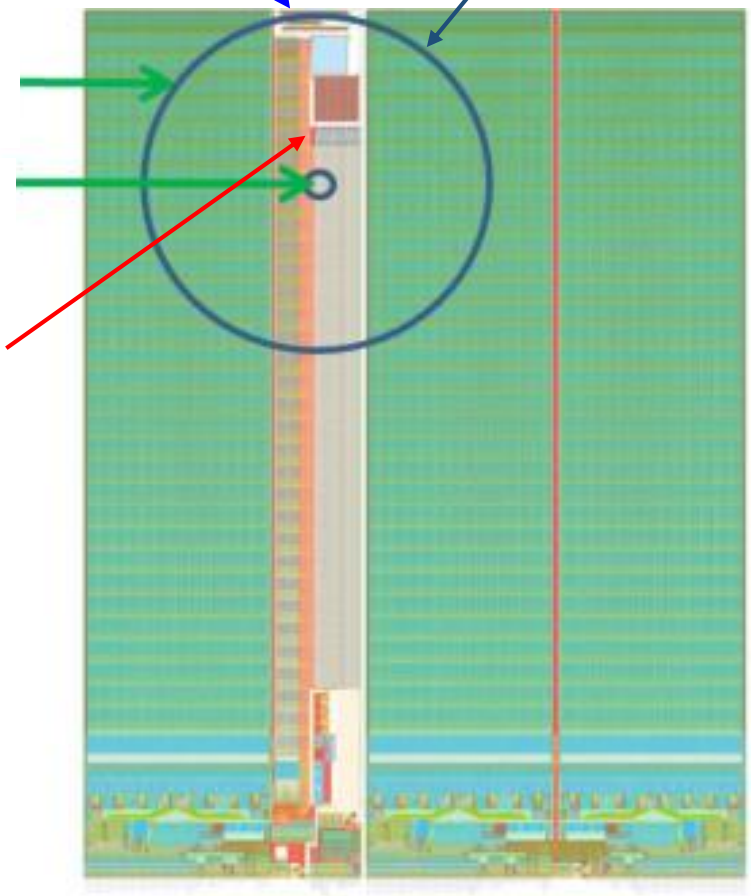
Edge-TCT structure
local fluence probably
less than nominal

