Characterization of diamond using broad-band electronics

(H. Pernegger , CERN)

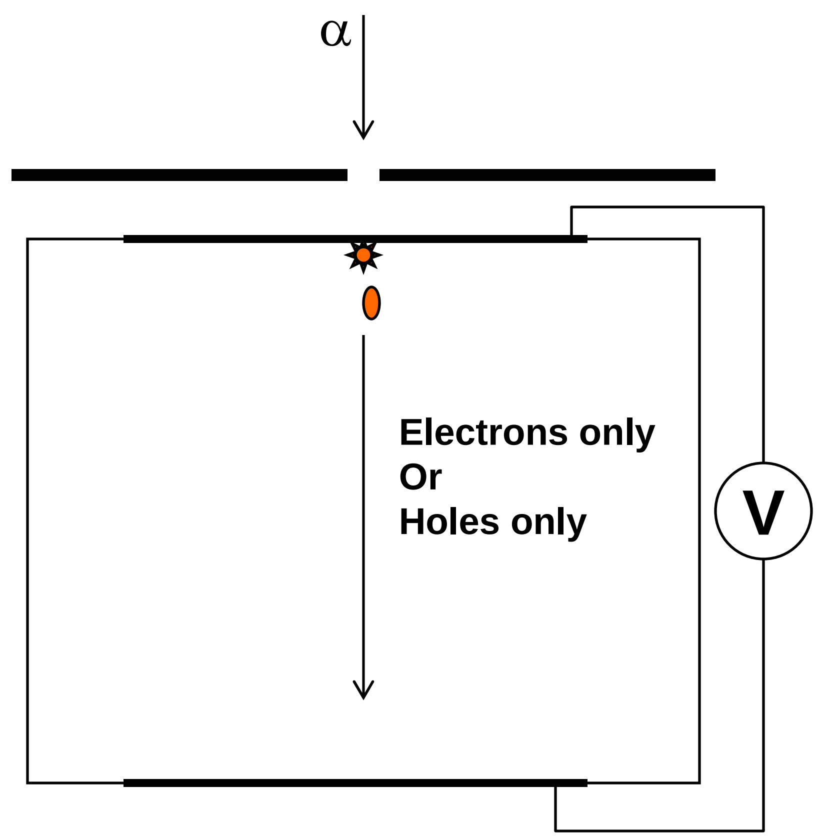
- Overview
  - The principle & Setup
  - Raw Measurements & Analysis
  - Measurement of drift velocity
  - Charge lifetime
  - Net effective space charge

The goal

- Measure the induced current signal WHILE ionization charges drift through the detector bulk material
- Record the pulse shape of induced current on the electrodes to get information on
    - Drift velocity (and mobility)
    - Charge lifetime
    - Internal electric field
- Drift process takes only few nano-seconds and therefore requires us to us fast current amplifiers

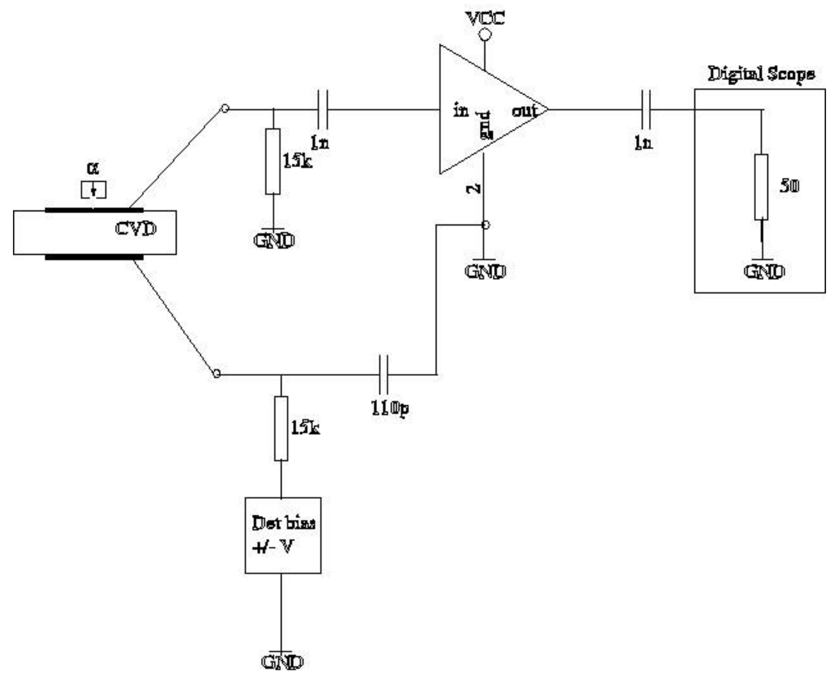
The principle

- Use α-source (Am 241) to inject charge
- measure charge carrier properties of electrons and holes separately
- Injection
  - Depth about 14mm compared to 470mm sample thickness
  - Use positive or negative drift voltage to measure material parameters for electrons or holes separately
  - Amplify ionization current



