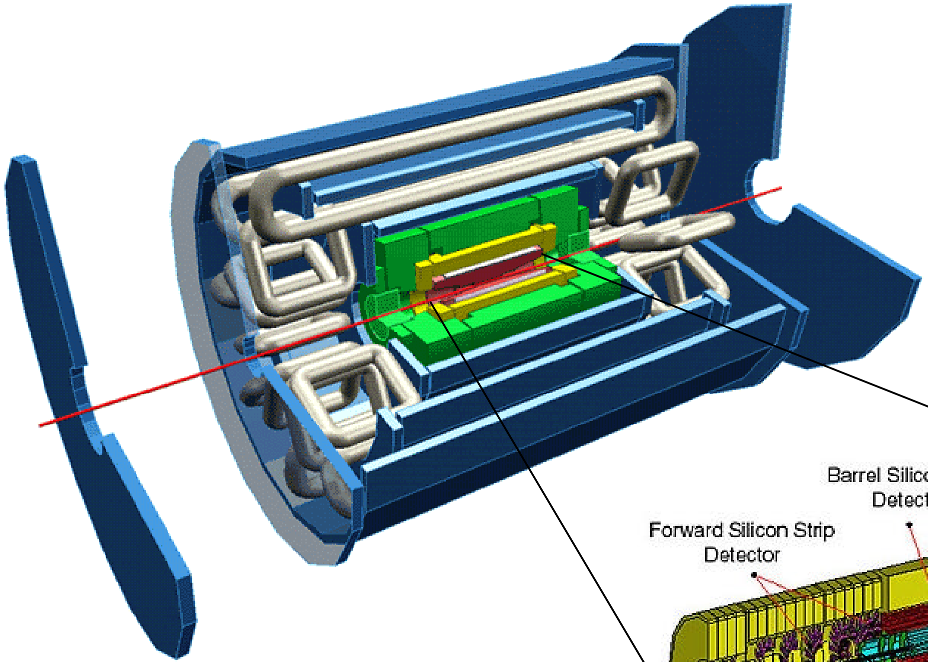
Measurement of the Trapping Time Constants in Silicon with the Transient Current Technique

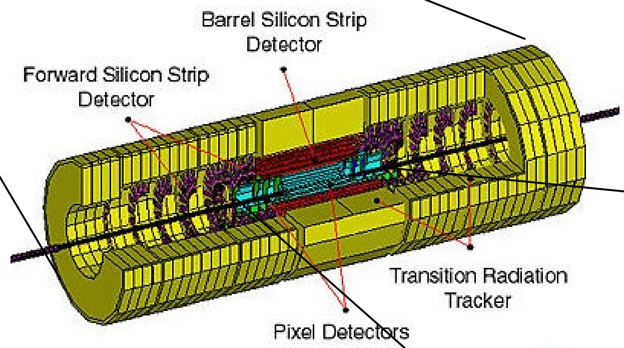
*O. Krasel, C. Gößling, J. Klaiber-Lodewigs, R. Klingenberg,
M. Maß, S. Rajek and R. Wunstorf for the ATLAS Collaboration

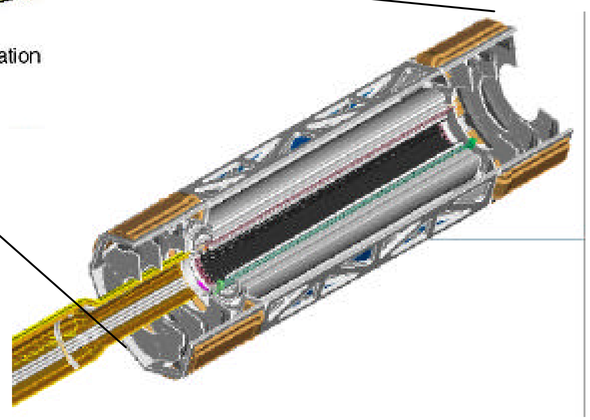
Lehrstuhl f. Experimentelle Physik IV, Universität Dortmund

Motivation: The ATLAS Pixel Detector



- innermost part of tracking system
- 3 points for tracking
- coverage $0 \leq \eta \leq 2.5$
- 3 barrel layers, 6 wheels
- total active area $\approx 2 m^2$ (1744 modules with $\approx$80 million pixel)





- fluence up to 10^{15} 1-MeV-n_{eq}/cm^2 for design luminosity

Data on charge collection efficiency are needed for:

- detector simulation
- optimization of operation conditions

Effective Trapping Time

- Trapping leads to charge carrier loss:

$$dQ(t) = -\frac{1}{t_{eff}} Q(t)dt, \quad \text{with } t_{eff} = t_{eff}(\Phi_{eq})$$

