Status Report: Charge Cloud Explosion

J. Becker, D. Eckstein, R. Klanner, G. Steinbrück
University of Hamburg
Detector laboratory

1. Introduction and Motivation
2. Set-up available for measurement
3. Measurements on pad diodes
4. Simulations by Weierstraß Insitute Berlin
5. Measurements on strip detectors
6. Conclusion and next steps

Introduction

Aim and main goal:

- **Determination of pulse shape of individual pixels with XFEL type irradiation.**
- **Agreement of experimental reference data and simulations**

Relevant XFEL-specification: Photon fluxes of 10^0 - 10^5 γ/pixel/pulse (12 keV)

Properties of the charge cloud are not well understood for more deposited energy than mips (~25000 e,h Pairs). Possible effects include:

- **Plasma effects: Distortion of pulses.**
- **Charge Cloud expansion: Charge sharing in neighboring pixels due to diffusion and electrostatic repulsion.**
- **Recombination losses: Signal loss due to electron-hole recombination (can most probably be neglected).**

A Multi-Channel TCT setup records pulse shapes and therefore allows to study these effects in a structured device (strip or pixel detector) -> experimental reference data

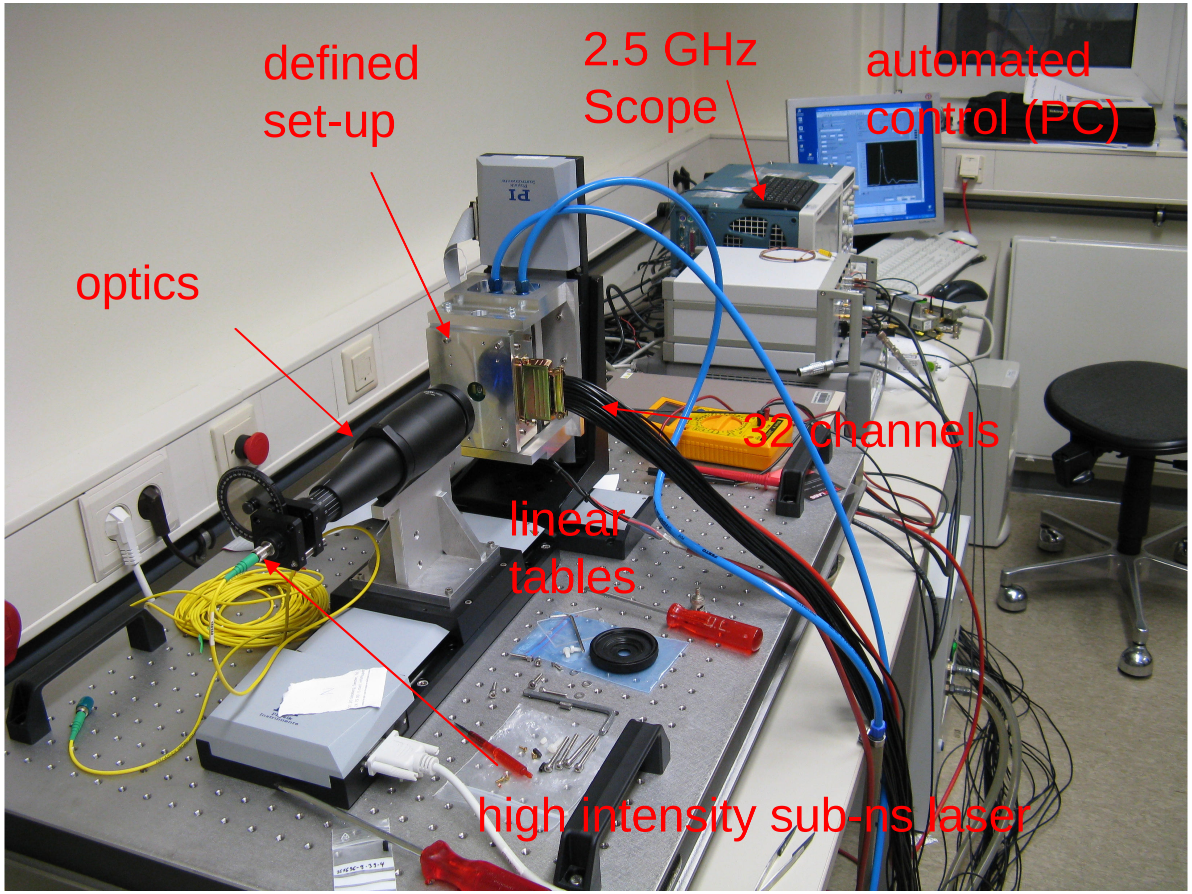
Set-up and measurement techniques

TCT (Transient Current Technique) records the time-resolved current of the device under test.

⇒ Pulse shape

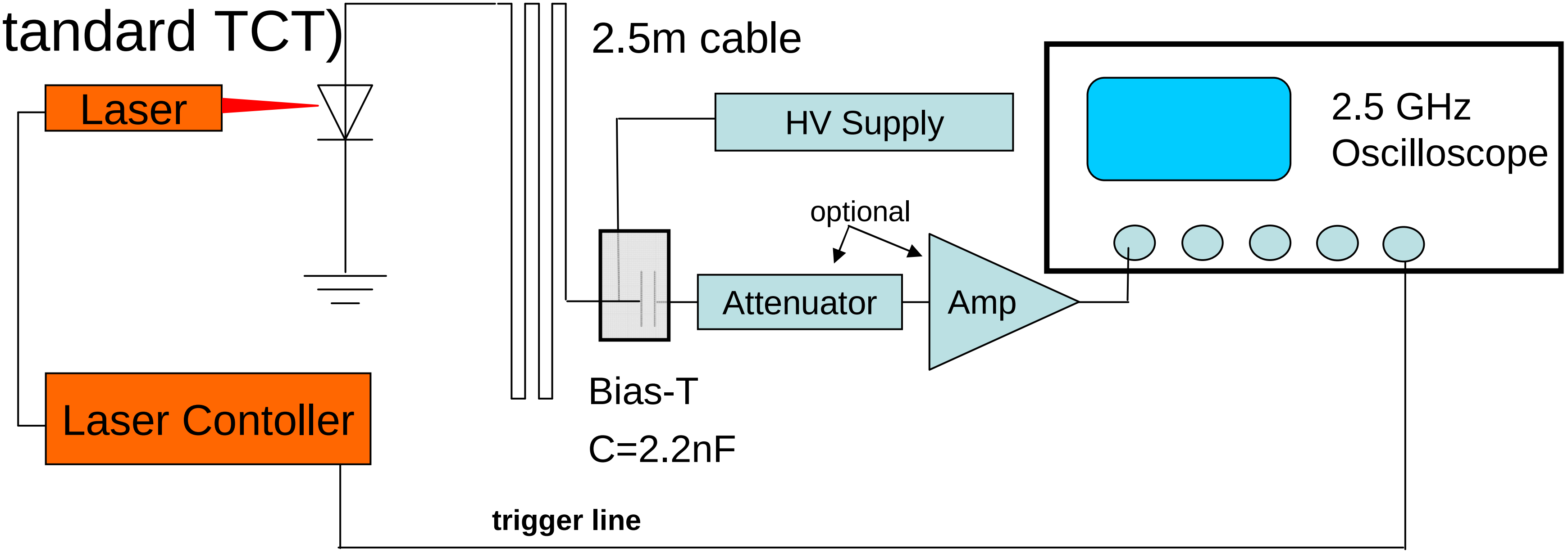
recent upgrade featuring the following improvements:

- Smaller spotsize due to improved optics
- Defined set-up allowing to investigate structured devices
- Improved electronics with multi GHz bandwidth



1st Configuration

Diode measurements (standard TCT)



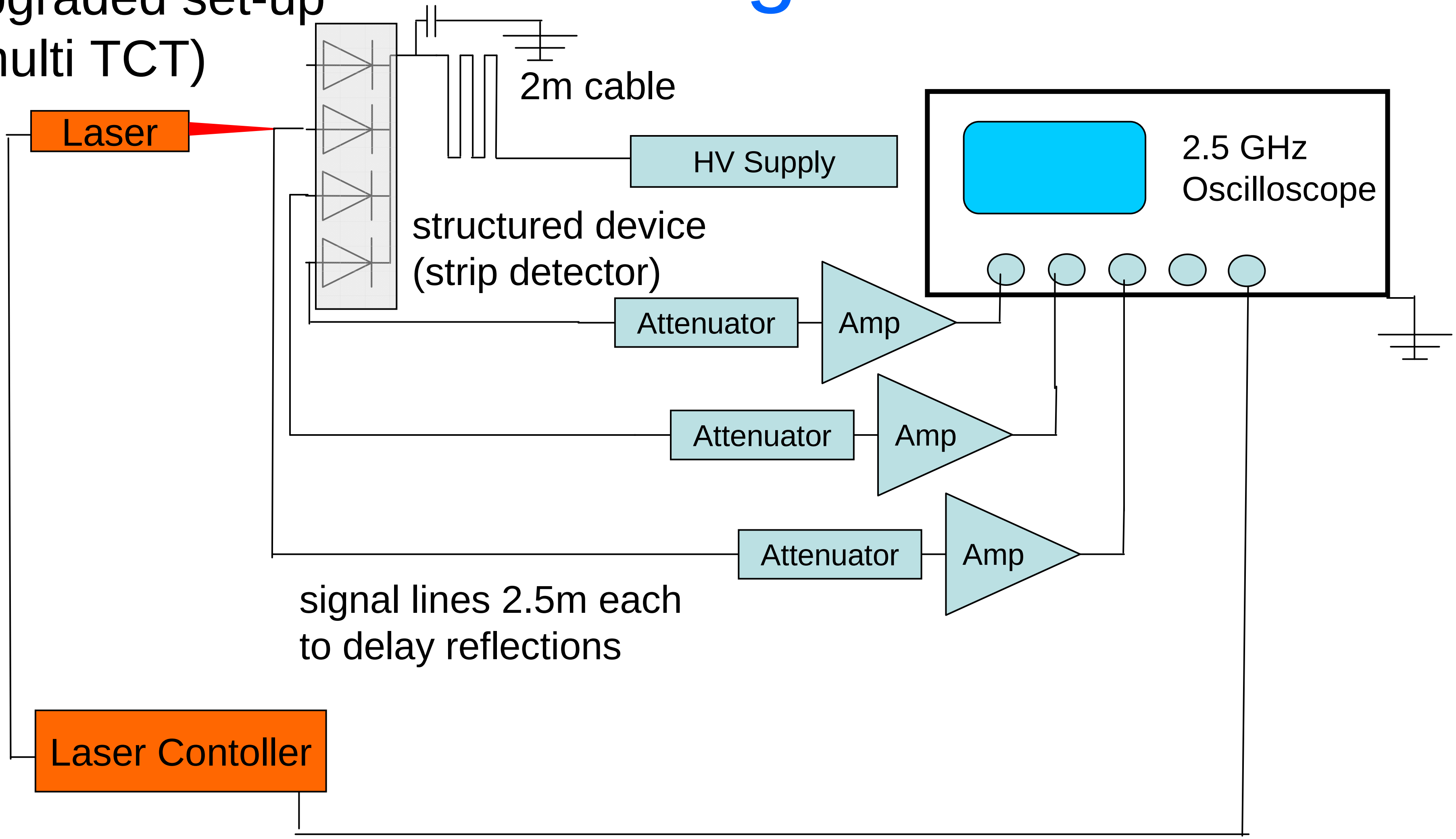
Element	Bandwidth	Risetime	
Bias-T:	18 GHz	45 ps	235 ps
Attenuator:	4 GHz	85 ps	
Oscilloscope:	2.5 GHz	115 ps	170 ps (no att & amp)
Amplifier*:	1.8 GHz	180 ps	

Pulse shape is electronically smeared!

* only necessary with low intensity injection

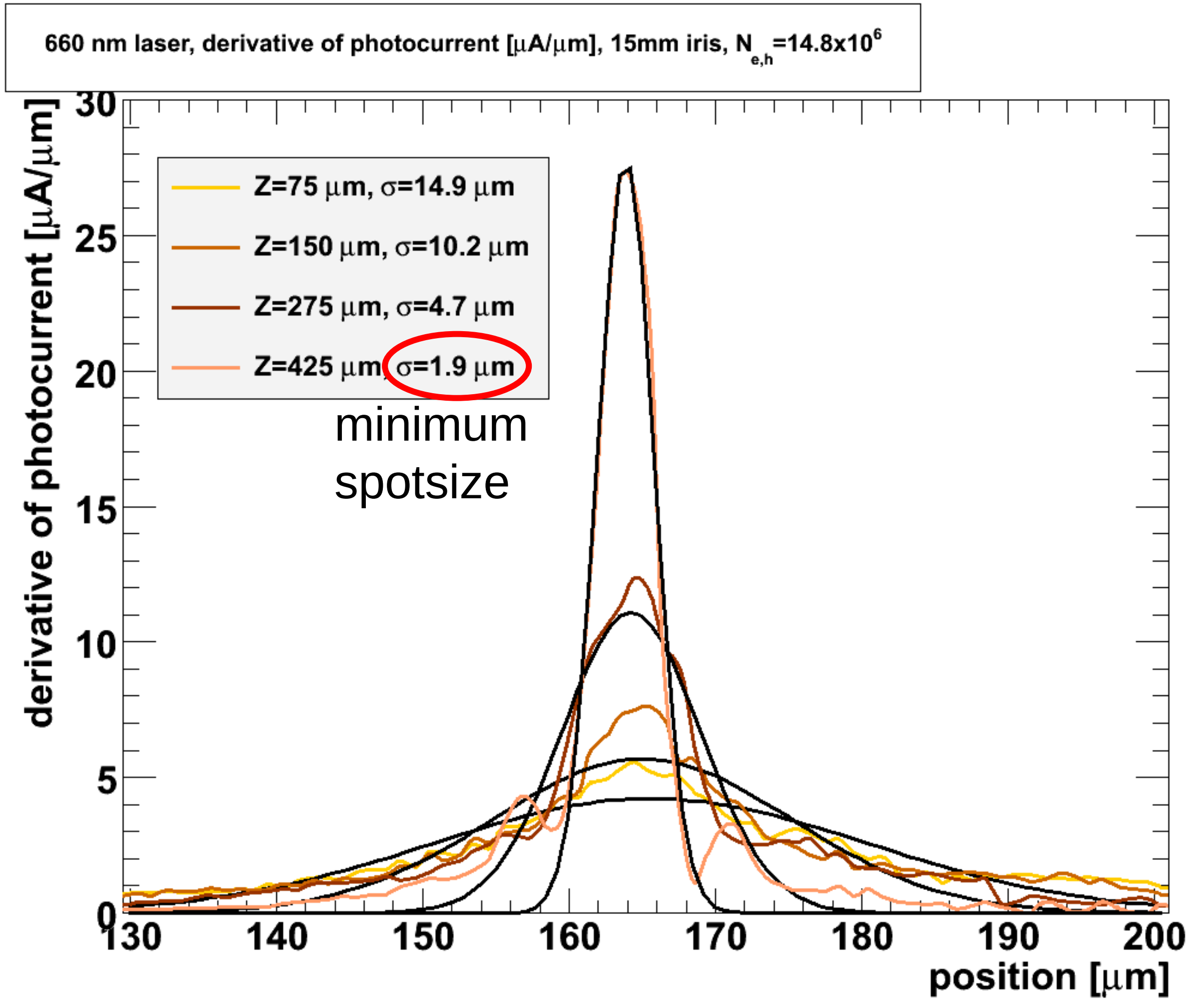
2nd Configuration

upgraded set-up
(multi TCT)



trigger line

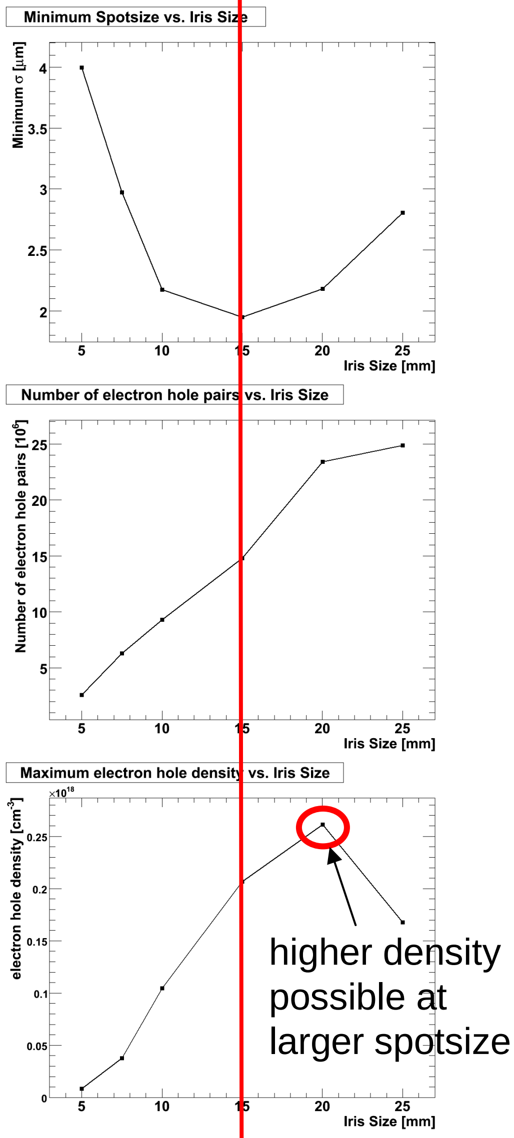
Beam characteristics



minimum spotsize

Beam profile

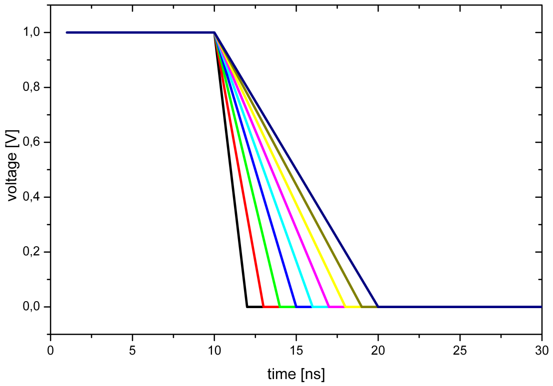
colored lines -> measurement
black lines -> gaussian fit

