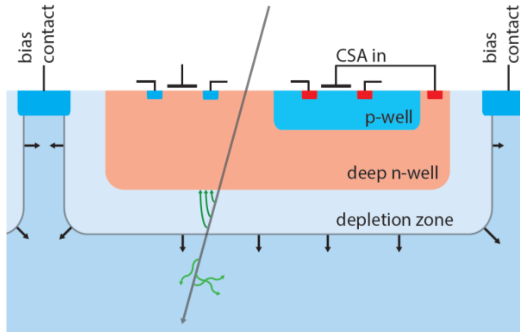
E-TCT measurements of irradiated HV-CMOS test structures

I. Mandić[1], G. Kramberger[1], V. Cindro[1], A. Gorišek[1], B. Hiti[1], M. Mikuž[1,2], M. Zavrtanik[1], et al.

[1]Jožef Stefan Institute, Ljubljana, Slovenia
[2]Faculty of Mathematics and Physics, University of Ljubljana, Slovenia

TCT measurements with HVCMOS structures made on different substrate resistivities from different foundries:



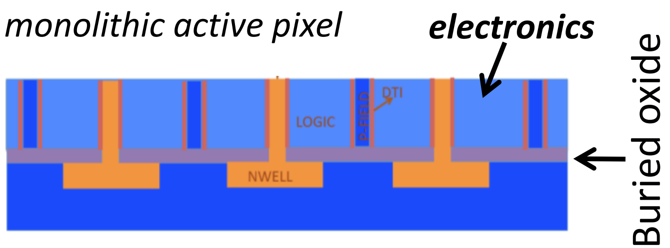
From: S. Fenandez-Perez, TWEPP 2015

AMS: **20 Ohm-cm**

- G. Krambergeret al, *Charge collection studies in irradiated HV-CMOS particle detectors,* 2016 JINST11 P04007
- I. Perić et al. , *Active pixel sensors in high-voltage CMOS technologies for ATLAS,* 2012 JINST ***7* *C08002.***
- **……..**

X-FAB :**100 Ohm-cm**, Silicon On Insulator, **SOI**

- S. Fernandez-Perez et al., *Charge collection properties of a depleted monolithic active pixel sensor using a HV-SOI process,* 2016 JINST 11 C01063
- T. Hemperek et al, *A Monolithic Active Pixel Sensor for ionizing radiation using a 180 nm HV-SOI process,* NIMA 796(2015)8-12



LFoundry: **2000 Ohm-cm,** with and without back plane processing

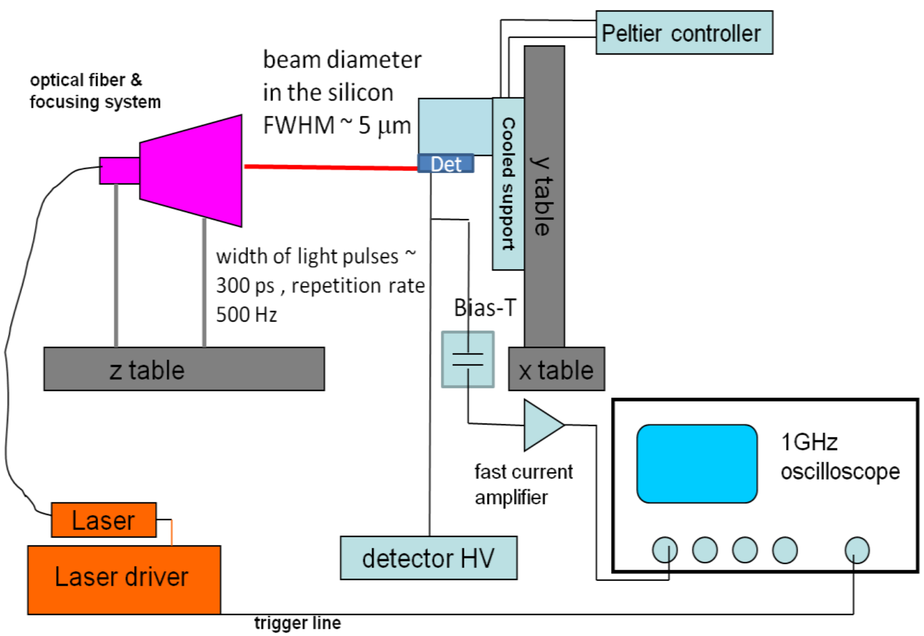
- Piotr RYMASZEWSKI et al., *Prototype Active Silicon Sensor in 150nm HR-CMOS technology for ATLAS Inner Detector Upgrade,* 2016 JINST 11 C02045

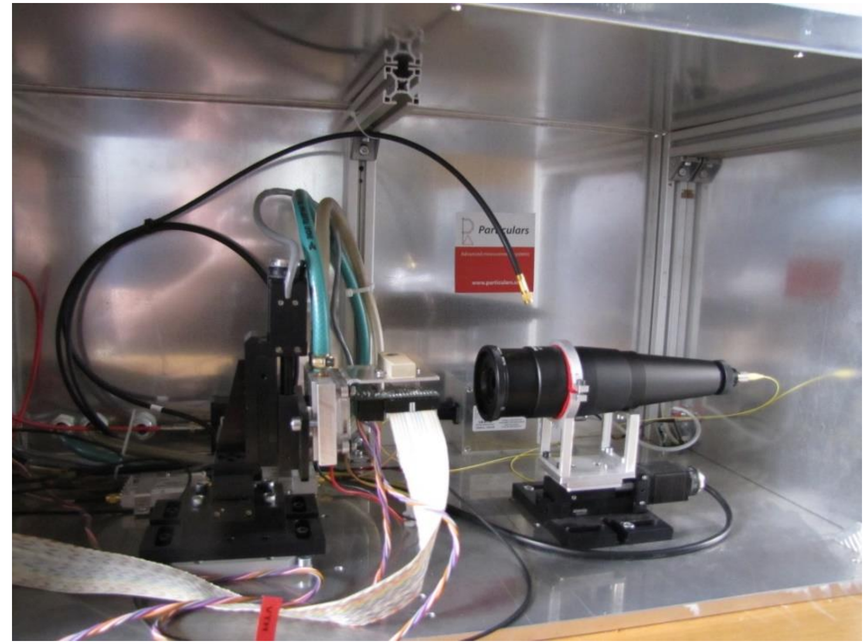
All devices are made on **p-type** substrates

These samples are being investigated as candidates for HV-CMOS detectors for trackers at HL-LHC

Edge TCT

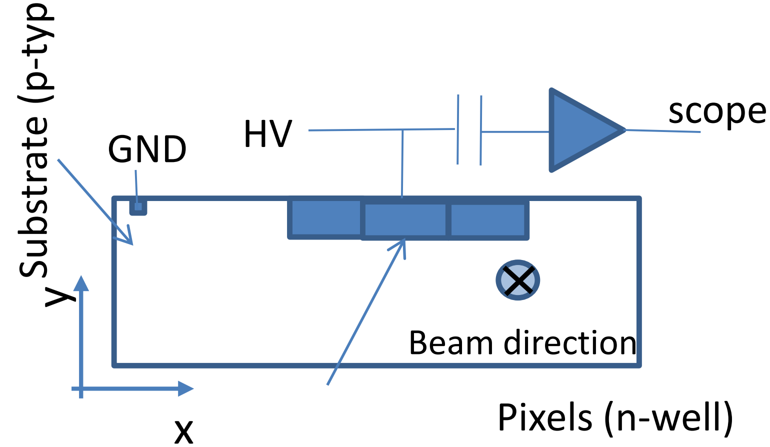
(more details: www.particluars.si)



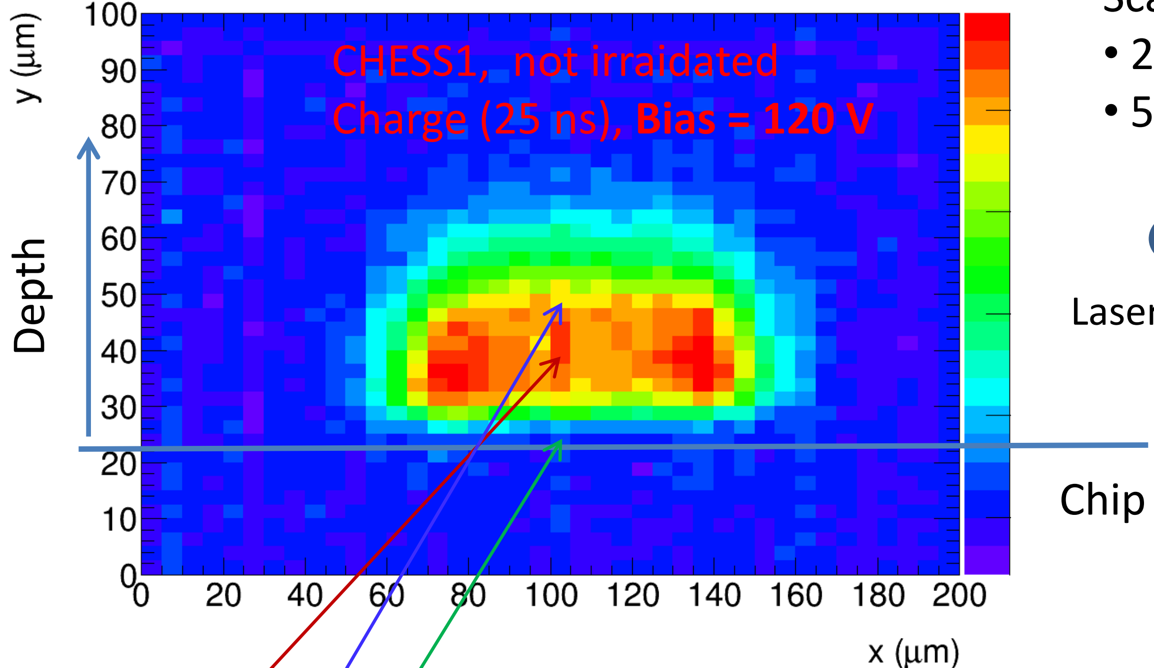


- TCT measurements with passive pixels (no amplifier in the n-well)
  ➔ collecting electrode connected to amplifier

