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TCT technique as the input for simulations

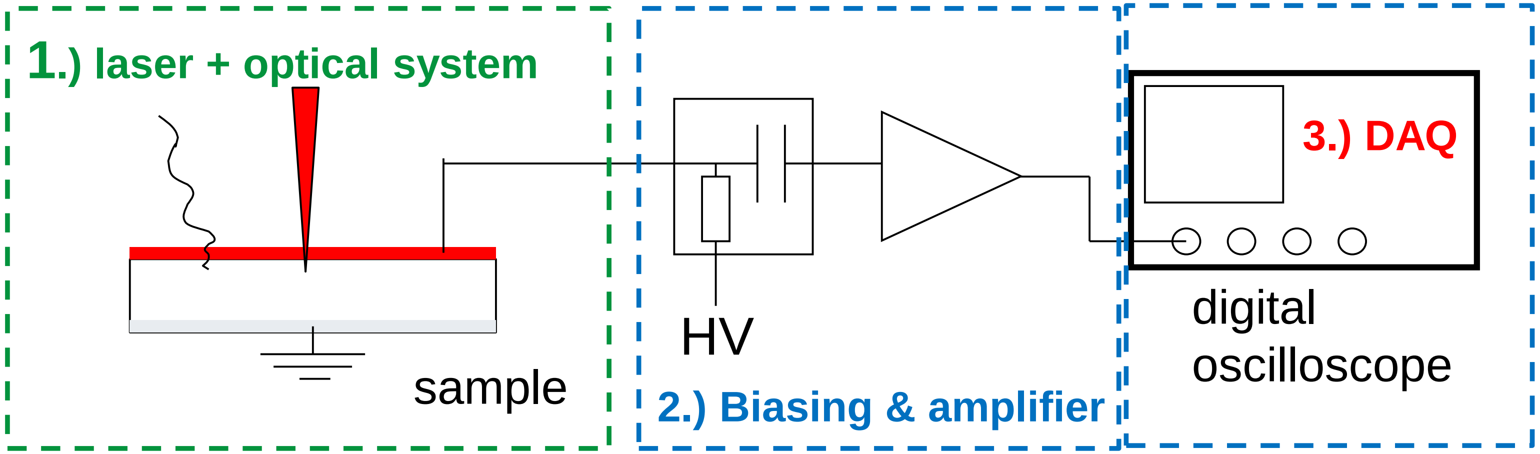
G. KRAMBERGER,

JOŽEF STEFAN INSTITUTE, LJUBLJANA

Motivation

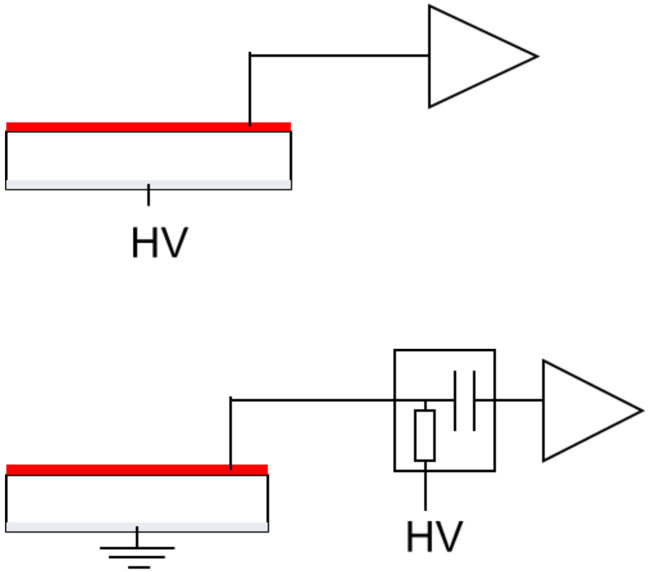
- Transient current technique (observing effects of non-equilibrium carriers in different devices) dates in the 1960s.
- From 1990s on the technique was widely used in studies of semiconductor detectors – materials, mostly pad detectors after irradiation
  - space charge
  - effective trapping times
  - charge collection efficiency
- In last decade the use of Scanning-TCT (focused laser beam) combined with new ways of using it has become a very useful tool to study segmented devices (examples will be shown).
- A new tool TPA-TCT (two photon absorption TCT) is becoming more widely used and will expand the possibilities further.
- The aim of this presentation is to:
  - Explain some basics of TCT pointing to the important details
  - Review different ways of using TCT

Basic principles of operation



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 multi-channel operation



TCT measurement - monitor the **current induced** by motion of carriers rather than only **charge** (usual way of detector operation in particle physics).

The price is the sensitivity – much more generated charge is needed for detection – mip particles can not/are more difficult to measure in sensors without the internal gain.

Usually light is used to generate e-h pairs, but can be also α, μ–beam.

Basic principles of operation (lasers)

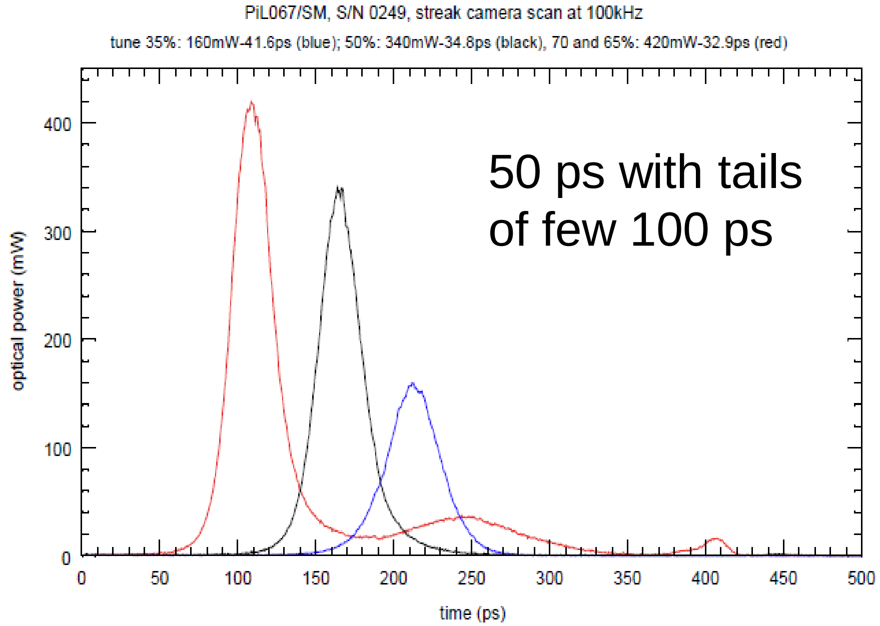
Creation of charge by laser has many advantages over the particles:

- averaging (no problem with noise)
- triggering (exactly known time of laser pulse)
- generation depth can be tuned by wavelength
- intensity tuning **– but hard to have absolute scale**
- controllable beam position

Laser pulse should be as short as possible (v_{sat}=100 μm/ns, pulse<<1ns), but,

- pay attention to long tails (can depend on power and wavelength) – high power is needed for certain applications
- jitter (pulse-trigger) is very important and can effectively spoil the resolution
- no need to go extremely “short” if other parts of your system are not fast enough
- Variable **pulse width and fast repetition rate** can be useful in several studies (rate effects, trapping/detrapping)
- Stability

- But also disadvantage over the α, μ–beam:
  - use for wide band gap semiconductors difficult **$E_g<h\nu$ (hard to get fast pulsed lasers)**
  - effects of field screening – plasma/ recombination, particularly of importance when focused to few μm
  - the structure needs to have opening in the metallization – can not study all the volume
  - laser pulse is not infinitely short


PiL067/SM, S/N 0249, streak camera scan at 100kHz

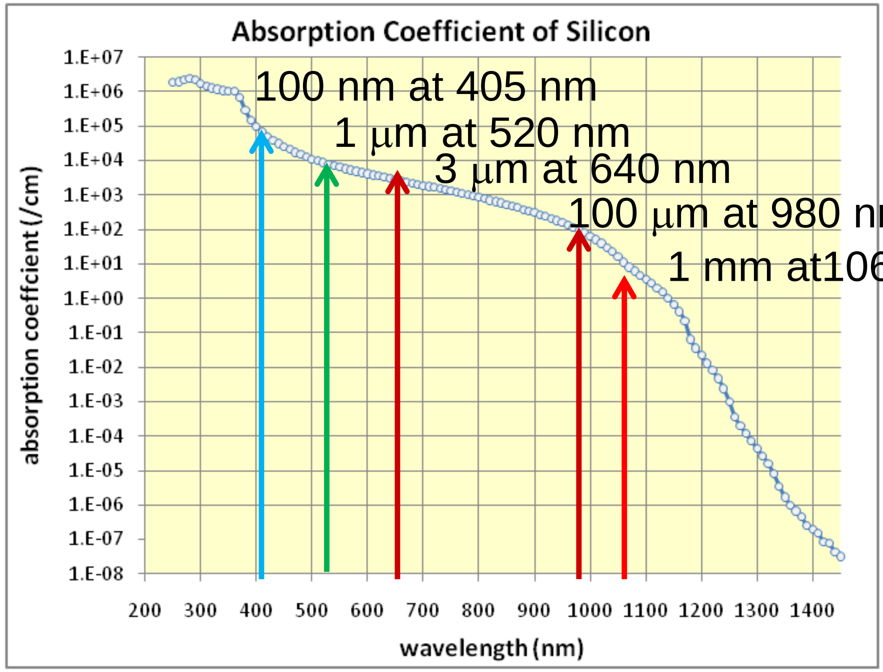
tune 35%: 160mW-41.6ps (blue); 50%: 340mW-34.8ps (black), 70 and 65%: 420mW-32.9ps (red)

50 ps with tails of few 100 ps

Basic principles of operation (lasers)

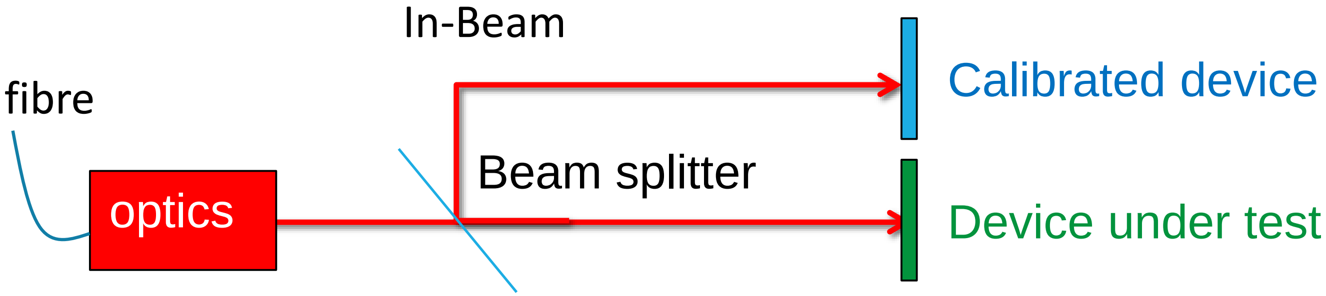
Light absorption in Si:
- mip like 1064 nm
- μ beam like 980 nm
- near surface 660 nm
- surface 405