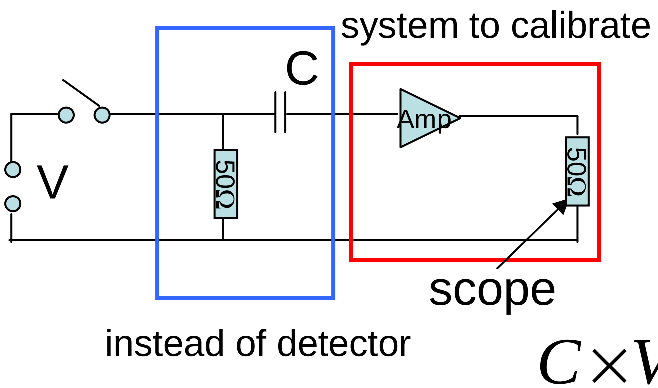


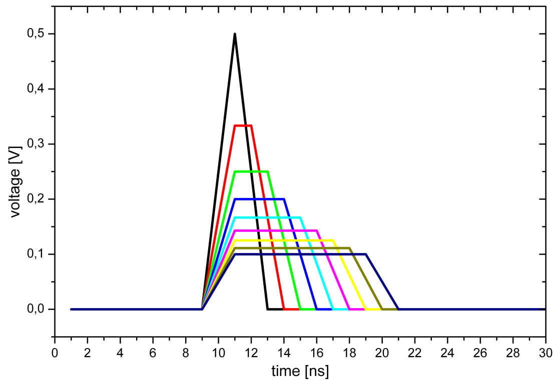
higher density possible at larger spotsize

System calibration

Calibration: injecting a step function (V) over a known capacitance (C) into the system







$$C \times V = K \int U_{osc}(t) / R_{osc} \, dt$$

so far the system is not calibrated

-> signal loss in cables and electronics is not accounted for

-> frequency dependent signal loss: 1dB/m@1GHz = 25 % loss in 2.5 m cable

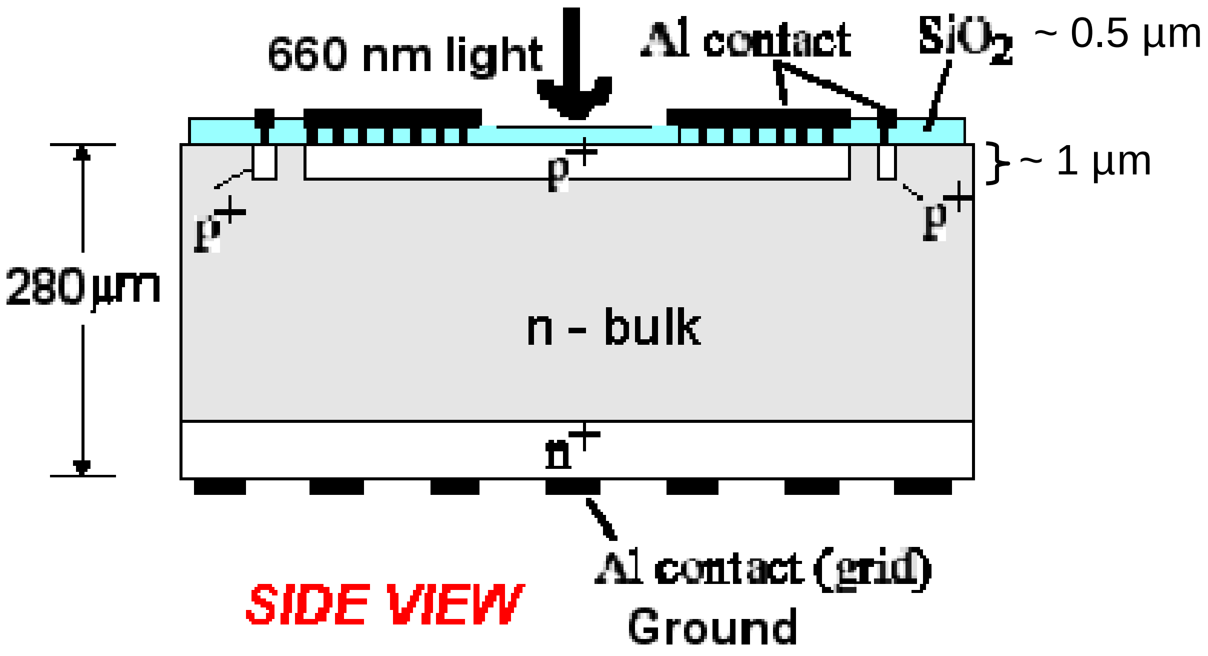
-> first measurements indicate signal loss of 23 % (K=1.3)

-> very little effect on relative measurements

-> up to 30% increase in number of electron hole pairs and thus 12 keV photons

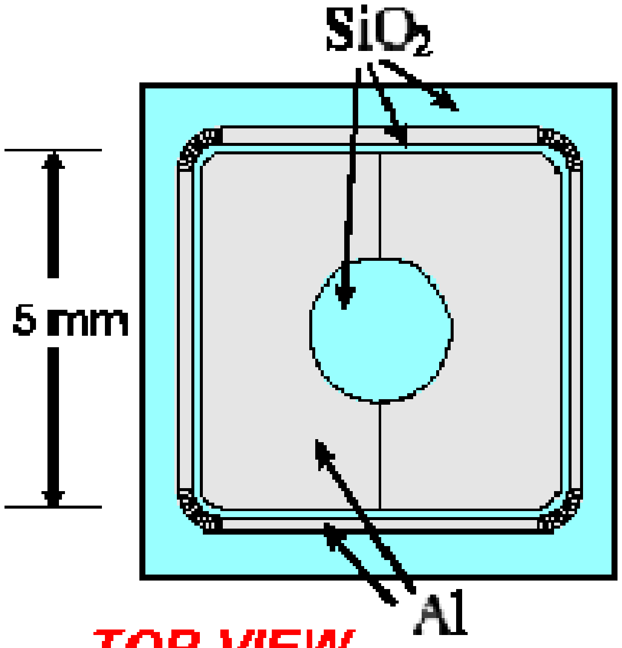
Measurements on pad diodes

CG1233 FZ-n-Si 280 µm, N_{eff}= 8x10^{11} cm^{-3}, U_{dep} = 48.5 V, C_{dep} = 9.5 pF, ρ= 5.3 kΩcm



SIDE VIEW

no to scale



TOP VIEW

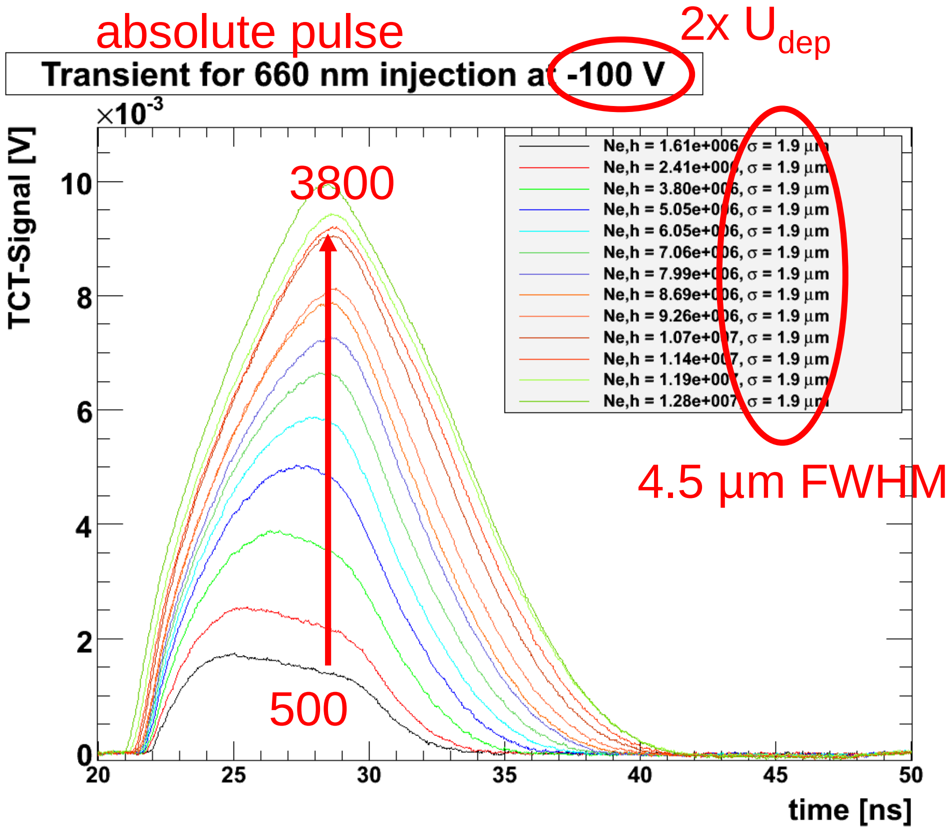
no to scale

Injection of 1.6 – 12.8 x10^6 e,h pairs

-> 500 – 3800 absorbed 12 keV γ (within 3 µm attenuation length)

Measurements on pad diodes

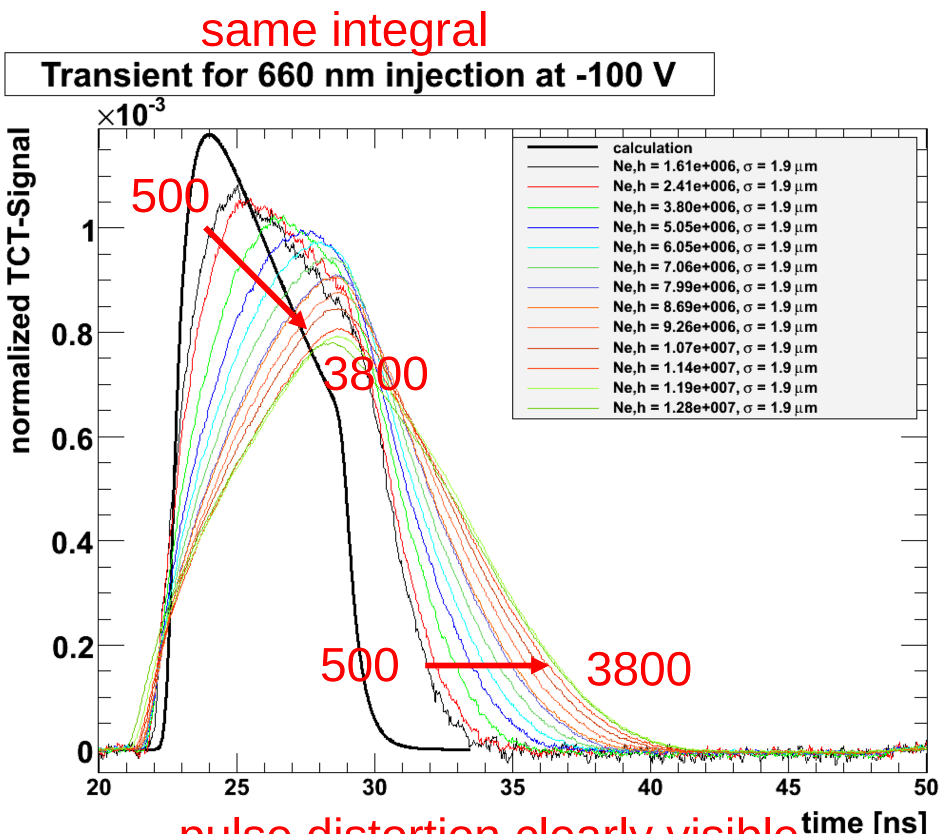
injection of 1.6 – 12.8 x10^6 e,h Pairs -> 500 – 3800 absorbed 12 keV γ



absolute pulse

2x U_{dep}

4.5 µm FWHM



same integral

pulse distortion clearly visible

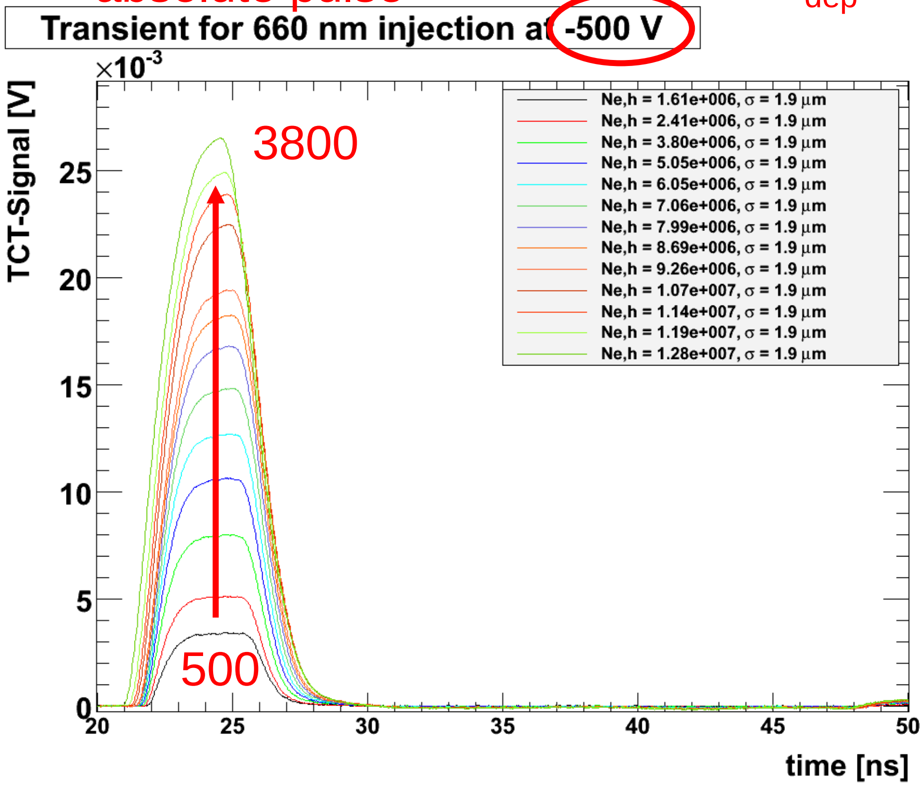
CG1233 FZ-n-Si 280 µm, N_{eff}= 8x10^{11} cm^{-3}, U_{dep} = 48.5 V, C_{dep} = 9.5 pF, ρ= 5.3 kΩcm

Measurements on pad diodes

injection of 1.6 – 12.8 x10^6 e,h Pairs -> 500 – 3800 absorbed 12 keV γ

absolute pulse

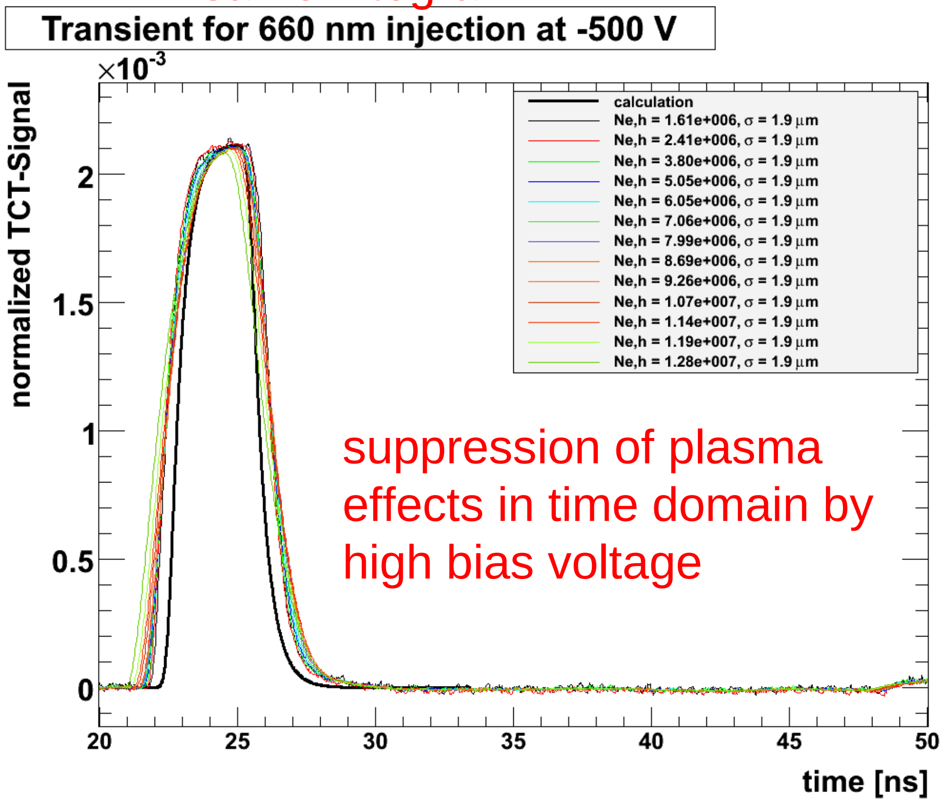
10x U_{dep}



3800

500

same integral



suppression of plasma effects in time domain by high bias voltage

CG1233 FZ-n-Si 280 µm, N_{eff}= 8x10^{11} cm^{-3}, U_{dep} = 48.5 V, C_{dep} = 9.5 pF, ρ= 5.3 kΩcm

