Advanced Transient Current Techniques

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Most of presented results were obtained within RD50, ATLAS and strip CMOS collaborations

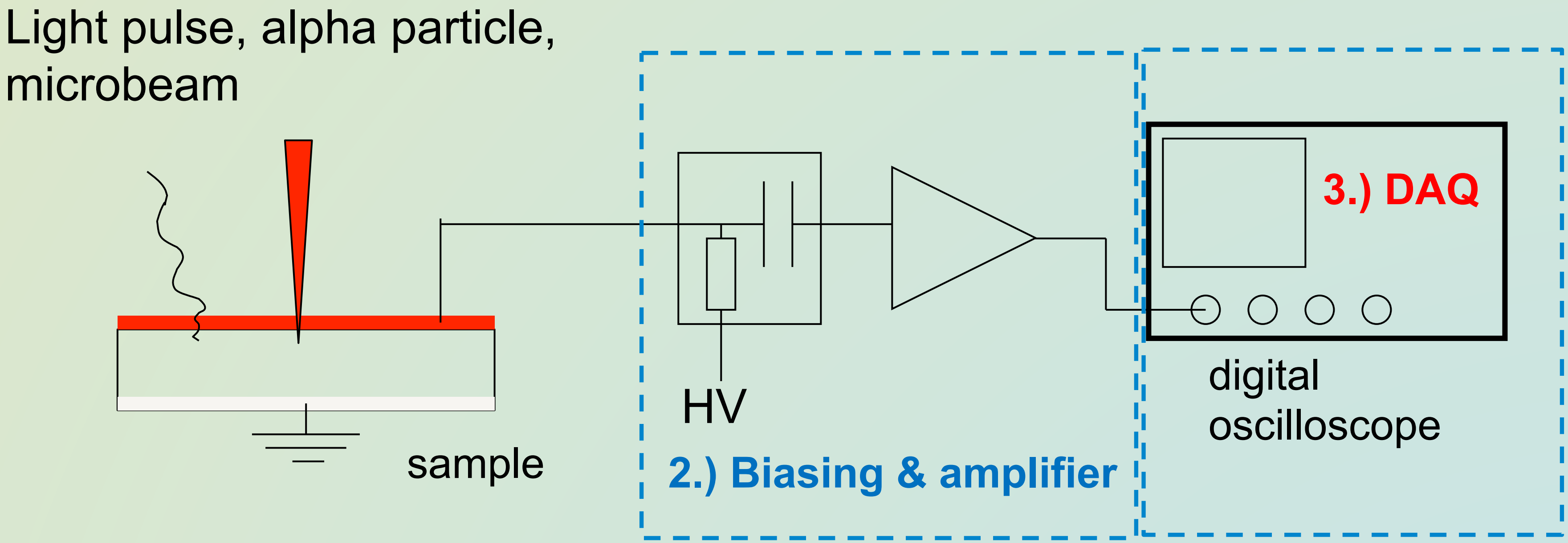
Overview

- The first measurements using TCT in 1960s
- Measurements of drift velocity and mobility in insulators and semiconductors
- From early 1990 widely used for measurements of radiation effects in semiconductors.
    - Electric field profile ➔ effective space charge
      ➔ full depletion voltage
    - Effective trapping times
    - Defect characterization

- Scanning TCT with a narrow laser beam for study of segmented detectors gained importance in the last decade

- Space charge/electric field (double junction/space charge inversion) from *I(t):*
  - V. Eremin et al, Nucl. Instr. and Meth. A 372 (1996) 388.
  - E. Fretwurst et al., Nucl. Instr. and Meth. A 388 (1997) 356
  - J. Härkönen et al., Nucl. Instr. and Meth. A 581 (2007) 347 - cryogenic temperatures
  - \+ very long list
- Charge collection efficiency/multiplication
  - J. Lange et al., Nuclear Instruments and Methods in Physics Research A 622 (2010) 49–58.
  - J. Lange et al.,. PoS (Vertex 2010) 025.
  - \+ very long list
- Effective trapping times:
  - "Charge Correction Method" – based *on* $Q(V>V_{fd})$~const. in absence of trapping – correct current pulse for trapping to achieve this.
  - T.J. Brodbeck et al., Nucl. Instr. and Meth. A455 (2000) 645.
  - G. Kramberger et al., Nucl. Instr. and Meth. A 481 (2002) 297-305.
  - O. Krasel et al., IEEE Trans. NS 51(1) (2004) 3055.
  - A. Bates and M. Moll, Nucl. Instr. and Meth. A 555 (2005) 113-124.
  - +long list
- Detrapping times
  - G. Kramberger et al., JINST 7 (2012) P04006

Principles of operation



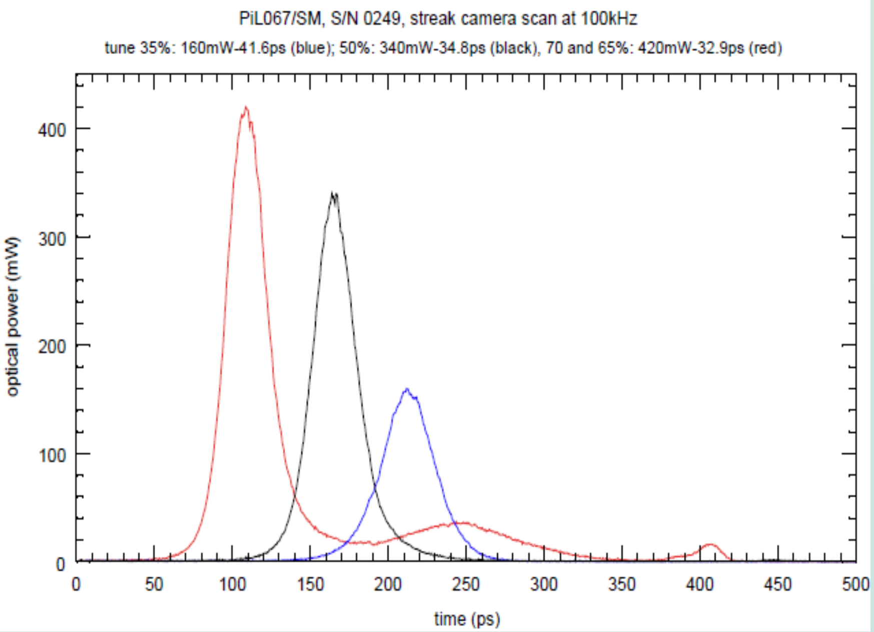
- Transient current technique – non equilibrium carriers are introduced in the material at well defined position in a short (< 1 ns) time
- motion of carriers in the electric field induces current on the electrodes
- current pulse shape is measured and analyzed
- laser pulse, alpha source or particle microbeam can be used

Creation of free charge carriers with light pulse has many advantages over creation with particles:

- Repetition (averaging) reduces noise
- triggering (exactly known time of the laser pulse)
- intensity tuning **– but hard to have absolute scale**
- controllable beam position
- no need for radioactive sources ➔ easier to implement for educational purposes

But also disadvantages over the α, μ-beam

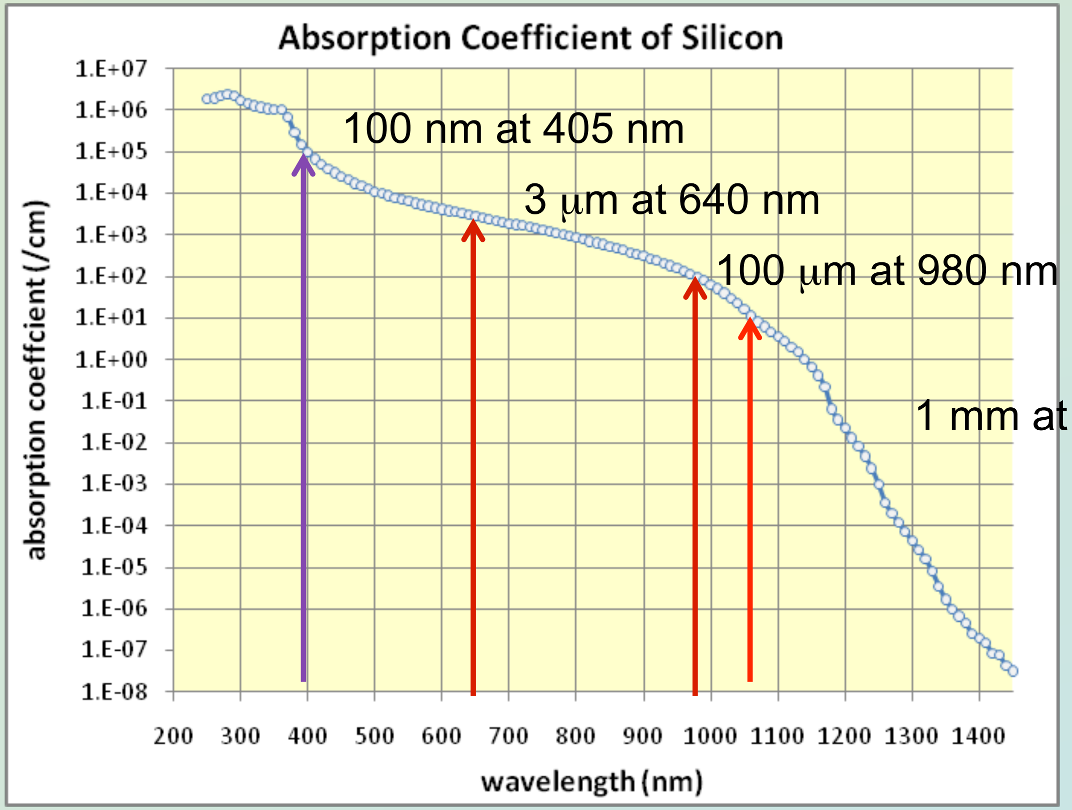
- use for wide band gap semiconductors difficult
- **E_g<hv** hard to get fast pulsed lasers with short wavelength
- effects of field screening – plasma/recombination, particularly important when focused to few μm
- The DUT should have opening in the metallization – can not study all the volume



50 ps laser pulse with tails of few 100 ps !!