Detector connection scheme:



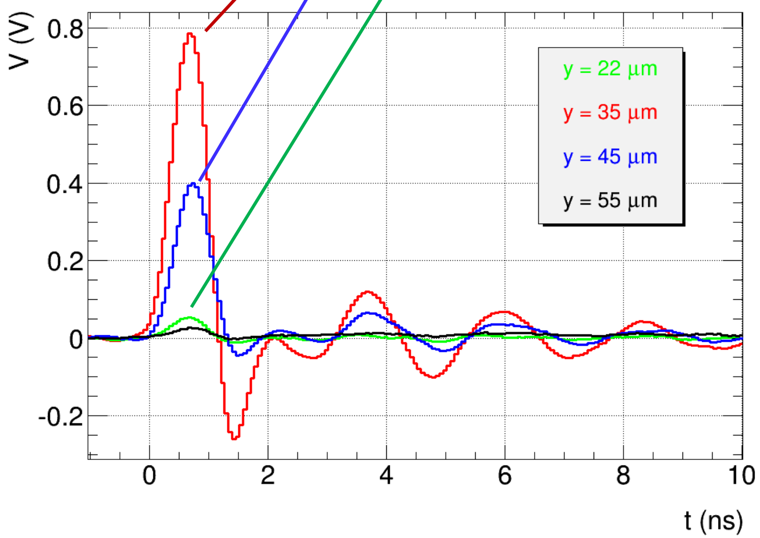
Edge-TCT



Scan across pixel:

- 2.5 µm steps in y
- 5 µm steps in x

Laser beam direction

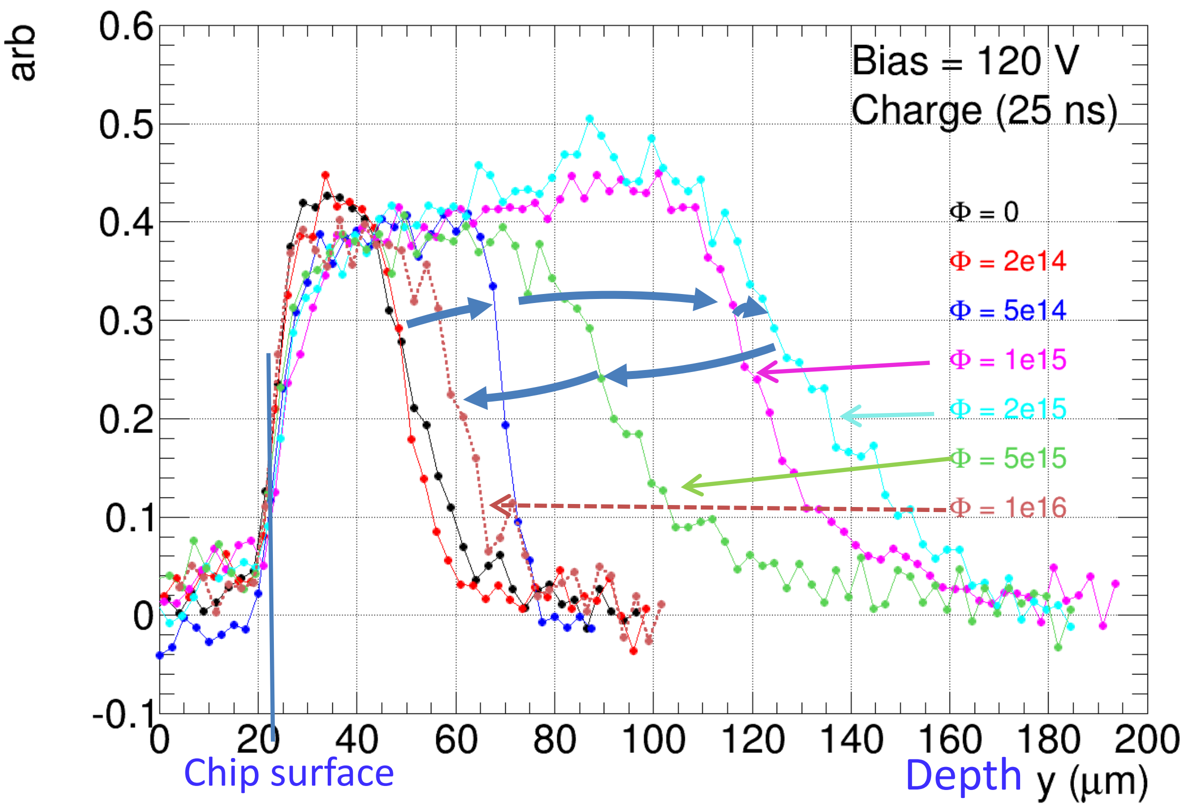


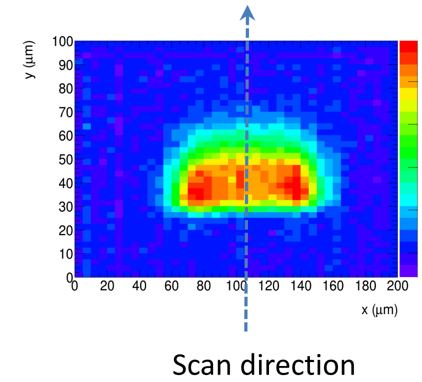
Induced current after laser pulse

Charge:
integral of induced current pulse

Charge collection profile, AMS (20 Ωcm)

Reactor neutrons, steps: 2e14, 5e14, 1e15, 2e15, 5e15, 1e16





- charge collection width increases with fluence up to ~ 2e15 n/cm^2

    ➔ initial acceptor removal

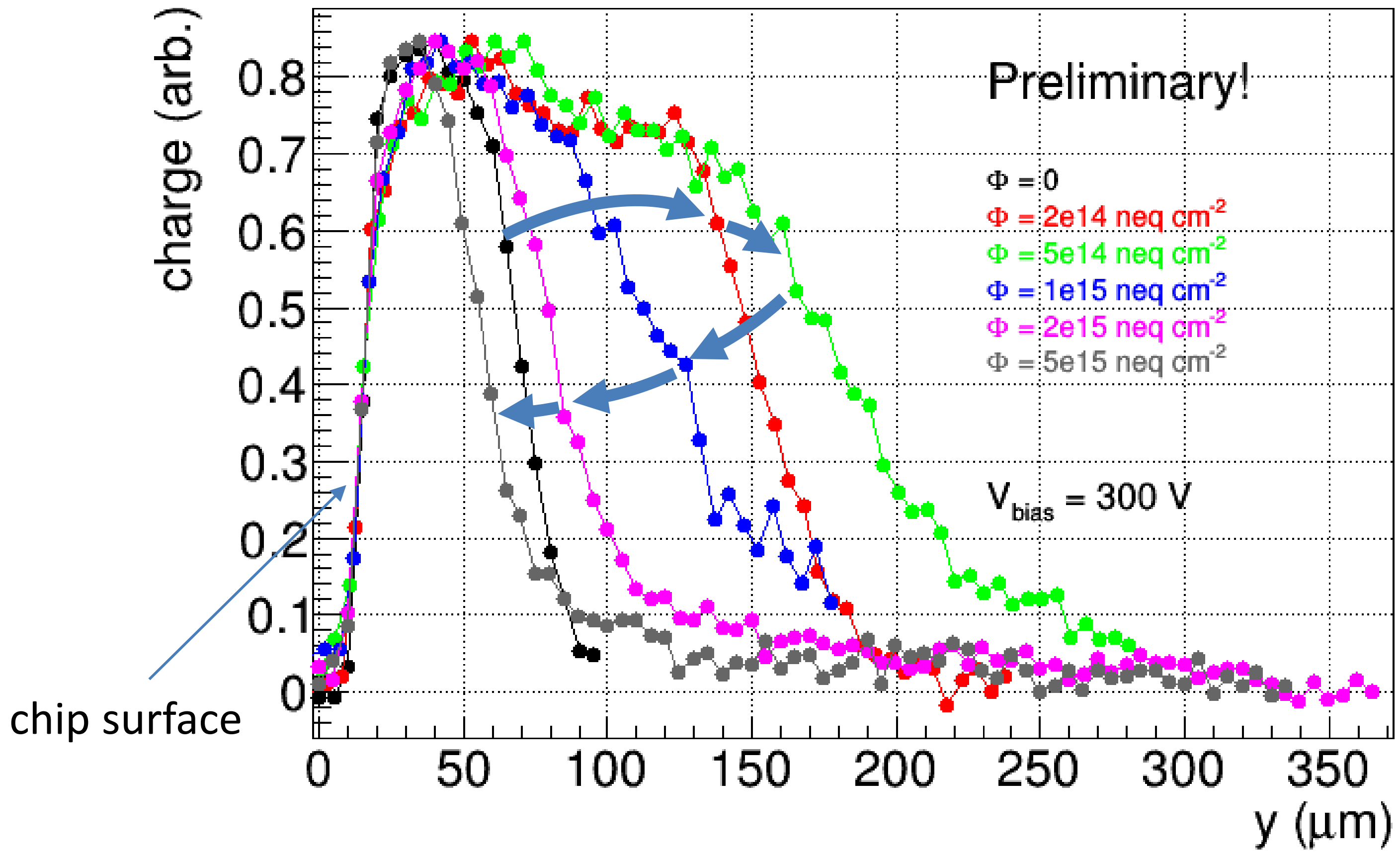
- charge collection width falls with fluences above ~ 2e15 n/cm^2

