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# Charge collection properties of irradiated CMOS detectors

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et al.

## Samples

- test structures from LFoundry demonstrator submission designed by University of Bonn:
  - ☐ Piotr RYMASZEWSKI et al., *Prototype Active Silicon Sensor in 150nm HR-CMOS technology for ATLAS Inner Detector Upgrade,* 2016 JINST 11 C02045
  - ☐ T. Wang et al., *Development of a Depleted Monolithic CMOS Sensor in a 150 nm CMOS Technology for the ATLAS Inner Tracker Upgrade,* 2017 JINST 12 C01039
- 150 nm HR-CMOS technology
- resistivity of p-type substrate > 2 kΩcm
- breakdown voltage from 175 V to over 400 V, depending on the test structure

- measurements shown here with passive pixel array

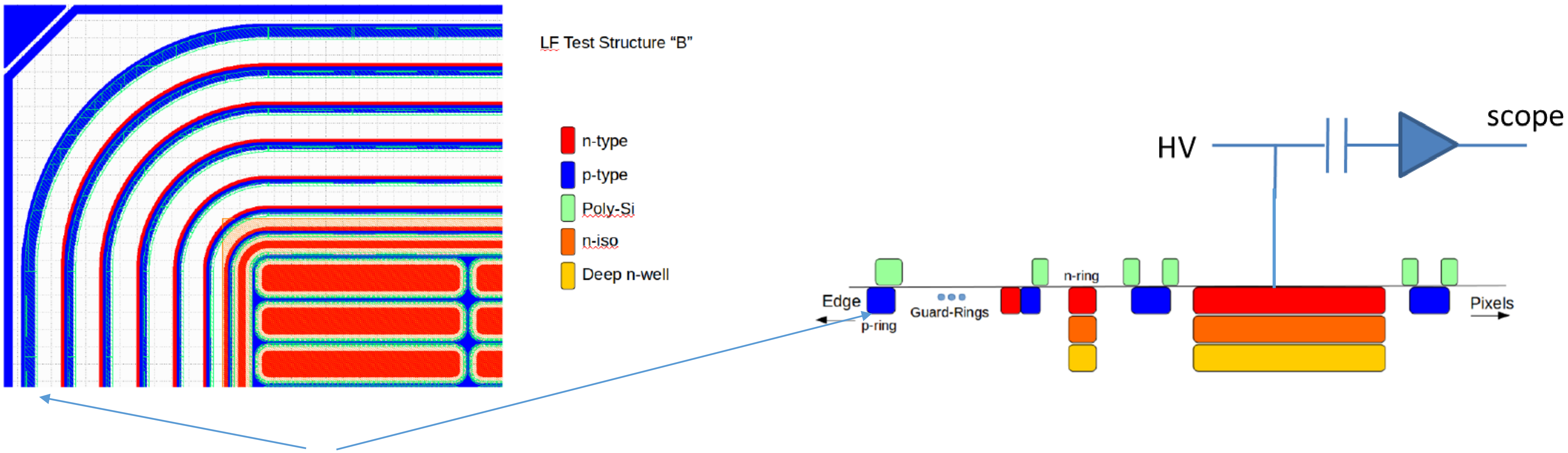
- Two sets:

  → not thinned (700 um), no back plane, substrate biased over implant on top
  → thinned to 200 um, back plane processed, bias through the BP

- Samples irradiated to 1e13, 5e13, 1e14, 5e14,1e15 and 2e15 with neutrons in TRIGA reactor in Ljubljana

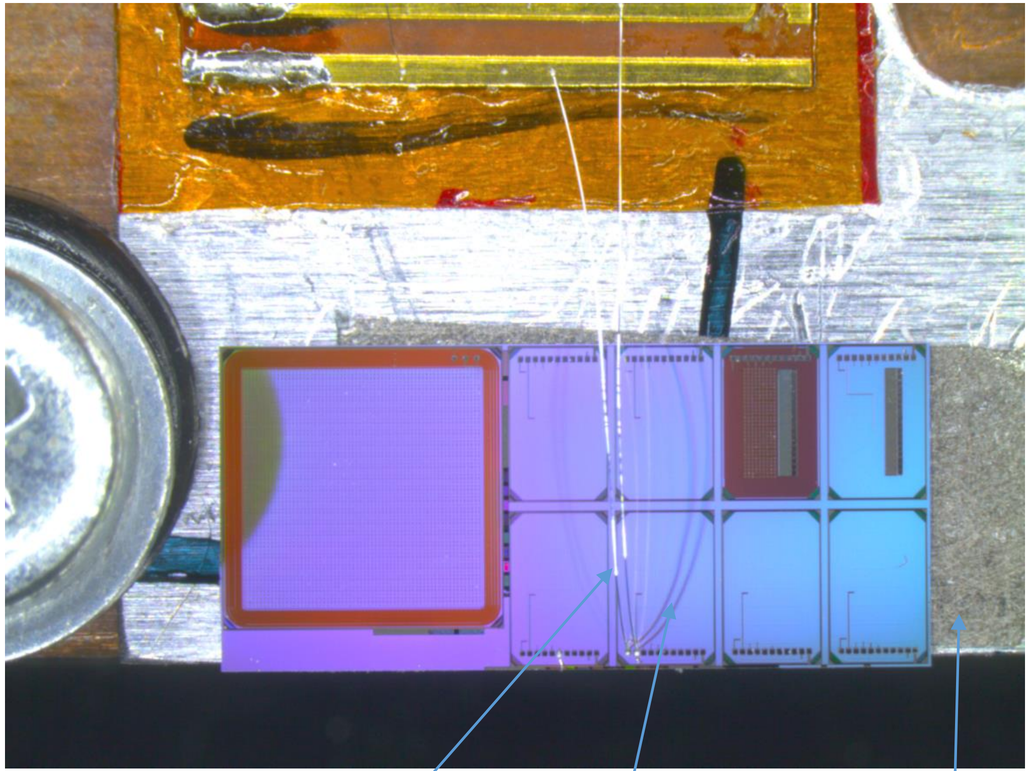
- E-TCT and Sr90 charge collection measurements

# Passive test structure B



- Bias ring at 0 V (or not connected if biased through the back plane)
- n-wells (pixels) connected to HV and amplifier (via bias-T)

# Passive test structure B



Bond wires to n-wells
(to readout and +HV)

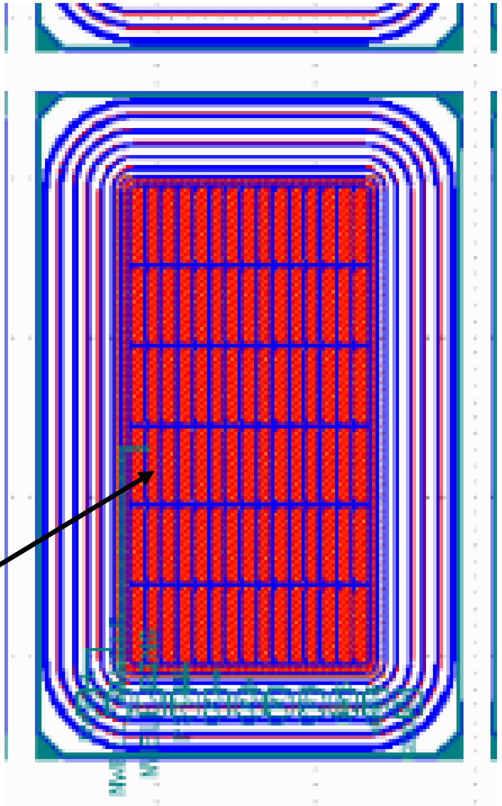
Structure B

Conductive glue (at GND)

15x6 array of
50x250 um$^2$ pixels

Contacts:

- single pixel
- all other pixels

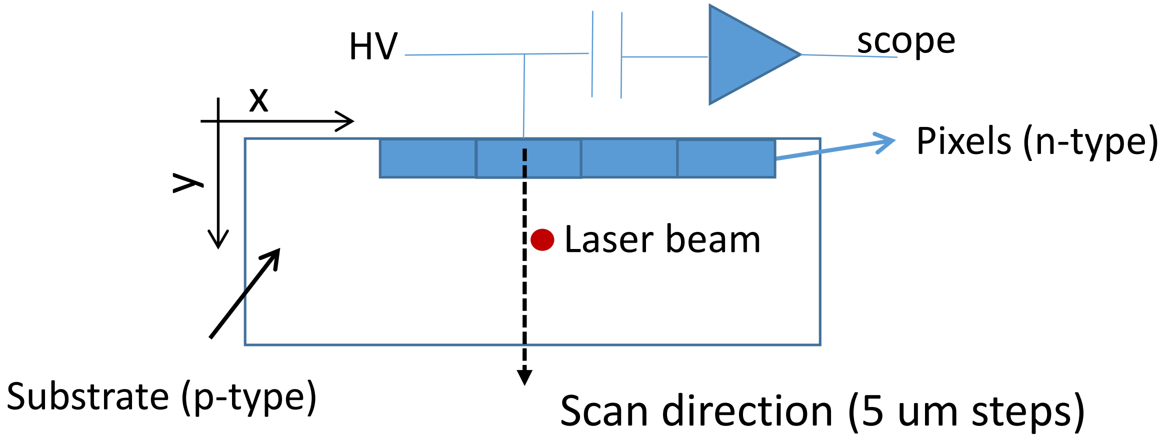


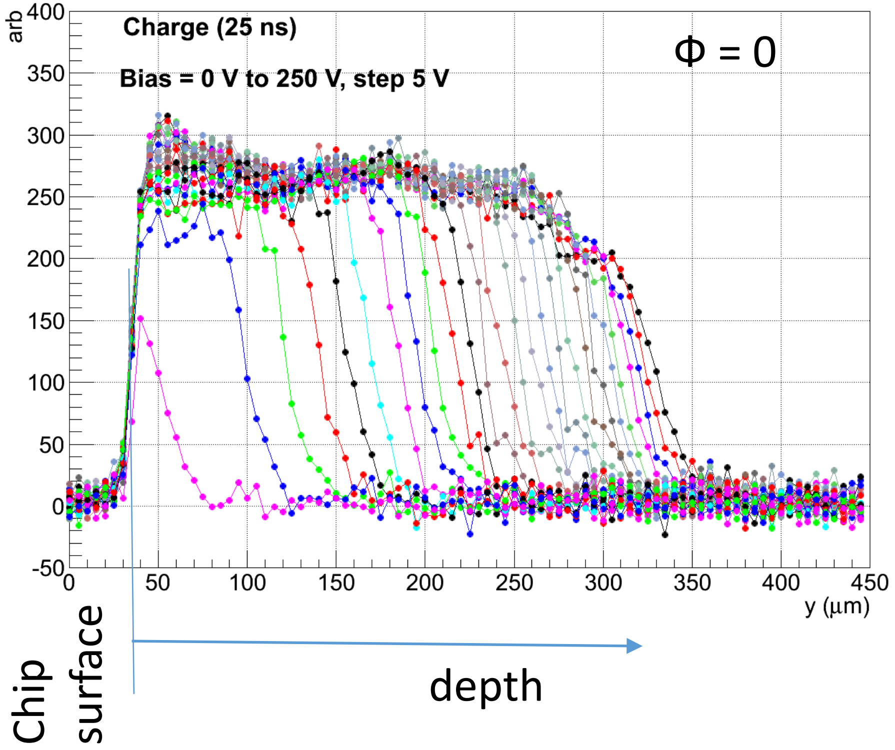
IR laser beam

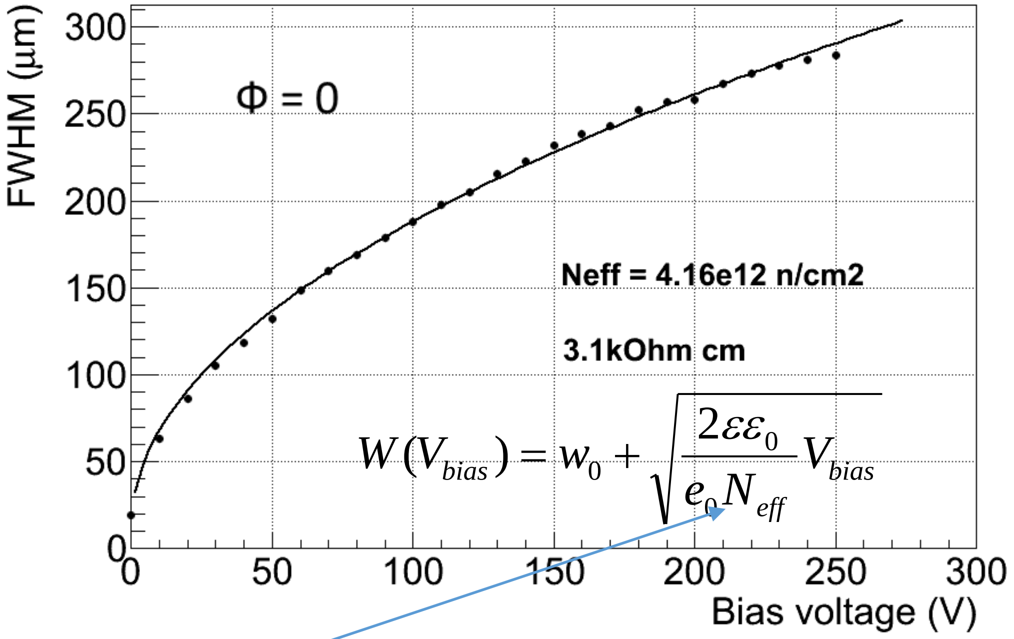
# E-TCT, before irradiation, not thinned

Charge profiles at different bias

- single pixel read out
- other pixels at HV but not read out
- Scan across the centre of the pixel







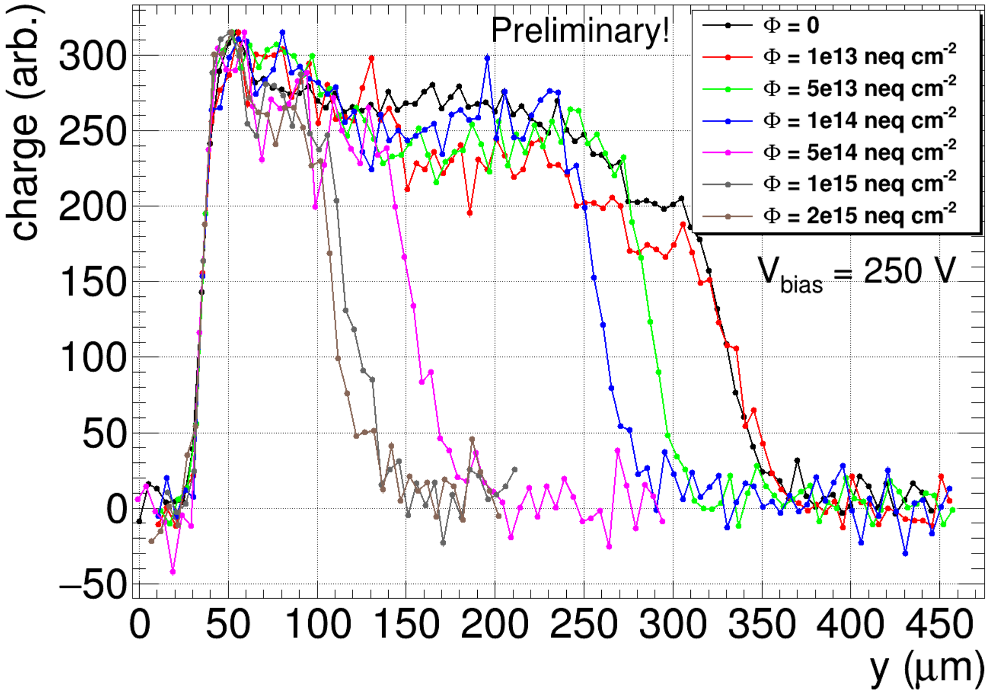
$$W(V_{bias}) = w_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} V_{bias}}$$

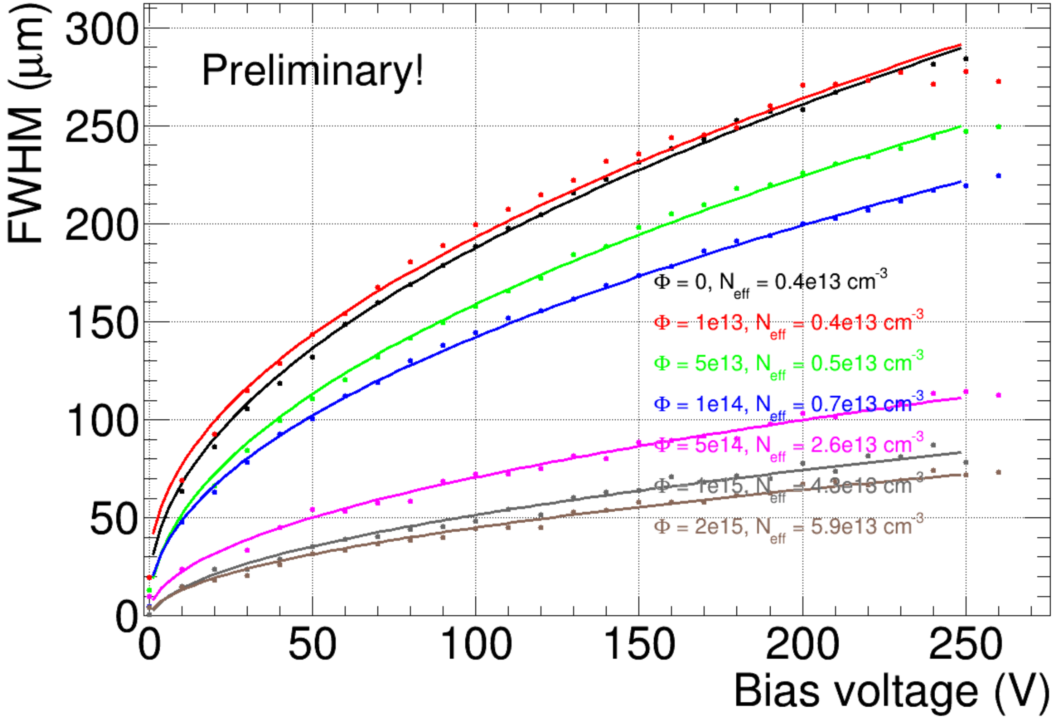
Estimate $N_{eff}$ from fit

➔ 3 kΩcm consistent with expected initial resistivity

# E-TCT, irradiated

- Not thinned:



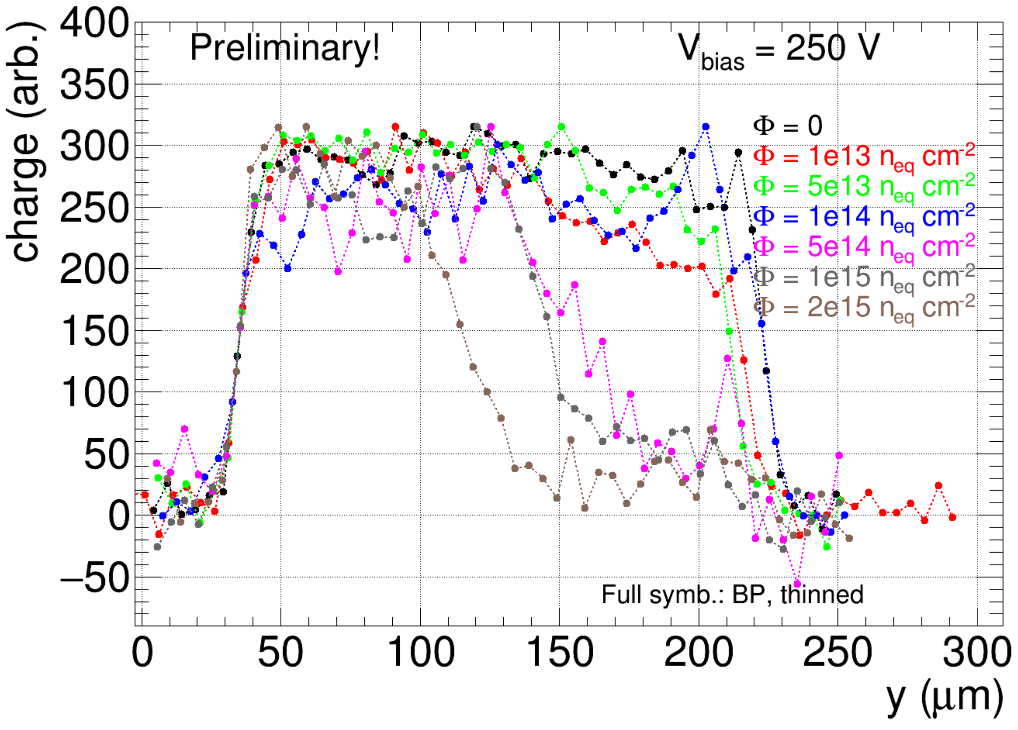


$$W(V_{bias}) = w_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} V_{bias}}$$

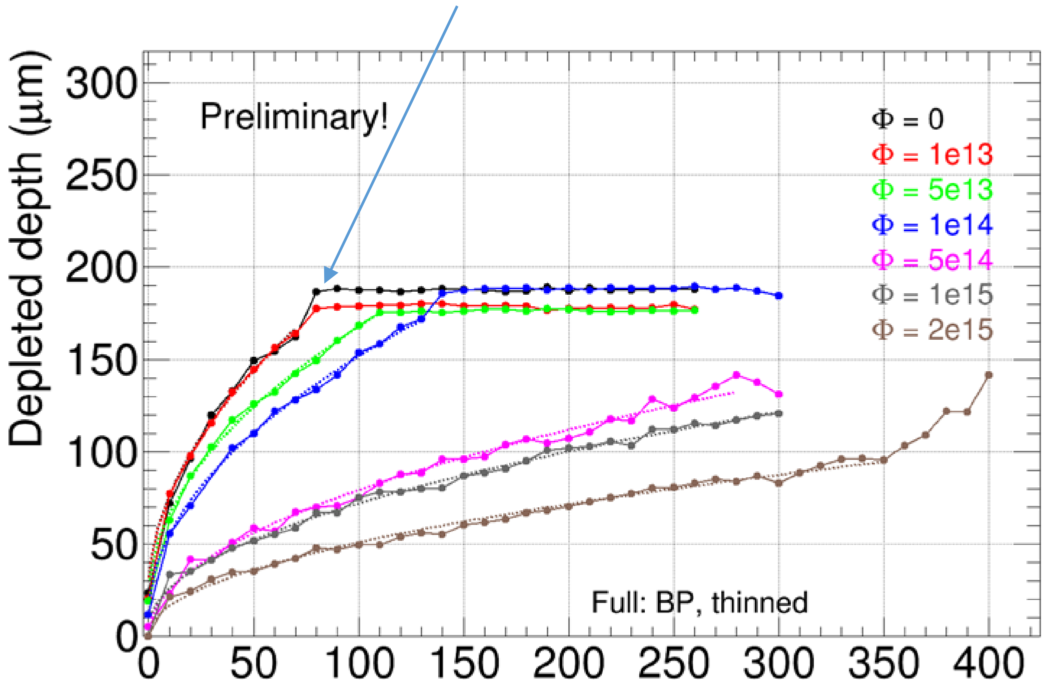
- $N_{eff}$ estimated from the fit of charge collection depth vs. bias voltage
- $N_{eff}$ increases with fluence (no significant acceptor removal seen) in these fluence steps ➔ low initial $N_{eff}$

# E-TCT, irradiated

- Thinned to ~ 200 μ with back plane:



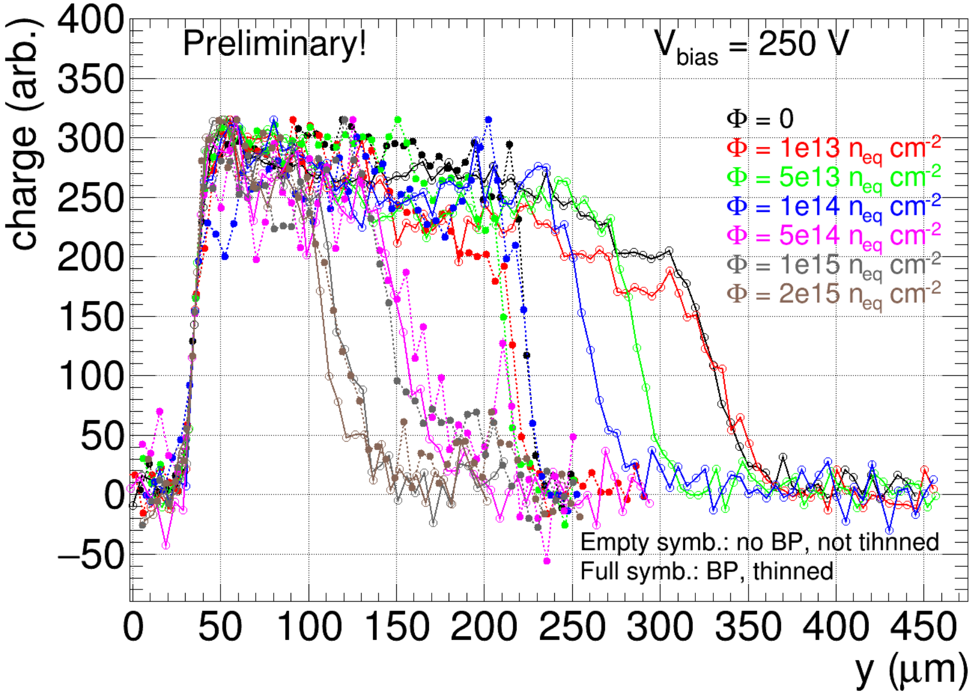
Full depletion

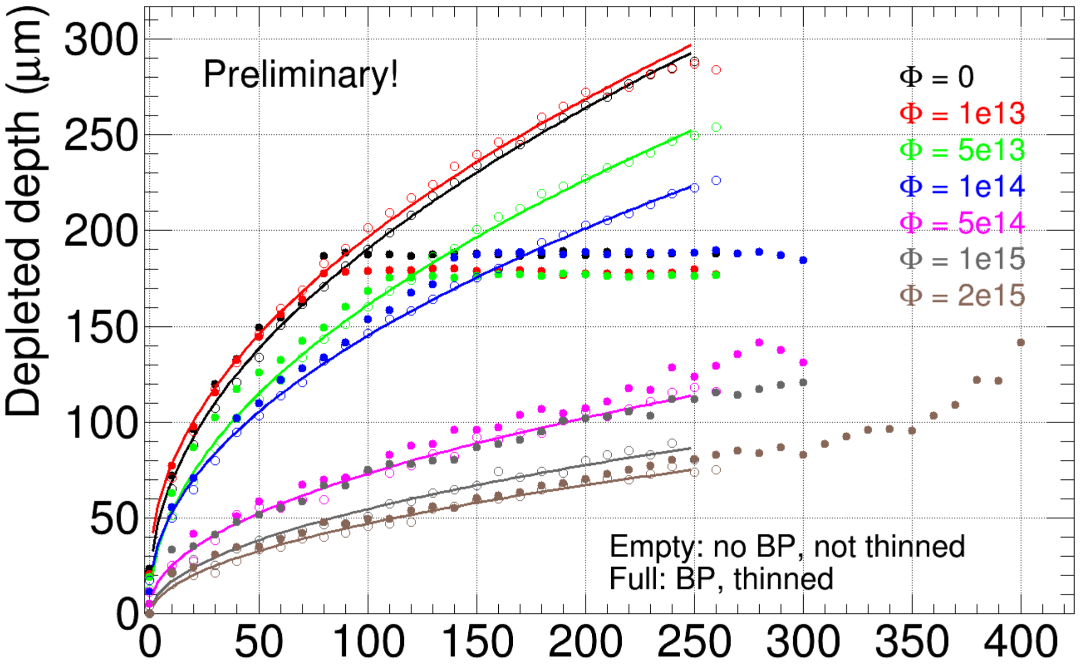


- Full depletion clearly seen
- *$N_{eff}$* can be extracted from the fit up to *$V_{fd}$* or from *$V_{fd}$* and known thickness

## **E-TCT, irradiated**

### Thinned and not thinned in the same plot



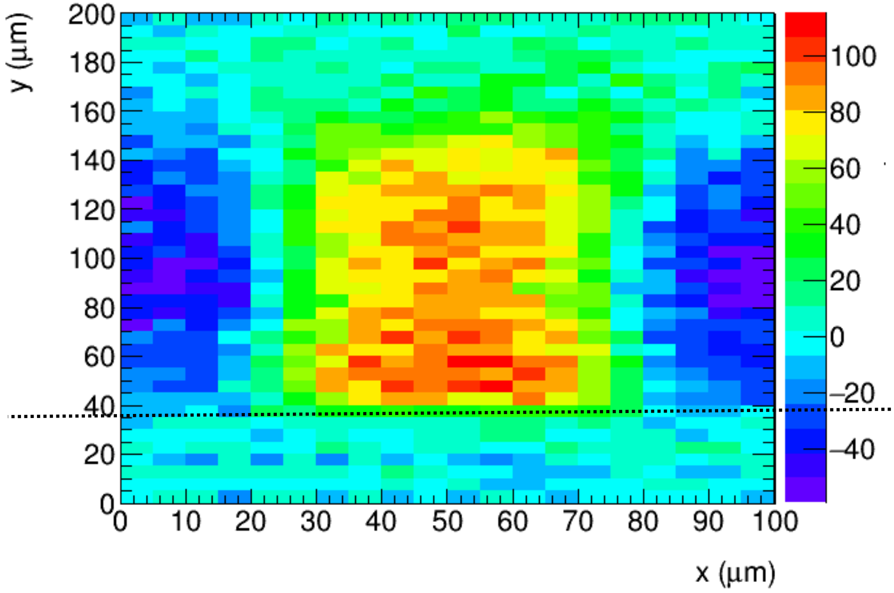


- charge profiles normalized to same maximum (to account for differences in laser beam power, edge surface…)
  ➔ very similar profile shapes in thinned with BP and not thinned samples below full depletion (except at 1e15)

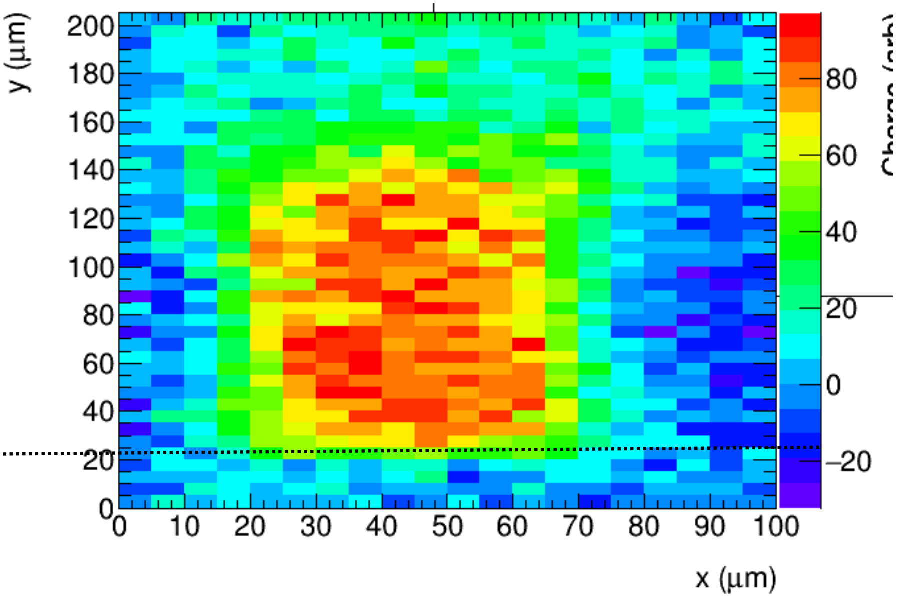
# E-TCT, examples of 2d charge profiles

- Single pixel read out
- 5e14, 250 V (thinned not not fully depleted)

Not thinned:



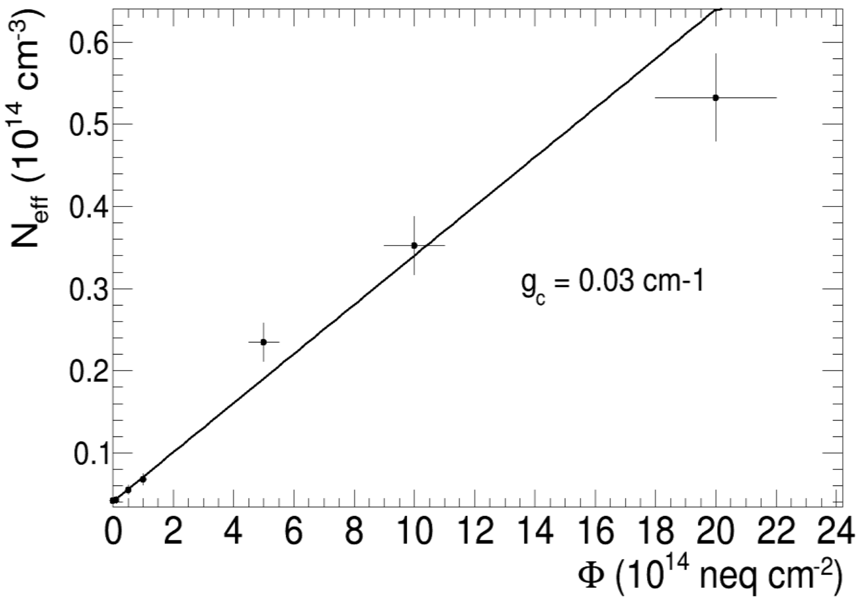
Thinned with back plane:



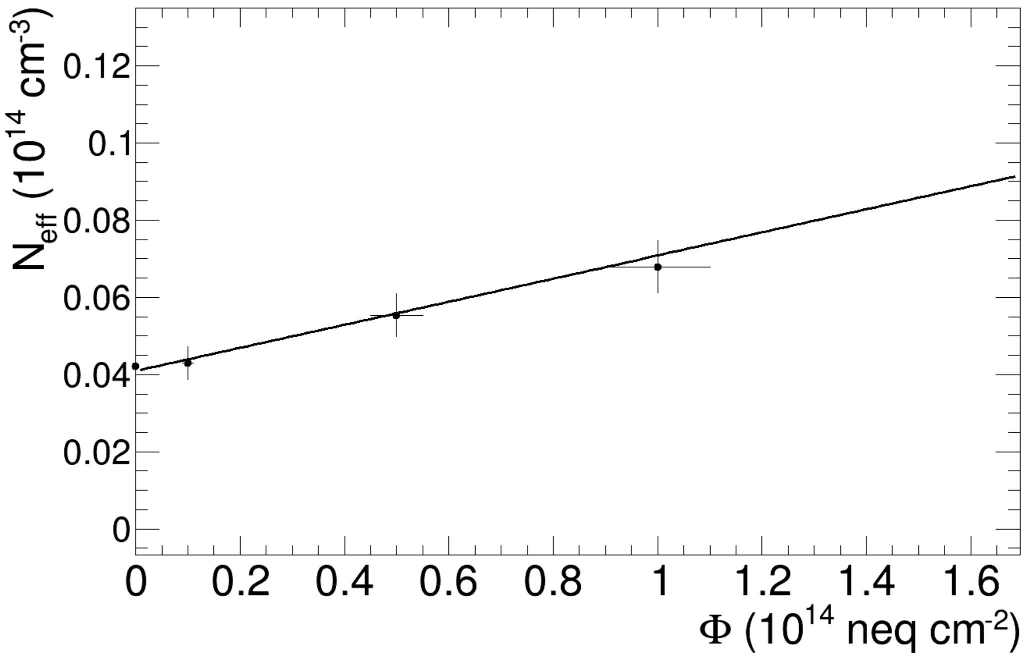
Chip surface

- not much difference between thinned and not thinned can be seen in these plots
- maybe slightly more uniform charge profile in thinned sample

## Neff vs. Phi



Zoom to low fluences

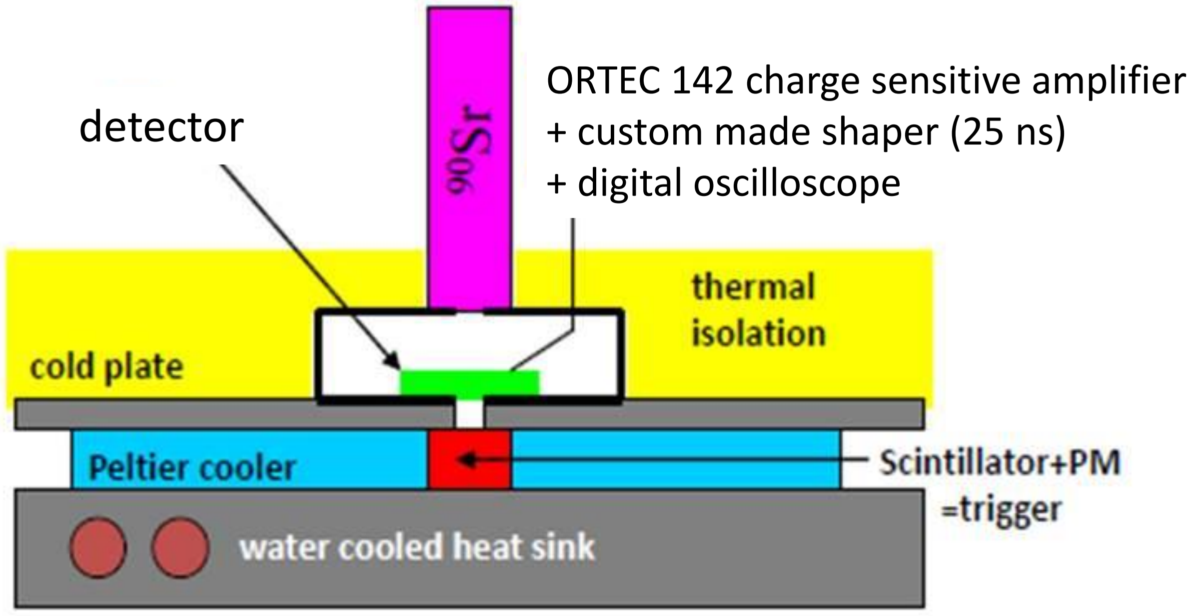


Fit: $$N_{eff} = N_{eff\,0} + g_c \cdot \Phi_{eq}$$

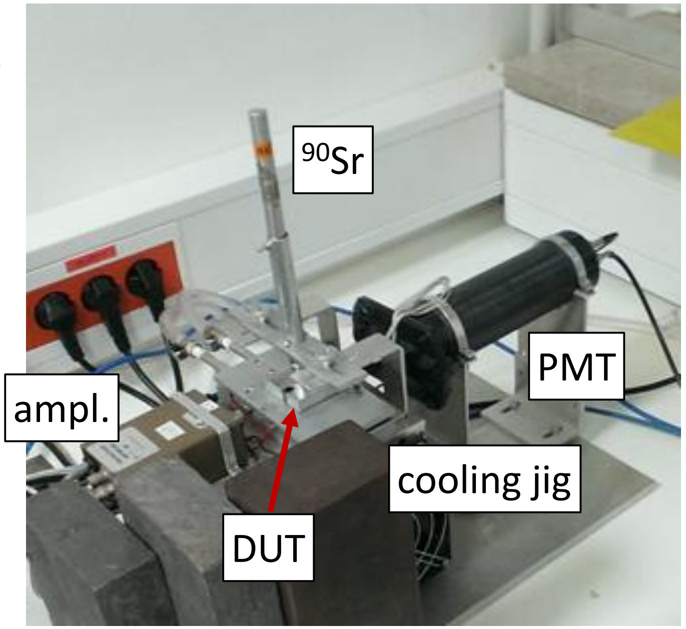
- small initial $N_{eff}$ (resistivity 3 kΩcm)
- $N_{eff}$ smaller than before irradiation not measured in these fluence steps
  ➔ should irradiate below 1e13 n/cm² to estimate acceptor removal constant

- linear fit good enough, $g_c$ = 0.03 cm$^{-1}$ (larger than “tpyical” value of $g_c$ ~ 0.02 cm$^{-1}$
  ➔similar as CCPD_LF, see: I. Mandić et al., "Neutron irradiation test of depleted CMOS pixel detector prototypes", 2017 JINST 12 P02021

# $^{90}$Sr setup



ORTEC 142 charge sensitive amplifier
+ custom made shaper (25 ns)
+ digital oscilloscope



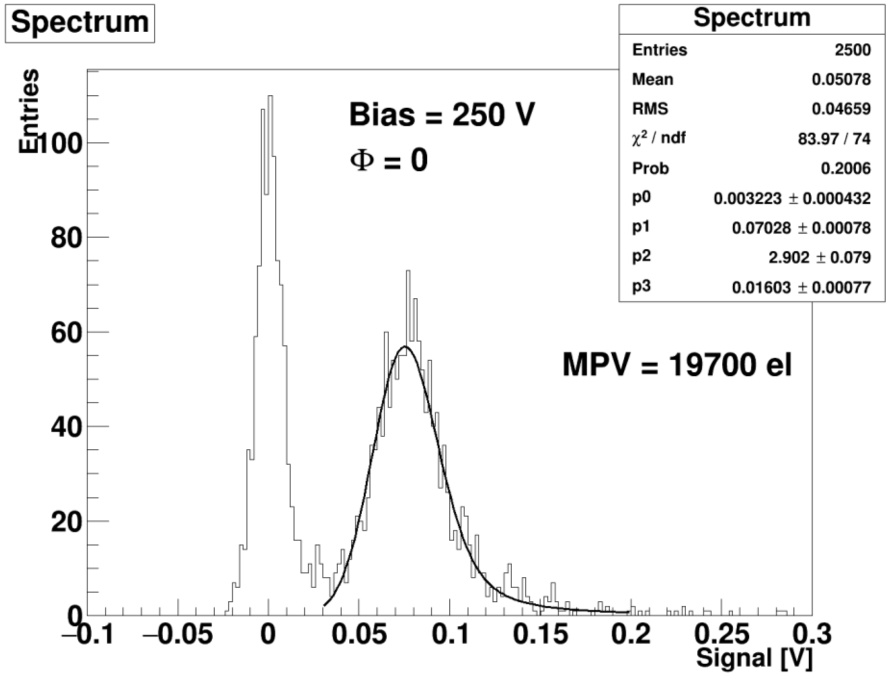
- Collimator 1mm diameter above and below the detector

