New results of measurements with irradiated CMOS detectors in Ljubljana

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et al.

CMOS detector structures from 3 different foundries:

AMS: **10**, **20 Ohm-cm**

- A. Afolder et 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.***

➔ **new results with CHESS2 chips from 50 and 200 Ohm-cm wafers**

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

➔ **new point at 1e16**

LFoundry: **2000 Ohm-cm**

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

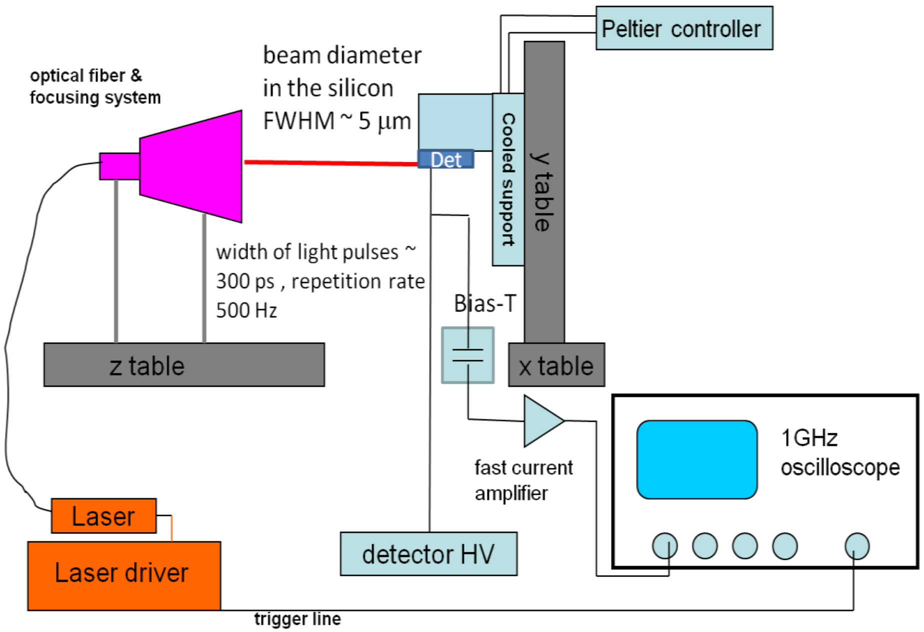
➔ **measurements with devices thinned to 100 µm**

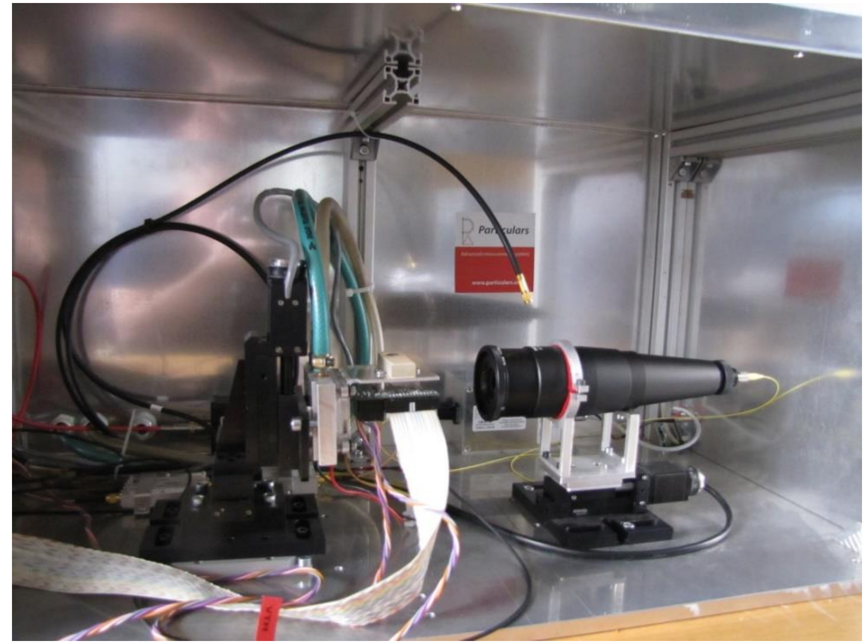
All devices are made on **p-type** substrates with **n-type** charge collecting electrodes
All devices are **passive** detectors → no amplifier circuit on sensor (standard Si diode detector)

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

Edge TCT

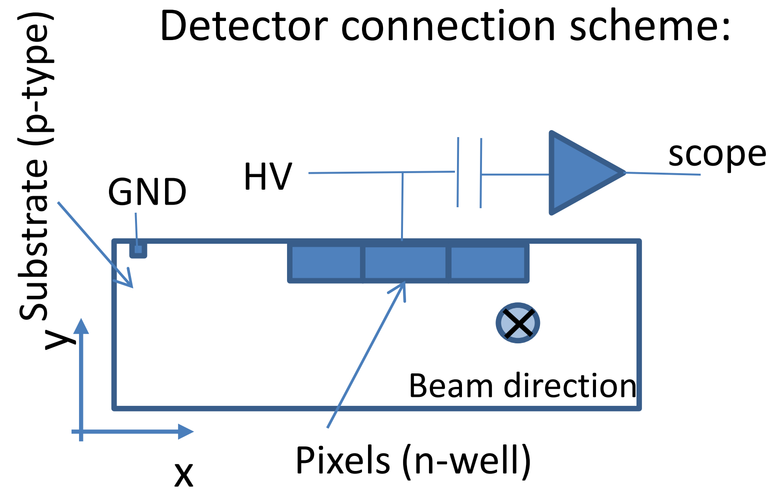
(more details: www.particluars.si)



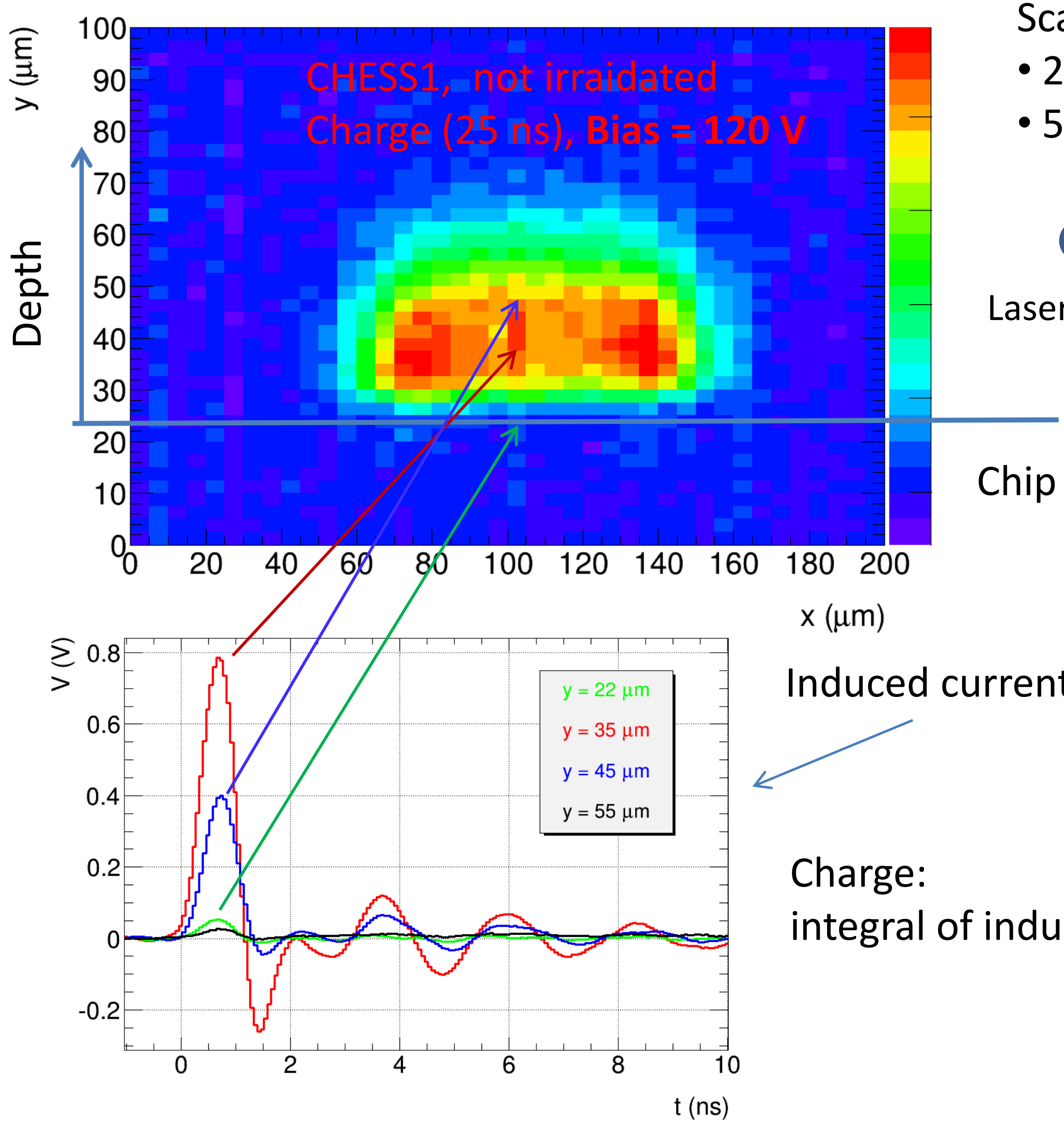


- TCT measurements with passive pixels (no amplifier in the n-well)
  ➔ collecting electrode connected to amplifier