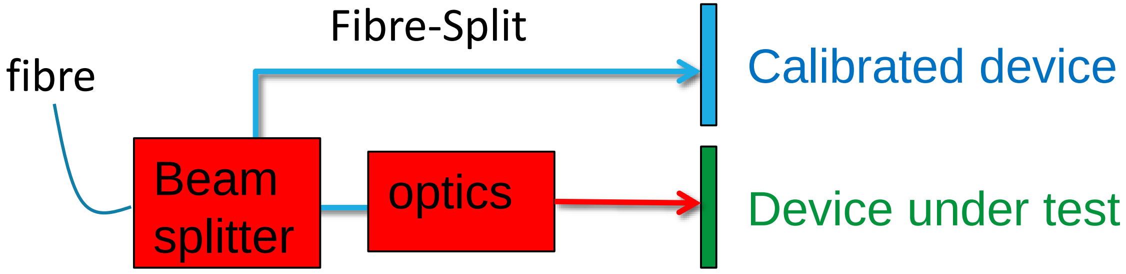
In other materials:
SiC – ~3-3.4 eV (>405 nm)
C – 5.5 eV (223 nm)



Absolute calibration and laser intensity

- Apart from relative comparison of waveforms at different position/bias/T, absolute measurements can/could be performed with calibrated device)
- Two different approaches – “in-beam” and “fibre-split”
- Adjustment of intensity with neutral density filter if pulses are distorted at different pulse energies





Basic principles of operation (signal)

$$I_{e,h}(t) = e_0 \cdot N_{e-h} \cdot \exp(-t/\tau_{eff,e,h}) \cdot \vec{E}_w \cdot \vec{v}_{e,h}(t)$$

Multiplication/
Recombination

trapping

detector
geometry

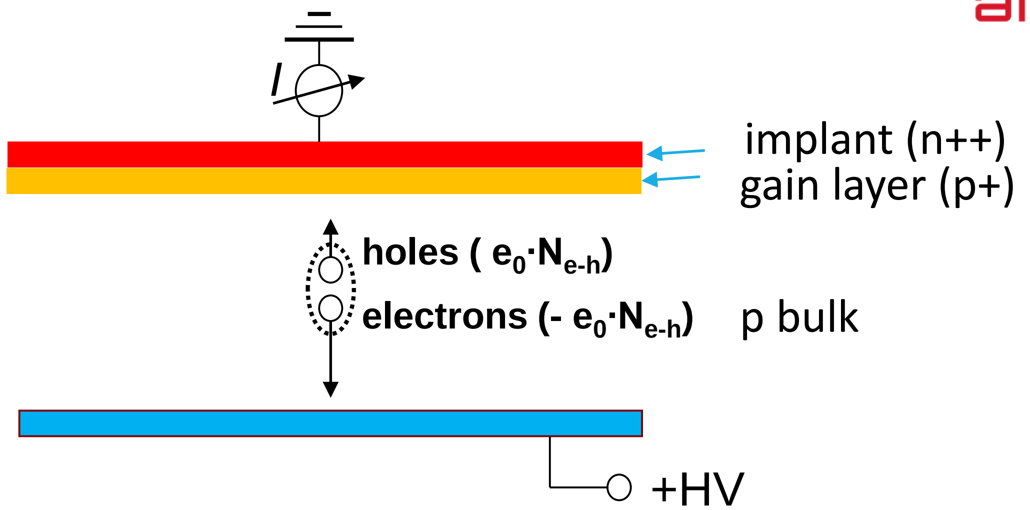
electric field

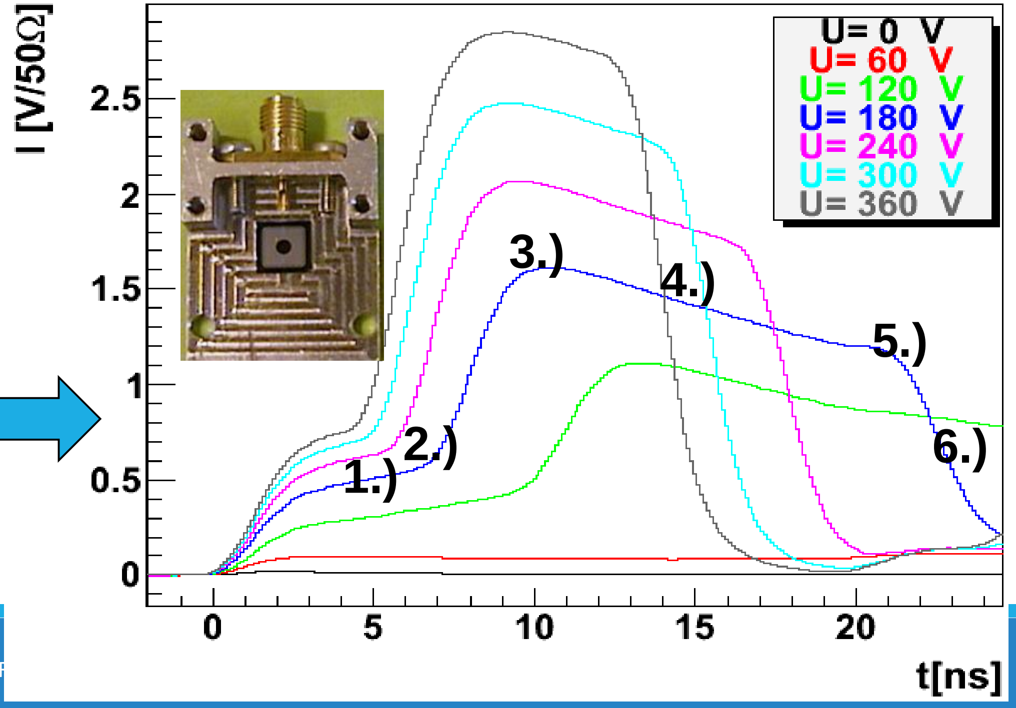
$$I(t) = I_e(t) + I_h(t)$$

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

Example – 300 μm LGAD

- 1.) drift of electrons
- 2.) onset of multiplication
- 3.) end of multiplication
- 4.) drift of holes
- 5.) end holes drift
- 6.) tail (diffusion + electronics)





electron injection with 660 nm at the back

Basic principles of operation (analysis)

Transfer function of electronics is crucial and depends on many things – mostly on amplifier, bias-T, oscilloscope (can be measured with very thin sample 25 μm where the current pulse is very short)

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

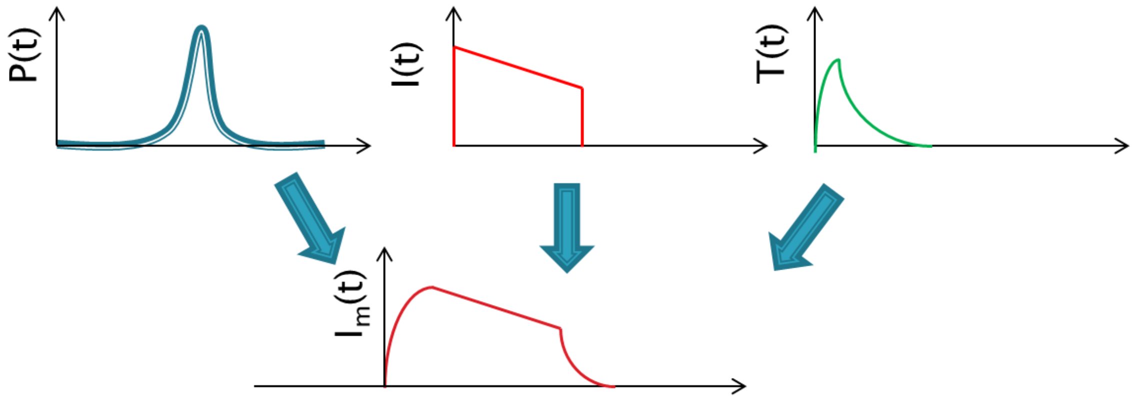
measured

transfer function

induced current

laser pulse

$$I(t) = FT^{-1}\left(\frac{FT(I_m)}{FT(P)FT(T)}\right)$$



In general a complicated task to extract *I(t)* from the measured current. For most of the systems roughly the following two assumptions can be made:

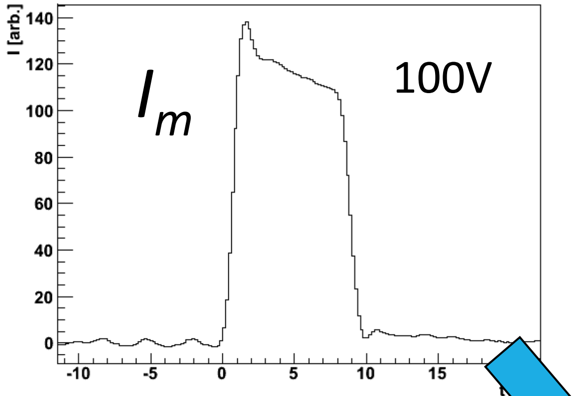
$$T(t) = \frac{A}{\tau_{RC}}\exp(-t/\tau_{RC}) \qquad P(t) = B\delta(t)$$

R=input impedance of the amp.
C=connected electrode capacitance

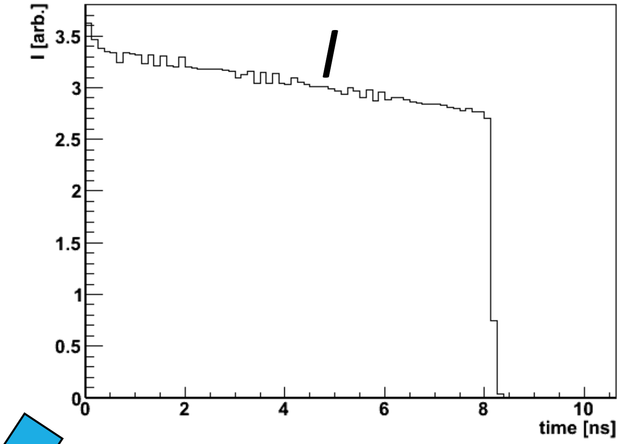
which allow for solution in time domain (no need for FT)

If, however, you are looking in effects on timescale longer that few 100 ps: $I_m(t) \sim I(t)$

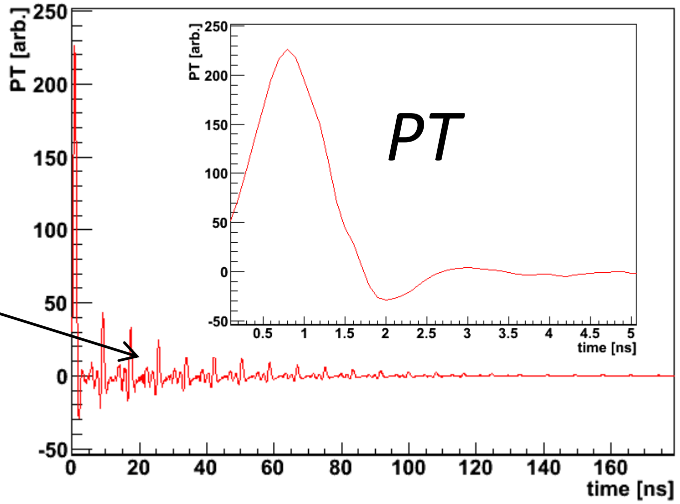
Basic principles of operation (analysis)

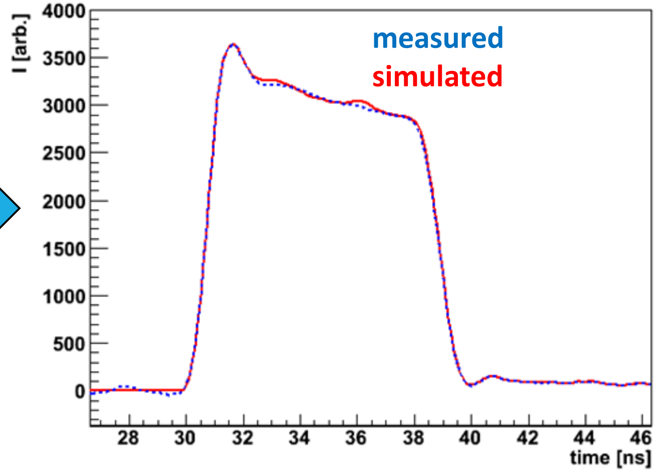


300 μm p-n pad detector (n bulk)
15 kΩ cm material (V_{fd}~20V)
I_m=measured current with TCT
I=simulated/calculated current with KDetSim



higher harmonics





The problem is that for very fast signals even the bond length (inductance) and sensor capacitance, bulk resistance change the transfer function and it is often difficult to use the same "PT" to extract the induced current.

