Theoretical background for measurements

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Outline

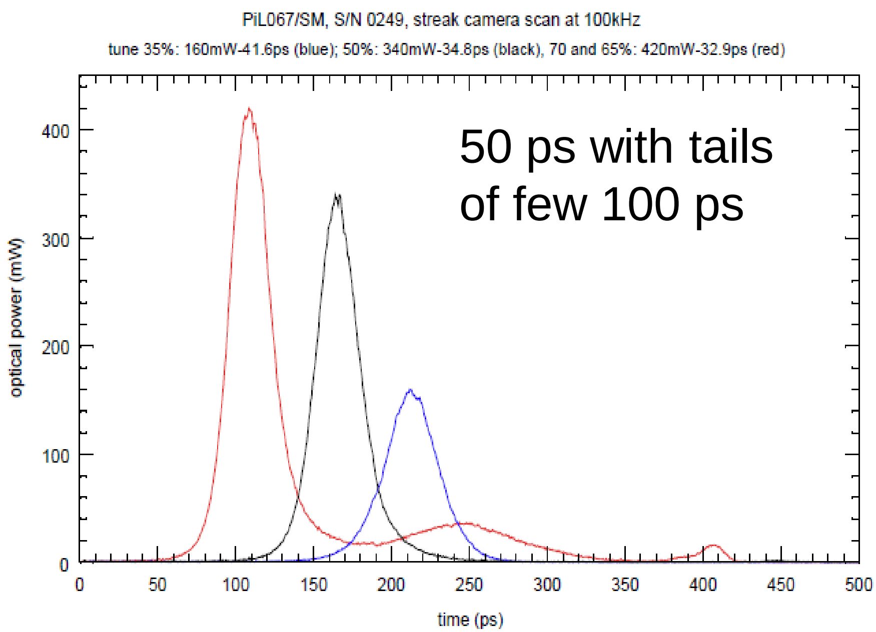
- Basic principles of operation
- Top-TCT
  - Pad diodes
  - Example of strip detectors
- Edge-TCT
- Beyond high energy physics
- Conclusions

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<hν (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

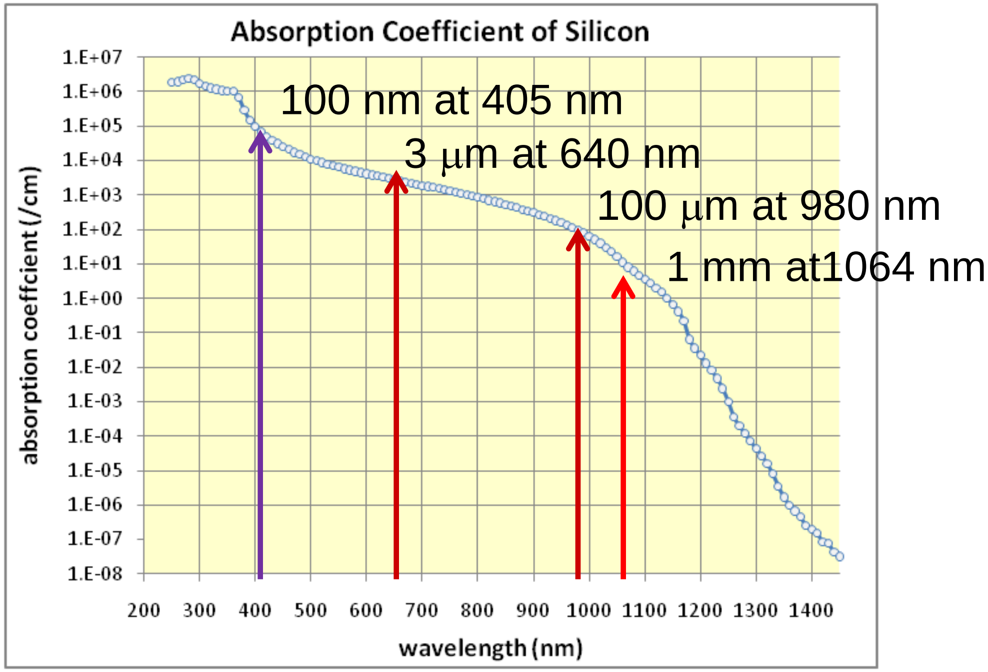


Basic principles of operation (lasers)

Light absorption in Si:

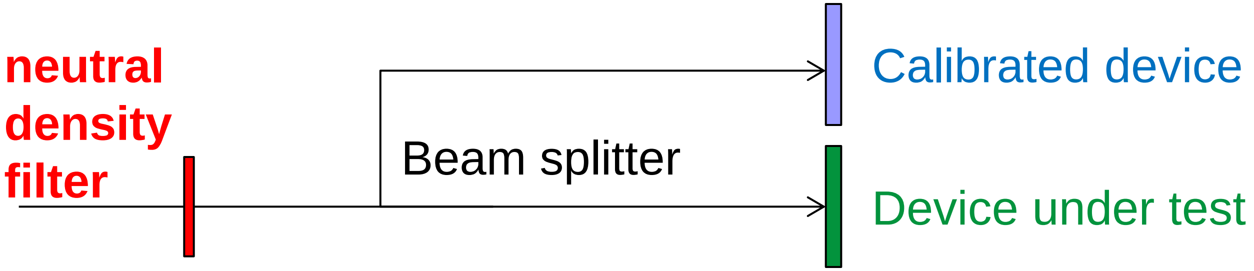
- mip like 1064 nm
- μ beam like 980 nm
- near surface 660 nm
- surface 405

In other materials:
SiC – ~3-3.2 eV (405 nm)
C – 5.5 eV (223 nm)



Absolute calibration and laser intensity

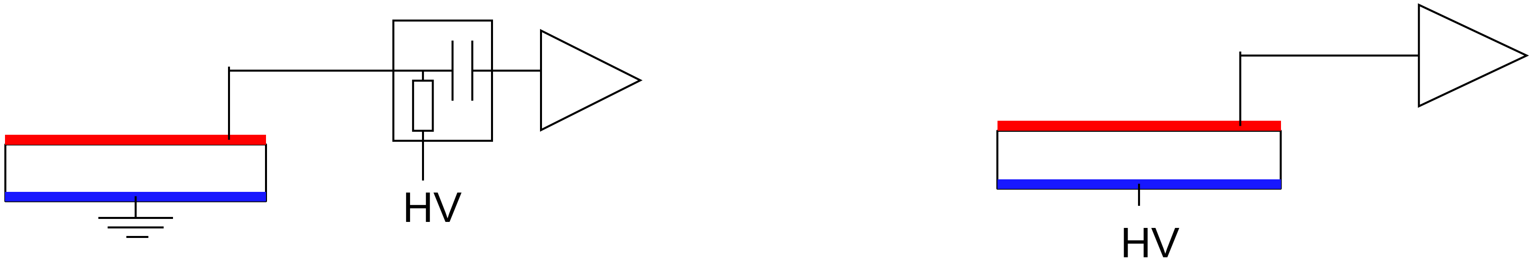
- Apart from relative comparison of waveforms at different position/bias/T, absolute measurements can/could be performed with calibrated device)
- Better to adjust it with neutral density filter than electronically if pulses are distorted