Simulations from WIAS Berlin

Simulations using numerical solutions to the van Roosbroeck system of (partial) differential transport equations on a Delaunay grid (don‘t ask for details)

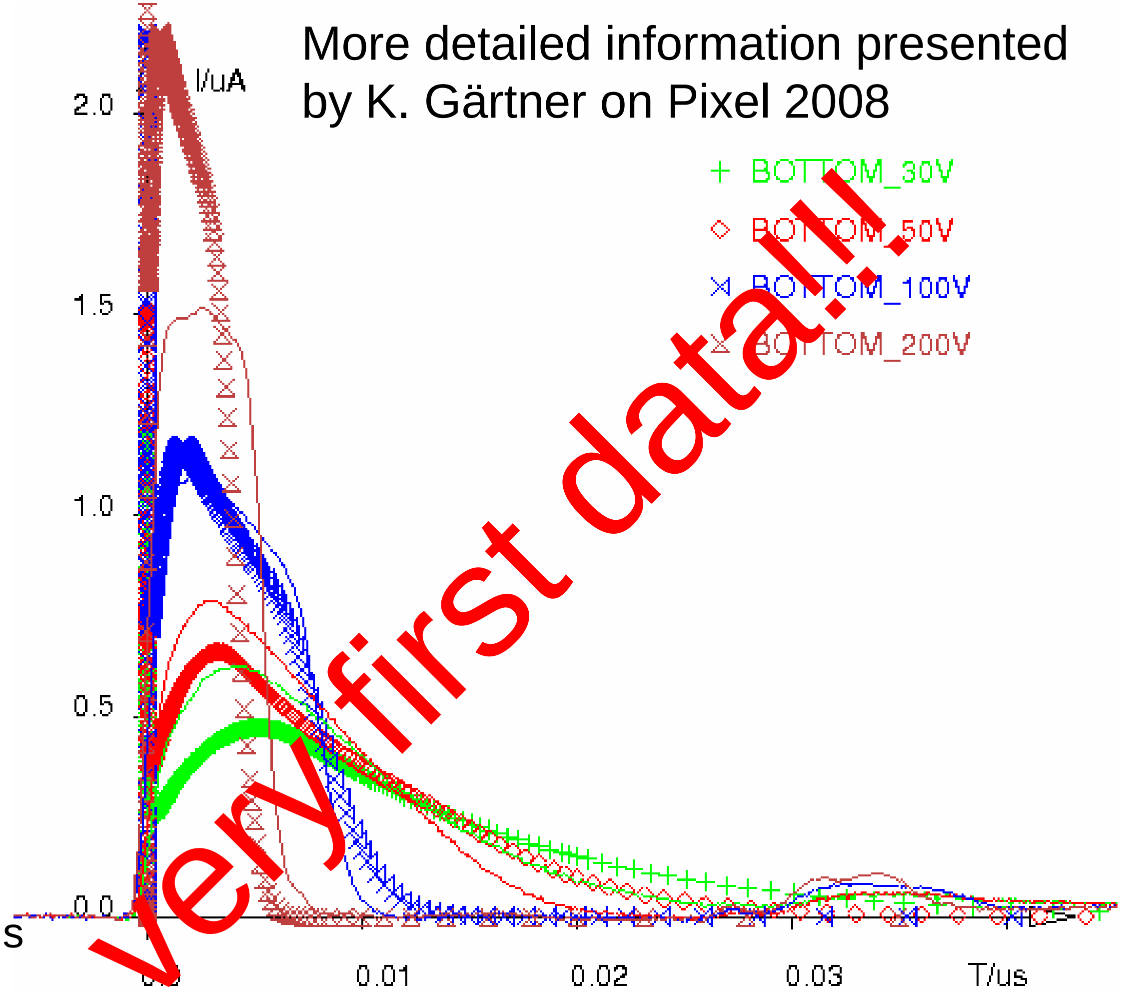
Major features:

- includes diffusive transport
- includes charge carrier interactions (repulsion, recombination, etc)

Open points:

- so far using constant mobility
  -> no electric field/density corrections
- so far no simulation of electronics
  -> to be done with external circuit simulation (SPICE)

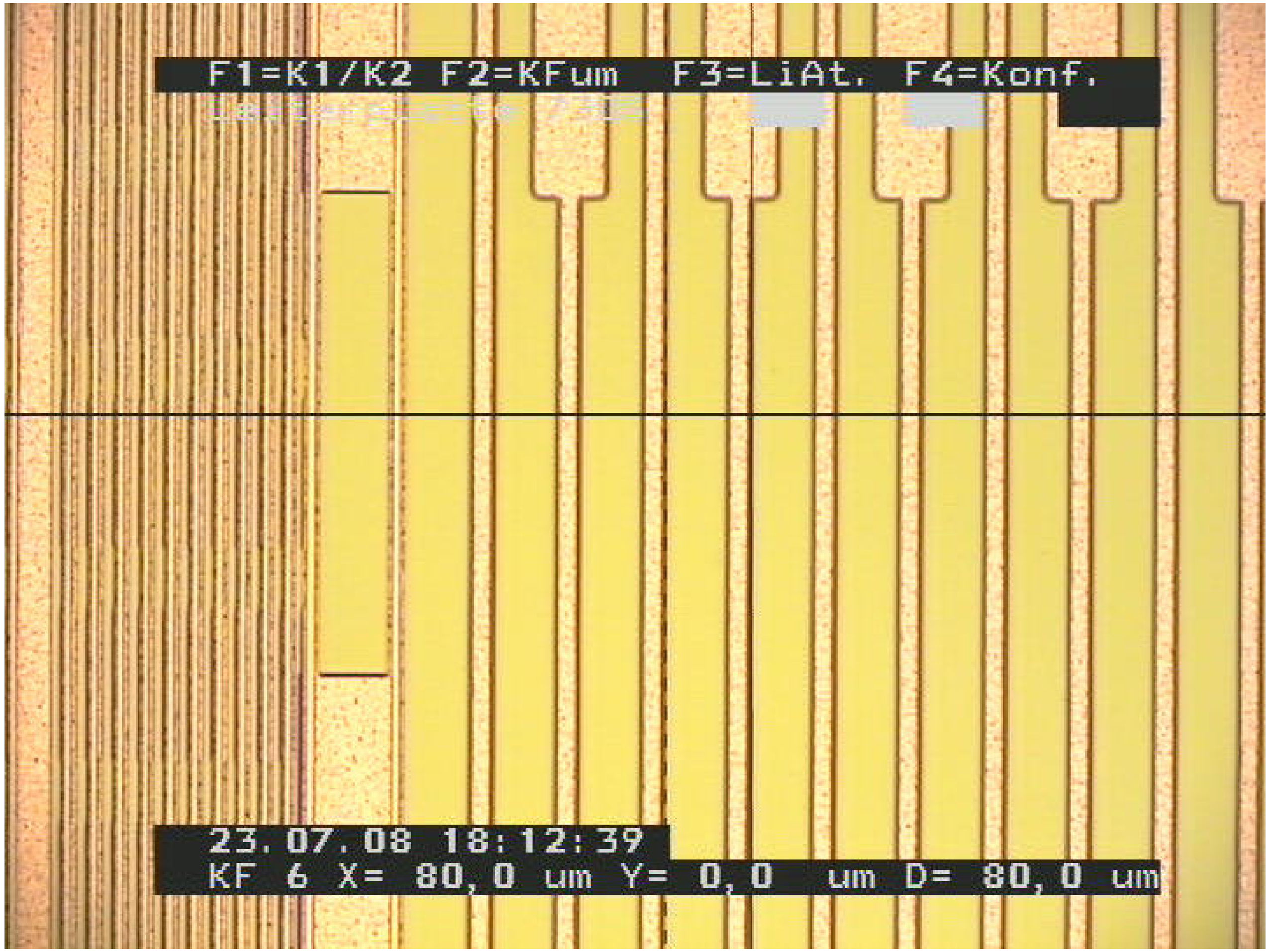
More detailed information presented by K. Gärtner on Pixel 2008



BOTTOM=30 ... 200V, TOP=0V, tau_SRH=0.001s, 1.8M pairs,

lines: measurement s10_1.8Meh_deconv 30, 50, 100, 200V

Measurements on Strip detectors



CG1017 Strip detector

same Wafer as CG1233

FZ n-type Silicon

Thickness 280 µm

U_{dep} ~ 50 V

N_{eff} ~ 8×10^{11} cm^{-3}

ρ ~ 5 kΩcm

Pitch 80 µm

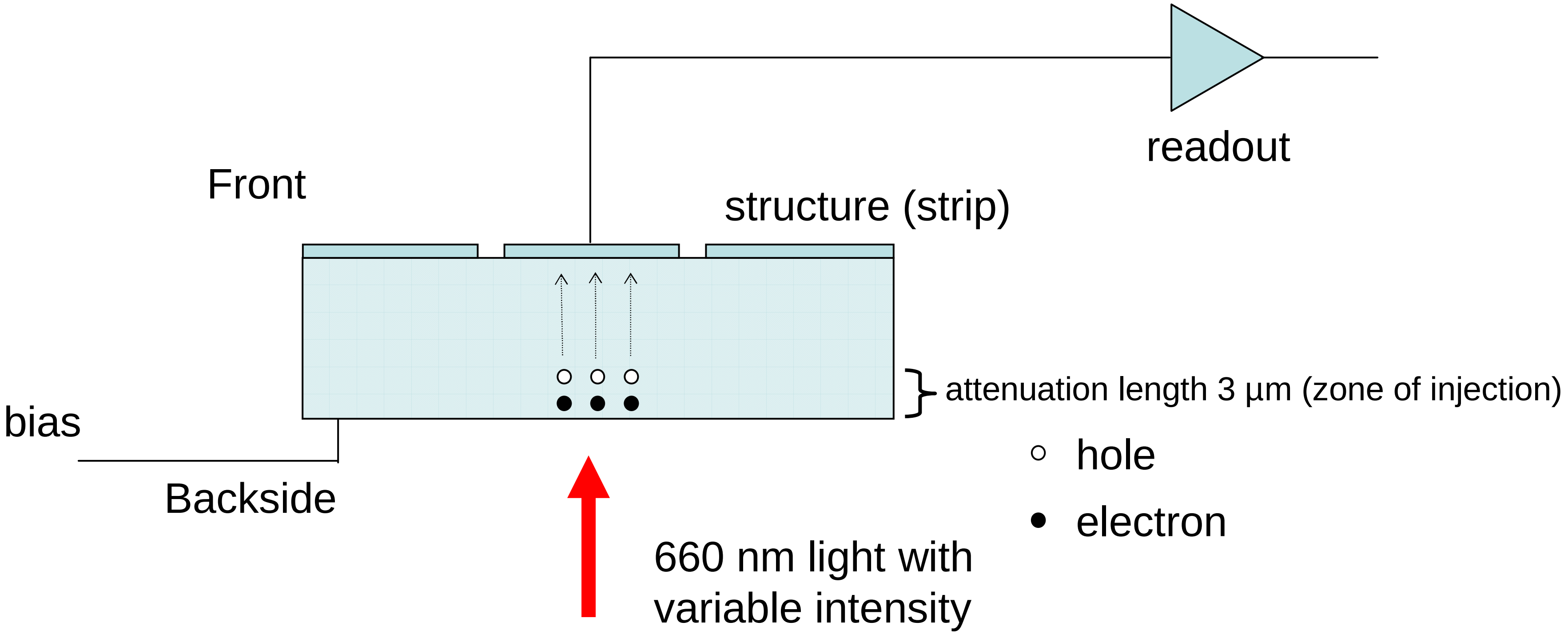
Width 25 µm
(determined from microscope picture)

Intensity sensitive measurements

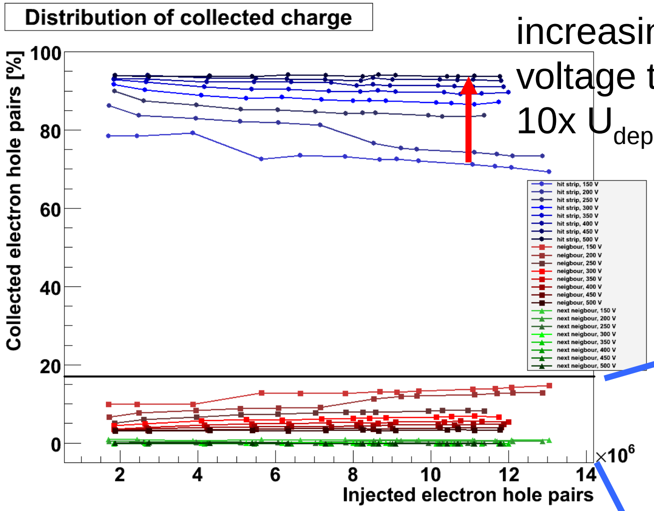
Intensity scan with spotsize FWHM 5 µm and fixed injection position (center of strip)

injection of 660 nm light from backside (holes)