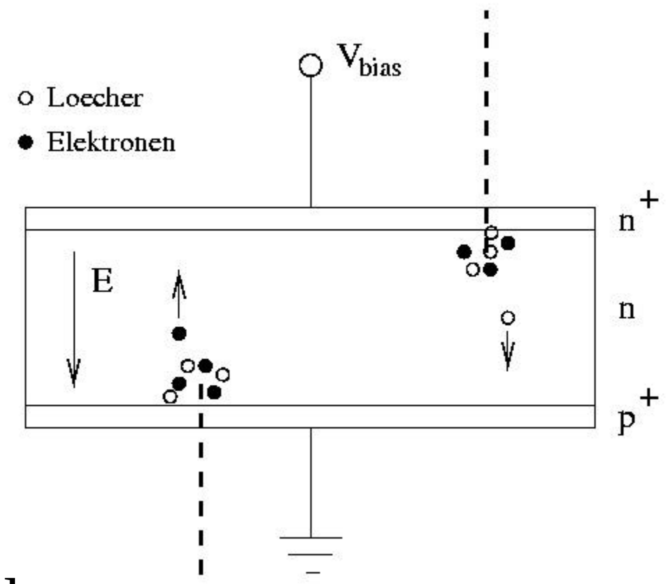
- charge induced on electrodes by drifting charge (Ramo's theorem):

$$dq = \frac{Q}{d}\, dx = \frac{Q}{d}\, v(t)\, dt$$

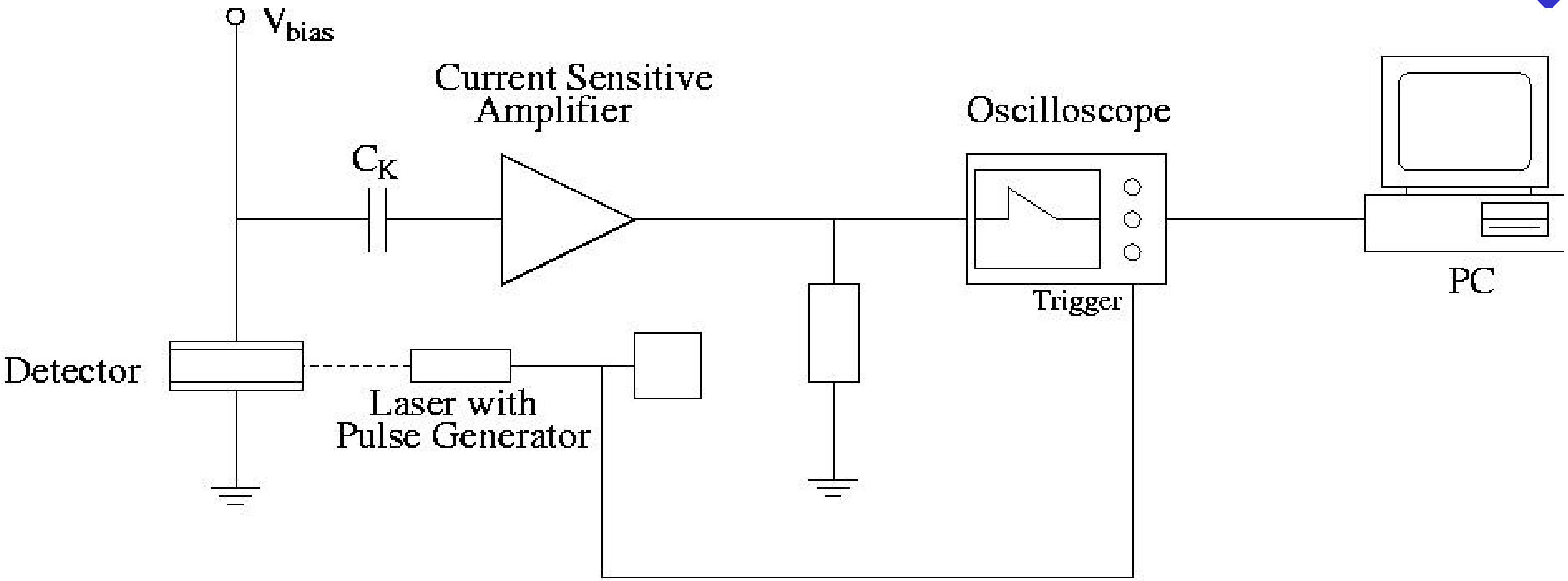
- resulting (measured) signal current:

$$i_m(t) = \frac{Q_0}{d} v(t) \exp(-t/t_{eff})$$

- injection with short range laser from one side allows to distinguish between electron and hole signal