Detector connection scheme:



Edge-TCT



Scan across pixel:

- 2.5 µm steps in y
- 5 µm steps in x

Laser beam direction

Chip surface

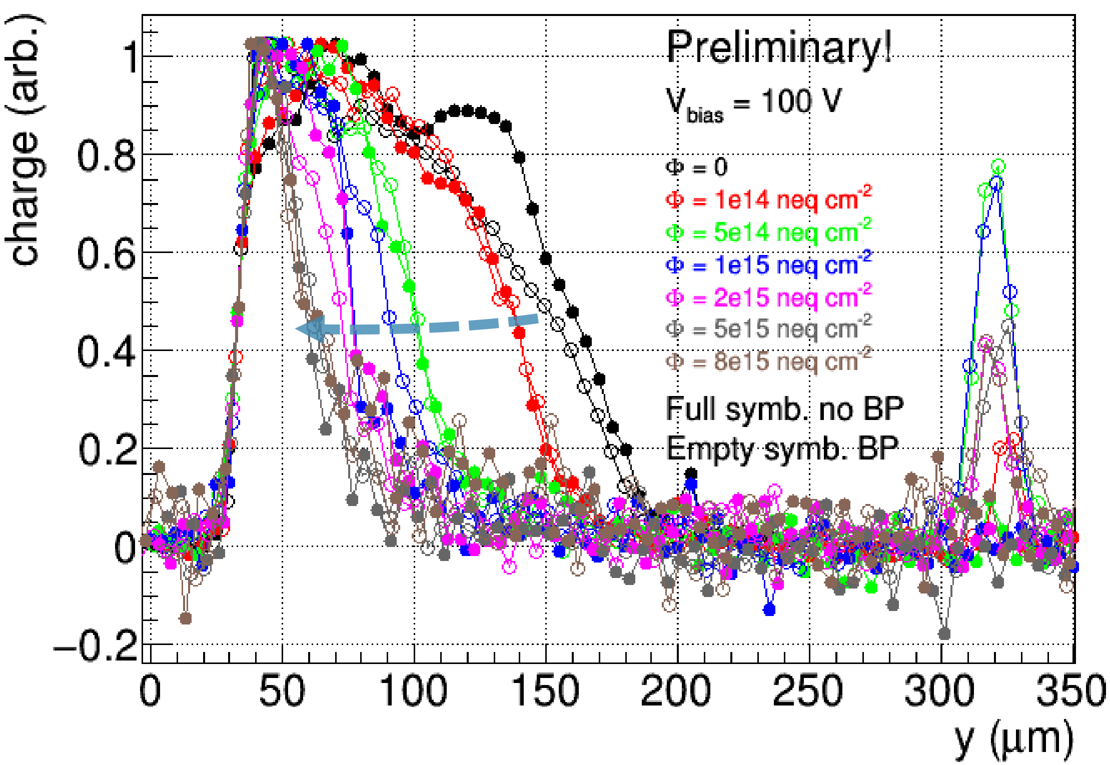
Induced current after laser pulse

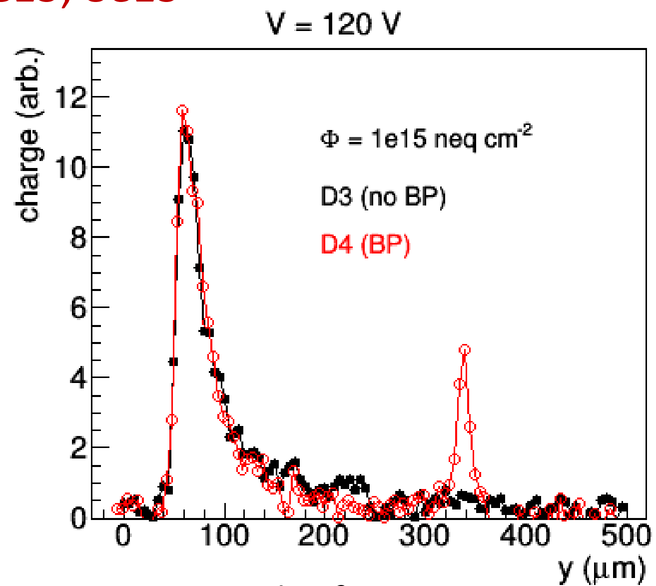
Charge:
integral of induced current pulse

Charge collection profiles LFoundry (2 kΩ·Ohm-cm)

- Not thinned, no back plane (**no BP**) processing, bias via implant on top
- Thinned to 300 µm, back plane processed (**BP**) , bias through the back plane

Reactor neutrons, fluence steps: 1e14, 5e14, 1e15, 2e15, 5e15, 8e15

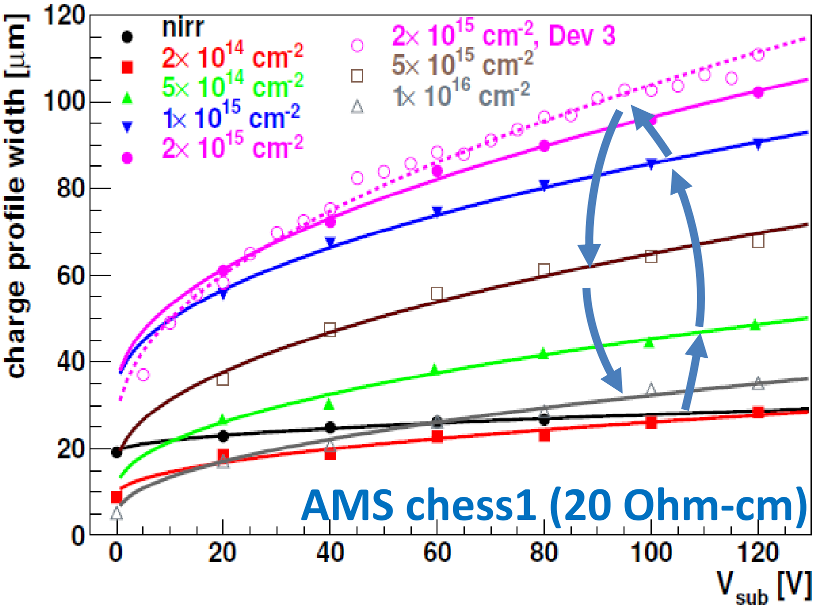


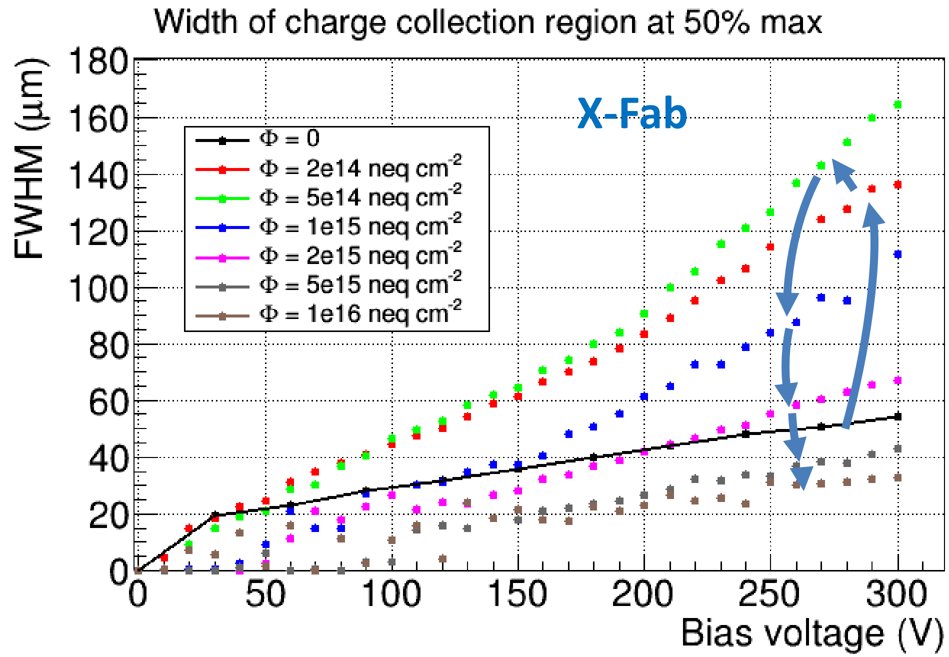


1e15 n/cm^2:
calibrated CC profile
w/ and w/o backplane
(beam intensity monitor)