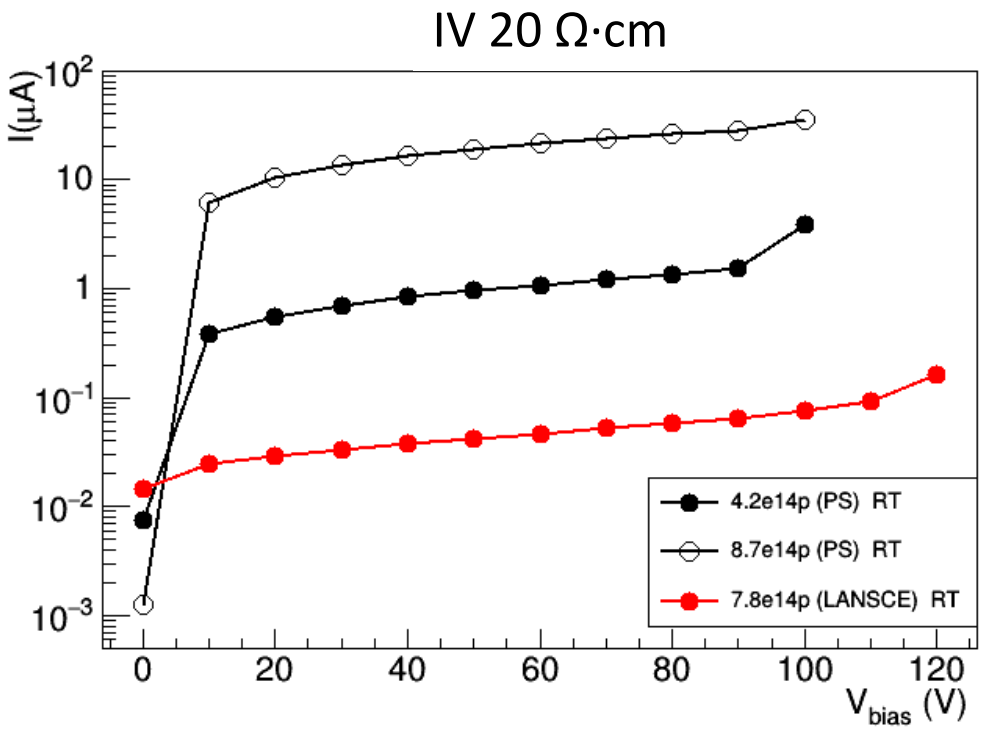
proton beam
position at LANSCE

σ = 0.5 cm
beam radius

beam target

^{90}Sr pad

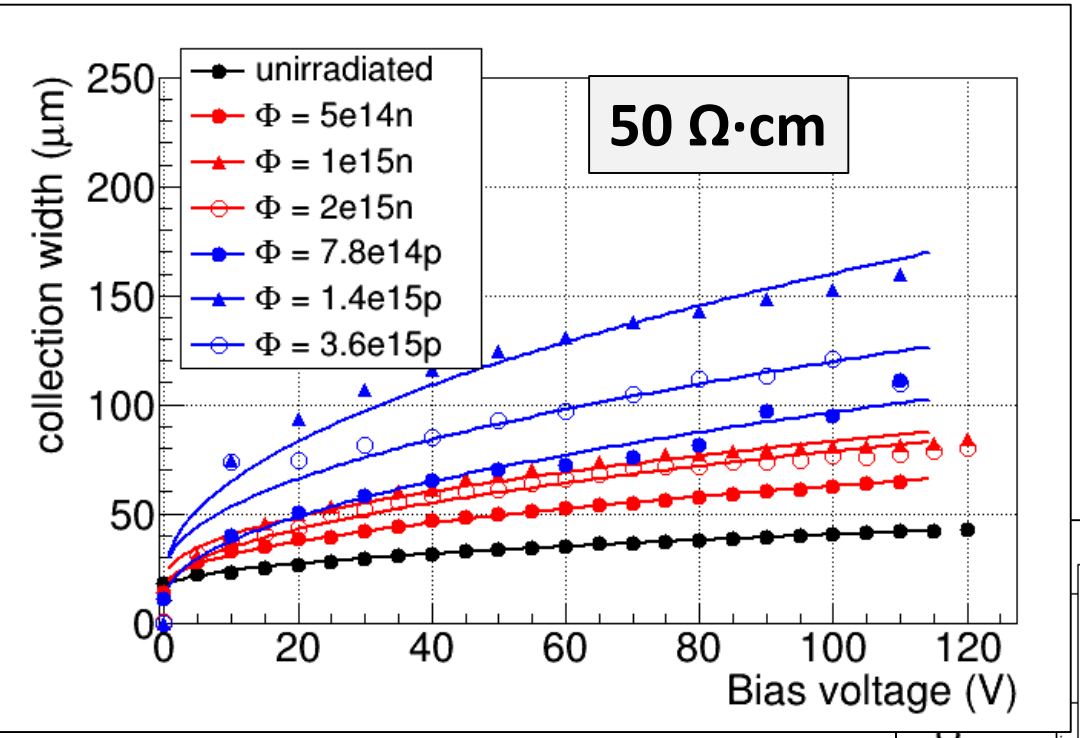




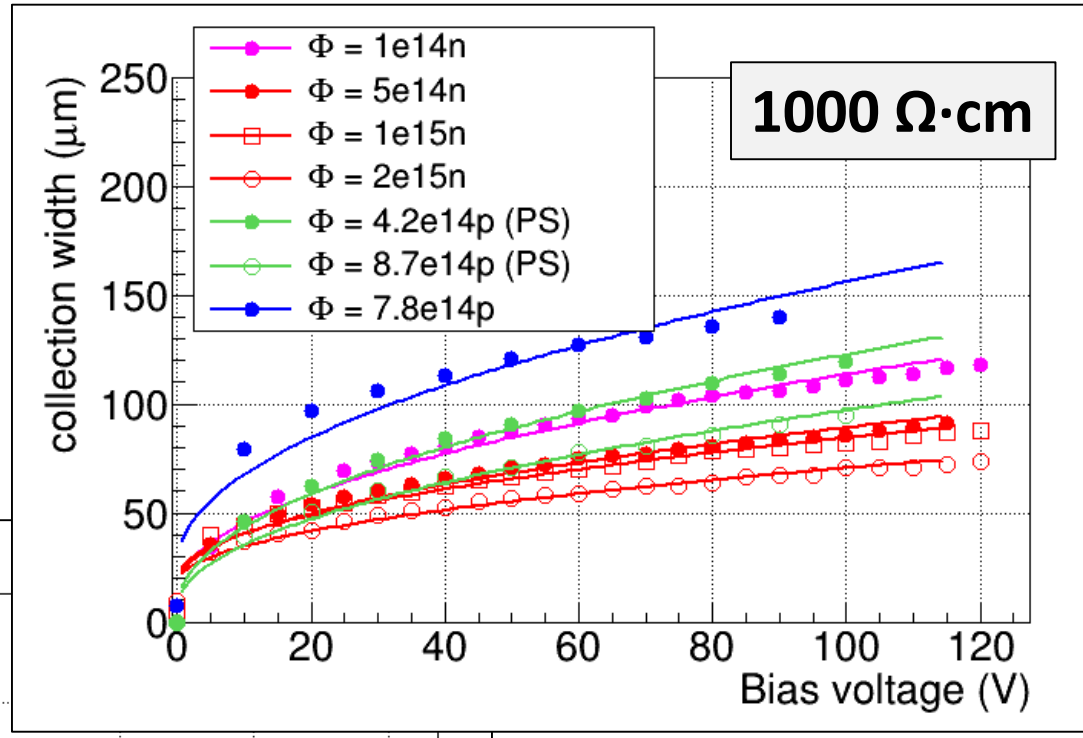
Due to the beam position at LANSCE the received fluence in the Edge-TCT structure is relatively sensitive to placement precision.

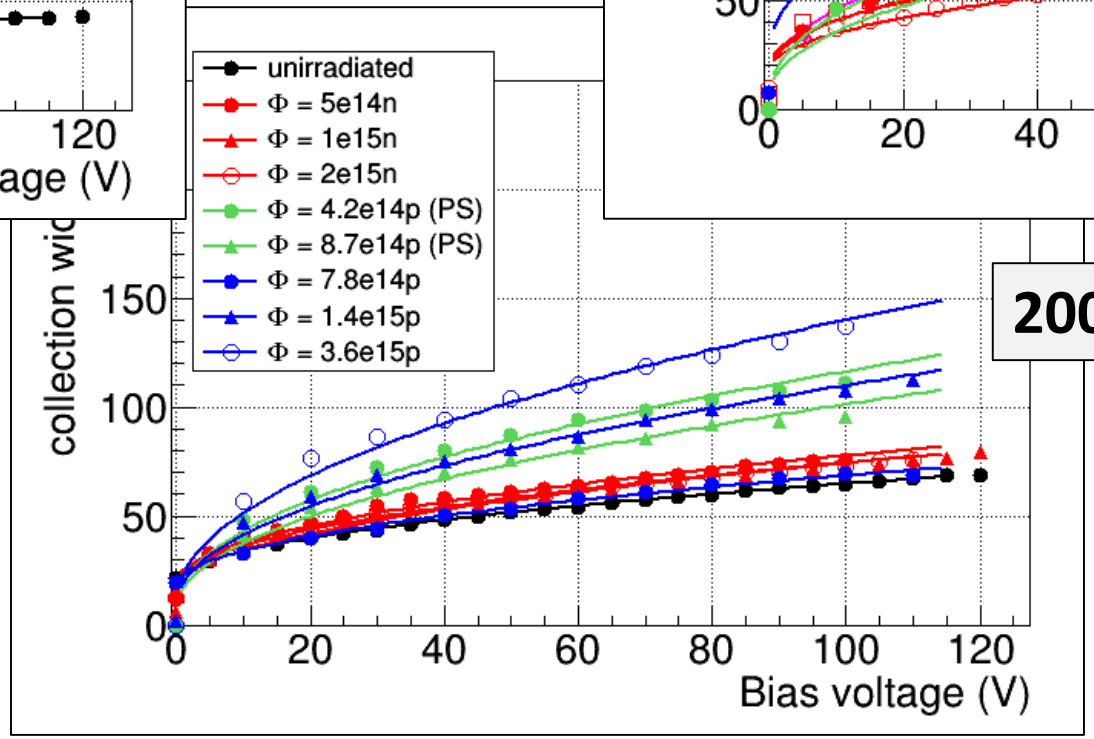
Large error margins on fluence have to be assumed.

Depletion depth at remaining resistivities



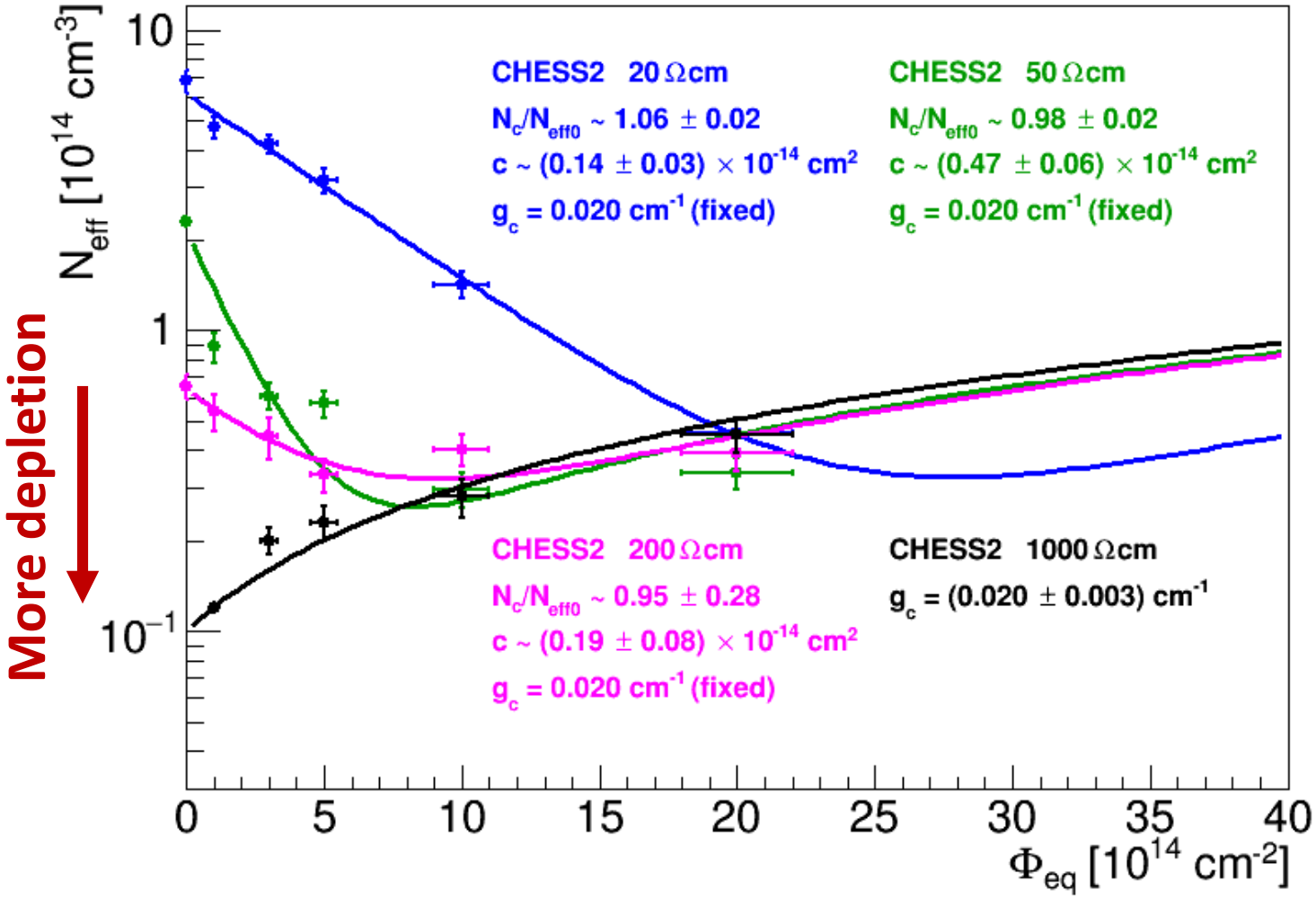
black – unirrad.
red – neutrons
green – PS
blue – LANSCE