Basic principles of operation (electronics)

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



- Bias-T : pay attention to:
  - Frequency response (the bandwidth of the circuit is important, depending on your application)
  - HV capability (not many available for >1000 V)
- Wide band current amplifier :
  - Frequency response
  - Gain – depends very much on application/laser color (10 dB – 53 dB) – should be as high as possible to be sensitive for low signals, but signals should match the dynamic range of your ADC
- Connections:
  - make sure everything is shielded with as few of “patch-connections” as possible.
  - Impendence matching (ideally frequency independent impendence)

Basic principles of operation (signal)

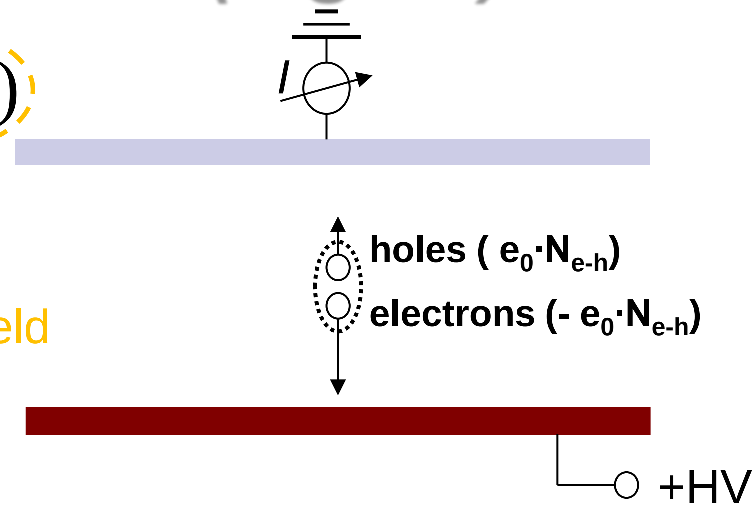
$$I_{e,h}(t) = e_0 \cdot N_{e-h} \cdot \exp(-t/\tau_{eff,e,h}) \cdot \vec{E}_w \cdot \vec{v}_{e,h}(t)$$

Generation/ Recombination

trapping

detector geometry

electric field

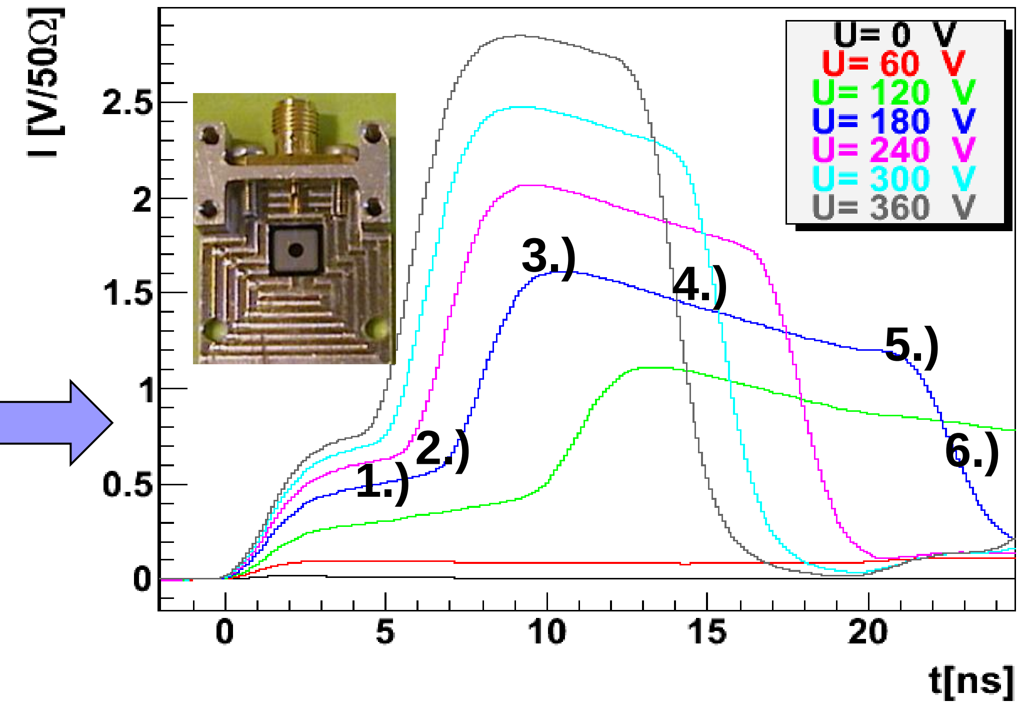


$$I(t) = I_e(t) + I_h(t)$$

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

Example - 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)



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)

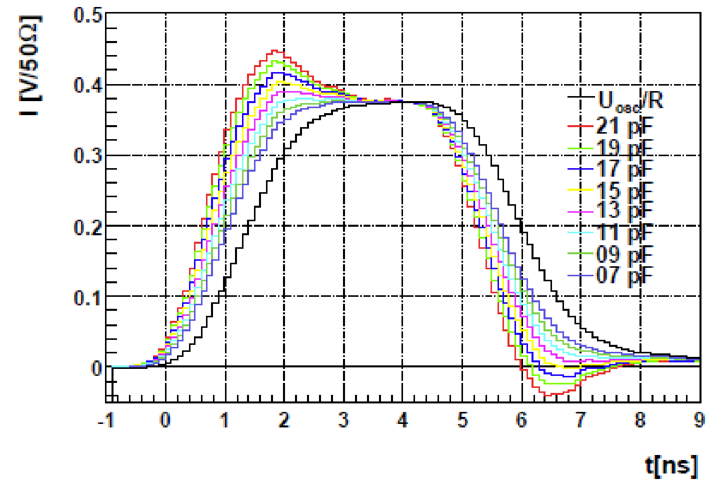
$$I_m(t) = \iint T(t-t')\, I(t'-t'')\, P(t'')\, dt'\, dt''$$

