Simulation of charge trapping in irradiated silicon

- Introduction
- Charge drift in silicon
- Simulation of pixel detector response
- Simulation of diode response to laser pulse

Introduction

Charge trapping probability scales linearly with fluence:

$$1/\tau = \beta\Phi$$

$\beta \approx 5\ 10^{-16}\ cm^2\ s^{-1}$

$\Phi = 10^{15}\ n/cm^2$: $\tau = 2$ ns, $\lambda = v_d\ \tau = 100 \div 200\ \mu m$

$\Phi = 10^{16}\ n/cm^2$: $\lambda = 10 \div 20\ \mu m$

These mean free paths are lower than the depleted thickness at 600V for oxygenated sensors => serious limitation to the radiation hardness.

The simulation

We have developed a simulation of electron/hole drift in silicon and detector response. So far, we have used it to

1) Simulate of the response of (not irradiated and irradiated) pixel detectors to ionizing particles. Twofold aim: predict the performances of a detector given the trapping lifetimes and depleted depth, extract these parameters from test beam data.
Analysis of ATLAS Pixel test beam data currently in progress.

2) Simulate the response of a silicon diode to a laser pulse (TCT measurements). Aim: achieve a better understanding of the electric field distribution and lifetimes from TCT pulse shapes.
This application has been developed in collaboration with the Dortmund group which performs such measurements (see Olaf's talk)

Pixel detector simulation

Initial e/h pairs distribution

- The simulation runs inside the Geant4 framework. The user provides the detector geometry, declares the active volumes and specify the initial conditions for the particles (energy, direction, position, …). G4 takes care of particle tracking, physics processes simulation and energy deposits in the active volumes.
- Test beam and source measurements have been simulated.
- The energy deposits are converted in e/h pairs (3.6 eV/pair)

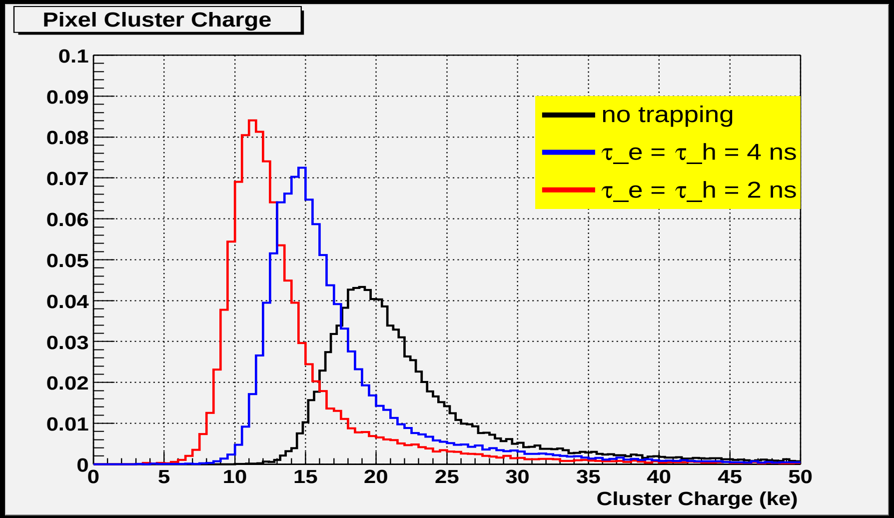
Charge drift in silicon

- This step is the same in the diode simulation.
- At each drift step, the drift velocity $v_d(E,T)$ and time are computed from the local electric field and temperature
- Lateral diffusion and trapping probability are computed.
- User-defined parameters are the field map, the temperature, electron and hole lifetimes.