- Acceptor removal observed
- Greater depletion depth in proton irradiated samples
- Depletion depths > 100 μm are reached
- N_{eff} extracted for all samples

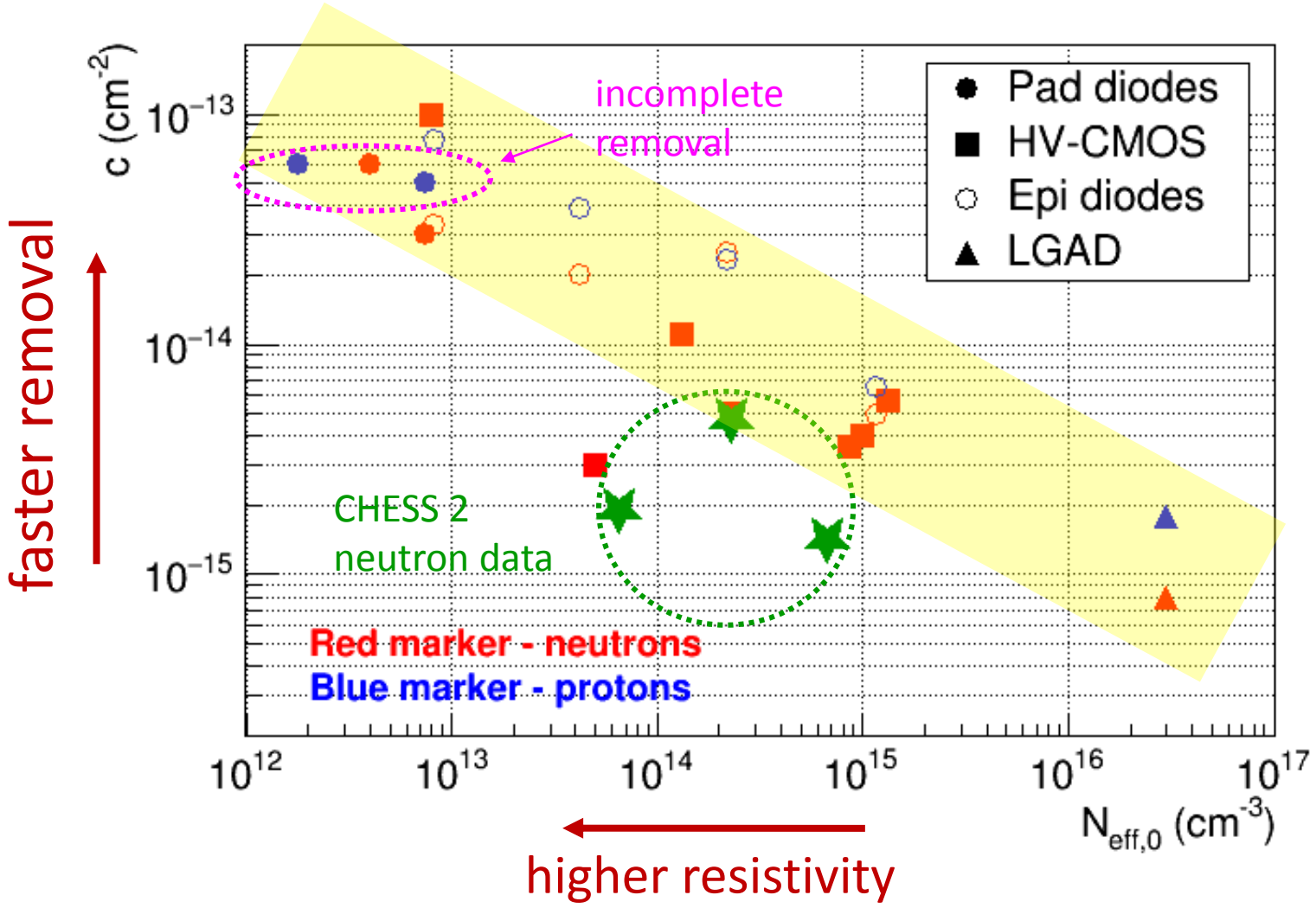
Effective space charge concentration – neutron irradiated samples



$$N_{eff} = N_{eff0} - \underbrace{N_c \cdot (1 - \exp(-c \cdot \Phi_{eq}))}_{\text{acceptor removal}} + \underbrace{g_C \cdot \Phi_{eq}}_{\text{acceptor introduction}}$$

- N_{eff} evolution with fluence described by the acceptor removal model
  - Removal of initial acceptors at lower fluences (beneficial for HV-CMOS)
  - Introduction with constant rate dominant at higher fluences
- Removal rate dependent on initial doping concentration – parameter *c*
- Complete removal observed with neutron irradiation $N_c / N_{eff,0} \approx 1$
- 1000 Ω·cm:
  no measurement before irradiation, more measurements at low fluences are needed to evaluate acceptor removal

Acceptor removal constant



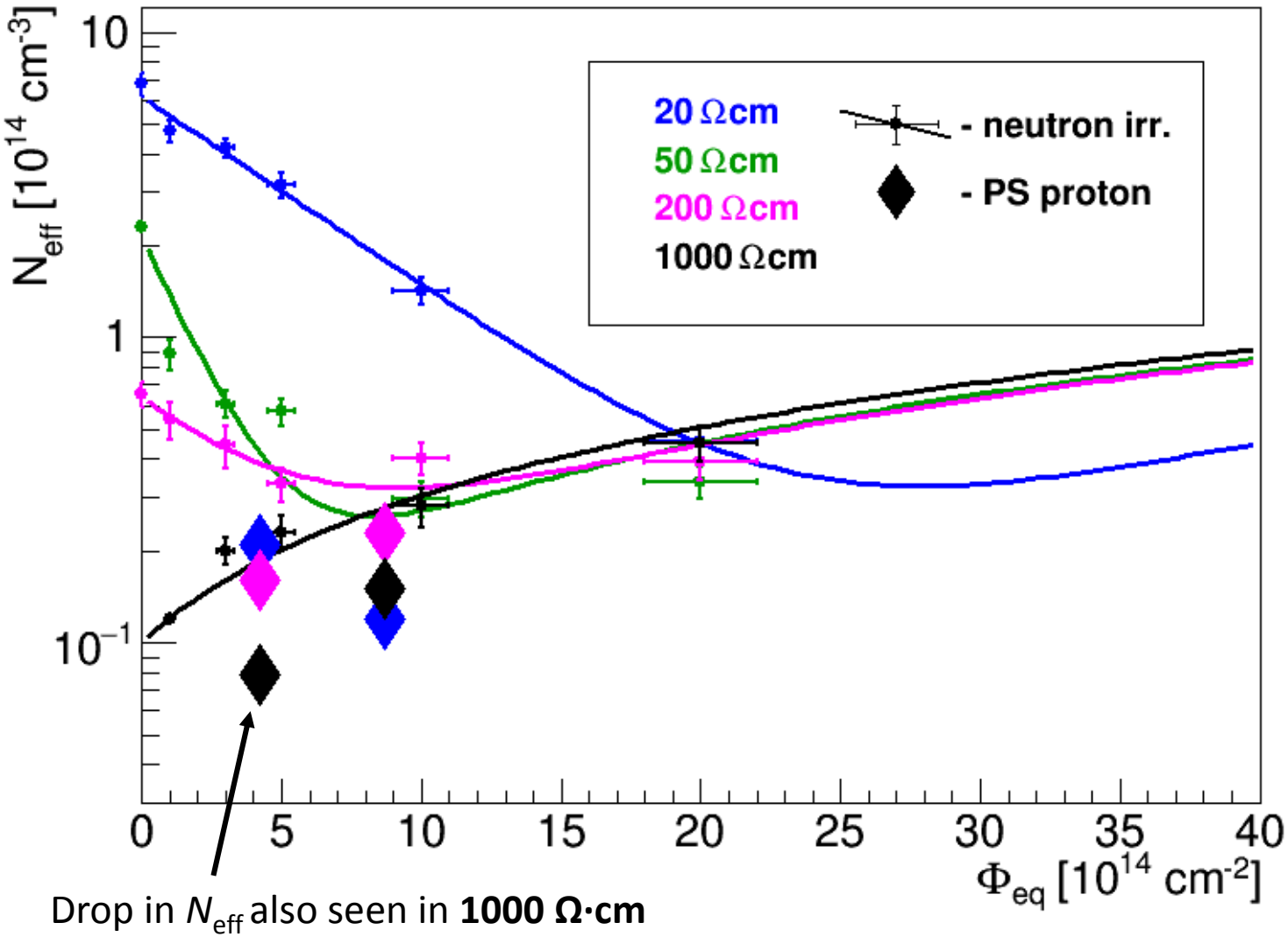
$$N_{\mathrm{eff}} = N_{\mathrm{eff0}} - N_{\mathrm{c}} \cdot (1 - \exp(-c \cdot \Phi_{\mathrm{eq}})) + g_{\mathrm{C}} \cdot \Phi_{\mathrm{eq}}$$