hole drift is slower than electron drift -> more time for expansion



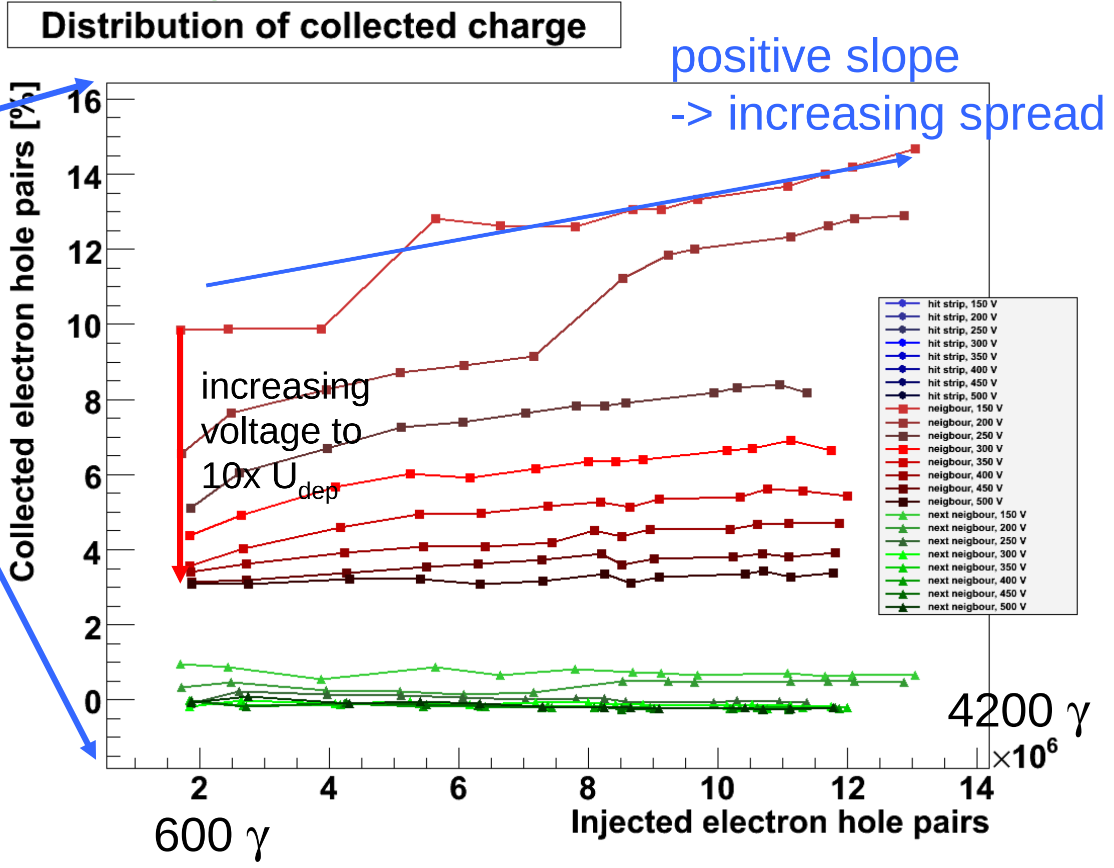
Intensity dependence



increasing voltage to 10x U_{dep}

Charge collected on 3 adjacent strips

- hit strip
- neighbour
- next neighbour



positive slope
-> increasing spread

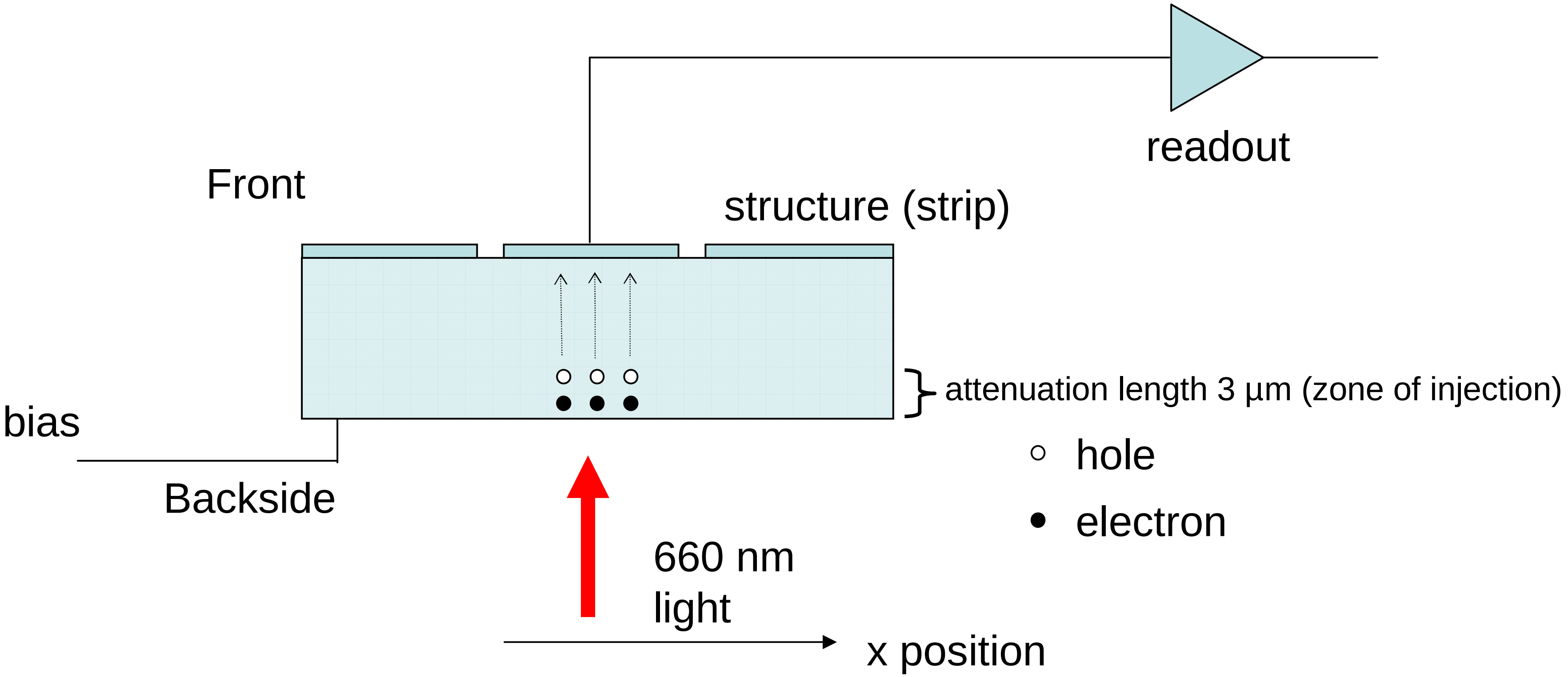
- „spread“ of charge is increasing with number of charge carriers (el.stat. repulsion)
- Effect can be partially counteracted by increasing bias voltage due to the reduction of carrier drift-time

Position sensitive measurements

Position scan with spotsize FWHM 5 µm

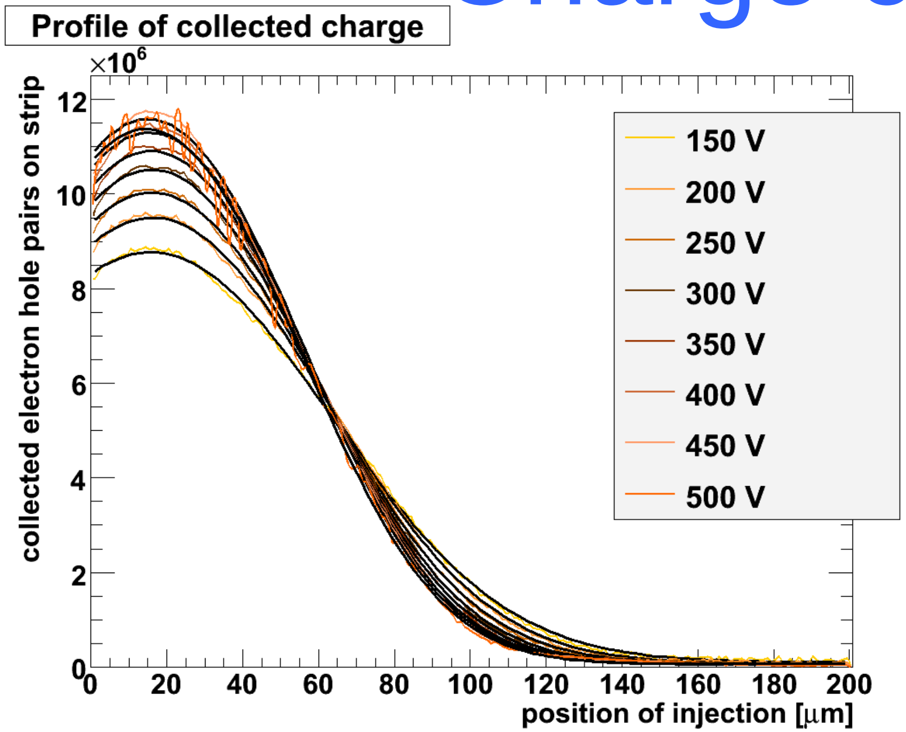
injection of 660 nm light from backside (holes)

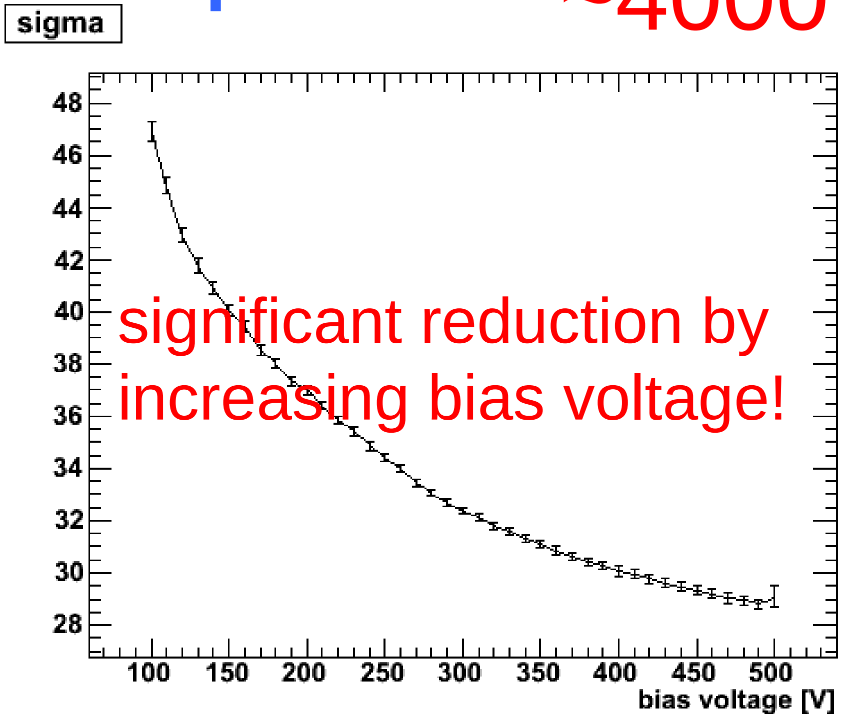
hole drift is slower than electron drift -> more time for expansion



Charge cloud profile

~4000 γ





significant reduction by increasing bias voltage!

- Fitting done with assumption of gaussian charge carrier distribution and box integration along strip pitch

- expected sigma for pure diffusion in the range of 5 µm

$$C(x) = c_0 + N_0 \int_{x-\frac{p}{2}}^{x+\frac{p}{2}} \exp\left(-\frac{(y-\mu)^2}{2\sigma^2}\right) dy$$

C(x) collected charge

x position of injection

c_0 contribution of noise

N_0 total number of injected carriers

p strip pitch

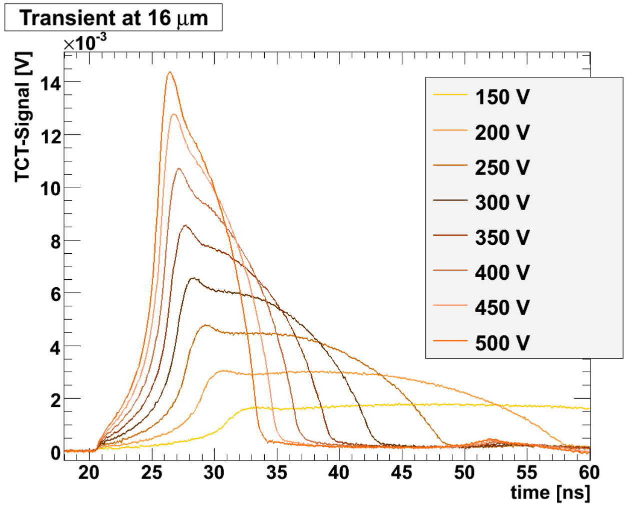
µ position of strip center

σ spread of charge carrier distribution

Position sensitive transients

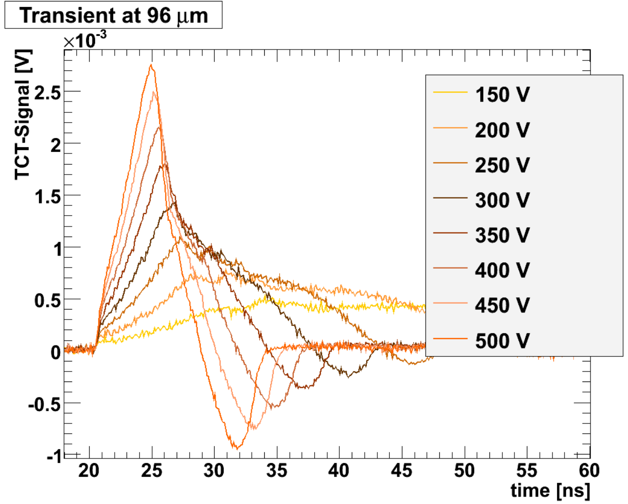
~4000 γ

central hit



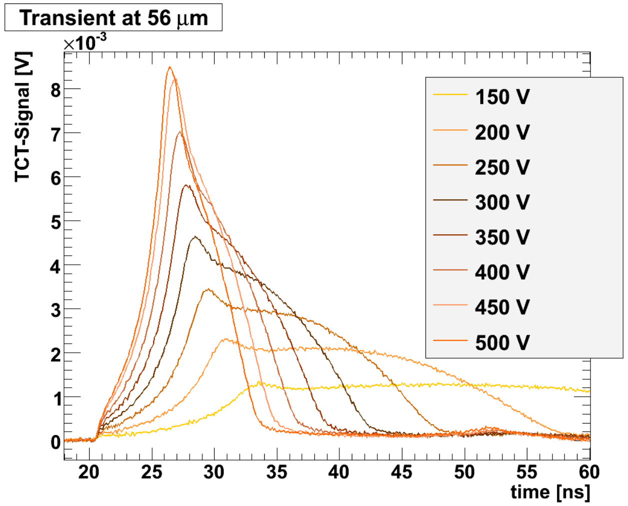
neighbor

bipolar pulse non-zero integral



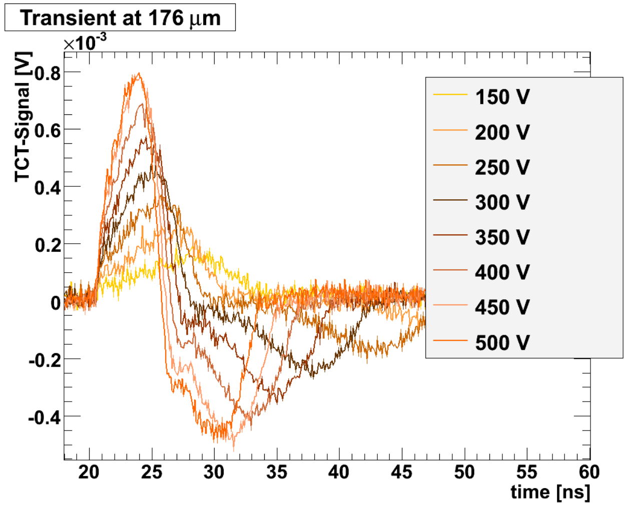
between strips

reduced signal



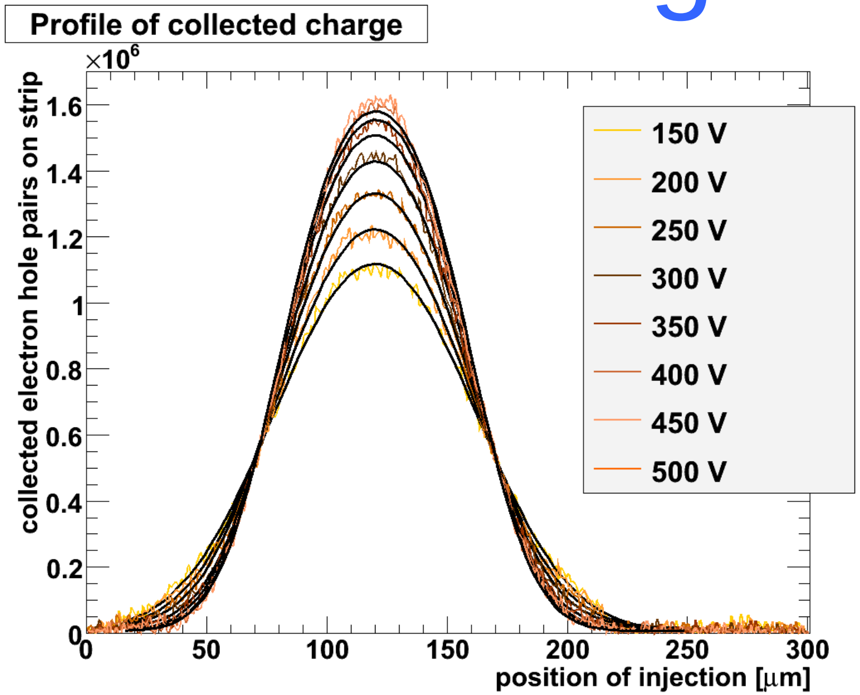
next neighbor

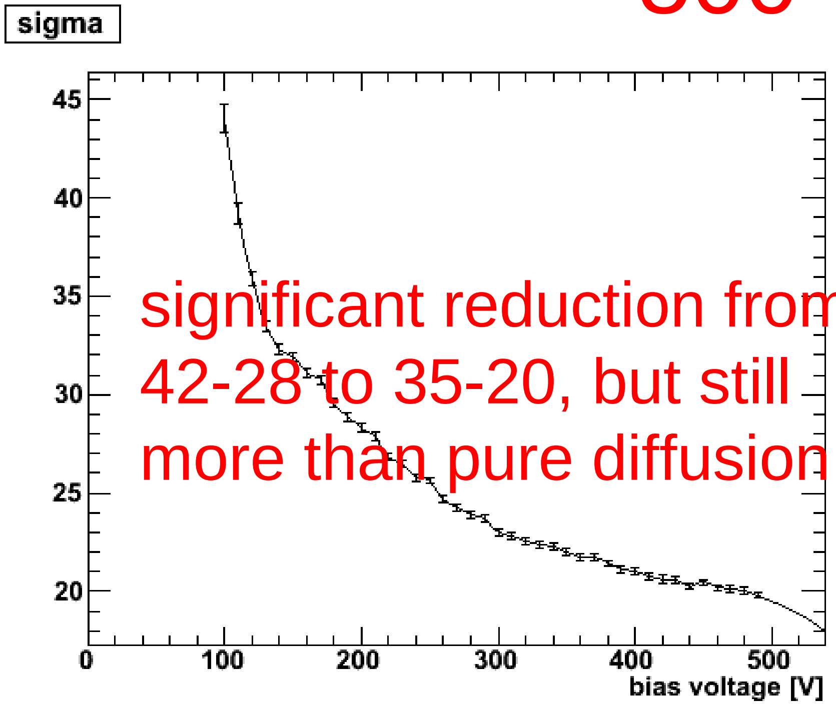
bipolar pulse zero integral



Charge cloud profile

~500 γ





significant reduction from 42-28 to 35-20, but still more than pure diffusion!

