TCT a tool to investigate silicon detectors

Gregor Kramberger

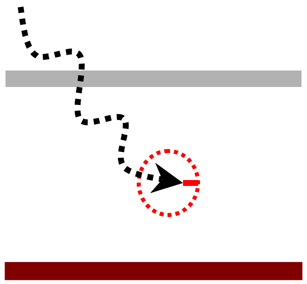
DESY, Hamburg

(on leave from Jozef Stefan Institute, Ljubljana, Slovenia)

- Basics of signal formation in silicon detectors
- TCT setup components and data analysis
- What can be measured with TCT and how it is done?
- Conclusions

Charge generation in silicon detector

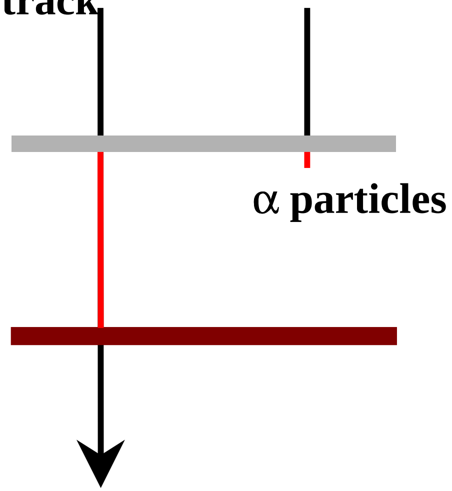
single γ generation (E_γ<1 MeV)
(photoeffect, compton)



x-ray imaging

- deposition of e-h pairs at the point of conversion

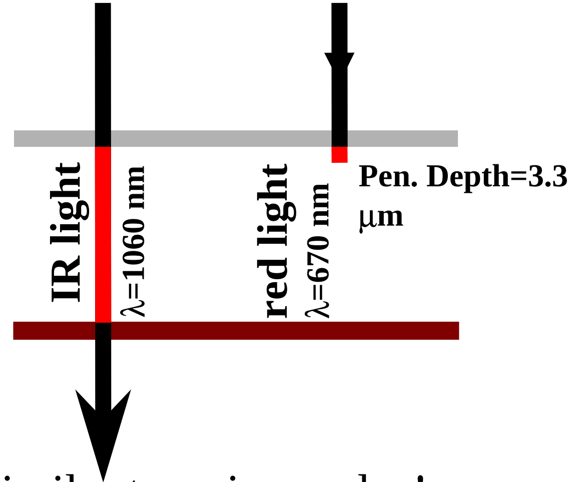
ionizing particle track



interested in m.i.p.:

- deposition of e-h pairs along the track
- most probable E loss 22500 e-h in 300 μm
- usually detected by charge sensitive preamplifiers

laser light generation
(~ UV- IR(1060 nm))



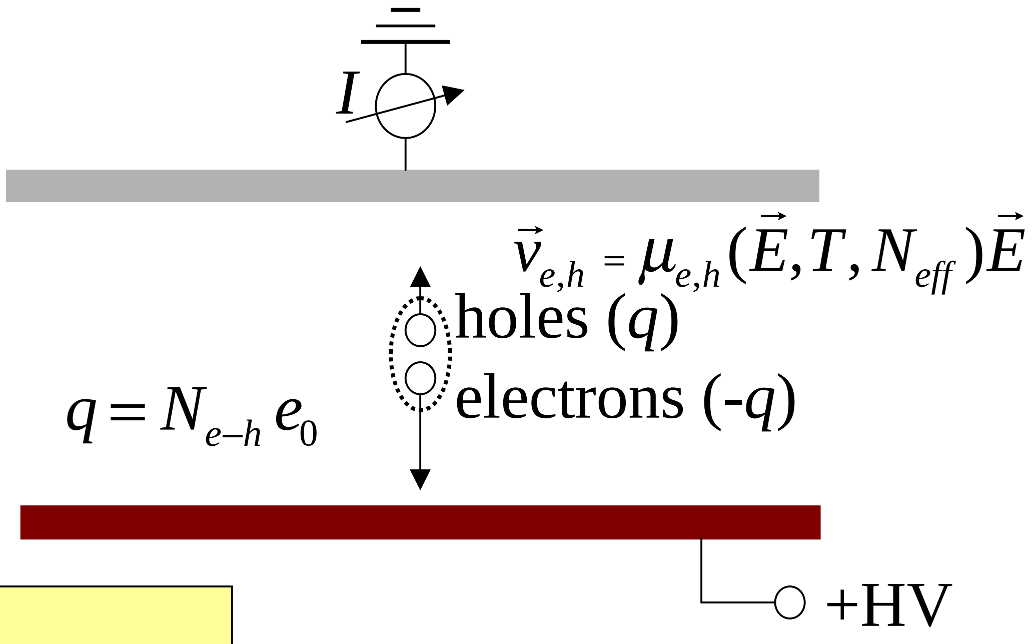
Similar to m.i.p. and α!

- a short pulse is required (~1 ns)
- the amount of the deposited charge can be varied
- exponential deposition profile (depth can be varied with λ)
- much wider deposition area

Induced current due to charge drift

The induced current depends on:

- **trapping of the *q***
- **weighting field**
- **drift velocity**



$$I_{e,h}(t) = -q\ \vec{E}_w \cdot \vec{v}_{e,h}(t)$$

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

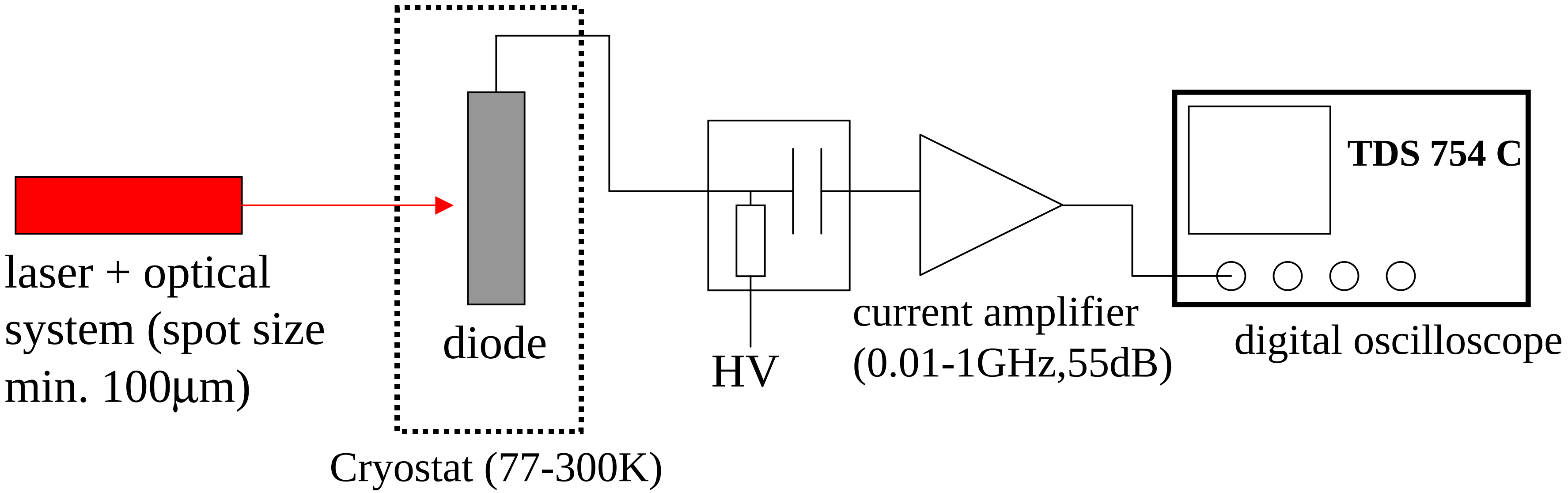
$$Q = \int I(t)\,dt = Q_e + Q_h$$

depend on creation point

charge induced by m.i.p. :

$$I^{mip}(t) = \sum_{pairs} I_e(t) + I_h(t)$$

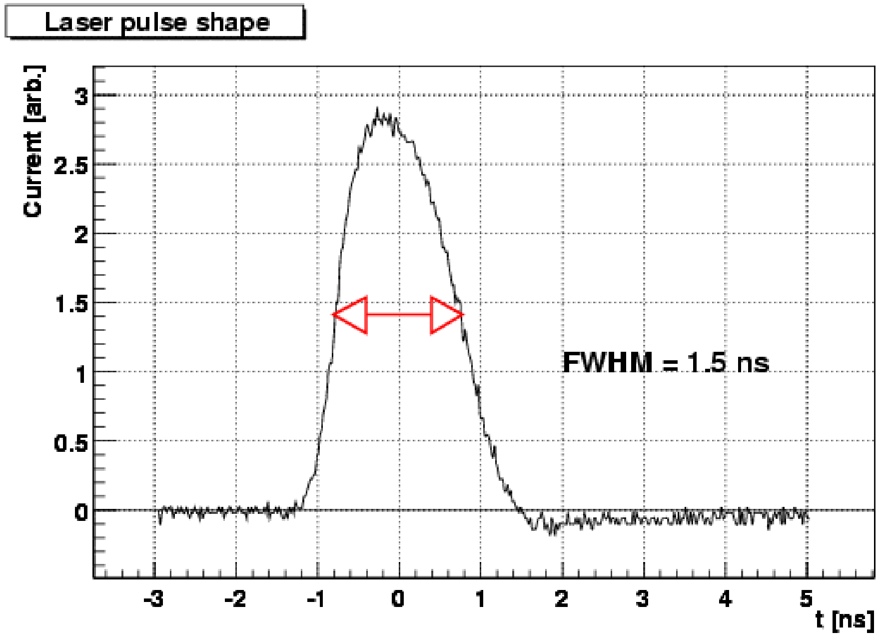
TCT set-up

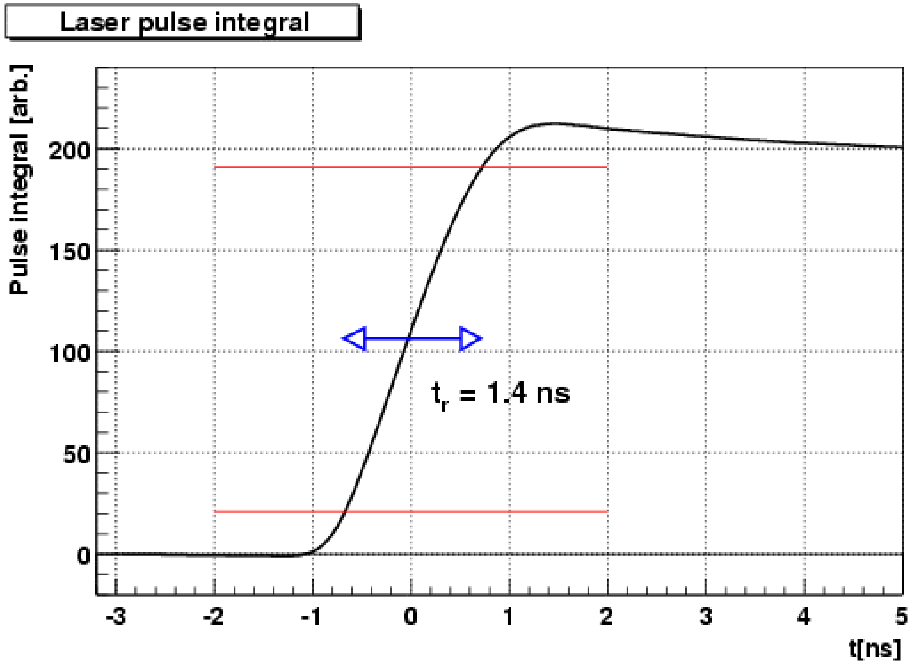


- light pulse repetition rate (can be set from 10^{-3} - 400k Hz)
- intensity of the light pulse can be tuned to charge equivalent from:

  few mip ($5\ 10^5$ electron-hole pairs/pulse) to few 100 mip
- samples have hole in metalization (p^+ contact) or mesh metalization (n^+ contact)
- an LN_2 pour fill optical cryostat used for cooling the samples

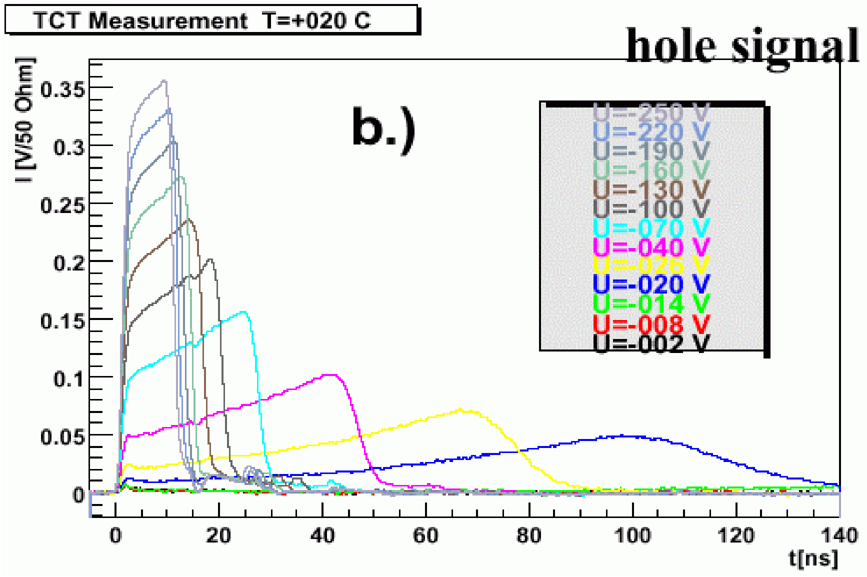
TCT set-up (laser pulse)