- A wide range of acceptor removal measurements available in literature
- General trend:
  Higher initial resistivity → faster removal
  The underlying process not yet understood
- With CHESS 2 chip measured removal rate is slower than in samples with similar doping

Epi diodes:	*P. Dias de Almeida,* 30th RD50 Workshop, 2017
LGAD, Pad diodes:	*G. Kramberger,* 10th Trento Worksop, 2015

HV-CMOS: *A. Affolder et al.,* JINST 11 P04007 2016
I. Mandić et al., JINST 12 P02021 2017
E. Cavallaro et al., JINST 12 C01074 2017
B. Hiti et al., JINST 12 P10020 2017

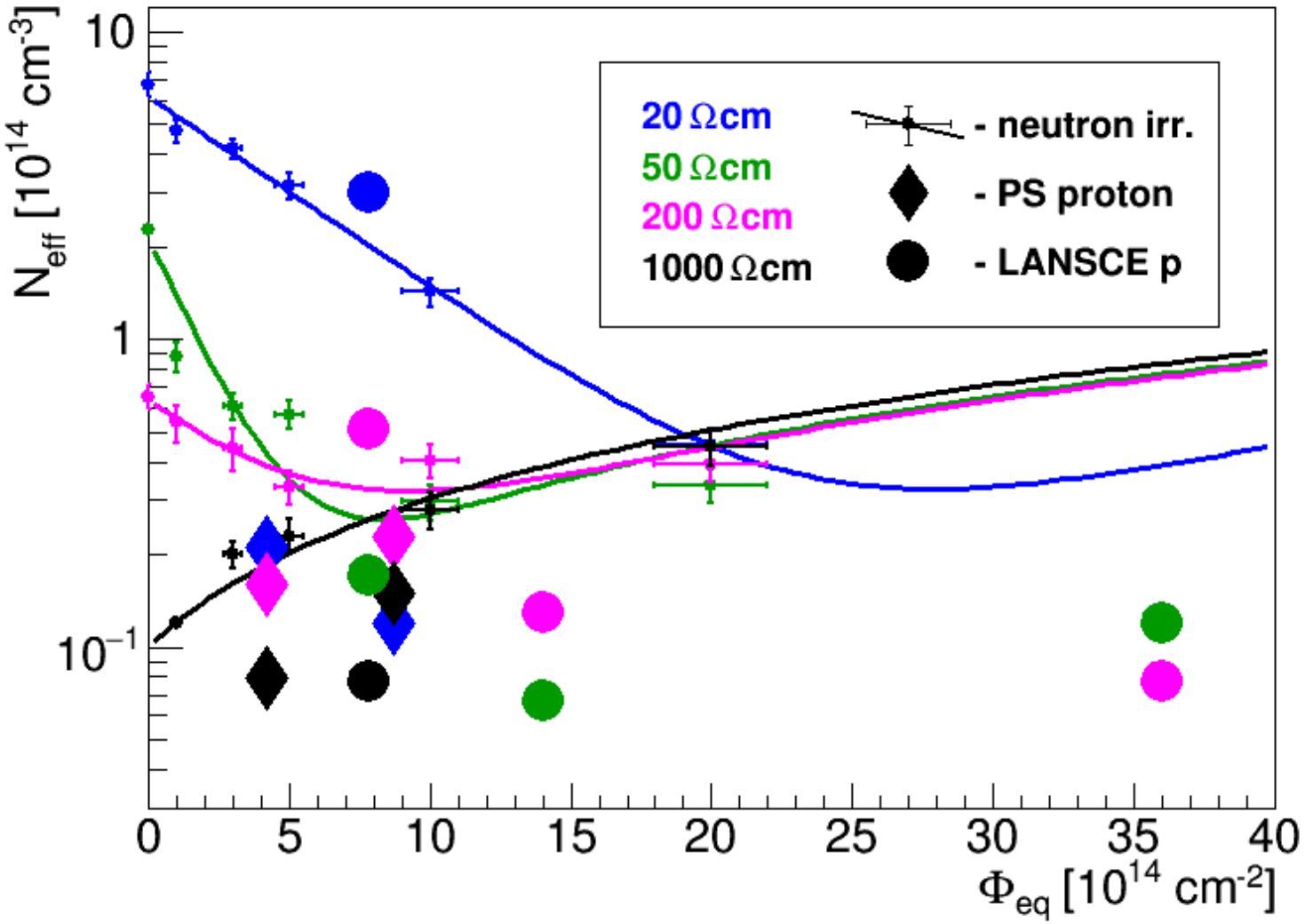
Effective space charge concentration – PS protons



Drop in N_{eff} also seen in **1000 Ω·cm**

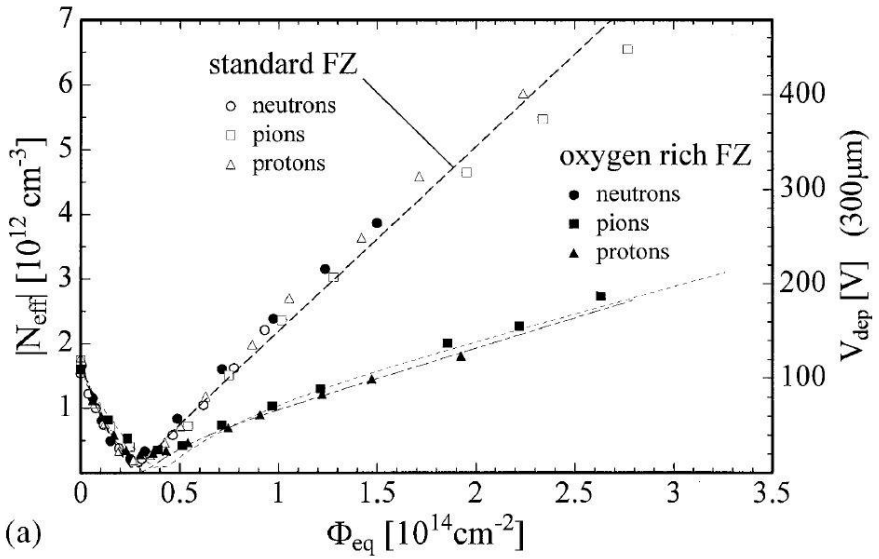
- In all measurements with proton irradiated (PS) samples N_{eff} is below the neutron irradiated samples
- Acceptor removal faster with protons than with neutrons

Effective space charge concentration – LANSCE protons



- LANSCE samples: received fluence is not known precisely
- High fluences: acceptor introduction rate lower with protons