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:

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

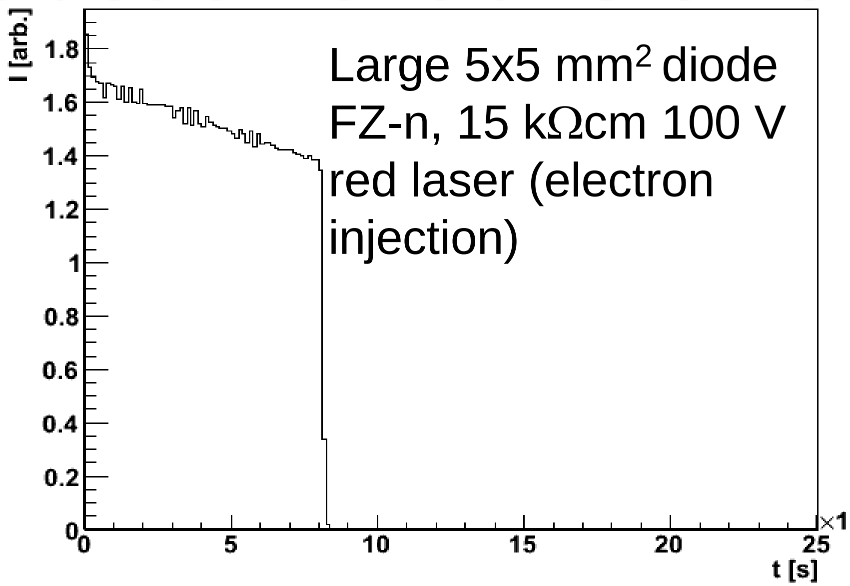
R=input impedance of the amp.
C=connected electrode capacitance

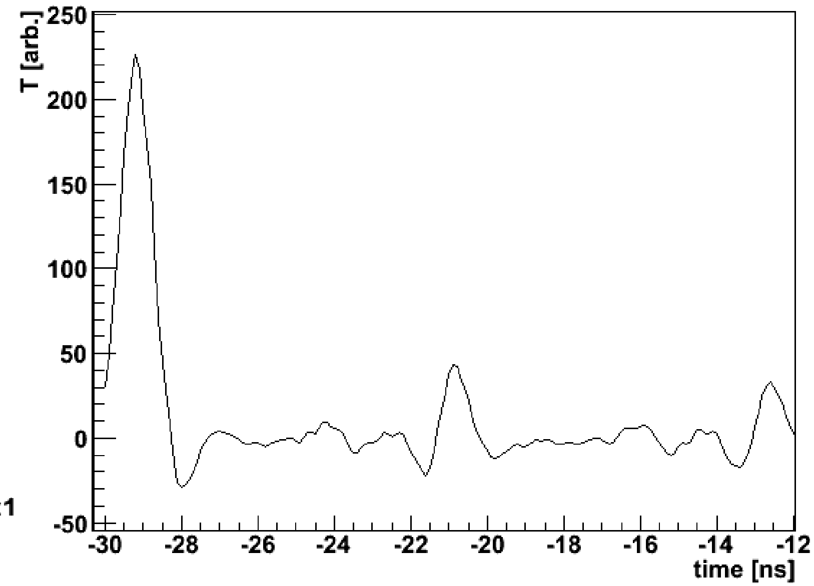
which allow for solution in time domain (no need for FT)

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

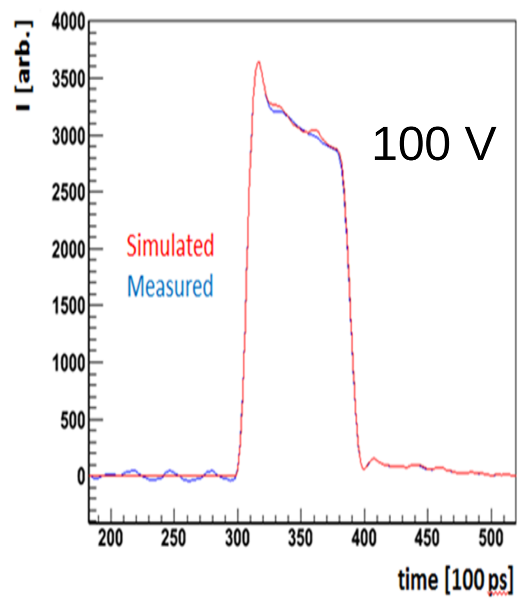
Extraction of transfer function

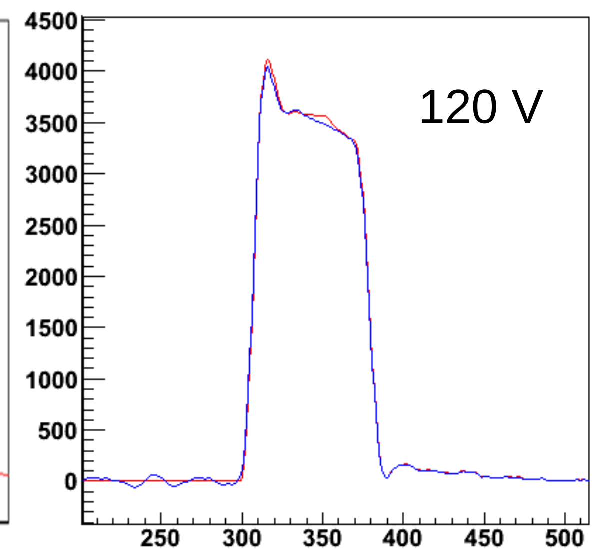
C. Scharf, R. Klanner, Determination of the electronics transfer function for current transient measurements , NIM A 779 (2015) 1.