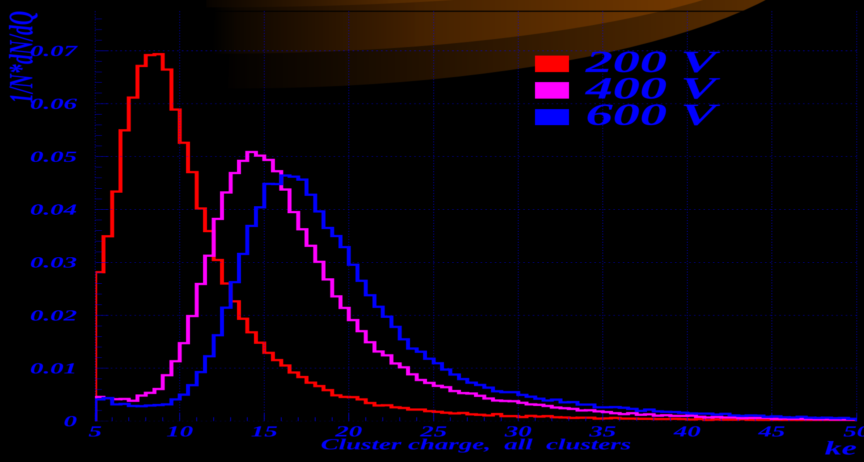
Pixel signal simulation

- The signal on the pixels is computed form the initial and final positions of the moving charges and the Ramo potential (preamplifier peaking time ⑦ drift time).
- Small pixels: signal induced is significant only for charges moving near the pixel (as opposed to diodes)
- Electronics threshold, noise, Xtalk are considered.

Trapping and collected charge



Simulation 600 V

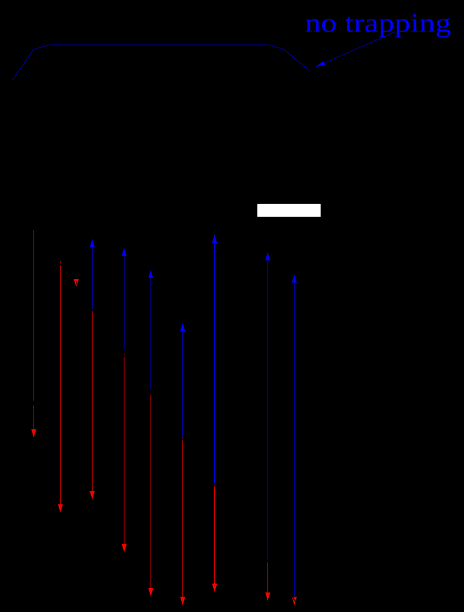


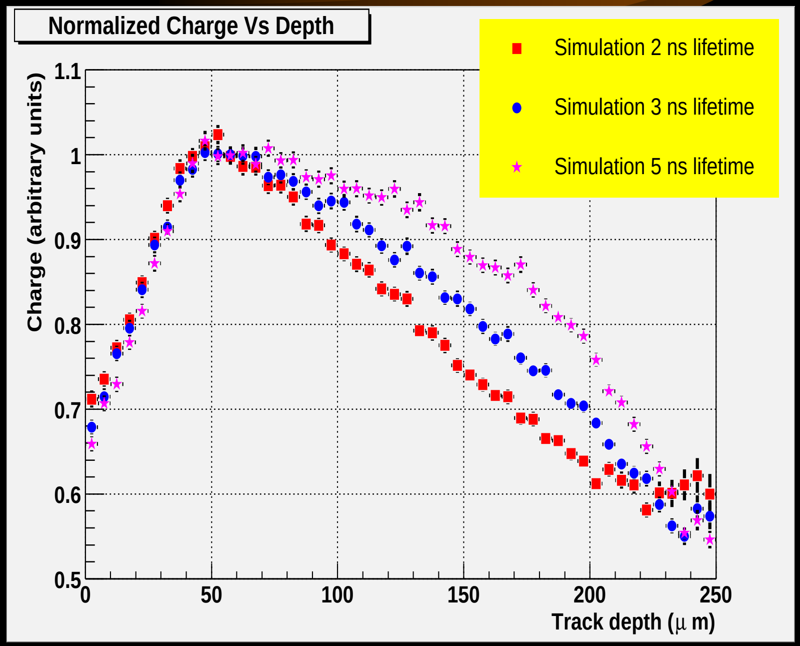
ATLAS Pixel data*

ATLAS pixel detectors irradiated to 1.1 10^{15} n/cm^2 and after 25h at 60C have (80±10)% CCE. This is better than what predicted by simulation for the expected 2 ns lifetime.

* A. Andreazza, performance of the ATLAS Pixel Detector performance modules, Leicester 2002

Charge vs track depth





Test beam data taken with an angle with a charge-sensitive pixel detector and track reconstruction can be used to derive an estimate of charge lifetime. Such an analysis is currently being performed with ATLAS Pixel test beam data (first results at the Pisa conference on advanced detectors, end of May).