    ➔ initial acceptor removal finished, space charge concentration increases with irradiation

- **at 1e16 charge collection width still larger than before irradiation**

Charge collection profile, Xfab (100 Ωcm)

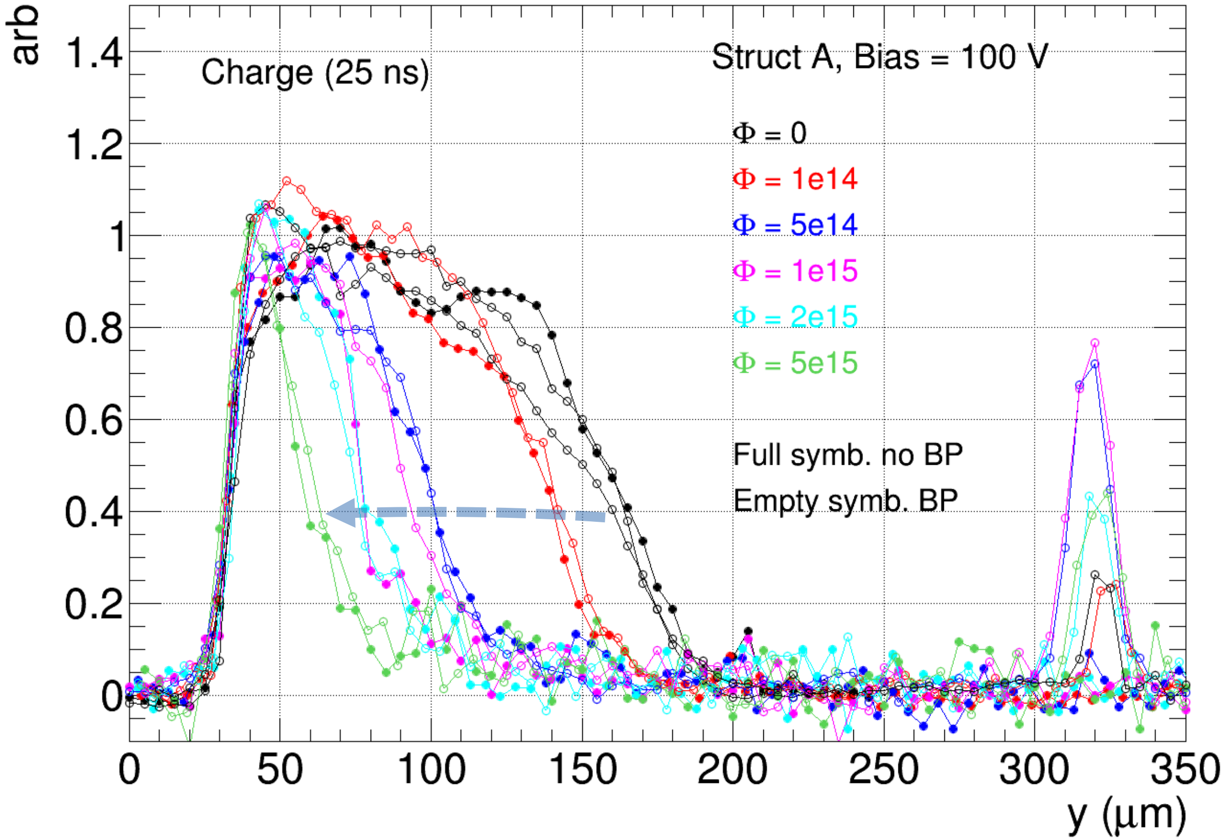
Reactor neutrons, fluence steps: 2e14, 5e14, 1e15, 2e15, 5e15



- large increase of charge collection region at lower fluence than AMS
- at 5e15 charge collection region narrower than before irradiation, but still 40 μm at 300 V

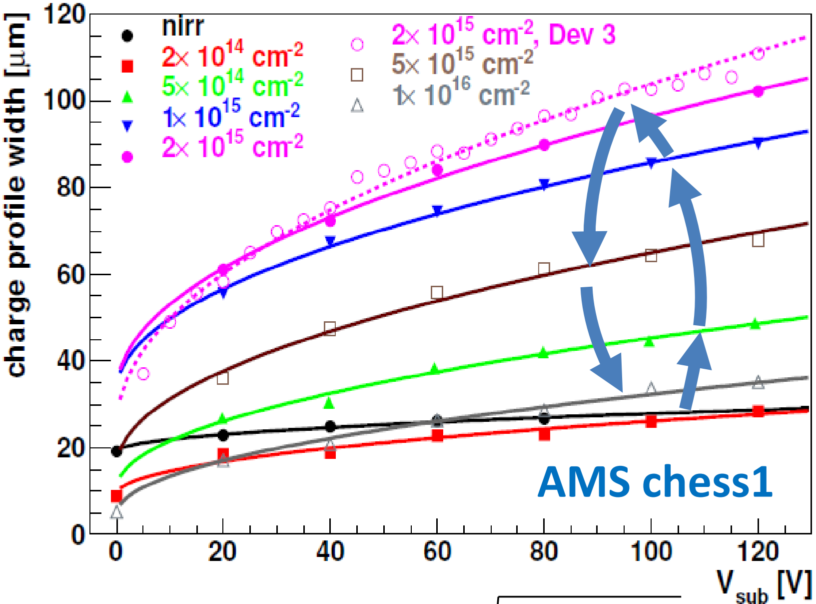
Charge collection profile, LFoundry (2000 Ωcm)

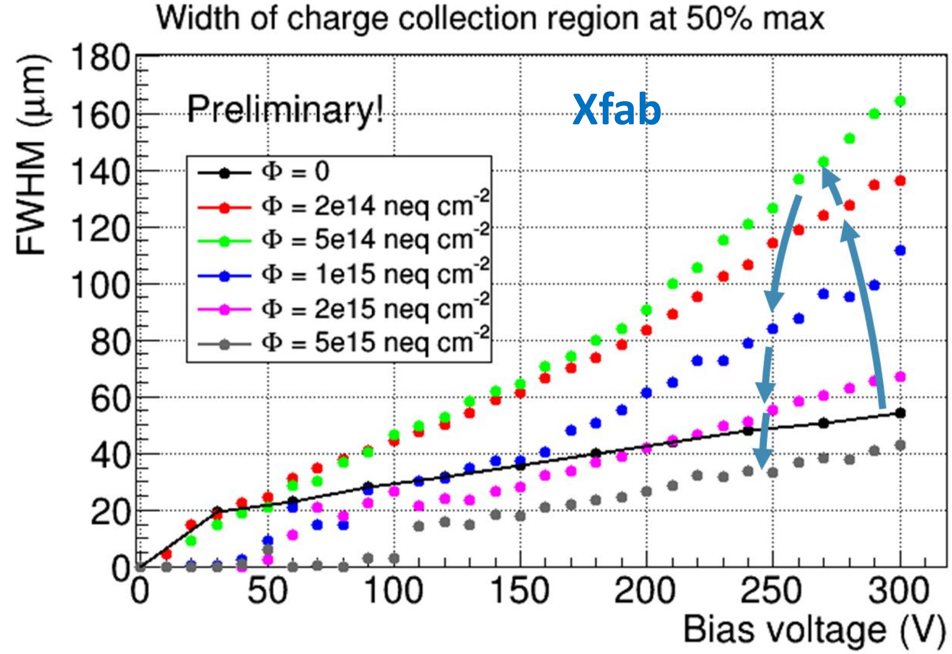
Reactor neutrons, fluence steps: 1e14, 5e14, 1e15, 2e15, 5e15