1. Simulate induced current in a well know device
2. Use FT to extract transfer function from the measured current
3. Check if it gives an agreement for other structures

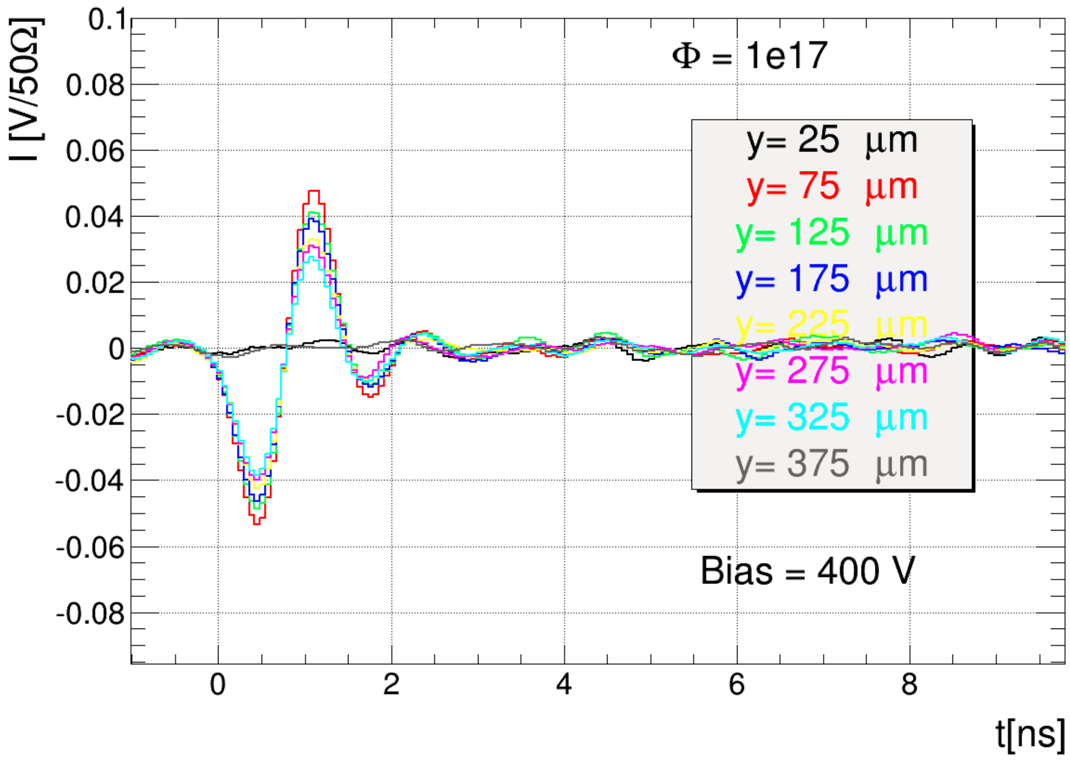




The procedure now being added to TCTAnalyse library.

Direct measurement of the transfer function

- Transfer function is the response to the delta function current pulse. Severe trapping makes highly irradiated detector ($10^{17}cm^{-2}$) a delta pulse.
- At very high fluences we always get a kind of oscillatory response? It wasn't possible to get rid of if in any configuration

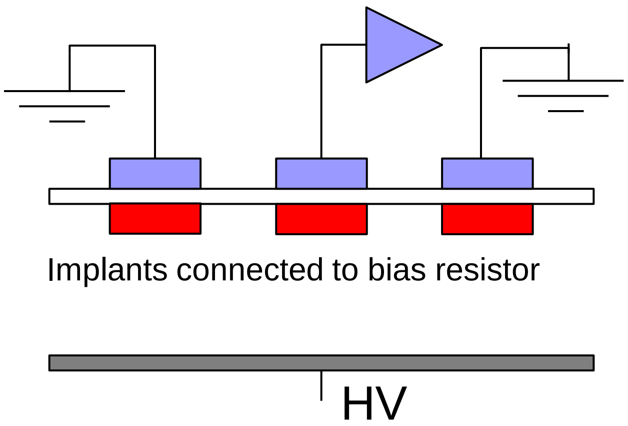


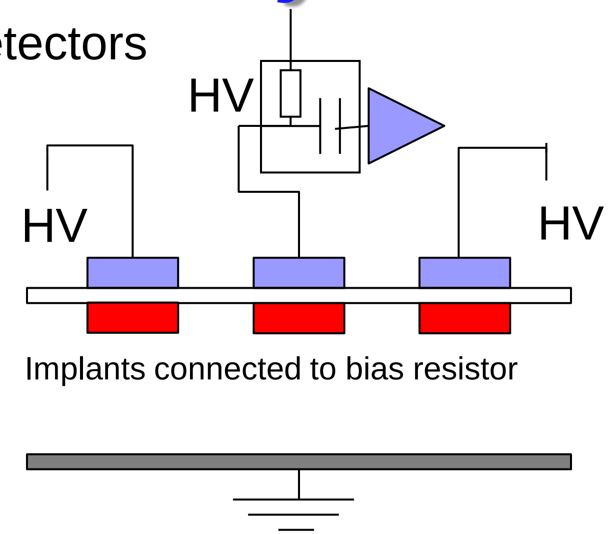
Intrinsic feature – signal oscillations?

- period ~5/4 ns
- CLR? (C~2pf=>L~20 nH~1 cm of wire)

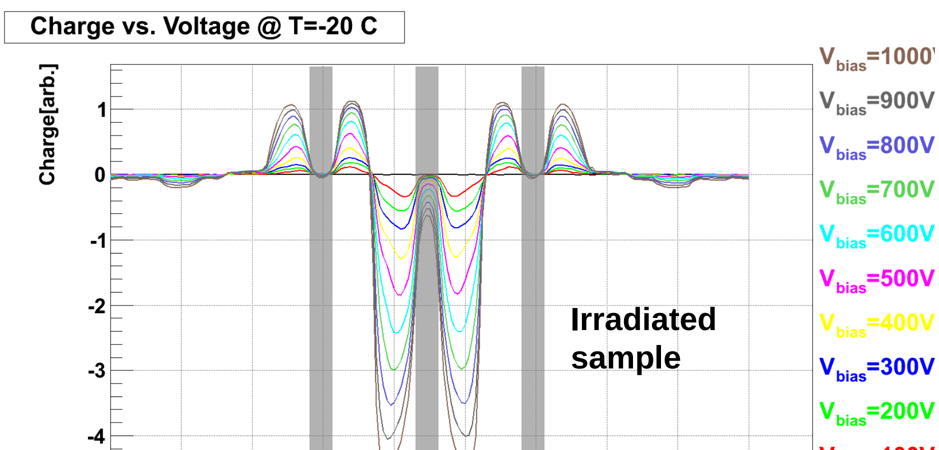
Connections in multi-electrode systems

Remember E_w plays a role in operation of silicon detectors

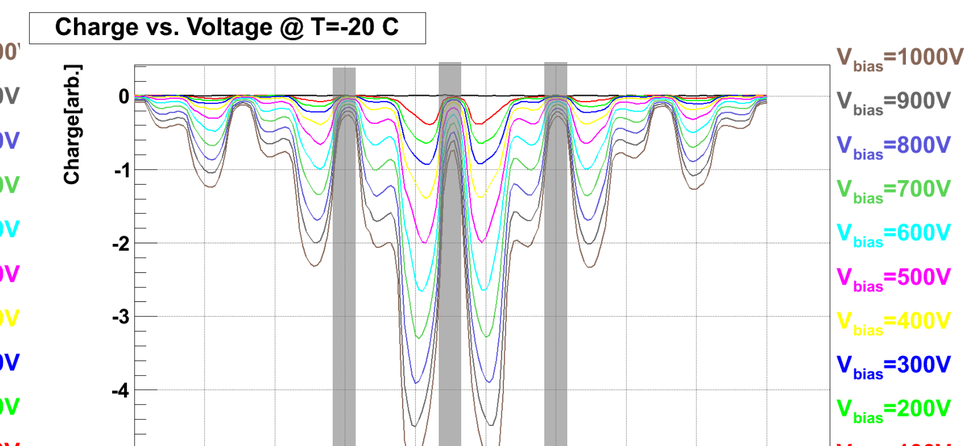




Always bond neighboring strips – otherwise they act as interpolation strips!