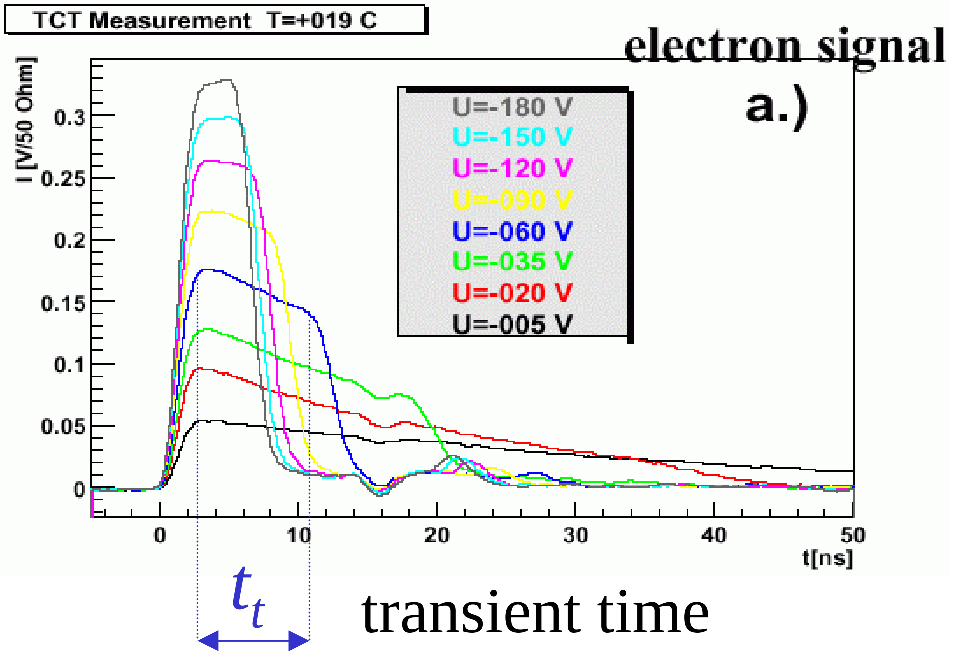


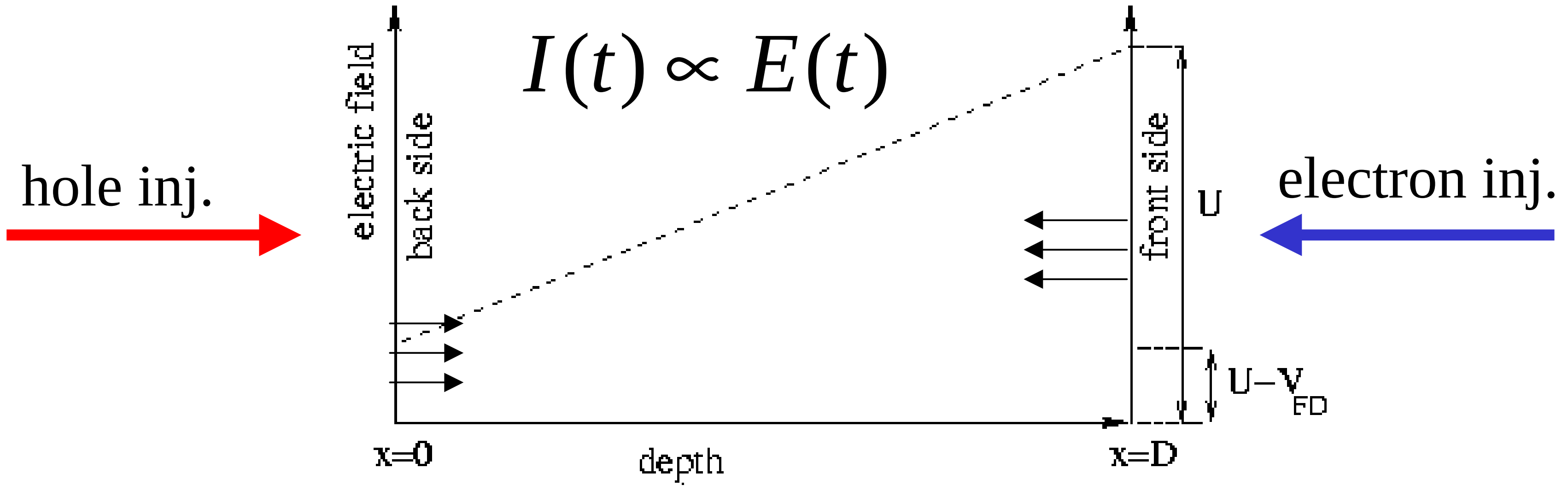


Measured with fast photo-diode!

Understanding TCT signal



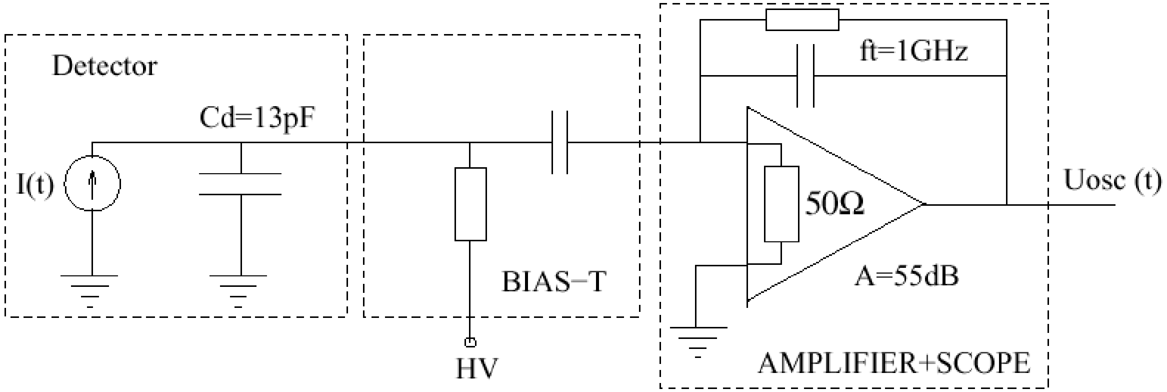




$$I(t) \propto E(t)$$

I. Processing of the TCT signal

electronic transfer function (C_d ,R_{osc})
impedance matching - reflections

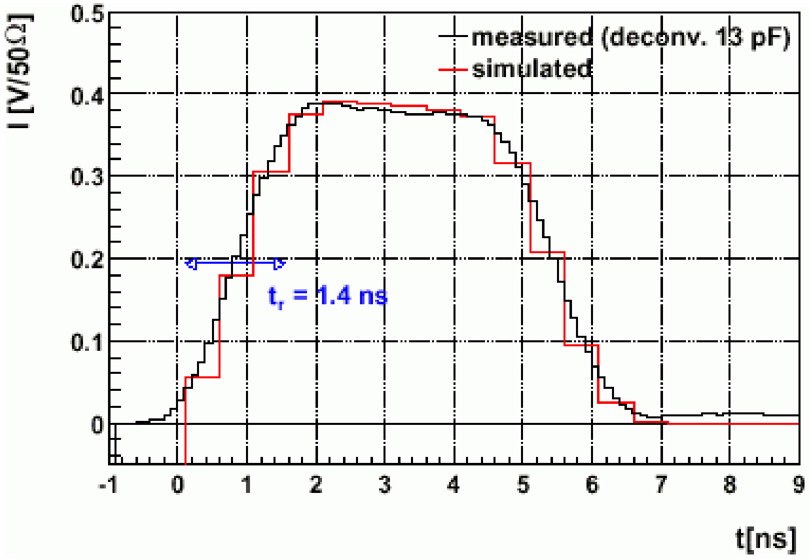


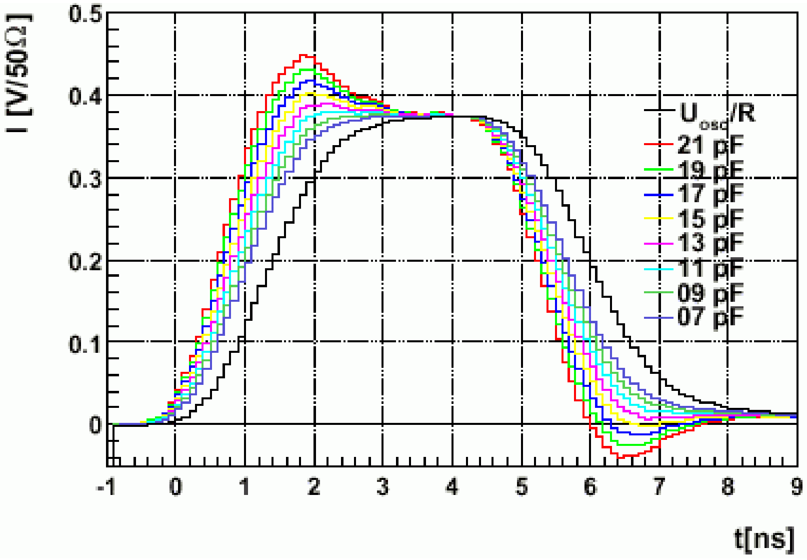
equivalent to RC cir.

$$I(t) = \frac{\tau}{R}\frac{dU_{osc}(t)}{dt} + \frac{U_{osc}(t)}{R}$$

$$\tau = R_{osc}C_d \approx 500 \text{ ps}$$

$$\frac{1}{2\pi\,\tau} < f_t \, , C_{dec} >> C_d$$





II. Processing of the TCT signal

finite duration of laser pulse

$$I_m(t) = \int P(x)\, I_t(t-x)\, dx$$

measured

laser pulse profile

desired

solution e.g. by using Fourier Transform

$$FT(I_m) = FT(P) \cdot \ FT(I_t)$$

$$\big\downarrow$$

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

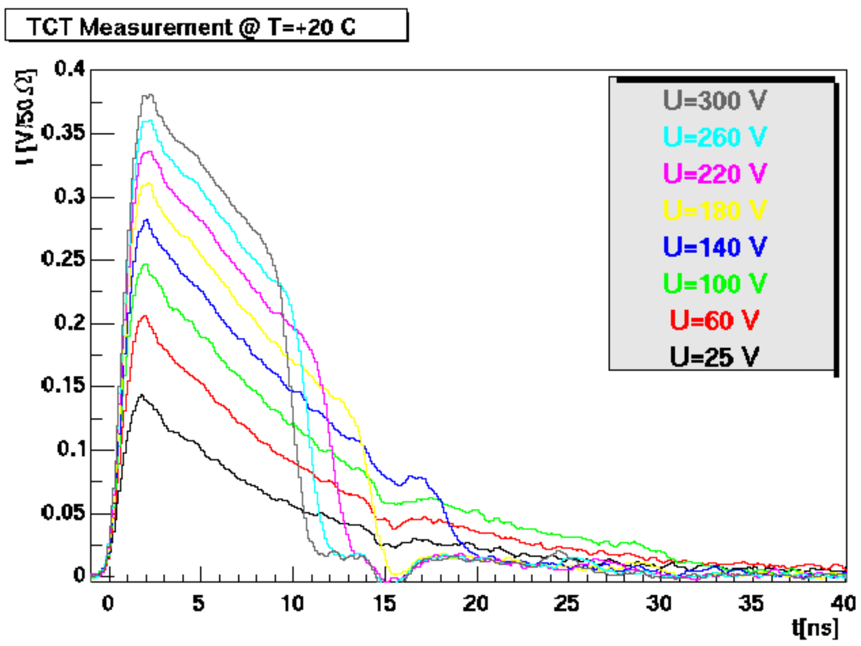
Main purpose of TCT:
Study of radiation damage on silicon detectors!