- no increase of charge collection width after irradiation seen
- no significant difference between samples with and without back plane (BP)

Charge profile width vs. bias voltage





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

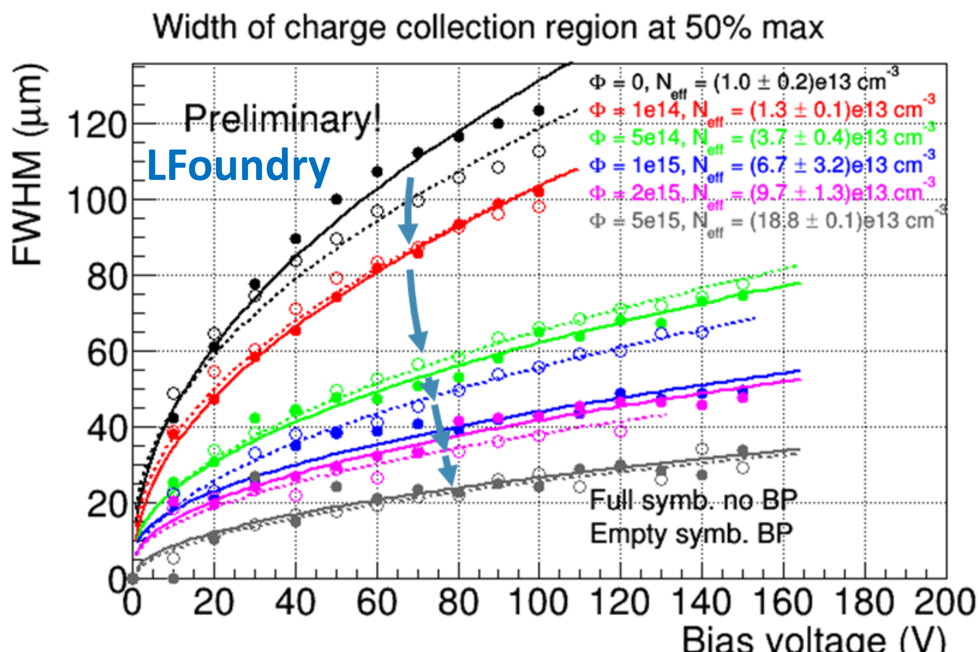
w_0 and N_{eff} free parameters

→works for AMS and LFoundry

X-FAB: can't fit with sqrt(V_{bias})

→ estimate N_{eff} from width at 300 V

- AMS: large increase of width at low bias
- Xfab: "knee" at low bias
  0 width up to 100 V at 5e15



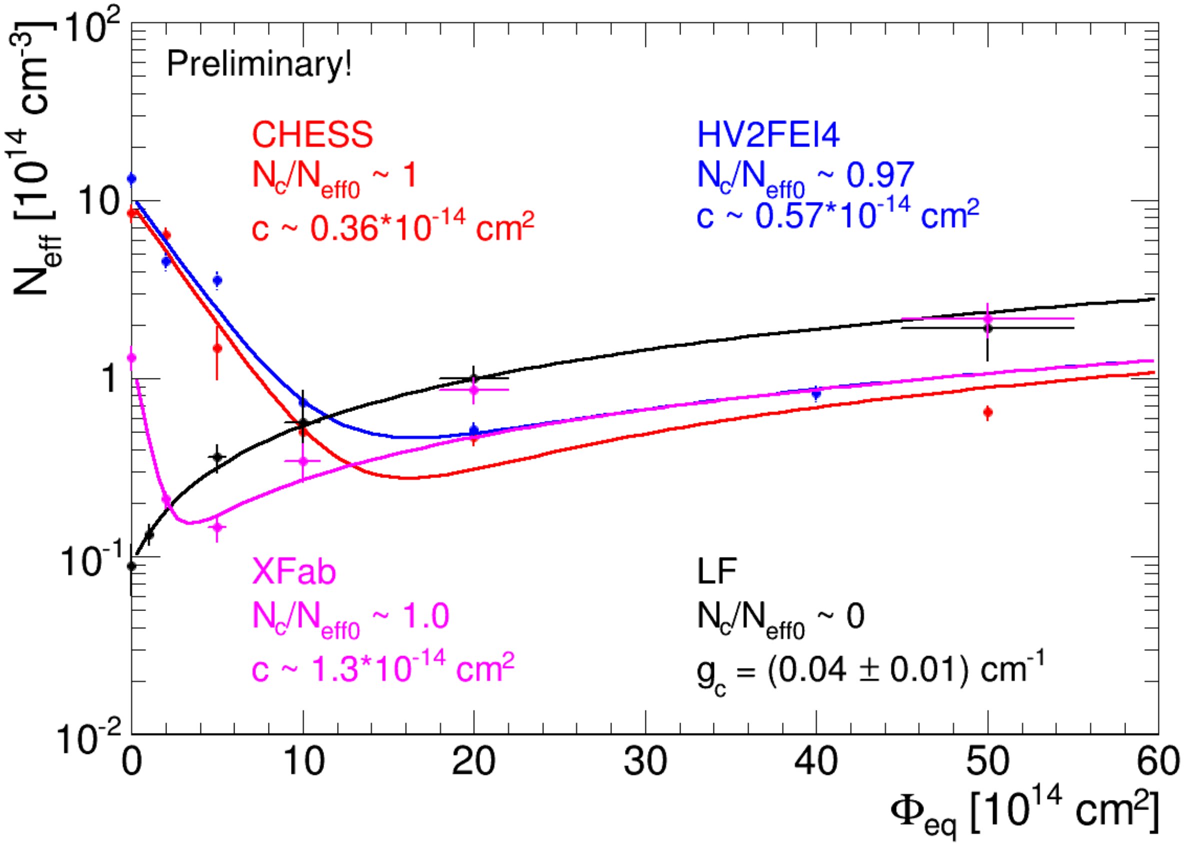
N_{ef} vs fluence

AMS and XFab:

Radiation introduced deep acceptors: $g \sim 0.02$ cm^{-1}

Fit: $N_{eff} = N_{eff0} - \underbrace{N_c \cdot (1 - \exp(-c \cdot \Phi_{eq}))}_{\text{acceptor removal}} + g \cdot \Phi_{eq}$ N_c, N_{eff0} and c free parameters, g fixed

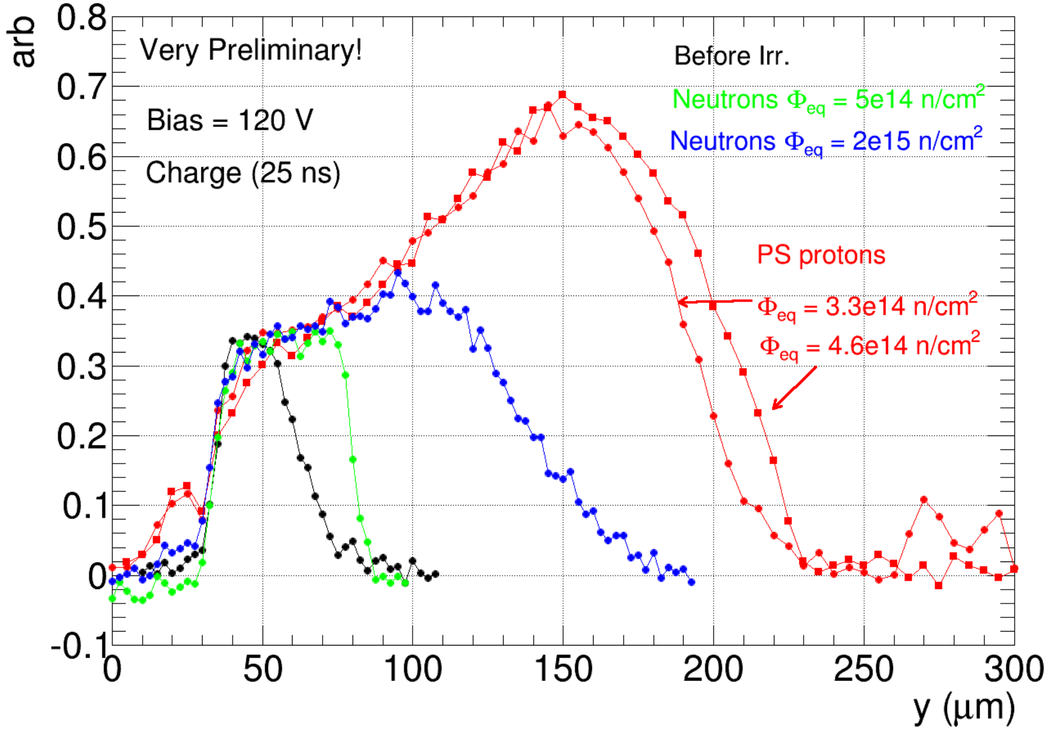
LFoundry: no removal ($N_c \sim 0$), fit: $N_{eff} = N_{eff0} + g \cdot \Phi_{eq}$ N_{eff0} and g free