Transient Current Technique, Set-up



- 672nm red laser (3.5µm absorption length, FWHM = 44ps),
- voltage source with picoamperemeter (Keithley 487)
- fast pulse amplifier (10×, 100 kHz - 1.8 GHz), (*current sensitive!*)
- oscilloscope (Tektronix TDS 784D, band width 1 GHz)
- rise time of system (incl. detector) about 1 ns
- PC readout system (LabVIEW)
- cooling system (-20°C - +20°C, RMS 0.2°C)

Charge Correction Method (CCM)

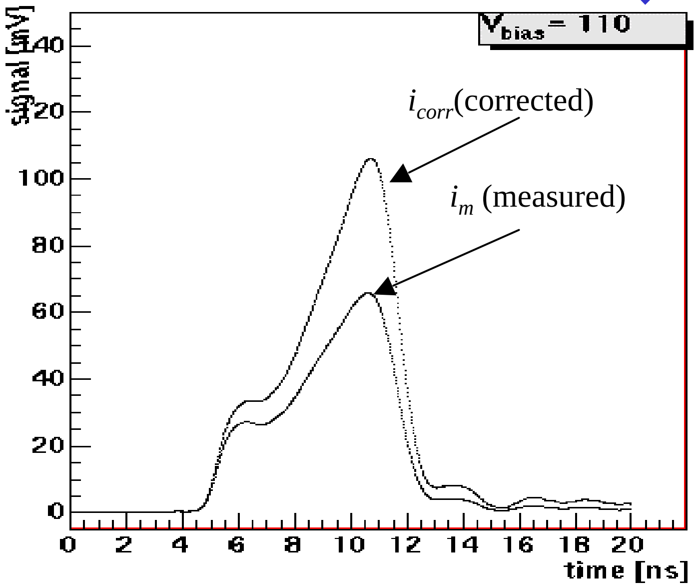
- correction of measured current:

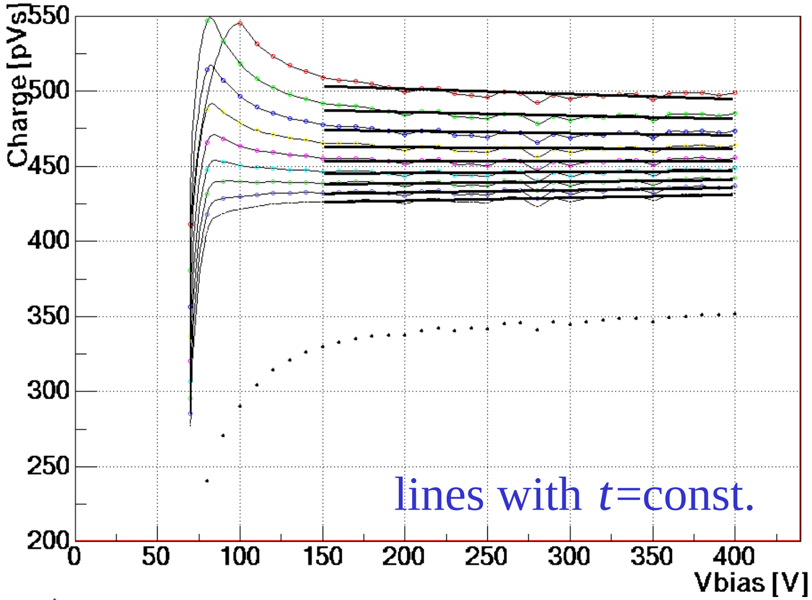
$$i_c(t) = i_{meas}(t) \cdot \exp(+t/t)$$

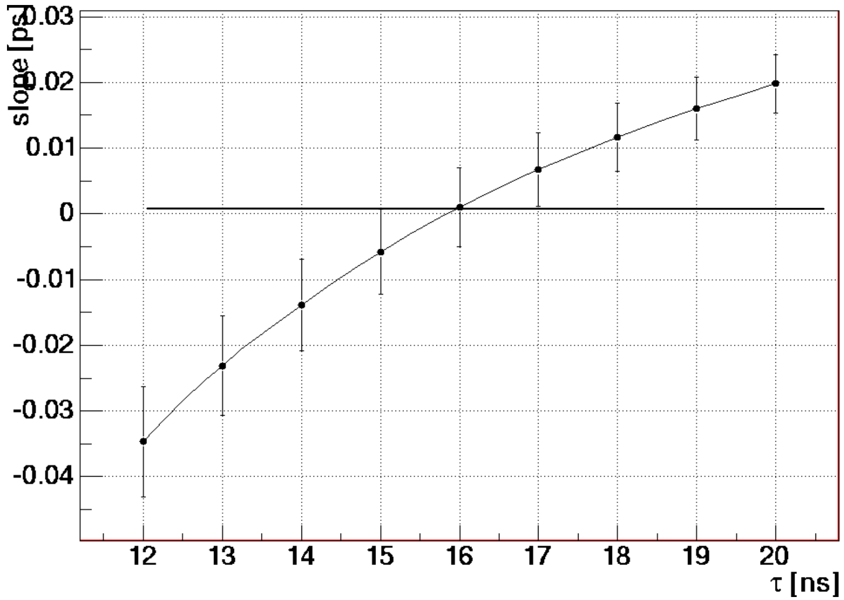
- $Q_c = \int i_c(t)\, dt = \text{const.}$