Neighbors bonded to low impedance



Neighbors not bonded

Top and Edge TCT

<u>Planar structures:</u>

Top TCT for planar structures relies on extraction of detector properties mostly on the time evolution of the pulse. Trapping damps the time evolution of the signal to the level of noise for heavily irradiated sensors – a large drawback.

Edge-TCT for planar structures relies on extraction of detector properties on externally controlled position of the beam.

<u>3D structures:</u>

The roles can be reversed concerning the direction of the drift .

Not all the aspects of TCT on 3D structures have been addressed so far.

Top TCT (pad diodes)

- Space charge/electric field (double junction/space charge inversion) from *I(t):*

  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.

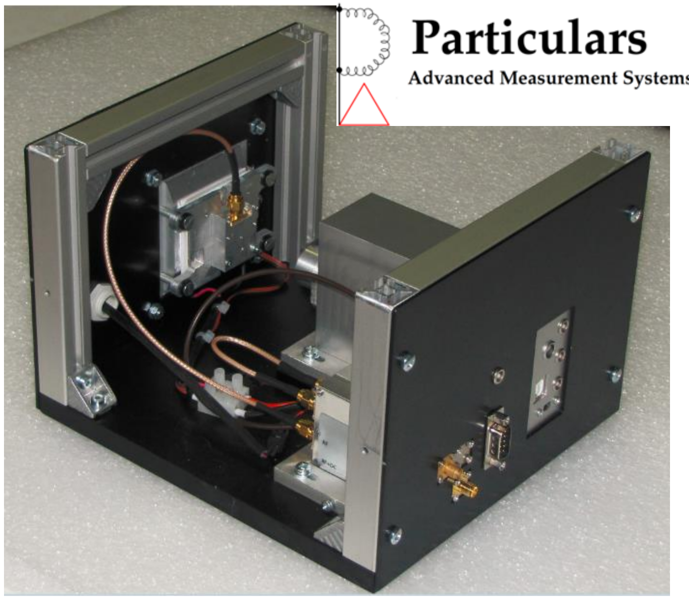
    O. Krasel et al., IEEE Trans. NS 51(1) (2004) 3055.

    A. Bates and M. Moll, Nucl. Instr. and Meth. A 555 (2005) 113-124.

    +long list

- Detrapping times

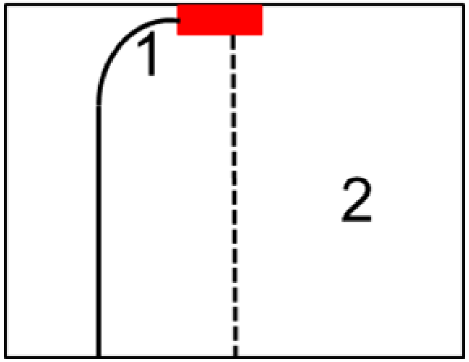
  G. Kramberger et al JINST 7 (2012) P04006