AMS (CHESS and HV2FEI4) from: G. Kramberger et al., 2016 *JINST11 P04007*

AMS CHESS1 chips (20 Ωcm) irradiated with PS protons

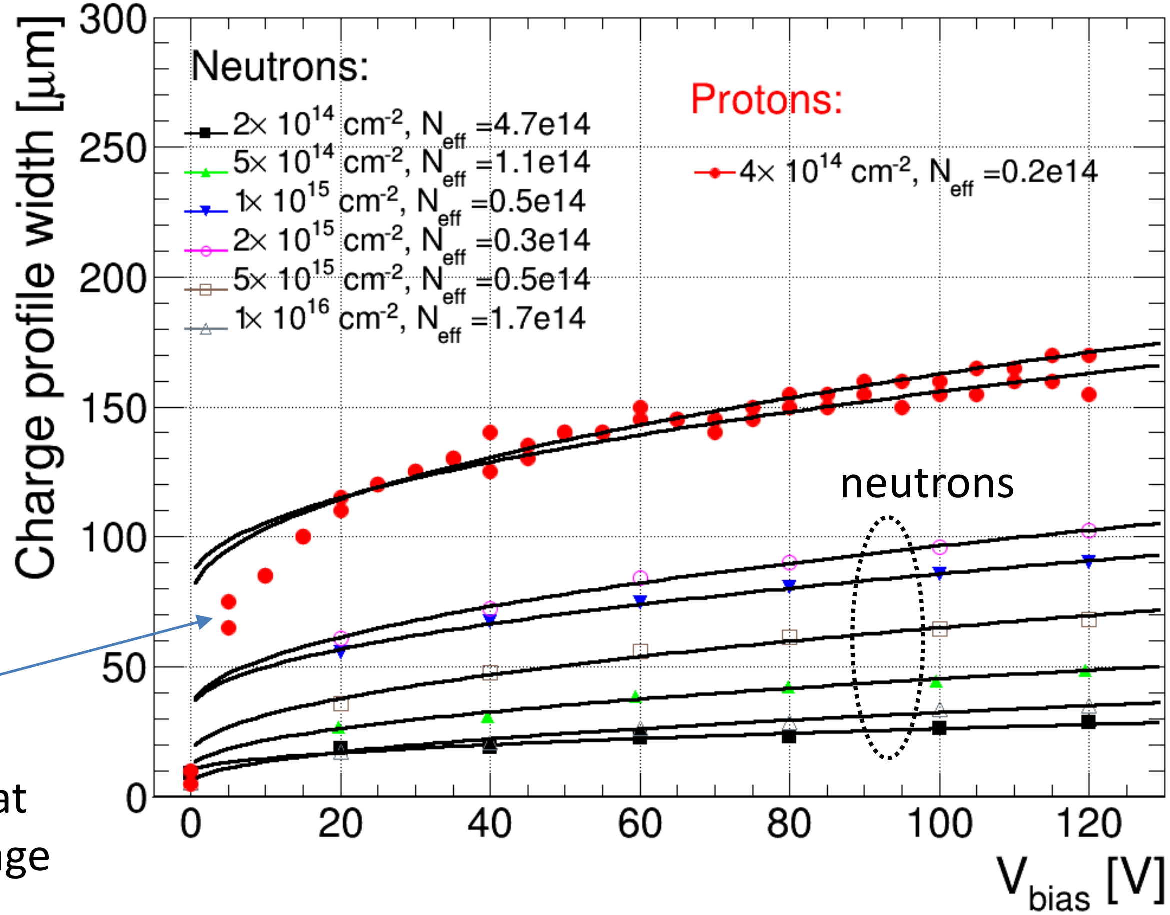
24 GeV protons, 1 MeV eq. fluences : 3.3e14 n/cm² and 4.6e14 n/cm²



➔ larger width than the largest after neutrons (at 2e15 n/cm²)

Irradiation with PS protons

- fit compatible with N_{eff} ~ 2e13 cm^{-3}
- less than after ~2e15 n/cm^2 reactor neutrons (N_{eff} ~ 3e13 cm^{-3})
  - → faster initial acceptor removal
  - → large rise of profile width low bias



Very fast rise at low bias voltage

Irradiation with PS protons

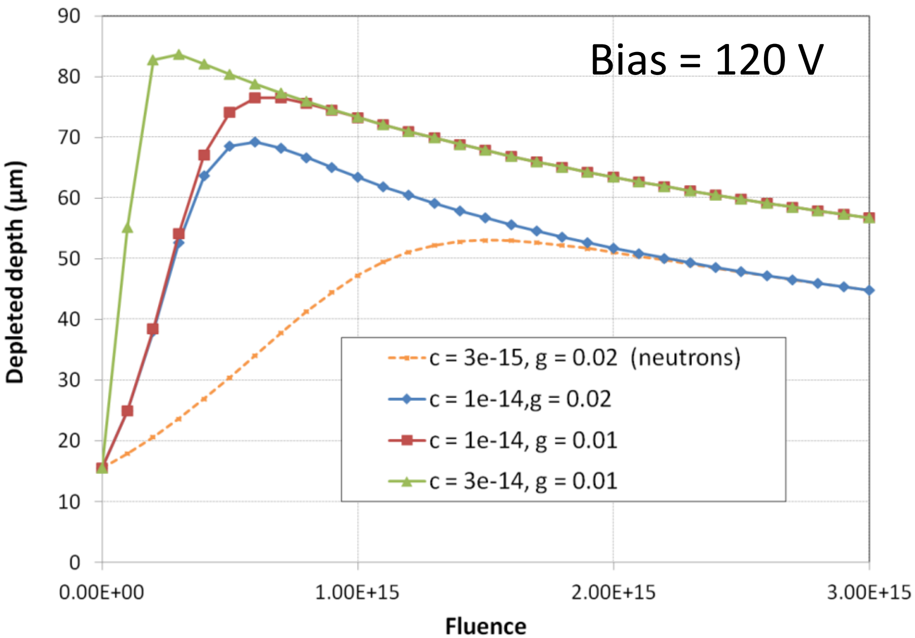
Larger depleted depth (lower N_{eff}) at lower fluence than after neutron irradiation:

➔ larger acceptor removal constant ***c*** (and smaller $\boldsymbol{g_c}$) after proton irradiation

➔ measurements in agreement with M. Fernandez et al.

Calculate depletion depth from N_{eff} using:

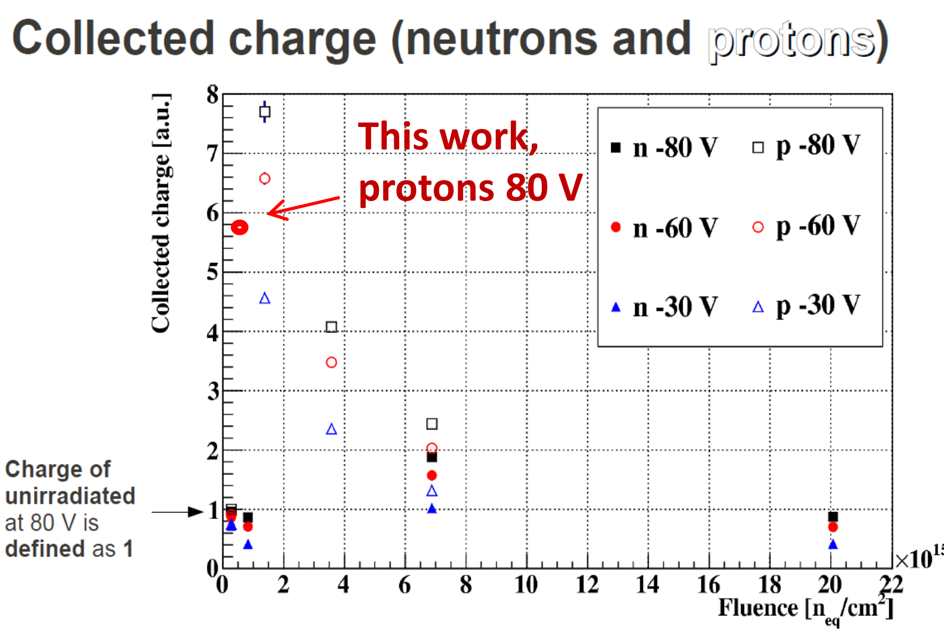
$$N_{\mathrm{eff}} = N_{\mathrm{eff0}} - N_{\mathrm{c}} \cdot (1 - \exp(-c \cdot \Phi_{\mathrm{eq}})) + g_c \cdot \Phi_{\mathrm{eq}}$$



