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Measurements of passive structures on irradiated HV-CMOS detectors

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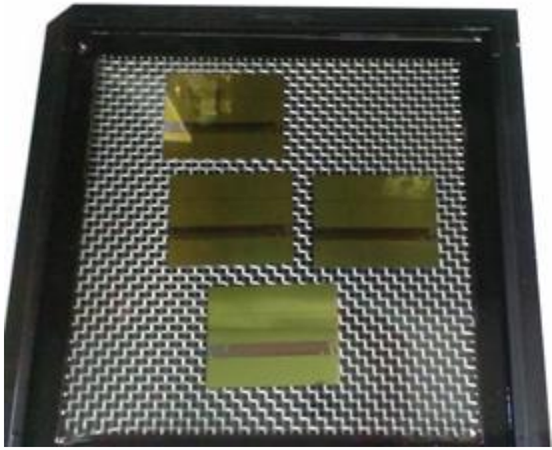
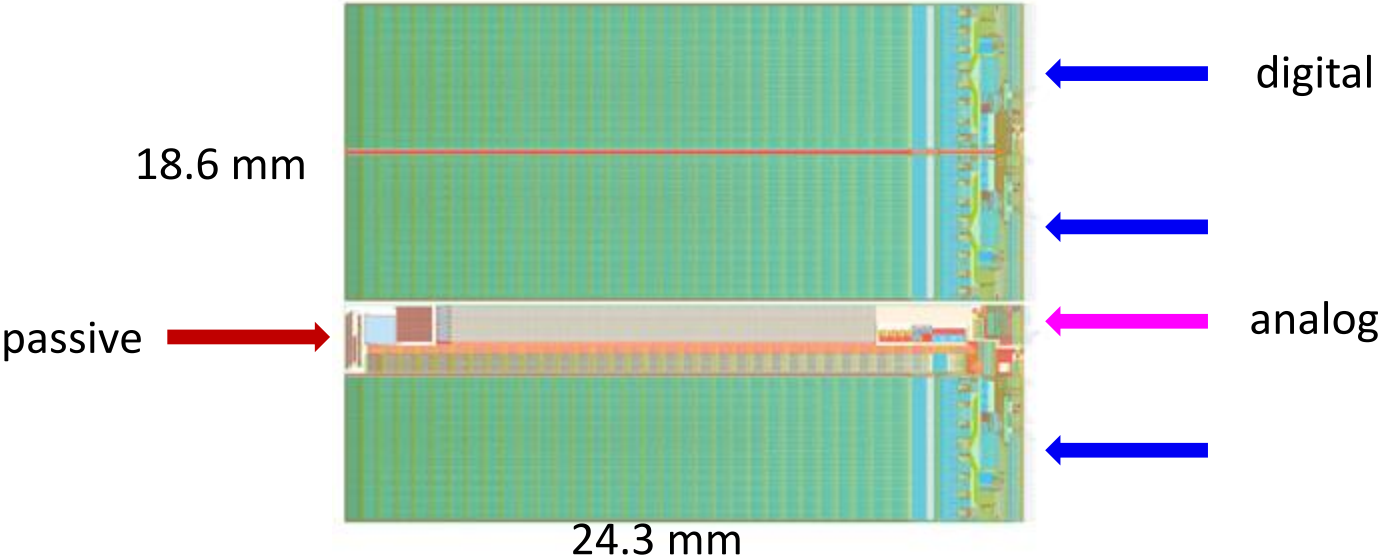
Outline

- CHESS 2 chip introduction
- Edge-TCT measurements
- Acceptor removal parameters
- ^{90}Sr measurements
- Summary

CHESS 2 chip

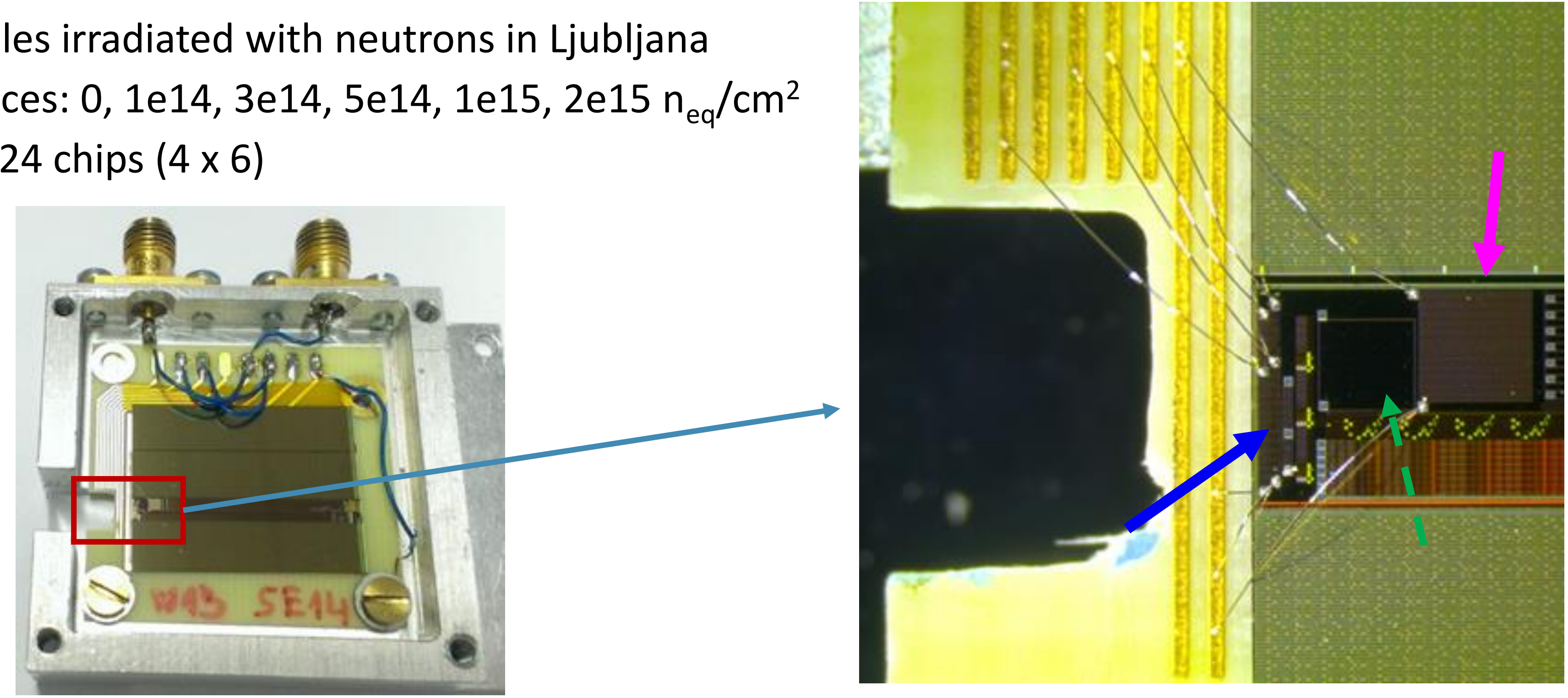
- Developed by the ATLAS Strip CMOS collaboration as a candidate for HVCMOS strip detector for ATLAS Phase II upgrade
- Design by UCSC, SLAC and KIT, produced in AMS H35 process, max. bias 120 V
  - H. Grabas, *Chess2 front end readout of the multi-segmented HV CMOS sensors*, FEE 2016
- Reticle size demonstrator chip, follow up of CHESS 1
  - 3 striplet arrays with fully digital encoding and readout
  - 1 pixel array with an in-strip amplifier and analog readout
  - Several passive arrays for material studies – subject of this talk





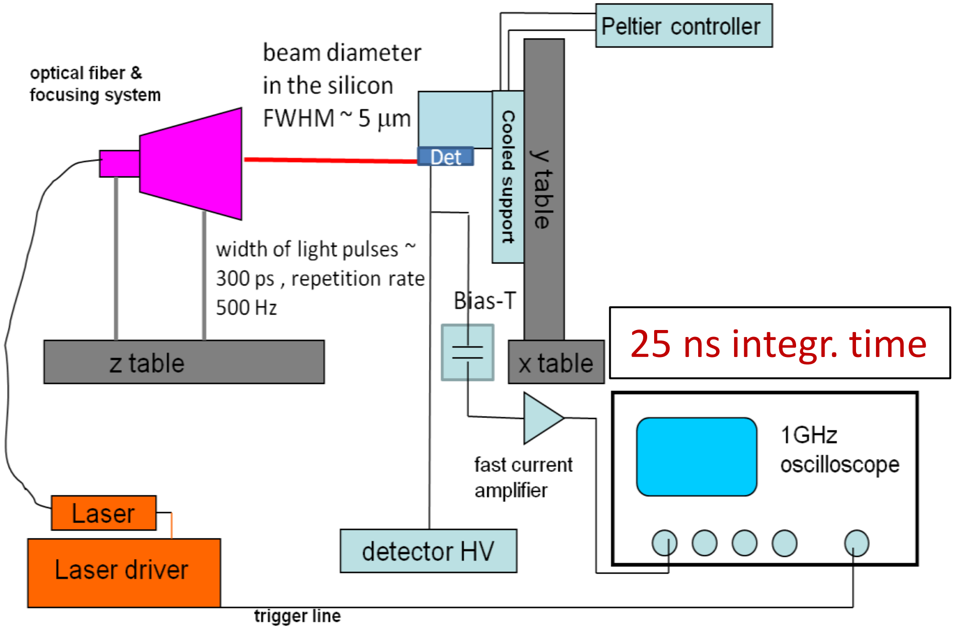
Passive test structures on CHESS 2

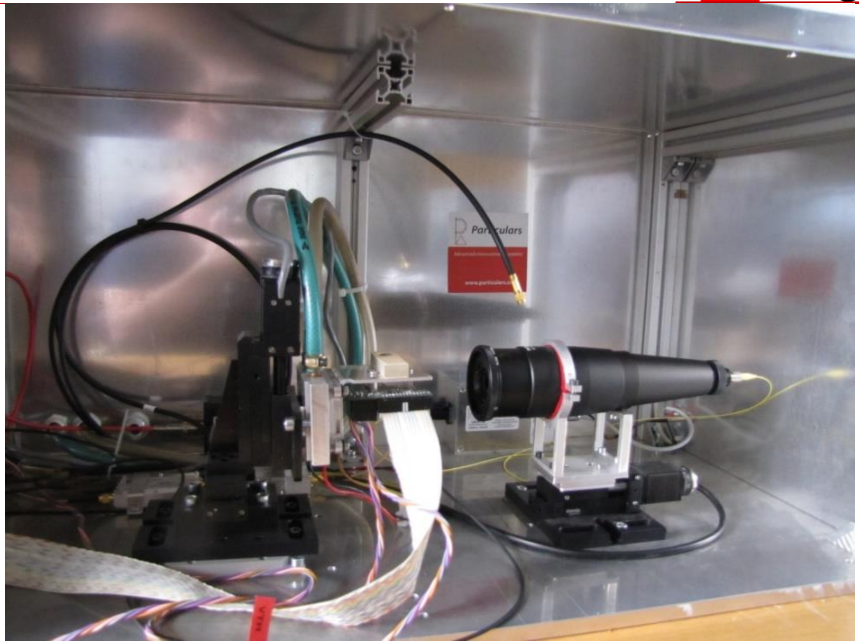
- Edge-TCT arrays, 3 x 3 pixels, pixel size: 630 x 40 µm^2 (six 90.2 µm x 24.3 µm nwells in each pixel)
- Large Passive Array, 1.3 x 1.3 mm^2 for ^{90}Sr measurements, implants ganged together (Large n-well, not used here)
- Chips produced on four different substrate resistivities
  - 20 Ω·cm, 50 Ω·cm, 200 Ω·cm, 1 kΩ·cm
- Irradiation study:
  - Samples irradiated with neutrons in Ljubljana
  - Fluences: 0, 1e14, 3e14, 5e14, 1e15, 2e15 n_{eq}/cm^2
  - Total 24 chips (4 x 6)



Edge-TCT

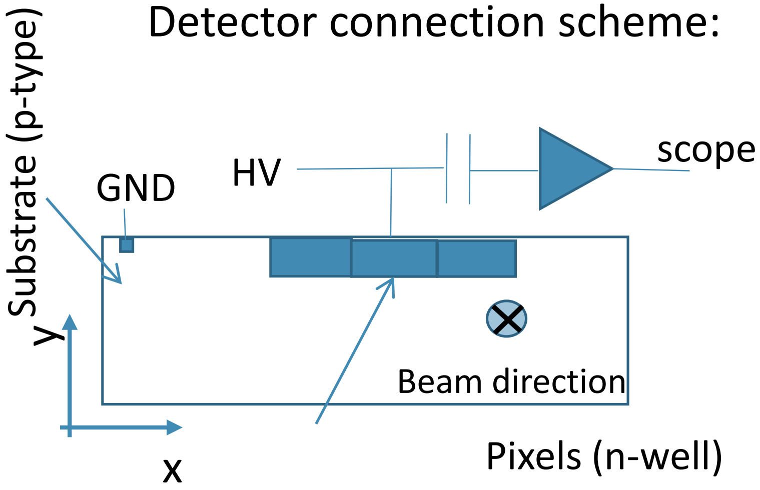
Edge-TCT setup





(more details: www.particulars.si)