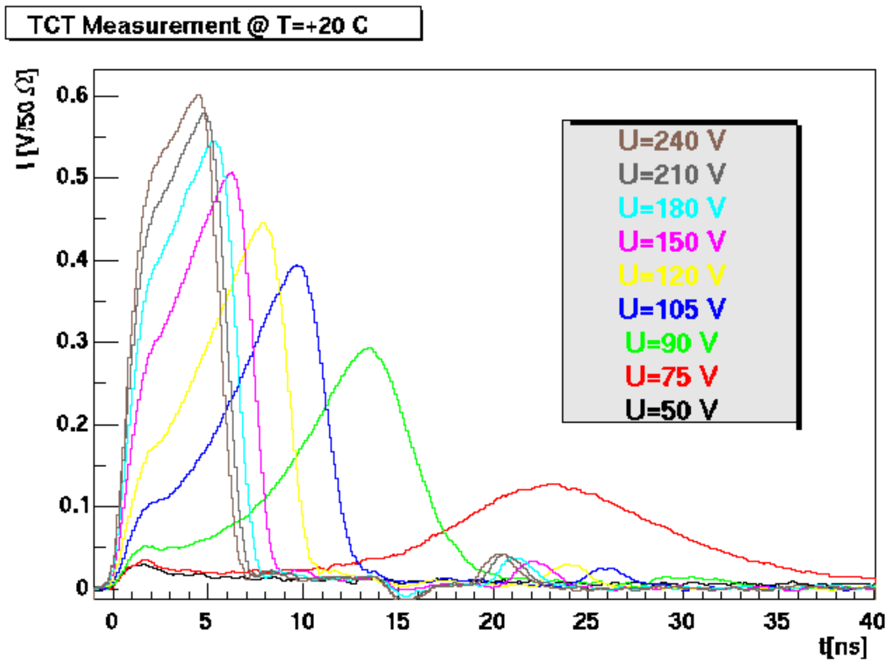
- Increase of N_{eff} and by that V_{FD}!
- Loss of the drifting charge due to trapping !
- Increase of leakage current $I=\alpha\ \Phi_{eq}$!

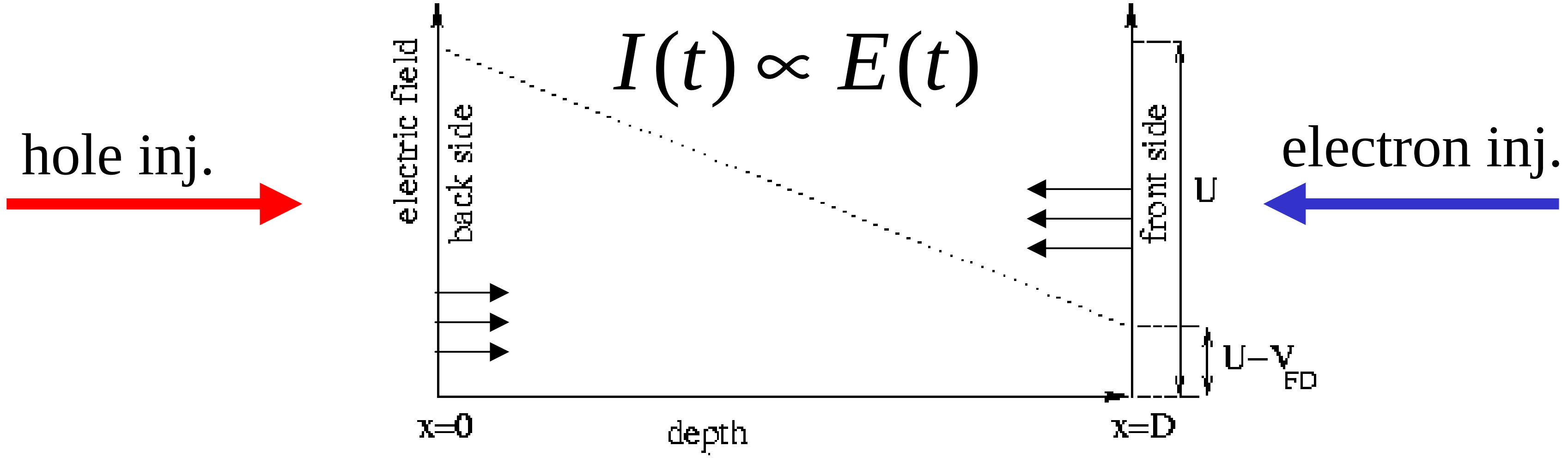
What can be measured with TCT?

- sign of the space charge in detector bulk
- full depletion voltage (CV)
- trapping time constants (charge collection efficiency) (DLTS)
- electric field (dopant) profile in the detector (CV?)
- de-trapping time constants (DLTS, TSC)
- charge collection studies in segmented devices

Sign of the space charge inversion







$$I(t) \propto E(t)$$

IIa. Full depletion voltage determination

- V_{FD} can be extracted from IR laser
- V_{FD} can be extracted from both electron and hole signal

In both cases: from evolution induced charge as a function of voltage!

$$\int_{t_0}^{t_1} I(t)dt = Q \quad \Rightarrow \quad Q(U)$$

:also called QV method

$N_{eff}(\vec{r}) = const.$
(before irradiation)

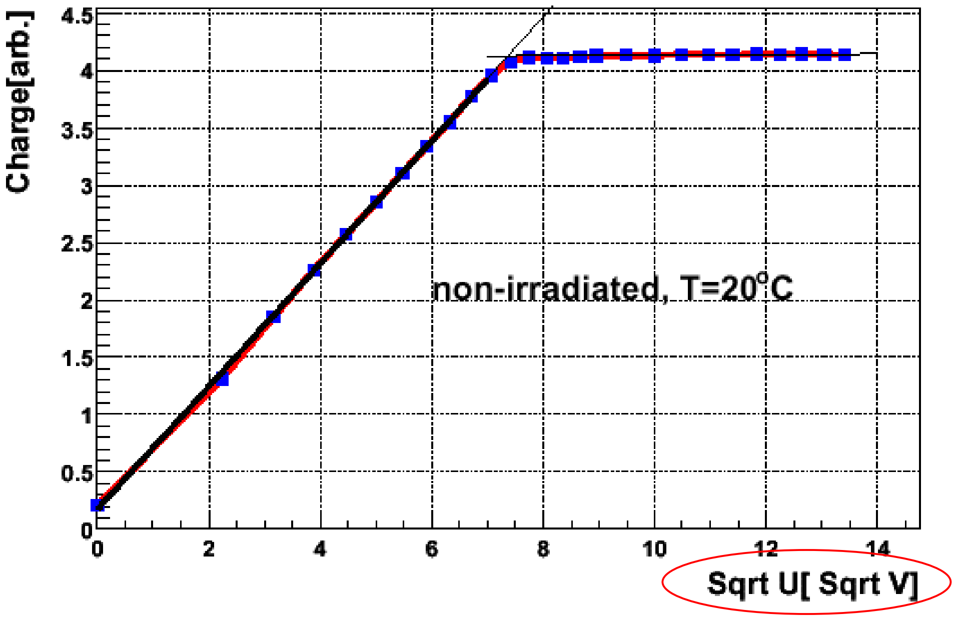
$$\frac{d}{D} = \sqrt{\frac{U}{V_{FD}}} \quad , \quad |N_{eff}| = \frac{2\varepsilon_0 \varepsilon V_{FD}}{e_0 D^2}$$

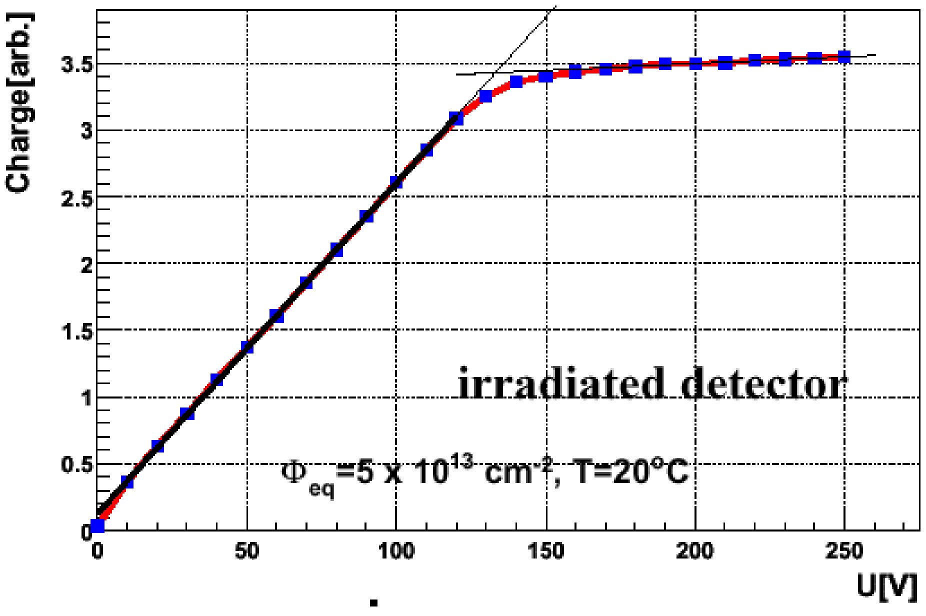
$N_{eff}(\vec{r}) \approx const.???$
(after irradiation)

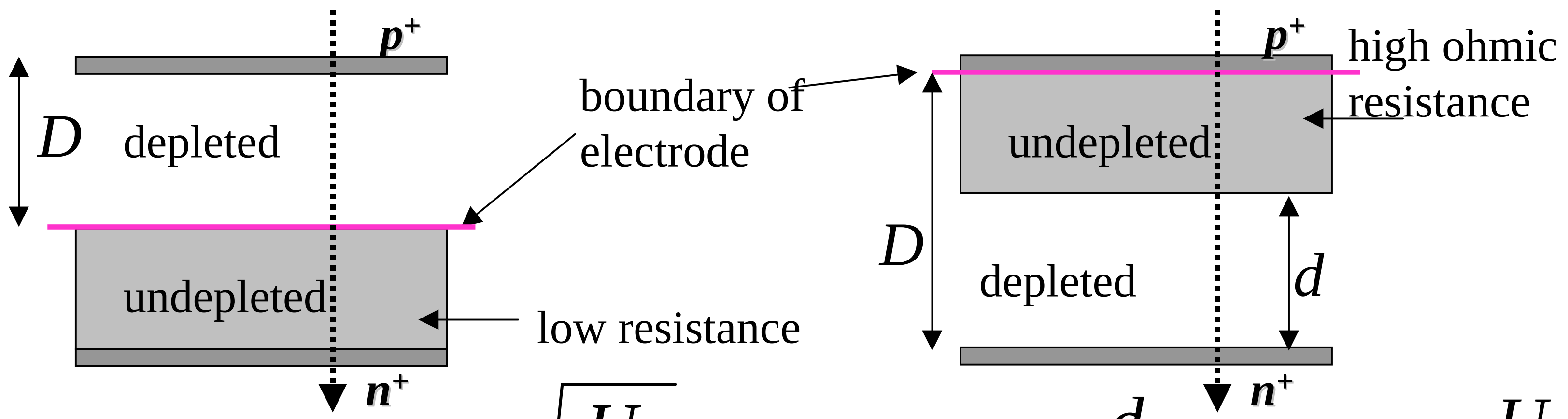
Is the above equation valid?

TCT allows to monitor space charge profile can be monitored

IIb. Full depletion voltage determination (IR laser)