Light absorption in Si:

- MIP like 1064 nm (infrared)
- μ beam like 980 nm
- near surface 660 nm
- surface 405 nm



In other materials:

- SiC – ~3-3.2 eV (405 nm)
- C – 5.5 eV (223 nm)

Two configurations:

- With Bias-T (simple housing&grounding), but Bias-T can influence the measured waveforms
- Without Bias-T (complicated housing&grounding&cooling), but easier multichannel operation

- In TCT induced current on electrode is measured →**weighting field** should be taken into account
- Induced current can be calculated according to Ramo's theorem

$$I_{e,h}(t) = e_0 \cdot N_{e-h} \underbrace{\exp(-t/\tau_{eff,e,h})}_{\text{trapping}} \underbrace{\vec{E}_w}_{\text{weighting field}} \cdot \underbrace{\vec{v}_{e,h}(t)}_{\text{drift velocity}}$$

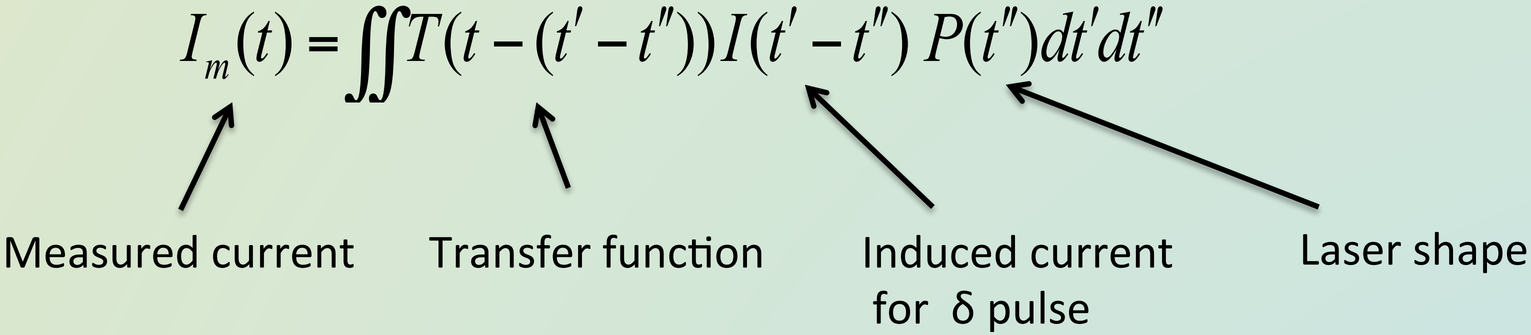
Defects → trapping
Geometry → weighting field
Electric field → drift velocity

$$I(t) = I_e(t) + I_h(t)$$

$$Q = \int I(t)\,dt$$

If charge is generated close to the electrode, drift of only one type of carriers is observed!

Measured current is related to the induced current:



$$I_m(t) = \iint T(t-(t'-t''))I(t'-t'')\ P(t'')dt'dt''$$

Measured current

Transfer function

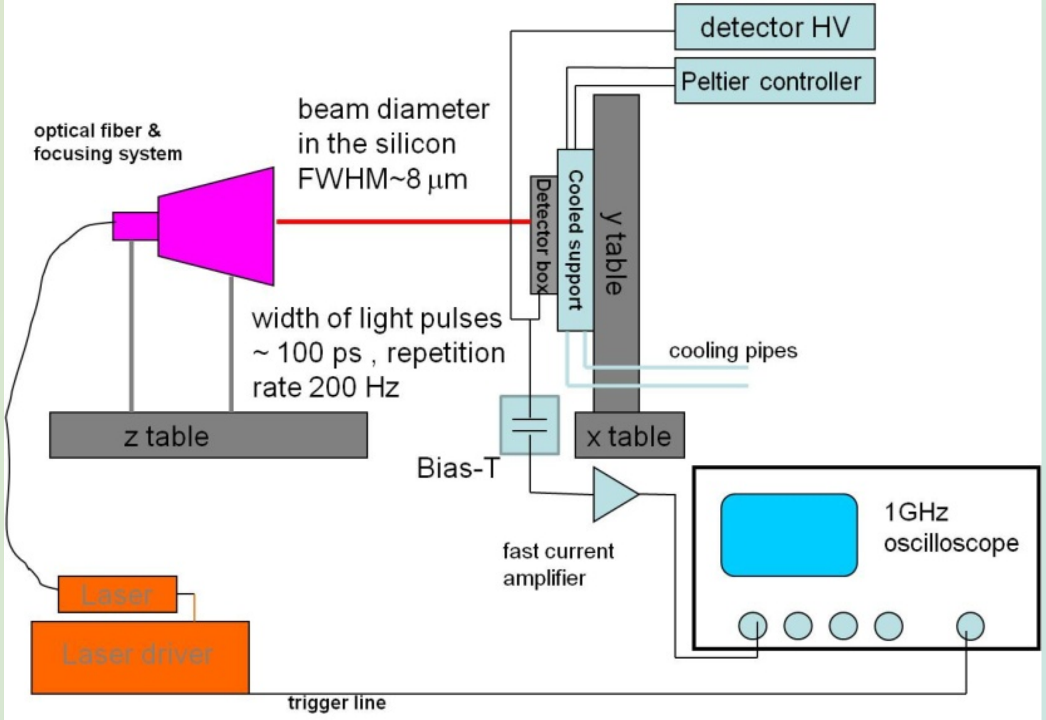
Induced current
for δ pulse

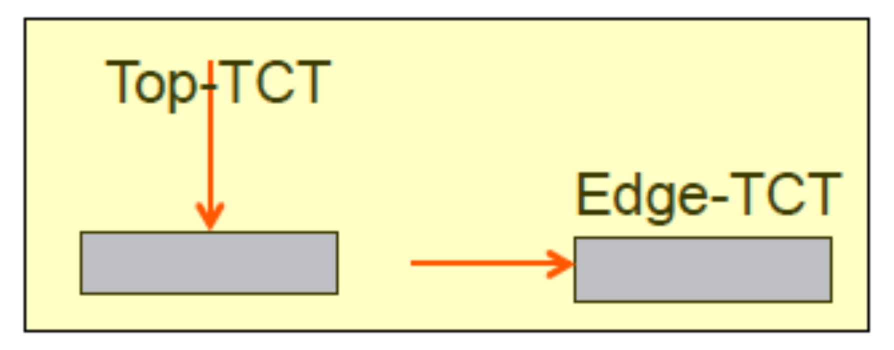
Laser shape

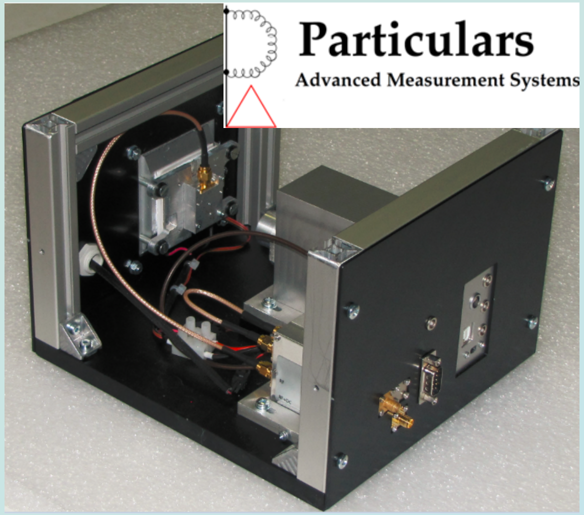
In general a complicated task to extract *I(t)* from the measured current.

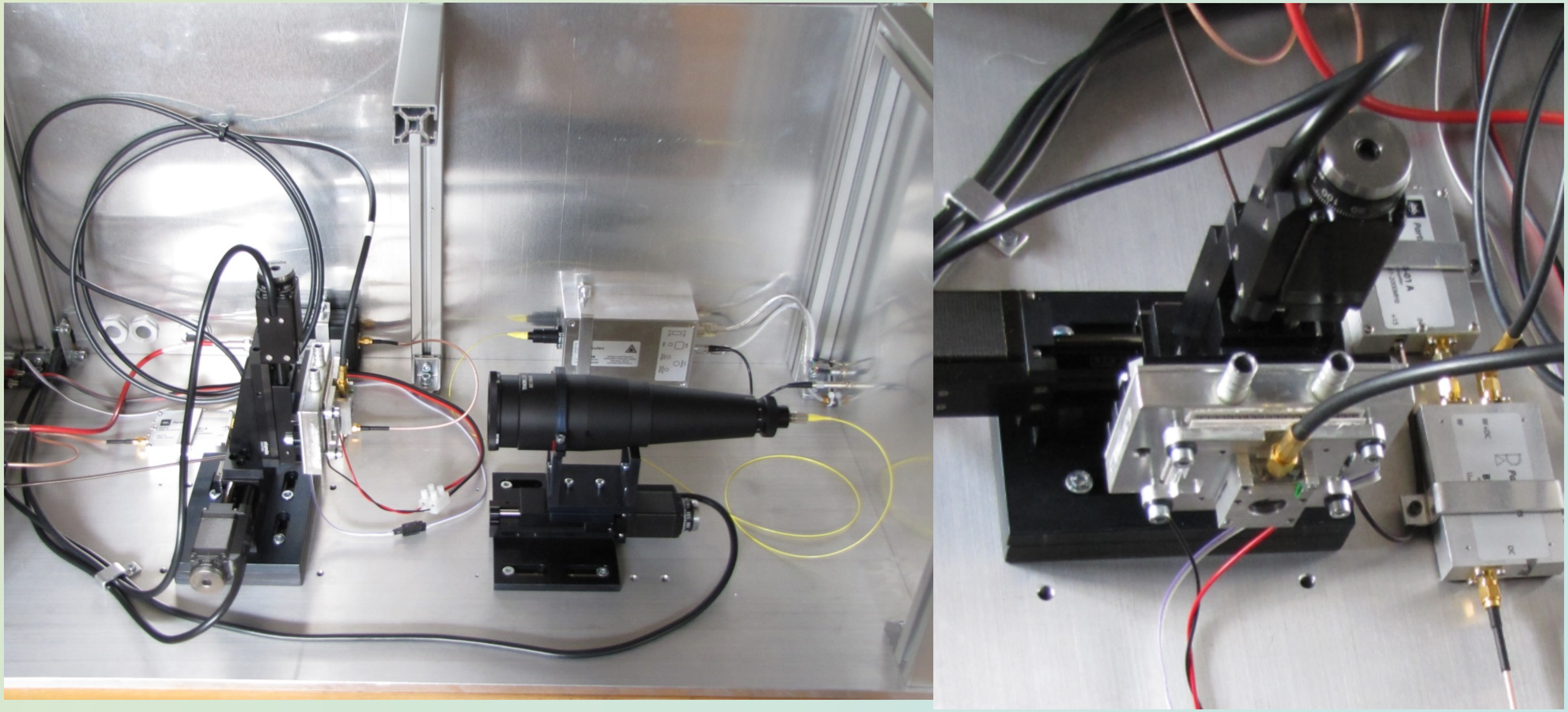
If we are looking in effects on timescale longer that few 100 ps: $I_m(t) \sim I(t)$ with short shaping