  for correct t and $V_{bias} > V_{dep}$

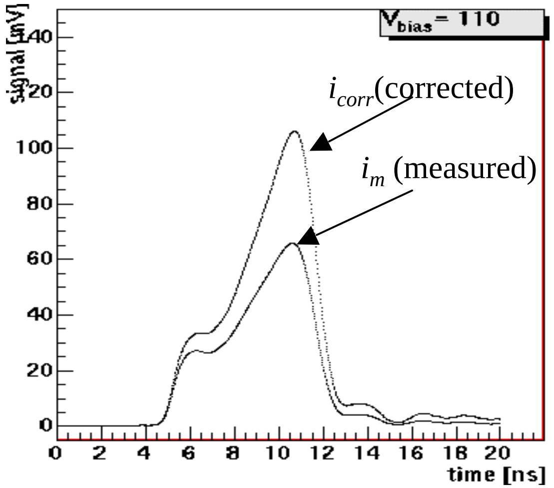
- t obtained from slope vs. t plot

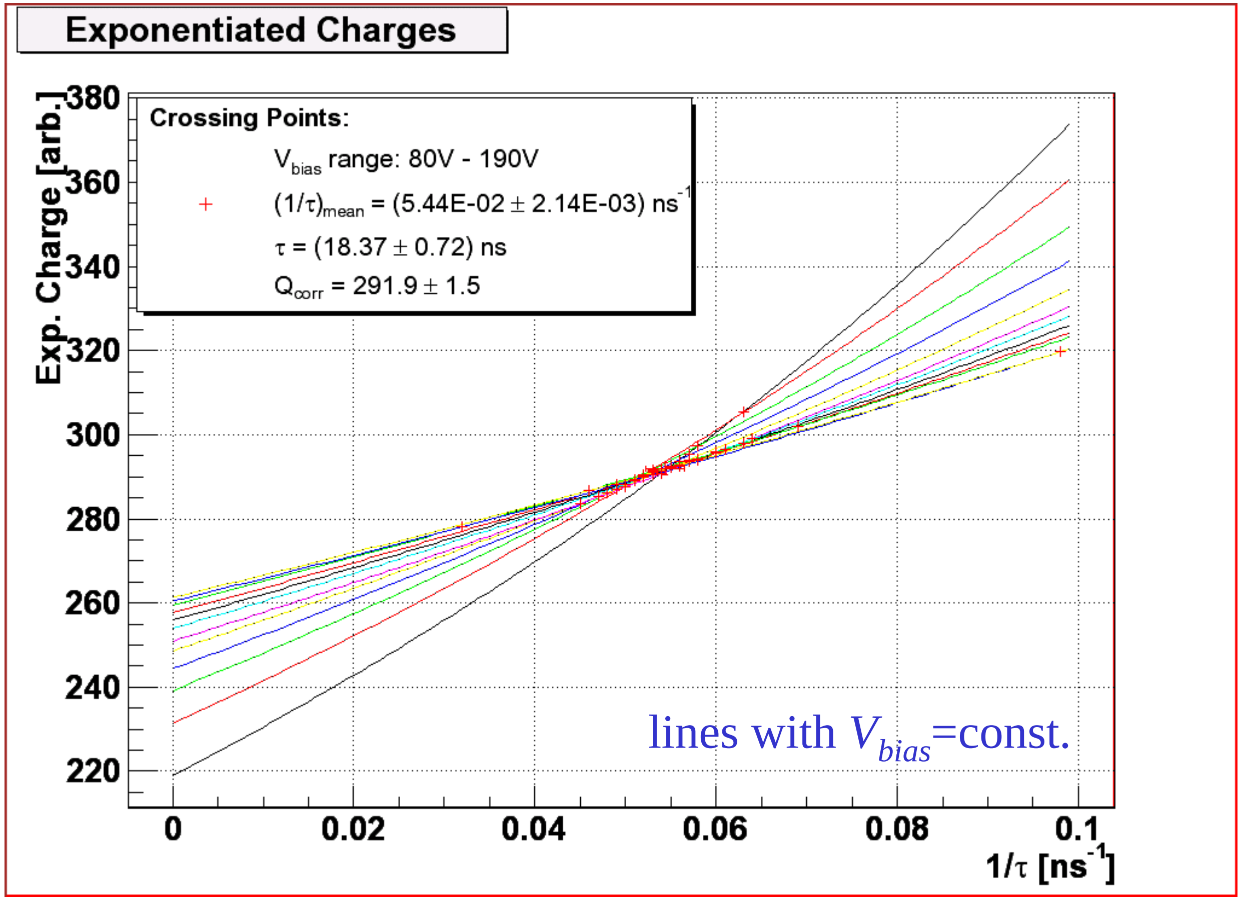






Exponentiated Charge Crossing (ECC)