Conventional-TCT (pad detectors/material studies)

Space charge/electric field (double junction/space charge inversion):

V. Eremin et al, Nucl. Instr. and Meth. A 372 (1996) 388.

+ 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.

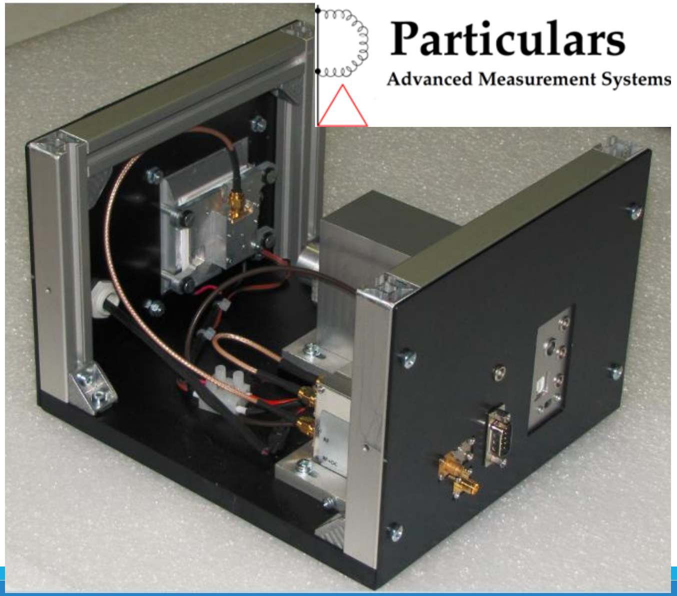
+long list

Detrapping times

G. Kramberger et al JINST 7 (2012) P04006

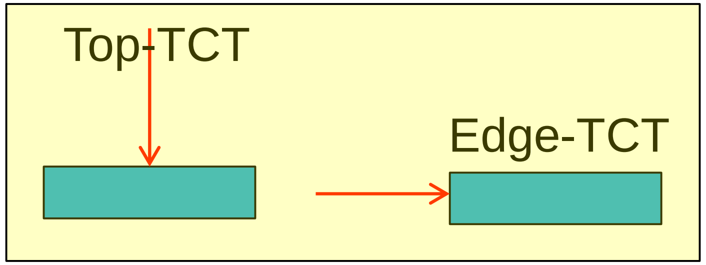
The material properties are extracted from the pad detector (E_w=1/D) and from the time evolution of the signal I(t).

$$I = e_0 N_{e-h} \exp\left(-\frac{t}{\tau_{eff\,e,h}}\right) v(t)$$

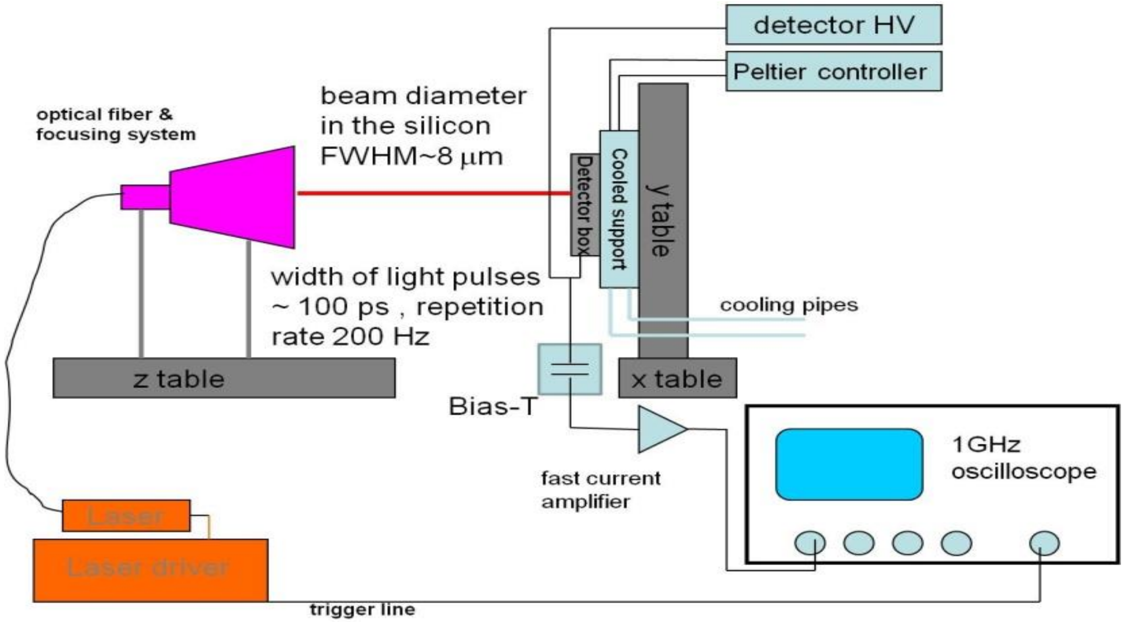


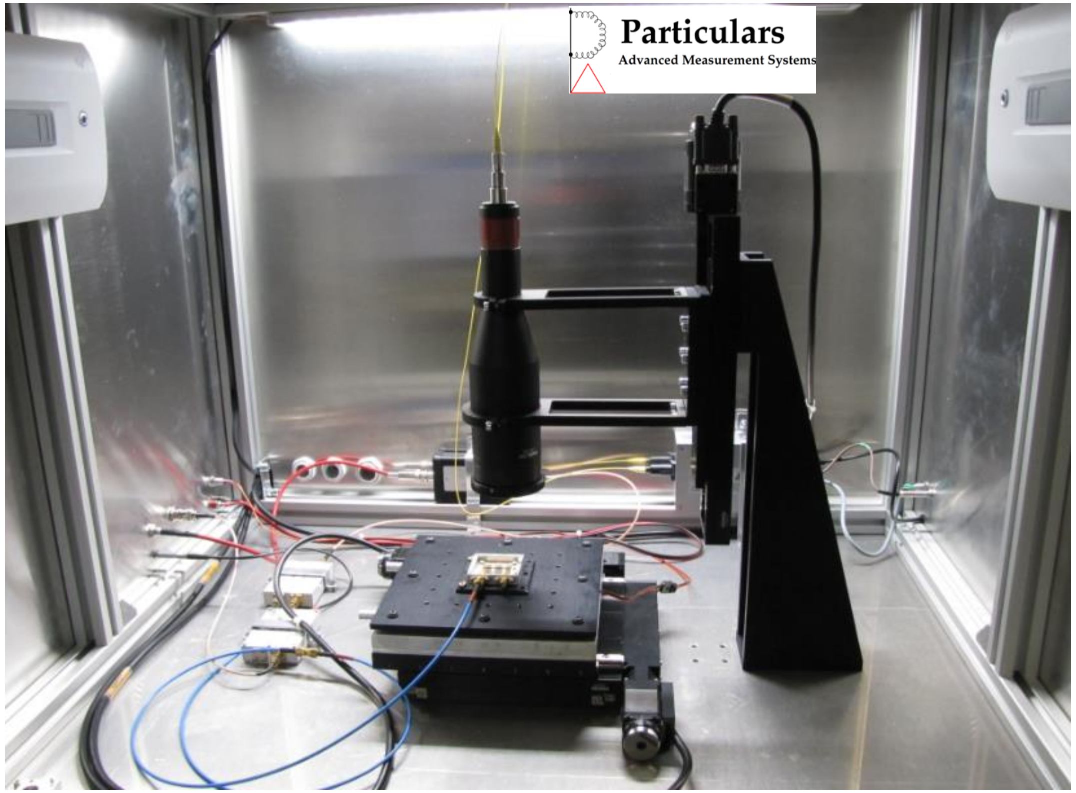
Scanning TCT system

A position resolved TCT
Two modes of operation: Top-TCT and Edge-TCT:



FWHM:
~8-10 μm for 1064 nm
~6-7 μm for 660 nm
~5 μm for 405 nm

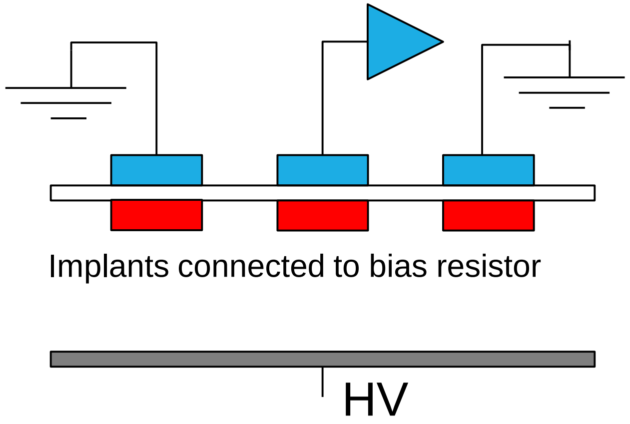




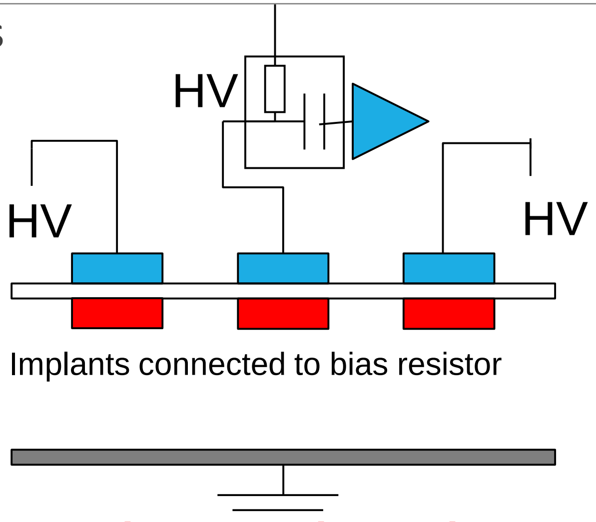
- Most of the system use fiber coupled lasers (no need to correct for astigmatism)
- The thinner the core the better focus can be achieved (4 μm is standard)
- Refractive index helps to achieve narrower beam width in Si than measured at the surface