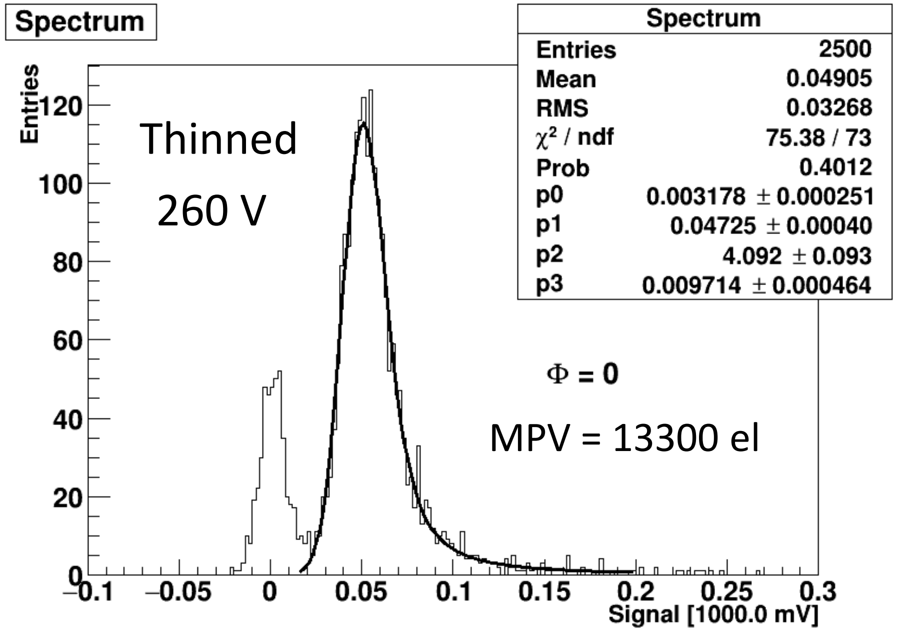
  ➔ if device smaller than collimator, landau can be fit only if signal and noise peak separate
- Calibrated with a 300 μm thick Si pad detector

## Sr-90, before irradiation

- Structure B, all pixels connected to readout (similar to pad detector)
- device small (1.5 mm x 0.75 mm) we can't collimate to measure only events with tracks passing through the detector

➔ before irradiation and at low fluences signal and noise peak well separated and Landau could be fit (can measure with these devices if MPV > ~ 4000 el)





Not thinned:

- depleted depth from E-TCT ~ 280 um

➔ expected MPV ~ 21000 el

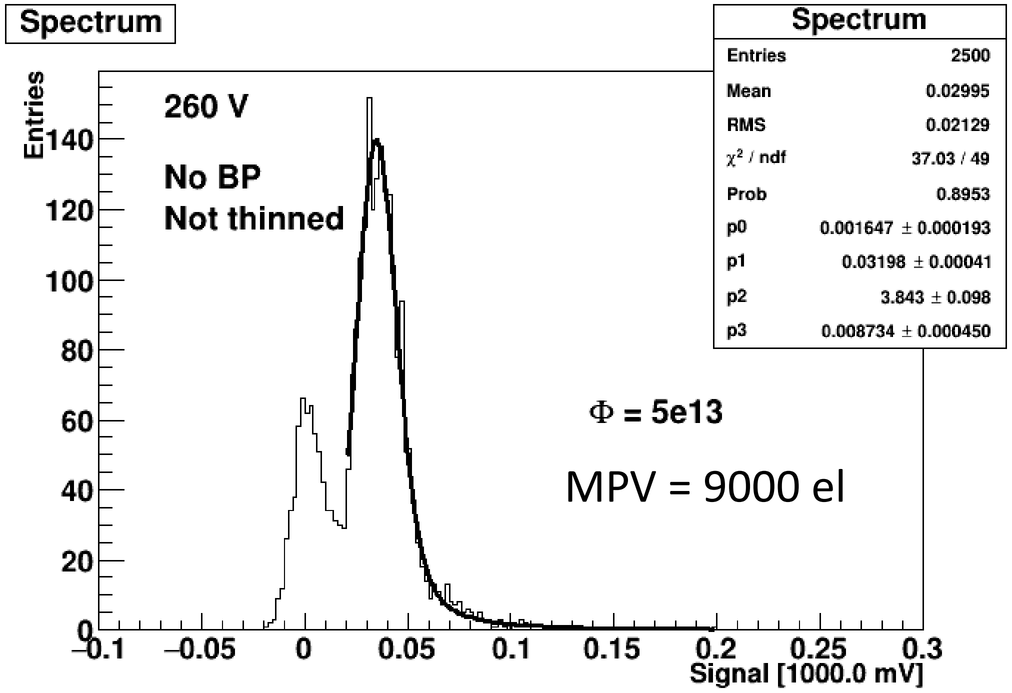
Consistent!

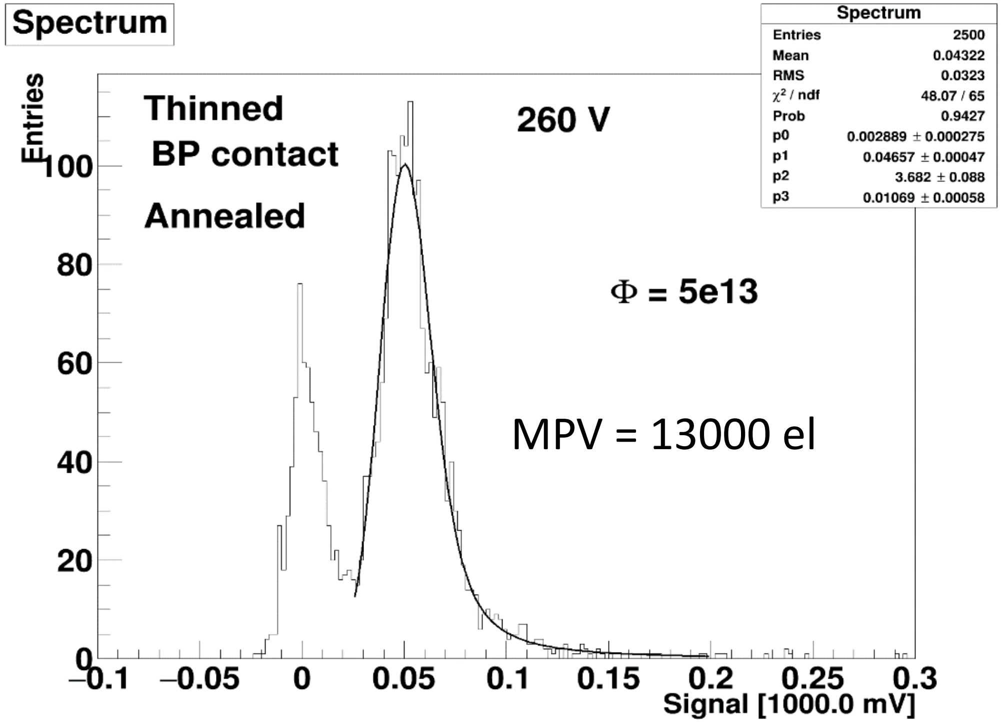
Thinned:

- Depleted depth from E-TCT ~ 190 um

➔ expected MPV ~ 13500 el

# Sr90, after irradiation to Φ = 5e13 n/cm²





Not thinned, substrate bias from top:

- depleted depth from E-TCT: ~ 260 um
  - ➔ expected (full collection) MPV ~ 19000 el
  - ➔ **measured MPV ~ 9000 el**

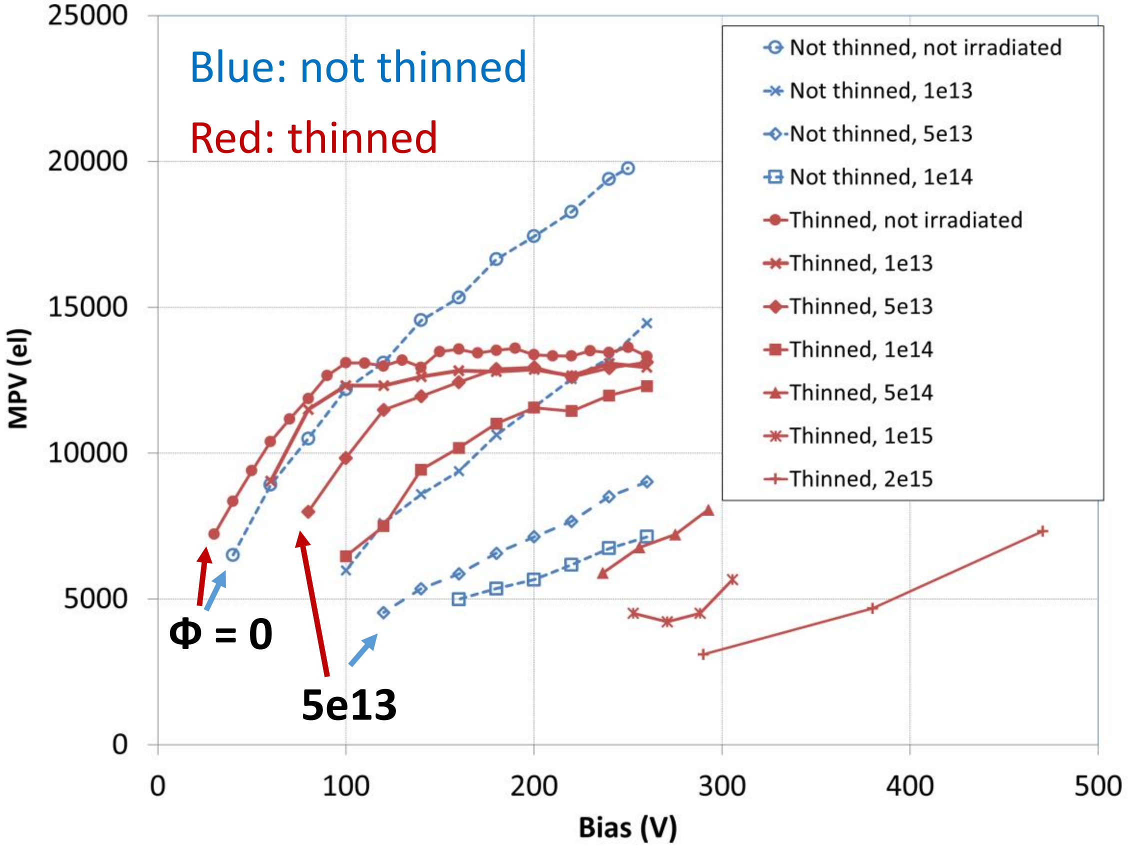
Thinned to ~ 200 um, substrate bias via back plane