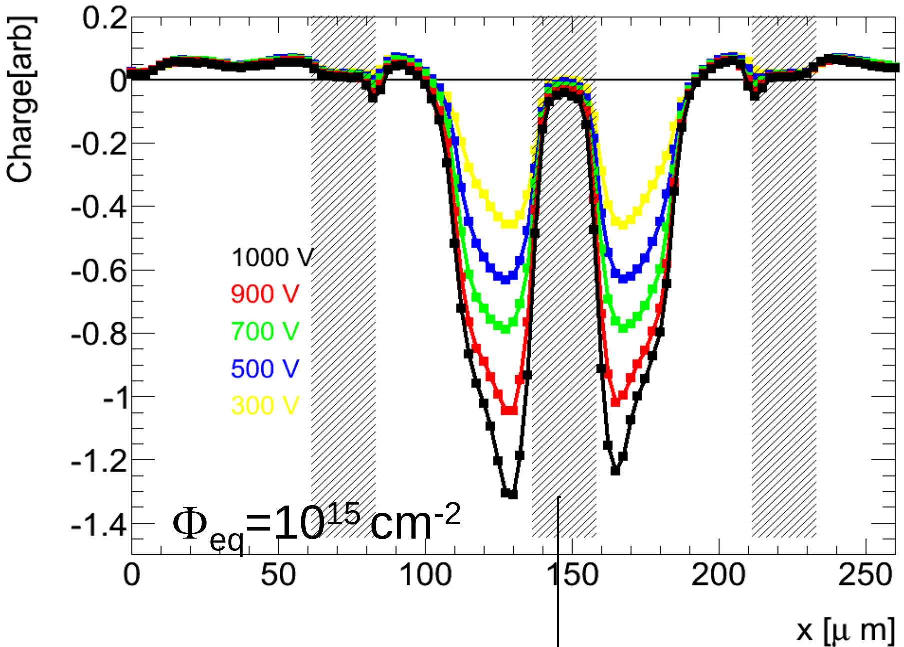


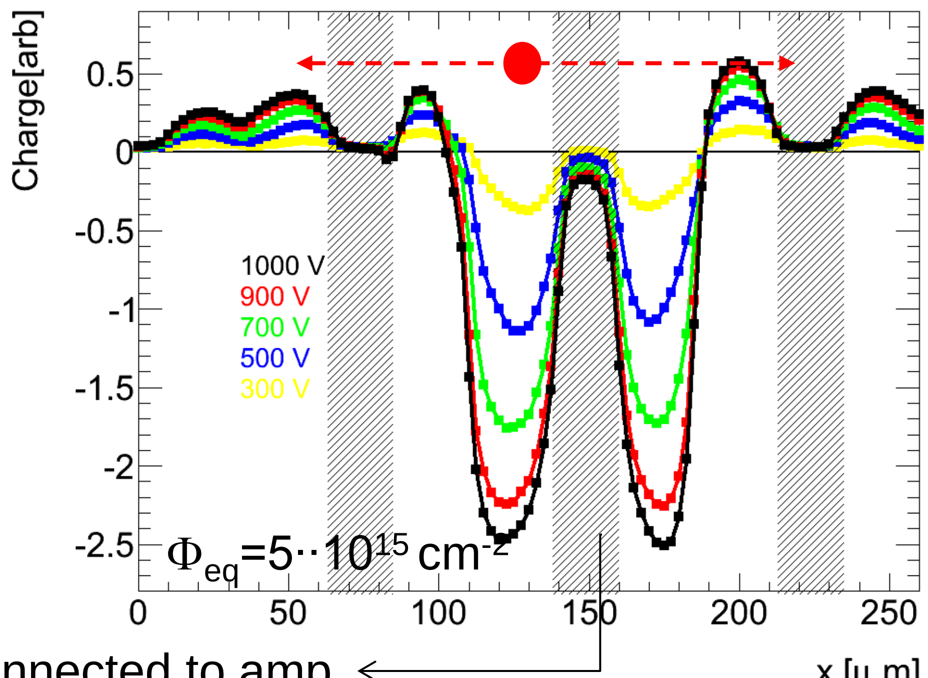
(TCTAnalysis library has built in functions for all these tasks)

Top TCT (strip profiling – baby strip)

- 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)

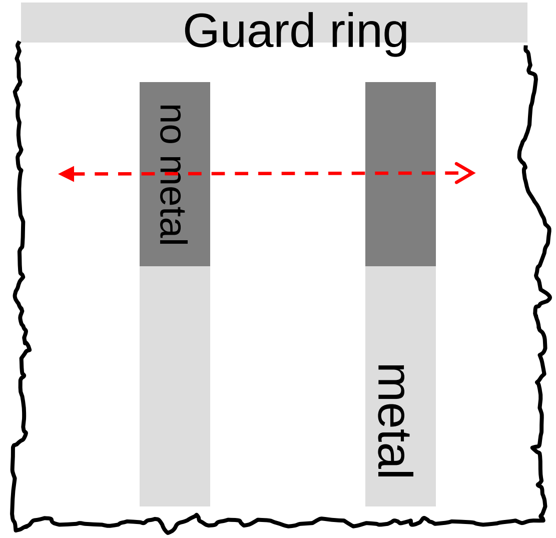




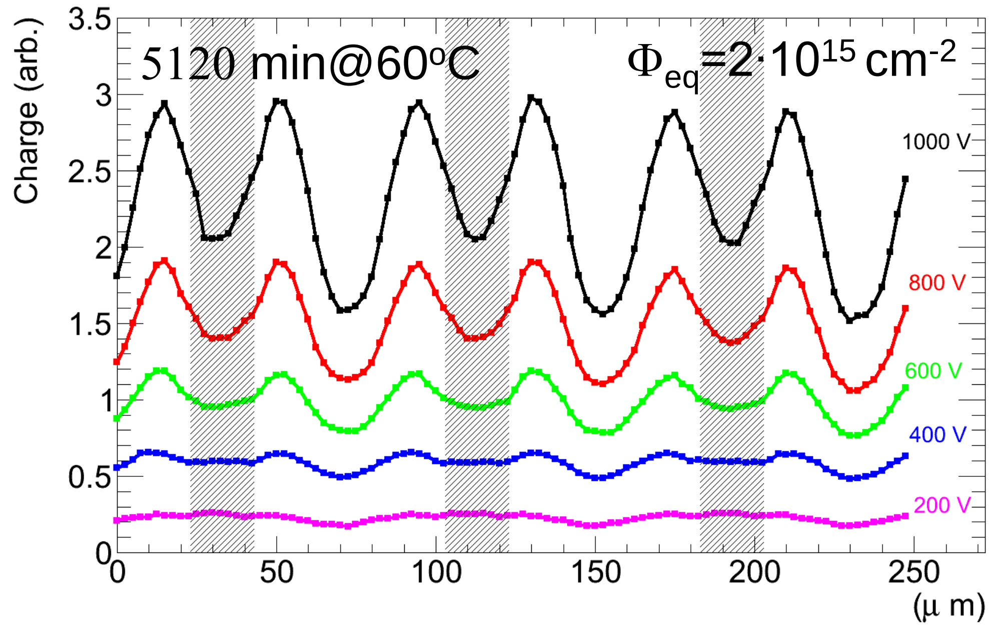


Connected to amp.

Top TCT (strip profiling - spaghetti)