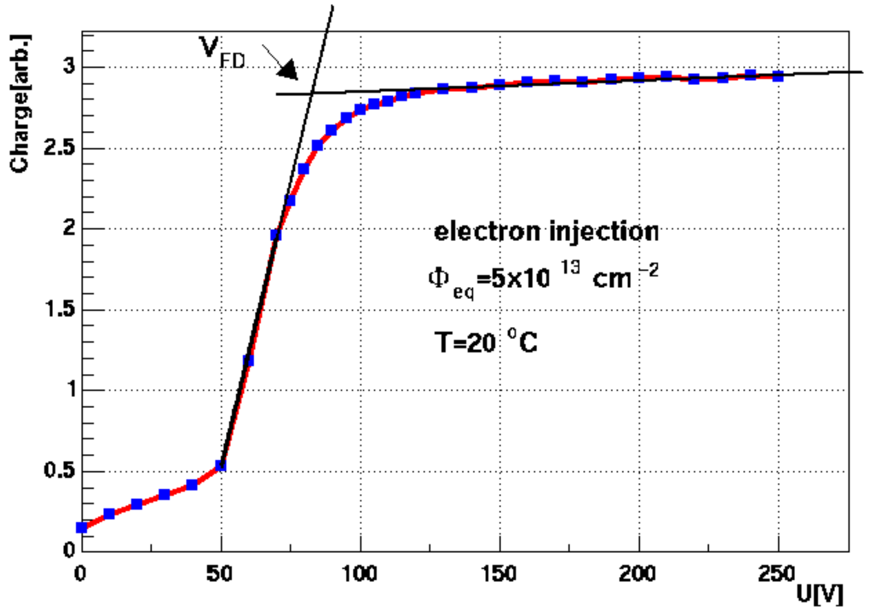


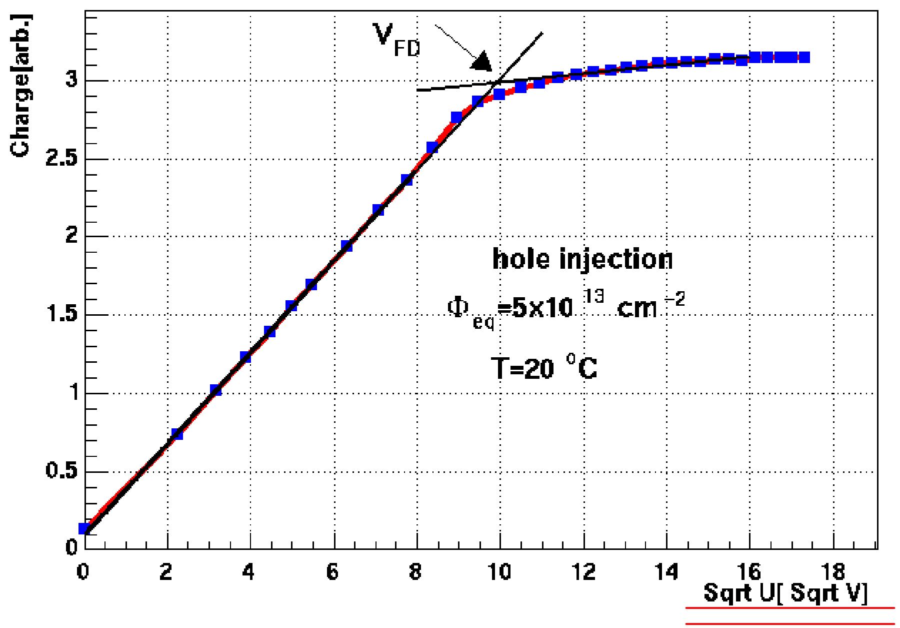


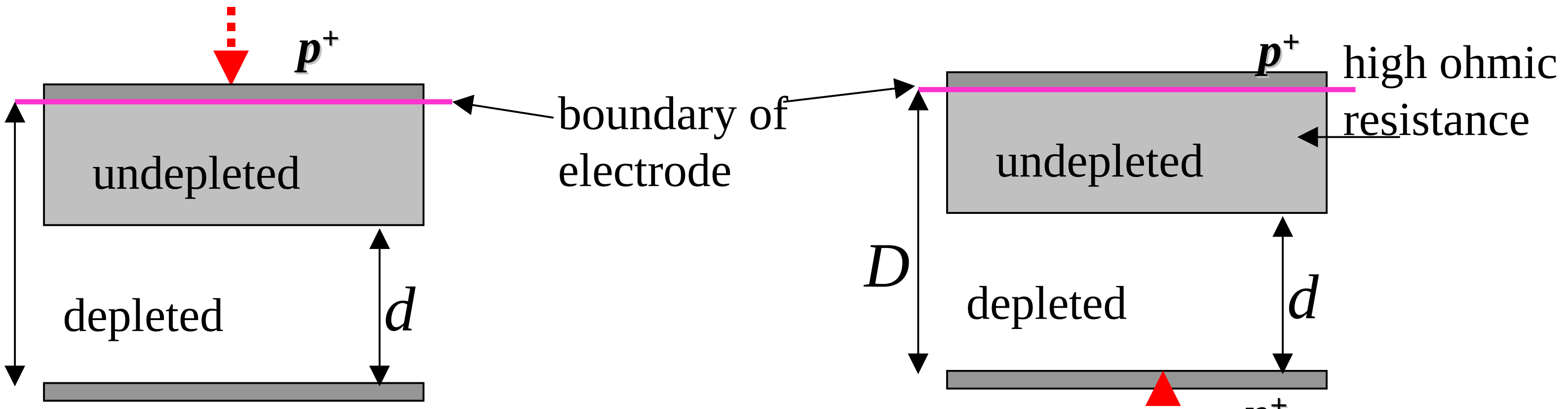
$$Q \propto D \Rightarrow Q \propto \sqrt{\frac{U}{V_{FD}}}$$

$$Q \propto \frac{d}{D} \cdot d \Rightarrow Q \propto \frac{U}{V_{FD}}$$

IIc. Full depletion voltage determination (red laser)

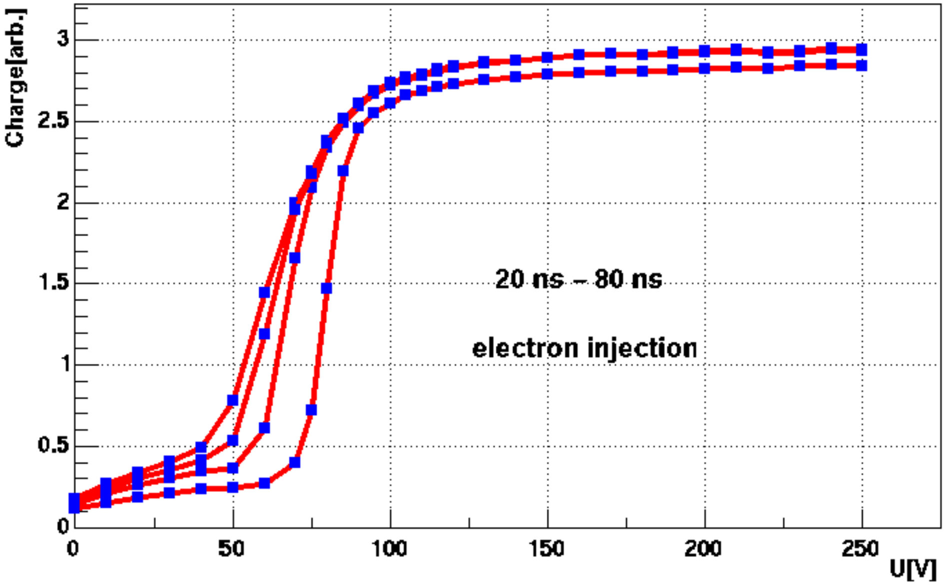


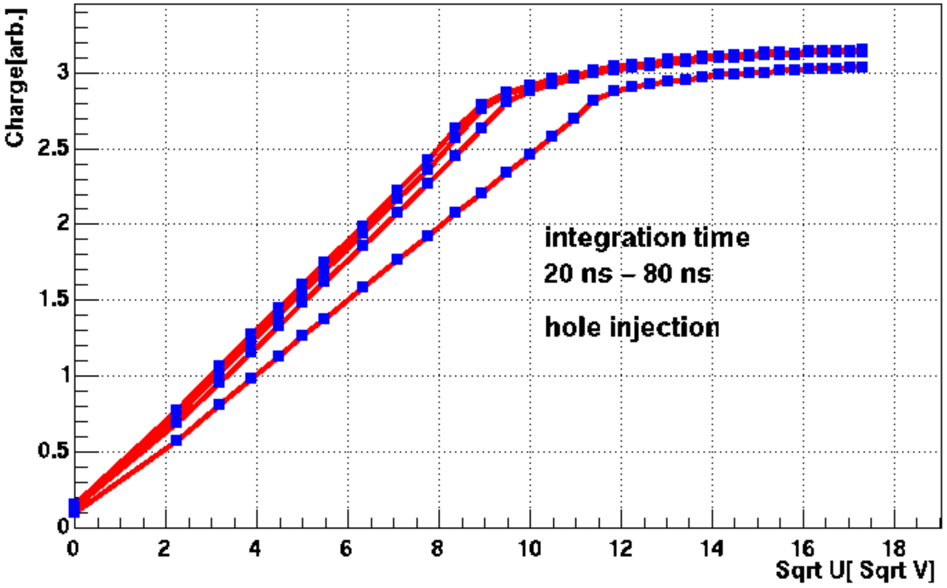




Steep transition at $U \sim V_{FD}$

$$Q \propto \frac{d}{D} \Rightarrow Q \propto \sqrt{\frac{U}{V_{FD}}}$$





The QV curve depends on integration time!
Above 40 ns this dependence becomes less important
if V_{FD}> few tens Volts

IIe. Full depletion voltage determination

Checking the electric field profile in the detector

Hole injection in irradiated silicon pad detector:

$$Q = Q_h \propto \frac{d}{D} \propto \sqrt{\frac{U}{V_{FD}}}$$

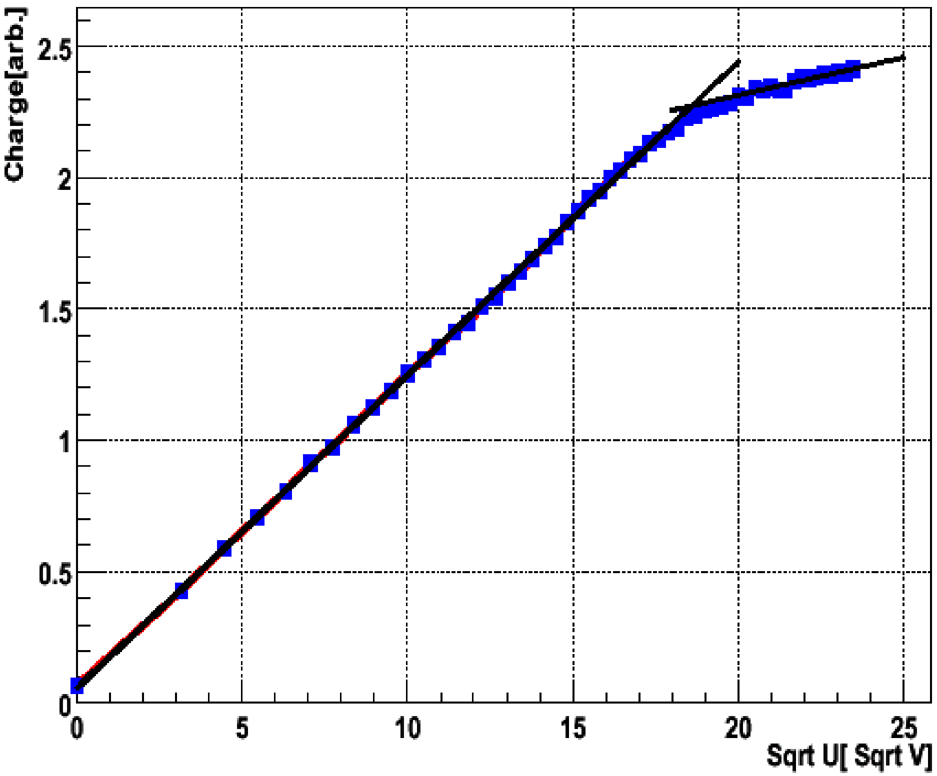
Only the carriers drifting in the depleted region contribute to the current. (diffusion of carriers through the undepleted high ohmic resistant bulk is slow - not included in the integral window of 60 ns)

A silicon material with high initial resistivity is used (V_{FD} ~*10* V before irradiation) to reduce importance of initial impurities!

↓

The effect of shallow levels is therefore minimized!

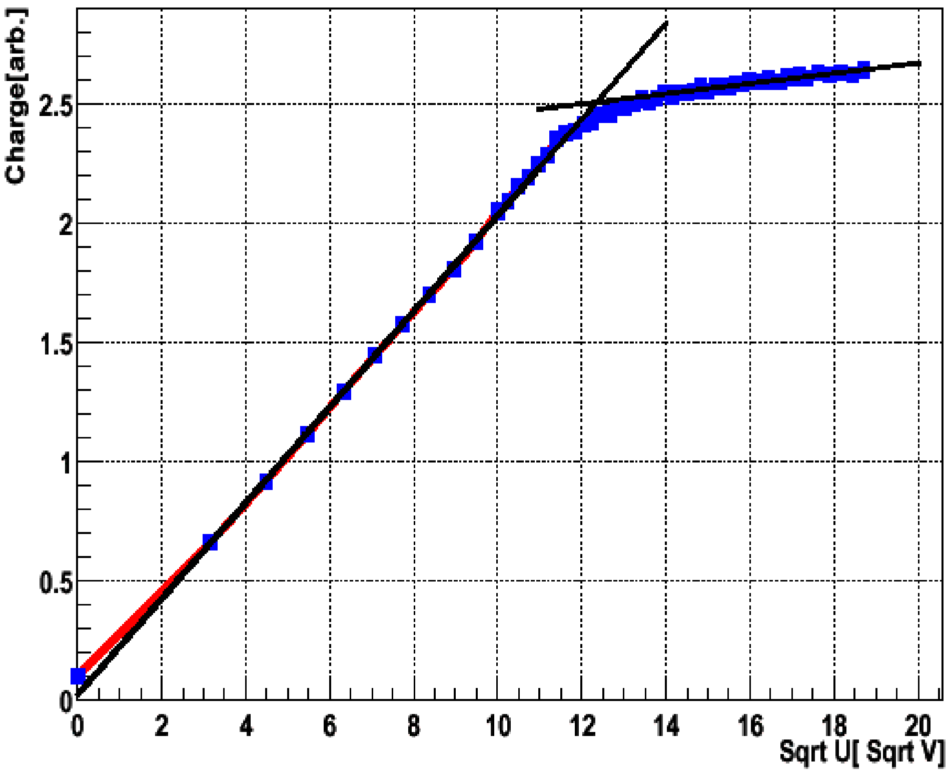
Standard material irradiated with neutrons:



Φ_{eq}=2x10^{14} cm^{-2}, V_{FD}=*295* V

$N_{eff} \approx$ *const.*

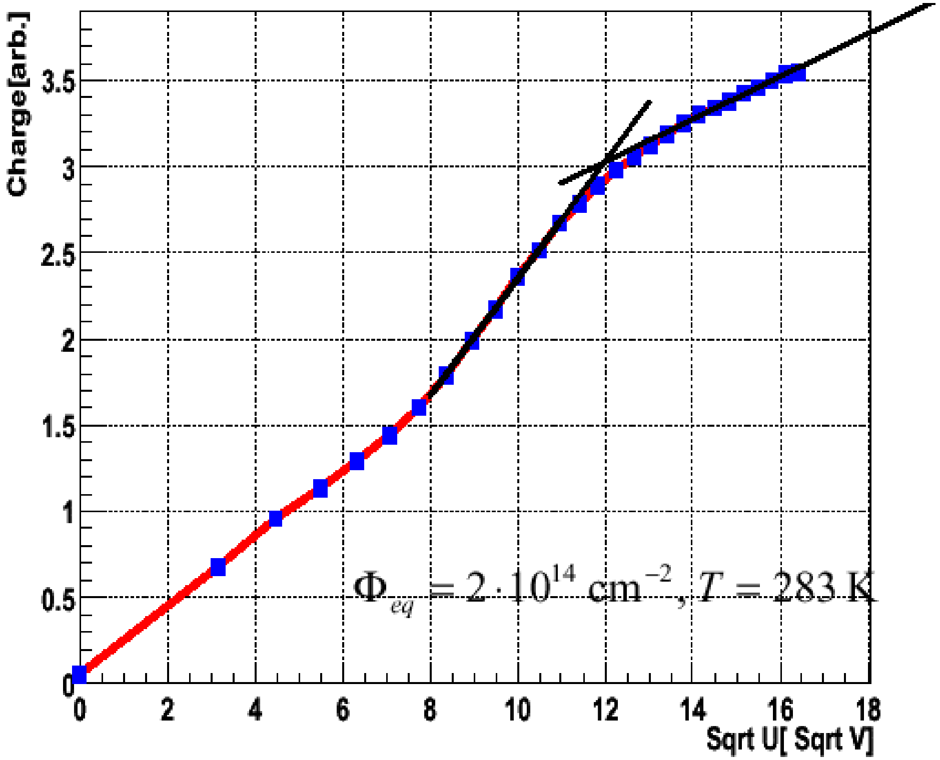
Oxygenated material irradiated with neutrons:



Φ_{eq}=7.5x10^{13} cm^{-2}, V_{FD}=*105* V

$N_{eff} \approx$ *const.*

Oxygenated material irradiated with protons to high fluence

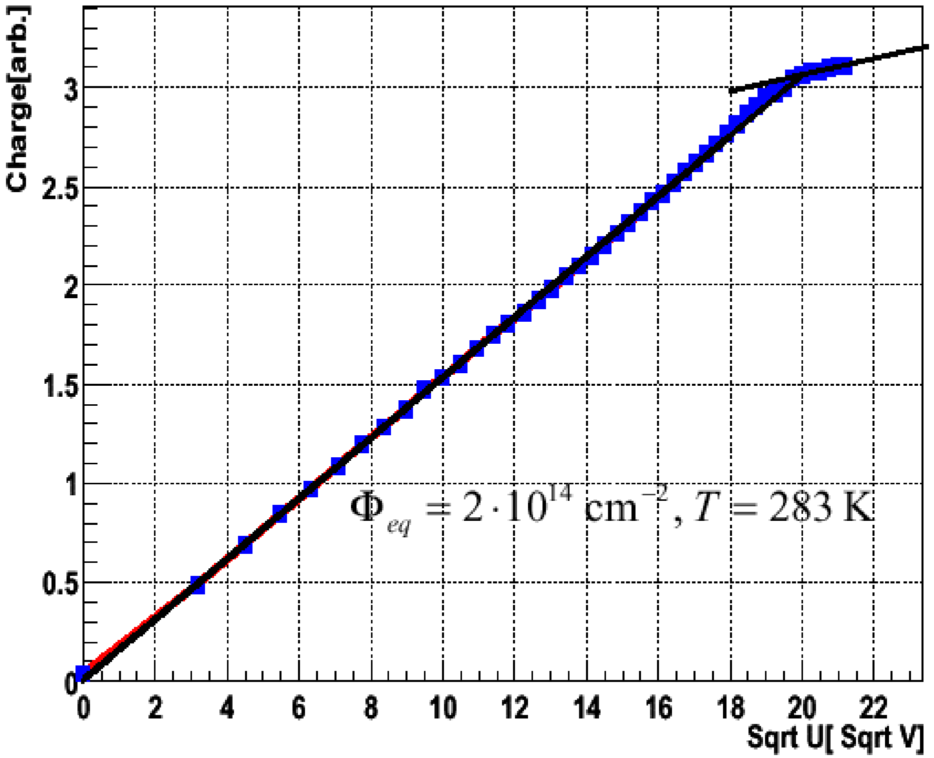


$N_{eff} \neq const.$

↓

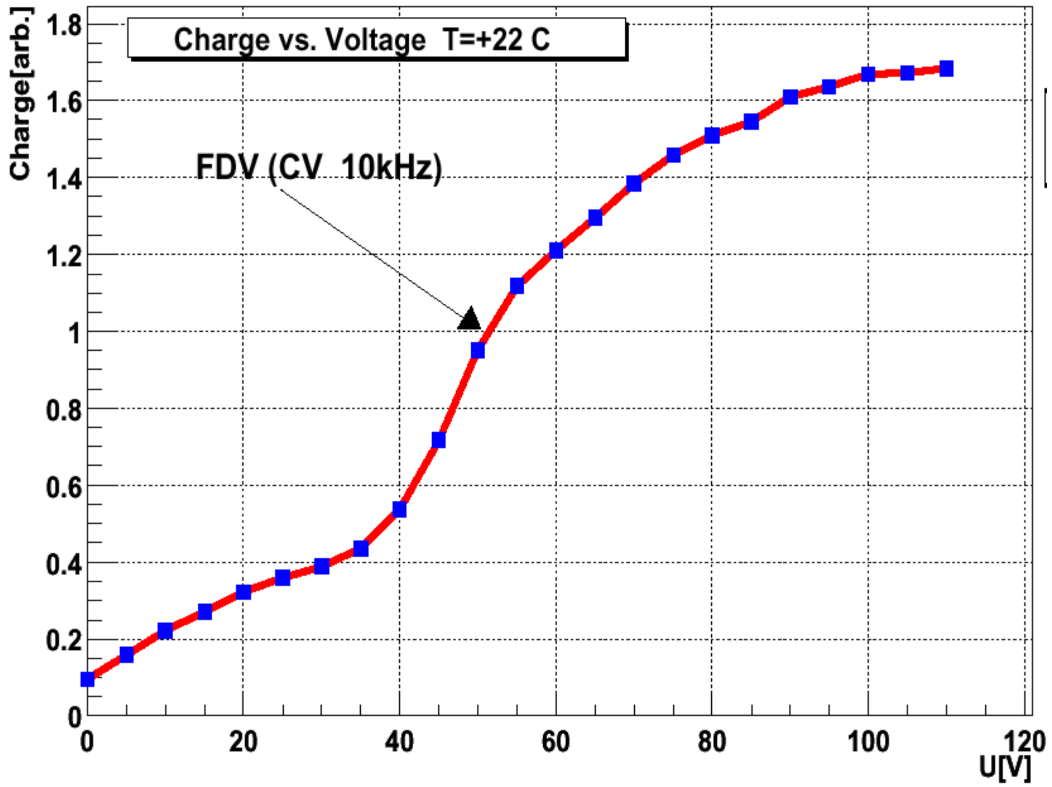
Shape of the so called:
"double junction"

Standard material irradiated with protons to high fluence



$N_{eff} \approx const.$

IIIa. Effective carrier trapping time determination



higher voltages(i.e. higher field)

↓

shorter drift

↓

less charge trapped

↓

increase of charge(U>V_{FD})

IIIb. Effective carrier trapping time determination

induced current after instant carrier injection in pad detector-diode

$$I_{e,h}(t) = \overbrace{e_0 \; N_{e,h}(t)}^{q(t)} \frac{1}{D} v_{e,h}(t)$$

decrease of the amount of the drifting charge

$$N_{e,h}(t) = N_{e,h}(0) \exp\left(\frac{-t}{\tau_{eff,e,h}}\right)$$

$$\boxed{I_{e,h}(t) = \left[e_0 \; N_{e,h}(0) \frac{1}{D} v_{e,h}(t) \right] \exp\left(\frac{-t}{\tau_{eff,e,h}}\right)}$$

IIIc. Effective carrier trapping time determination

trapping correction:

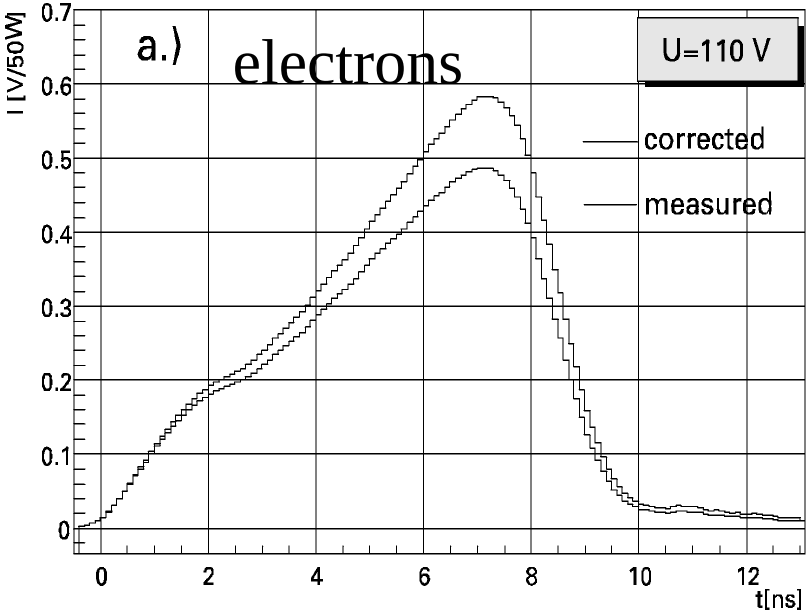
$$I_c(t) = I_m(t)\exp(\frac{t - t_0}{\hat{o}_{tr}})$$