Connections in multi-electrode systems

Remember E_w plays a role in operation of silicon detectors



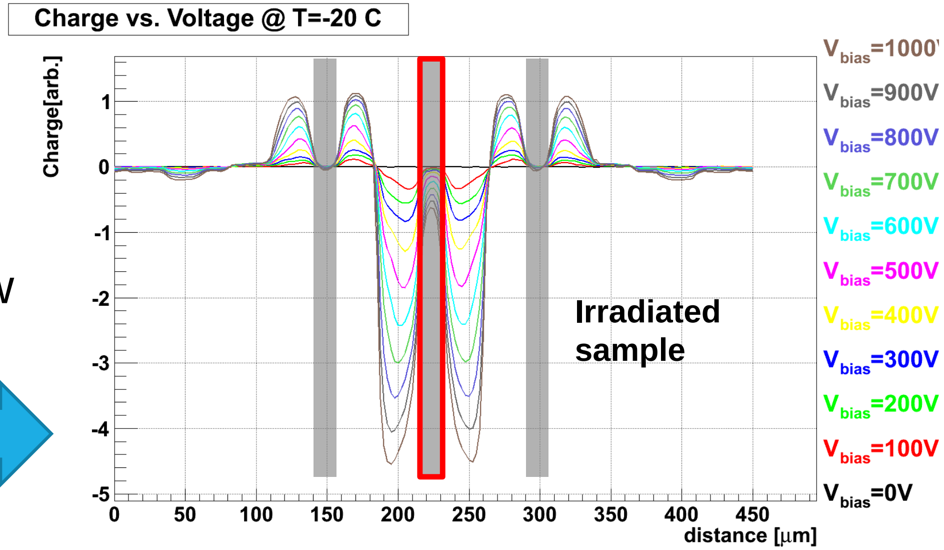
Implants connected to bias resistor

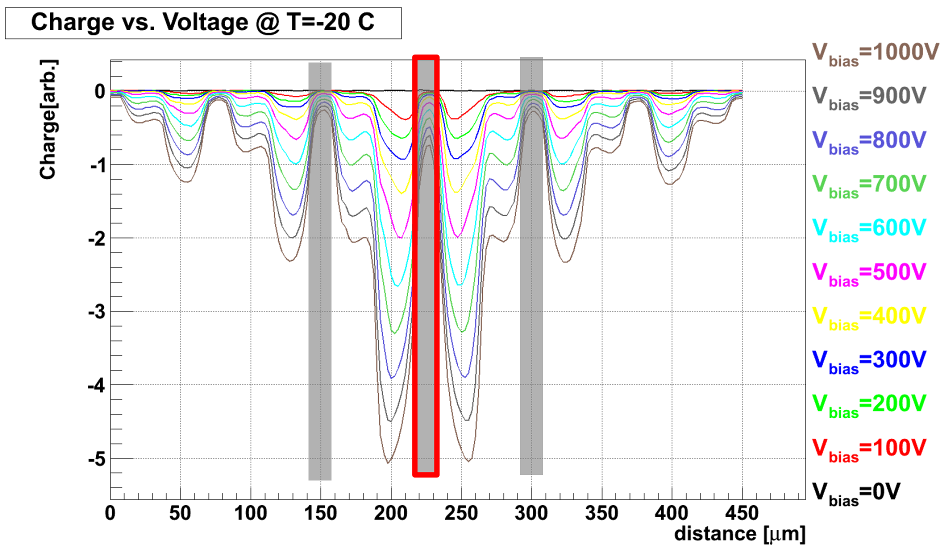


Implants connected to bias resistor

Always bond neighboring strips – otherwise they act as interpolation strips!

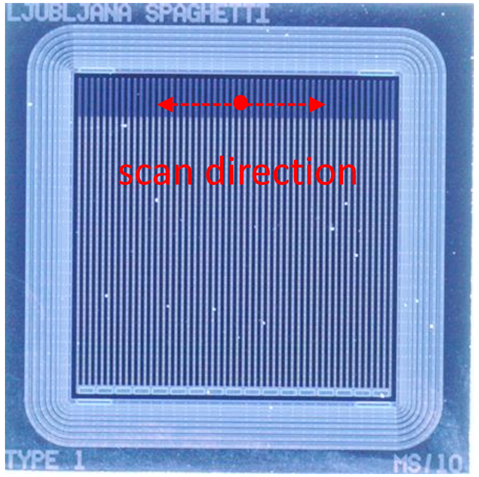
Neighbors bonded to low impedance

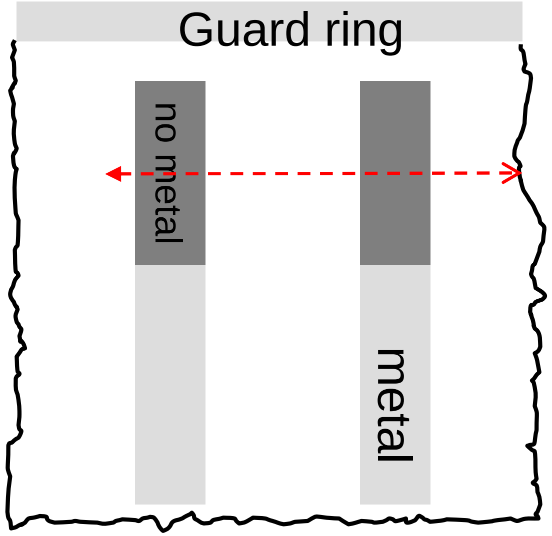




Neighbors not bonded

Examples of applications (strip profiling)

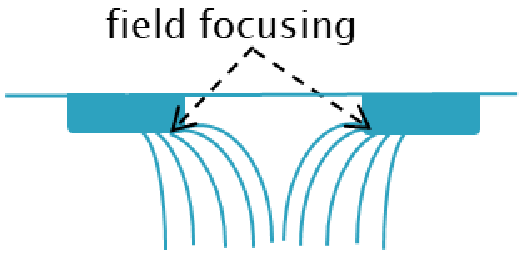


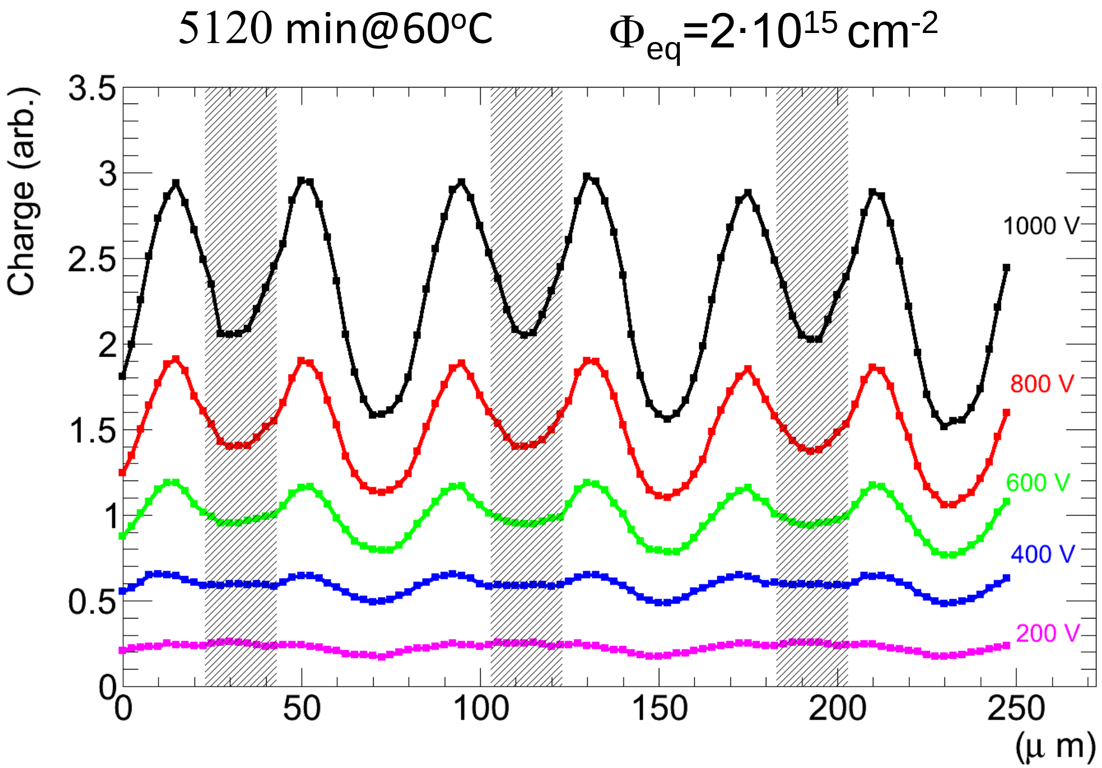


5x5 mm^2 spaghetti diodes
E_w similar to diode
E equal to strip sensor
All strips ganged together.

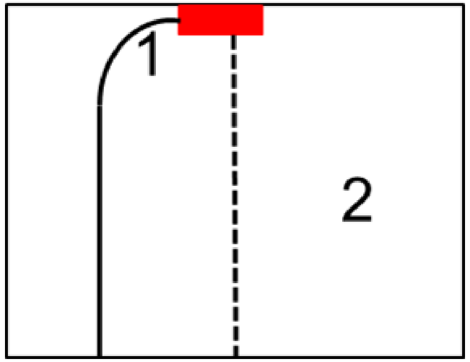
charge collection profiles:

- enhanced multiplication at the edge of implants
- Non-uniform charge collection along the strips



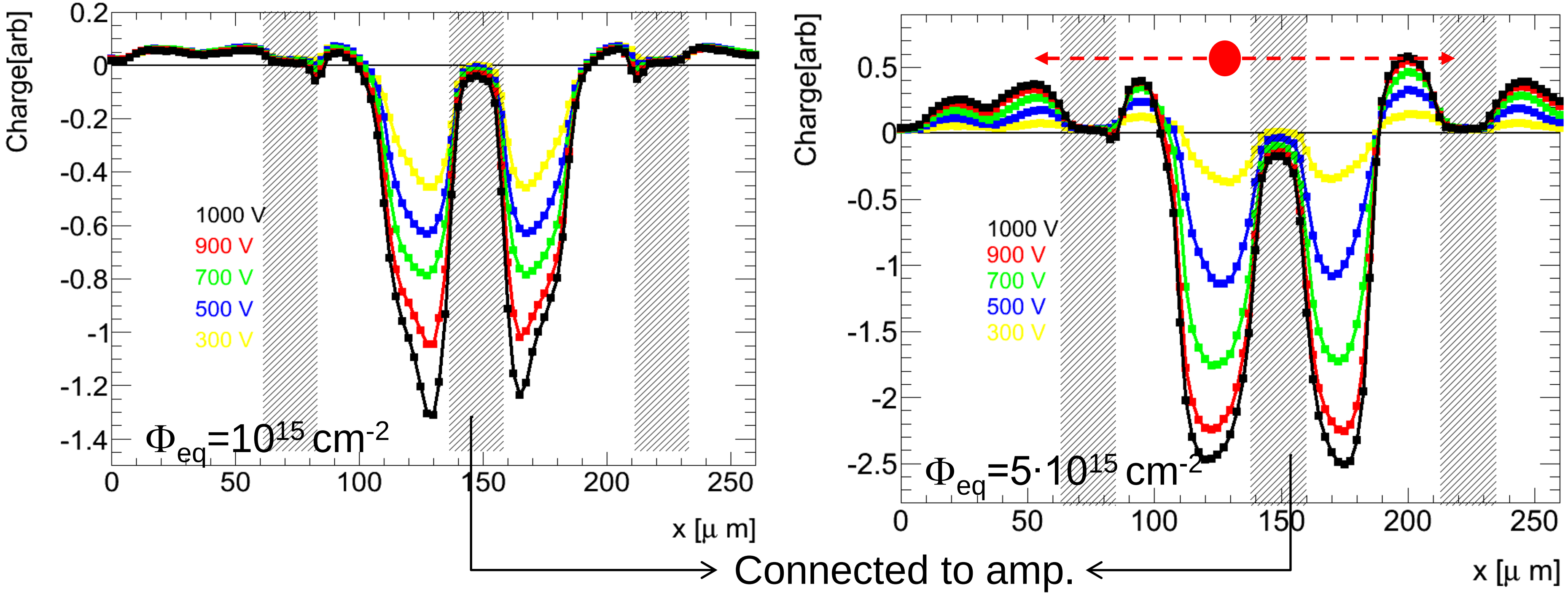


Examples of applications (strip profiling)