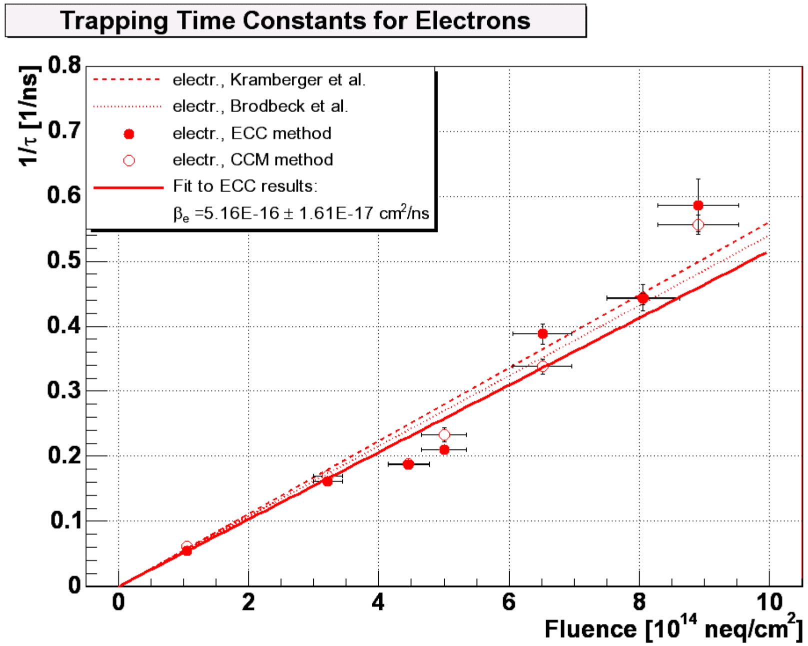
- exponentiated charges $Q_{\exp} = \int i_{meas}(t)\exp(+t/t)\,dt$ from different V_{bias} are plotted vs. $1/t$
- $1/t$ is obtained from mean of intersection points of lines

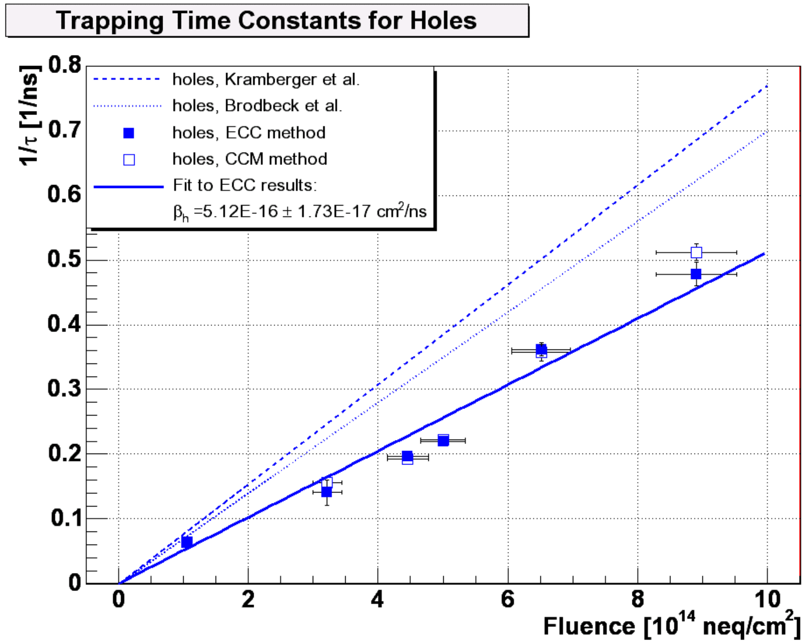
Samples

- irradiated with 24 GeV protons at CERN-PS, no biasing during irradiation
- 4 diodes from ATLAS-Pixel pre-production (CiS), irradiated to 1.1, 3.2, 5.0 and $8.9 \cdot 10^{14}$ n_{eq}/cm^2 annealed to minimum in V_{dep} at 60°C
- 2 diodes from SRD-Project (CiS), irradiated to 4.5 and $6.5 \cdot 10^{14}$ n_{eq}/cm^2; annealed to minimum in V_{dep} at room temperature
- $\langle 111 \rangle$ crystal orientation, 24h at 1200°C oxygenation