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

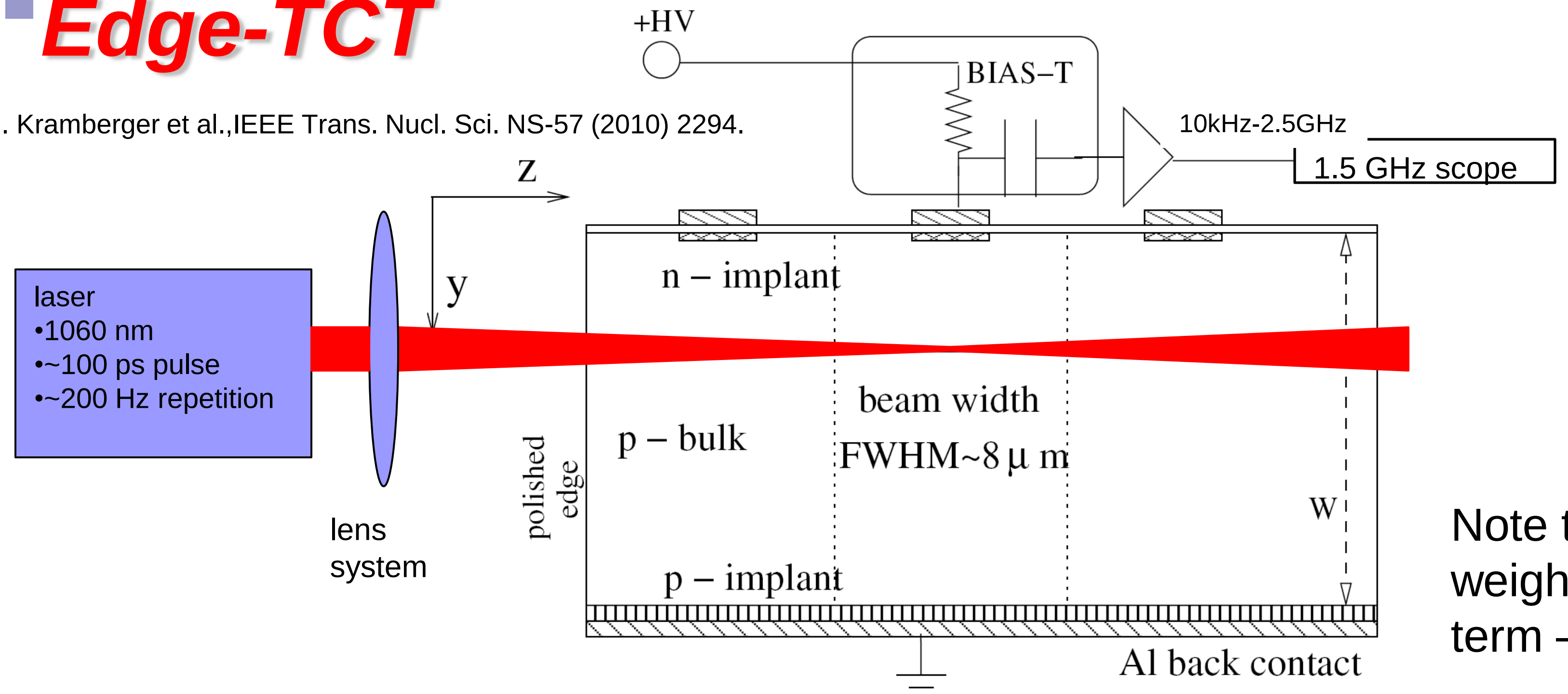


charge collection profiles:

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

Edge-TCT

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



Note the weighting field term – 1/W !

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

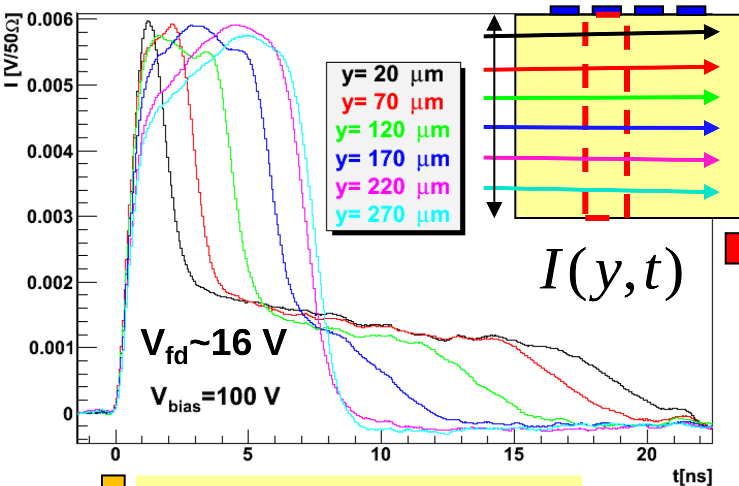
Constant

$$I(y,t\sim 0) \approx \frac{A e_0 N_{e,h}}{W} \left[\bar{v}_e(y) + \bar{v}_h(y)\right] \quad , \quad t << \tau_{eff,e,h}$$

The trapping can be completely taken out of the equation!

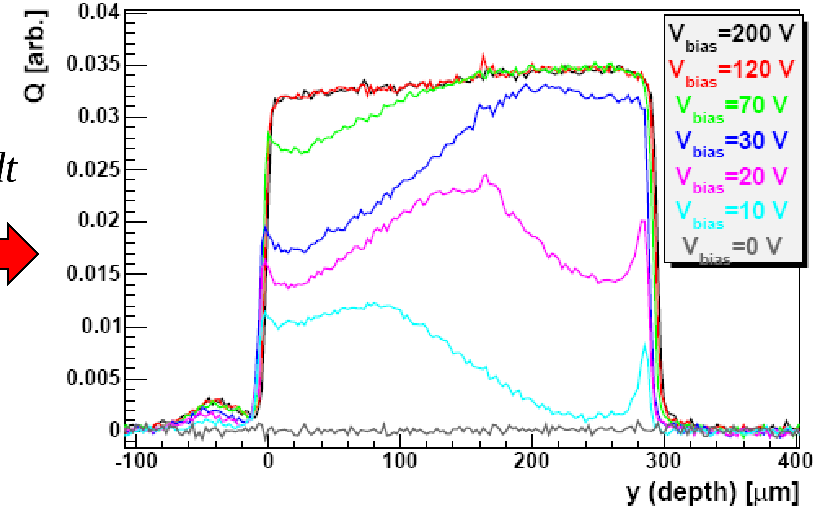
(The major obstacle of extraction of physics parameters from time evolution in conventional/Top-TCT is severe trapping)