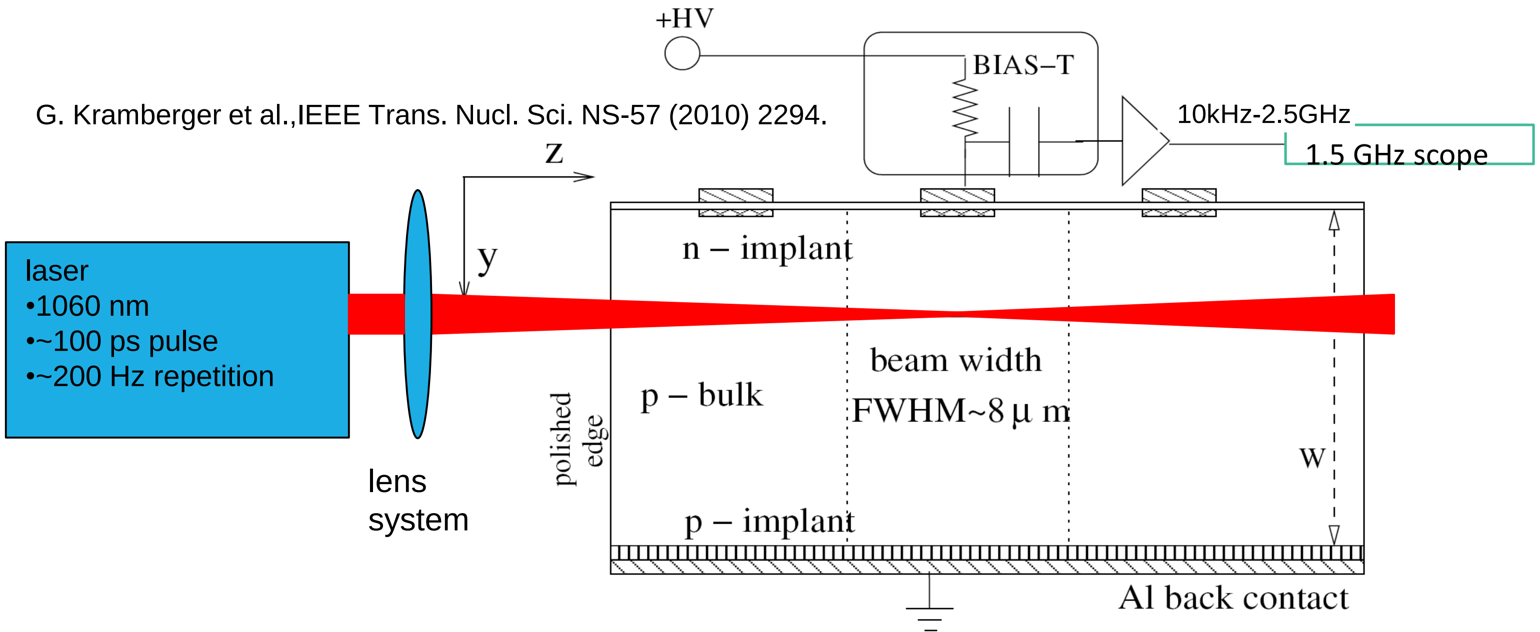
Observation of “Trapping induced charge sharing“ – non complete drift results in charge induced in other strips – for p-type detectors it is of the opposite polarity (G. Kramberger et al., IEEE Trans. NS 49(4) (2002) 1717)

The induced charge in the inter-strip region becomes larger than close to the strips – field focusing and more multiplication (I. Mandić et al., 2013 JINST 8 P04016)



Connected to amp.

Edge-TCT



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

$$\boxed{I(y,t) = I_e(y,t)+I_h(y,t) \approx e_0\, N_{e-h}\,\frac{1}{W}\left[v_e(y_e(t))\,e^{-t/\tau_{eff,e}} + v_h(y_h(t))\,e^{-t/\tau_{eff,h}}\right]}$$

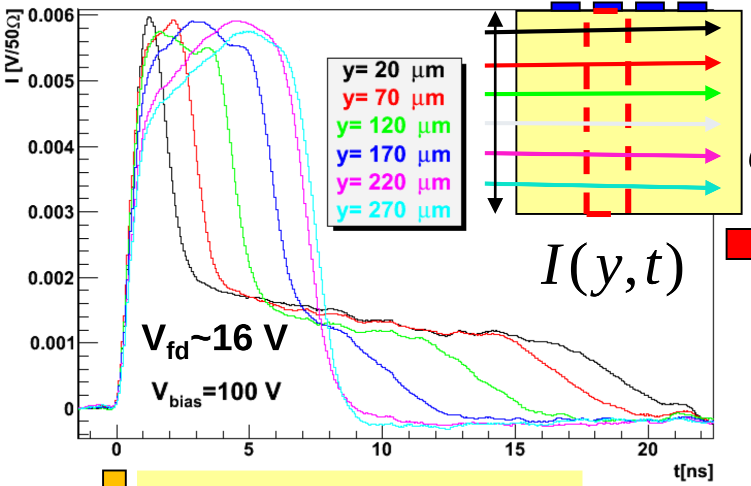
$$I(y,t\sim 0)\approx \overset{\text{Constant}}{\frac{Ae_0N_{e,h}}{W}}\left[\bar{v}_e(y)+\bar{v}_h(y)\right] \quad , \quad t \ll \tau_{eff,e,h}$$

The trapping can be completely taken out of the equation!

(The major obstacle of extraction of physics parameters from time evolution in conventional/Top-TCT is severe trapping)

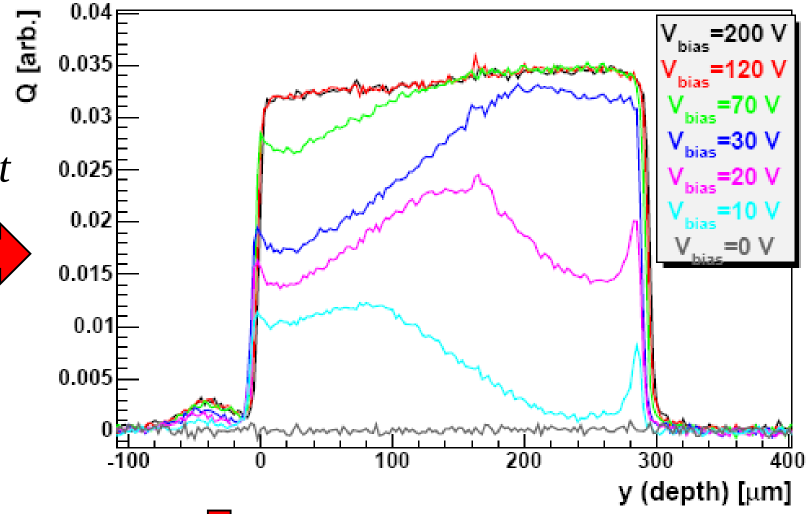
Charge collection and velocity profiles

G. Kramberger et al., IEEE TNS, VOL. 57, NO. 4 (2010) 2294.



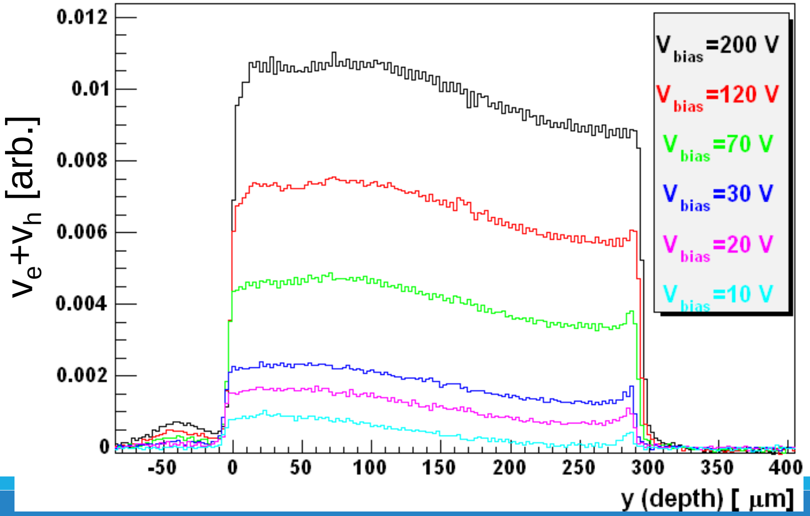
$$Q(y)=\int_0^{25ns} I(y,t)\,dt$$

CHARGE COLLECTION PROFILE

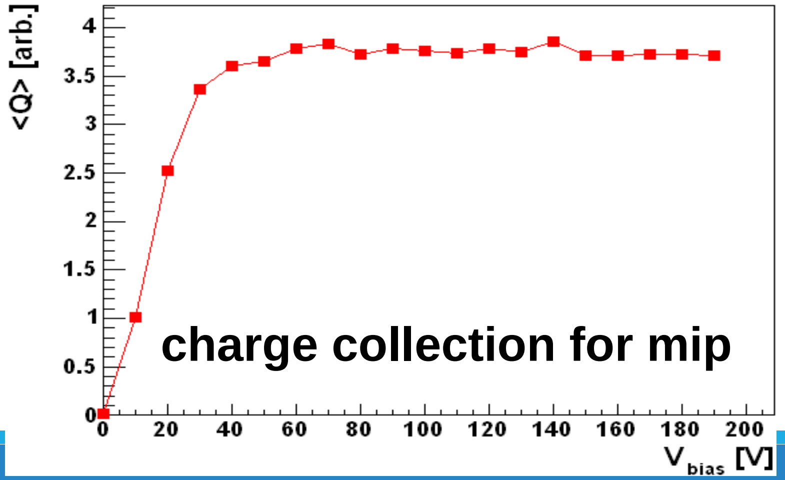


$$I(y,t\sim 0)\propto v_e+v_h$$

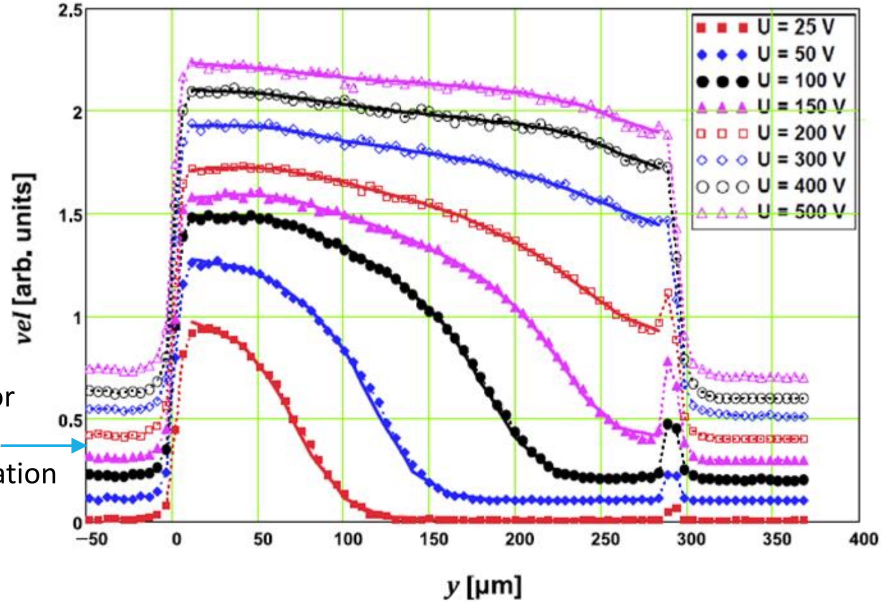
VELOCITY PROFILE



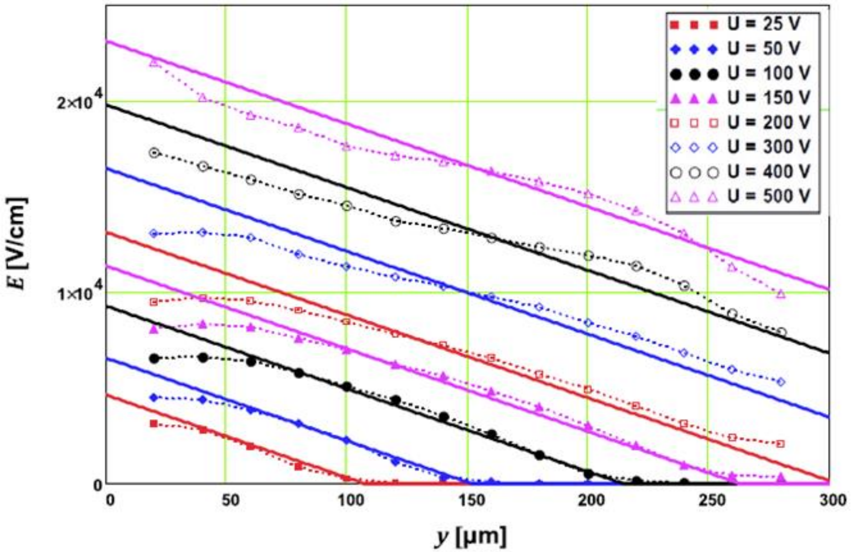
$$Q_{mip}\propto\langle Q\rangle=\int_0^W Q(y)\,dy$$