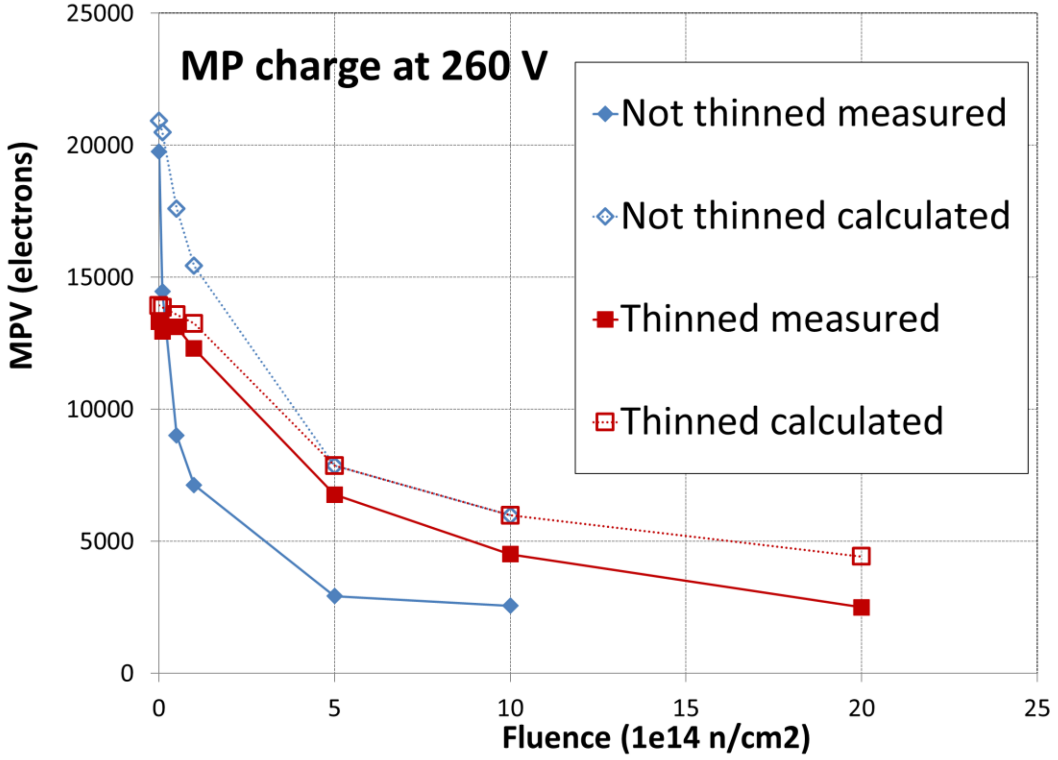
- depleted depth from E-TCT ~ 180 um (fully depleted)
  - ➔ expected (full collection) MPV ~ 13500 el
  - ➔ **measured MPV ~ 13000 el**

➔ Large difference between samples with and without back plane after irradiation!

# Sr-90, after irradiation

- significantly larger collected charge measured in thinned samples with back plane after irradiation





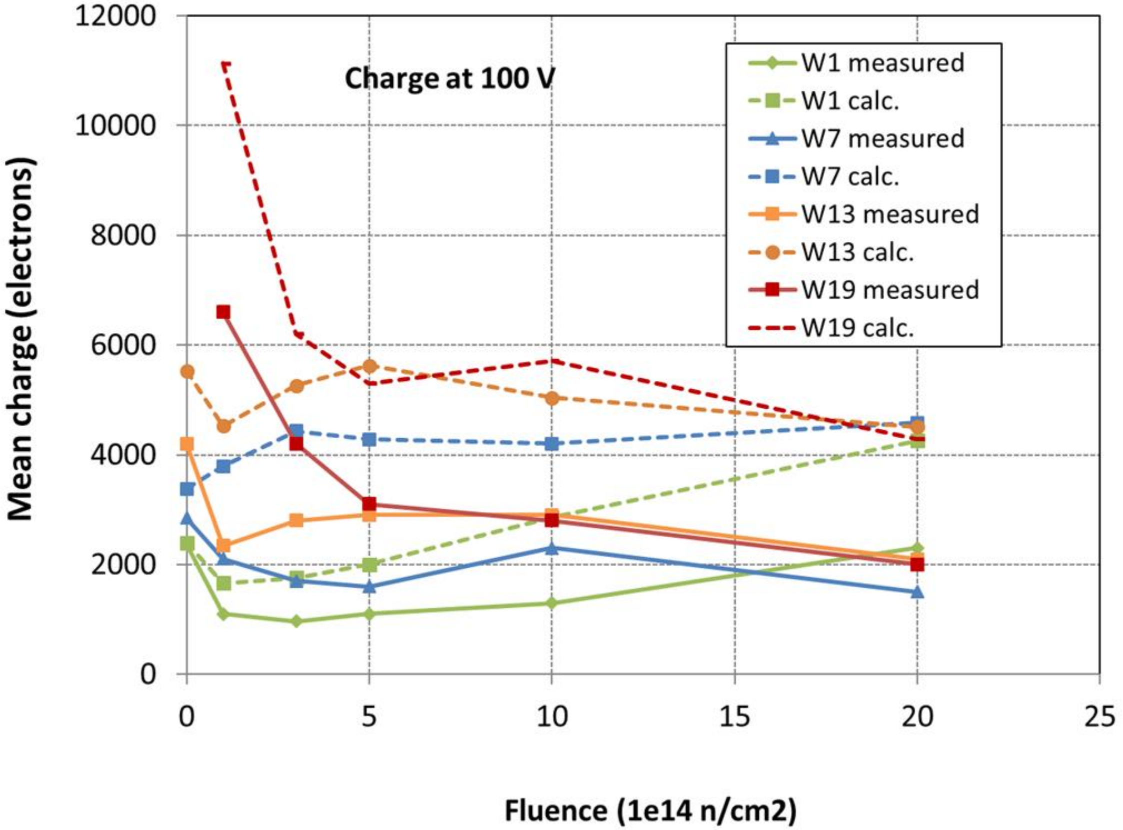
Calculated = Depleted_depth*(75 el/µm)* trapping_loss

➔ larger difference between calculated and measured after irradiation in not thinned samples

➔ good agreement if fully depleted (thinn, Φ < 5e14)

# AMS CHESS2 chip

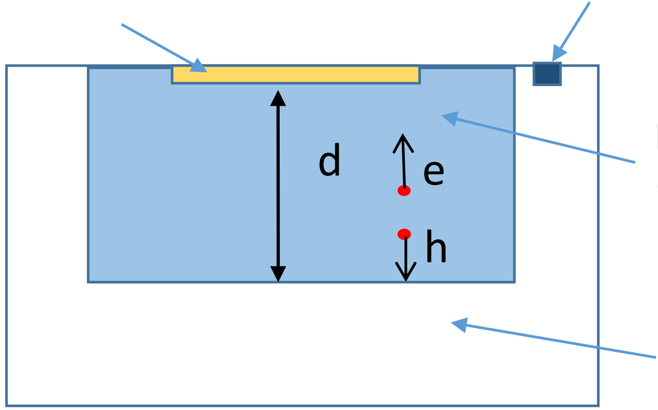
- Initial resistivities: W1: 20 Ω·cm, W7: 50 Ω·cm, W13: 200 Ω·cm, W19: 1 kΩ·cm
- bias from top, no back plane processing
- thickness 250 um



- much smaller collected charge than deposited in depleted region by a MIP (with trapping loss taken into account)
- for more info about measurements with chess2 chips see B. Hiti et al. at TREDI 2017: https://indico.cern.ch/event/587631/contributions/2471700/attachments/1415576/2167163/20170221_hiti.pdf