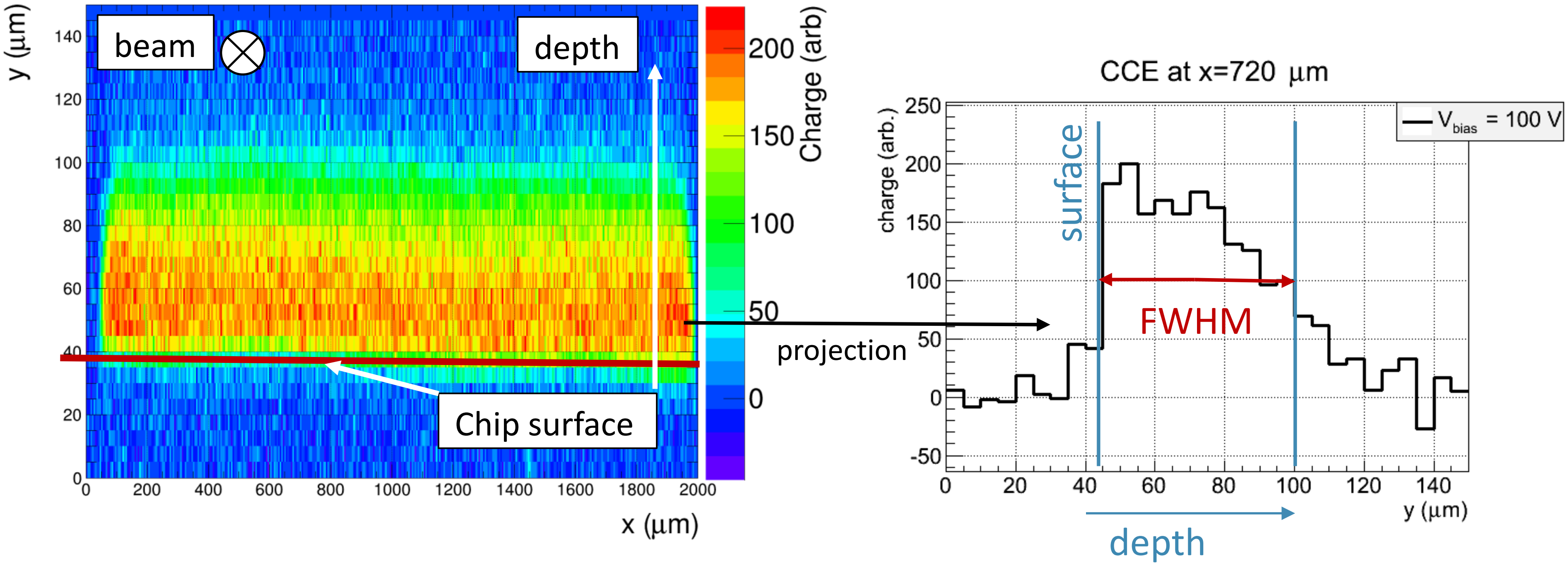
Detector connection scheme:



TCT measurements with passive pixels (no amplifier in the n-well)

➔ collecting electrode connected to the amplifier

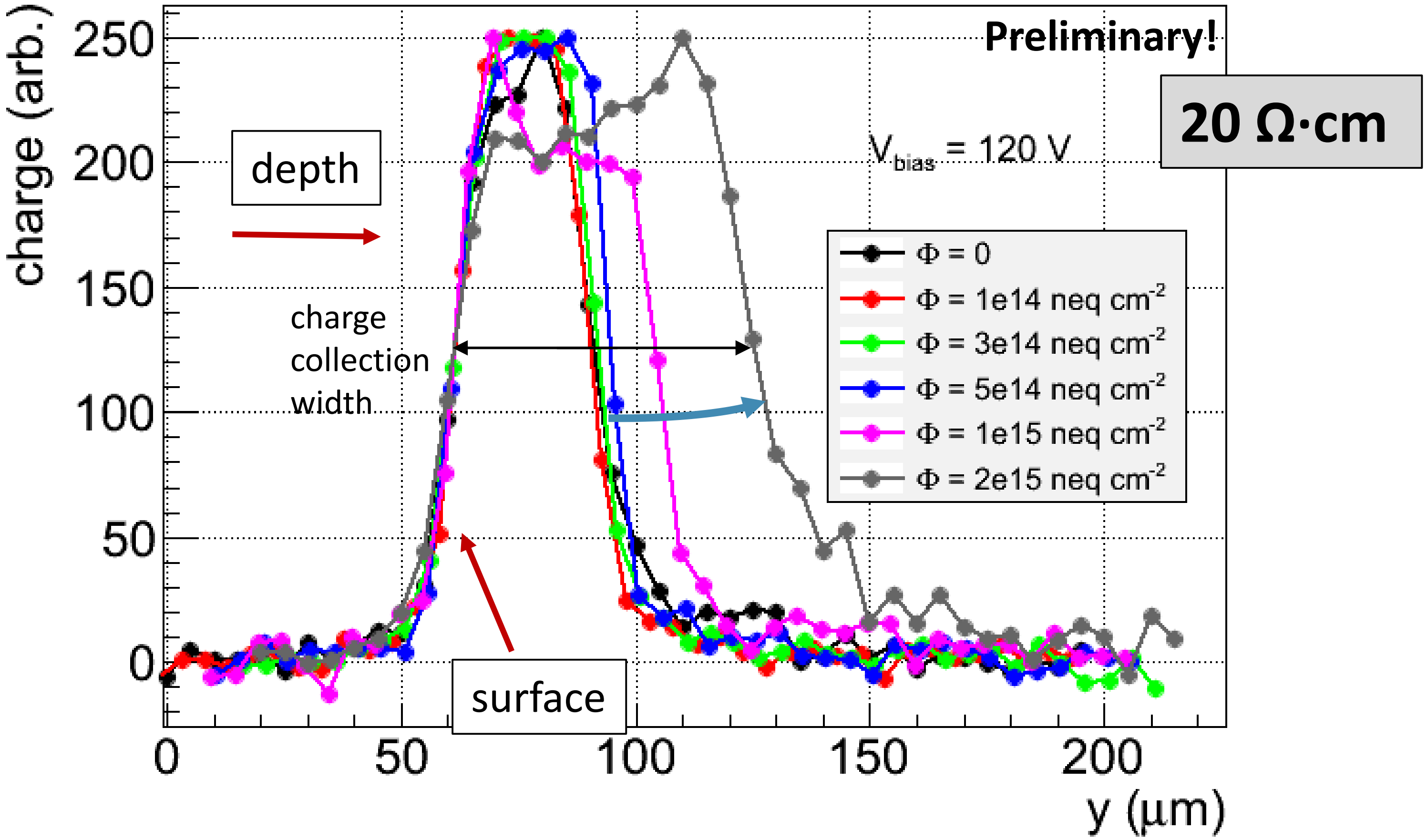
Edge-TCT measurements



- Sensors only partially depleted
- Edge-TCT allows to study the depletion depth dependence on voltage/fluence

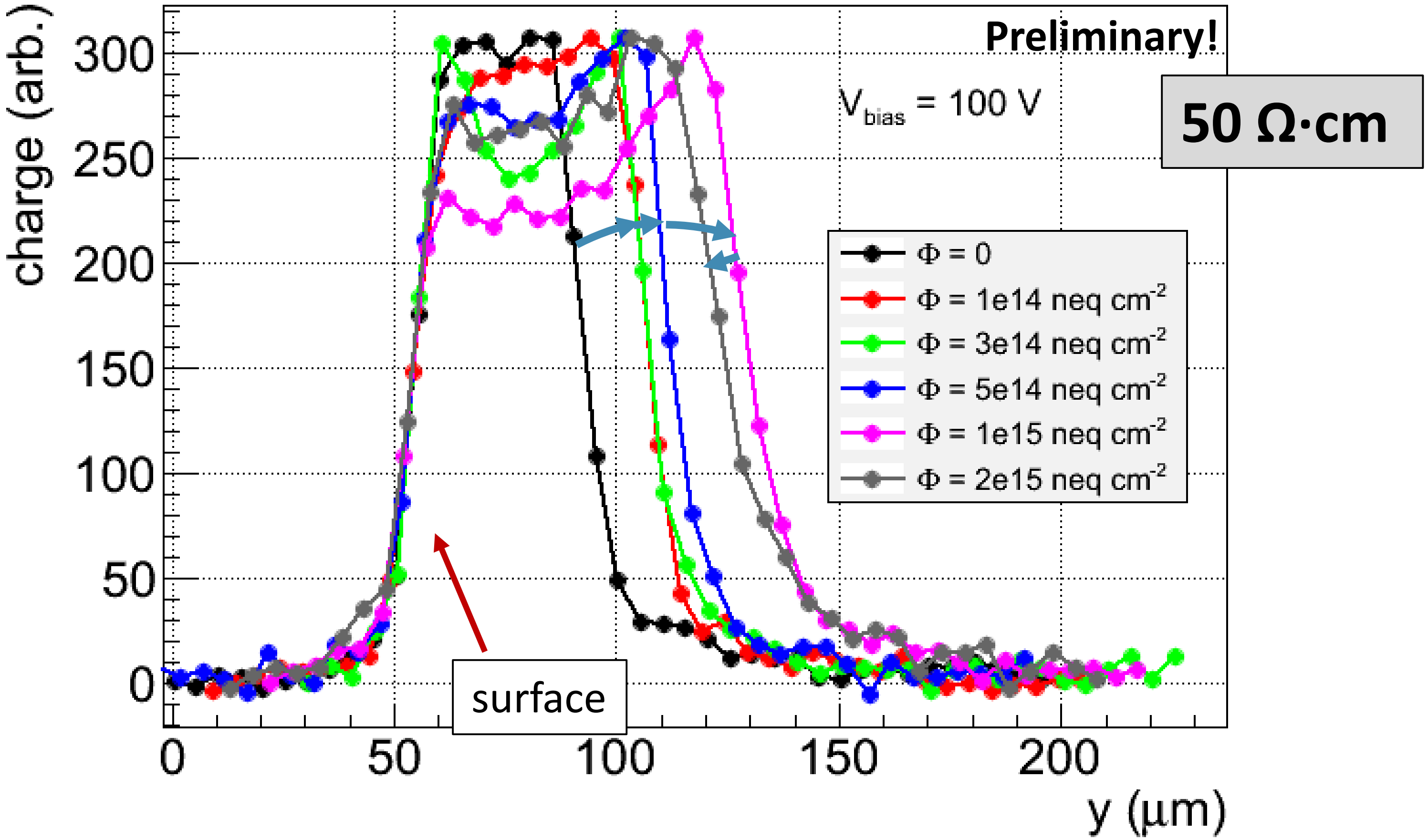
- Charge collection width = FWHM of the charge collection profile

20 Ω·cm Edge-TCT charge collection profiles



- Charge collection width at 120 V changes with irradiation
- Increase at fluences above 5e14 n_{eq}/cm^2 – initial acceptor removal
- Low substrate resistivity → late acceptor removal