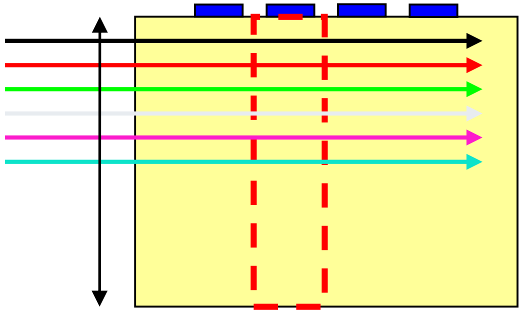
Examples of applications (E-TCT on strips)



Offset for easier presentation



R. Klanner et al,
NIMA 951 (2020) 162987



ATLAS07 samples Pitch 80 µm
Implant width 20 µm
Thickness 300 µm

$$\chi^2 = \frac{1}{\sigma_{vel}^2}\sum_{k=1}^{n_k}\left(1 - \frac{vel_k}{vscale \cdot u_k}\right)^2 + w_{pen}\sum_{i=2}^{n_E-1}\left(\frac{0.5\cdot(E_{i-1}+E_{i+1}) - E_i}{E_i}\right)^2$$

$$u_k = \left(\mu_h(E_k) + \mu_e(E_k)\right)\cdot E_k$$

Constrain:

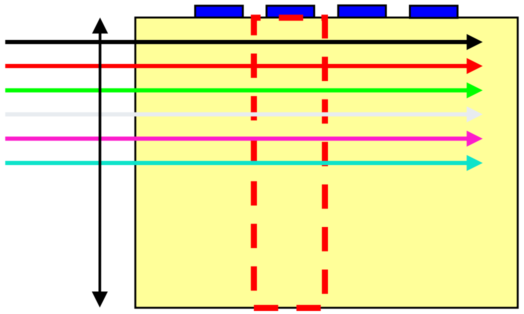
$$\int_0^d E(y)\,\mathrm{d}y = U$$

σ_{vel} – *relative uncertainty of velocities ~ 2%*
vel_k -measured velocity profiles
v_{scale} – measured scale is relative
w_{pen} – dumps large fluctuations of the field – not very important in the model, set to increase χ^2 by 50%

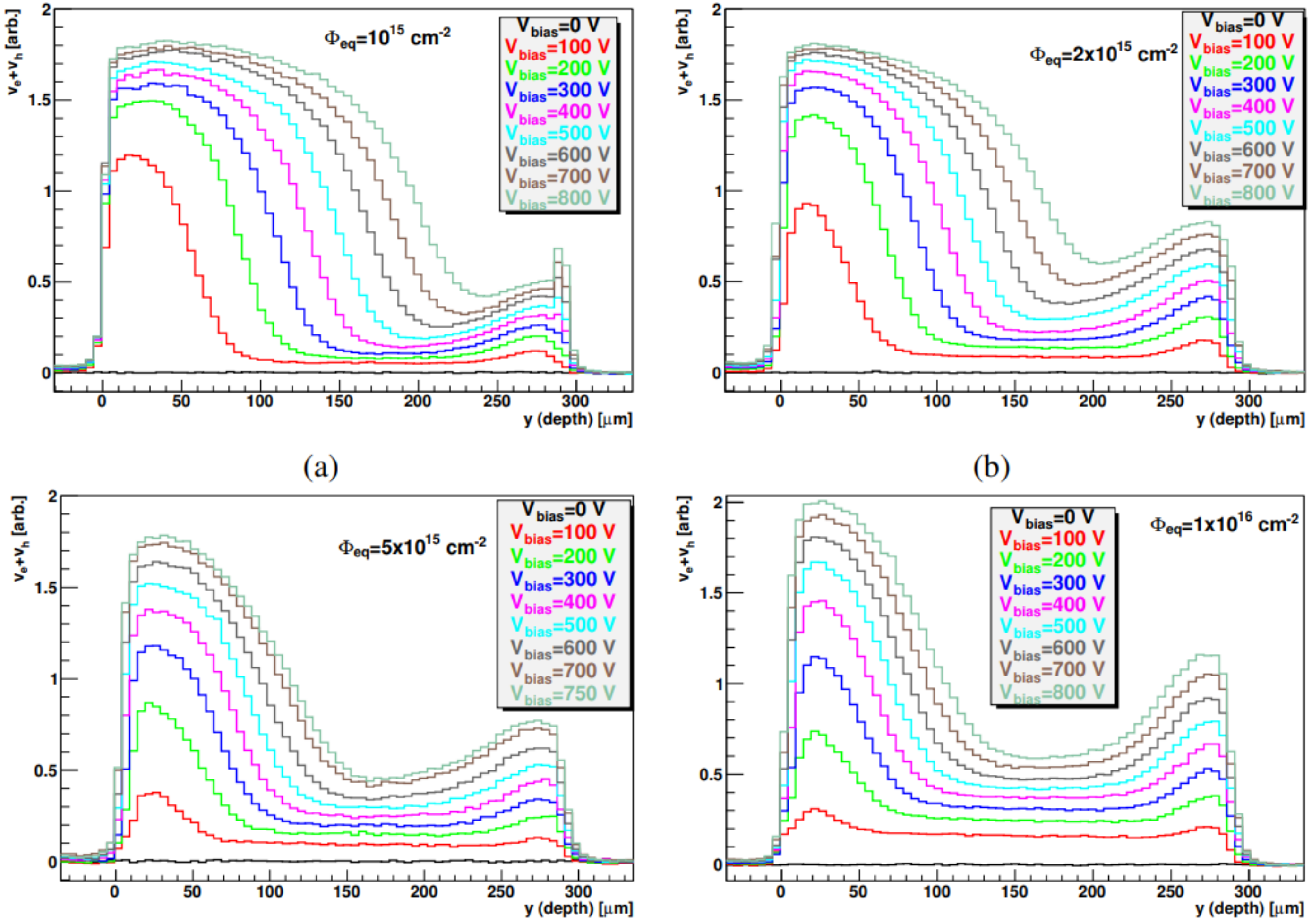
The constrain effectively also solves the cases where trapping is not negligible in comparison to t_{int} and $\tau_{eff} \neq \tau_{eff}(y)$

Examples of applications (E-TCT on strips)

G. Kramberger et al., JINST 9 (2014) P10016



ATLAS07 samples
Pitch 80 μm
Implant width 20 μm
Thickness 300 μm



(a) (b)

(c) (d)

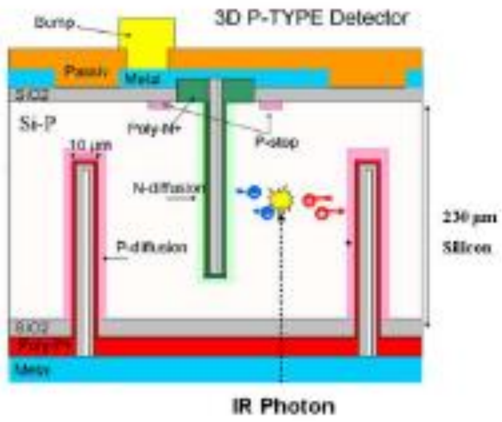
Velocity profile in **heavily irradiated silicon detector** – field modeling in irradiated silicon detectors

- Active SC region
- Neutral bulk
- Back SC region

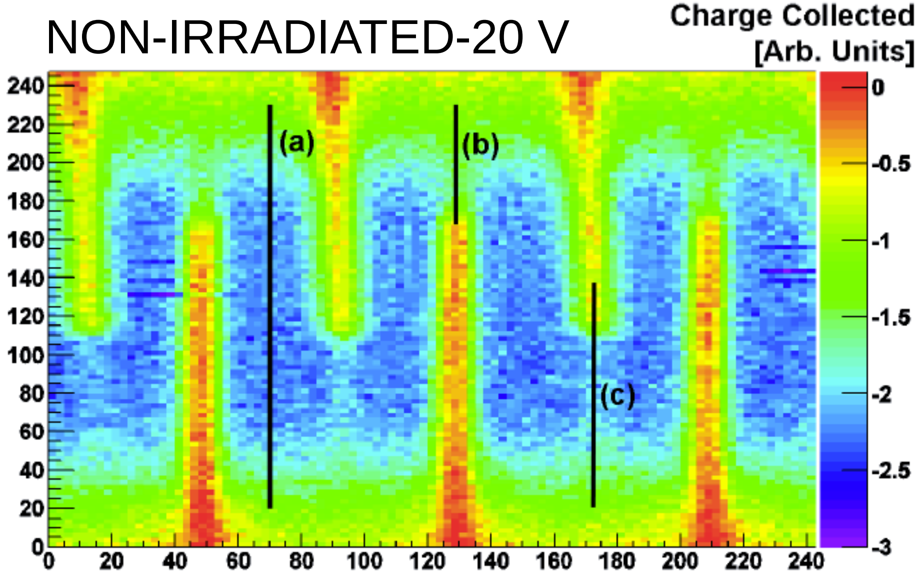
Reproduction of the profiles in simulations in a real challenge and benchmark for simulation model !