# **Different weighting field** in not thinned top biased devices and thinned devices with back plane after irradiation

## **No back plane**, substrate biased via implant on top



Collecting electrode: $U_w = 1$

Substrate bias: $U_w = 0$

Depleted region
→ electric field

Undepleted substrate

### Before irradiation:

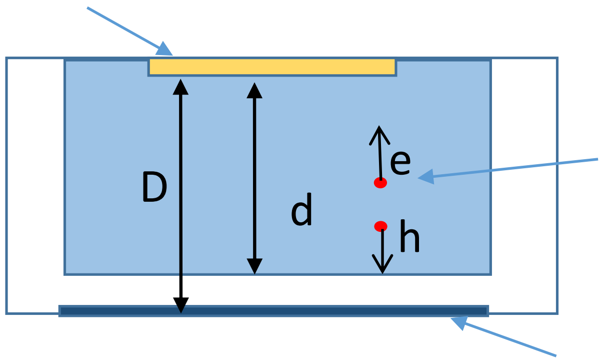
- Undepleted substrate: sufficient conductivity, weighting potential $U_w = 0$ everywhere in the undepleted substrate

➔ carriers drift across whole weighting field: all charge collected

### After irradiation:

- substrate conductivity low, $U_w = 0$ at the bias implant on top
  - ➔ carriers trapped in low field at the end of depleted depth, before drifting to the substrate bias electrode
  - ➔ carriers don't drift across all weighting field
  - ➔ partial charge collection

## **Back plane** (and thinned), substrate biased via back plane



Collecting electrode: $U_w = 1$

Depleted region
→ electric field

Substrate bias: $U_w = 0$

### Before irradiation:

- Undepleted substrate sufficient conductivity, weighting potential $U_w = 0$

➔ carriers drift across all weighting field: all charge collected

### After irradiation:

- substrate conductivity low, $U_w = 0$ at the back plane implant
  - ➔ if fully depleted D = d full charge collection (except trapping loss)
  - ➔ if not fully depleted carriers don't cross all weighting field
    - → charge collection reduced (in pad geometry by a factor **d/D)**
  - ➔ depending on geometry and device thickness this factor can be much larger than in the case of top bias and not thinned devices

Effects of weighting field in irradiated pixel detectors see e.g.: *G. Kramberger, D. Contarato, NIM A 511 (2003) 82–87*

# Summary

## E-TCT

- Dependence of depleted depth on bias voltage and fluence measured
- $N_{eff}$ as function of fluence estimated
  ➔ no significant acceptor removal observed at measured fluences → high initial resistivity (3 kΩcm), removal could probably seen at lower fluences
  ➔ $N_{eff}$ increases linearly with fluence $g_c$ = 0.03 cm$^{-1}$
  ➔ behavior similar as CCPD_LF devices, see: *I. Mandić et al., 2017 JINST 12 P02021*
- No significant difference seen between thinned devices biased via back plane and not thinned devices biased from top at bias voltages below $V_{fd}$ of thinned devices ➔ depleted region & electric field similar

## Charge collection with Sr-90

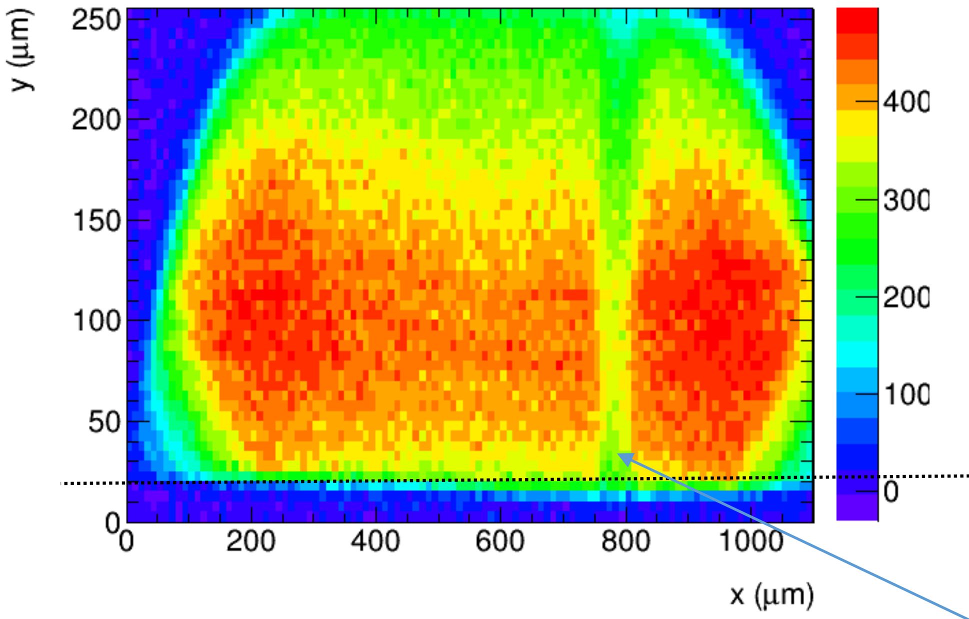
- Measured with charge sensitive amplifier with 25 ns shaping time
  → ~ 20000 electrons at 260 V in not thinned device and ~ 13000 el in thinned device at 260 V before irradiation
  → ~ 7500 electrons after **2e15** n/cm$^2$ at 470 V in thinned device with back plane

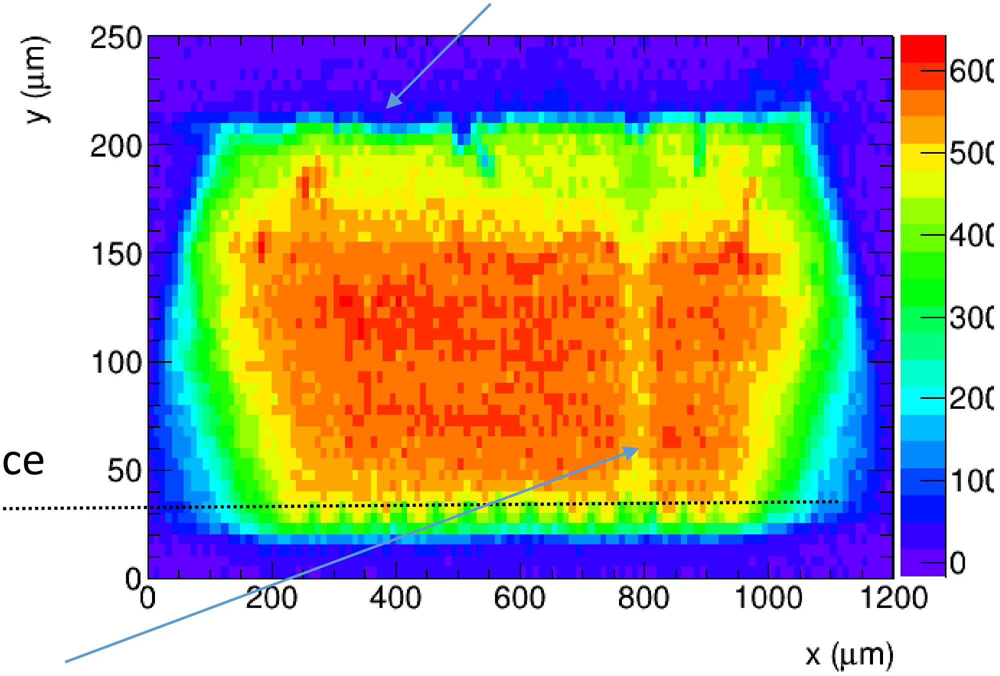
- Before irradiation: collected charge as expected from depleted thickness measured with E-TCT
- After irradiation: much smaller charge measured with not thinned devices without processed back plane although depleted regions seen with E-TCT similar
  ➔ different charge collection because of different weighting field in these two cases

**➔ thinning and back plane improve charge collection after irradiation in these devices!**

# E-TCT, examples of 2d charge profiles

- All except one pixel read out
- 5e13, 250 V, thinned fully depleted





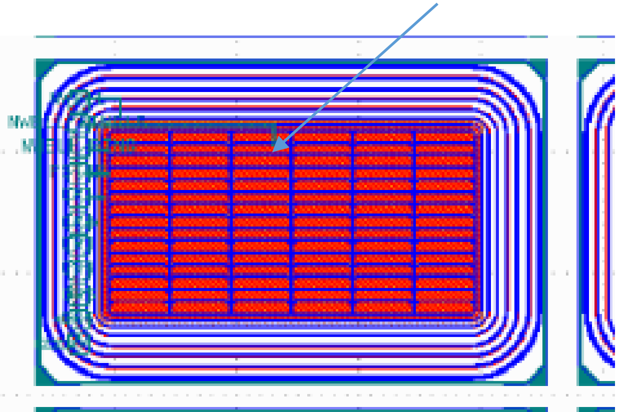
Back plane

Chip surface

Gap because of the pixel
not connected to readout

- no efficiency gaps between pixel columns seen

Pixel not read out



IR laser beam