50 Ω·cm Edge-TCT charge collection profiles

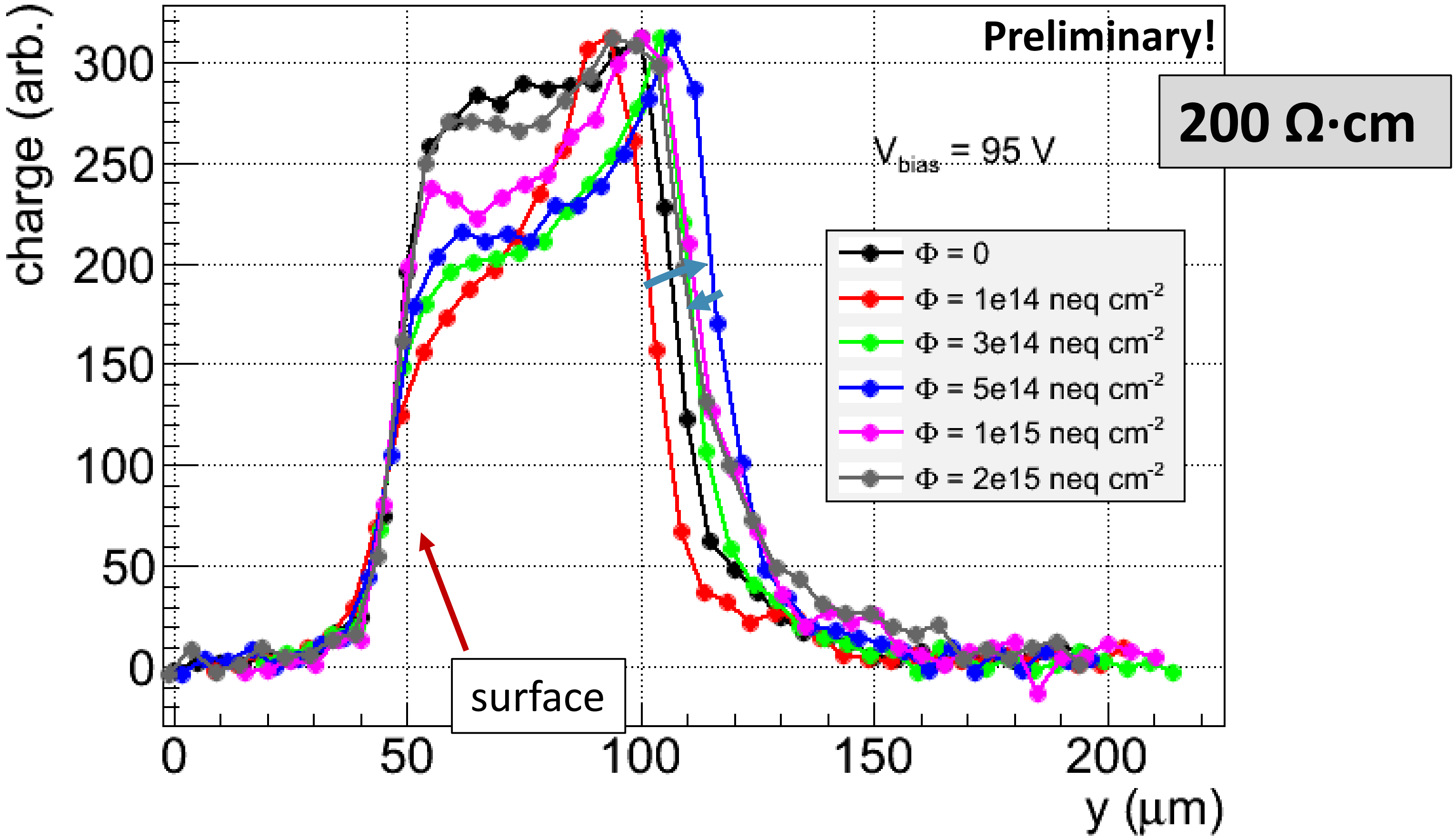


50 Ω·cm

surface

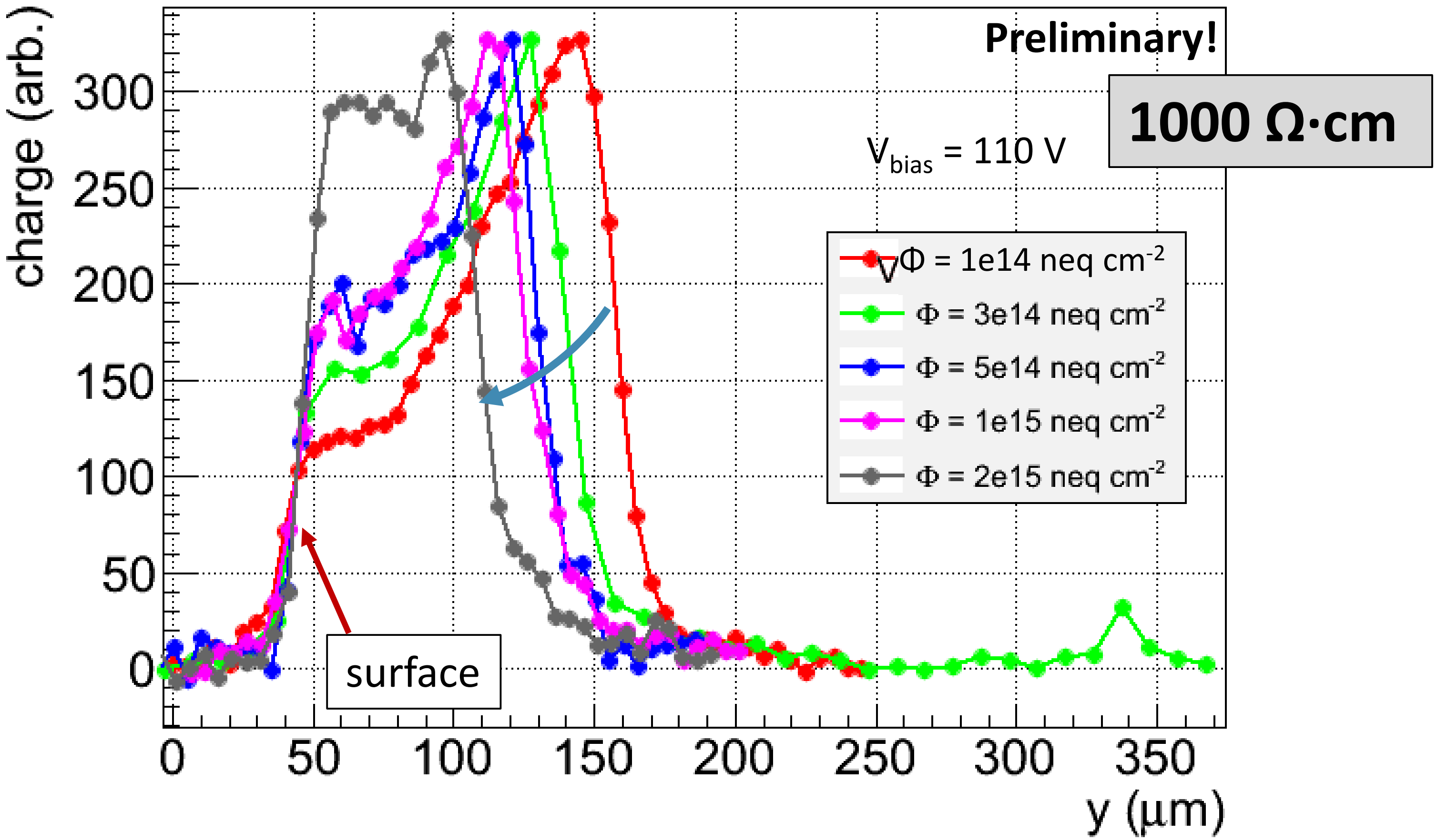
- Charge collection width increases up to 1e15 n_{eq}/cm^2, then reducing
- Acceptor removal finished earlier than with 20 Ω·cm substrate

200 Ω·cm Edge-TCT charge collection profiles



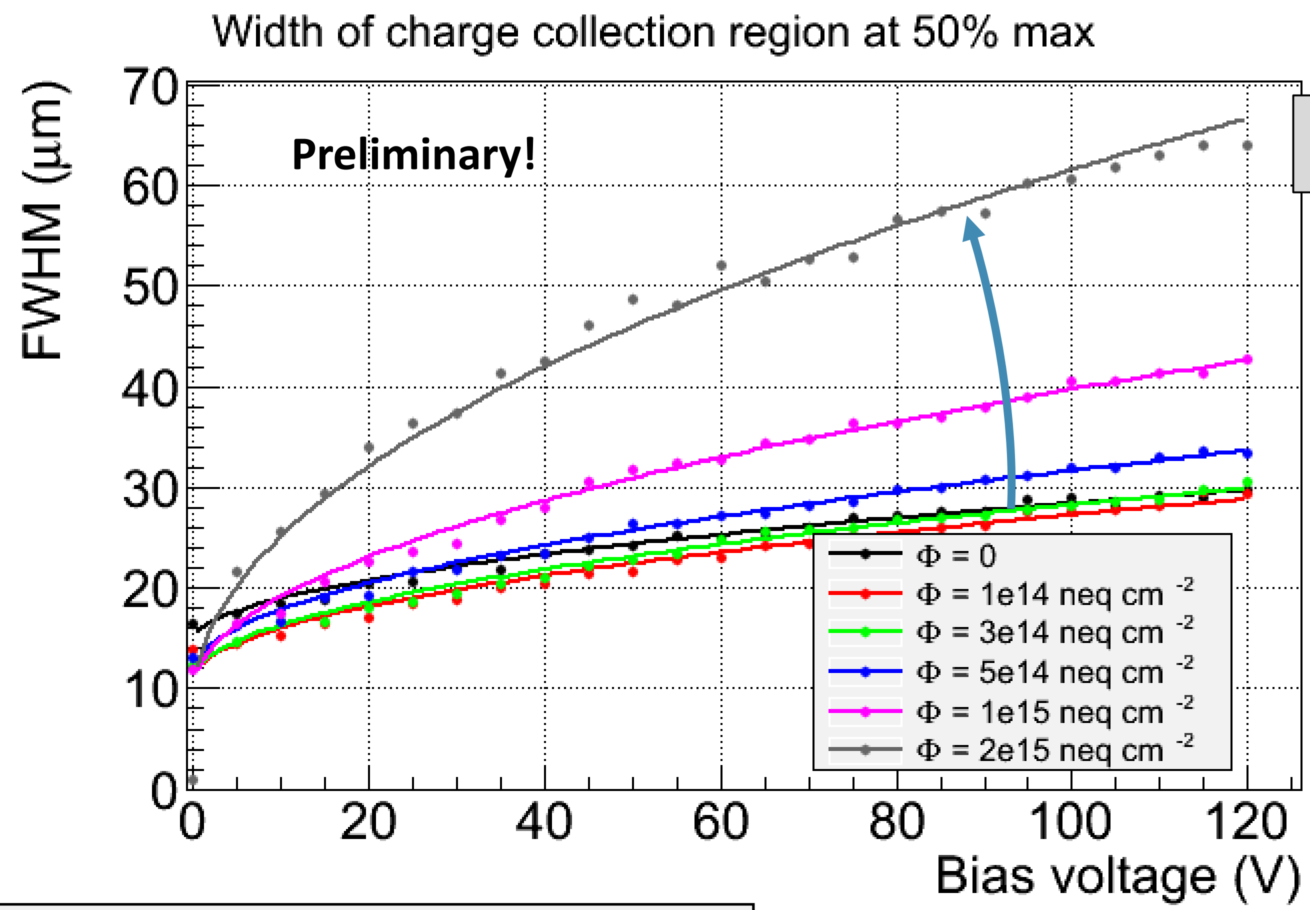
- variations of charge collection width are small
- Maximal width reached around 5e14 n_{eq}/cm^2

1000 Ω·cm Edge-TCT charge collection profiles



- Unirradiated sample could not be biased (breakdown)
- Initially large charge colleciton width > 100 µm
- Charge collection width monotonously falling with irradiation
- High resistivity → acceptor removal completed below 1e14 n_{eq}/cm^2

20 Ω·cm charge collection width vs. bias voltage



20 Ω·cm

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

0 V offset

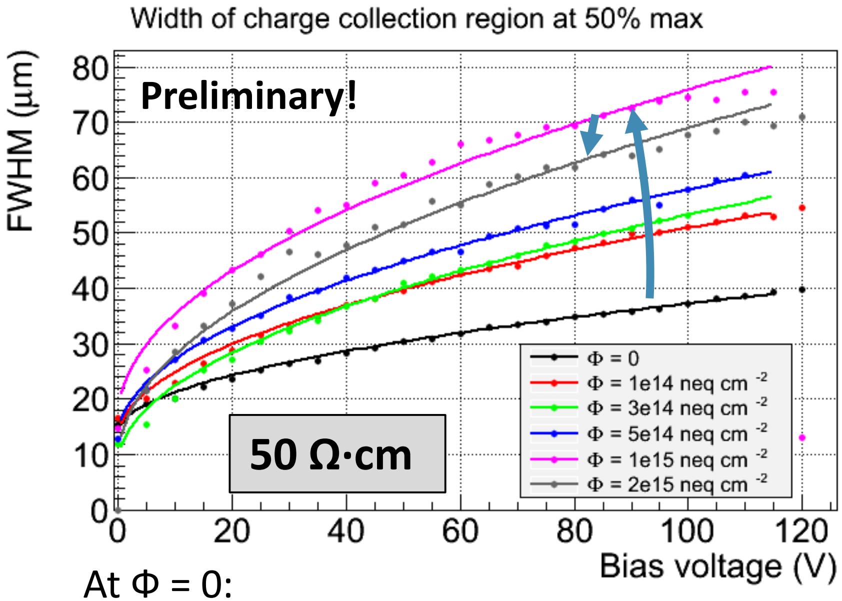
Extract value of N_{eff} from fit

At Φ = 0:

N_{eff} = 6.7e14 cm^{-3} ➔ 20 Ω·cm

Good agreement with nominal resistivity

50 Ω·cm charge collection width vs. bias voltage

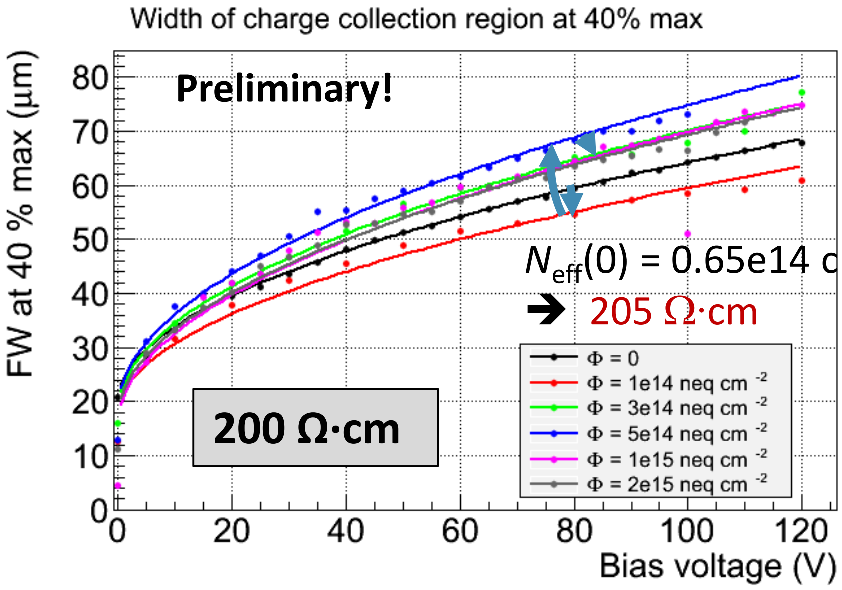


At Φ = 0:

N_{eff} = 2.3e14 cm^{-3} ➔ 58 Ω·cm

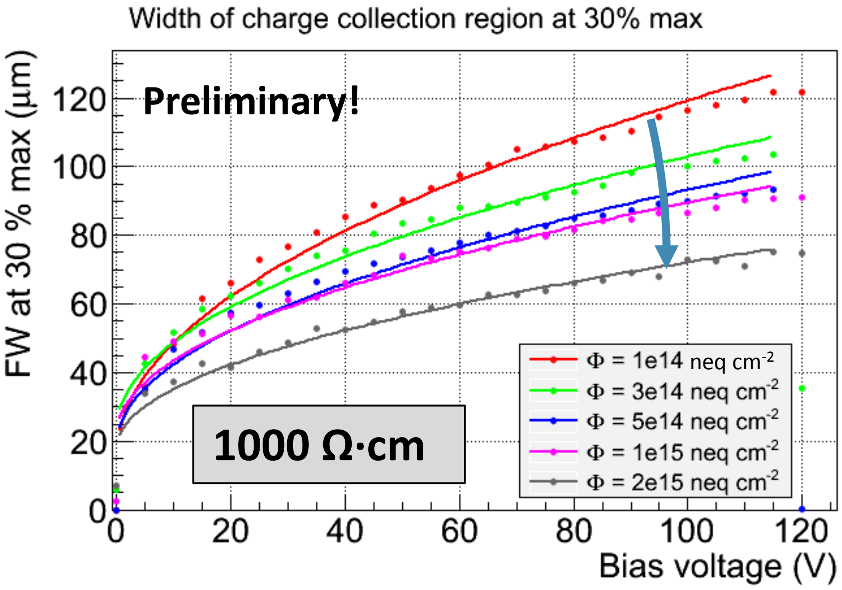
$$\text{Width}(V_{\text{bias}}) = w_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{\text{eff}}} V_{\text{bias}}}$$

- 1000 Ω·cm best material in terms of depletion depth
- But sensitive breakdown behaviour