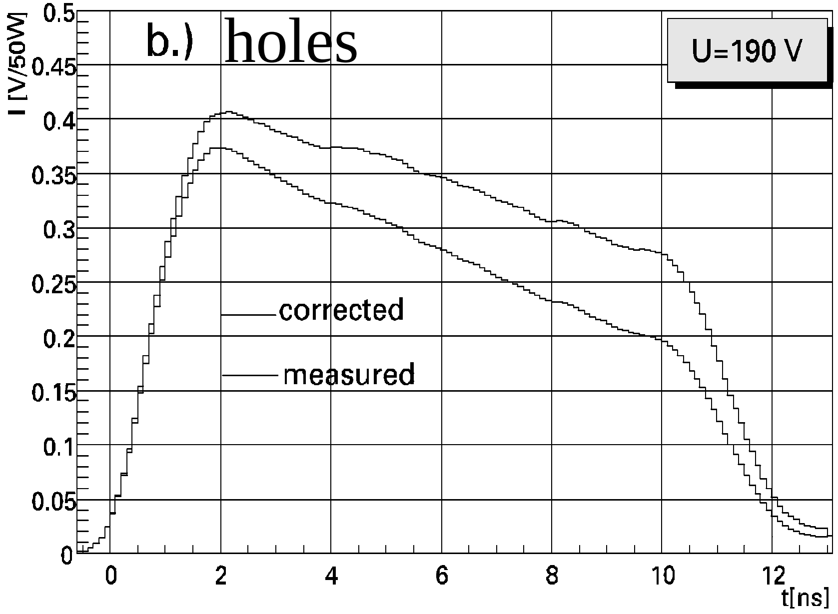
start of the laser pulse

correction time constant

corrected current

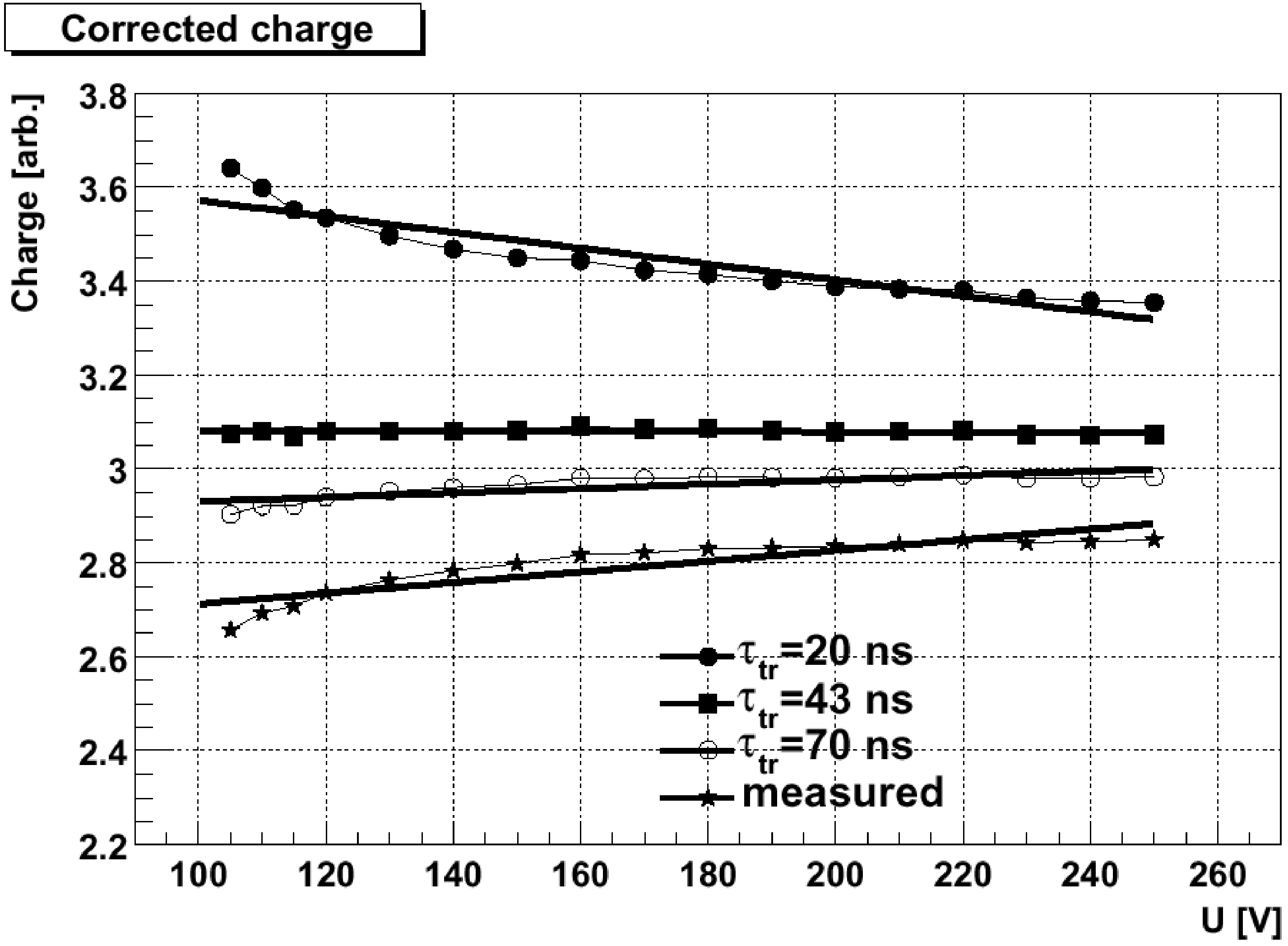
measured current





IIId. Effective carrier trapping time determination

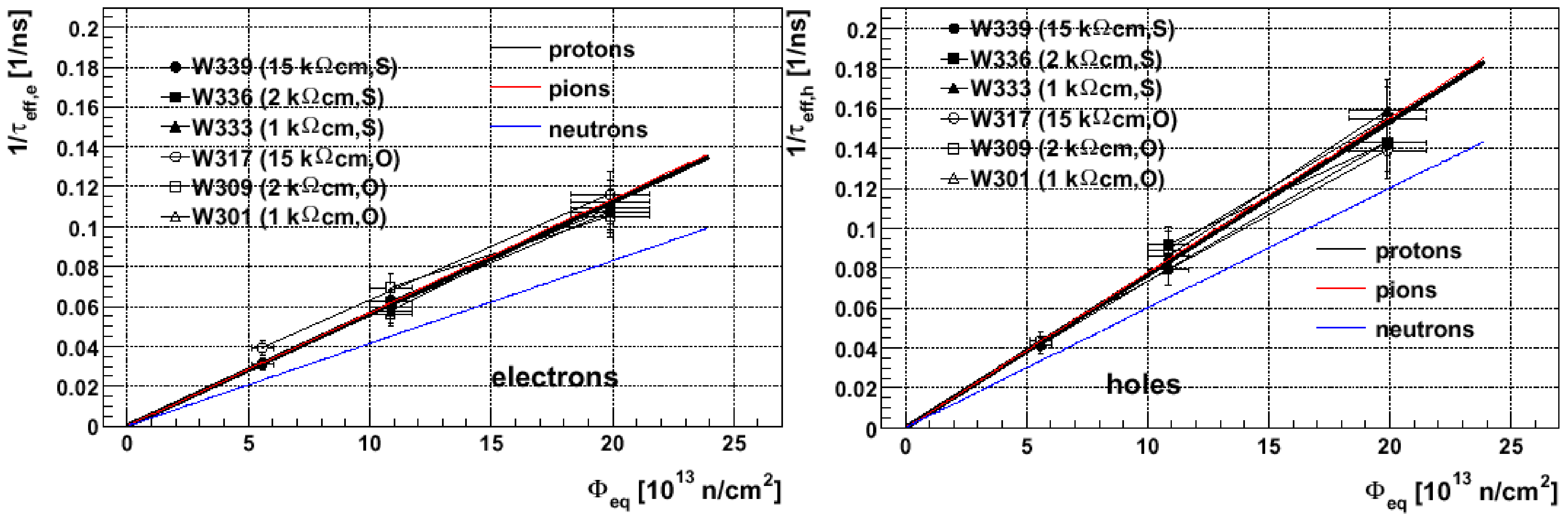
$\tau_{eff} = \tau_{tr}$ that gives equal current integral above V_{FD} (compensate the trapping)



$\tau_{tr} > \tau_{eff}$ - lower voltages are under weighted

CCE can be determined from the corrected charge and measured charge ratio!!

IIIe. Effective carrier trapping time determination



$$\frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(t,T)\,\Phi_{eq}$$

T=-10°C	$\beta_e[10^{-16}cm^2/ns]$	$\beta_e[10^{-16}cm^2/ns]$
reactor neutrons	4.1±0.1 (~5-8)	6.0±0.2 (~2-3)
pions	5.7±0.2	7.7±0.2
protons	5.6±0.2	7.7±0.2

Different material were studied in terms of: oxygen content, carbon content, initial resistivity, different silicon wafer producers and manufacturers (topsil-BNL,wacker-STM)

IVa. Electric field profile in the detector (diode)

induced current pulse shape (measured) ✓
weighting field (pad detector-1/D) ✓
mobility parameterization (literature) ✓
effective trapping times of *e,h* ✓

$$\left.\right\} \Rightarrow \boxed{\text{extract } \boldsymbol{E(x)}\ (E(x(t)),\, x(t))} \Downarrow \boxed{\text{determine } N_{eff}(x)}$$

$$\color{green}{\enclose{circle}{I_{e,h}(t)}}\color{black}{} = N_0 \exp\left(\frac{-t}{\color{green}{\enclose{circle}{\tau_{eff_{e,h}}}}}\right)\frac{1}{D}\, v_{e,h}(t)$$

$$\color{red}{\enclose{circle}{x_{e,h}(t)}}\color{black}{} = \int_{t_0}^{t} I_{e,h}(t')\,\frac{D}{\color{red}{\enclose{circle}{N_0}}}\exp\left(\frac{t'}{\tau_{eff_{e,h}}}\right) dt' \quad\Rightarrow\quad \color{green}{\enclose{circle}{D}}\color{black}{} = x_{e,h}(\color{green}{\enclose{circle}{t_t}}\color{black}{})$$

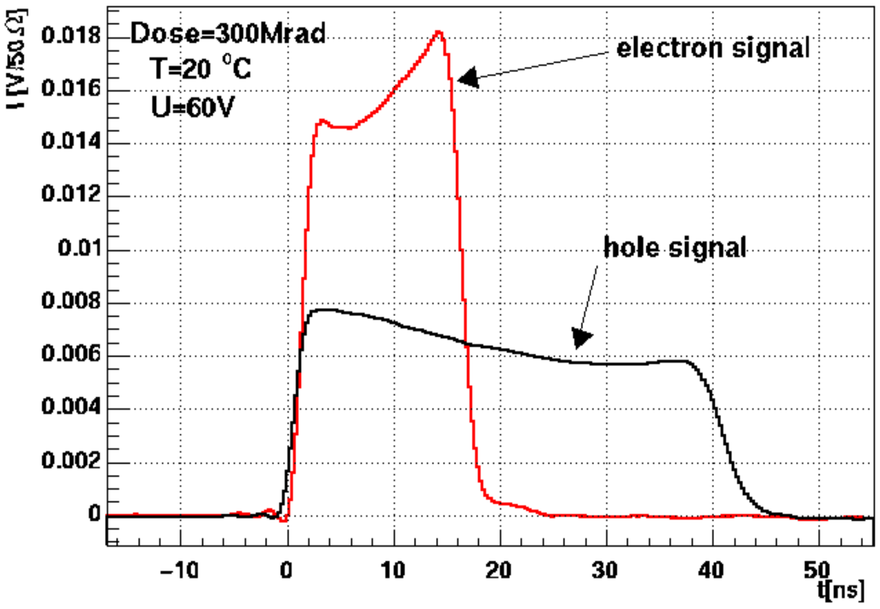
$$v_{e,h}(t) = \color{red}{\enclose{circle}{\mu_{e,h}(E(t))\,E(t)}}\color{black}{} = I_{e,h}(t)\,\frac{D}{N_0}\exp\left(\frac{t}{\tau_{eff_{e,h}}}\right)$$

$\color{green}{\bigcirc}$ input-meas. parameters

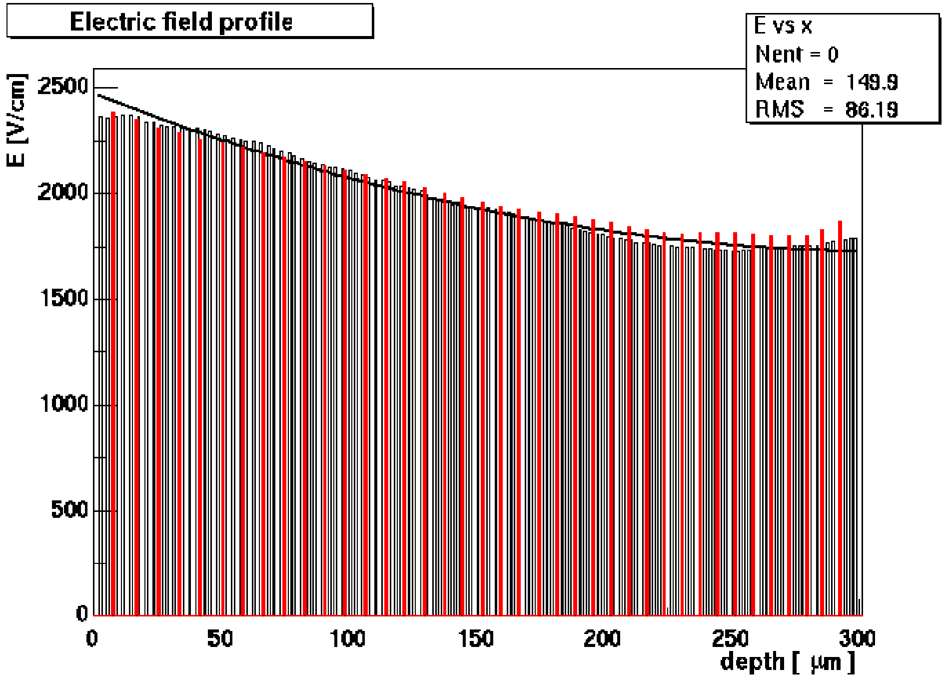
$\color{red}{\bigcirc}$ unknown parameters

More reliable determination from holes signals
(longer signal, less influence of laser width)!

IVb. Electric field profile in the detector (diode)



measured TCT pulse shapes

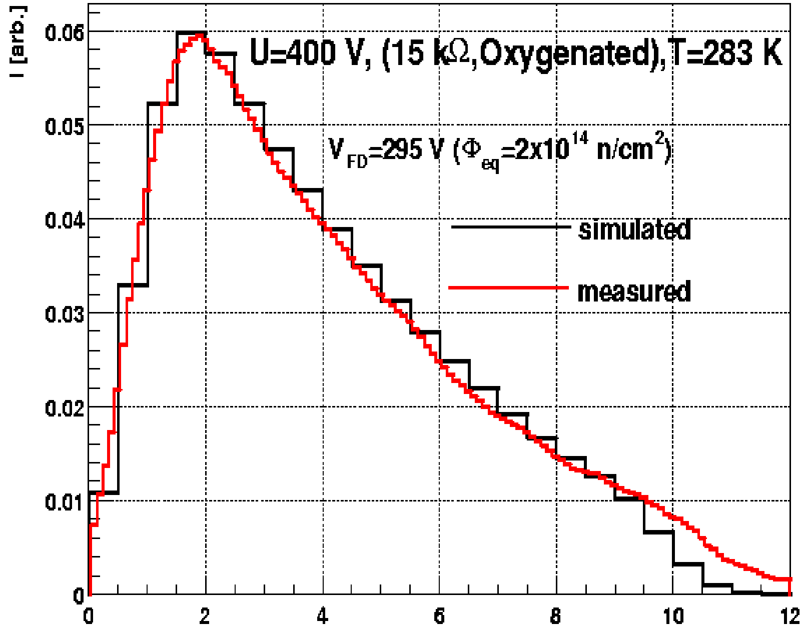


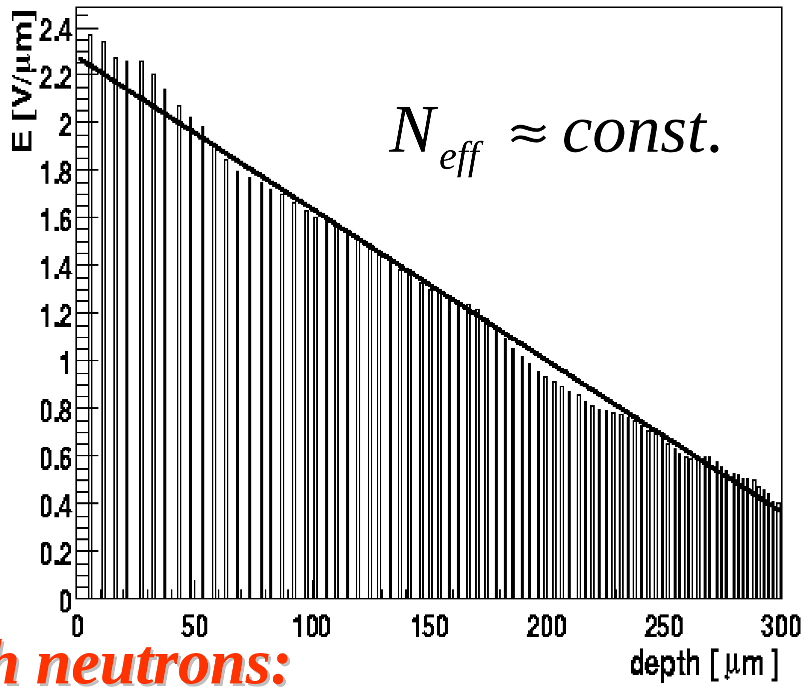
electric field profile
obtained from meas.