- Fitting done with assumption of gaussian charge carrier distribution and box integration along strip pitch
- expected sigma for pure diffusion in the range of 5 µm

$$C(x) = c_0 + N_0 \int_{x-\frac{p}{2}}^{x+\frac{p}{2}} \exp\left(-\frac{(y-\mu)^2}{2\sigma^2}\right) dy$$

C(x) collected charge

x position of injection

c_0 contribution of noise

N_0 total number of injected carriers

p strip pitch

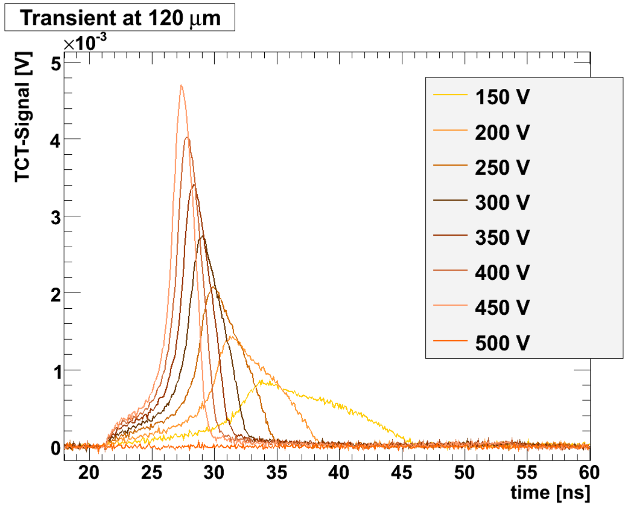
µ position of strip center

σ spread of charge carrier distribution

Position sensitive transients

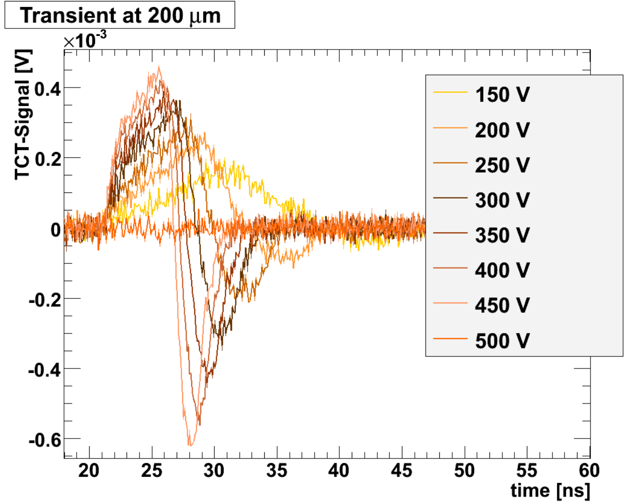
~500 γ

central hit



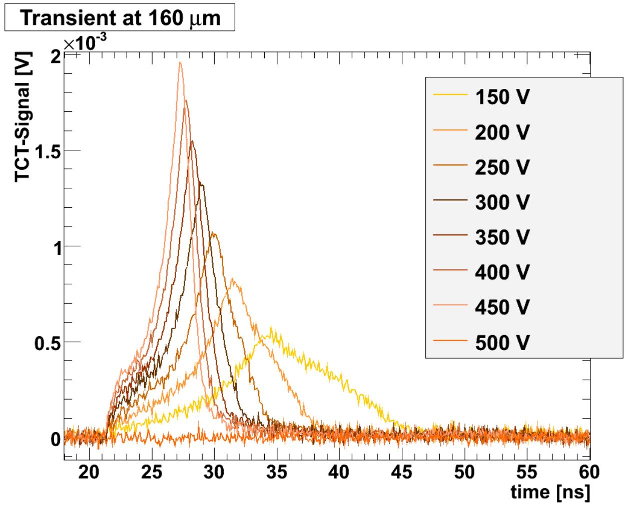
neighbor

bipolar pulse non-zero integral



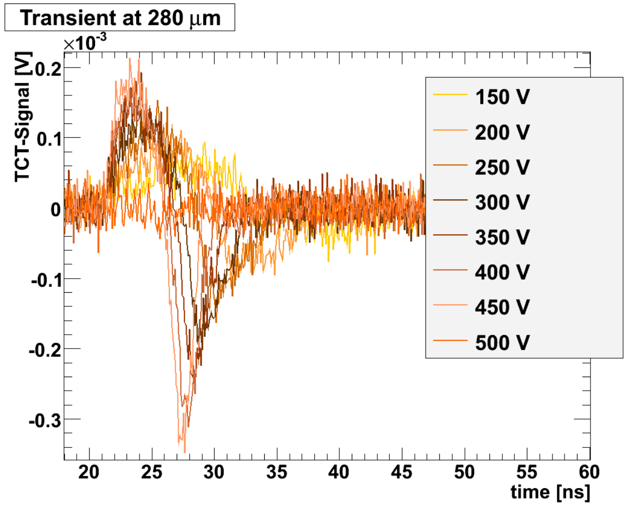
between strips

reduced signal

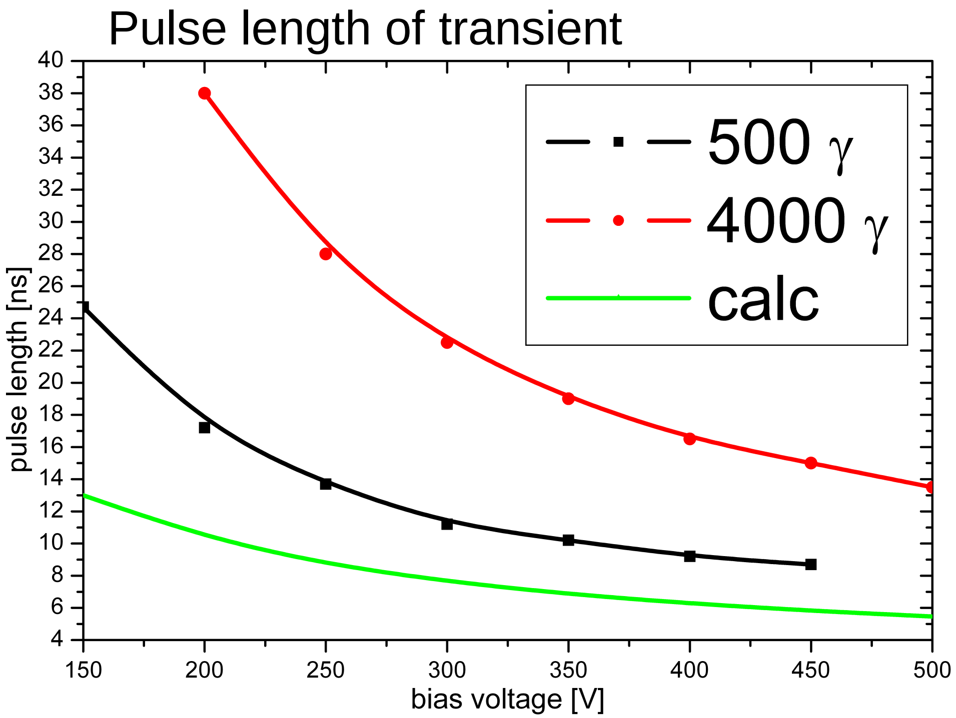


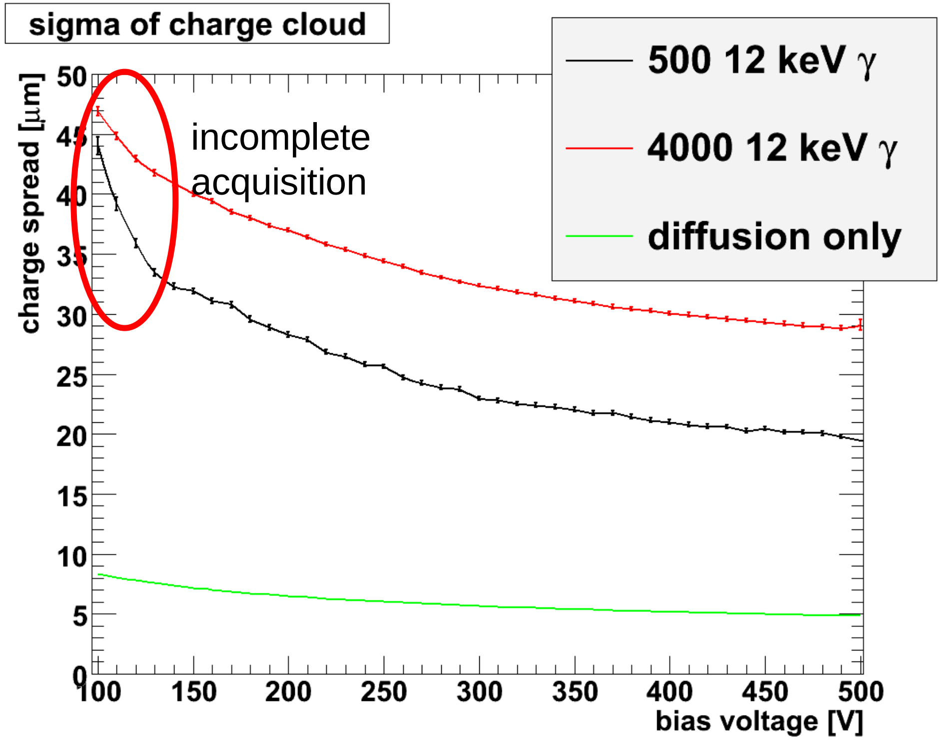
next neighbor

bipolar pulse zero integral



Effects at different intensities





significant increase in pulse length and charge spread already for 500 γ

diffusion spread and pulse length calculated using average field, field depended mobility and Einstein relation for diffusion (1st order approx.)

$$E_{avg} = U_{bias} / d$$

$$v_{drift,avg} = \mu_{avg}(E_{avg}) \times E_{avg}$$

$$t_{drift} = d / v_{drift,avg}$$

$$D = \mu_{avg}(E_{avg}) \frac{kT}{q}$$

$$\sigma = \sigma_i + \sqrt{2Dt} = \sigma_i + \frac{d}{\sqrt{U_{bias}}} \sqrt{\frac{2kT}{q}}$$

Sensor thickness

Effects of sensor thickness?

higher thickness -> longer drift path

higher thickness -> higher depletion voltage
-> lower electric field

$$E(x) = \tfrac{1}{d}\left(U_{bias} - \left(1 - \tfrac{2x}{d}\right)U_{dep}\right)$$

$$U_{dep} = \frac{e_0 N_{eff} d^2}{2\varepsilon_{Si}\varepsilon_0}$$

For Pad-Diodes only! (1D)

x position in diode

d thickness

N_{eff} effective doping

average drift path

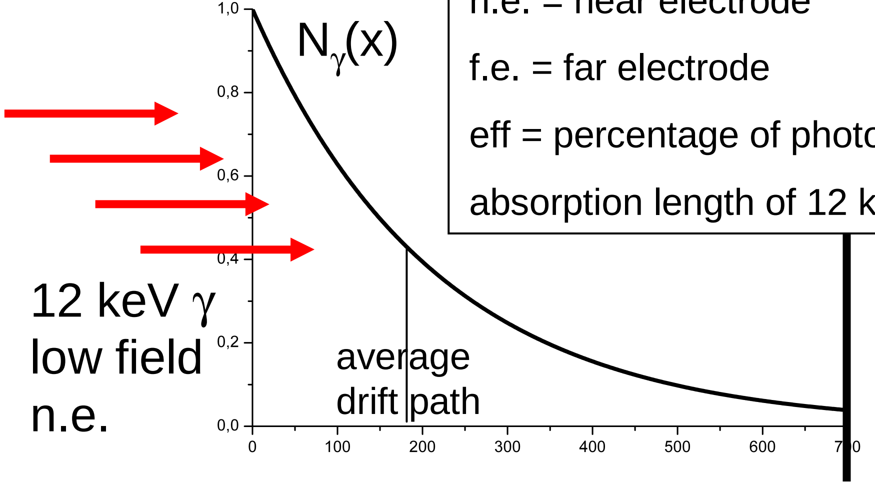
d [µm]	n.e. [µm]	f.e. [µm]	eff [%]
300	115	185	75
400	140	260	84
500	160	340	90
600	175	425	94
700	190	510	96

n.e. = near electrode

f.e. = far electrode

eff = percentage of photons collected

absorption length of 12 keV γ = 215 µm



280 µm drift investigated

readout
high field
f.e.

Effects in 200 µm pixels

~4000 γ

estimation of total collected charge

sigma = 30 µm

~ 500 V = 10x U_{dep} (280µm)

~ 750 V = 5x U_{dep} (500µm)

~ 1500 V = 5x U_{dep} (700µm)

sigma = 50 µm

~100 V = 2x U_{dep} (280µm)

~150 V = U_{dep} (500µm)

~300 V = U_{dep} (700µm)

central hit

99.8%	0.04%
	0.00002%
91.1%	2.17%
	0.05%

(50µm/50µm) hit

90.7%	4.55%
	0.22%
70.6%	13.3%
	2.5%

$$C_{pixel} = \frac{100\%}{2\pi\sigma^2}\int_{left}^{right}\int_{bottom}^{top}\exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}\right)dxdy$$

Conclusions

Charge explosion is a time dependent process

Most critical parameter:
drift time of charge carriers

$$\sigma \sim \sqrt{t}$$

Parameters influencing the charge carrier drift time:

Position of charge carrier in detector: $\sigma \sim d$

The longer the way to the collecting electrode the more the cloud will expand

Electric Field:

The higher the electric field at a given position the faster the carrier will drift (but saturation velocity!)

$$\sigma \sim U_{bias}^{-0.5}$$

Charge carrier mobility:

drift velocity = mobility x field (but saturation velocity!)

Increase bias voltage to counteract expansion!
But be aware of electric breakdown!

Next steps

- further investigations on spreading with different intensities
- further investigations on recombination effects
- calibration of the system
- further measurements in cooperation with WIAS
- further comparison to simulations of WIAS
- measurements with 1052 nm laser (more mip like -> flat e,h distribution in detector)
- measurement campaign on prototype detectors
- studies of irradiated prototypes (Doris running again)

Backup

Key features of the setup

- Red and IR lasers with short pulses (~100 ps)*
- range of injection from 0.5 – 20 x 10^6 e,h pairs (red laser)
  ≙ 150 – 6000 12 keV-γ (absorbed)
- minimum spotsize of ~5 µm (FWHM, red laser)
- position steps with 0.1 µm repeatability
- mounts for (standard) 10x10 mm^2 and 5x5 mm^2 diodes (frontside injection only)

Available on upgraded set-up:

- space for device of 13x26 mm^2
- 4 readout channels (expandable), 32 channels total
- backside injection (hole signal with 660 nm laser)
- temperature control (30°C to -10°C)

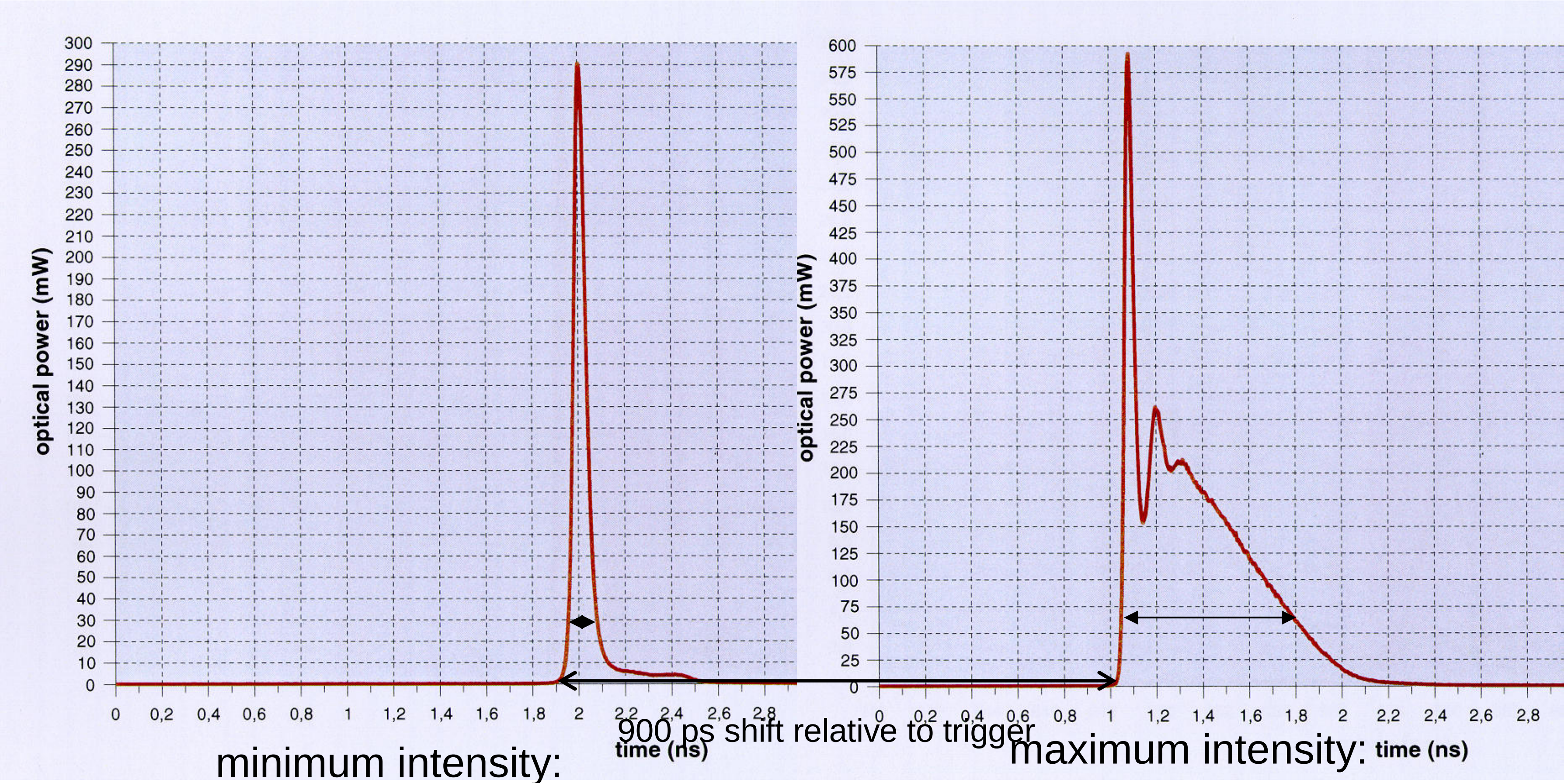
* Red laser λ=660nm => 3µm absorption length