Charge collection and velocity profiles



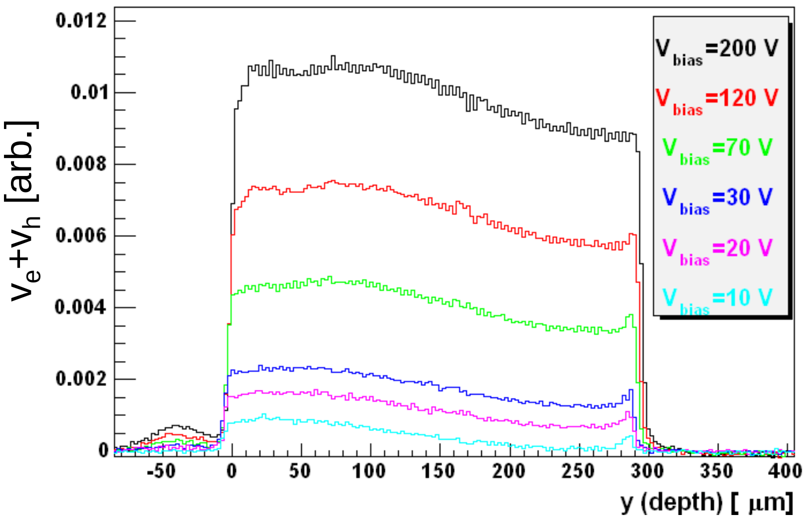
$$Q(y) = \int_0^{25ns} I(y,t)\,dt$$

CHARGE COLLECTION PROFILE

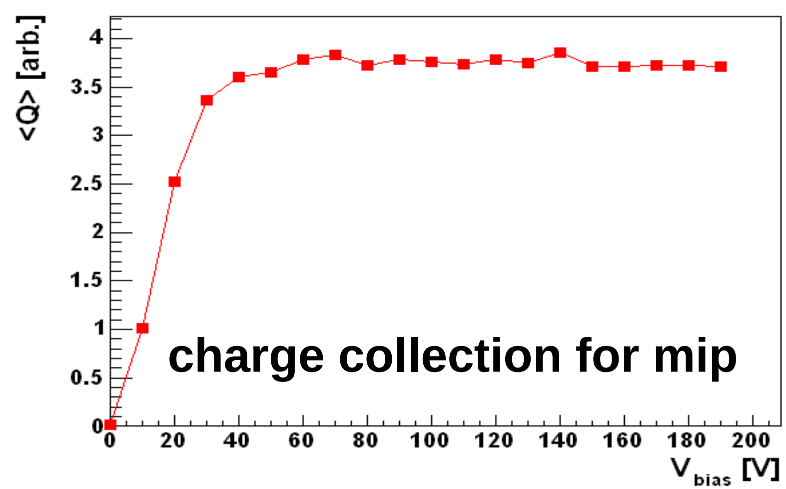


$$I(y, t \sim 0) \propto v_e + v_h$$

VELOCITY PROFILE

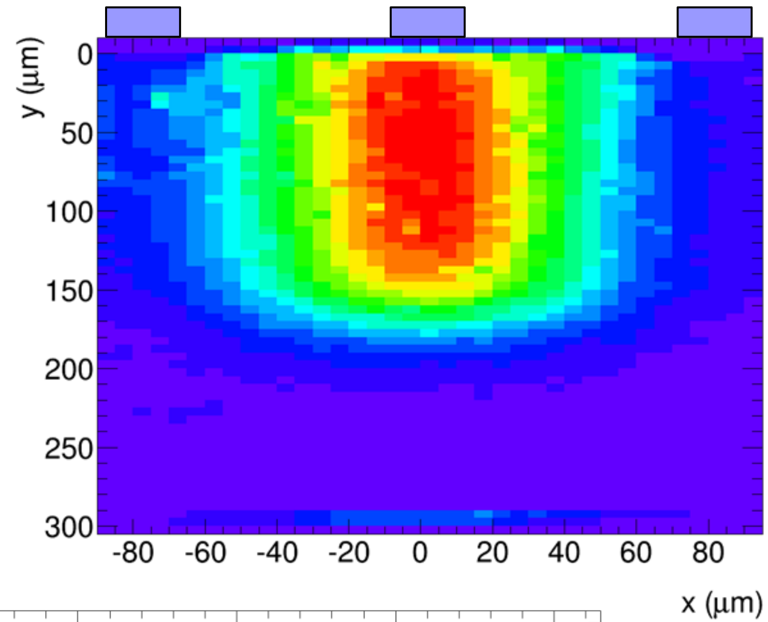


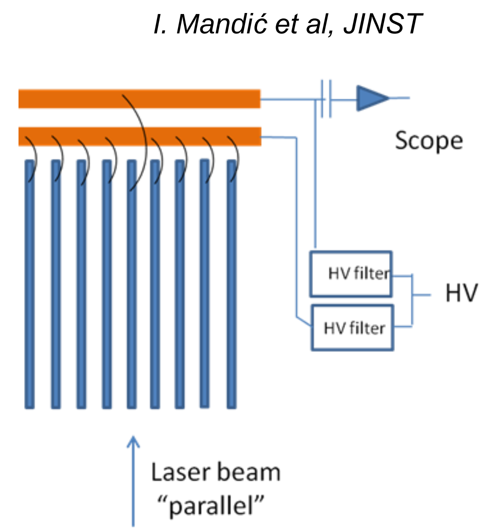
$$Q_{mip} \propto \langle Q \rangle = \int_0^W Q(y)\,dy$$

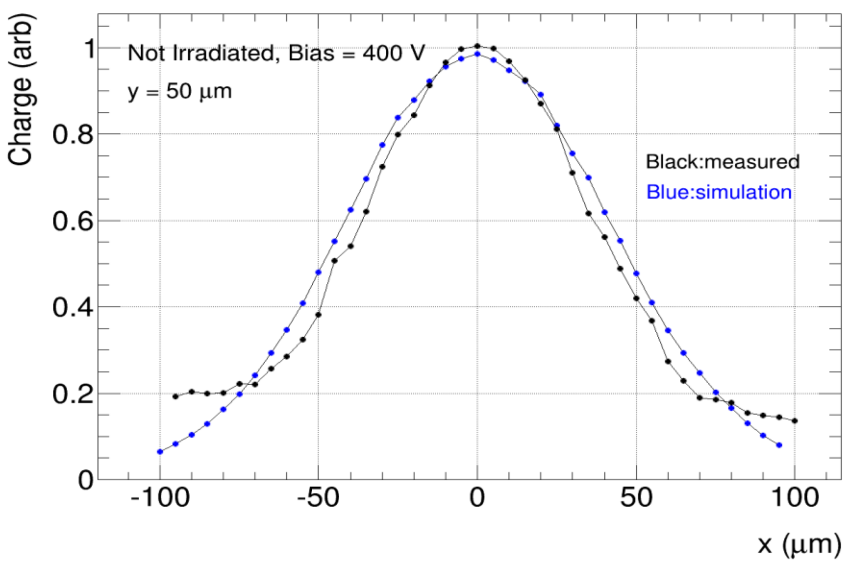


Edge-TCT-direction parallel to strips

HPK ATL12 detector
FZ-p, 200V<V_{fd}
Pitch 74.5 μm,
Width 16 μm







- More similar to mip operation – weighting field of the strip detector
- Attenuation helps from spreading the beam to neighboring strips
- Difficult quantitative interpretation

Edge-TCT - limitations

- the response is averaged over the strip width
- the beam has a sizeable width
- the weighting field close to the strips is not exactly 1/D which would imply due to many channel induction, but has similar shape as electric field (see the work on simulation)
- Velocity profiles:
  - Similar results for I(t~0), Q(t~0),dI/dt(t~0)
  - Our experience with a very tempting idea:

$$I(y) \approx \frac{Ae_0 N_{e,h}}{W}\left[\mu_e + \mu_h\right]\overline{E}(y)$$

$$v_{e,h}(y) = \left[\mu_e + \mu_h\right]\overline{E}(y)$$

$$V_{bias} = \int_0^W \overline{E}(y)dy$$

Iteration solving the velocity equation for E with free proportionality factor which is then constrained by bias voltage. However:

- Close to saturation the uncertainty is huge
- The precision close to the strips is too small.

Conclusions

↓

Questions?