Examples of applications (3D detectors)

3Dstrip detectors processed by CNM
230 μm thick
Strip pitch 80 μm
Column width 10 μm
overlap= 150 μm
T=-20^{o}C



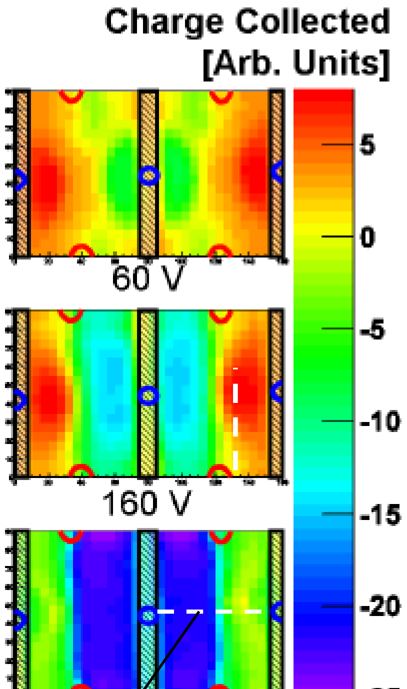
EDGE-TCT

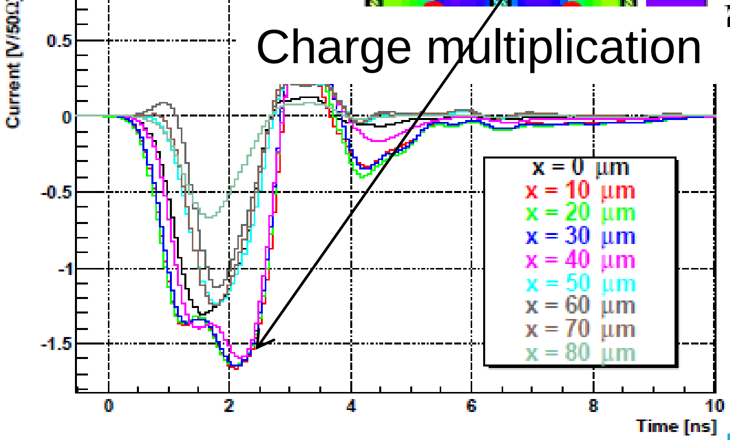


G. Stewart et al., JINST Vol. 7 (2013) .

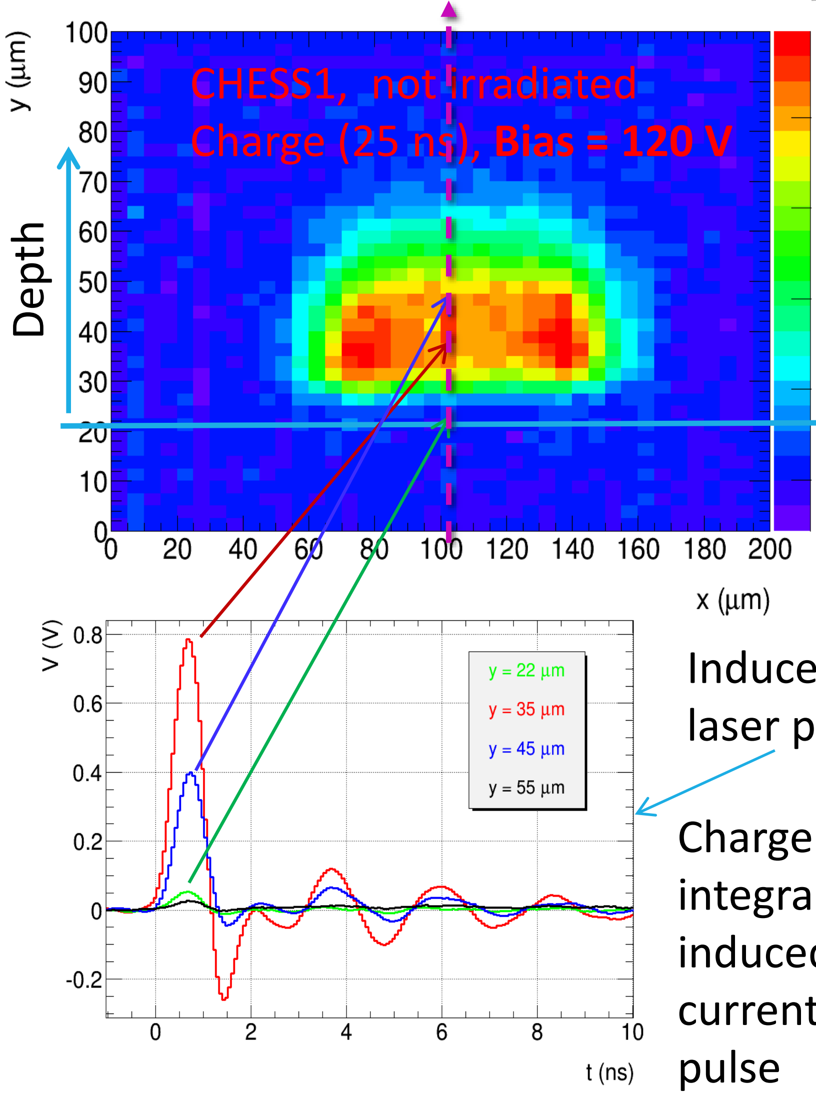
TOP-TCT

Φ_{eq}=5·10^{15} cm^{-2}
Profiling of CCE within the cell
Multiplication seen in induced current





Examples of applications (HVCMOS)



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

⊗

Laser beam direction

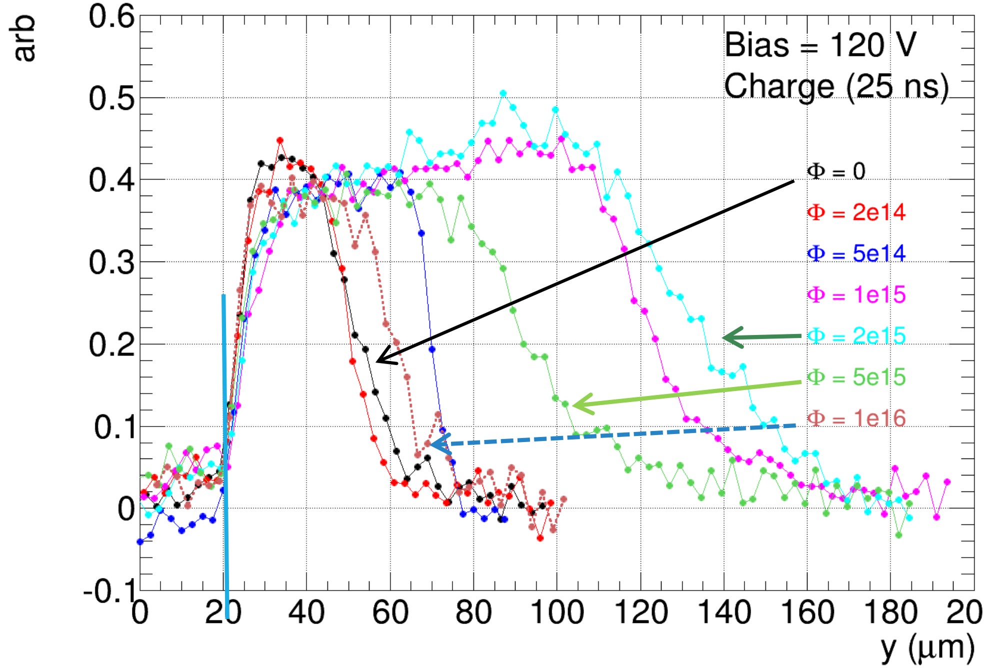
Chip surface

Induced current after laser pulse

Charge: integral of induced current pulse

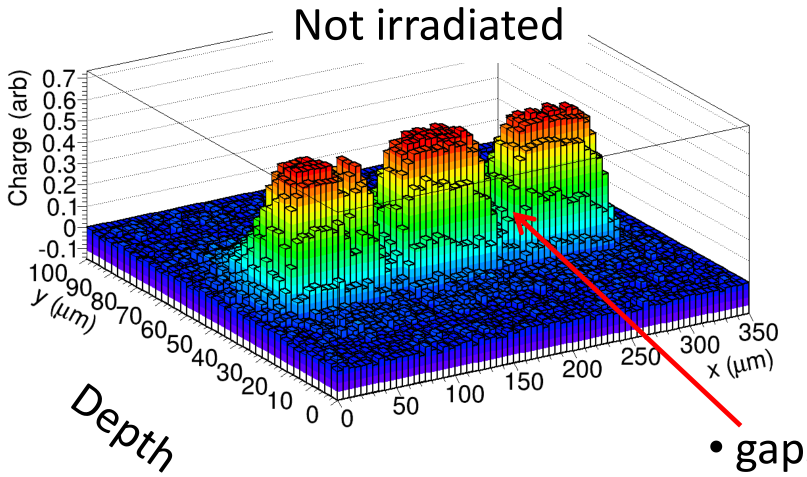
AMS (20 Ωcm)

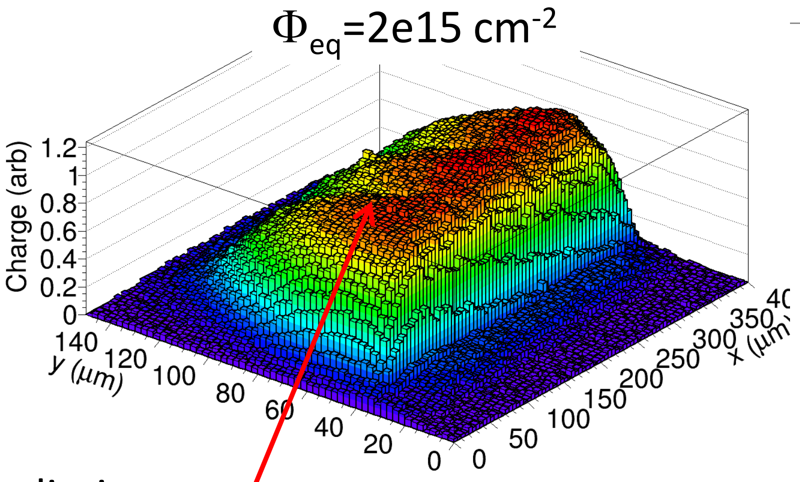
Chess1, irradiated with neutrons up to 1e16 n/cm2
Fluence steps: 2e14, 5e14, 1e15, 2e15, 5e15, 1e16



- charge collection width (depleted depth) increases with fluence up to ~ 2e15 cm^{-2}
  ➔ concentration of initial acceptors falls with irradiation faster than new acceptors are created
- collection depth gets smaller with larger fluence
  ➔ initial acceptor removal finished, space charge concentration increases with irradiation

Examples of applications (HVCMOS)

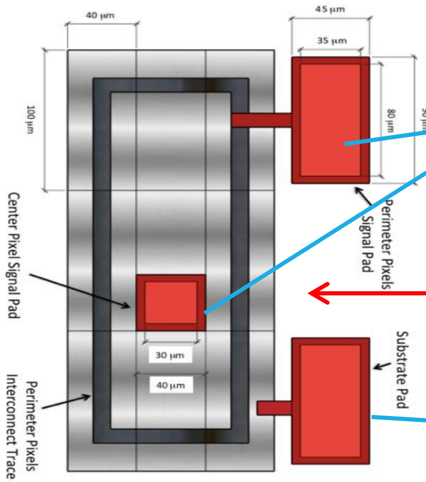




- gaps before irradiation
- guard ring gaps smaller after Φ_{eq}=2e15 cm^{-2}
- gaps better seen again after Φ_{eq}= 1e16 cm^{-2}

AMS (20 Ωcm)

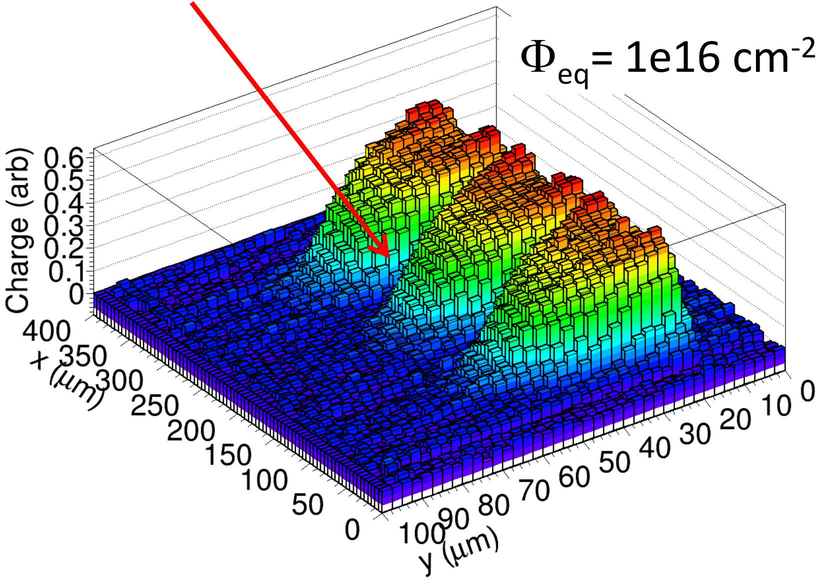
Bias = 120 V, all 9 pixels connected to readout



to HV and readout
(via Bias-T)