- no increase of charge collection width after irradiation seen
- no significant difference between samples with and without back plane (BP)
- 10 – 20 % increase of charge collection width after annealing

Charge profile width vs. bias voltage





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

w_0 and $\boldsymbol{N_{\mathrm{eff}}}$ free parameters

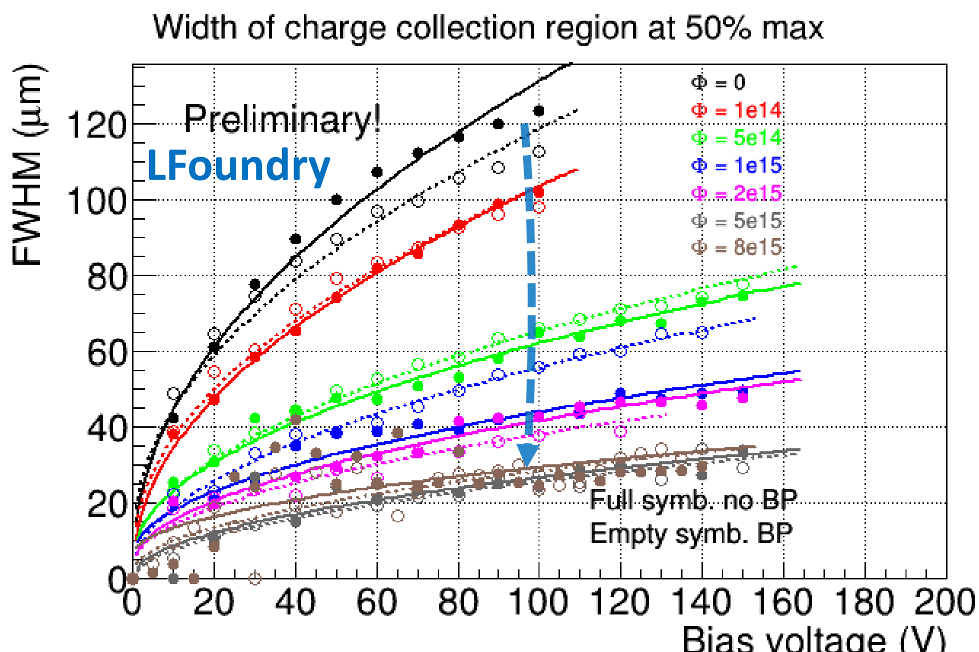
→works for AMS and LFoundry

X-FAB: cannot fit with sqrt(V_{bias})

→ estimate N_{eff} from width at 300 V

- "knee" at low bias 0 width up to 100 V at 1e16

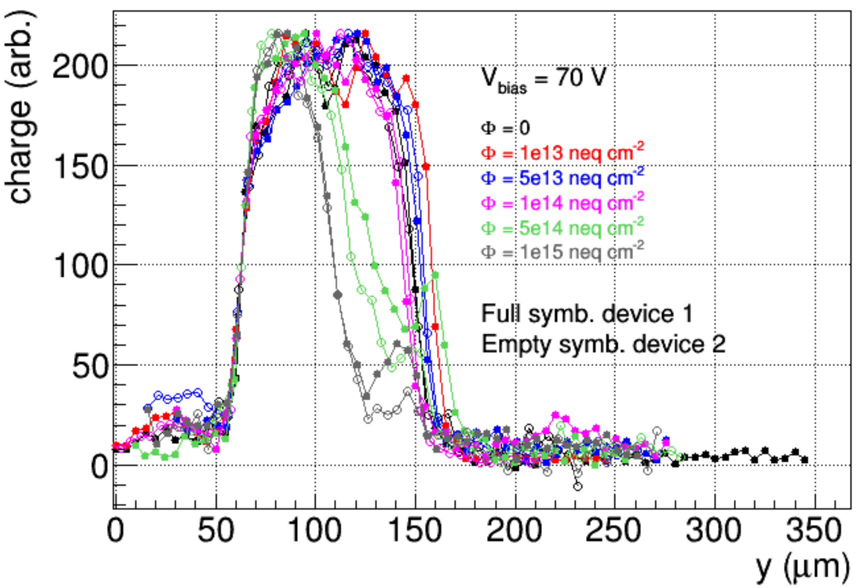
- AMS: large width at low bias

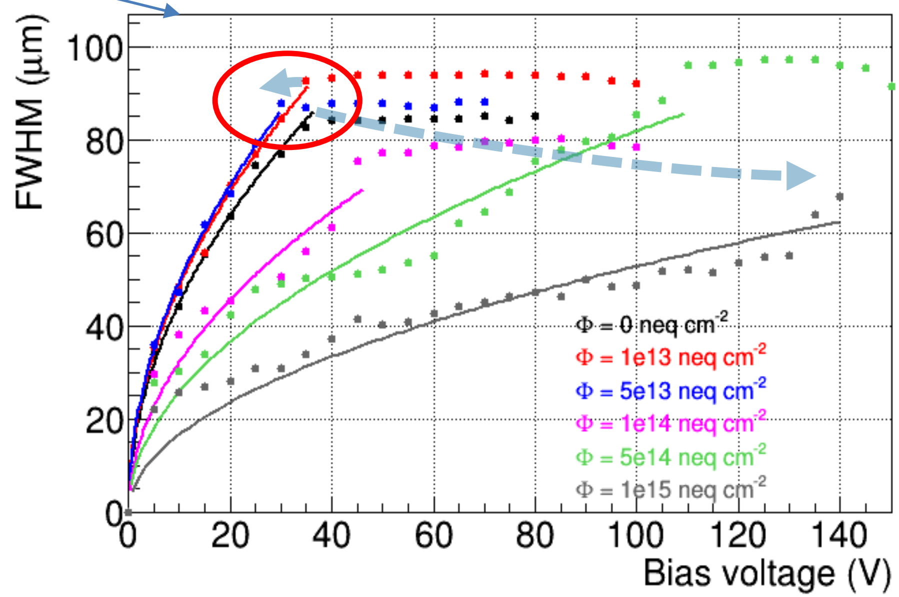


LFoundry (2 kΩ·cm)

- thinned to 100 µm, bias via back plane
- Reactor neutrons, fluence steps: 1e13, 5e13, 1e14, 5e14, 1e15

full depletion voltage drops after first
Two irradiation steps





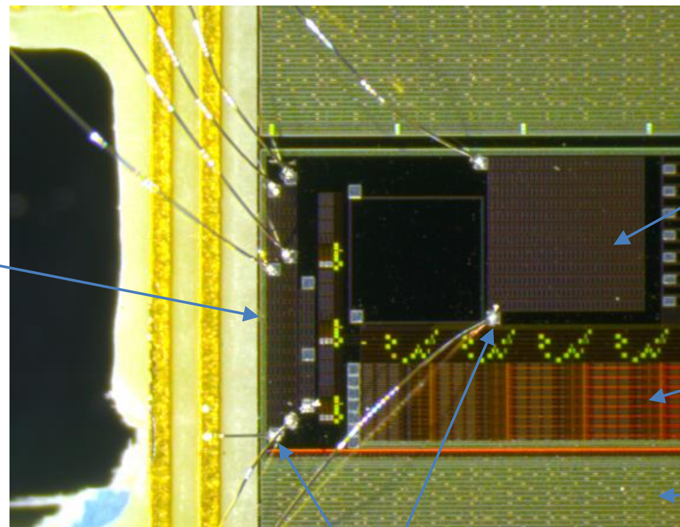
- Full depletion voltage lower after irradiation for fluences below 1e14 n/cm^2
- can estimate N_{eff} from V_{fd} and known thickness