TCT measurements simulation

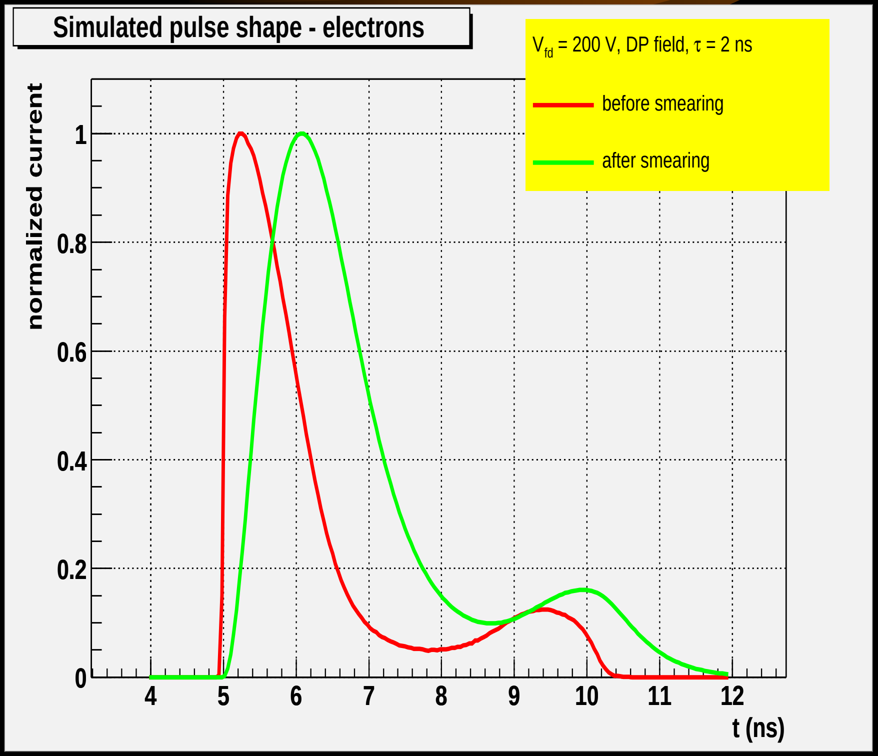
- The shape of the current pulse induced by a laser in a diode allows to get information about the electric field distribution and the carrier lifetimes (see Olaf's talk)
- An initial e/h pairs distribution in the diode is generated according to the laser spot size, pulse duration and penetration depth
- Electrons and holes are drifted in silicon, as in the pixel detector simulation. The current induced on the electrodes as a function of time is computed.
- The pulse shape on the electrodes is smeared according to the response function of the experimental setup.

Some parameters….

I will present plots obtained with the following values:

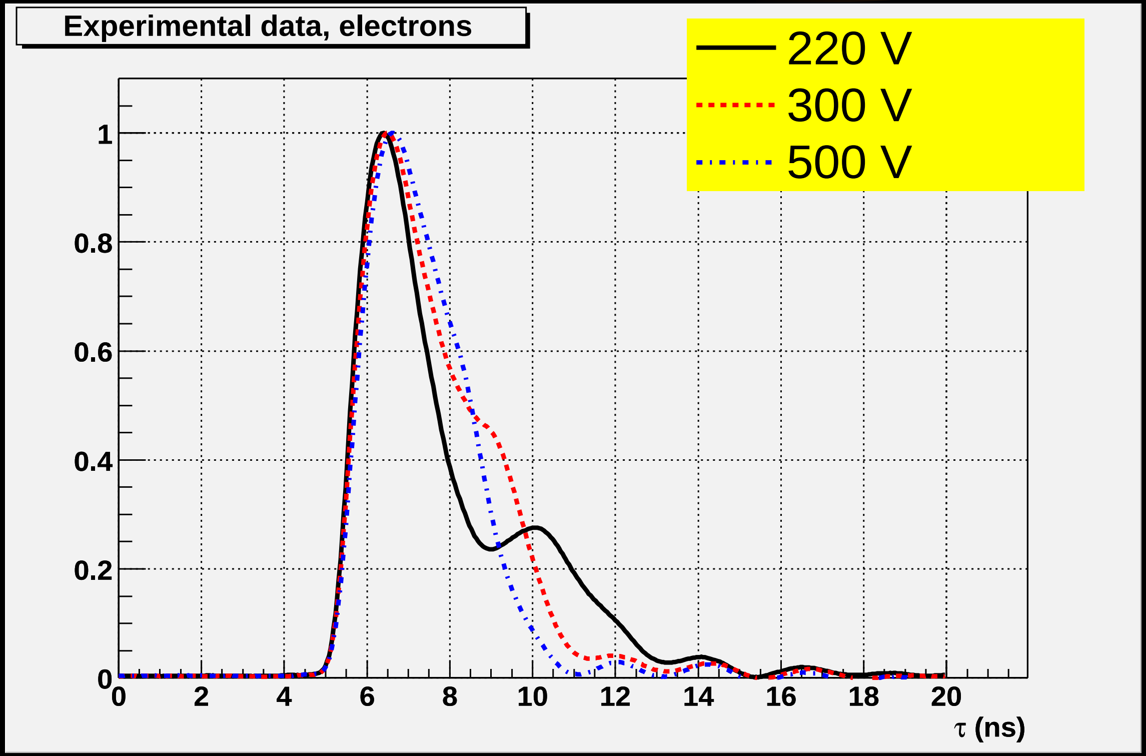
Pulse time: 20 ps Gaussian
Pulse penetration: 3.6 µm
Temperature: 273 K
Full depletion voltage: 200 V
Hole, electron lifetime: 2 ns
Smearing: t*exp(-t/0.35 ns)