Beam

- to ground



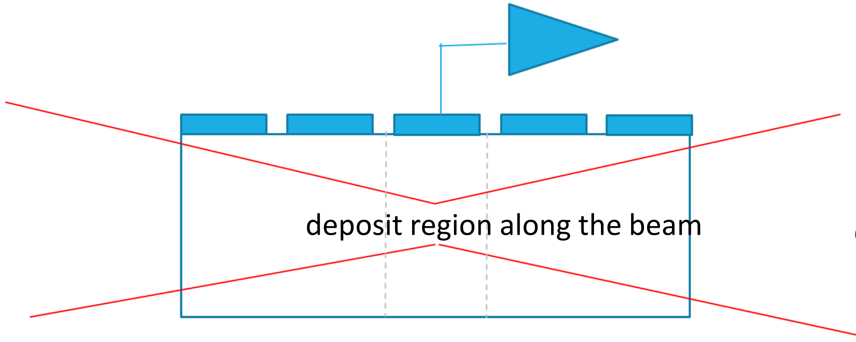
Two photon absorption TCT

- Standard - TCT rely on single photon absorption which can not produce spatially localized point ionization – a real 4D probing of the device is possible with tow photon absorption (TPA-TCT) *(I. Villa et al., RD50 workshop 2014 CERN)*

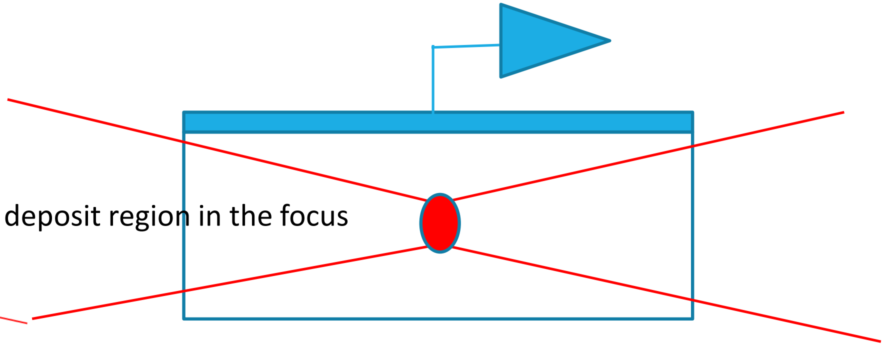
- TPA offers a solution – the beam is “compressed” in time (<250 fs) and space (~few μm) that not a single photon excites the electron from valence to conduction band but two/more - the energy of the photon is smaller than the band gap
  - Diamond TPA with ~405 nm *(APL Vol. 114 (2019) 203504)*
  - Silicon TPA ~1550 nm *(JINST 12 (2017) C01038, NIM A845 (2017) 69. , NIM A958 (2020) 162865 ….)*

- As the condition is fulfilled only in focal point the charge deposition is localized - advantages:
  - **no need to have finely segmented devices as for SPA in edge-TCT configuration**
  - **a localized deposition can be achieved also underneath the metal if approached through the back**
  - **the deposition of the charge is almost as short as the one from the particle**

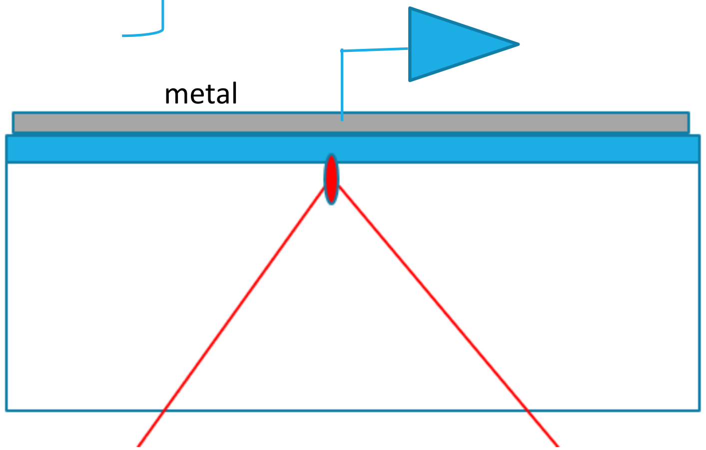
Table top lasers are becoming available
(IEEE TNS 68 (2021) p. 220)



SPA - edge TCT

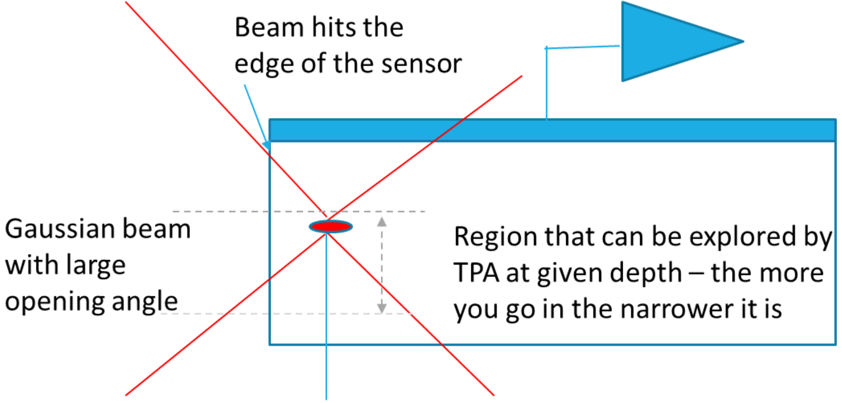


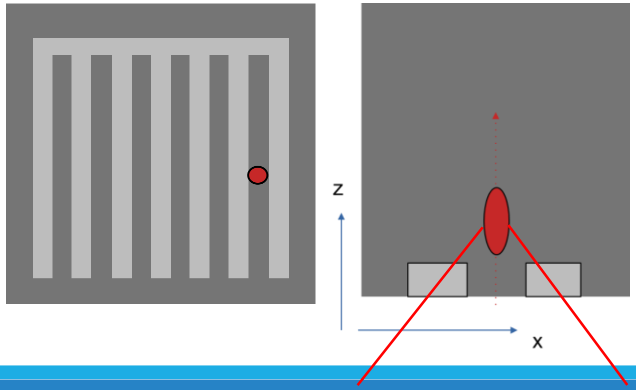
TPA – edge TCT

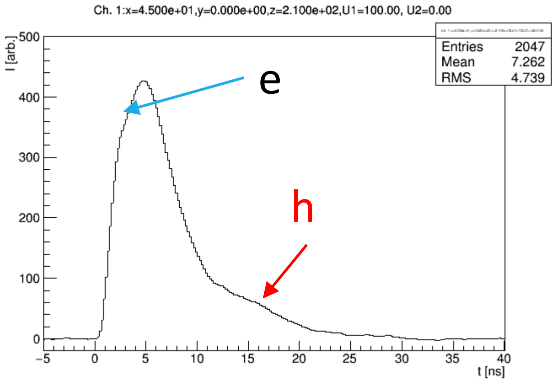


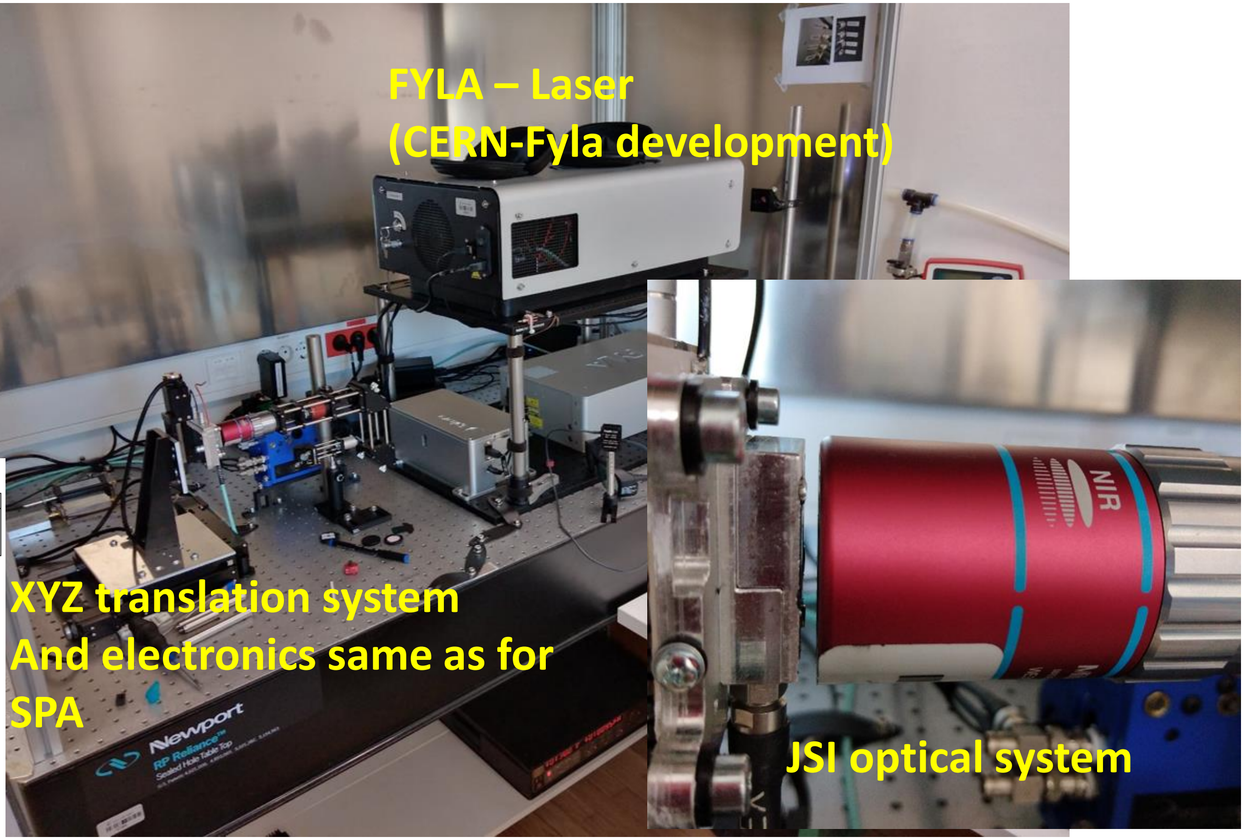
Two photon absorption TCT

- Difficulties:
  - Very good focusing requires wide angles so the reach of investigated area away from the device border is much smaller than for SPA – edge TCT
  - In irradiated devices the energy levels in the band gap will result in trap-band carrier excitations leading to SPA even if photon energy is below the band gap – different approaches are investigated on how to mitigate that (reference defocused signal subtraction …)
  - Affordability, availability and complexity of the system









Conclusions

- TCT has been around in HEP for almost 20 years, first as a tool used to study material properties on pad detectors. A workhorse of RD48/50 collaborations – lots of tools (software and hardware) around
- Conventional-TCT – ideal for pad detector and material studies mostly based on extraction of parameters from time evolution of the pulse
- Scanning-TCT systems are excellent tools to study properties of segmented detectors. Powerful analysis techniques have evolved along. There are plenty of measurements which should serve as a reference for simulations – much larger abundance of information wrt. to simple CCE/test beam measurements.
- TPA-TCT – the future of TCT, but can it is complementary tool to Scanning SPA TCT, rather than its replacement.