Improvements to be done:

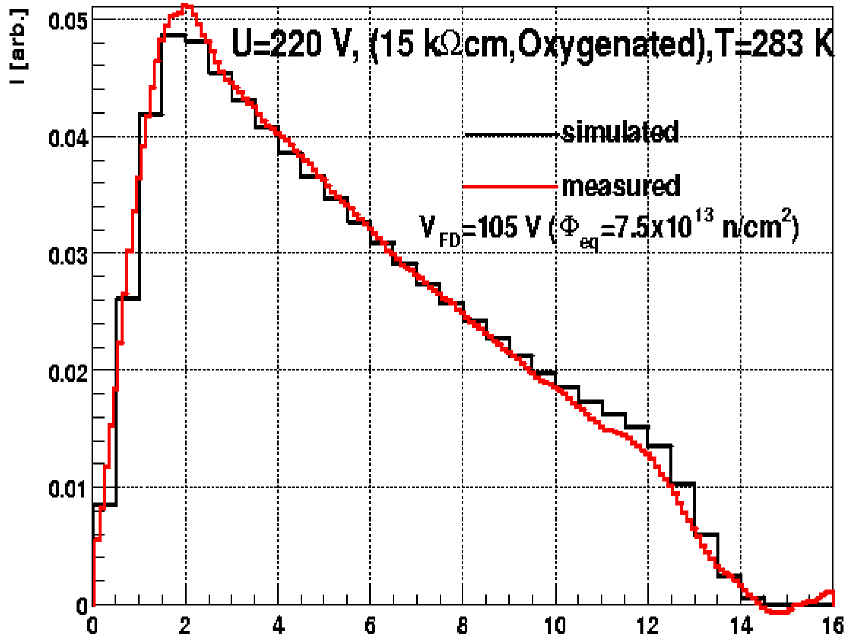
- deconvolution of measured current for laser pulse to be taken into account!
- choice of t_c is to some extent (of order ~1 ns) arbitrary!

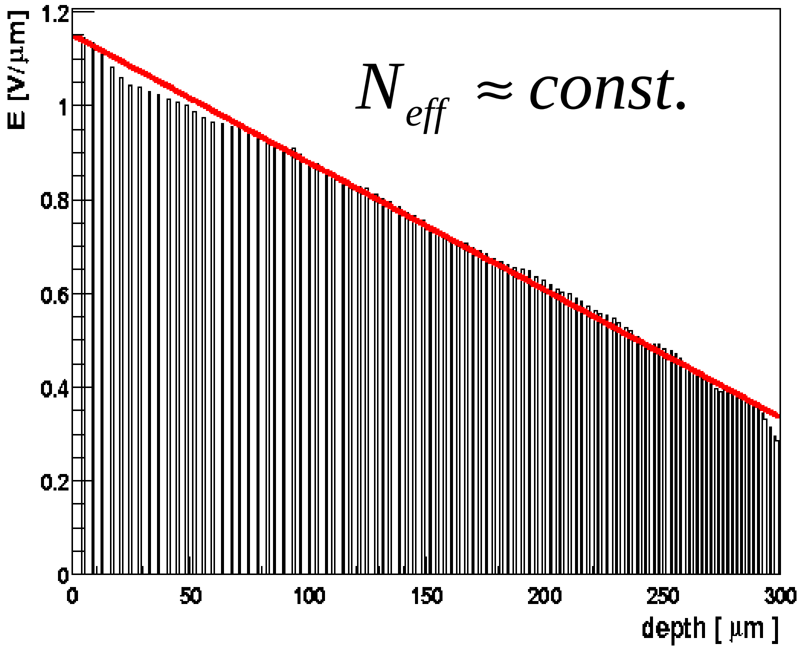
Standard material irradiated with neutrons:



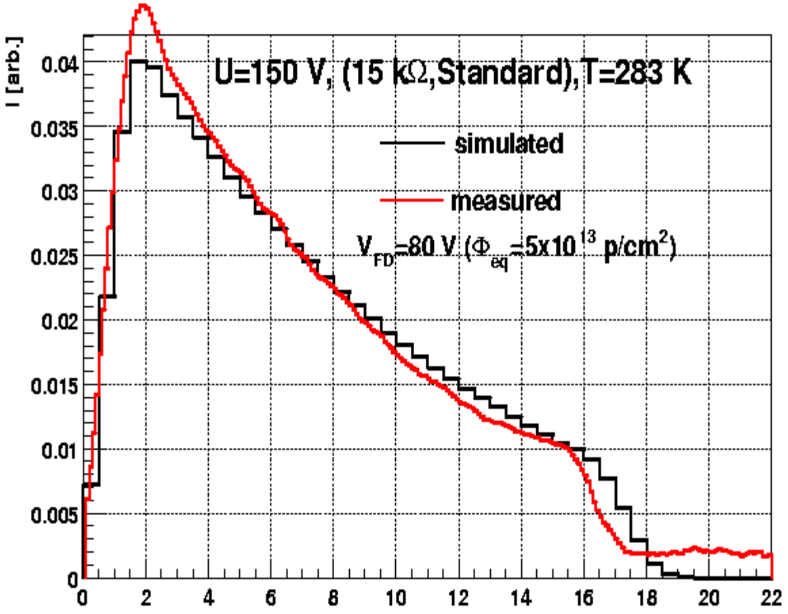


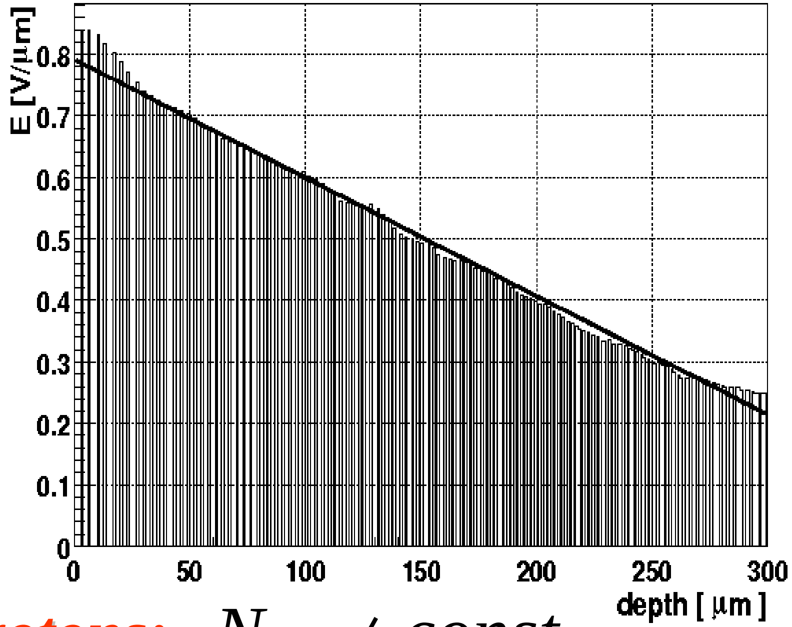
Oxygenated material irradiated with neutrons:



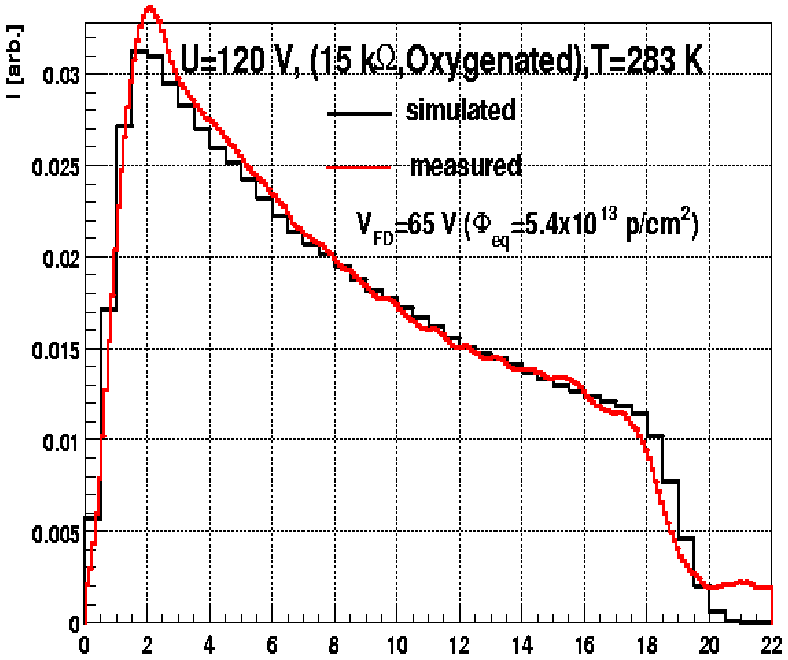


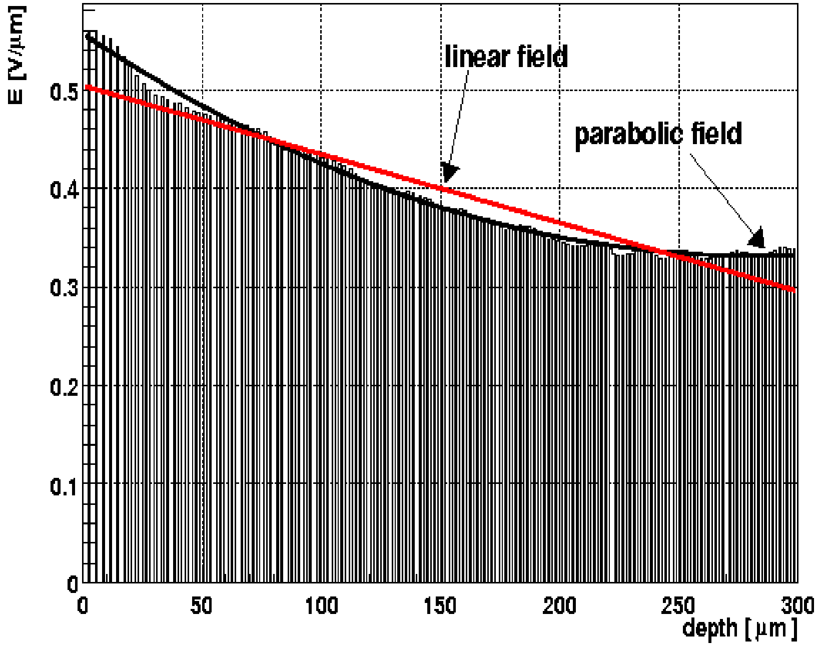
Standard material irradiated with protons: $N_{eff} \approx const.$





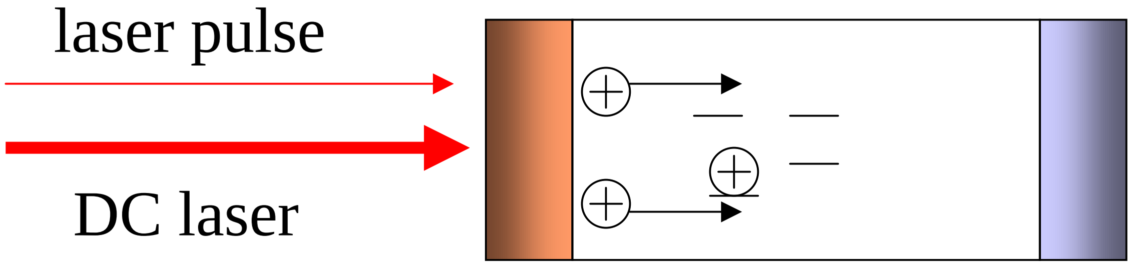
Oxygenated material irradiated with protons: $N_{eff} \neq const.$