Scanning TCT system









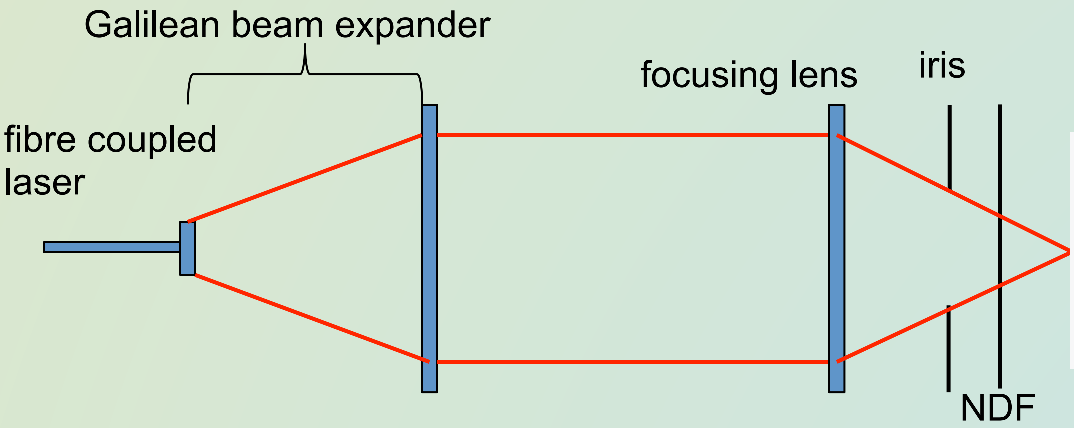
Particulars

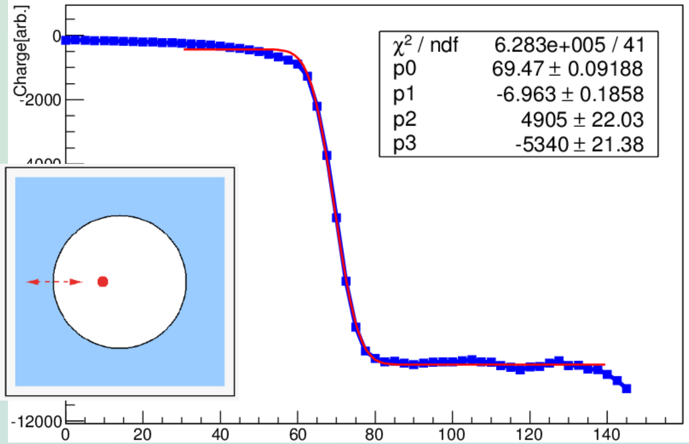
Advanced Measurement Systems

see www.particulars.si for additional information

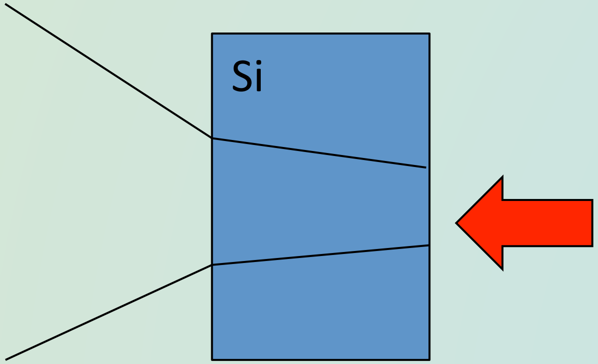
Optical system

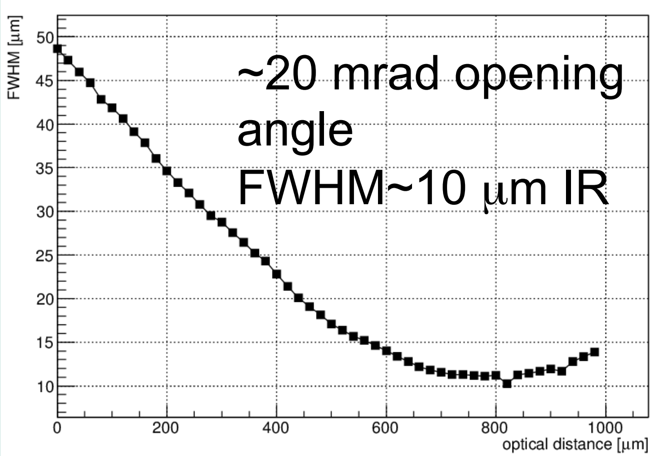
- Fiber coupled lasers usually used
- The thinner the core the better focus can be achieved (4 μm core is standard in this application)
- Focus is usually measured by “knife edge technique” where the light crosses the edge of metallization





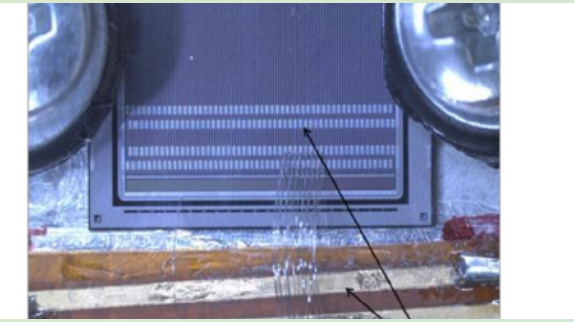
Refractive index helps to achieve narrower beam width in Si than measured at the surface





~20 mrad opening angle
FWHM~10 μm IR

TOP-TCT with IR light – evidence for multiplication after irradiation

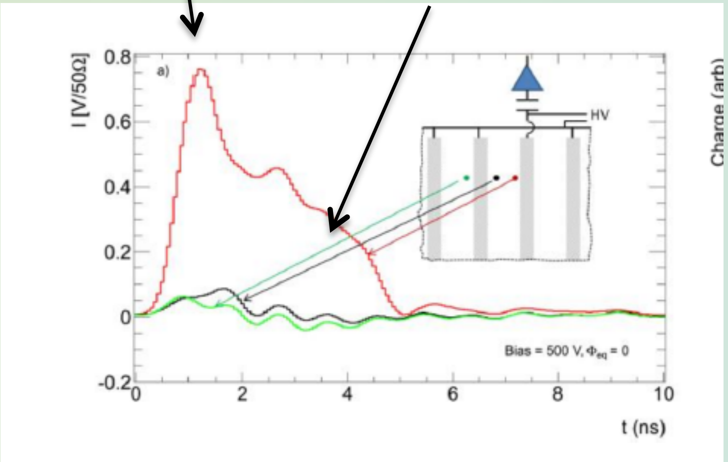


Scanning over top surface with **IR laser**
ATLAS 07 detectors
75µm pitch, 22µm AC coupled metal, 320 µm thick
p-type FZ

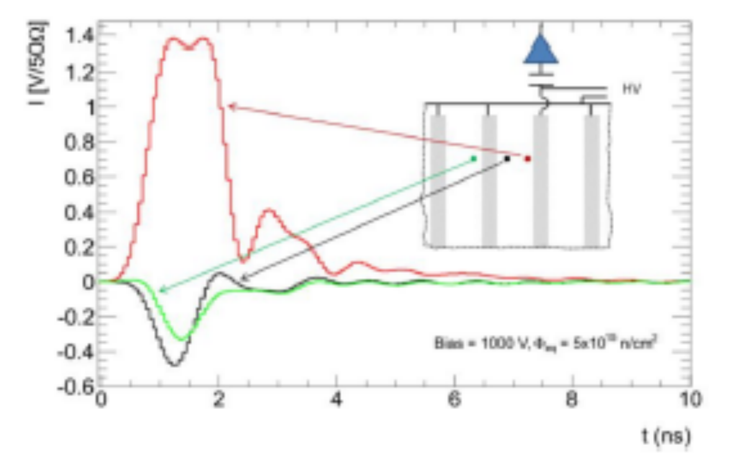
I. Mandić et al, 2013 JINST 8 P04016

Electrons

Holes



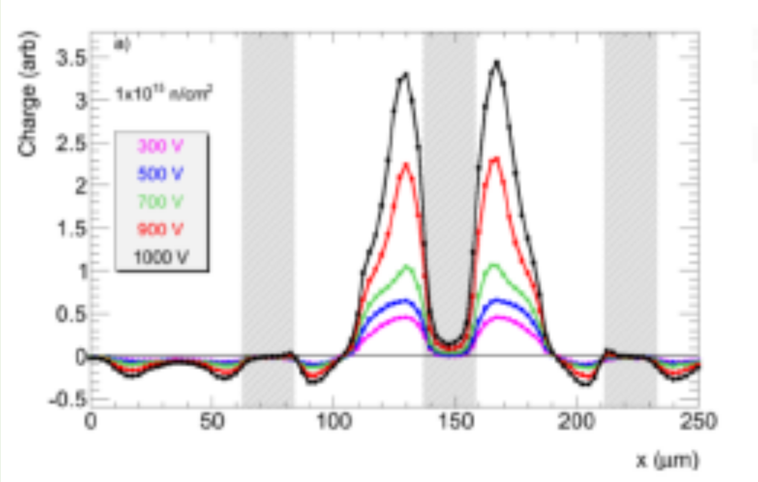
Before irradiation



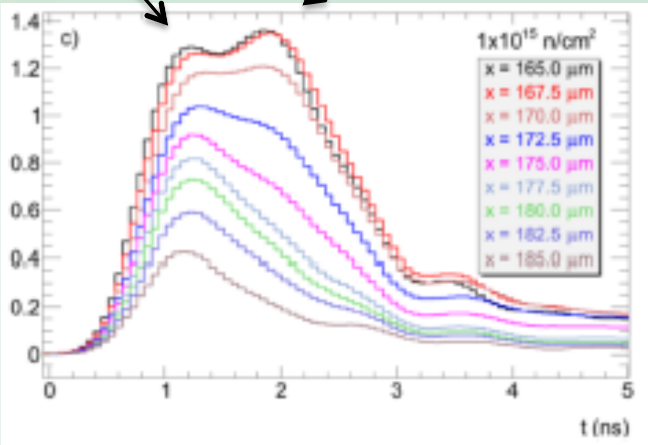
After irradiation – opposite signals on neighbor channels