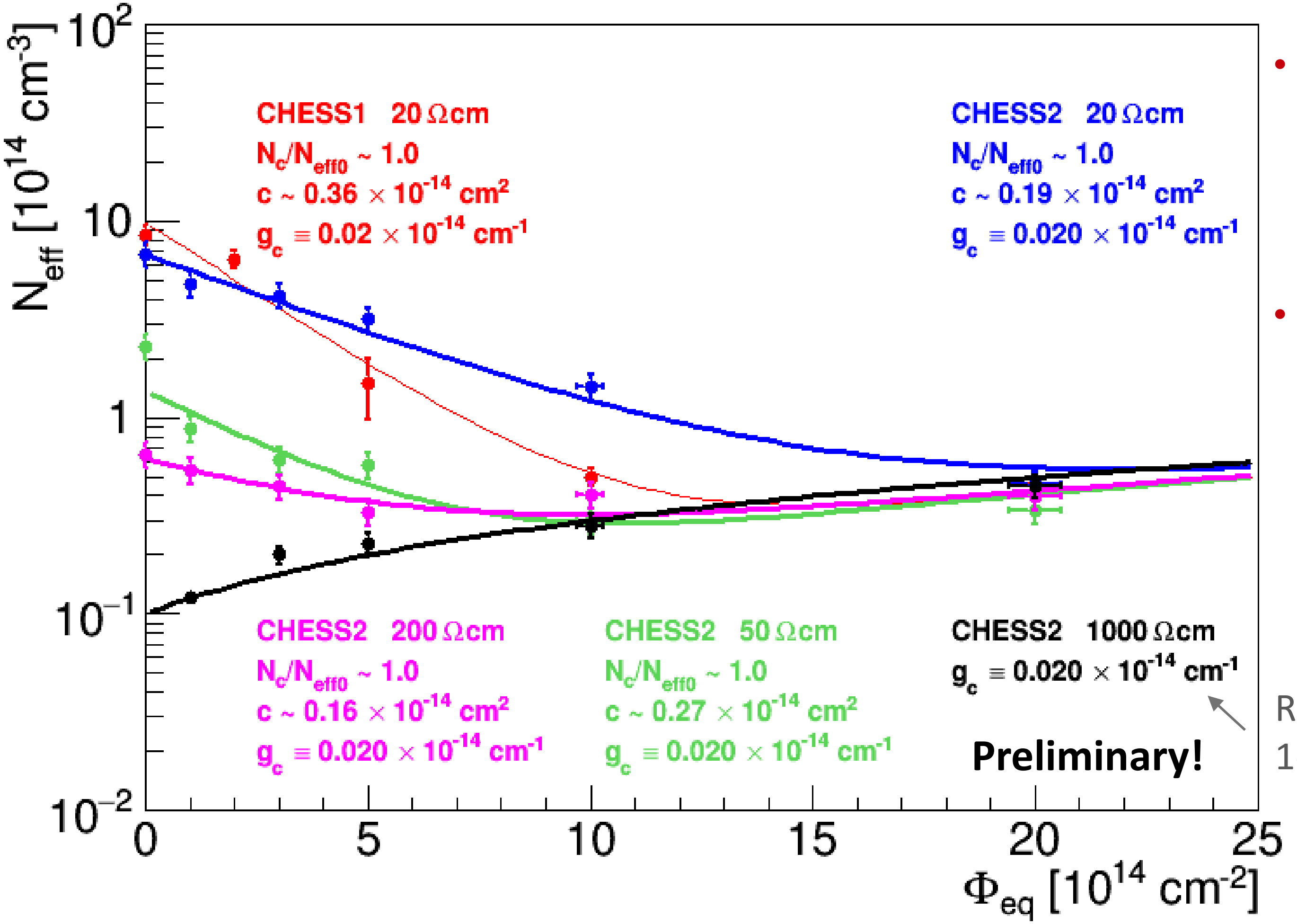
$N_{\text{eff}}(0)$ = 0.65e14 cm^{-3}

➔ 205 Ω·cm



N_{eff} vs. fluence

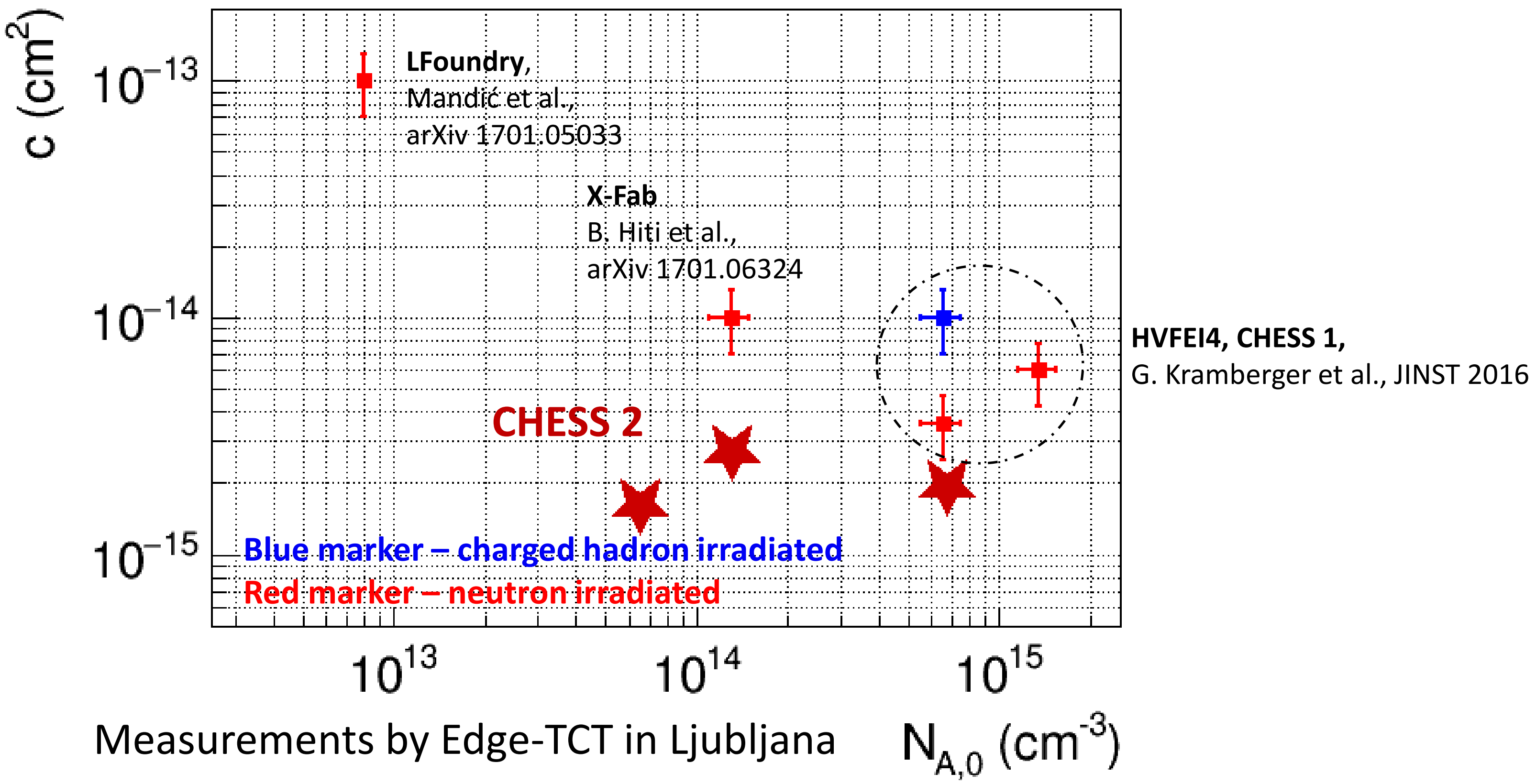
$$N_{\text{eff}} = N_{\text{eff0}} - \underbrace{N_{\text{c}} \cdot (1-\exp(-c \cdot \Phi_{\text{eq}}))}_{\text{acceptor removal}} + \underbrace{g_c \cdot \Phi_{\text{eq}}}_{\text{radiation induced deep acceptors } (g_C = 0.02\ \text{cm}^{-1}\ \text{fixed})}$$



- N_{eff} evolves differently for different initial wafer resistivities
- Behaviour converges for fluences above 1e15 n_{eq}/cm^2

Removal completed below 1e14 n_{eq}/cm^2

Acceptor removal constant vs. initial doping



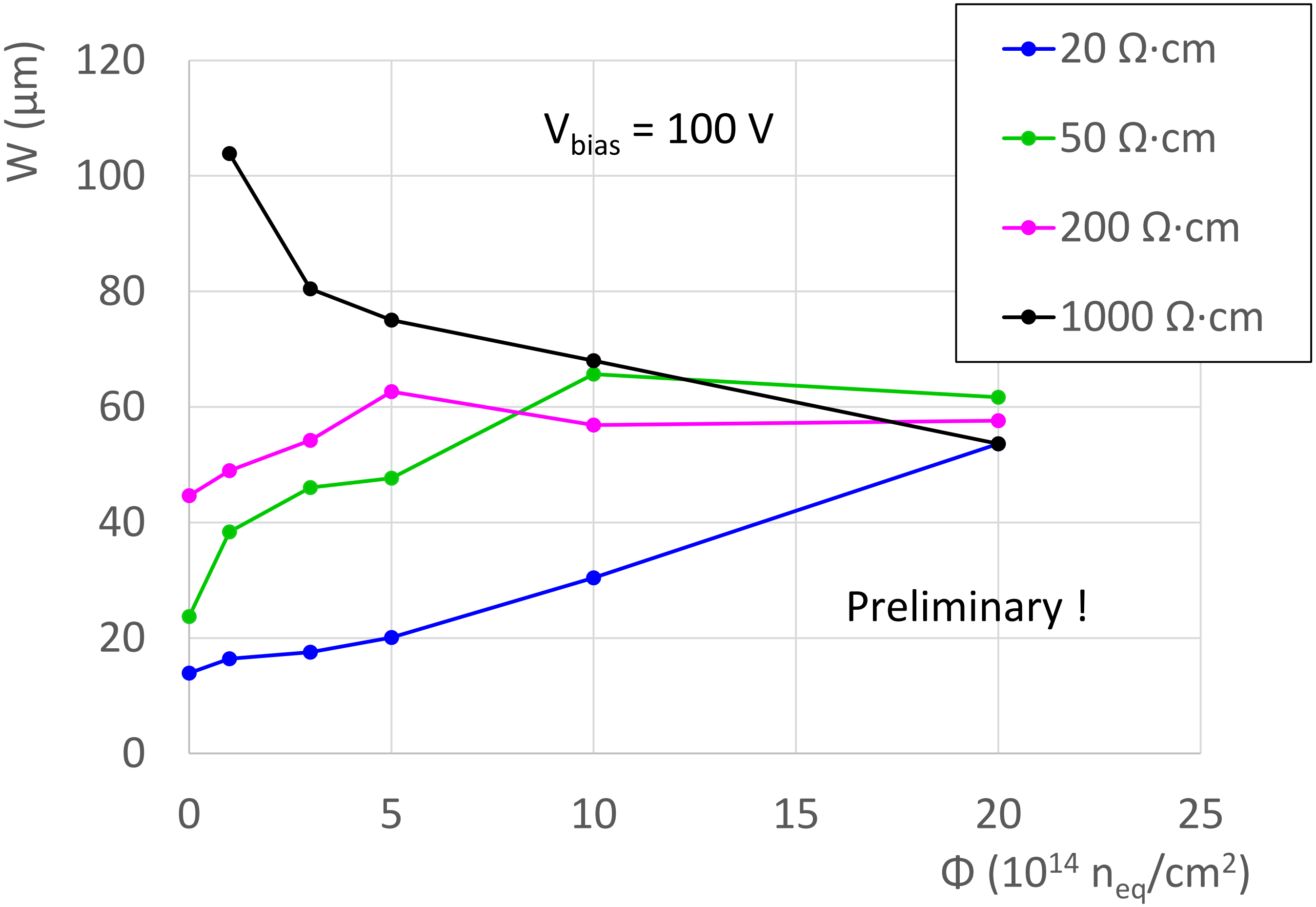
Measurements by Edge-TCT in Ljubljana

High resistivity ↔ fast acceptor removal (finished at low fluence)

Low resistivity ↔ slow acceptor removal (finished at high fluence)

- CHESS2 (partly) fits in this picture
- Removal constant for CHESS2 1kOhm-cm still not measured

Charge collection width vs. fluence in CHESS 2

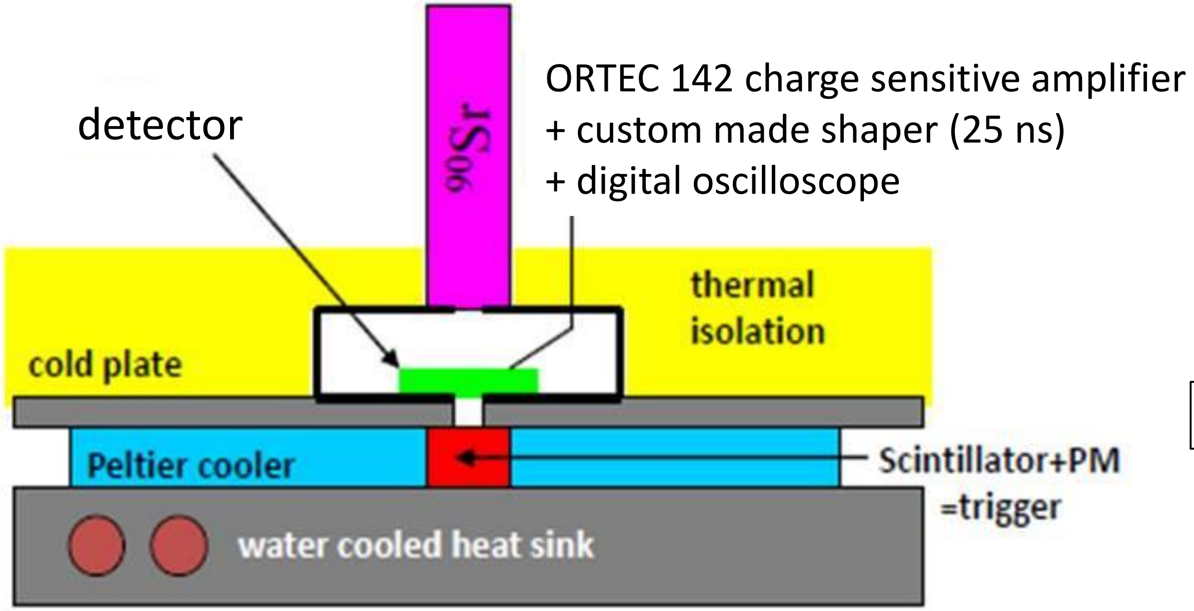


- Charge collection width at 100 V for different wafers/fluences
- Calculated from N_{eff} measured with Edge-TCT using formula