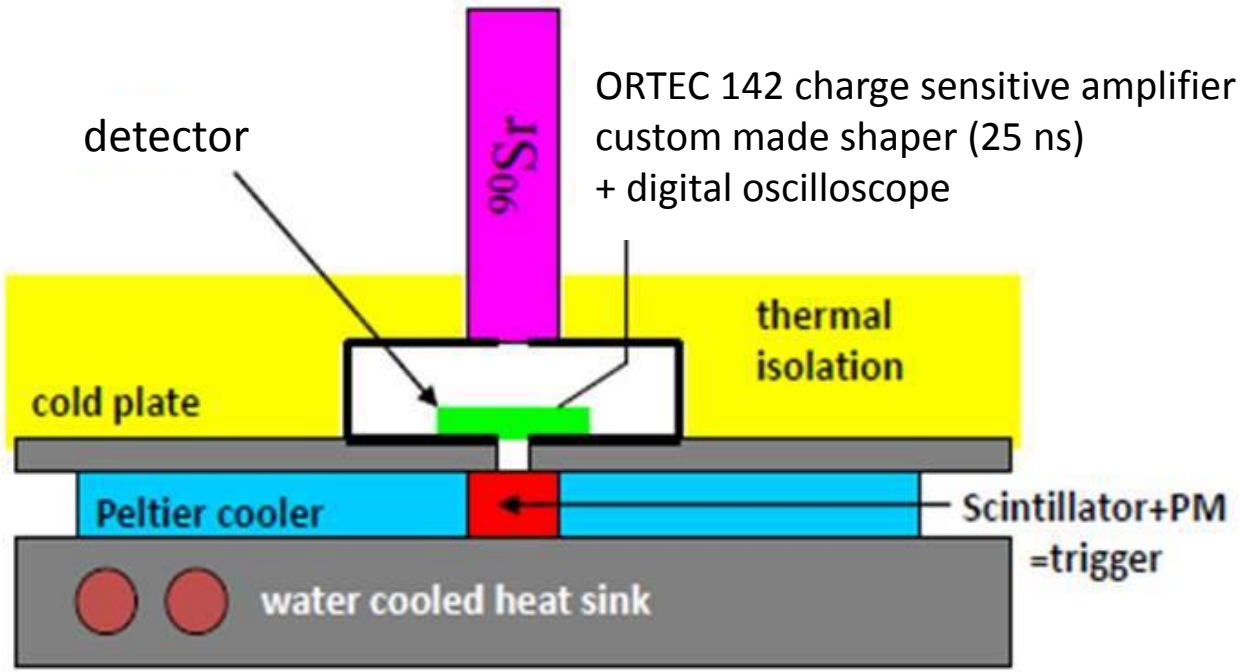
  Common in oxygen rich silicon (literature: g_C = 0.01 cm^{-1})