After **irradiation** with neutrons at TRIGA reactor in Ljubljana:

$1\ 10^{15}\ n_{eq}cm^{-2}$ trapping time ≈ 2.5 ns



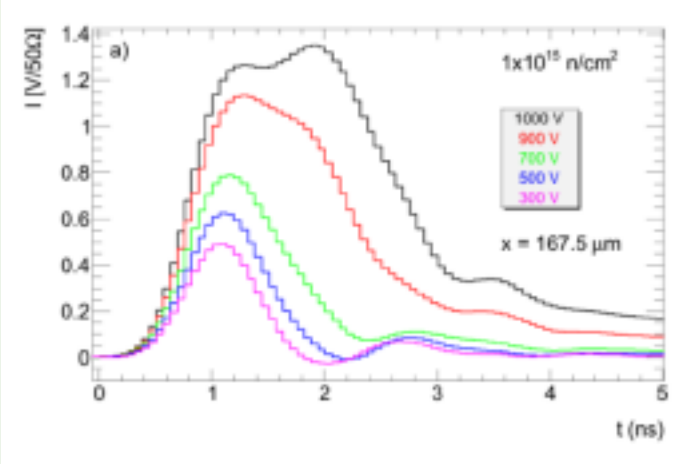
Signal charge (15 ns integral)



initial movement

amplification

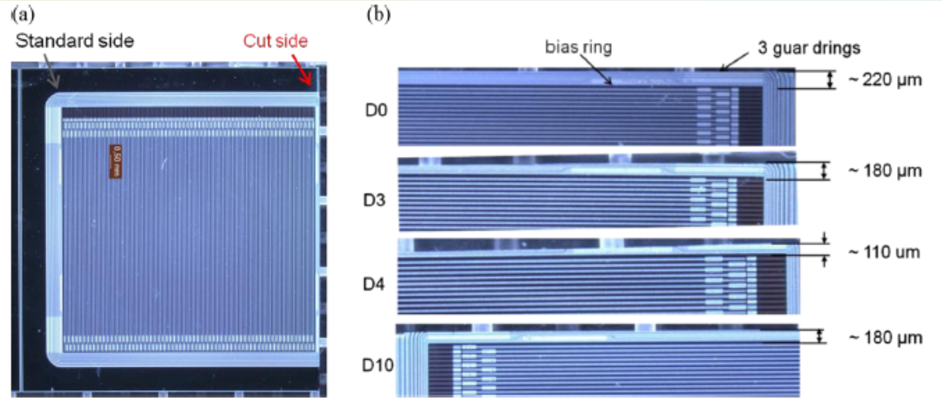
Signal shape at different positions



Annealed 5120 min at 60°C

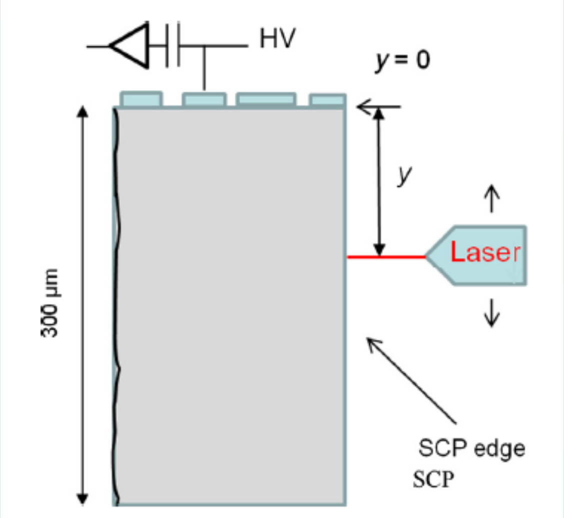
Signal shape at different voltages

Top and edge TCT – slim edge measurements



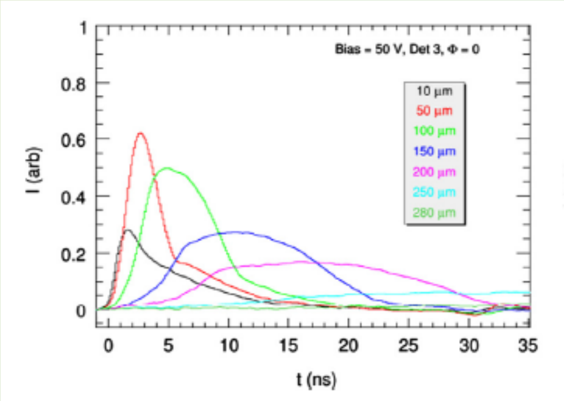
Edge of detector thinned with
Scribe cleave passivate (SCP)
method (ATLAS)

I. Mandić et al. NIM A 751 (2014) 42

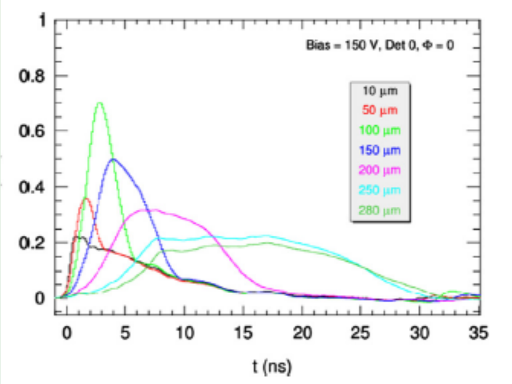


edge impact of red beam

Pulses measured at different distances of laser beam from the top, **FDV= 50 V**



U = 50 V

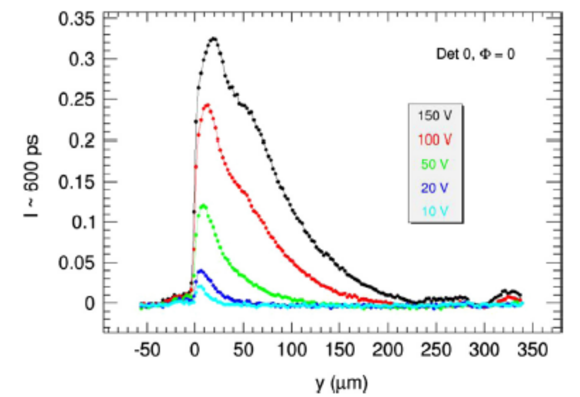


U = 150 V

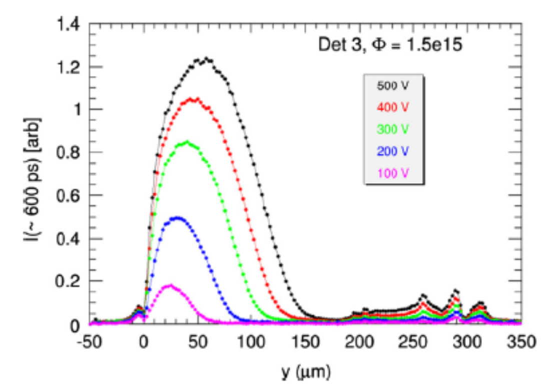
Electric field at the detector edge is different than in the bulk !
Explained by negative space charge in the surface processed Al_2O_3

Calculated depletion depth and the depth at which initial induced current at the detector edge becomes low ➔ influence of the surface charge on electric field becomes low at high N_{eff} and depletion depth at the edge is similar as in the bulk.

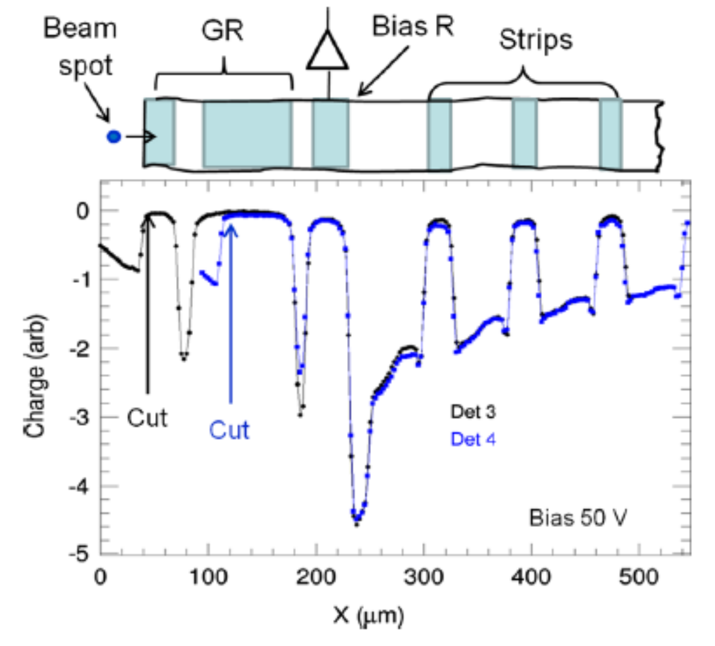
Induced current pulse measured after 600 ps - measures drift velocity at the position of beam.