Neutrons: c = 3e-15 cm^2, g_c = 0.02cm^{-1}

Protons would fit c ~ 1e-14 cm^2 or larger

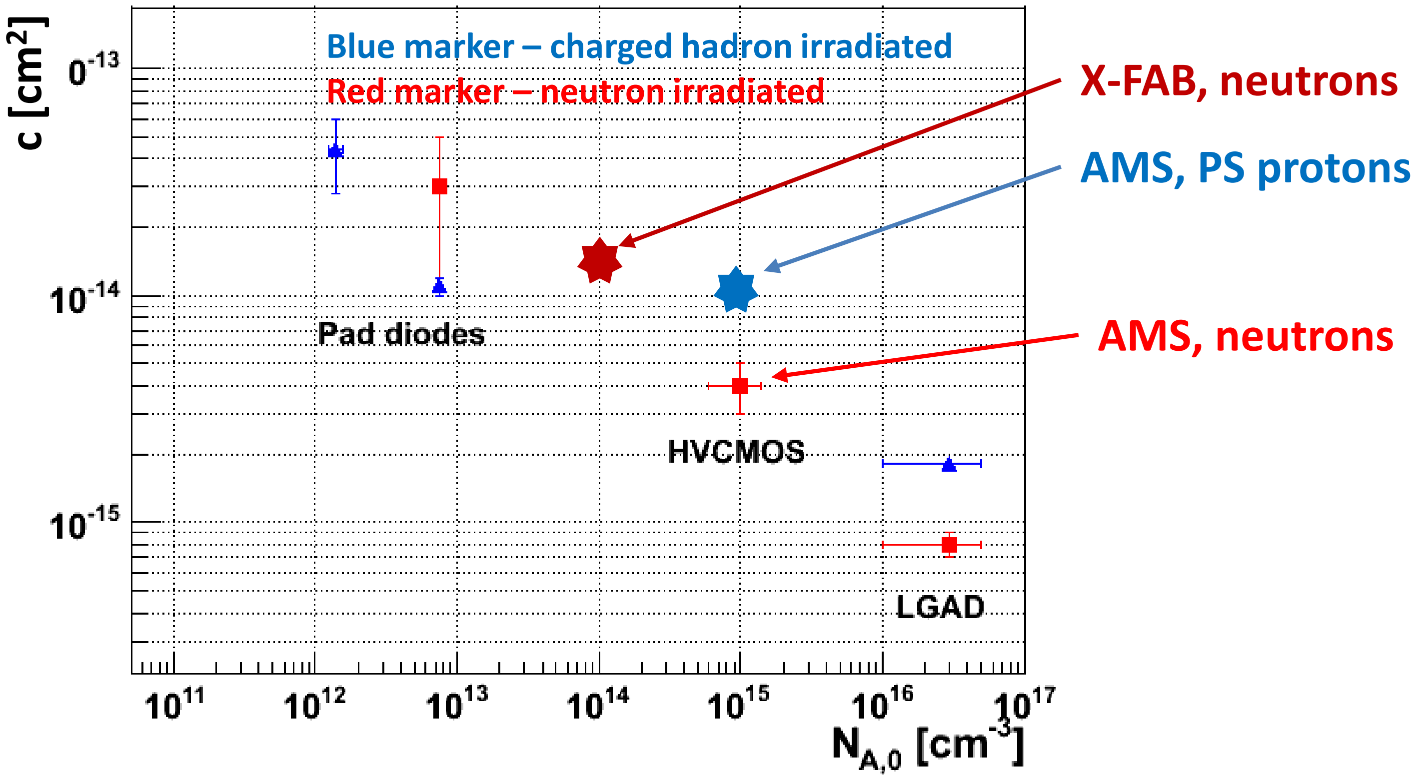
E-TCT with HVCMOSv3, (AMS 180 nm, 10 Ohm-cm) irradiated with PS protons and neutrons:
M. Fernandez, RD50 meeting, December 2015:



- Collected in **5 ns**, over **200 µm**. Showing 3 different voltages.

Acceptor removal

G. Kramberger et al, 10th Trento Meeting, Feb. 17-19, 2015



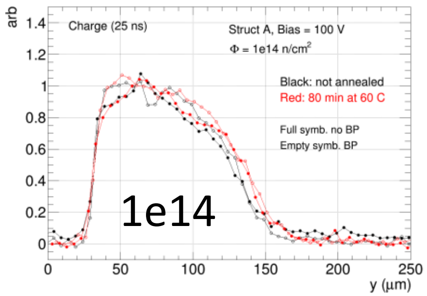
- AMS (20 Ωcm, N_{A0} ~ 10^{15} cm^{-3}): c ~ $4 \cdot 10^{-15}$ cm^2, N_c/N_{eff0} ~ 1, PS protons: c ~ $1 \cdot 10^{-14}$ cm^{-2}
- X-FAB (100 Ωcm, N_{A0} ~ 10^{14} cm^{-3}): c ~ $1.3 \cdot 10^{-14}$ cm^2, N_c/N_{eff0} <~ 1
- LFoundry (2000 Ωcm, N_{A0} ~ $6 \cdot 10^{12}$ cm^{-3}), acceptor removal not observed in this study
  - ➔ deep acceptor introduction rate comparable or faster than removal rate
  - ➔ initial acceptor concentration low → difficult to observe reduction of a small value
  - ➔ removal not complete N_c/N_{eff0} < 1 and/or small c to be observed in this measurement

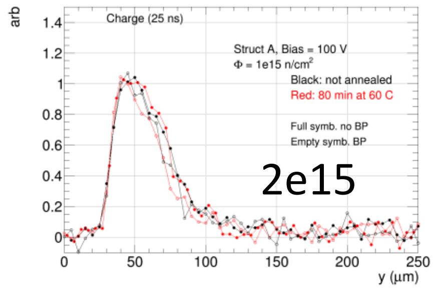
Charge collection profile - annealing

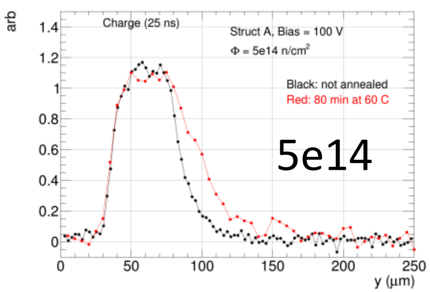
Measurement before and after 80 minutes at 60 C

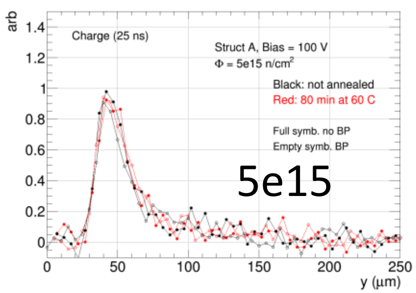
→ 10% to 20 % increase of charge collection width after annealing

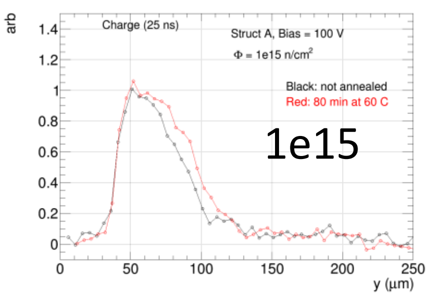
Lfoundry:



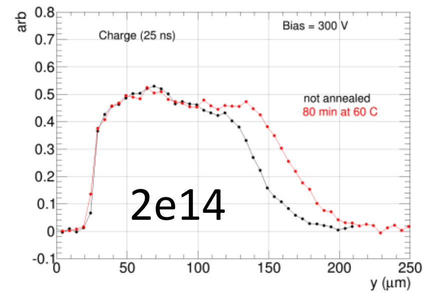


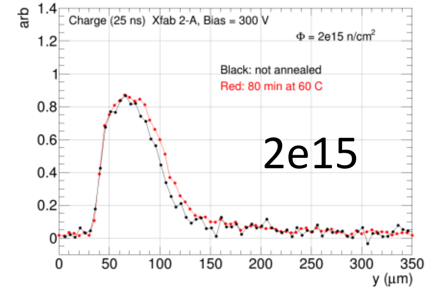


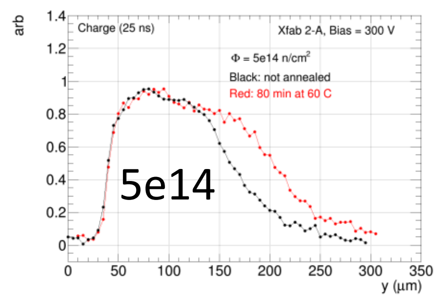


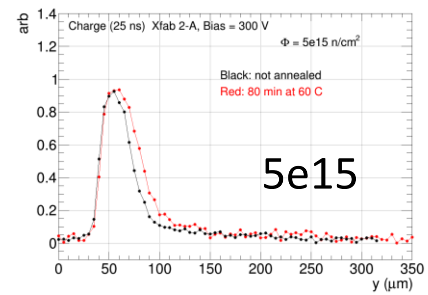


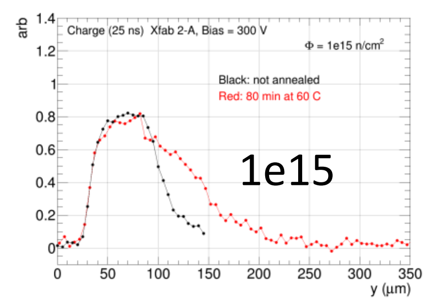
Xfab





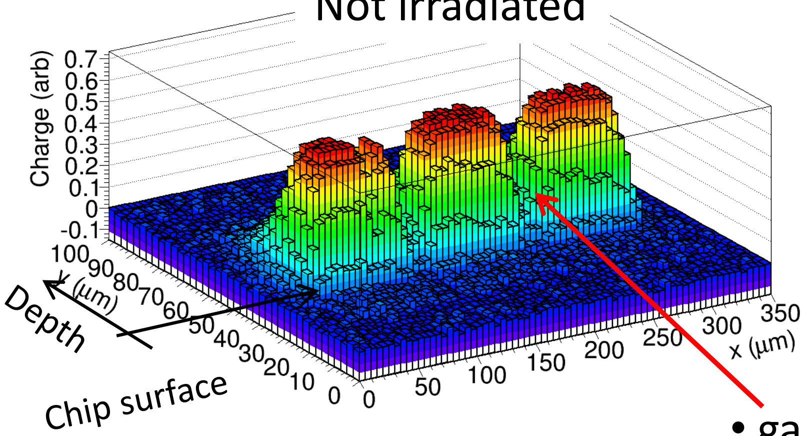


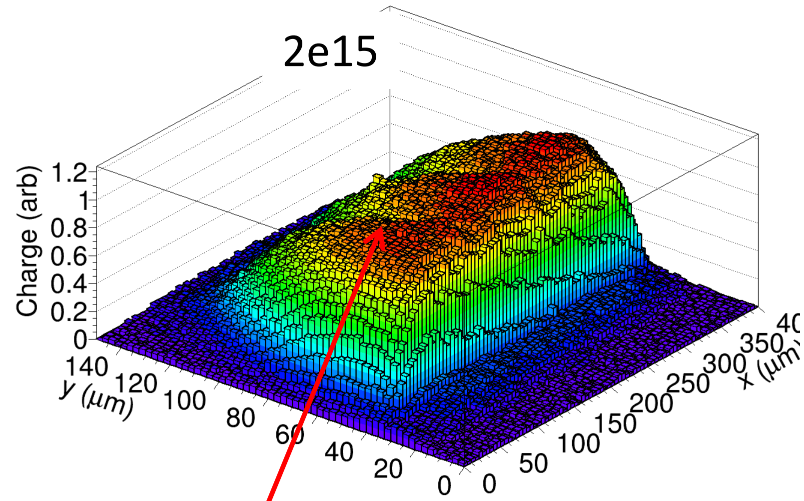




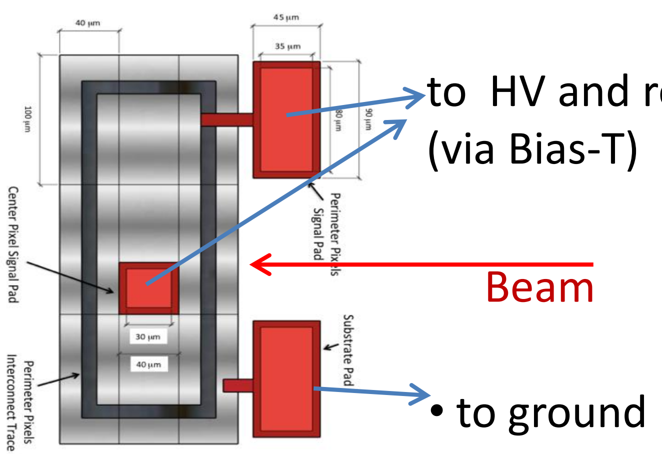
<u>Scan across pixel array: AMS (20 Ωcm)</u>

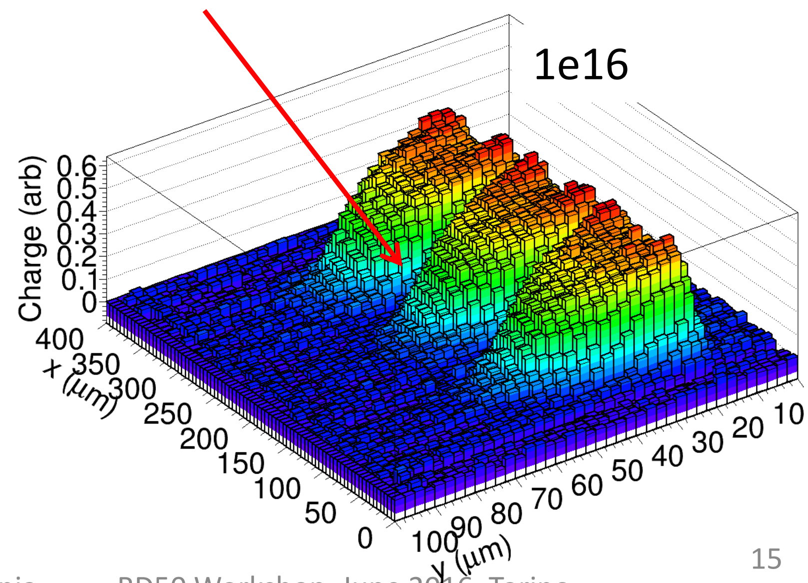
Bias = 120 V, all 9 pixels connected to readout, charge (25 ns)





- gaps before irradiation
- guard ring gaps smaller after 2e15
- gaps better seen again after 1e16

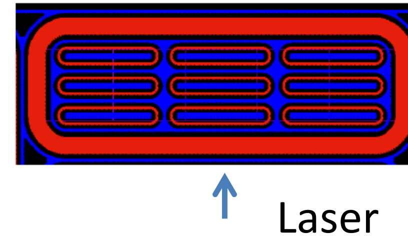


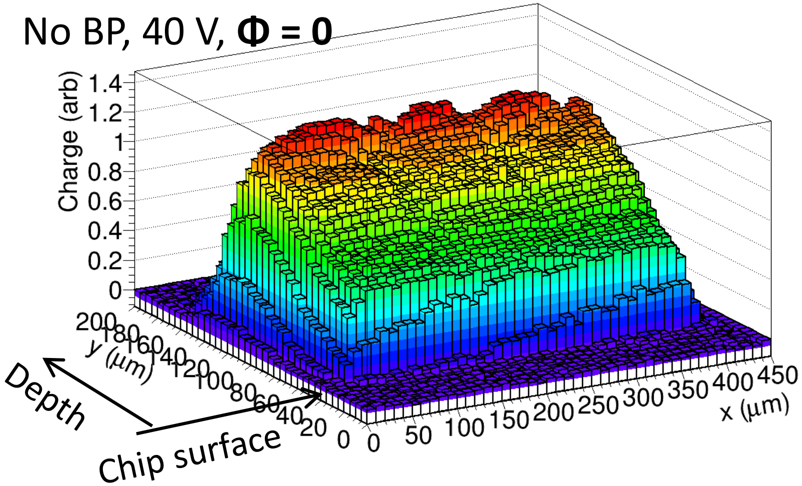


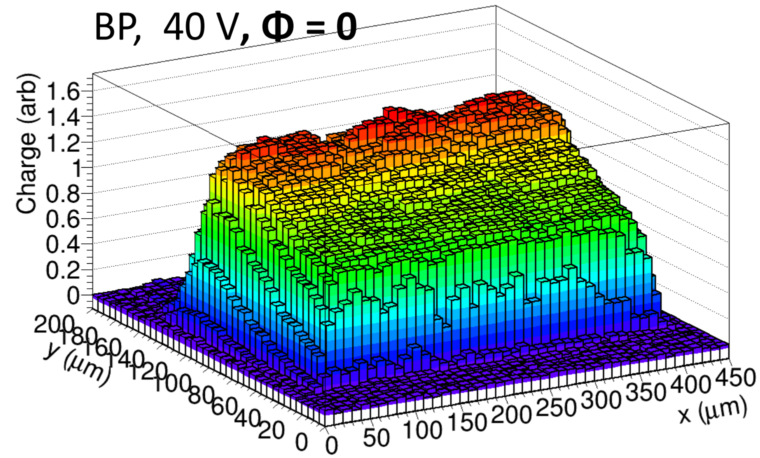
LFoundry, Structure F, all pixels read out