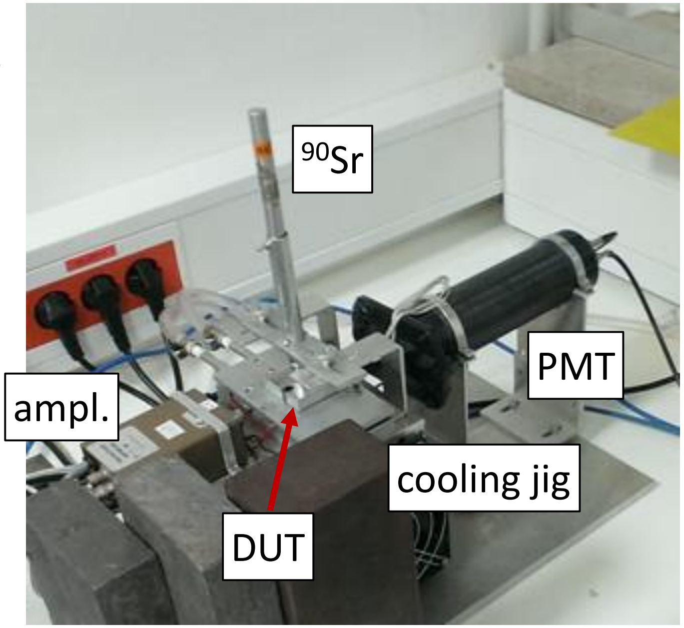
$$\mathrm{Width}(V_{\mathrm{bias}}) = \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{\mathrm{eff}}} V_{\mathrm{bias}}}$$

^{90}Sr measurements

^{90}Sr setup

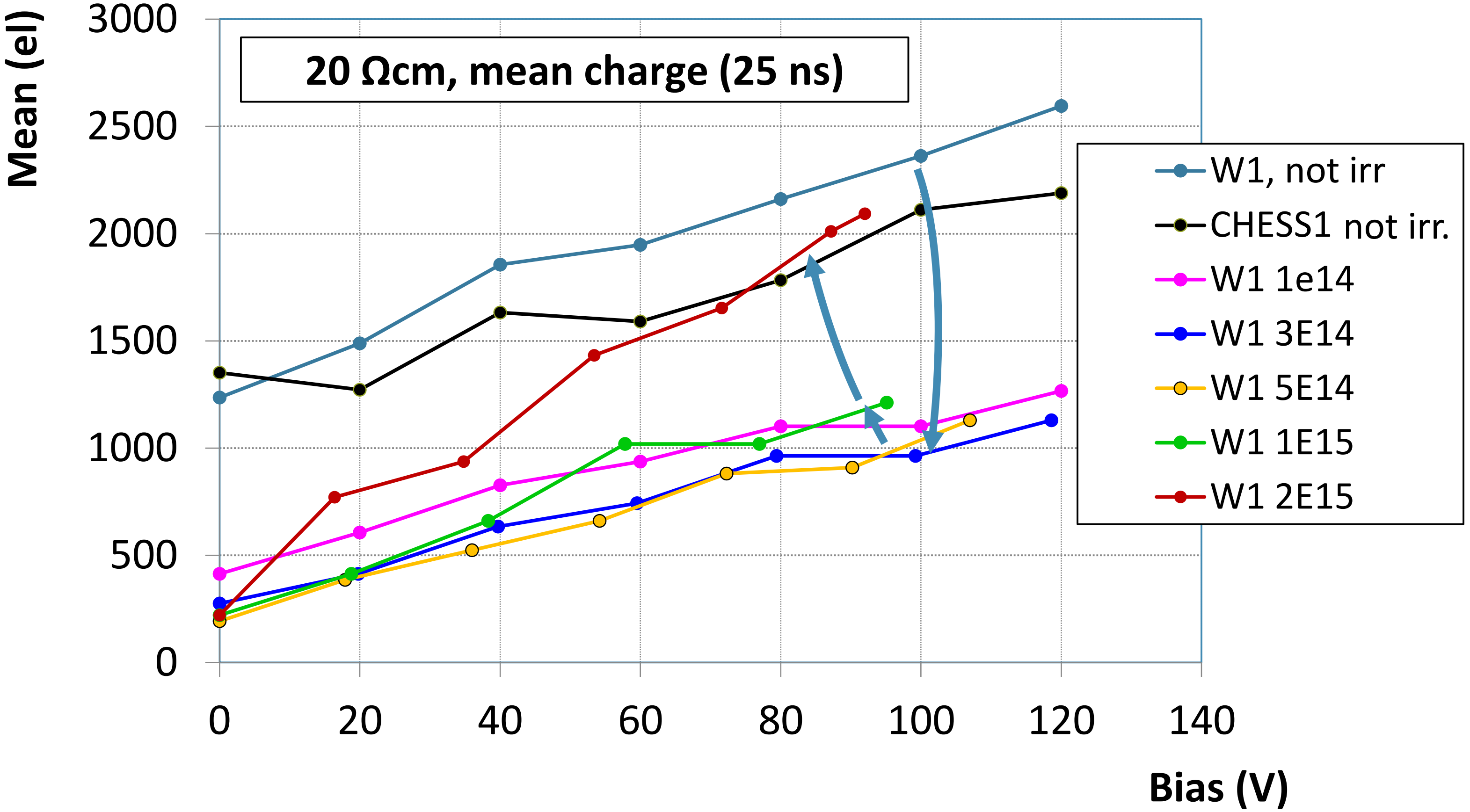


ORTEC 142 charge sensitive amplifier
+ custom made shaper (25 ns)
+ digital oscilloscope



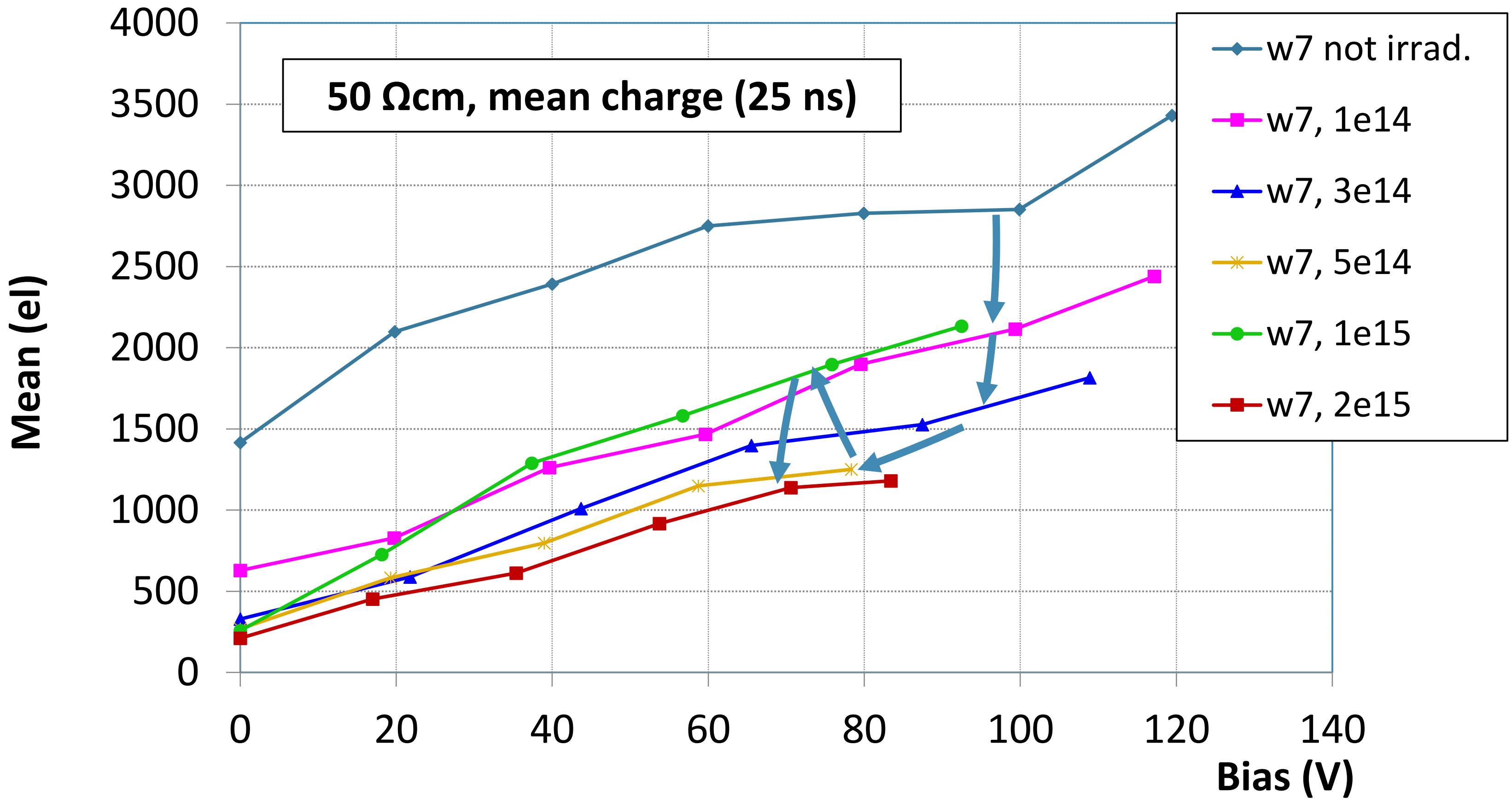
- HV-CMOS: small signals, large noise → S/N very low
  - clean sample of events needed (no hits missing DUT)
  - require a large detector (trigger rate), good collimation, small scintillator
- Measurement:
  - Calibration with a 300 µm thick Si pad detector
  - 1) Record *N* (= 2500) waveforms
  - 2) Average over all waveforms and determine time of the signal peak
  - 3) Sample waveforms at the peak
  - 4) Fill spectrum

20 Ω·cm, ^{90}Sr



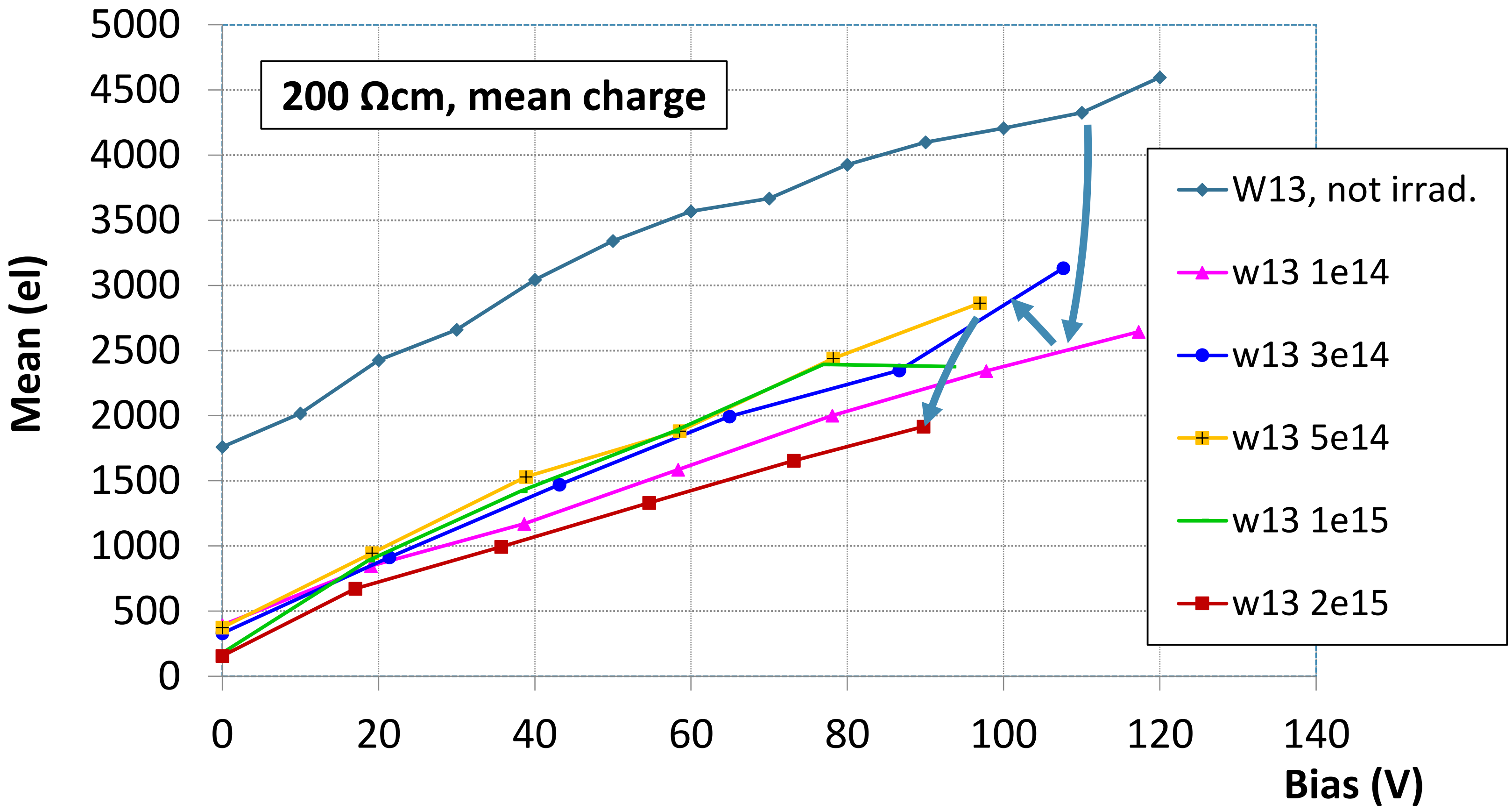
- Diffusion contribution of approx. 1000 e^- vanishes after irradiation
- Signal increase due to acceptor removal at high fluences
- Minimal mean charge at 100 V: 1000 e^- (but would expect > 1600 el from N_{eff})