this is obtained with an RLC series, with R = 50 Ohm, C = 14 pF, L = $RC^2/4$



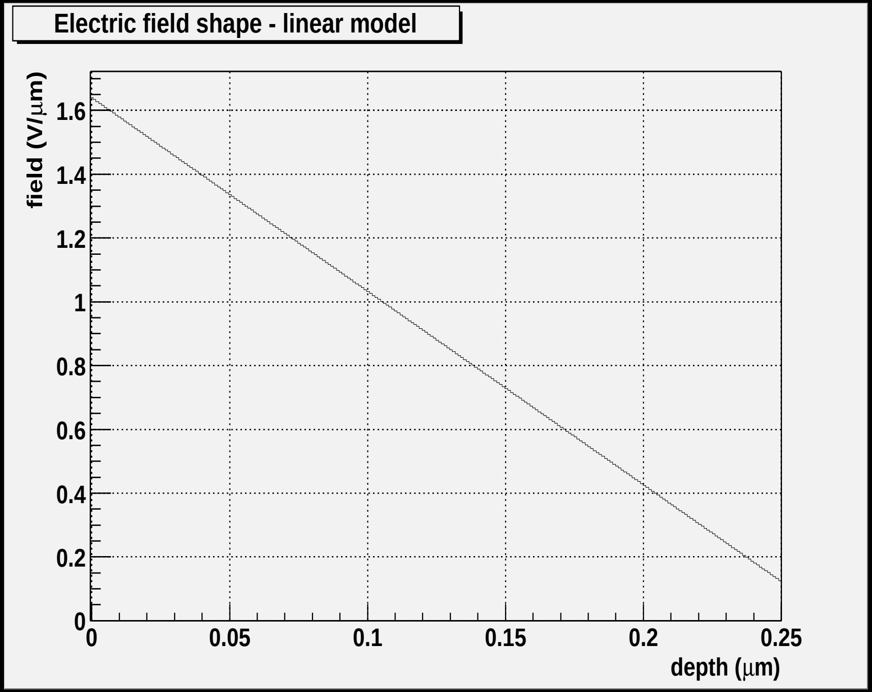
Experimental data

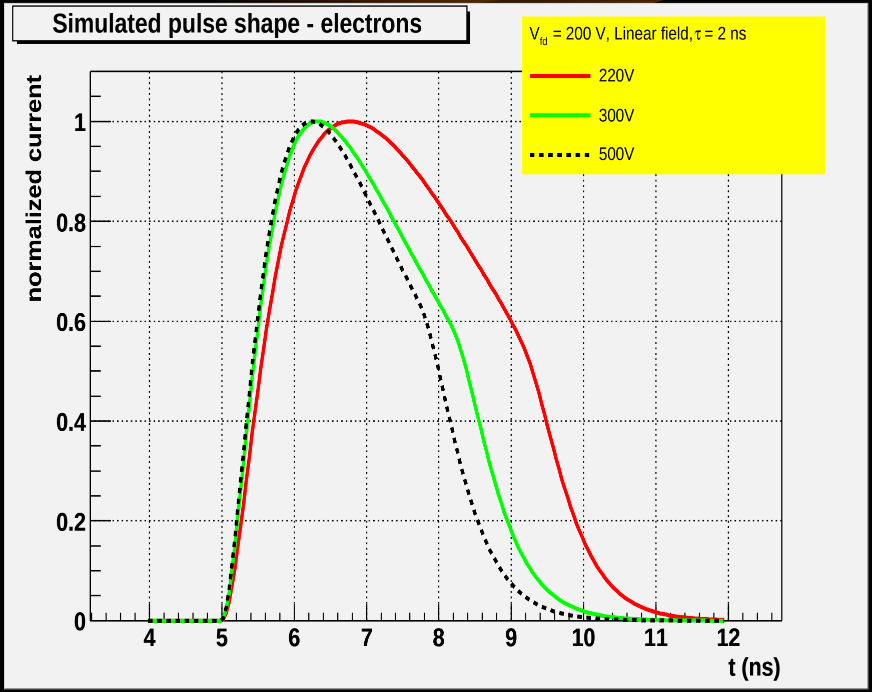
TCT measurements made by the Dortmund group