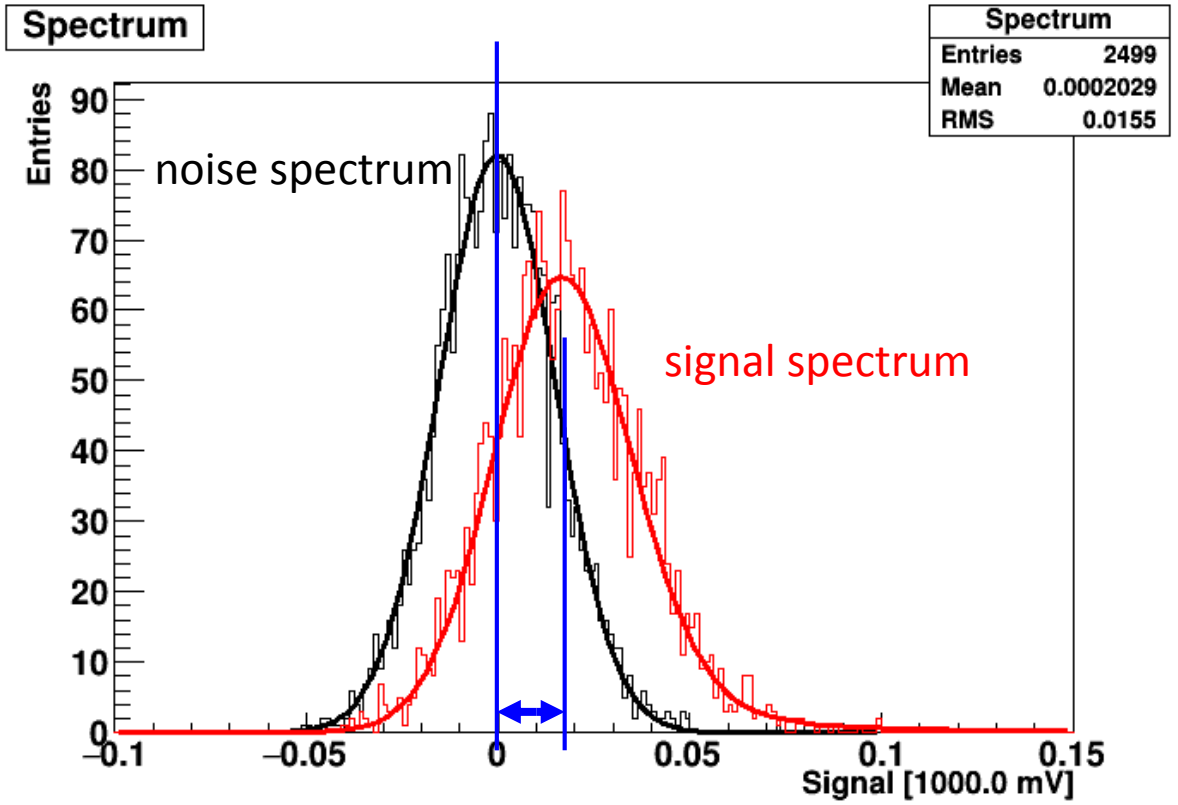


G. Lindstroem et al., NIMA 466 (2001) 308–326

- Insufficient number of points to fit the acceptor removal function

^{90}Sr setup

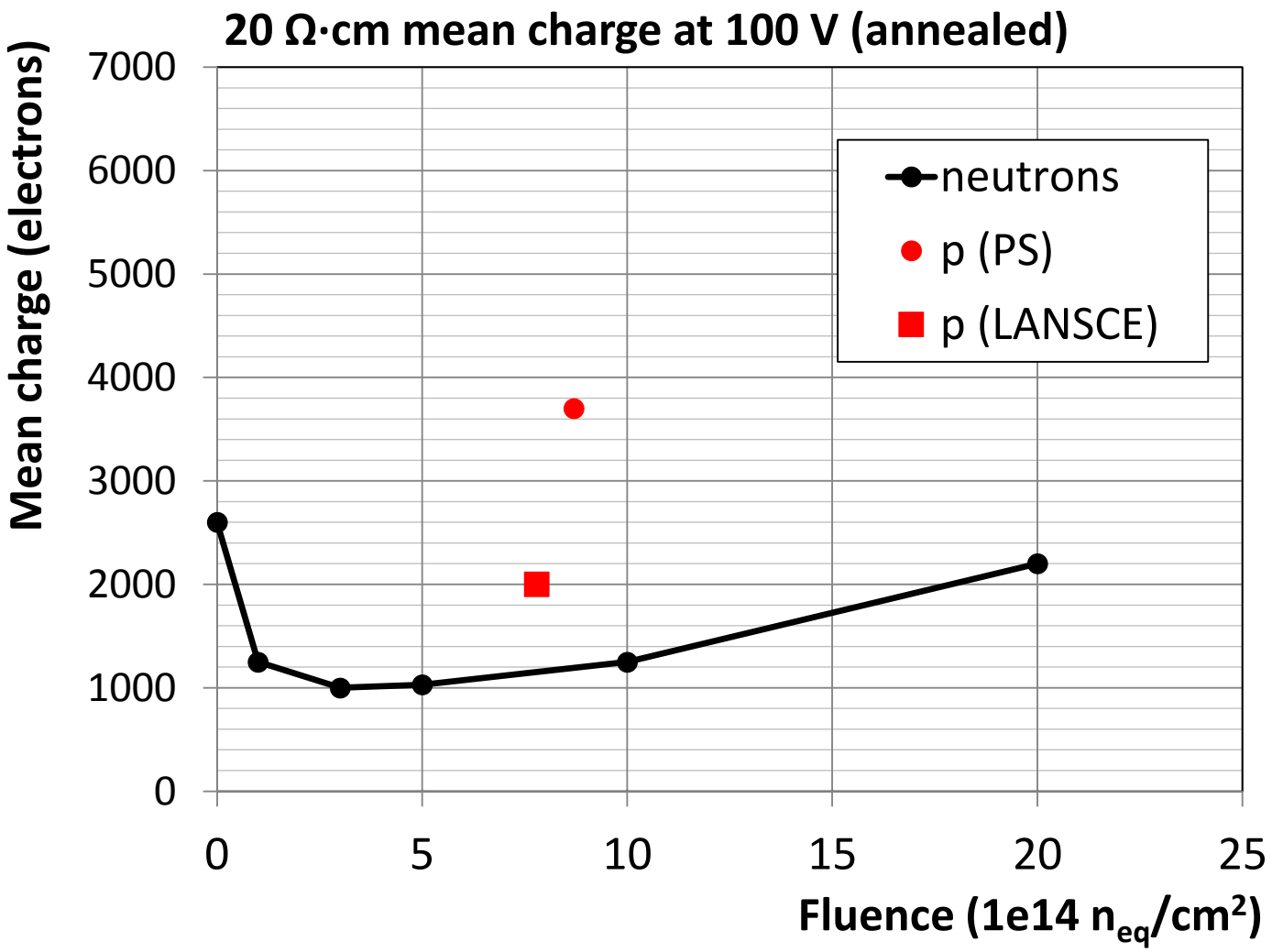




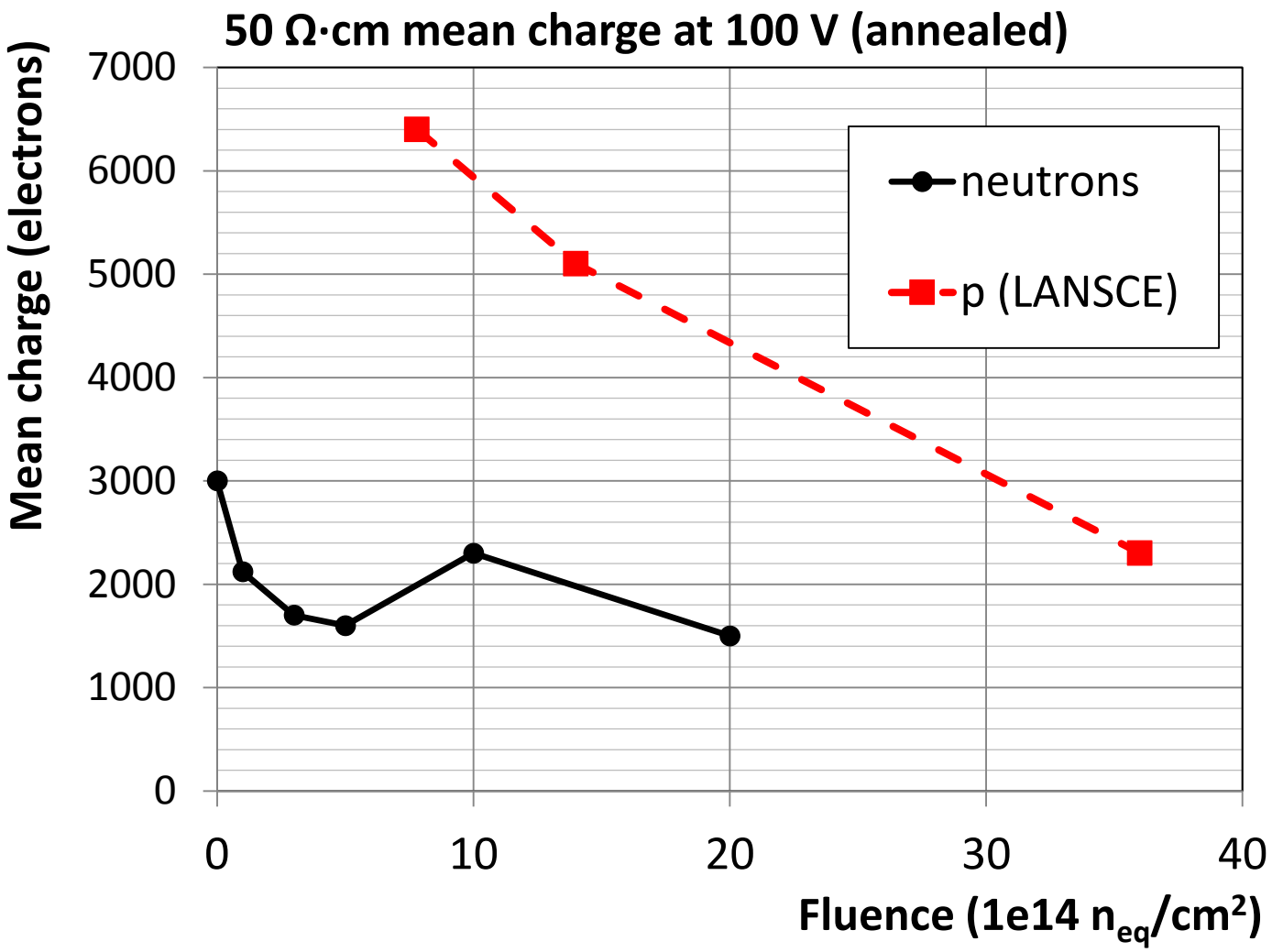
deposited signal = mean (signal) – mean (noise)