For the irradiation of the samples I want to thank M. Glaser,
M. Moll (CERN) and P. Sicho (Acadamy of Sciences, Prague)

Trapping Times: Fluence Dependence

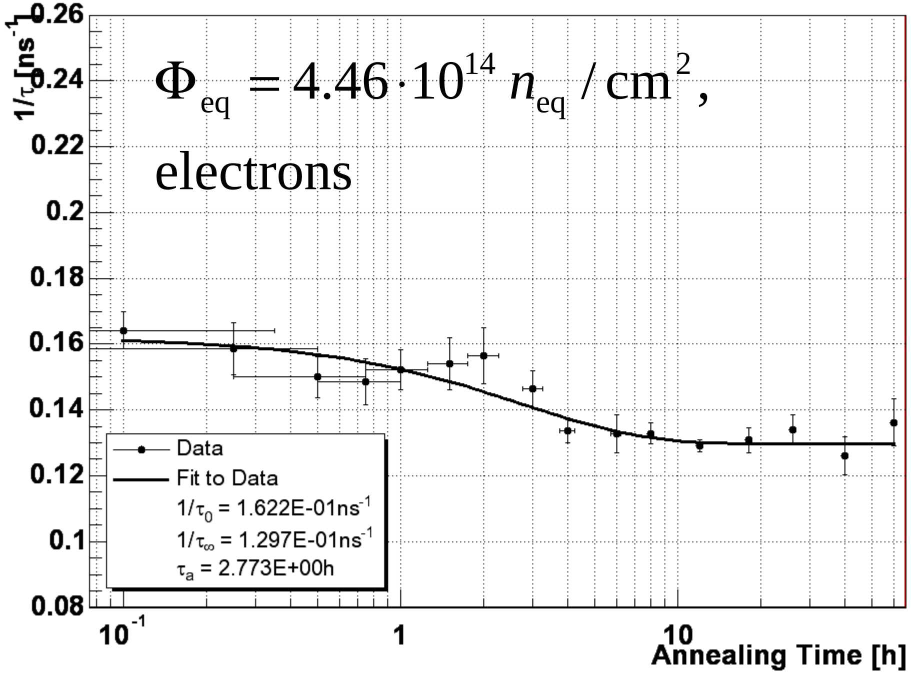


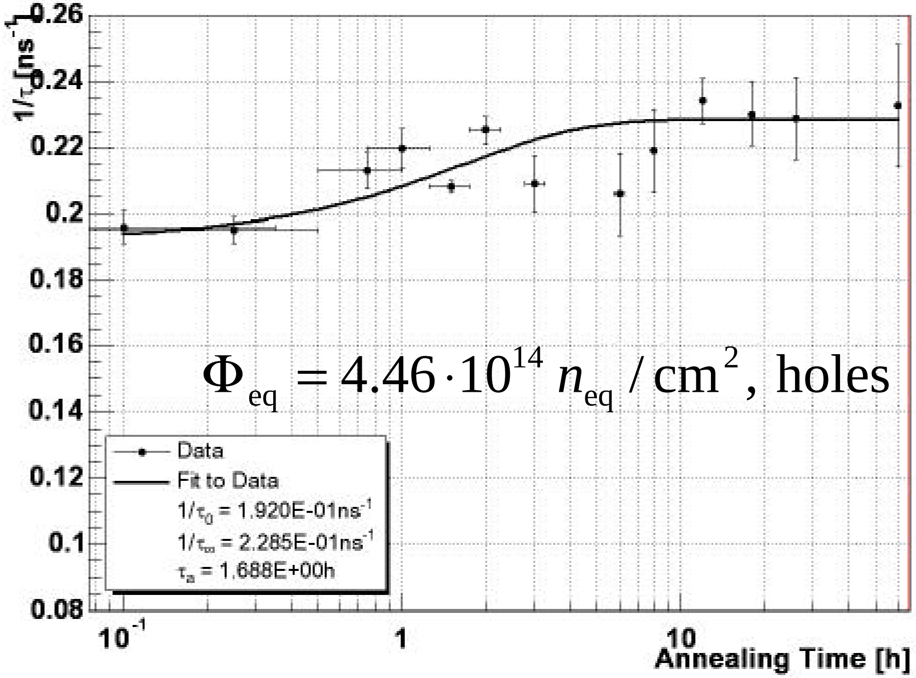


$$b_e = (5.16 \pm 0.16) \cdot 10^{-16}\ \mathrm{cm}^2/\mathrm{ns} \qquad b_h = (5.04 \pm 0.16) \cdot 10^{-16}\ \mathrm{cm}^2/\mathrm{ns}$$

- errors include only “statistical” error, systematics not yet included
- comparison with results obtained by other groups (extrapolated from data taken at fluences < $2.4 \cdot 10^{14} n_{eq}/cm^2$): agreement for electrons, deviation for holes