➔ initial acceptor removal seen also in LFondry samples

CHESS2 chip

- new AMS H35 chip developed by **Strips CMOS collaboration** was produced on wafers with 4 different initial resistivites: 20 $\Omega\cdot$cm, 50-100 $\Omega\cdot$cm, 200-300 $\Omega\cdot$cm and 600-2000 $\Omega\cdot$cm
  - ➔ full reticle size chip with digitally readout strips made of **630 µm x 40 µm** pixel segments
  - ➔ part of chip used for analogue and passive devices:

Edge TCT:
3x3 pixel passive array
Contacts for:
- central pixel
- surrounding pixels



Large passive array for Sr-90
2x32 pixel array (**1.2 mm x 1.2 mm**)
- all pixels connected together

analogue active pixel array

digital active pixel array

Max bias voltage 120 V, substrate biased via implant on top (back plane not processed)

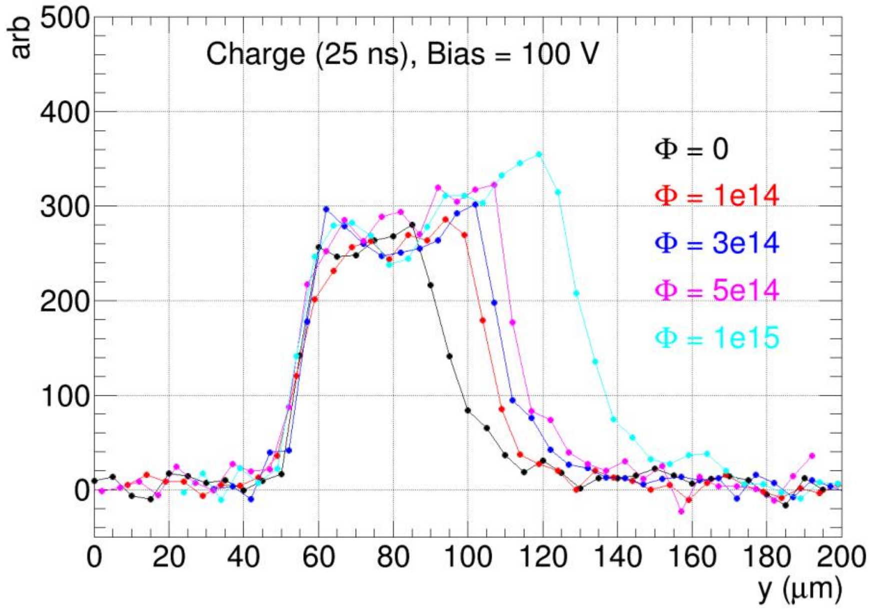
- chips irradiated in reactor to: 1e14, 3e14, 5e14, 1e15 and 2e15
- measurements made with W7 (50-100 $\Omega\cdot$cm) and W13 (200-300 $\Omega\cdot$cm)

More detail: P. Caragiulio at all., Presentation at *11th "Trento" Workshop on Advanced Silicon Radiation Detector*
https://indico.cern.ch/event/452766/sessions/99173/

CHESS2 chip

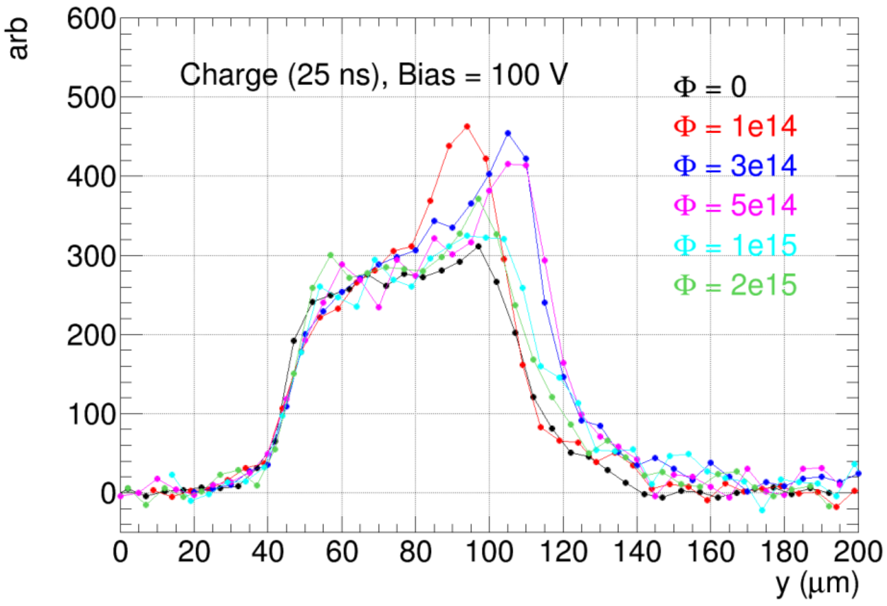
- Edge-TCT charge collection profile across central pixel

W7 (50 Ω·cm)



- increase of width with fluence up to 1e15

W13 (200 Ω·cm)

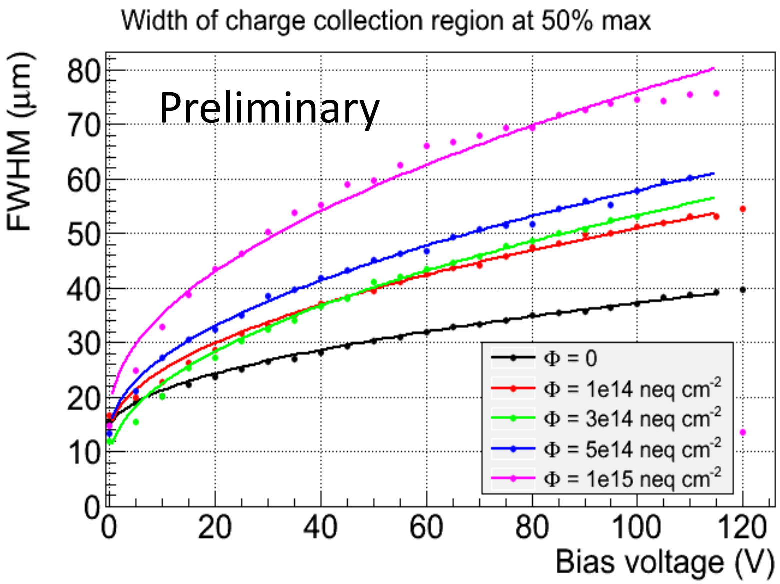


- not much change of profile width with fluence

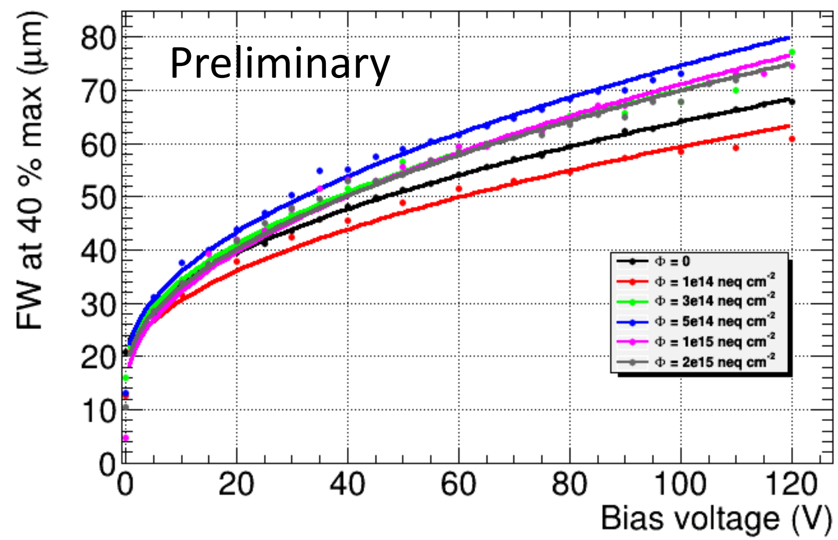
CHESS2 chip

- width of charge collection profile vs. bias

W7 (50 Ω·cm)



W13 (200 Ω·cm)



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

At Φ = 0

- W7: N_{eff} = 2.3e14 cm^{-3} ➔ 56 Ω·cm
- W13: N_{eff} = 6.6e13 cm^{-3} ➔ 200 Ω·cm