- 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

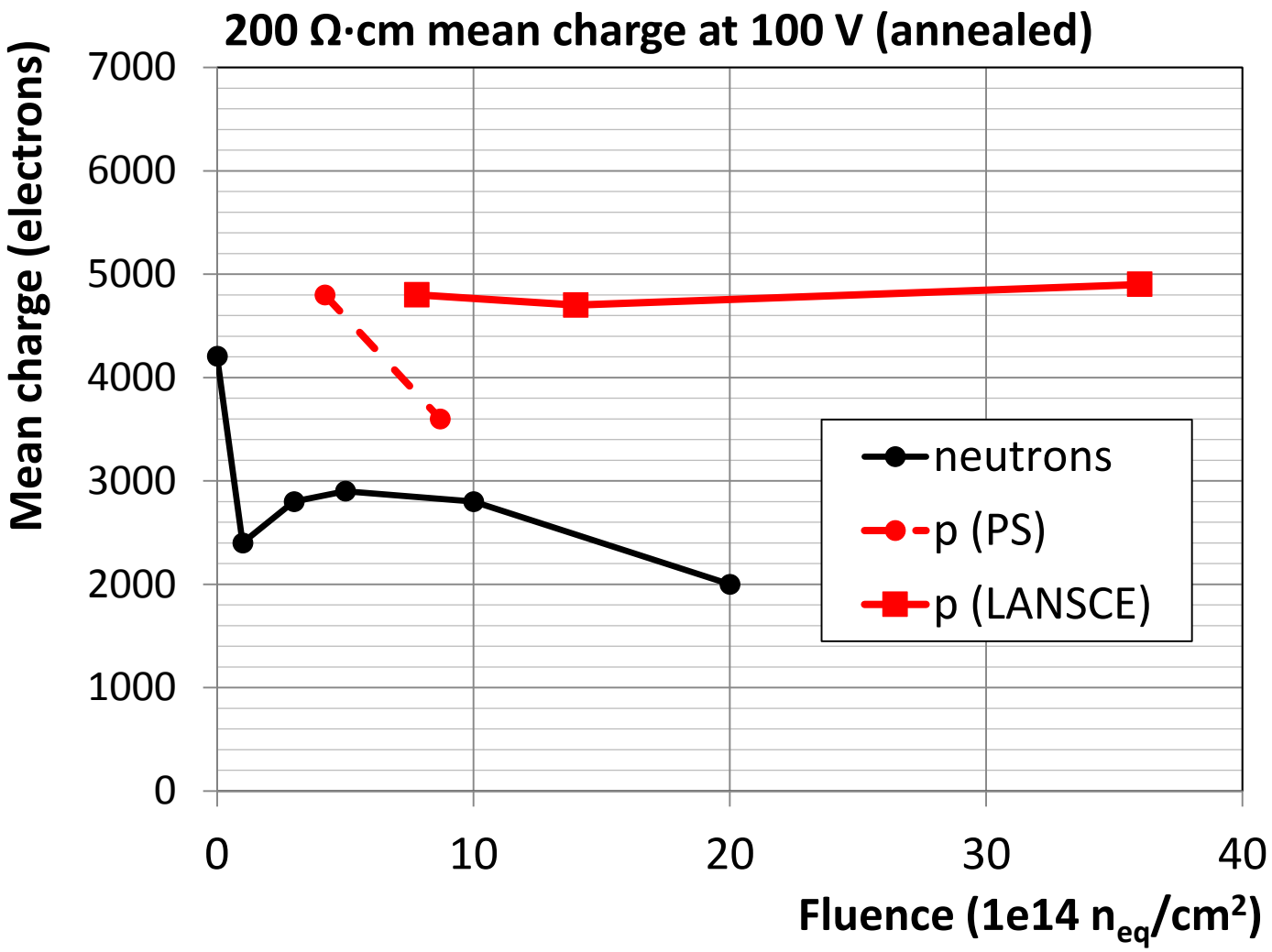
^{90}Sr collected charge 20 Ω·cm



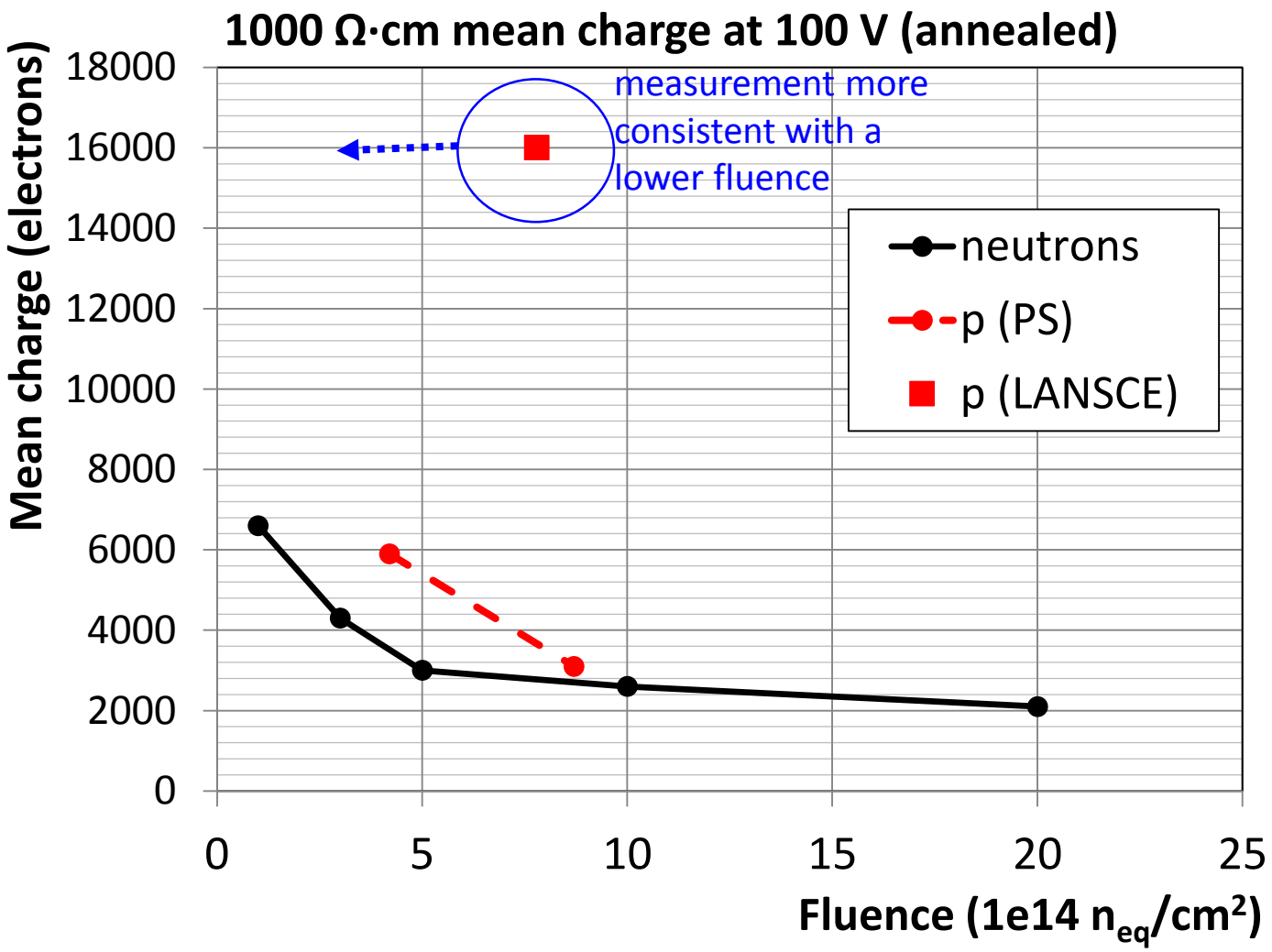
^{90}Sr collected charge 50 Ω·cm



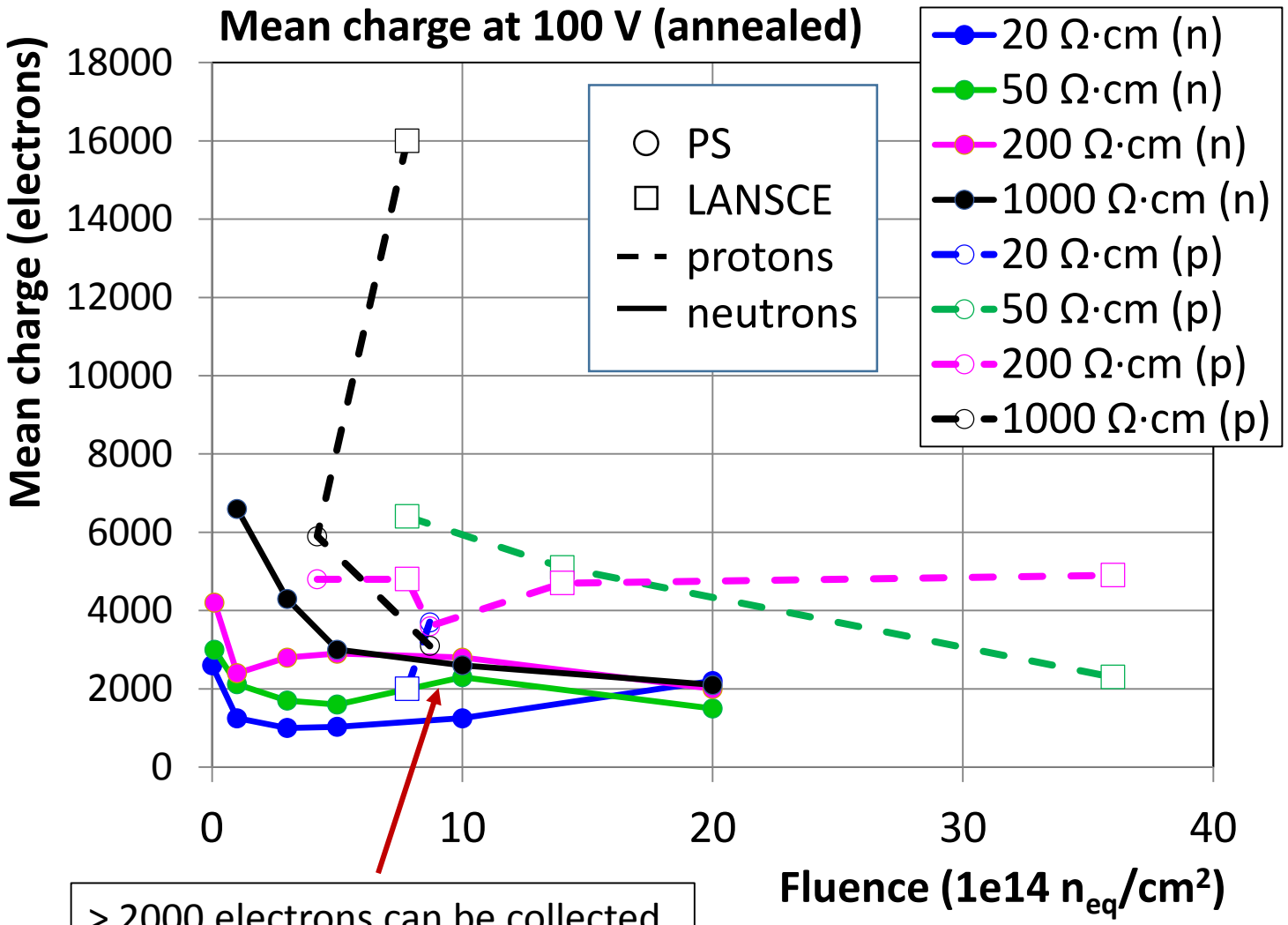
^{90}Sr collected charge 200 Ω·cm



^{90}Sr collected charge 1000 Ω·cm



^{90}Sr collected charge



> 2000 electrons can be collected with 200 and **1000 Ω·cm**

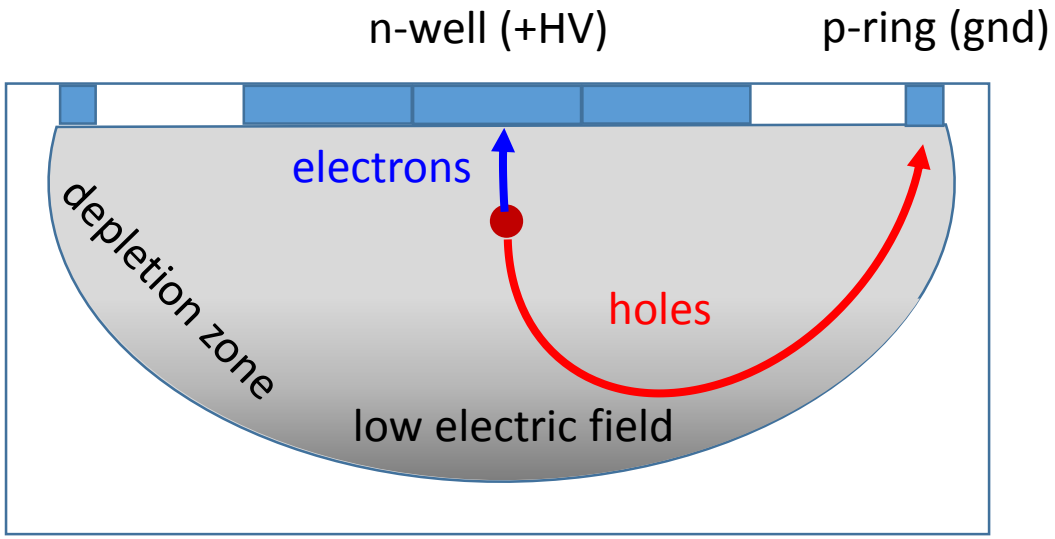
- More charge collected in proton irradiated than in neutron irradiated sample at any fluence/resistivity
- Acceptor removal:

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

  ≈ 10 % more charge after 80 min at 60 °C for all resistivities
- Very constant response of 200 Ω·cm sample with respect to fluence (both n and p)
- Comparison with Edge-TCT
  Example: 50 Ω·cm and 200 Ω·cm measured depletion depth > 100 µm
  - Deposited mean charge > 10000 e$^-$
  - Collected mean charge < 5000 e$^-$

^{90}Sr collected charge

- In irradiated samples only ≈ 50 % of the deposited charge (Edge-TCT) is collected (^{90}Sr)
- The reason for low CCE is 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 mitigated by thinning and back plane metalization
    - Observed in LFoundry CMOS chips with and without processed back plane
  - For pixels/strips the effect is not so crucial since most of the signal comes from drift close to the implants (weighting field)