IR laser λ=1052nm => 900µm absorption length

IR beam properties not established yet

Timing structure of 660 nm laser

provided by manufacturer

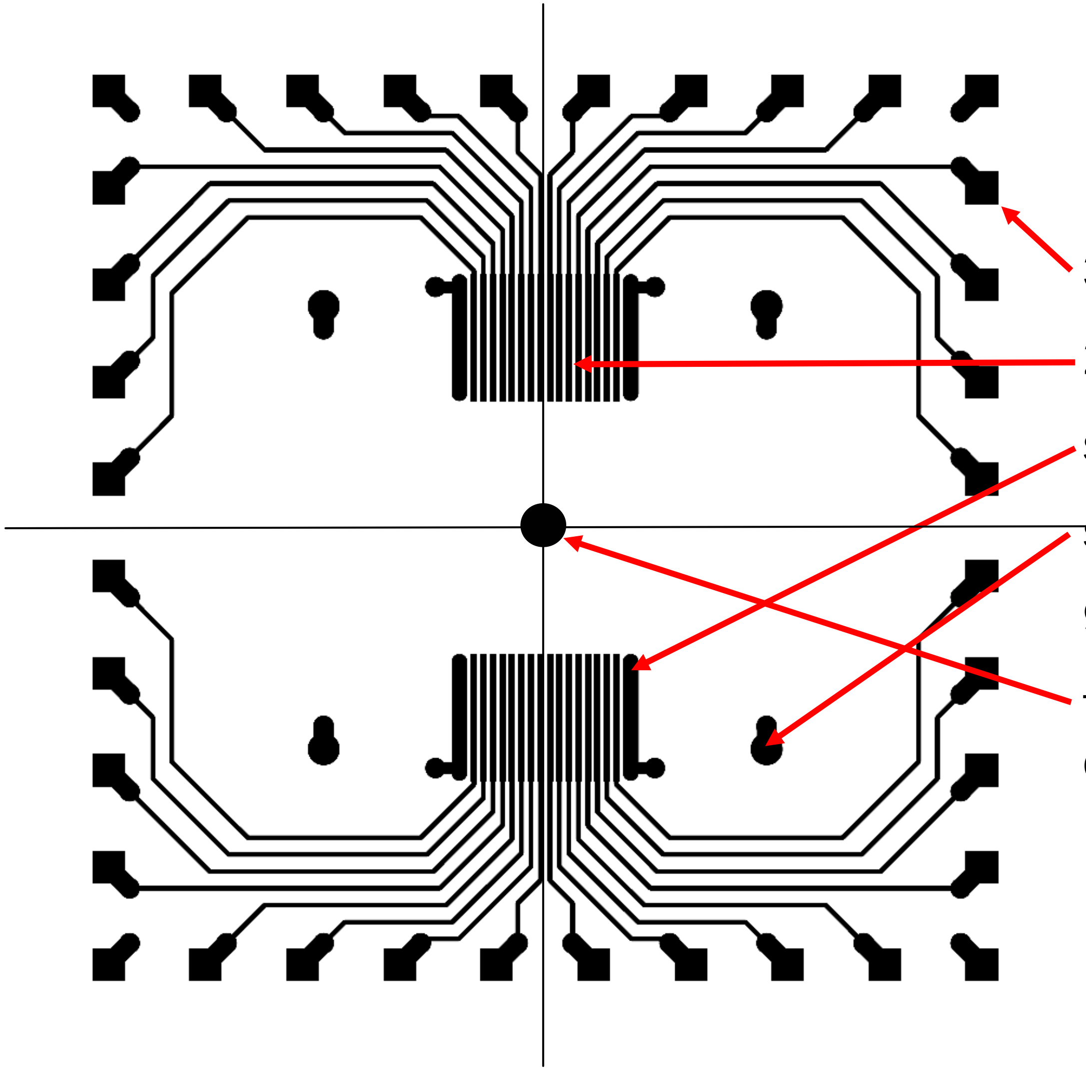


900 ps shift relative to trigger

minimum intensity:
≈ 1.6 Meh -> 500 12 keV γ
≈ 70 ps pulse width

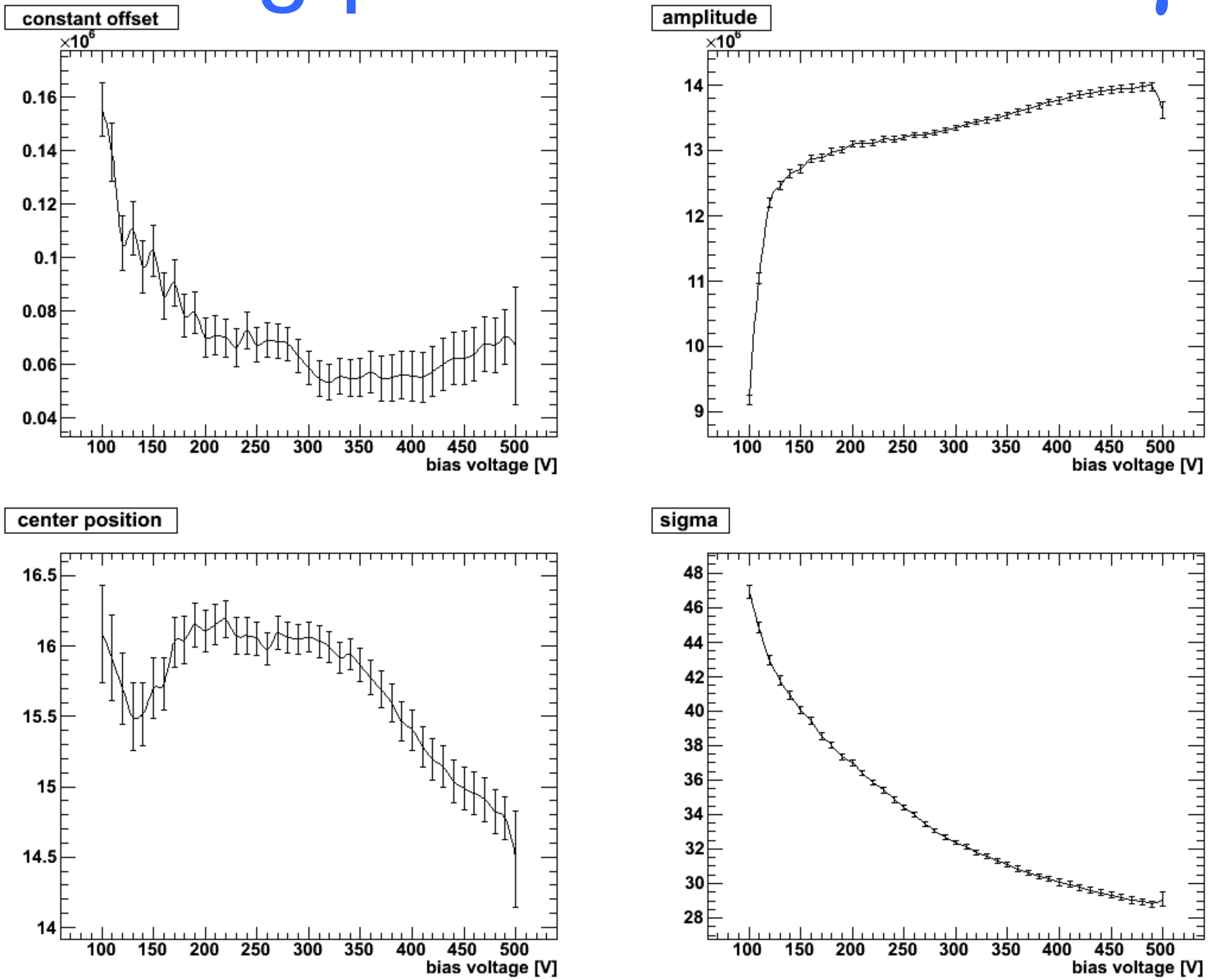
maximum intensity:
≈ 12.8 Meh -> 4000 12 keV γ
≈ 800 ps pulse width

M-TCT ceramics

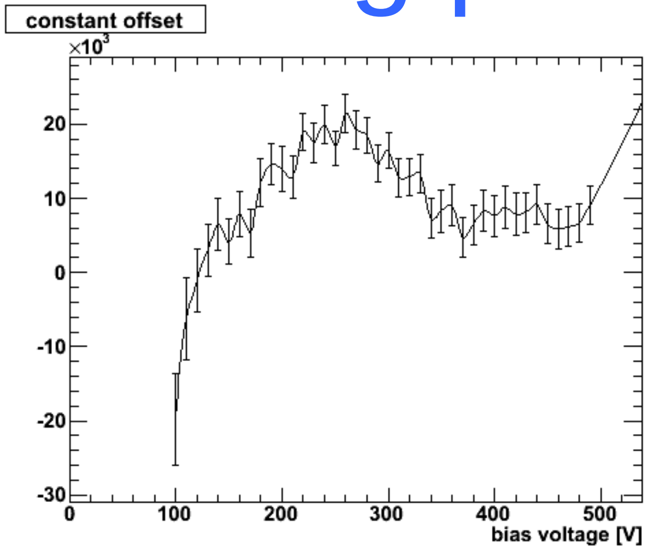


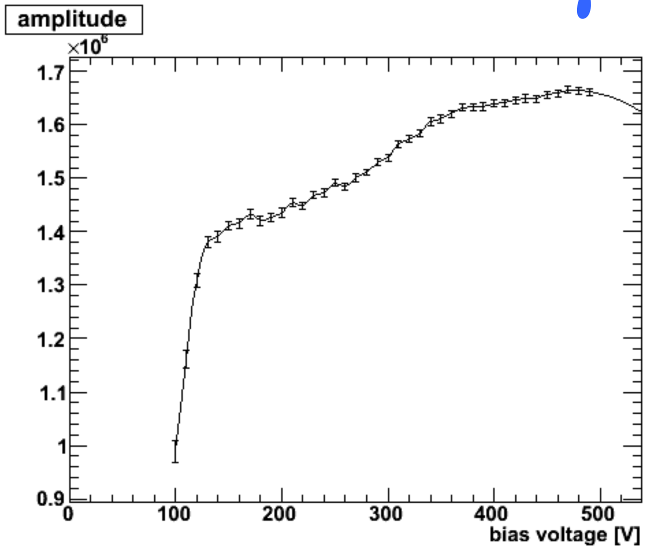
- 13x26 mm^2 space for d.u.t
- 32 Pads -> individual channels
- 2x 16 landing zones for wire bonds
- separate pads for ground contact
- separate pads for HV contact
- 90° rotation symmetry
- flip symmetry (vias at pads) and central hole for backside injection