I would like to obtain something like this...

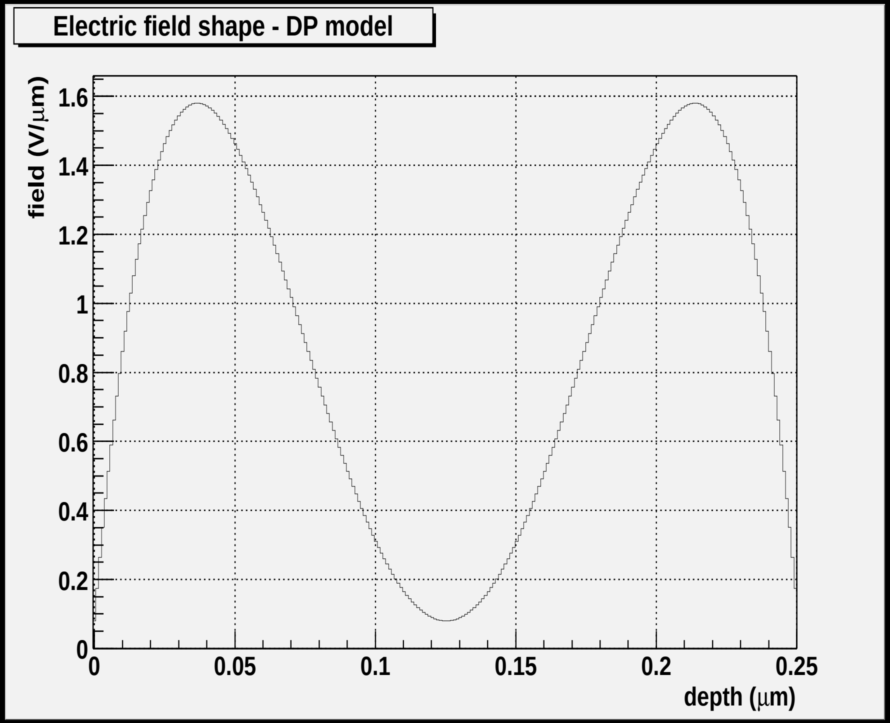
Simulation linear field

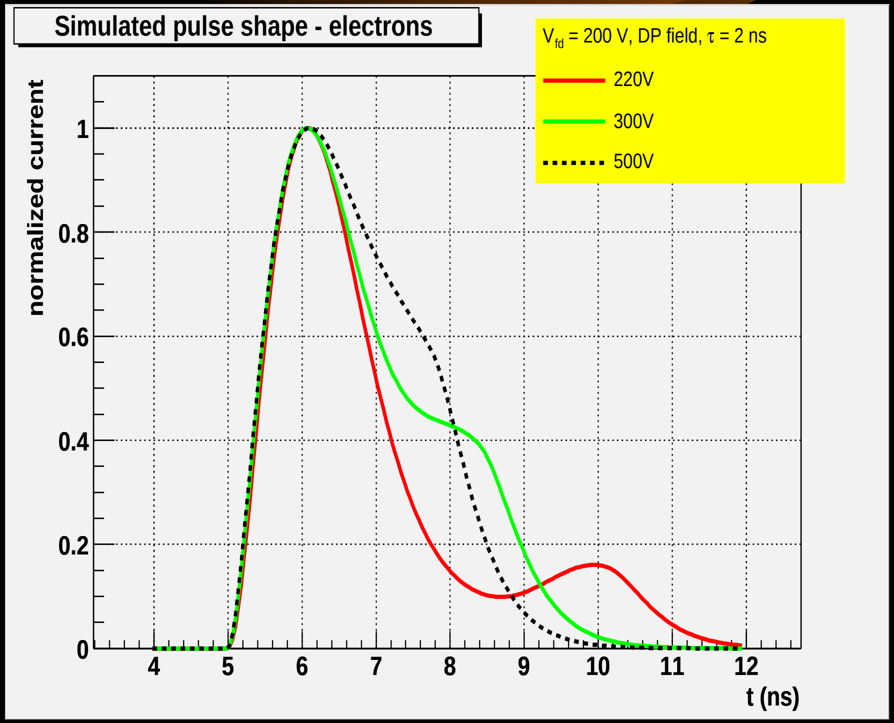




Uniform space charge density. It does not look like the data...

Simulation double-peak field

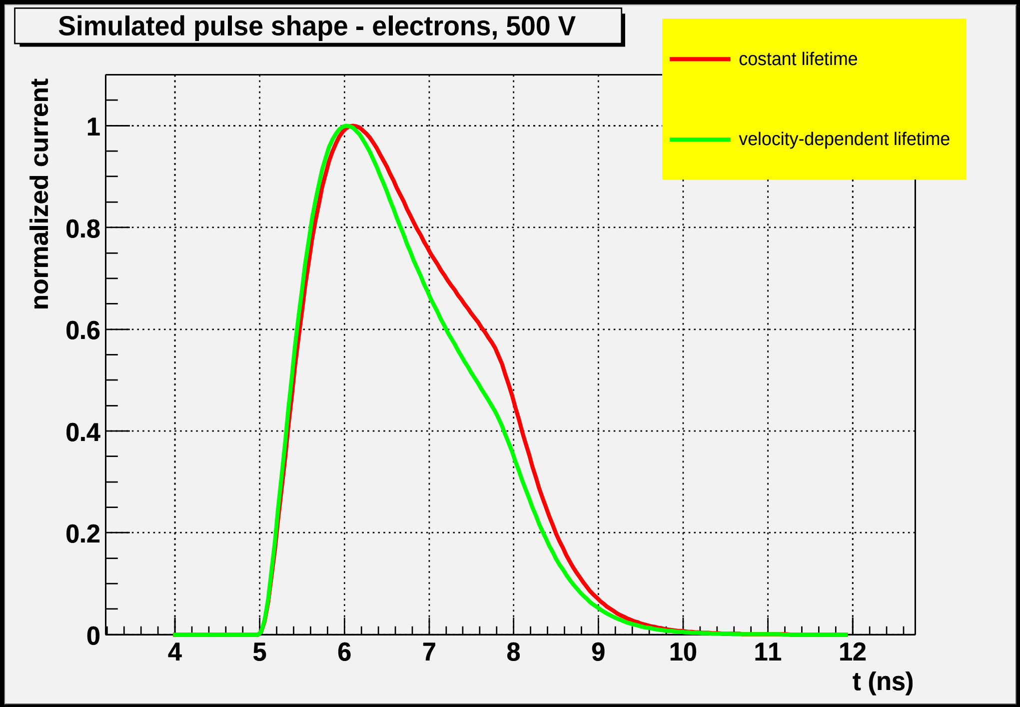




This looks much more like the data

Trapping models

Here I compare the curves obtained with a constant lifetime, and a lifetime depending on velocity: $\tau = 1/n\sigma v \propto 1/v$, $v^2 = v_d^2 + v_{th}^2$



$V_{th} = 10^7$ cm/s

Both curves are produced with $\tau = 2$ ns at low velocity.