50 Ω·cm, ^{90}Sr



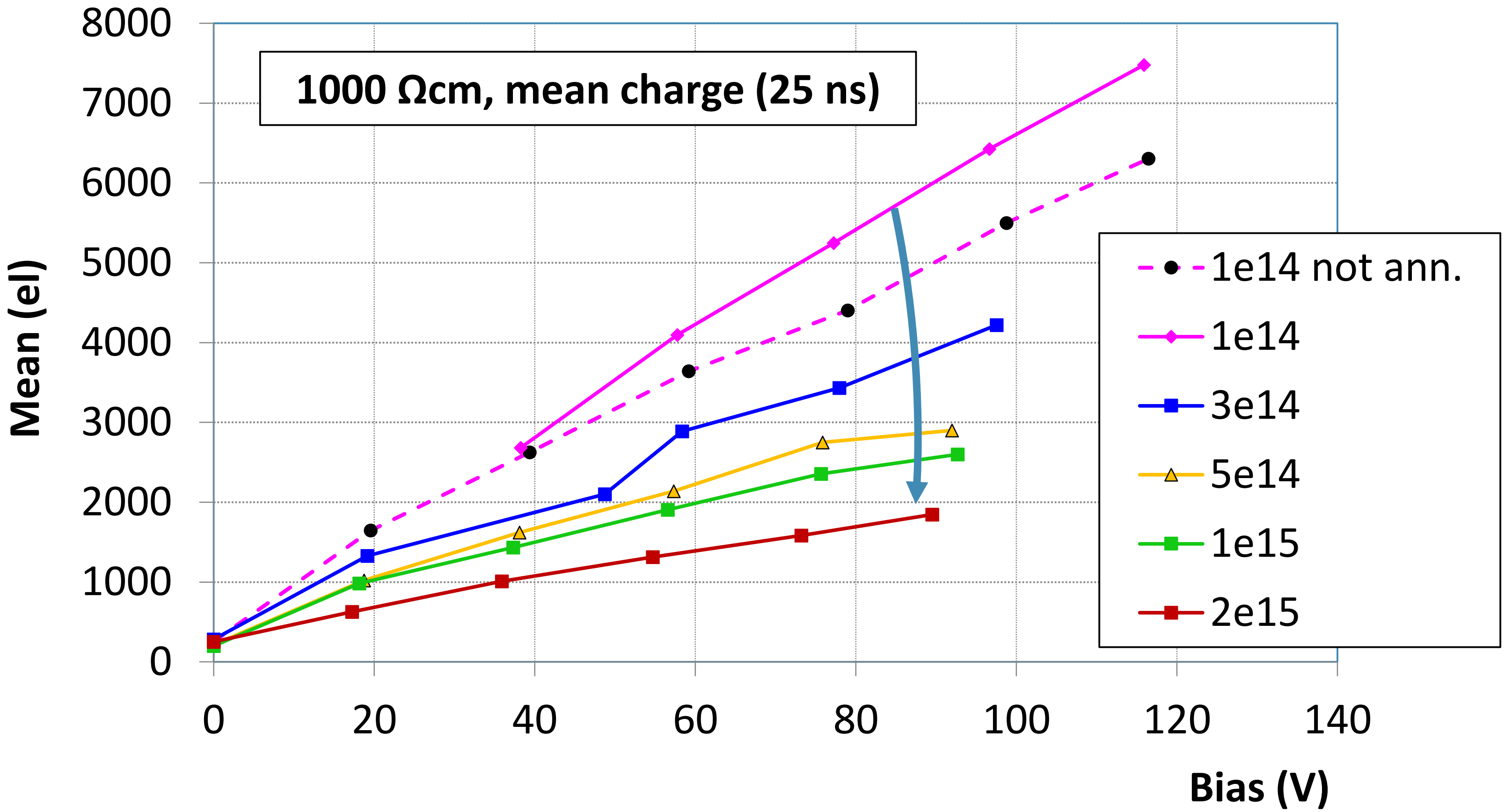
Minimal mean charge at 100 V: 1300 e$^-$ (extrapolated)

200 Ω·cm, ^{90}Sr



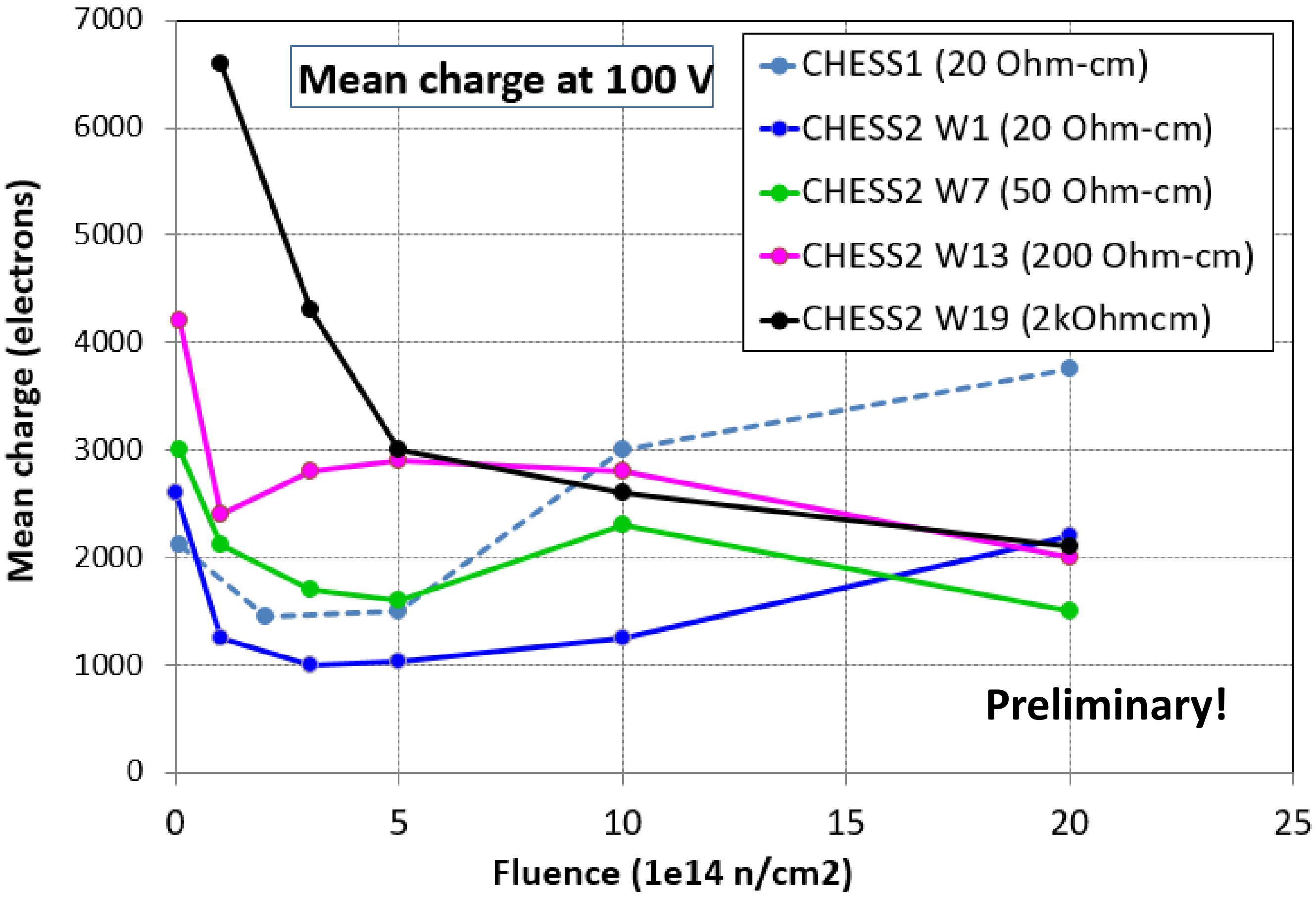
Minimal mean charge at 100 V: 2000 e^- (extrapolated)

1000 Ω·cm, ^{90}Sr



Minimal mean charge at 100 V: 2000 e$^-$ (extrapolated)

^{90}Sr comparison for different substrates



- CHESS 1 vs. CHESS 2 (20 Ω·cm) : trend is similar, but mean charge differs could be due to a different wafer composition → different acceptor removal
- More than 2000 el in whole fluence range for 200 Ohm-cm and 1 kOhm-cm
- Measured charge after irradiation smaller then expected from depleted depth calculated from N_{eff}

Summary

- Completed measurements of charge collection on passive structures on CHESS 2
  - 4 wafer resistivities 20 – 1000 Ω·cm, each wafer 6 neutron fluences up to 2e15 n/cm2
  - Edge-TCT and ^{90}Sr MIPs

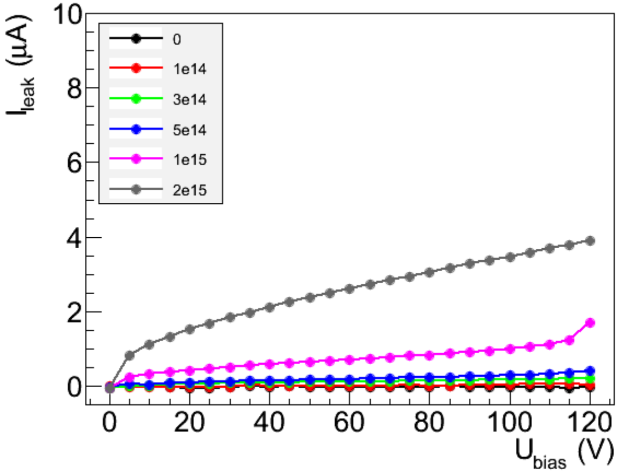
- Edge-TCT:
  - Study of charge collection width for different substrates / irradiation levels
  - Charge collection width may increase with irradiation → acceptor removal
  - Determined parameters of the acceptor removal model

- ^{90}Sr
  - Mean collected charge at least 1000 electrons for any substrate and fluence
  - Collected charge roughly follows the behaviour from Edge-TCT (increase due to acc. removal)
  - Mean signals more than 2000 e^- in whole fluence range for 200 Ω·cm and 1000 Ω·cm
  - 200 Ω·cm: smallest changes over whole fluence range