Trapping Times: Annealing





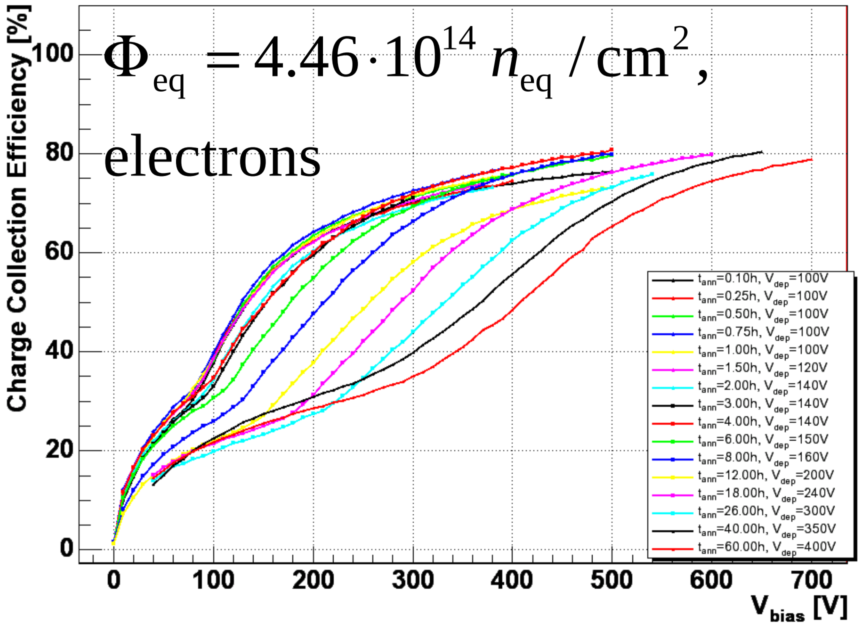
- ansatz for annealing function:

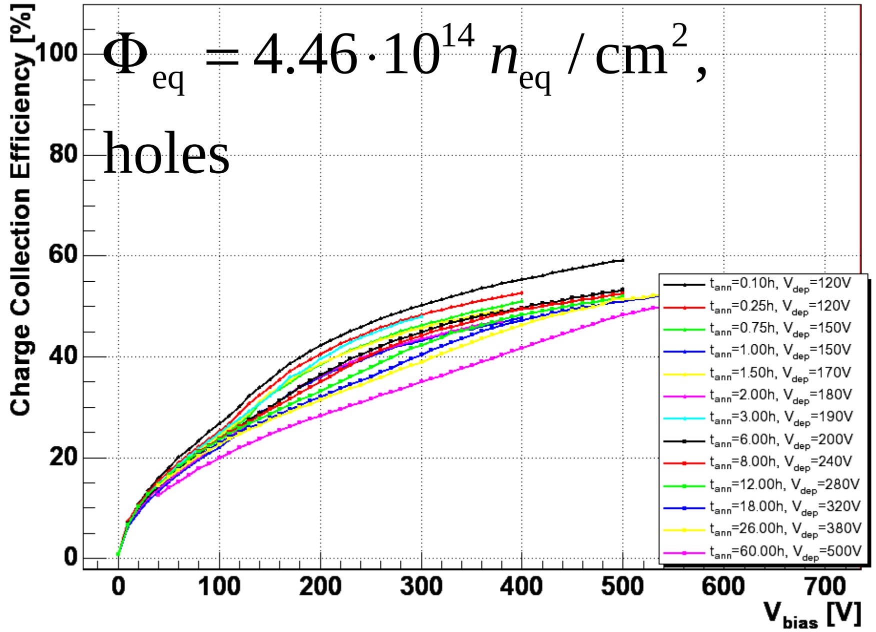
$$b(t) = b_0 \cdot \exp(-t/t_a) + b_\infty \cdot (1 - \exp(-t/t_a))$$