Va. Defect characterization

Observation of TCT signals at different T and presence of continuos illumination!



$$p = \frac{\Delta I}{S\, v_h\, e_0}$$

Increase of leakage current due to illumination

drift time of holes through the detector

N_{eff} controlled by:

- illumination intensity (p)
- operation voltage (p)
- temperature (trapping -detrapping process)

capture

emission

$$\frac{dp_t}{dt} = c_p\, p\, [P_t - p_t] - e_p\, p_t$$

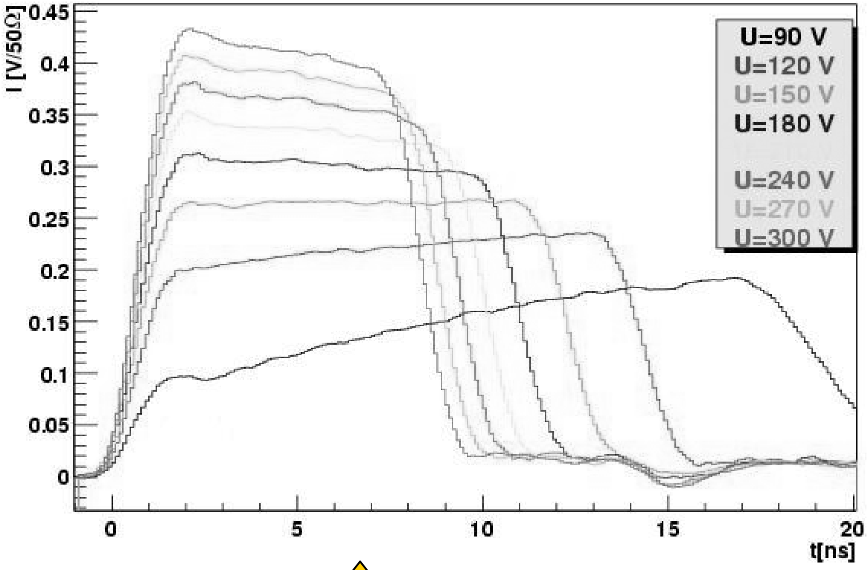
concentration of free traps

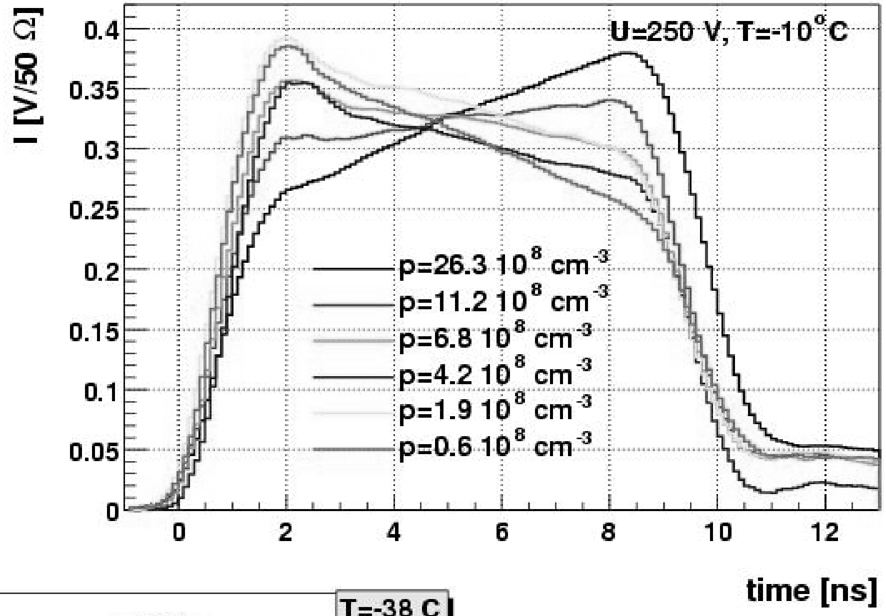
$$p_t(t) = c_p\, p\, P_t \tau_{td,p} \left[1 - \exp\left(-\frac{t}{\tau_{td,p}}\right) \right]$$

$$\tau_{td,p} = (c_p\, p + e_p)^{-1}$$

$$\xrightarrow{t \to \infty} N_{eff}(T, p) = N_{eff,0} + p_{t\infty}(E_t, p, T)$$

Vb. Defect characterization (steady state)





Hole injection!

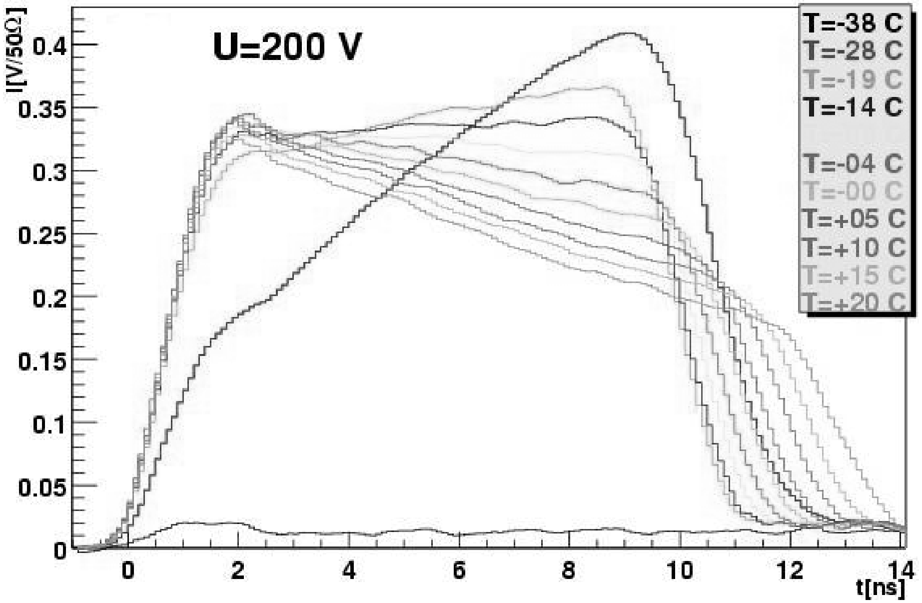
Φ_{eq}=5 x 10^{13} cm^{-3}

different voltages

p=2-14 x 10^{8} cm^{-3}
T=263 K

different temperatures

p~3 x 10^{8} cm^{-3}



Hole injection!

Φ_{eq}=7.5 x 10^{13} cm^{-3}

different light intesisties

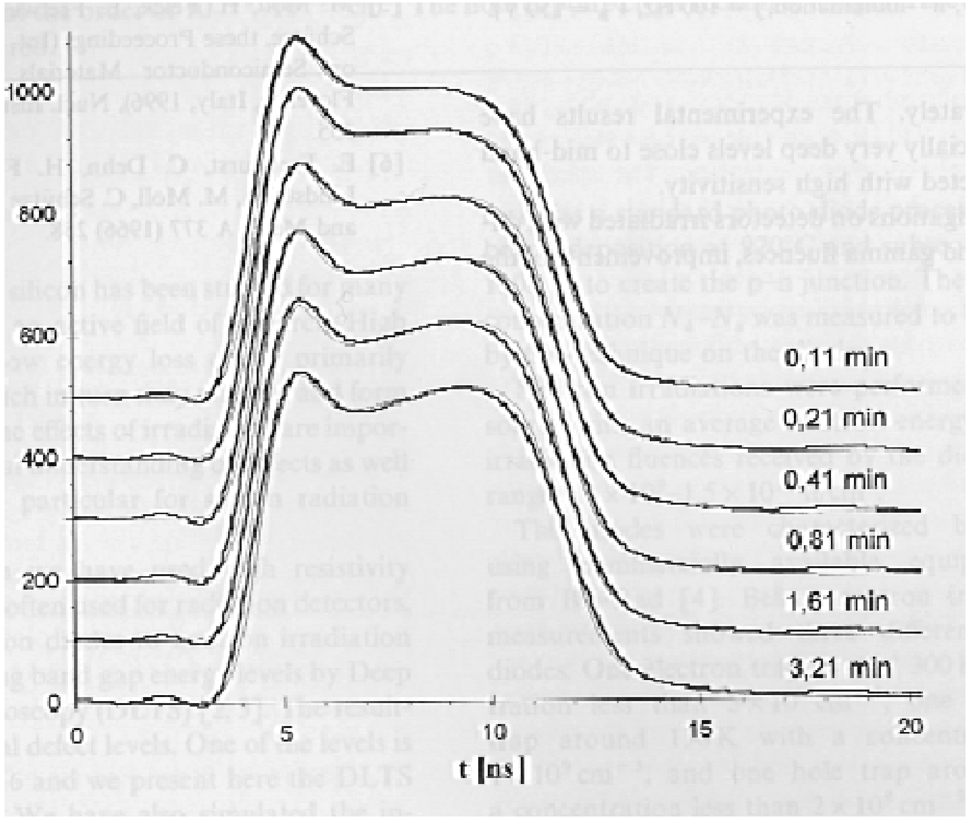
T=263 K , U=180 V

N_{eff} can be estimated from the slope of the signal!

Vc. Defect characterization (transient analysis)

Transient analysis:

E. Fretwurst et al. NIMA 388,p. 356



trap filling and change of electric field

↓

from fits to measured signals one can obtain

effective dopant concentration

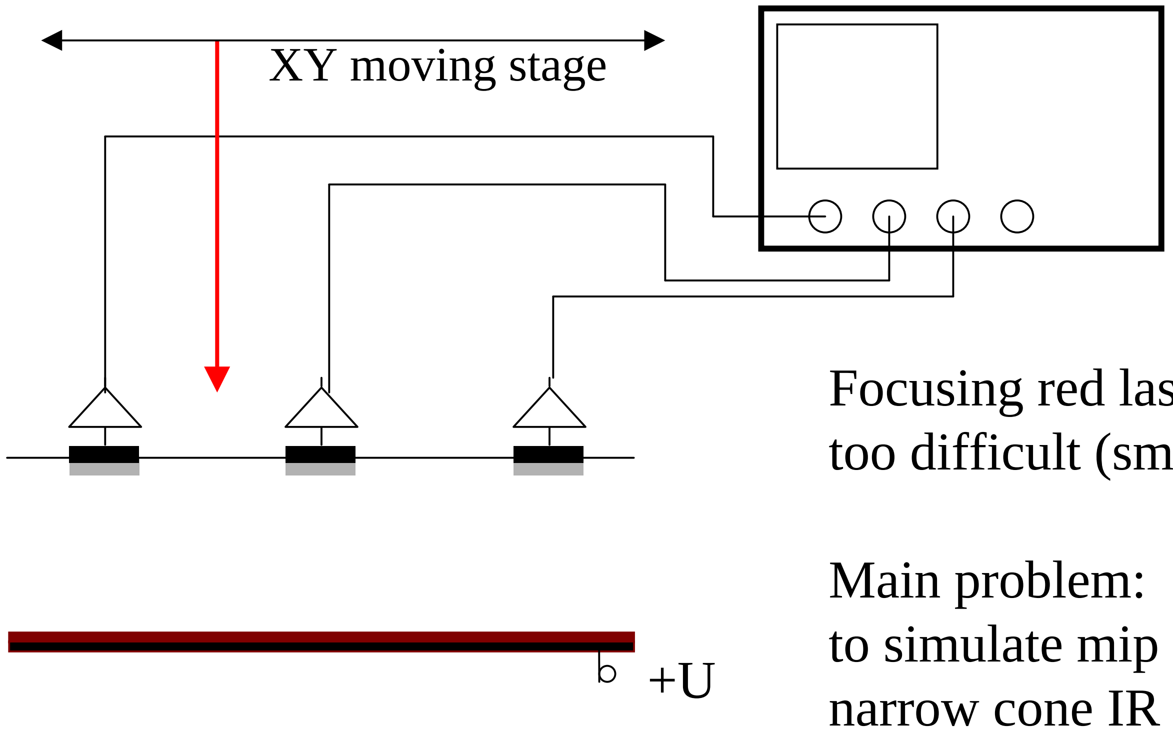
↓

parameters ($\sigma_{e,h}$, P_t) of traps can be extracted

transient analysis at different T has to be performed to reveal different traps

VI. Charge collection in segmented devices (FUTURE WORK)

E_w depends on geometry of segmented (multi electrode) devices and causes different signal formation properties as expected from simple planar diodes!



Focusing red laser to few mm is not too difficult (small penetration depth)

Main problem:
to simulate mip particles
narrow cone IR laser is needed !

Potential interest:

- study of transfer coefficients for silicon detectors with intermediate strips
- charge sharing between electrodes induced by charge trapping
- study of electric field profile (dead pockets)

Conclusions

A TCT is a powerful and yet simple tool to investigate large number of silicon detector properties!

Crucial building blocks of a TCT set-up are:
- short laser pulse (driver, red, IR)
- fast amplifier and fast oscilloscope + good cabling
- cryostat

A review of various measurement quantities mostly related to measurements of irradiated detectors are given:
- sign of the space charge
- voltage of full depletion
- determination of effective trapping times
- extraction of electric field profile
- usage of TCT to determine the properties of traps