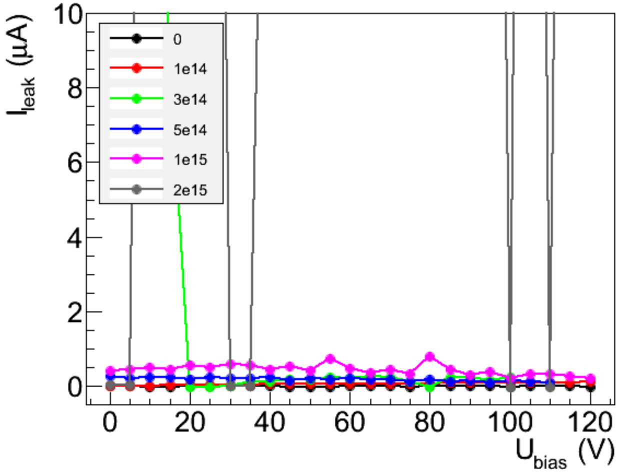
BACKUP

I-V characteristics

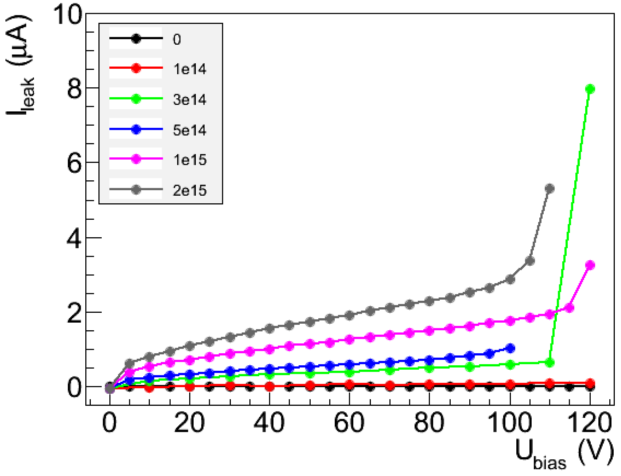
20 Ω·cm



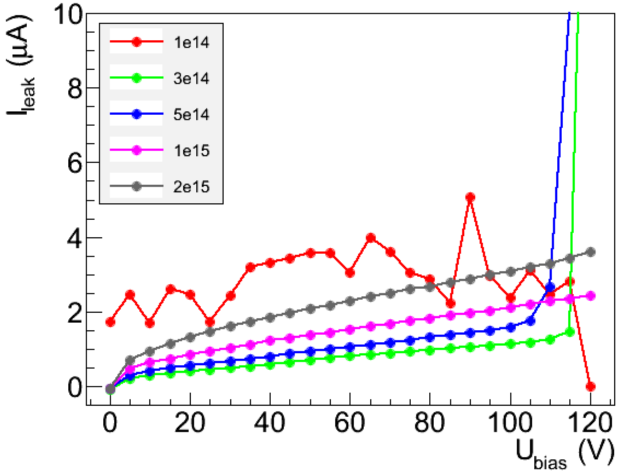
50 Ω·cm



200 Ω·cm



1000 Ω·cm

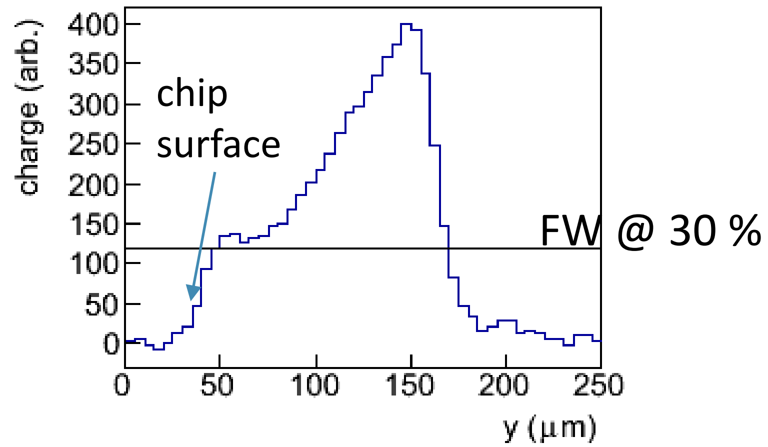


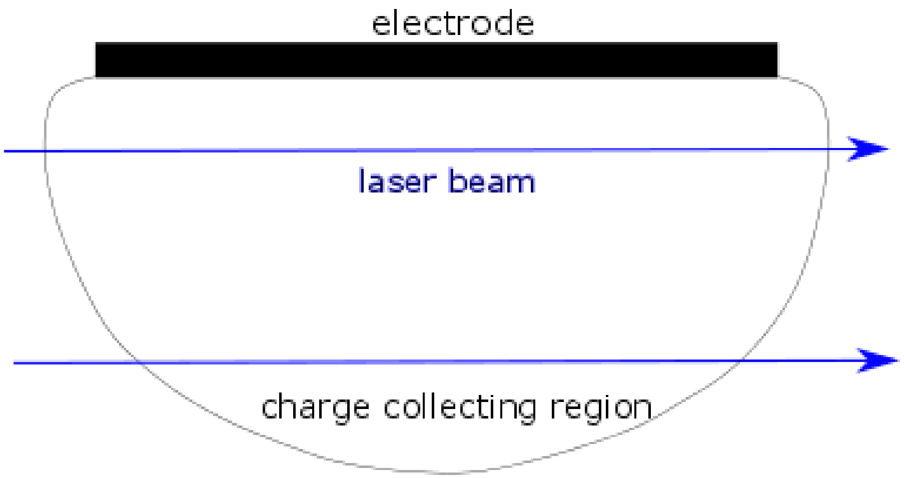
Measured on a TCT array (3 x 3 pixels, pixel size 630 x 40 μm^2)
At room temperature

not all measurement are good

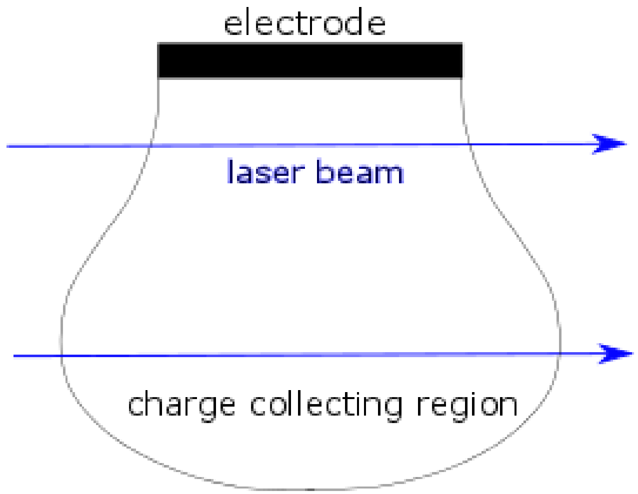
Depletion zone shape at large depths

- Large peak at the back side of charge collection profiles is commonly observed (especially with high resistivity samples)
- This is due to an expansion of the depletion zone along the direction of the beam (pear shape)
- Extra charge is due to an increased path of the beam in the sensitive region
- This occurs for depleted depth ≥ structure width and on narrow structures (few neighbours)



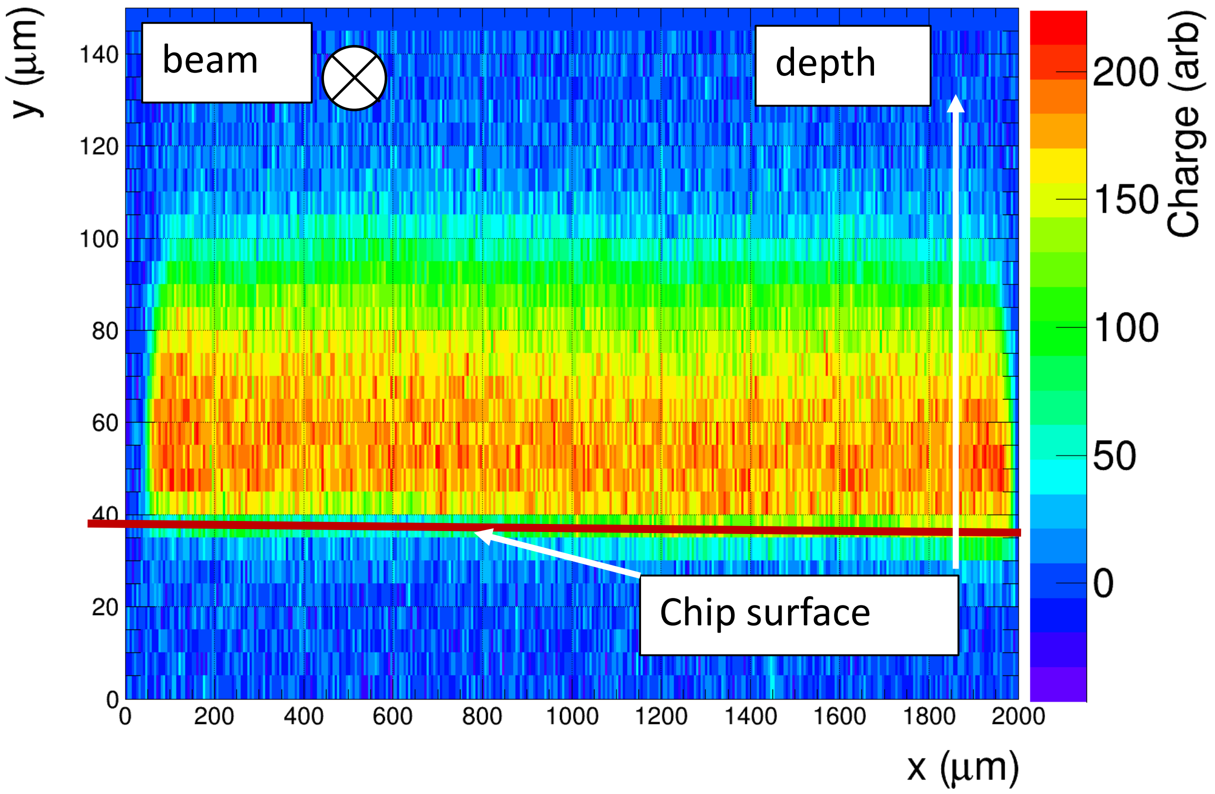


Case A: depleted depth << structure size
no back peaks



Case B: depleted depth ≈ structure size
pear shape

2d Edge-TCT scan



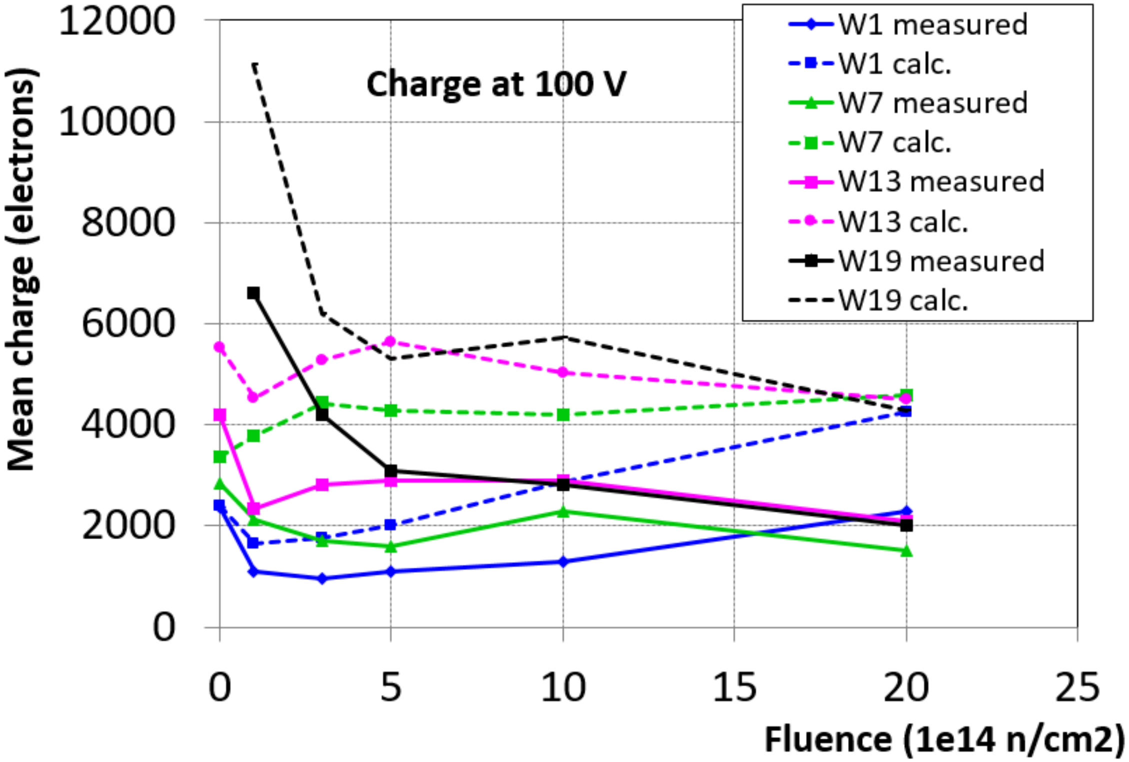
200 Ω·cm, 3e14 n_{eq}/cm^2

Good response uniformity – no gaps between n-wells

Comparison of results from Edge-TCT and ^{90}Sr

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

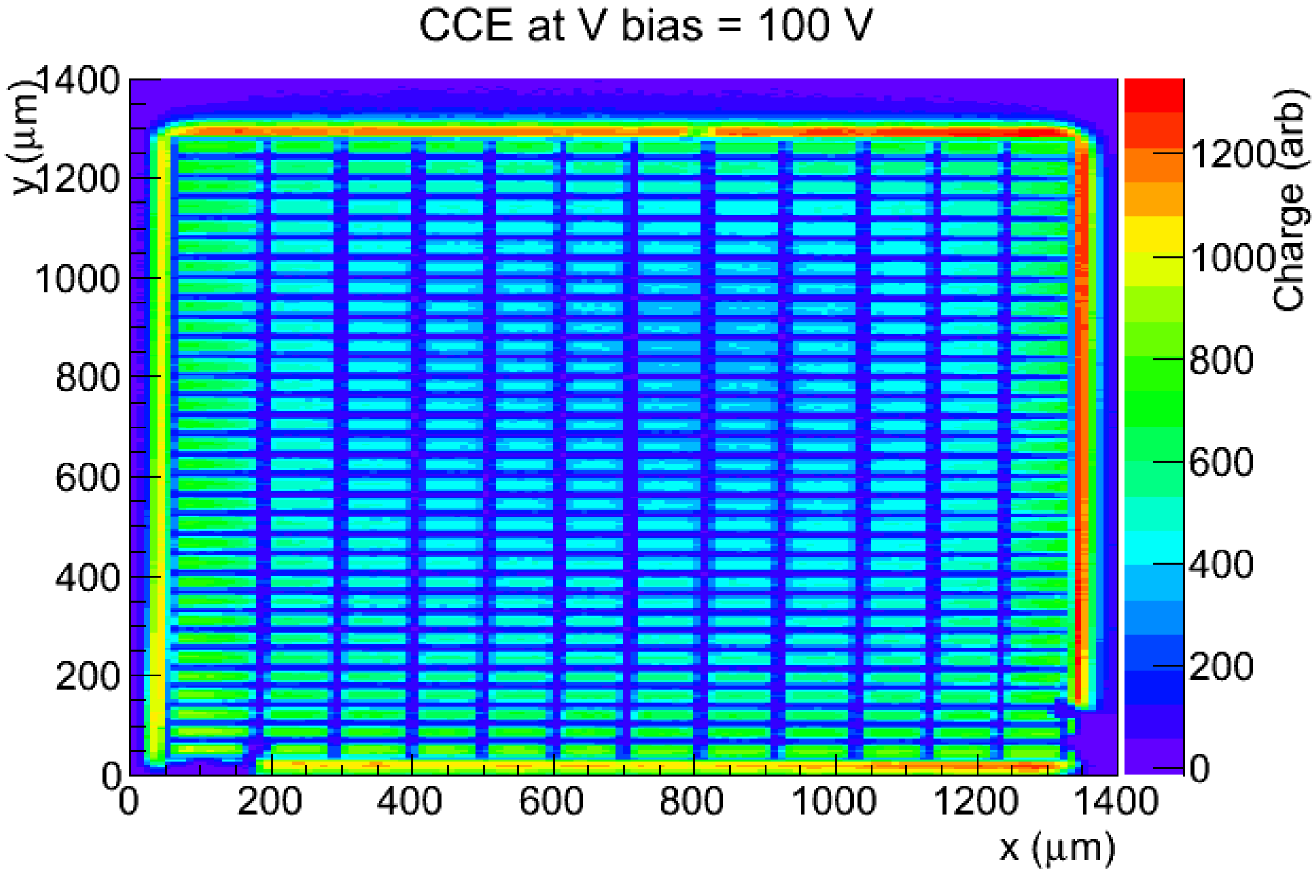
- From Edge-TCT (N_{eff}) calculate depleted depth *W*
- assume 1000 e from diffusion before irradiation
- Simulate charge collection in a pad detector of thickness *W* to estimate trapping loss



- Observation: with ^{90}Sr less charge is collected than expected from Edge-TCT
- The reason is not understood: maybe simple pad detector approximation not correct, hints: different behaviour of border vs. central pixels (see backup)

Top TCT 1

- On irradiated samples charge from ^{90}Sr measurements systematically less than expected for the depletion depth measured by Edge-TCT
- Investigation with top TCT
  - IR light – 980 nm, absorption depth in Si 100 µm → no reflections from back plane