→ Good fit, good agreement with nominal resistivity

N_{eff} vs fluence

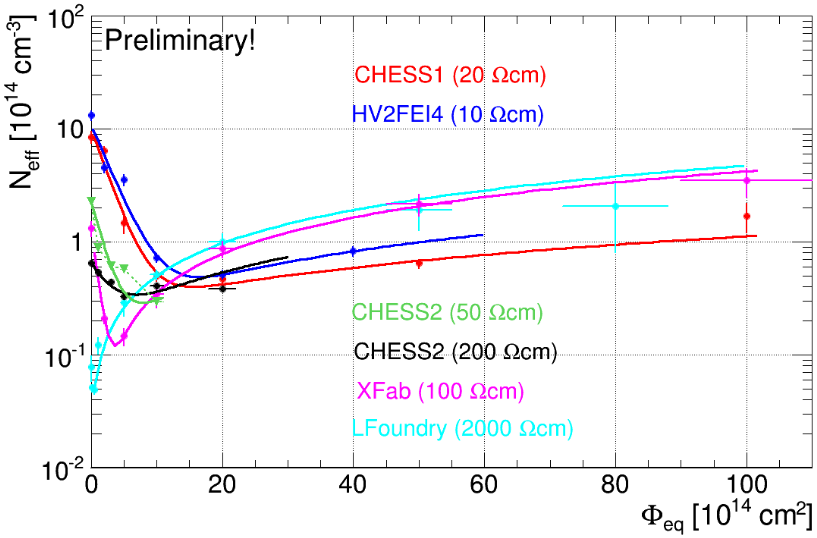
Fit: $$N_{\mathrm{eff}} = N_{\mathrm{eff0}} - N_{\mathrm{c}} \cdot (1 - \exp(-c \cdot \Phi_{\mathrm{eq}})) + g_c \cdot \Phi_{\mathrm{eq}}$$

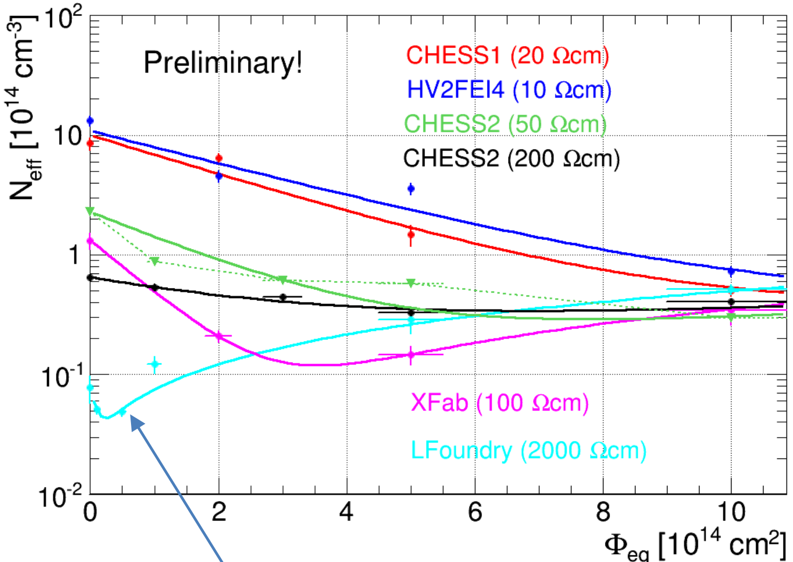
acceptor removal

Radiation introduced deep acceptors

N_c, N_{eff0}, c and g free parameters

Zoom to lower Φ:

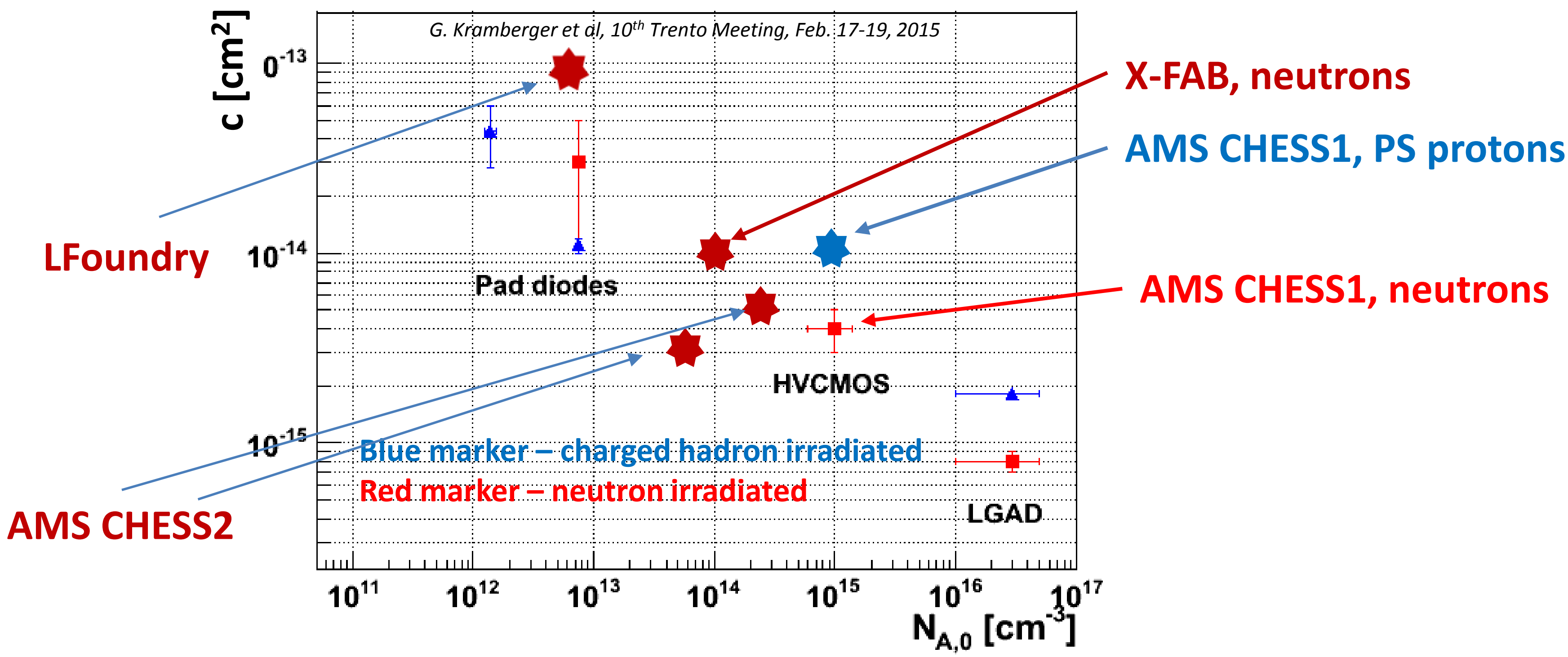




CHESS1, HV2FEI4 numbers published in: *2016 JINST11 P04007*

LFoundry: removal seen at low Φ

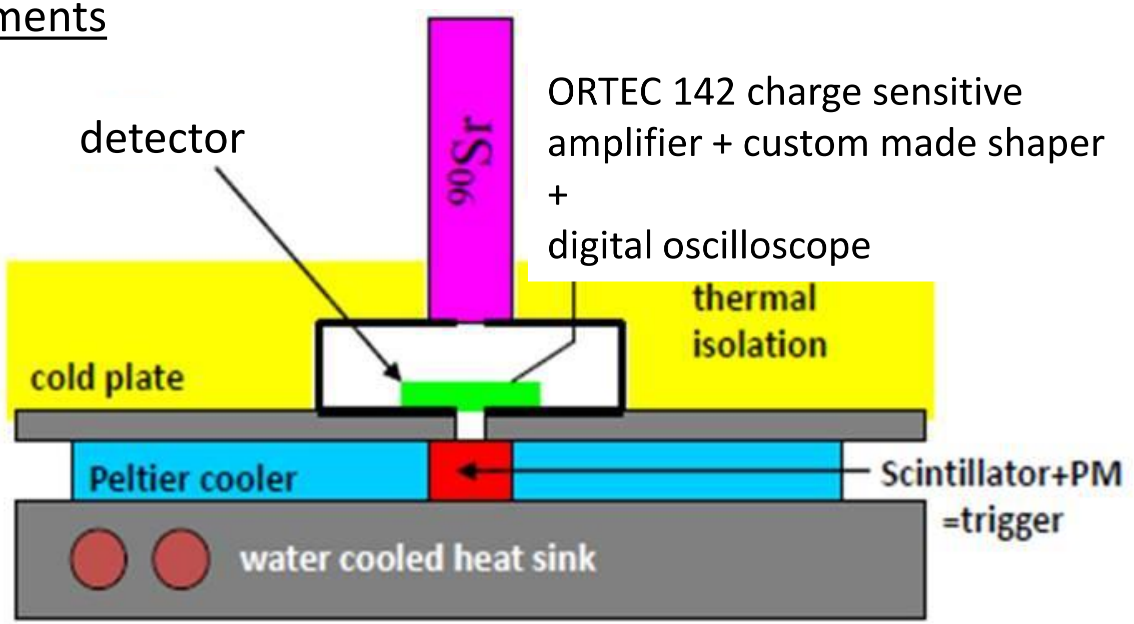
Acceptor removal



Chip	ρ (Ohmcm)	c (1e-14 cm-2)	Neff/Neff_0	g_c (cm-1)
HV2FEI4	10	0.6	1	0.02 (fixed)
CHESS1	20	0.4	1	0.01
CHESS2	50	0.5	1	0.02 (fixed)
Xfab	100	1	1	0.043
CHESS2	200	0.3	0.8	0.02 (fixed)
LF	2000	10	0.6	0.047

- acc. removal parameter *c* for CHESS2 similar as CHESS1 although higher initial resistivity
- g_c for **Xfab** and **LF** somewhat higher than usual for neutron irradiation!

Sr90 measurements



- HV-CMOS: small signals, large noise → S/N very bad
  - ➔ must have clean sample of events
  - ➔ need large detector for reasonable trigger rate and good collimation, small scintillator

Measurement:

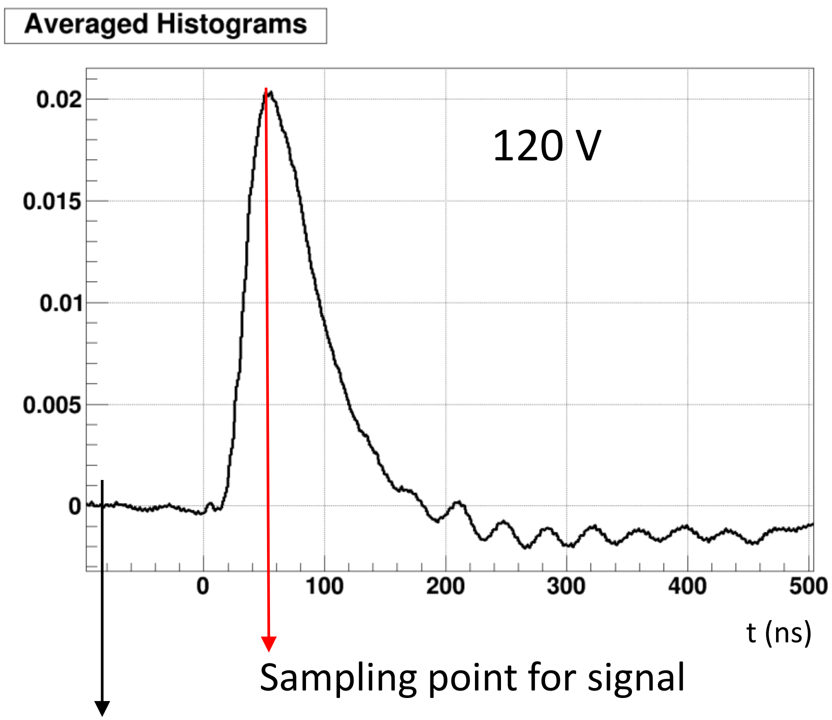
→ Calibrate with 300 µm thick Si pad detector

1) Record N waveforms
2) average over all waveforms and determine signal peak
3) sample waveforms at the peak
4) Fill spectrum

CHESS2

- W13(200 Ω·cm), large passive array, 25 ns shaping

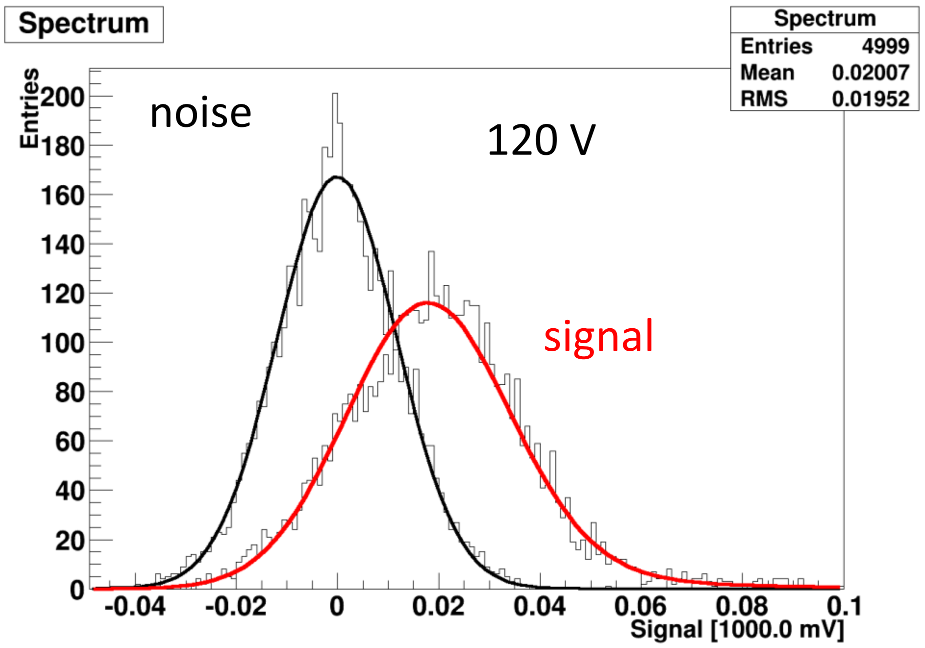
Average waveform:



Sampling point for signal

Sampling point for noise

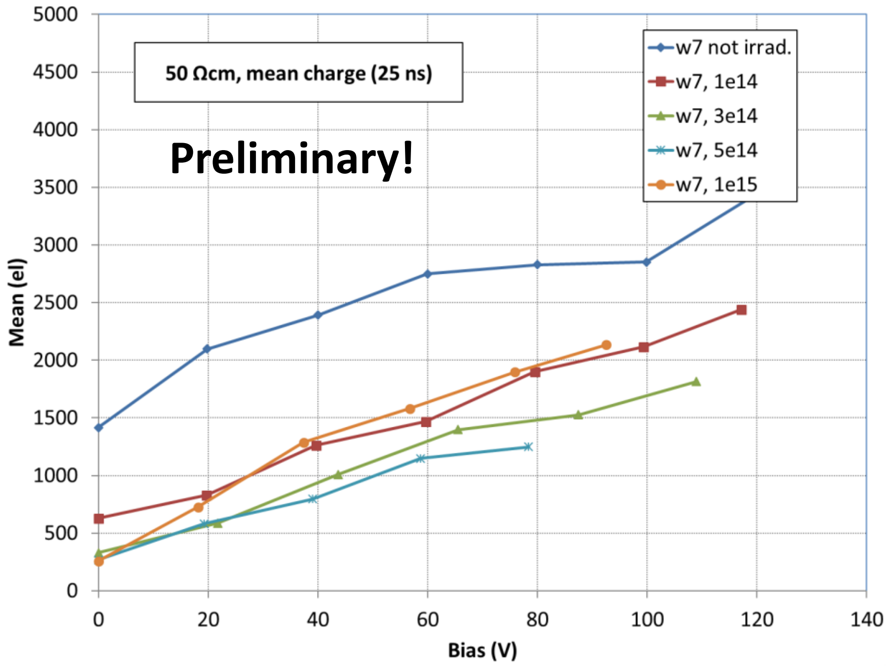
Spectrum of values sampled at peak



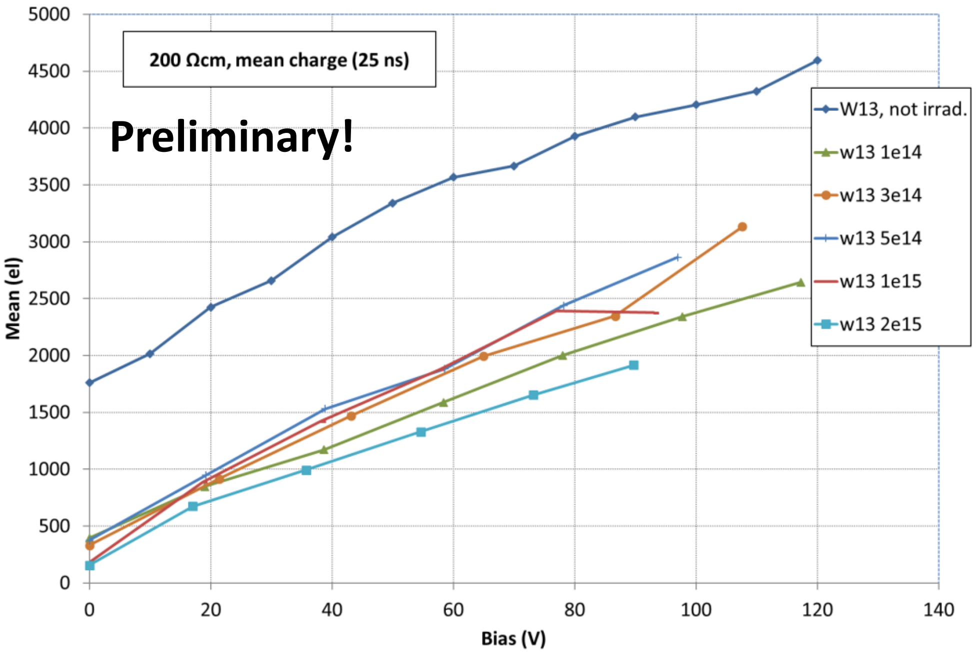
- the shift of distribution mean from 0 interpreted as the mean charge
- OK only if the sample of event is clean → no events without charge deposition in the detector

Sr90, CHESS2, charge vs. bias

W7 (50 Ω·cm)

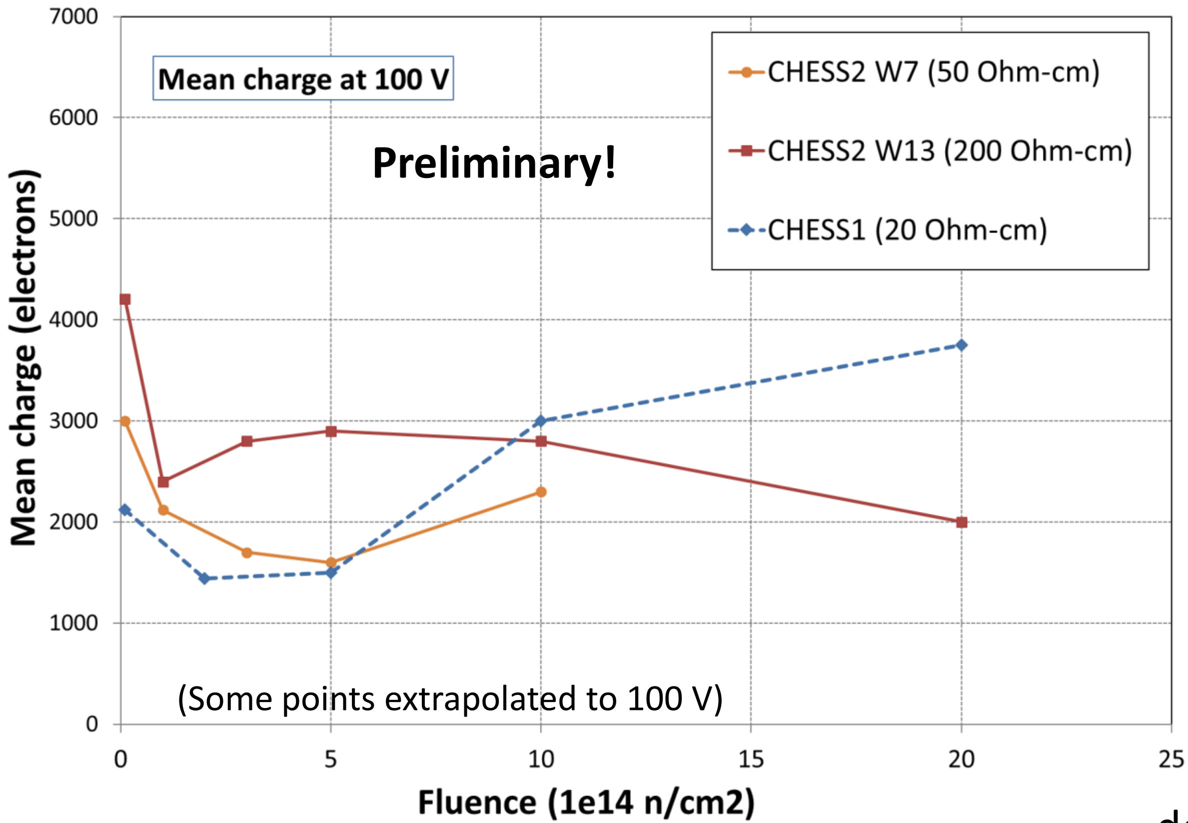


W13 (200 Ω·cm)



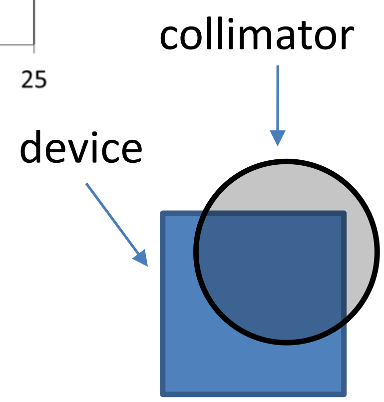
- large drop of collected charge (~ 1300 el) after first irradiation step to 1e14 n/cm2
  ➔ reduced contribution from diffusion

Sr90, CHESS2, collected charge vs. fluence



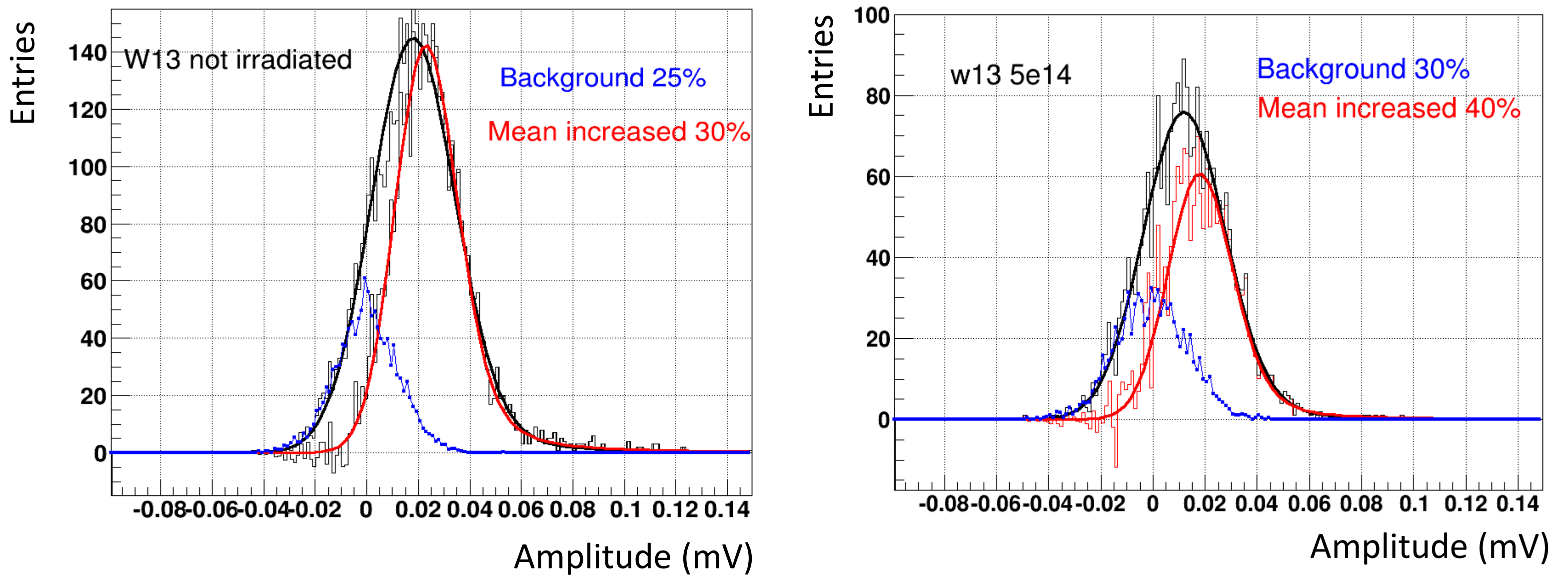
➔ Measured charge in CHESS2 might be underestimated!