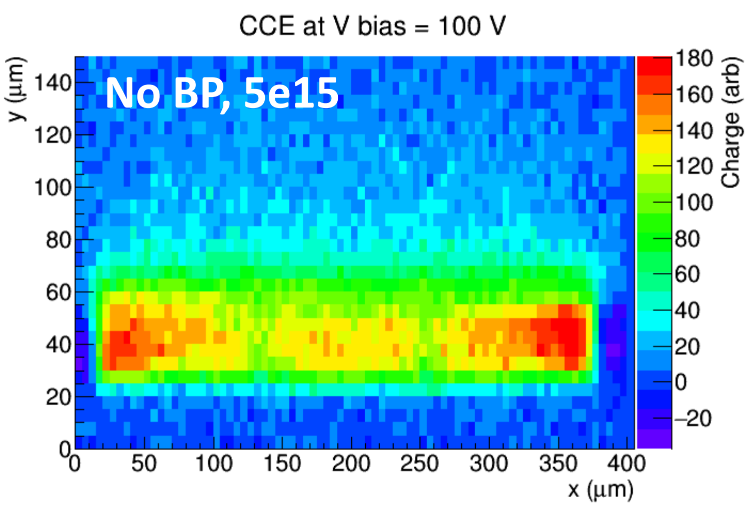
- ➔ no significant efficiency gaps between pixels
- ➔ no large difference between BP and no BP devices

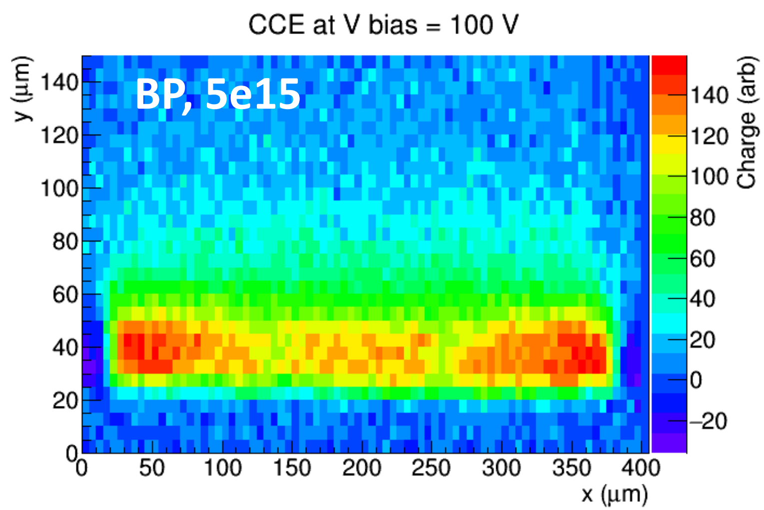
Structure F, 3x3 pixels,
125 µm x 33 µm



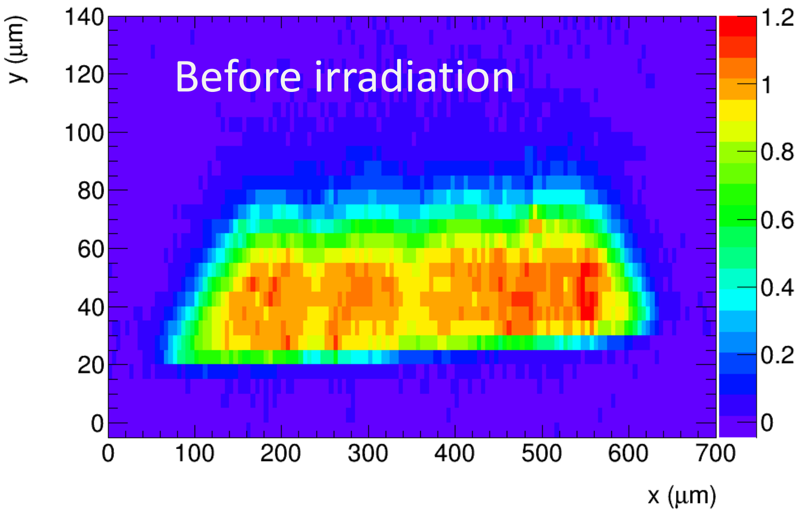




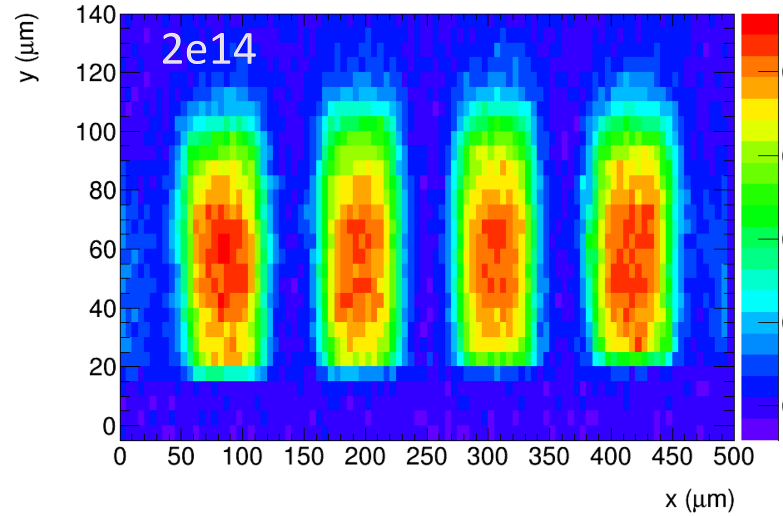


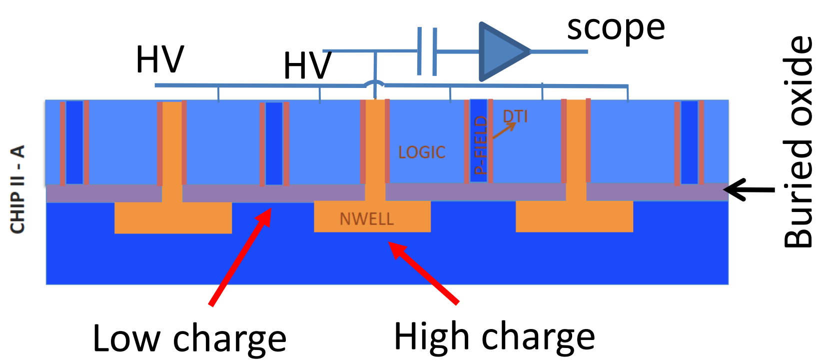


X-FAB: 100 Ωcm, 4x4 pixel array, Bias = 300 V

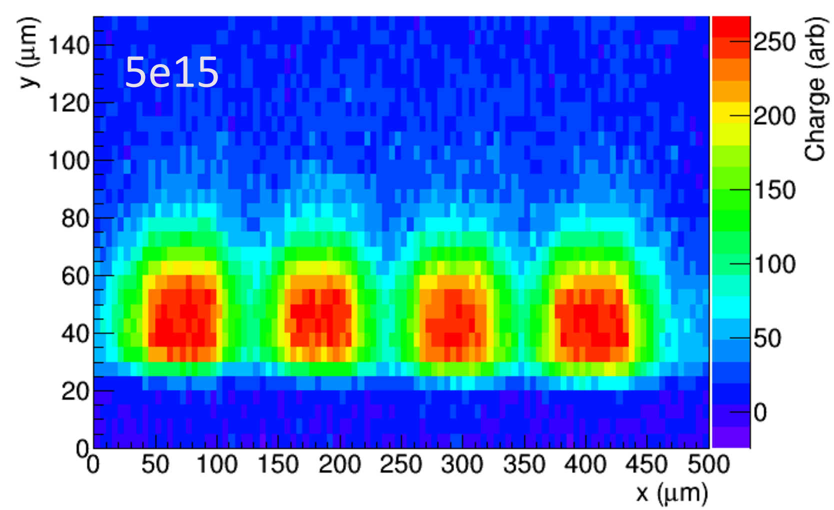


Efficiency gaps between pixels after irradiation
→ nuch smaller gaps at 500 ns integration





→ gaps less evident after high fluence



→ carriers drift to the oxide between n-wells
  → behaves as "parasitic AC coupled electrode"
→ more detail showed at *Trento workshop, Paris 2016*:
https://indico.cern.ch/event/452766/contributions/1117348/

Summary

- **Edge-TCT** measurements with passive test structures made on 3 different substrate resistivities:
  AMS : 20 Ωcm, **X-FAB**: 100 Ωcm, **LFoundry**: 2000 Ωcm
  → charge collection profiles measured up to 1e16 n/cm^2
  → significant charge collection width after highest fluence in all samples

- **AMS and X-FAB:** large increase of charge collection width after irradiation with neutrons
  →dependence of charge collection width with fluence consistent with effective acceptor removal
  → acceptor removal in X-FAB faster than in AMS → faster removal at larger initial resistivity

- **AMS:** large increase of charge collection width after irradiation with **PS protons**
  → increase larger and at lower fluence than for neutrons
    → faster acceptor removal and smaller deep acceptor introduction rate
  → fast increase of charge collection width, faster than sqrt(V) at low bias voltage (seen also after neutron irradiation)

- **LFoundry**: charge collection width decreases with increasing fluence
  → introduction of deep acceptors faster than removal of initial acceptors
    - removal not complete N_c/N_{eff0} < 1 and/or too slow
    - compensated material? (donoros and acceptors removed at different rate ➔ we only see the sum)
  → no significant difference between samples with and without back plane contact
  → no significant efficiency gaps between pixels

- **X-FAB**: large efficiency gaps between pixels after irradiation (at 25 ns integration times)
  → low efficiency between n-wells due to parasitic charge collection