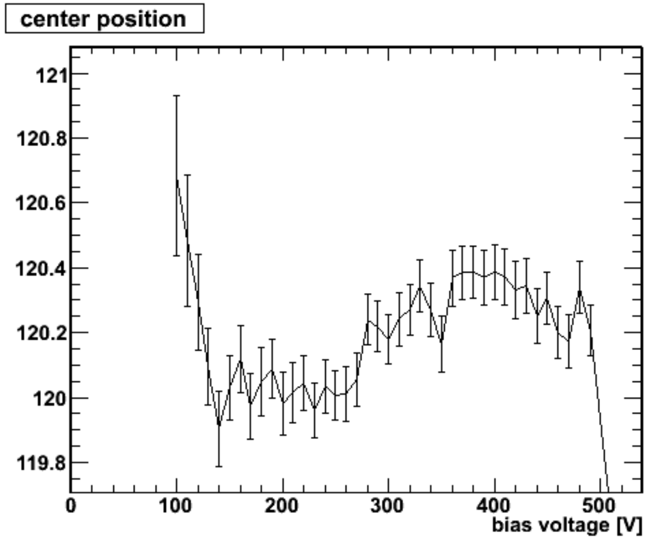
Fitting parameters 4000 γ

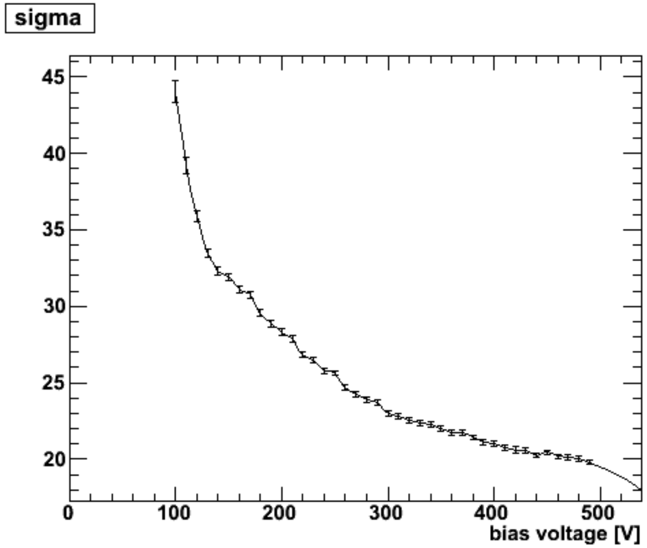


Fitting parameters 500 γ

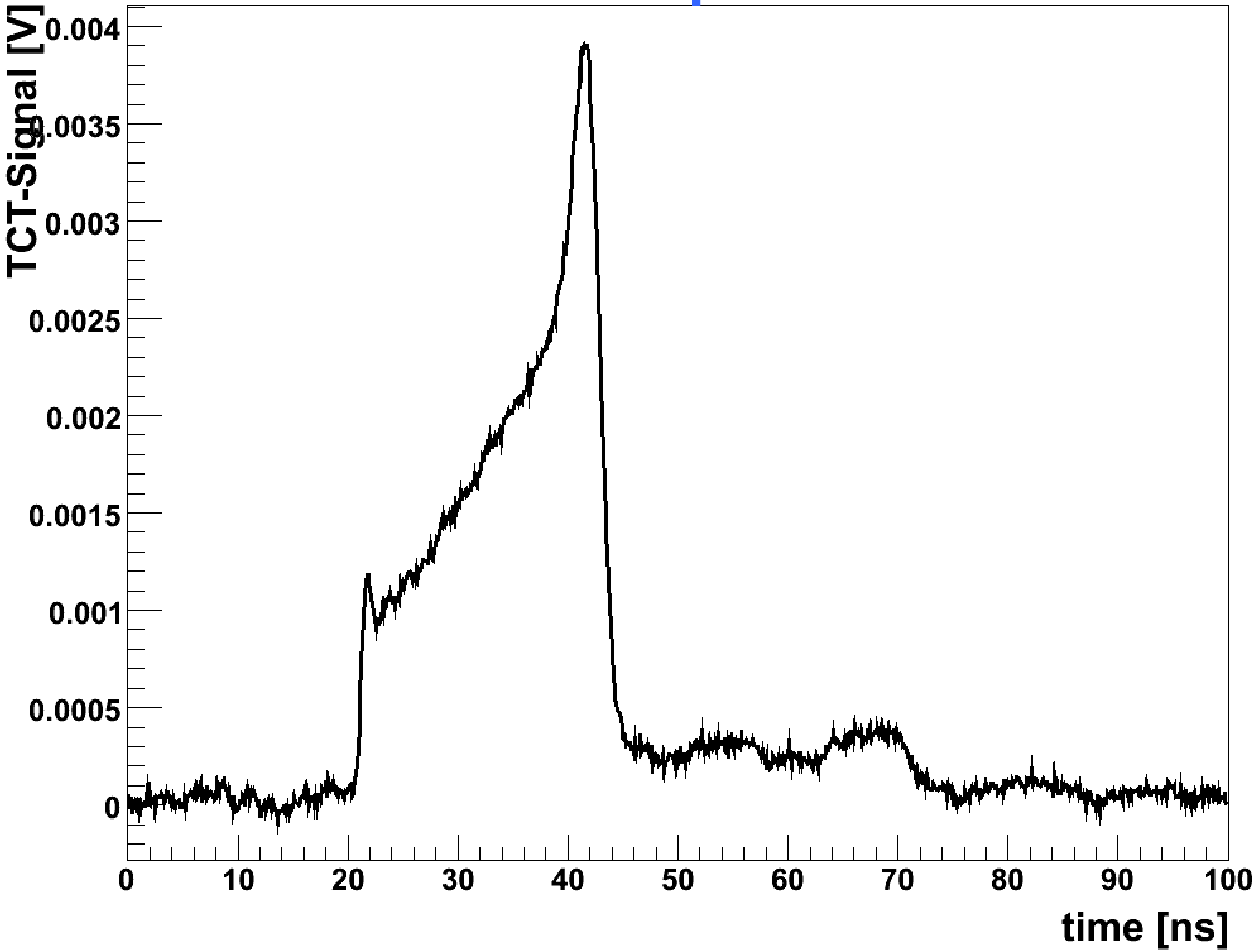

constant offset


amplitude

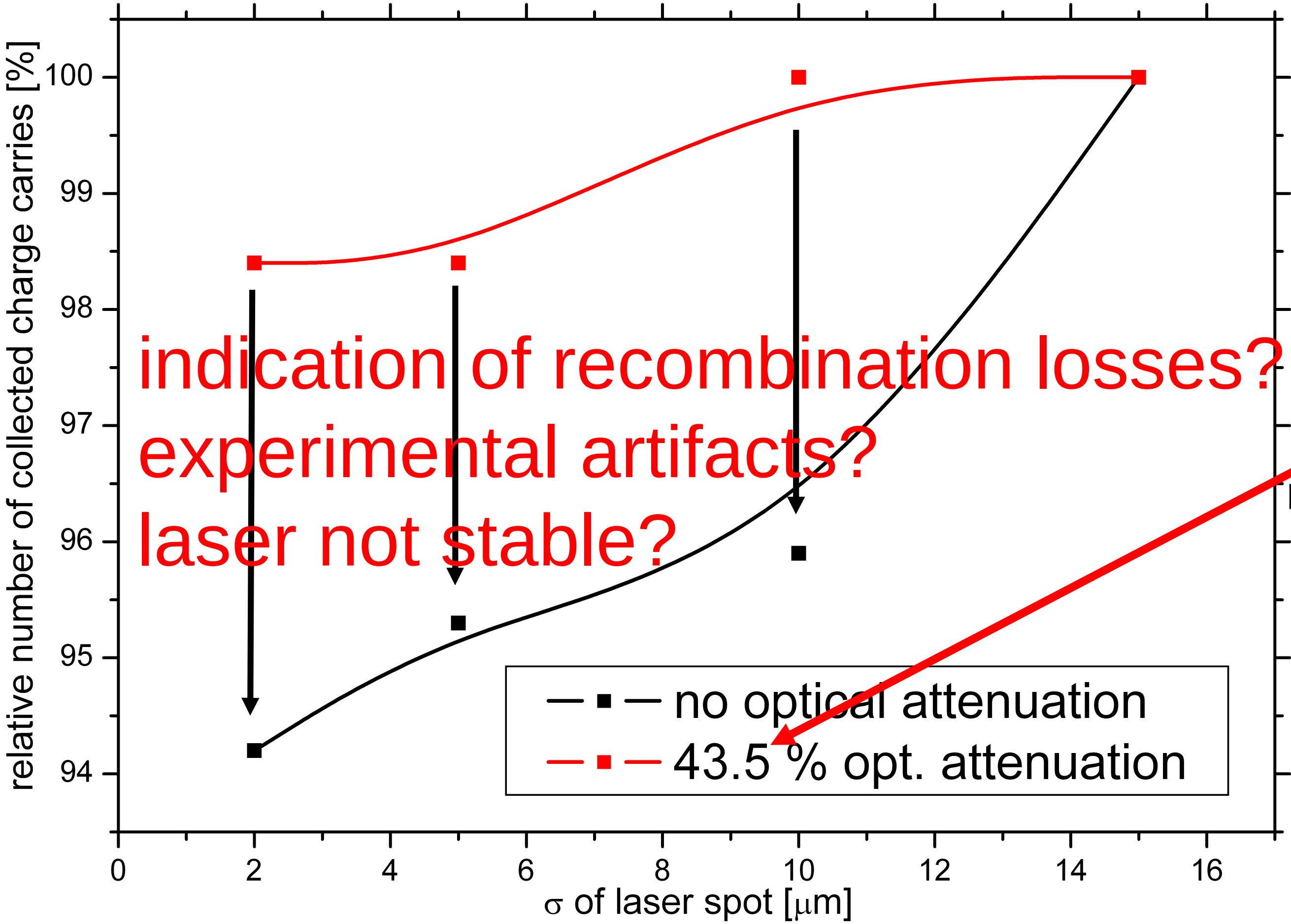

center position


sigma

Transient little plasma effects



Recombination losses ?



indication of recombination losses?
experimental artifacts?
laser not stable?

measured at 500V Bias voltage

•1.72 Meh (500 γ)

•0.62 Meh (180 γ)

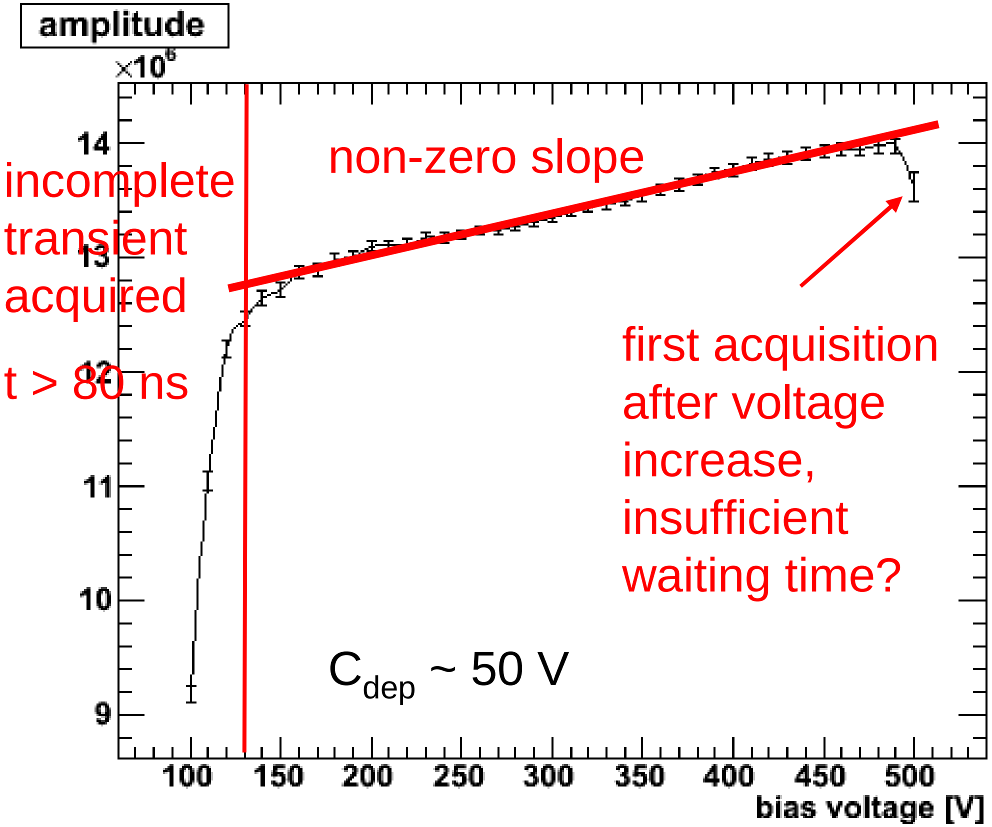
(36% ratio)

mismatch

further investigations needed !!!

Recombination losses ?

~4000 γ



Effect due to recombination losses (undepleted regions between strips?) or fitting artifacts?

$$C(x) = c_0 + N_0 \int_{x-\frac{p}{2}}^{x+\frac{p}{2}} \exp\left(-\frac{(y-\mu)^2}{2\sigma^2}\right) dy$$

C(x) collected charge

x position of injection

c_0 contribution of noise

N_0 total number of injected carriers

p strip pitch

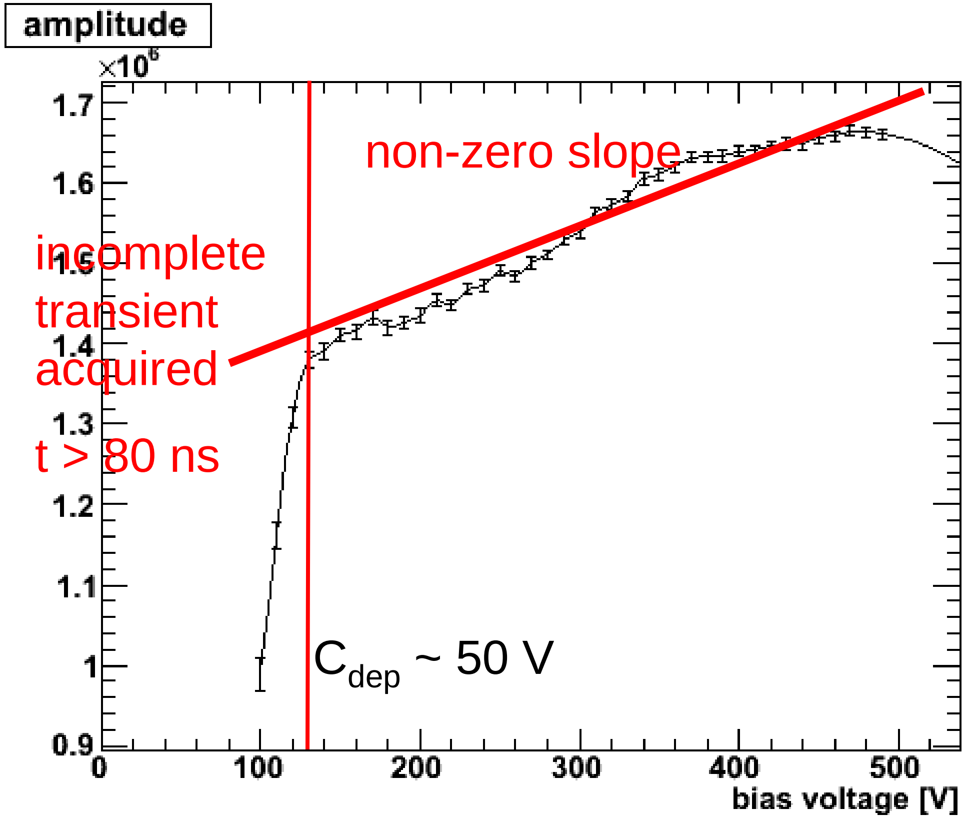
μ position of strip center

σ spread of charge carrier distribution

further investigations needed !!!

Recombination losses ?

~500 γ



non-zero slope

incomplete
transient
acquired

t > 80 ns

C_{dep} ~ 50 V

further investigations needed !!!

Effect due to recombination losses (undepleted regions between strips?) or fitting artifacts?

$$C(x) = c_0 + N_0 \int_{x-\frac{p}{2}}^{x+\frac{p}{2}} \exp\left(-\frac{(y-\mu)^2}{2\sigma^2}\right) dy$$

C(x) collected charge

x position of injection

c_0 contribution of noise

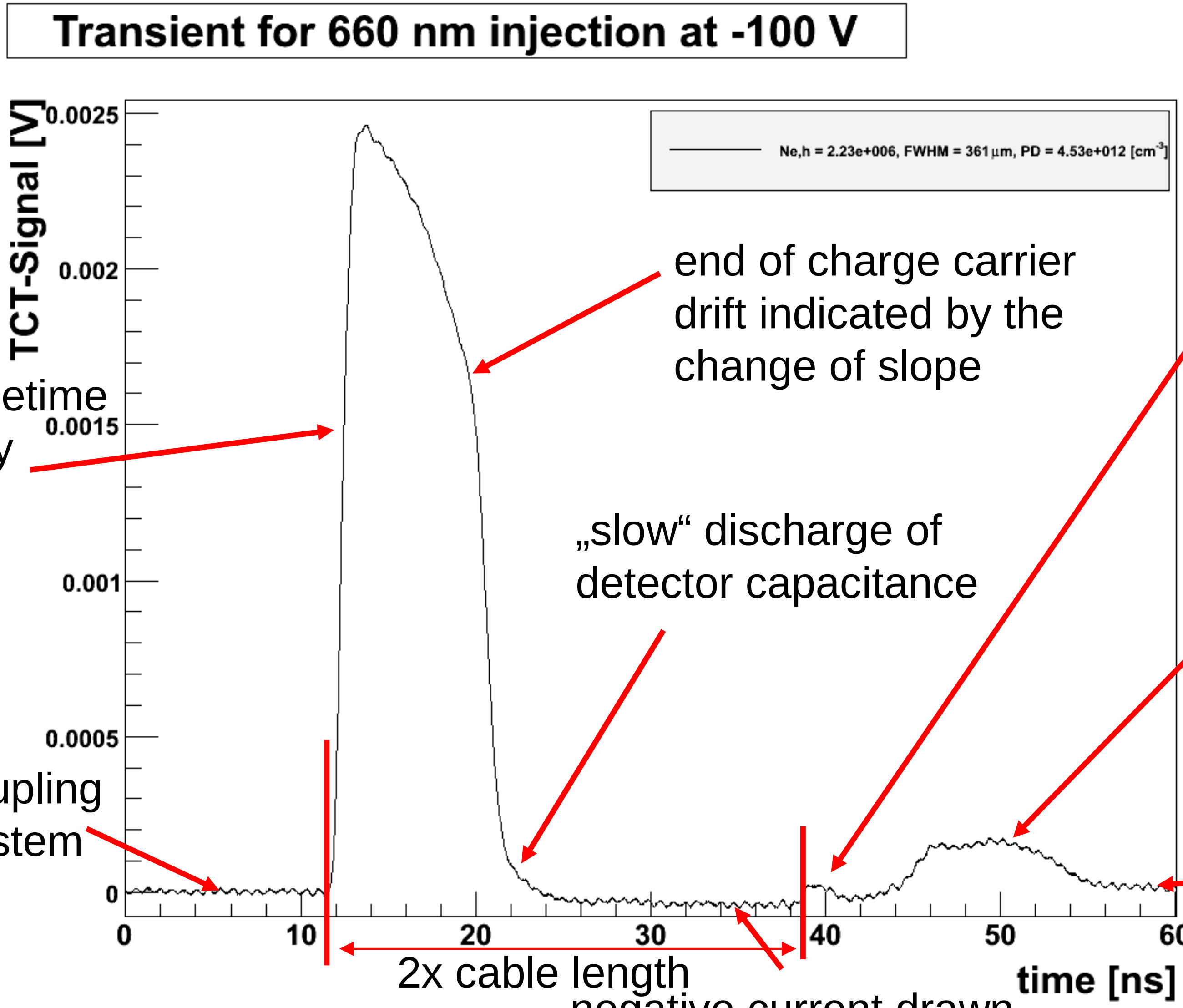
N_0 total number of injected carriers

p strip pitch

μ position of strip center

σ spread of charge carrier distribution

Example of a recorded waveform



signal risetime limited by system risetime

end of charge carrier drift indicated by the change of slope

small reflection due to impedance mismatch at bias-t

„slow“ discharge of detector capacitance

reflection due to impedance mismatch at amplifier

750 MHz noise coupling to the system

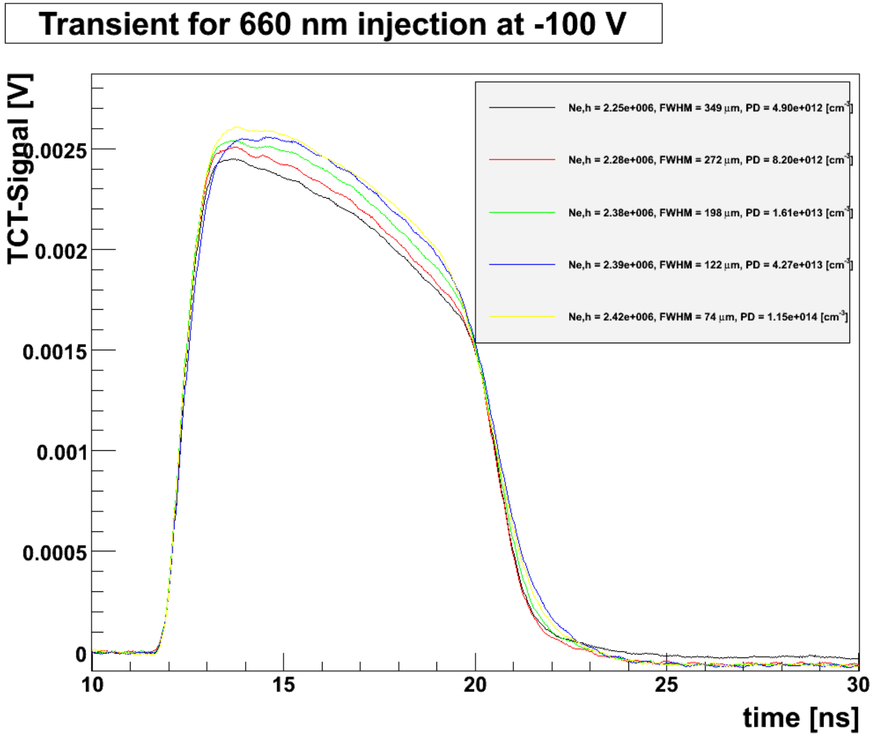
positive current drawn

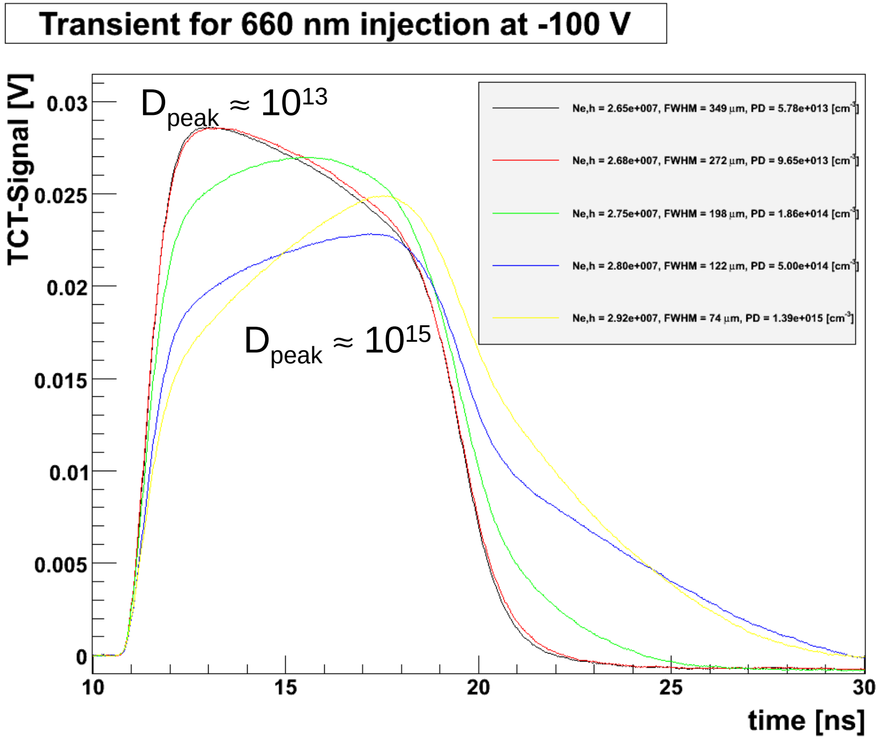
2x cable length

negative current drawn

Measurements on pad diodes

- medium (2x106 e,h => 600 absorbed 12 keV γ) and high (3x107 e,h => 9000 absorbed 12 keV γ) electron injection with 660nm laser
- Pulse distortion clearly visible