$$t_{a,e} = (2.77 \pm 0.80)\ \mathrm{h},\ \text{decrease by} \approx 20\%,$$

$$t_{a,h} = (1.69 \pm 0.59)\ \mathrm{h},\ \text{increase by} \approx 19\%$$

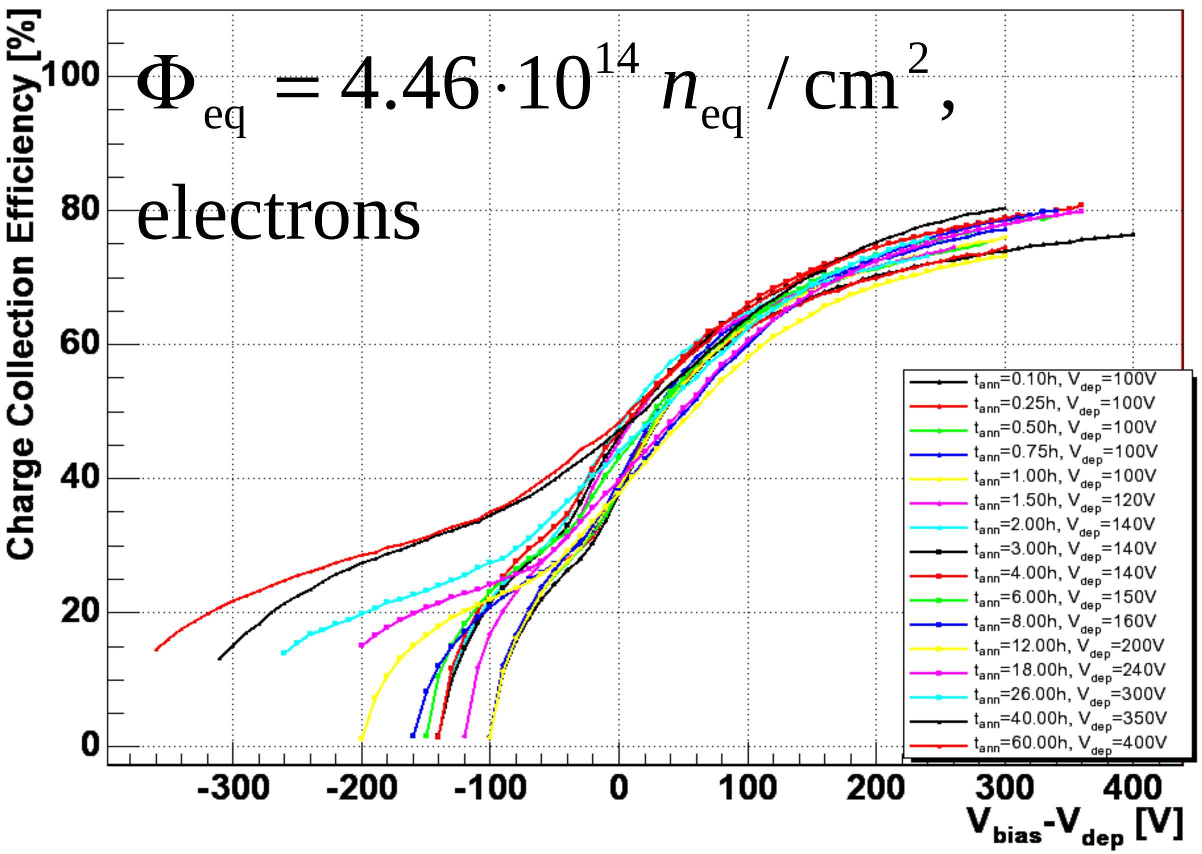
Charge Collection Efficiency





- CCE changes during annealing due to changes in N_{eff} and t
- charge collection efficiencies $\mathrm{CCE}_{\mathrm{min}}$ refer to charges injected close to surface
- therefore they give only a lower limit for CCE interesting in HEP experiments

Charge Collection Efficiency



V_{dep} from charge collection curve, ? V_{dep}=15V

- CCE_{min} for electrons is
  40-50% at V_{dep}
  50-60% at V_{dep}+50V (as foreseen in ATLAS)

Conclusions

- the effective trapping times of holes and electrons in silicon have been measured for fluences between 1.1 and $8.9 \cdot 10^{14}$ 1-MeV-n_{eq}/cm^2
- $b_e = (5.16 \pm 0.16) \cdot 10^{-16}\ \mathrm{cm}^2/\mathrm{ns},\ b_h = (5.04 \pm 0.16) \cdot 10^{-16}\ \mathrm{cm}^2/\mathrm{ns},$

  $b_e \approx b_h$ (contrary to other measurements!)
- $1/t = b \cdot \Phi_{eq}$ confirmed
- results for electrons are consistent with extrapolation of measurements at lower fluences (Brodbeck et al., 2000; Kramberger et al., 2000)
- trapping times for holes are not consistent with these measurements
- annealing of t is negligible, for electrons it even improves slightly (important for n^+-on-n-pixels)

Finally...

THE END

Signal Treatment

- bandwidth:

$$u_m(t) \rightarrow u_m(t) + t_{RC}\,\dot{u}_m(t)$$
$$= u_{BW}(t)$$
$$t_{RC} = RC_D$$

- tail (problems with reflections/oscillations):

$$u_{BW}(t) \rightarrow \begin{cases} u_{BW}(t) & \text{for } t \le t_{ip} \\ u_0 \exp(-t/t_f) & \text{for } t > t_{ip} \end{cases}$$

t_{ip} = inflection point

u_0, t_f are fit parameters