W19 5e14
Large pass. array for ^{90}Sr
(1.3 mm x 1.3 mm)

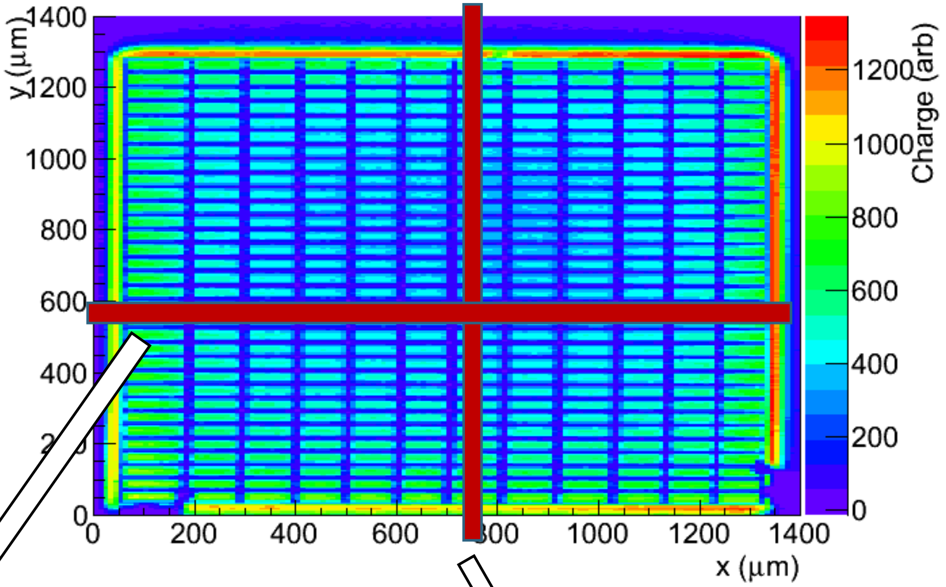
Gaps between pixels due to metalization on top of the chip

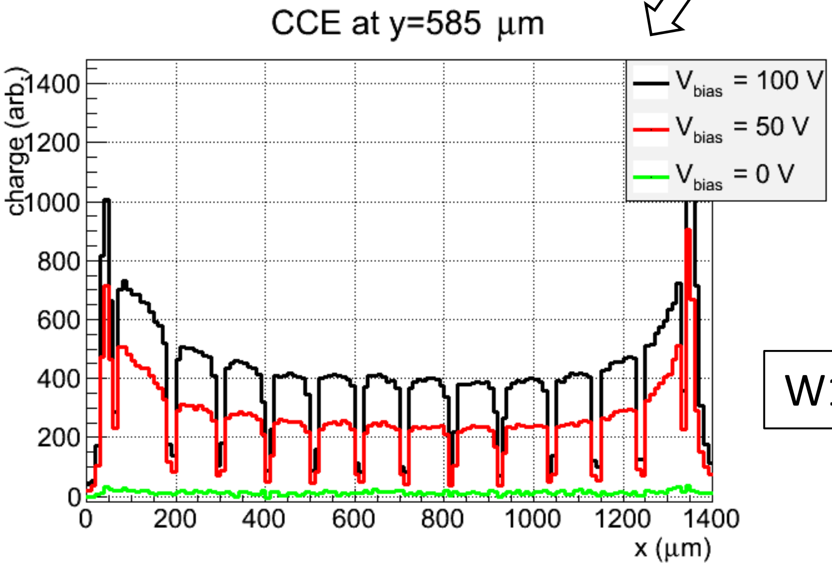
But on the large scale **intensity in central pixels less than on edges !**

Top TCT 2

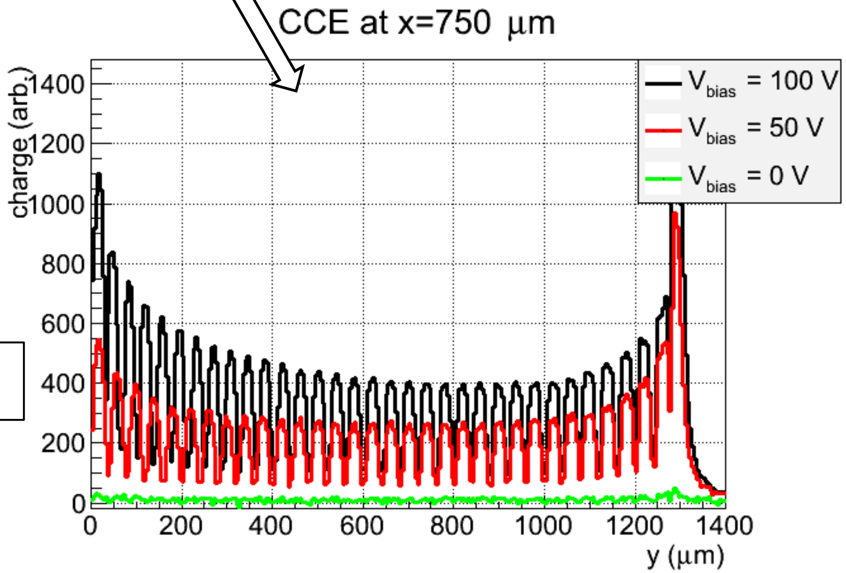
Difference in the collected charge indicates a larger depletion depth on the edges of the ^{90}Sr array.

Edge-like pixels also measured in Edge-TCT. This may be a reason for discrepancy between the measurements.





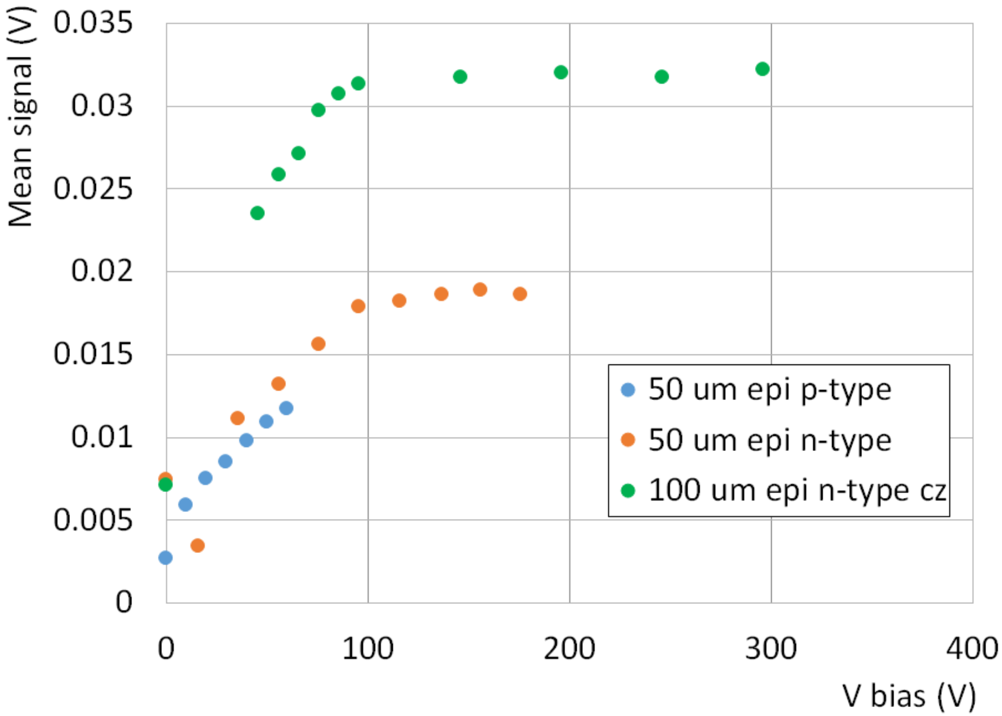
W19 5e14



Q-TCT calibration 1

Sr90 calibration procedure

- using epitaxial diodes with known thickness (*d* = 50 and 100 µm) – similar thickness to CHESS 2, well known response
- after epi-layer is fully depleted extract scaling factor $A = d \times 100$ pairs/µm / V_{sig}



Only n-type diodes could be biased highly enough for calibration
p-type breaks down at 60 V, before full depletion

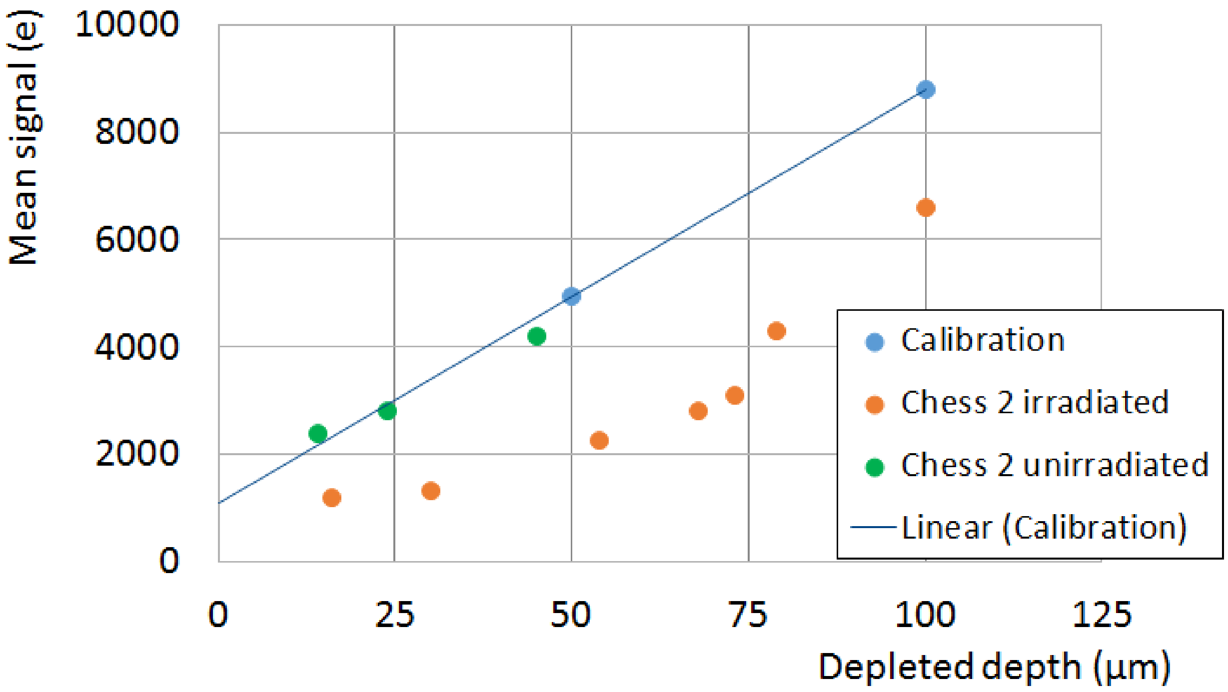
Q-TCT calibration 2

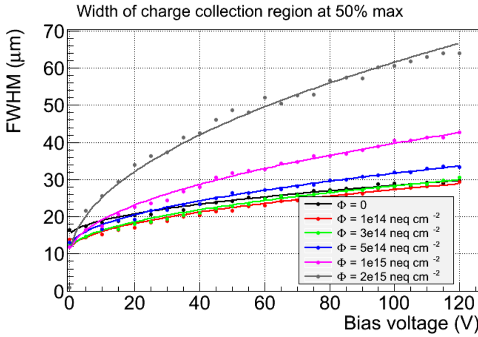
Results:

calibration with n-type epi diodes

unirradiated CHESS 2 devices are compatible with the calibration

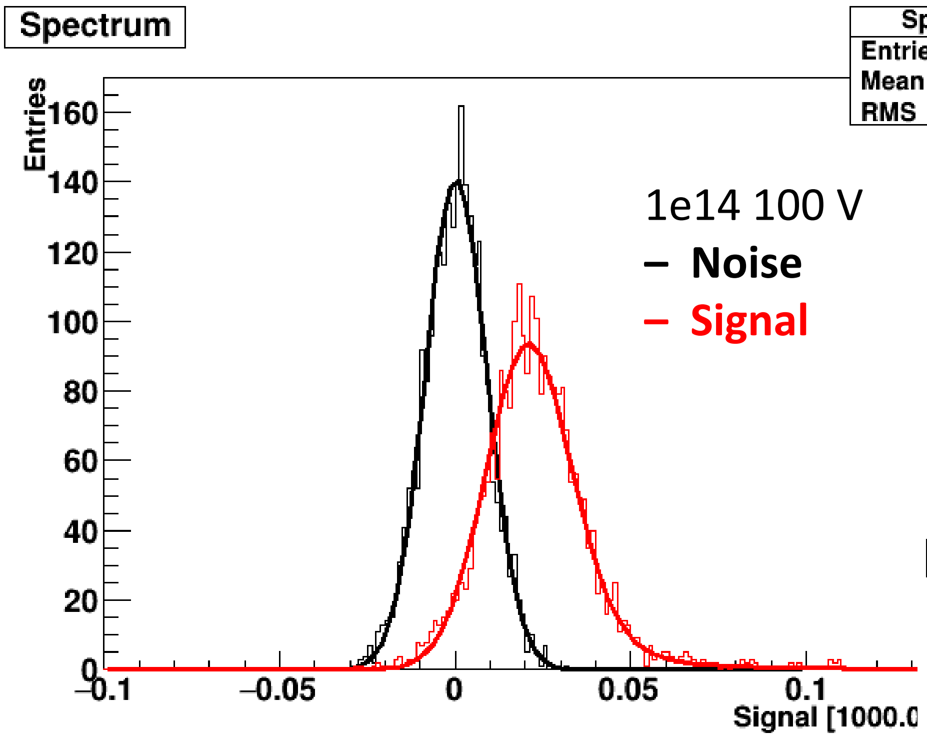
irradiated CHESS 2 devices (different wafers) have less charge than expected:





* Depleted depth for CHESS 2 is determined from the formula: $d = \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{\text{eff}}} V_{\text{bias}}}$

^{90}Sr spectra 1000 Ω·cm



- High resistivity wafer - Relatively good separation between signal and noise
- No peak around 0 in signal spectrum → misalignment does not seem to be the main factor for smaller charge