→device: ~ 1.mm x 1. mm, collimator r ~ 1 mm
→ difficult to align correctly



Sr90, CHESS2, background study

- Scale measured noise distribution to fit the tail of signal distribution and subtract from the measured signal distribution
  → significant number of entries could be tracks not passing through the pixel array



- If there is misalignment between collimator and device (small (1x1 mm^2))
  → background events in the sample
  → measured mean (or MPV) charge could be underestimated 40%

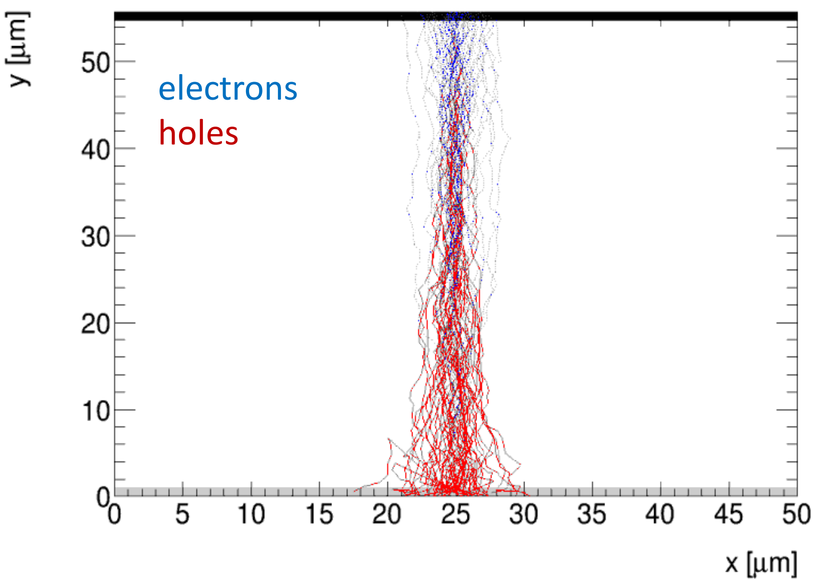
Simulation

1. calculate depleted depth using $N_{eff} = N_{eff\,0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq})) + g \cdot \Phi_{eq}$
   N_{eff0} = 6.5e13 cm^{-3}, c = 3e-15 cm^{-2}, g = 0.02 cm^{-1}, planar geometry, bias = 100 V

2. detector thickness same as depleted depth

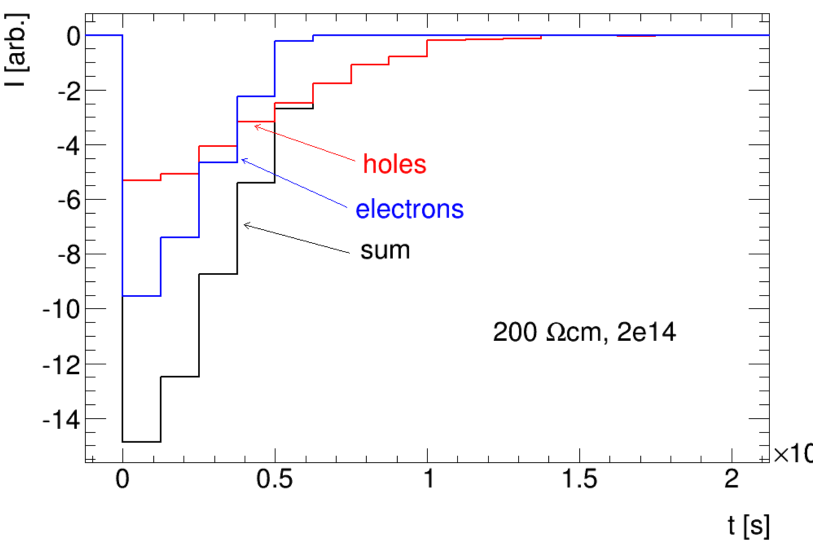
3. calculate trapping loss at given depth and Φ using $\beta = 4 \cdot 10^{-16}\ ns^{-1} cm^2$

Passage of a MIP



- buckets of charge treated as point charge
- (http://www-f9.ijs.si/~gregor/KDetSim/)

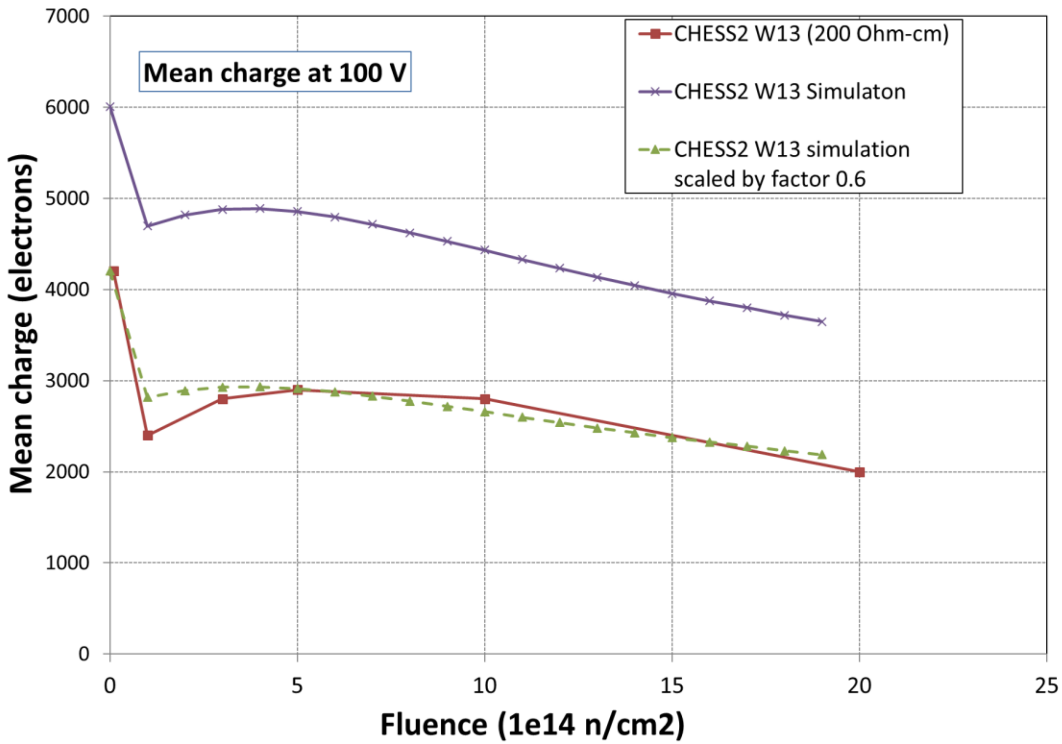
Simulated induced currents



-multiply with $I(t) = I_0(t) \cdot e^{-t/\tau_{eff}}$
to estimate trapping loss at given depth and Φ

Sr90, CHESS2, collected charge vs. fluence

Mean Charge = depletion(µm)* 100 el/µm * trapping_loss + { 1500 electr. at $\Phi = 0$; 0 electr. at $\Phi > 0$ } diffusion



- ➔ good agreement with measurements if simulation scaled by factor of 0.6
- ➔ measurements too low because of imperfect alignment of detector and collimator

Summary

Edge-TCT measurements with passive test structures made on several substrate resistivities:

- **AMS** : 20, 50, 200 $\Omega\cdot$cm, **X-FAB**: 100 $\Omega\cdot$cm, **LFoundry**: 2000 $\Omega\cdot$cm
  → charge collection profiles measured up to 1e16 n/cm^2
  → depleted depth clearly visible up to highest fluences

- increase of depleted depth with irradiation observed in all samples in different fluence ranges

- change of depleted depth with fluence can be described with effective acceptor removal

- acceptor removal constant tends to be larger in materials with larger initial resistivity

- no significant differences observed in LFoundry detectors with and without back plane (if not fully depleted)

Charge collection measurements with Sr90 with passive CMOS detectors on CHESS2 chip
➔ need large device for good measurement with external amplifier

- evolution of measured charge with fluence follows the behavior measured with E-TCT
  ➔ **but** large drop of collected charge measured after first fluence step (1e14 n/cm2) because of supressed contribution of charge from diffusion