Φ =0



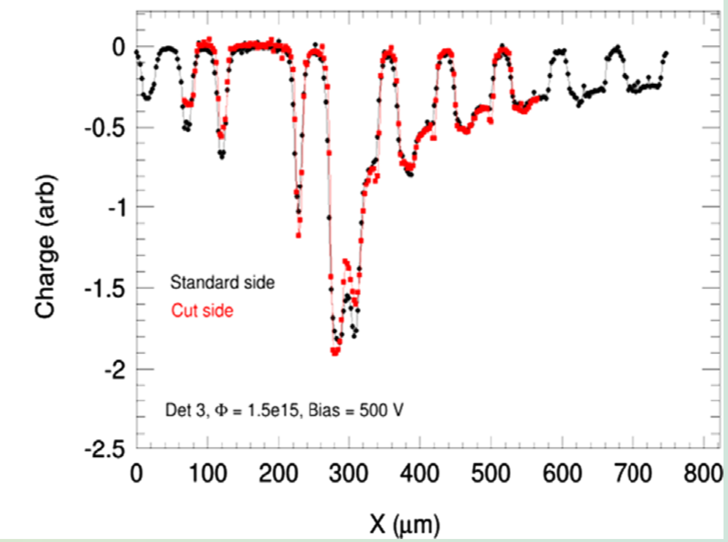
Φ = 1.5 10^{15} $n_{eq}cm^{-2}$ (FDV ≈ 1850 V, 80 min at 60^oC)



IR light and top TCT

charge normalized at x = 500 μm
only one strip (ring) on low (AC) impedance!!

- ➔ Charge collection in the sensitive region is not affected by the edge cut even for non irradiated detectors
- ➔ similar result after neutron irradiation (to be confirmed after charged particle irradiation)



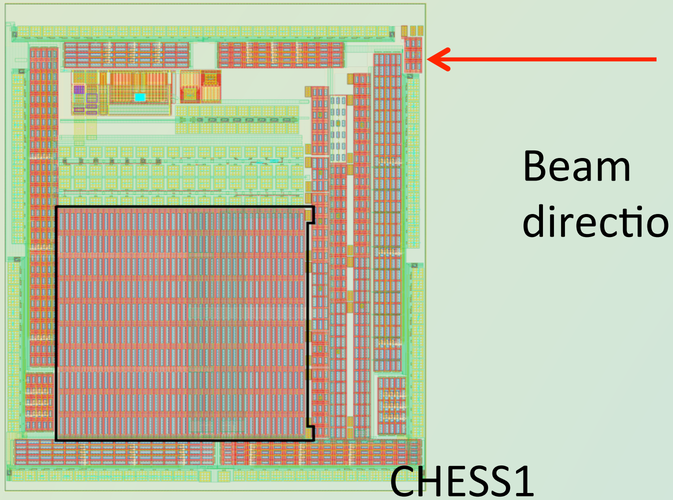
after neutron irradiation $\phi_{eq} = 1.5\ 10^{15}\ \mathrm{cm}^{-2}$
500 V

Edge-TCT on CHESS1 CMOS sensor

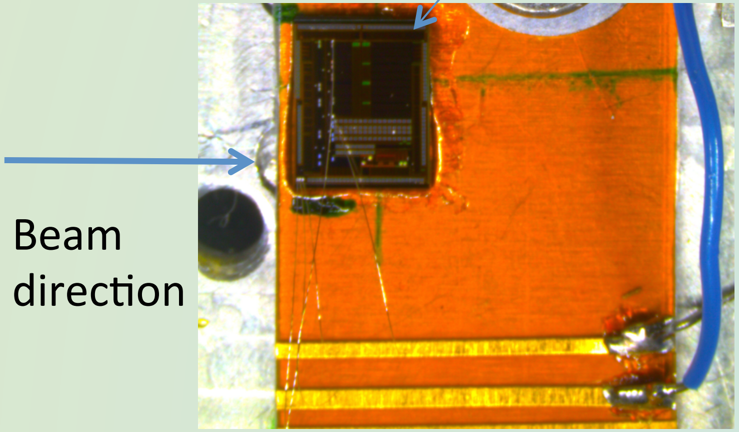
350 nm AMS, 20 Ωcm, 120 V max

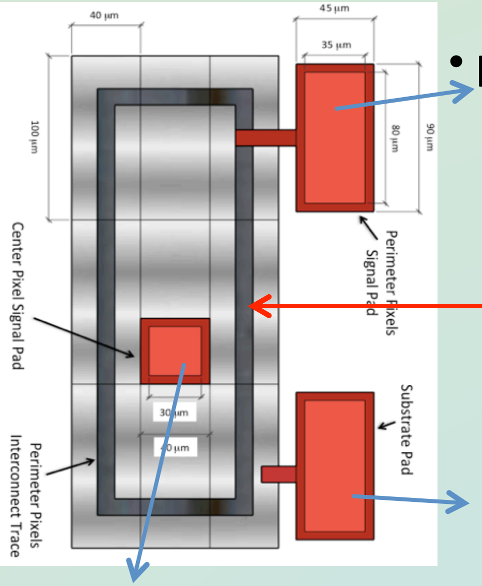
I. Mandić, G. Kramberger – 17th Trento workshop, 2015

- passive 40 x 100 µm pixels in the corner


Beam direction

CHESS1


Beam direction

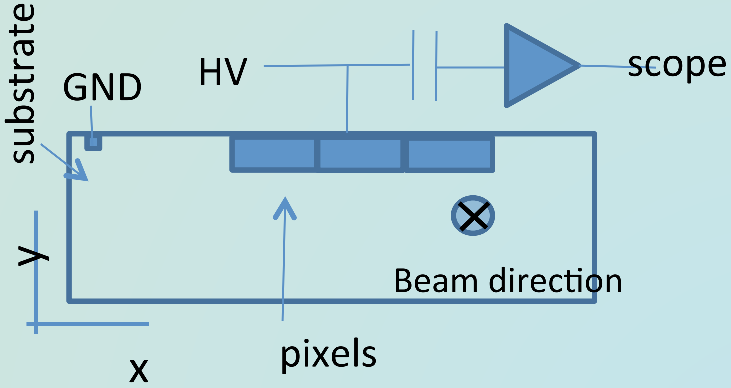


- perimeter to HV

Beam

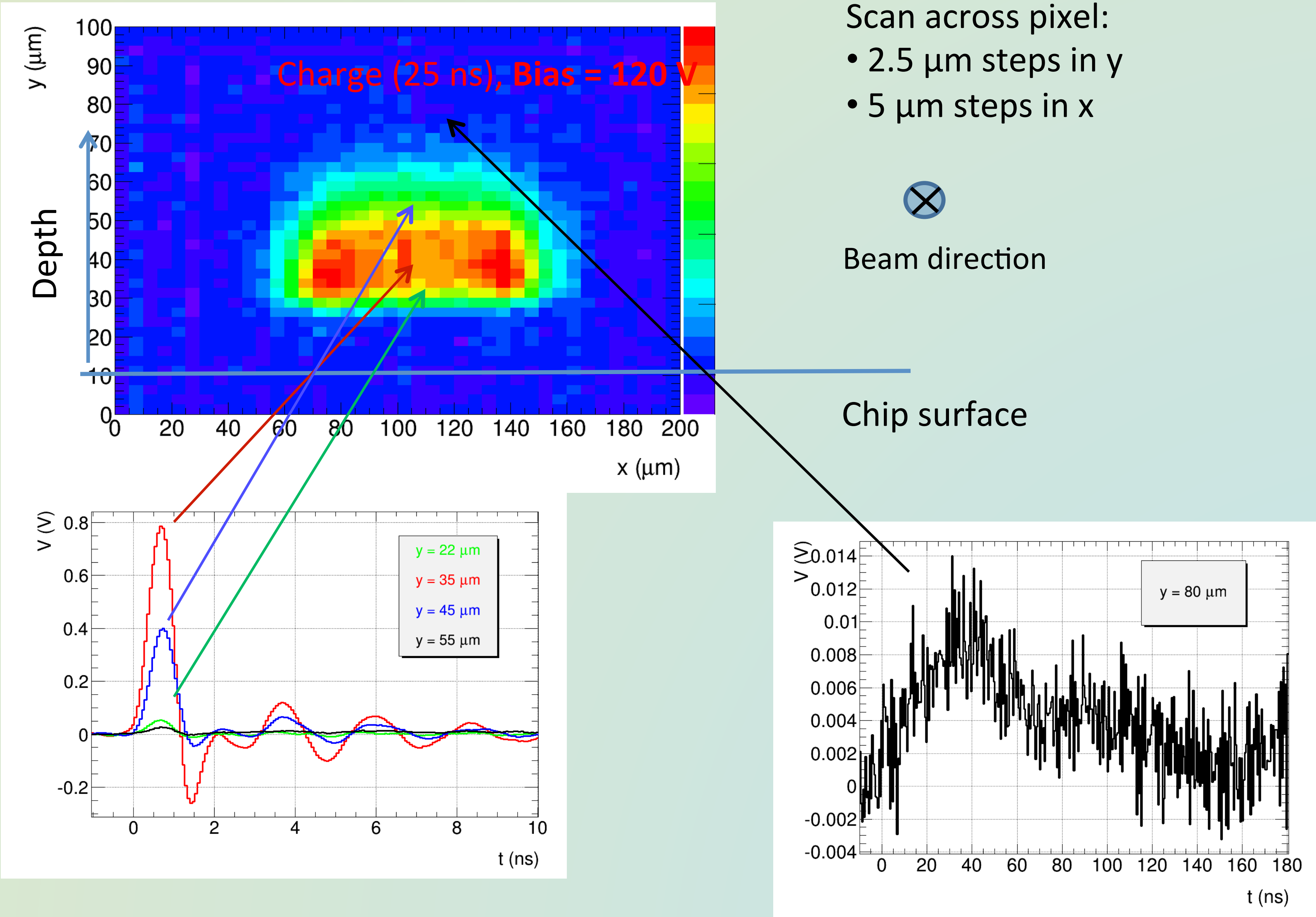
- to ground
- signal to high voltage and readout (via Bias-T)

Detector connection scheme:



Edge-TCT

Chess1, not irradiated, pixel 100 µm x 45 µm



Scan across pixel:
- 2.5 µm steps in y
- 5 µm steps in x

⊗

Beam direction

Chip surface

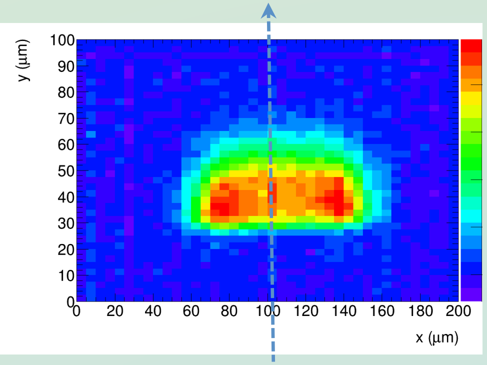
Edge-TCT

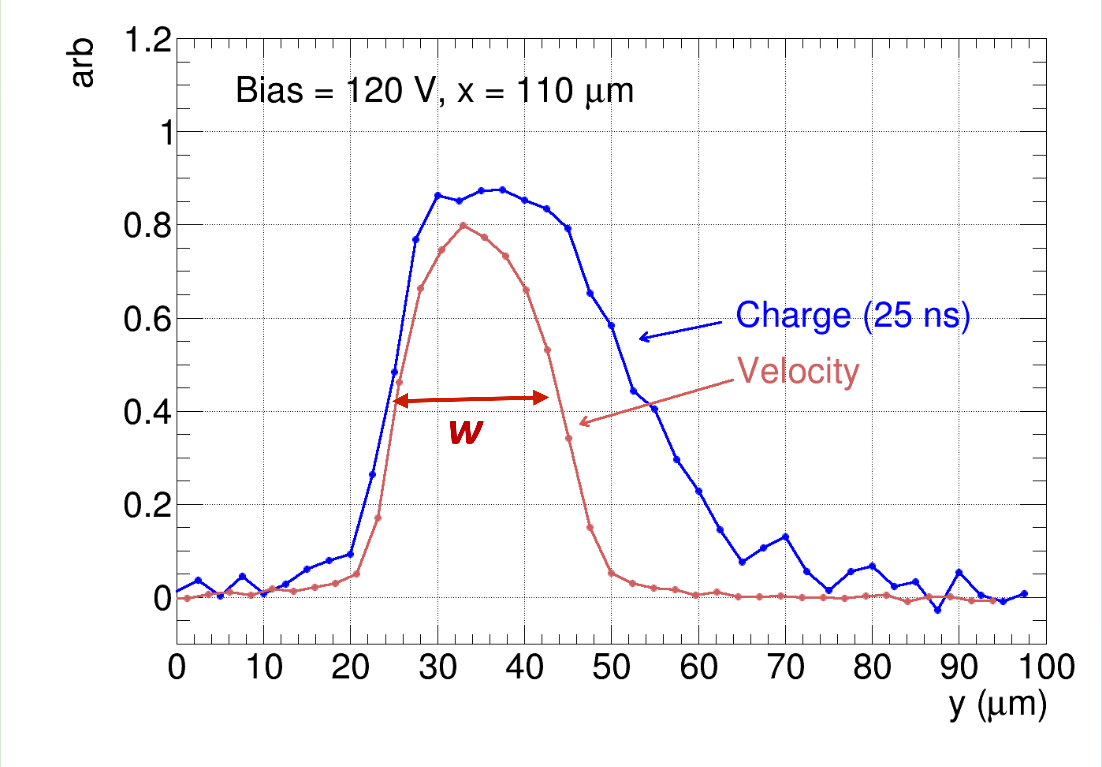
Chess1, not irradiated

1) **charge:** integral of induced current pulse

2) **velocity** (in E-TCT): induced current immediately after the laser pulse

$$I(x,y,t\sim 0)\approx qE_w(x,y)\left[\bar{v}_e(x,y)+\bar{v}_h(x,y)\right]; \quad \bar{v}_e(x,y)+\bar{v}_h(x,y)\propto E$$

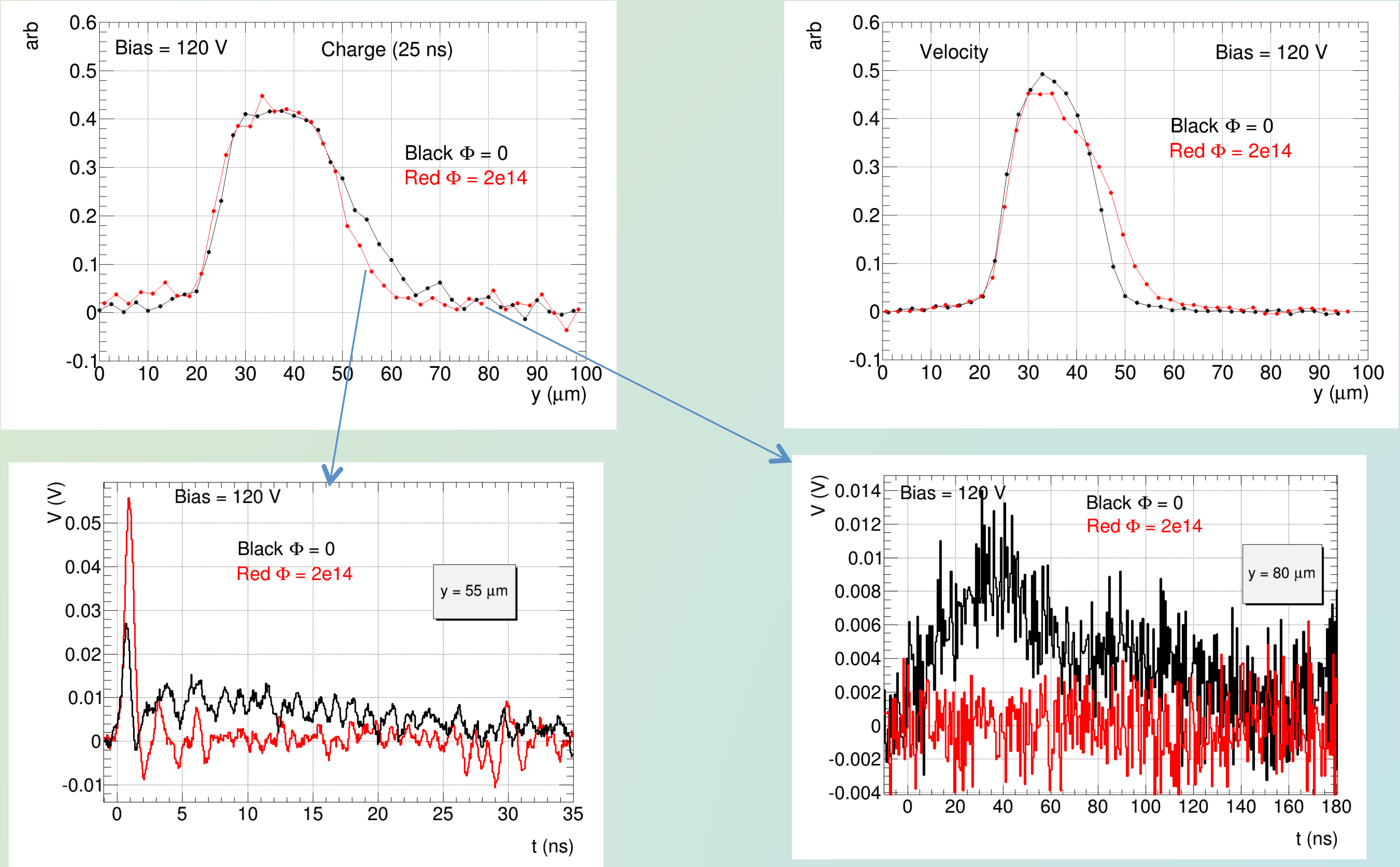




- **high velocity ~ depleted region** ~ 20 µm → about 60% charge within this region
- total charge collection region wider (diffusion)
  - ➔ take into account laser beam width

Edge-TCT
Chess1, irradiated with 2e14 n/cm^2

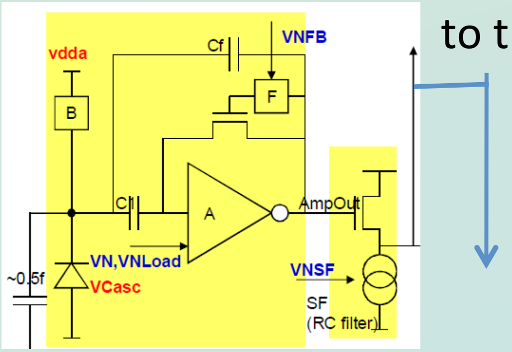
- charge collection region narrower
- field region (velocity) increases ➔ acceptor removal
- no long tails of induced current pulses ➔ less diffusion



Samples

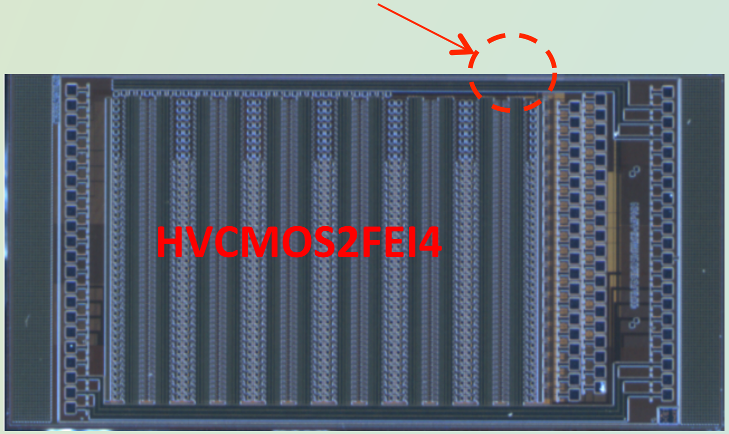
2) HV2FEI4 chip (ATLAS CMOS pixels studies): 180 nm, AMS, 20 Ωcm, 60 V max bias, Active pixels: output of the amplifier monitored on the scope

Single cell charge sensitive amplifier:

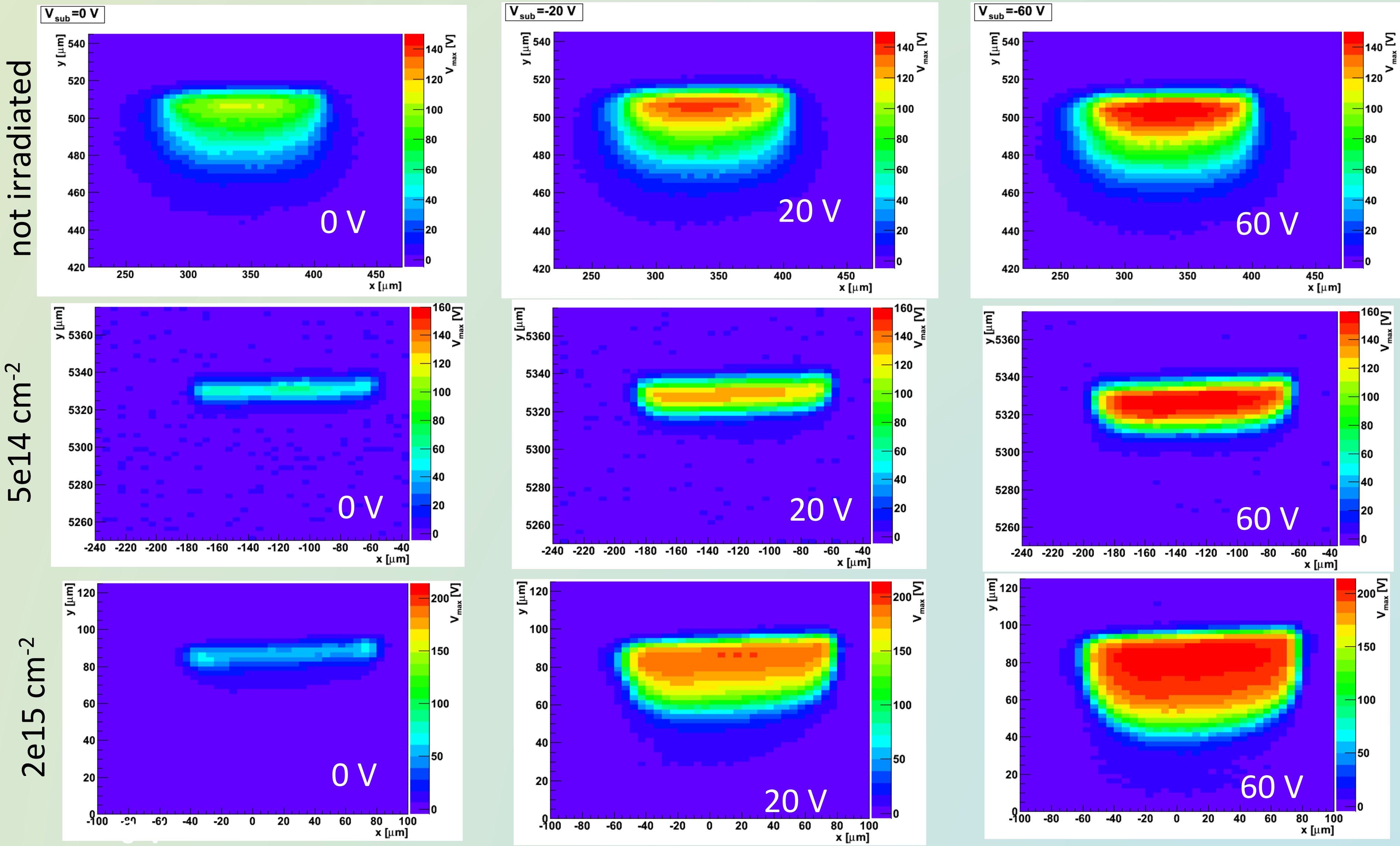


to the scope

E-TCT on single cell, 125 x 33 μm^2 readout after the charge sensitive amplifier (not observing induced current)

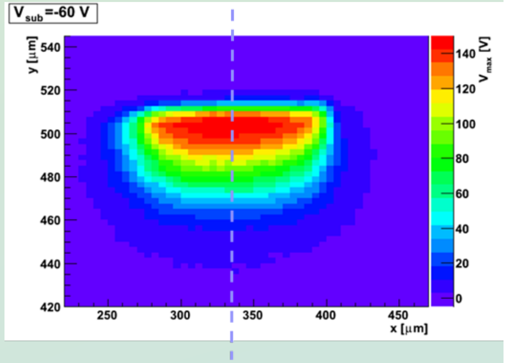


Edge-TCT, HV2FEI4, pixel 125 µm x 33 µm, irradiated with neutrons in Ljubljana

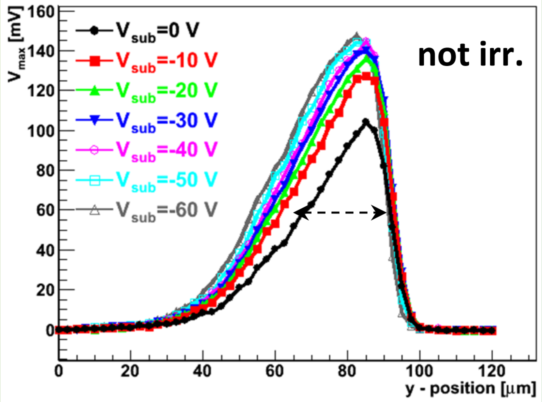


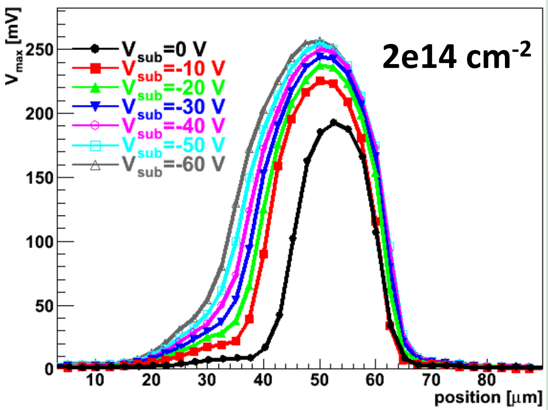
Charge collection region larger at high fluence

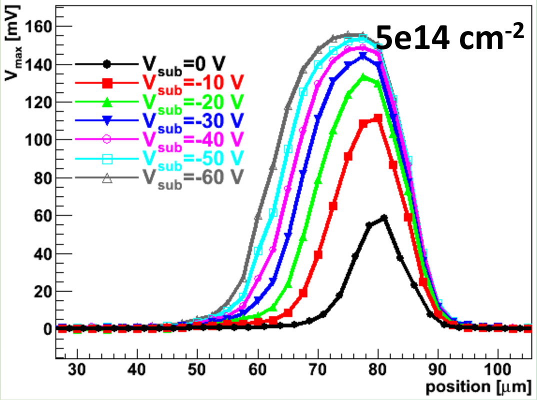
Edge-TCT, HV2FEI4

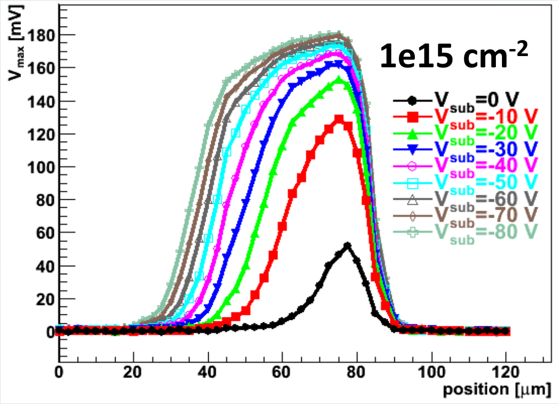


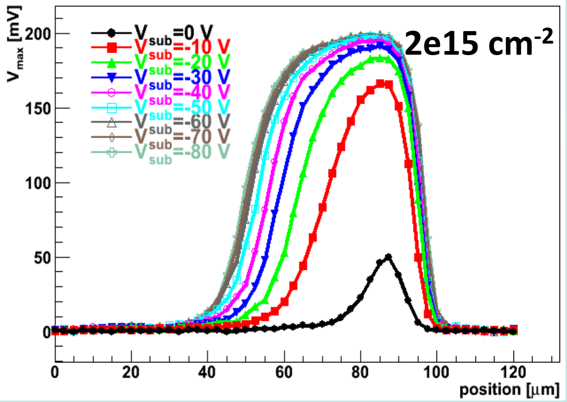
Charge collection profiles across center of the pixel









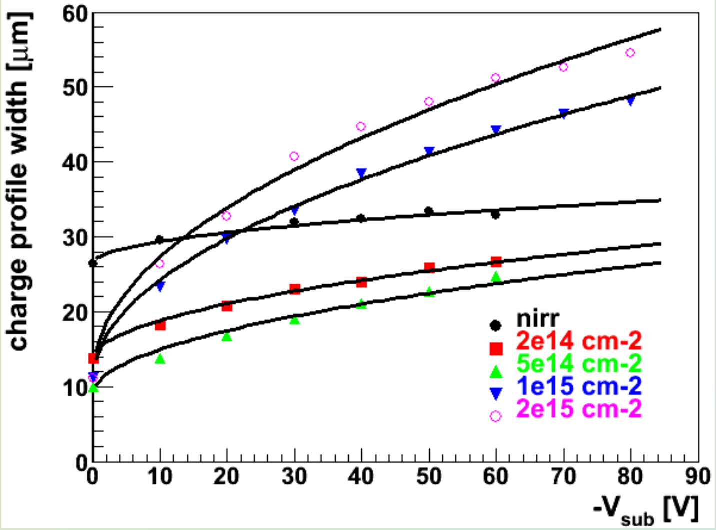


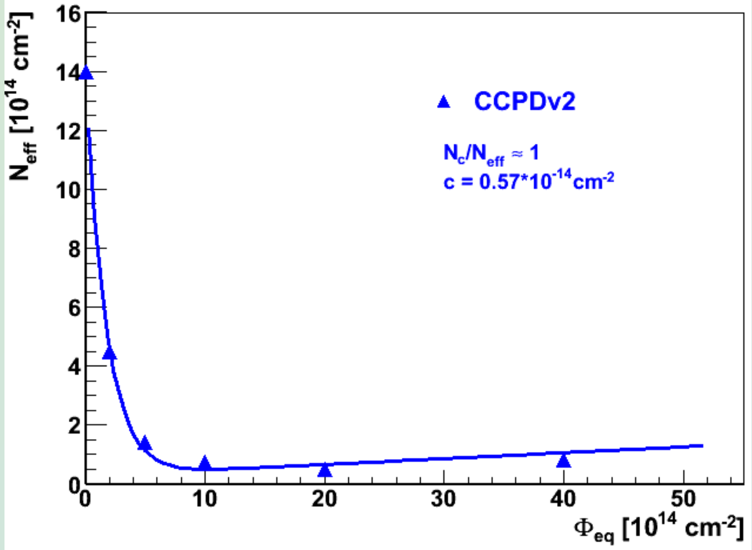
- tail (diffusion) seen before irradiation, almost disappears at 5e14 cm^{-2}