Summary and conclusions

- Extensive sensor radiation hardness study conducted with AMS CHESS 2 samples of different resistivities up to 2e15 (neutrons) and 3.6e15 n_{eq} cm^{-2} (protons)
- Acceptor removal is an important beneficial effect in irradiated HV-CMOS
  - Larger depletion depth and greater charge than before irradiation can be observed at some fluences
  - Deeper depletion and more charge after proton irradiation than after neutrons at comparable fluences for all resistivities
    - Faster removal with protons
    - Smaller acceptor introduction rate with protons
  - Acceptor removal parameters determined for n irradiated samples
- Optimal case (200 Ω·cm):
  - > 60 µm depletion depth (Edge-TCT)
  - > 2000 electrons collected (^{90}Sr MIPs)

  } for any irradiation type and fluence in the relevant range
- Back plane metalization would likely improve charge collection after irradiation

Acknowledgements

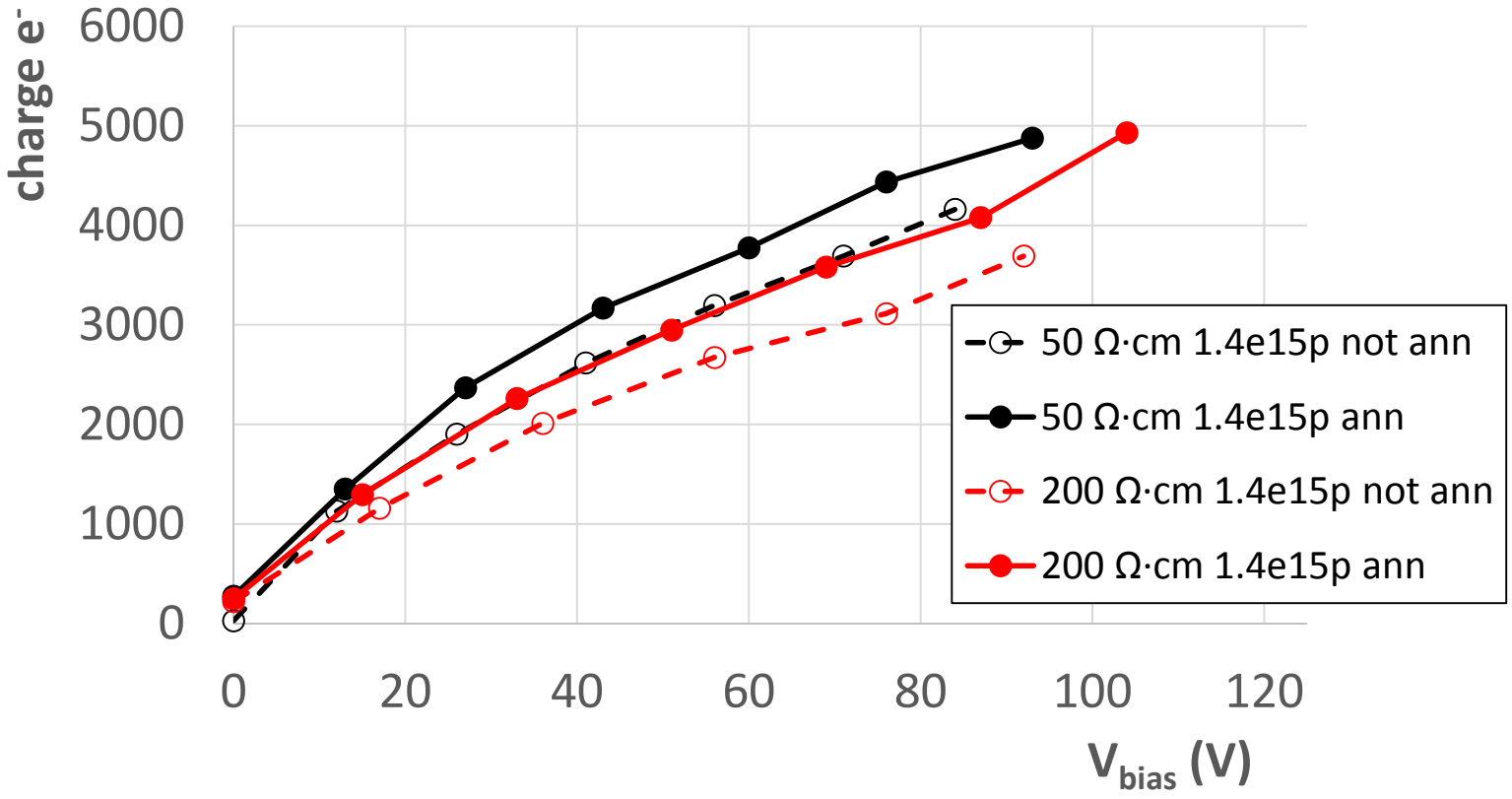
The authors would like to thank the crew at the TRIGA reactor in Ljubljana, the IRRAD facility at CERN, and Los Alamos Neutron Science Center for help with irradiation of detectors.

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P1-0135 and project ID PR-06802).

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

BACKUP

Annealing (^{90}Sr)



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