Investigation of TCT systematic

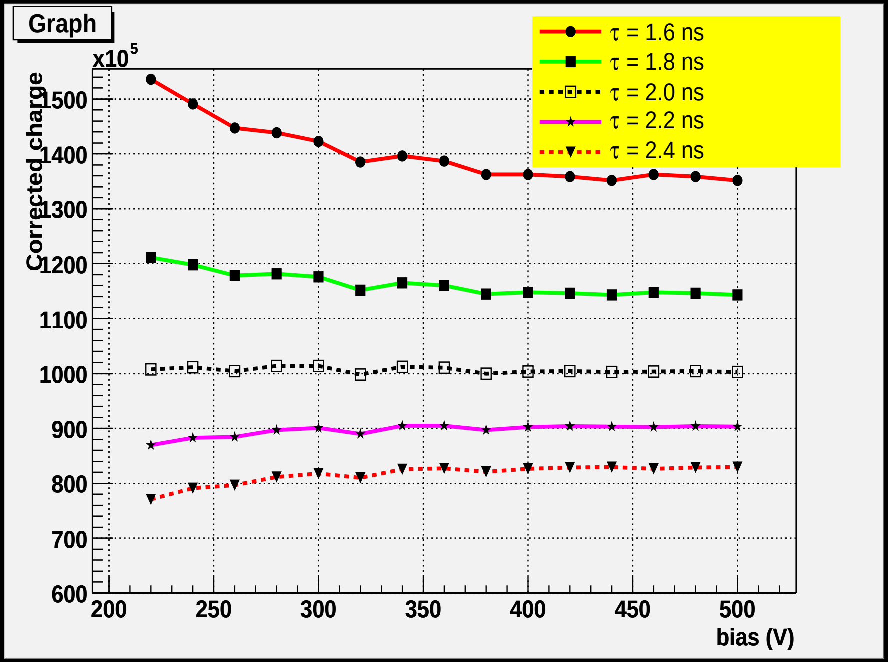
A simple trapping analysis was made on simulated pulse shapes:

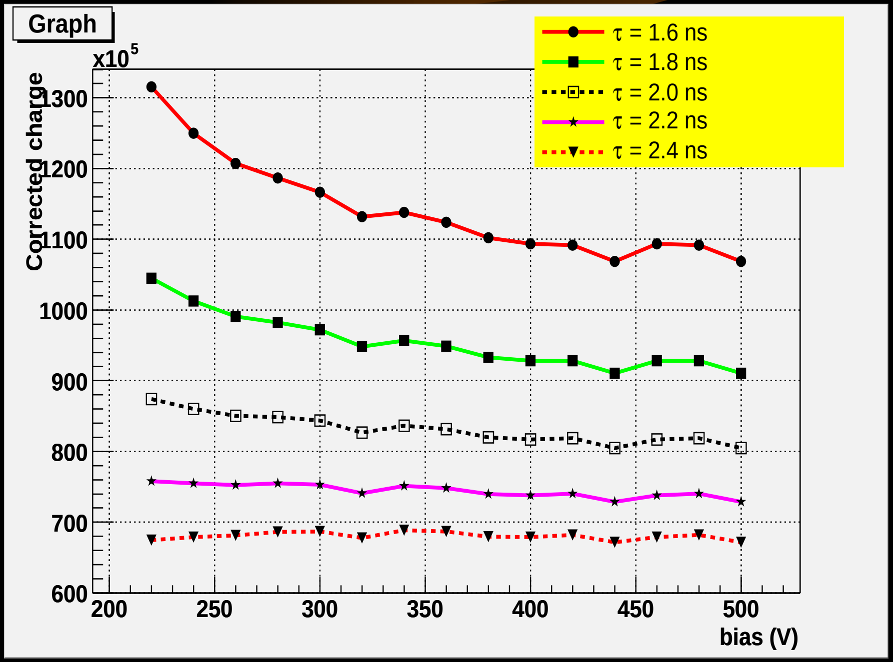
• the curve is multiplied by a positive exponential $\exp(t/\tau)$

• the integral (charge Q) is computed as a function of bias voltage

• The τ for which Q does not depend on the bias voltage is compared with the true (simulated) value.

Corrected charge vs bias





Constant lifetime = 2 ns

Low-field lifetime = 2 ns

$\tau \propto 1/\mathrm{sqrt}(v_d^2 + v_{th}^2)$

Lifetime depends on bias voltage, while the signal correction assumes it constant.

Summary and outlook

- A simulation of pixel detectors was developed. It can be used to predict the performances of a detector given a set of parameters (trapping, depletion, threshold, noise, pixel geometry, …) and as a tool in the analysis of test-beam data.
- Next: extrapolate silicon performances at high fluences, simulate other materials, compare results with other simulation tools.
- The simulation of laser measurements allows to obtain realistic pulse shapes. Much still to be done…
- Next: understand better the Dortmund measurement setup to get a good agreement with data. This would allow deconvolute electric field distribution from data. Simulate hole pulse shape. Investigate eventual systematic (is my formula for field-dependent lifetime correct?) .