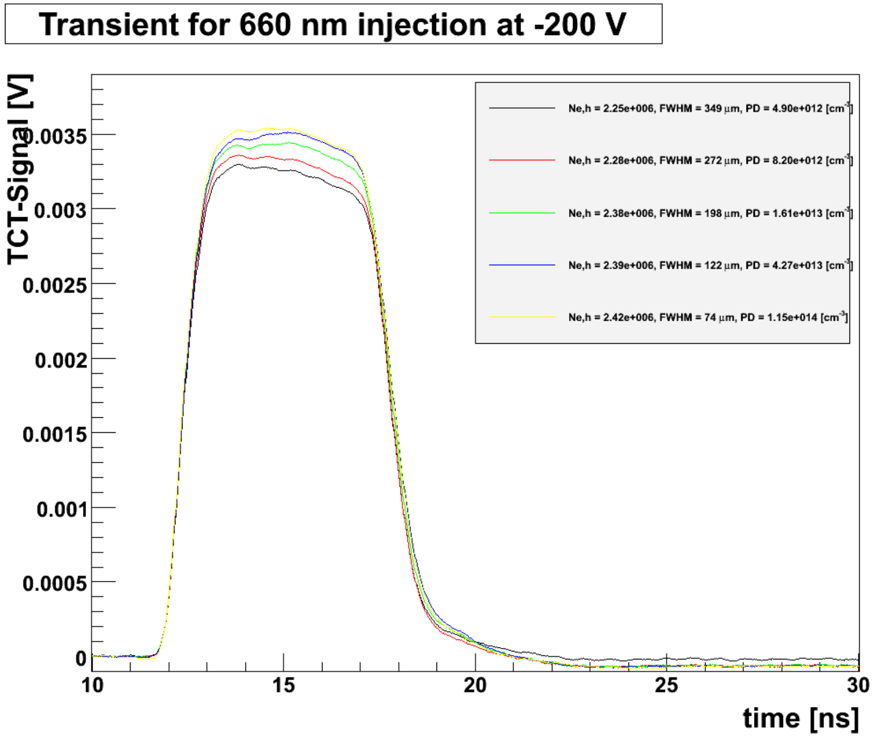
$D_{peak} \approx 10^{13}$

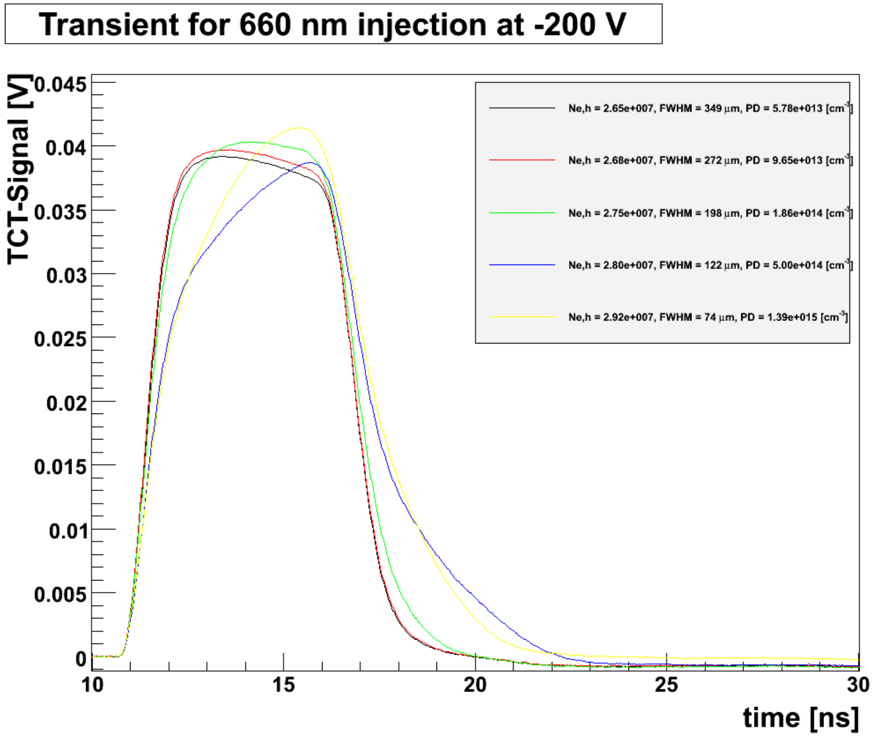
$D_{peak} \approx 10^{15}$

CG1233 FZ-n-Si 280 µm, N_{eff}= 8×10^{11} cm^{-3}, U_{dep} = 48.5 V, C_{dep} = 9.5 pF, ρ= 5.3 kΩcm

Measurements on pad diodes

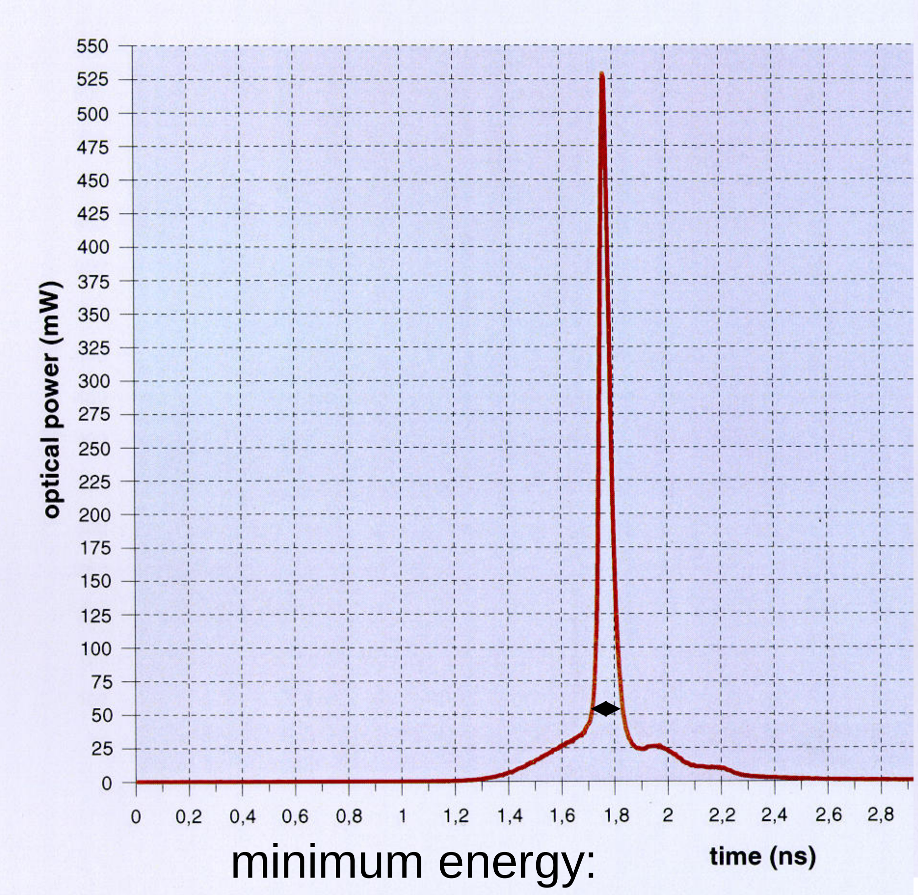
- medium (2x10^6 e,h => 600 absorbed 12 keV γ) and high (3x10^7 e,h => 9000 absorbed 12 keV γ) electron injection with 660nm laser
- Pulse distortion clearly visible


Transient for 660 nm injection at -200 V


Transient for 660 nm injection at -200 V

CG1233 FZ-n-Si 280 µm, N_{eff}= 8x10^{11} cm^{-3}, U_{dep} = 48.5 V, C_{dep} = 9.5 pF, ρ= 5.3 kΩcm

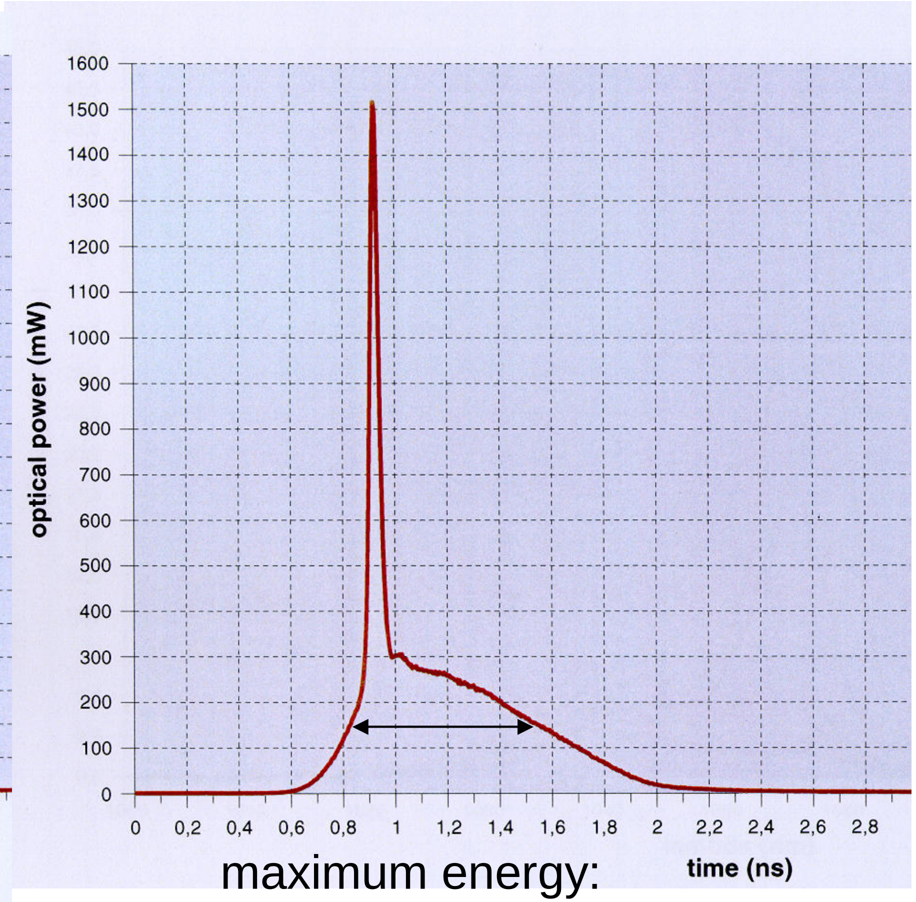
Laser system (IR)



minimum energy:

≈ 44 pJ/pulse

≈ 70 ps pulse width



maximum energy:

≈ 275 pJ/pulse

≈ 700 ps pulse width

4. Data from neon ion beam at GSI

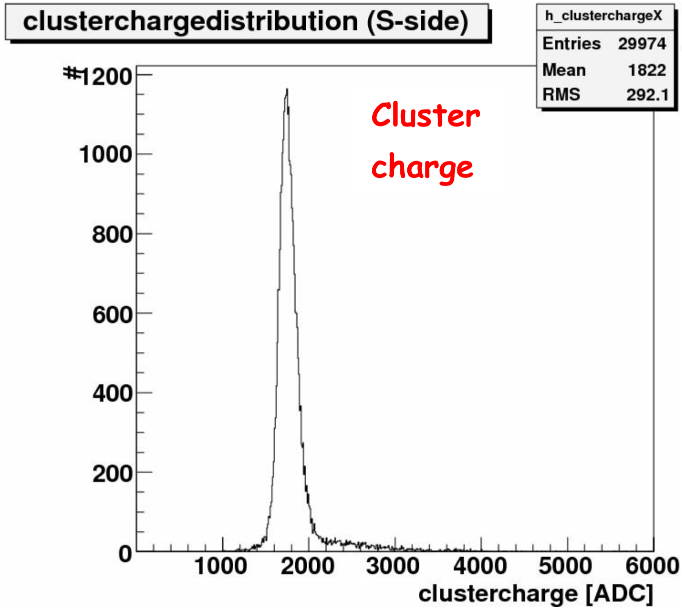
Goal: Experimental verification of charge collection in silicon at large charge carrier densities: Can use heavy ions instead of high intensity γ's: Large dE/dx due to Z²-dependence in Bethe-Bloch Formula.

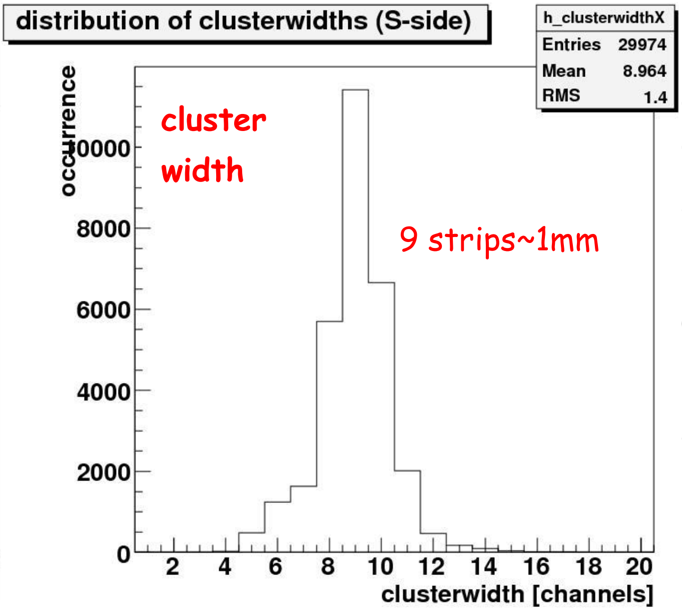
Ongoing analysis of data from test beam at GSI by UHH students.

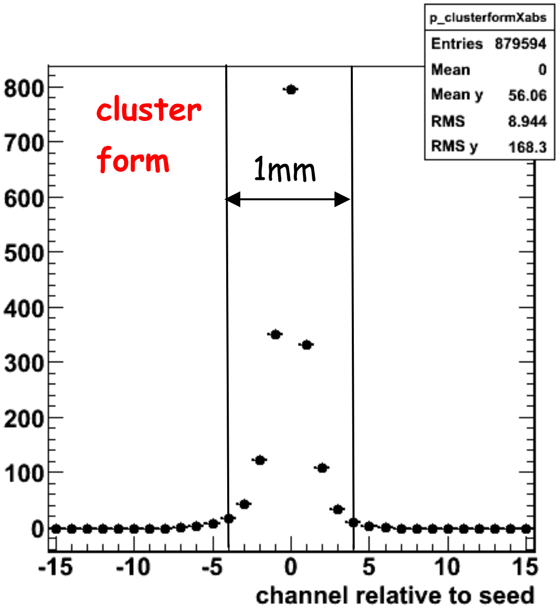
Some preliminary results (for Neon: Z=10):

S-side:

r/o pitch 110 μm







Next steps:

- Understand proton-signal (also present).
- Analysis of data taken with other ions to investigate Z-dependence: B (Z=5), C (Z=6), Mg (Z=12), P (Z=15) and Ar (Z=18).