- profile width **(FWHM)** is a measure of charge collection region (drift + diffusion)
  → the width of the laser beam (~ 8 um FWHM) should be taken into account

Edge-TCT, HV2FEI4

Dependence of charge collection region on bias voltage

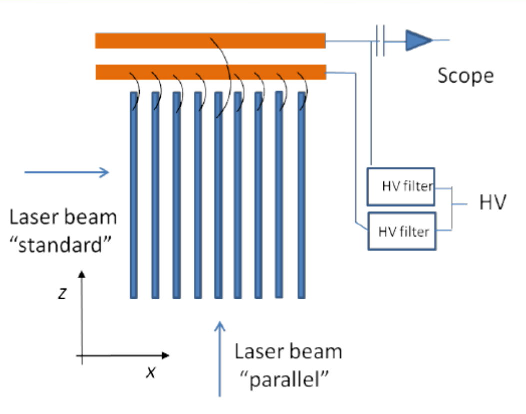




- at $V_{sub}=0$ V it is assumed that charge is collected by diffusion (note the FWHM of the beam)
- any additional bias increases depletion layer which adds to the diffusion
- effective doping concentration seems to decrease with fluence
  → **depletion region wider after irradiation!**

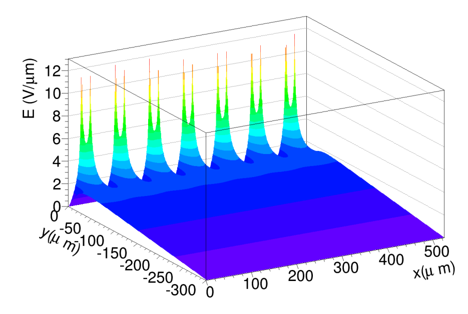
Effective acceptor removal !!

EDGE TCT – impact **parallel** to the strips

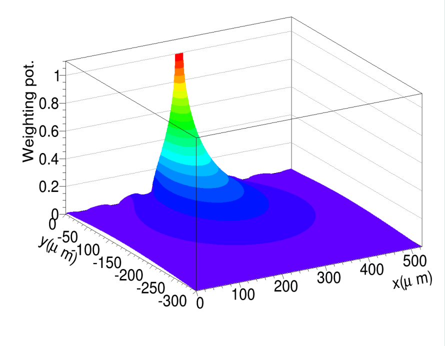


ATLAS 12 p-type detectors
FDV = 370 V before irradiation
pitch = 75 µm

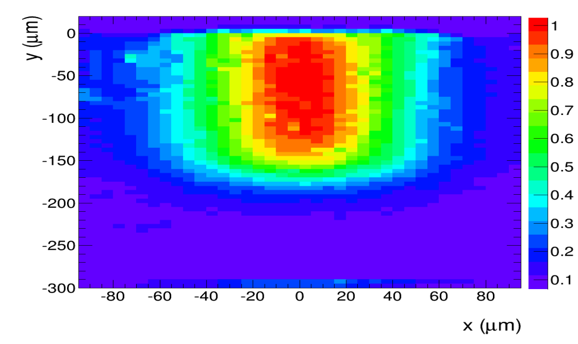
Ideal case - carriers are released in the same electric and weighting field. In reality the beam spot grows with distance because of diffraction. Simulation shows that this effect is more important in the region between the strips than under the strips. Absorption depth of 1060 nm light is 1014 µm



Calculated electric field

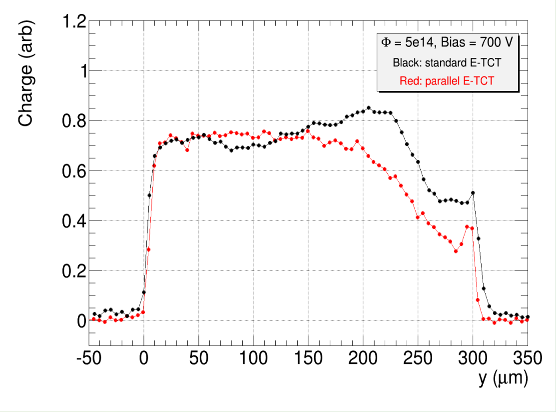


Calculated weighting potential

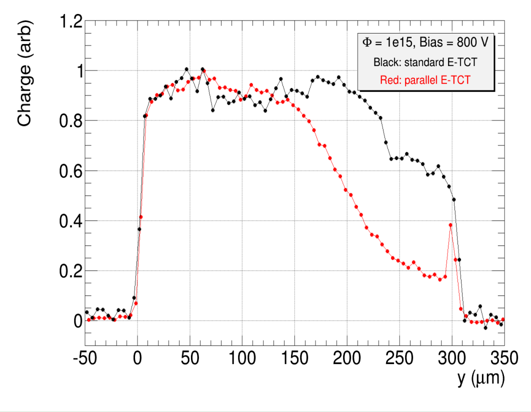


Charge collection, nonirradiated, U=100V

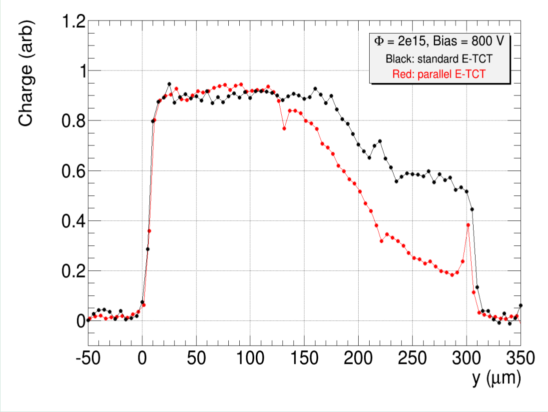
Collected charge, neutron irradiated detectors,



Φ_{eq} = 5 10^{14} cm^{-2}



Φ_{eq} = 10^{15} cm^{-2}

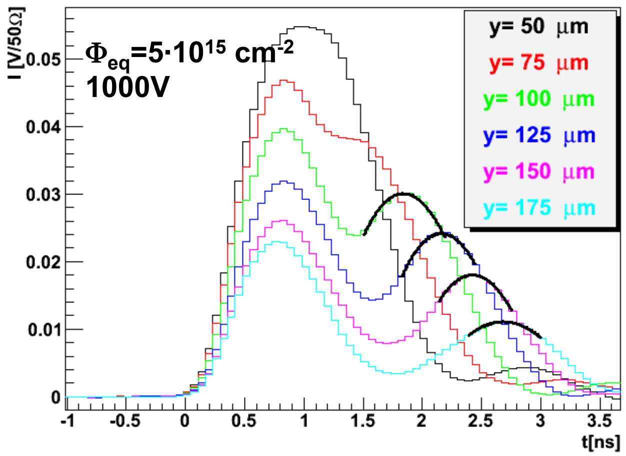


Φ_{eq} = 2 10^{15} cm^{-2}

red – parallel TCT, black standard TCT

- standard E-TCT measurements overestimate the contribution from larger detector depths.
- standard E-TCT is recommended for measurement of velocity profile because it has more uniform weighting field in the strip detector
- parallel E-TCT should be used to measure charge collection profiles to predict performance of irradiated strip detectors in charge particle tracking experiments.

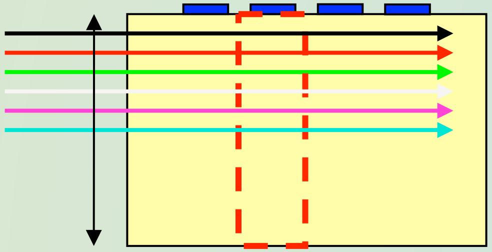
Modeling of the electric field with edge TCT

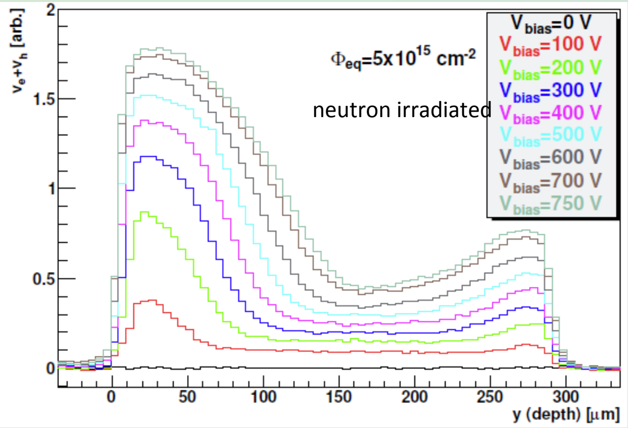


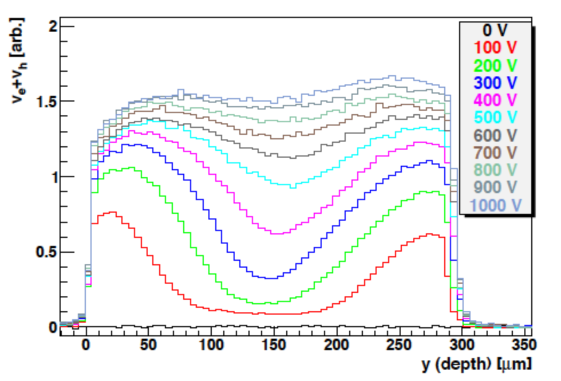
Shape of current pulse – multiplication !!!

G. Kramberger et al. IEEE Trans Nucl. Sci. NS-57 (2010) 2294

$$I(y,t\sim 0)\propto v_e+v_h$$







(b)

Pion irradiated
Φ_{eq} = 1.6 10^{15} cm^{-2}

Velocity profile in irradiated silicon detector ↔ field modeling

- Active SC region
- Neutral bulk with electric field
- Back SC region
- Different field shape in neutron and pion irradiated sensor
  G. Kramberger et al. JINST 9 2014 P10016

Conclusions

- TCT is a powerful tool to study material properties on pad detectors.
- Scanning-TCT systems proved to be very useful to study properties of segmented detectors and gave important information about charge collection, electric field, velocity profile, effective dopant concentration …before and after irradiation
- Systems have become commercially available