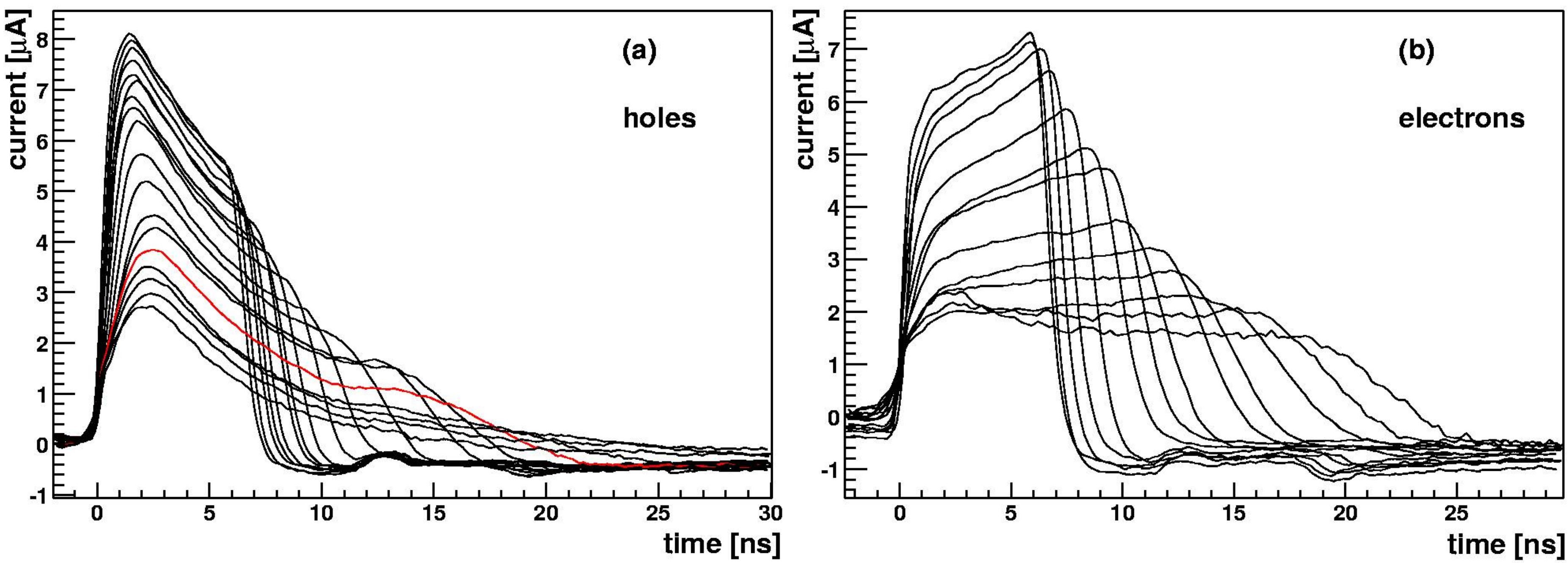
The readout

- Use current amplifier to measure induced current
  - Bandwidth 2 GHz
  - Amplification 11.5
  - Rise time 350ps
- Inputimpedance 45 Ohm
- Readout with LeCroy 564A scope (1GHz 4Gsps)
- Correct in analysis for detector capacitance (integrating effect)
- Cross calibrated with Sintef 1mm silicon diode
  - μ_e = 1520 cm2/Vs
  - I = 3.77 eV +/- 15%



$$i_m(t) = \frac{1}{R_{in}A}\left(R_{in}C_d\frac{dU(t)}{dt} + U(t)\right)$$

The measured current curves



$$i_{e,h}(t) \propto e^{\frac{t}{\tau_{eff_{e,h}}} - \frac{t}{\tau_{e,h}}}$$

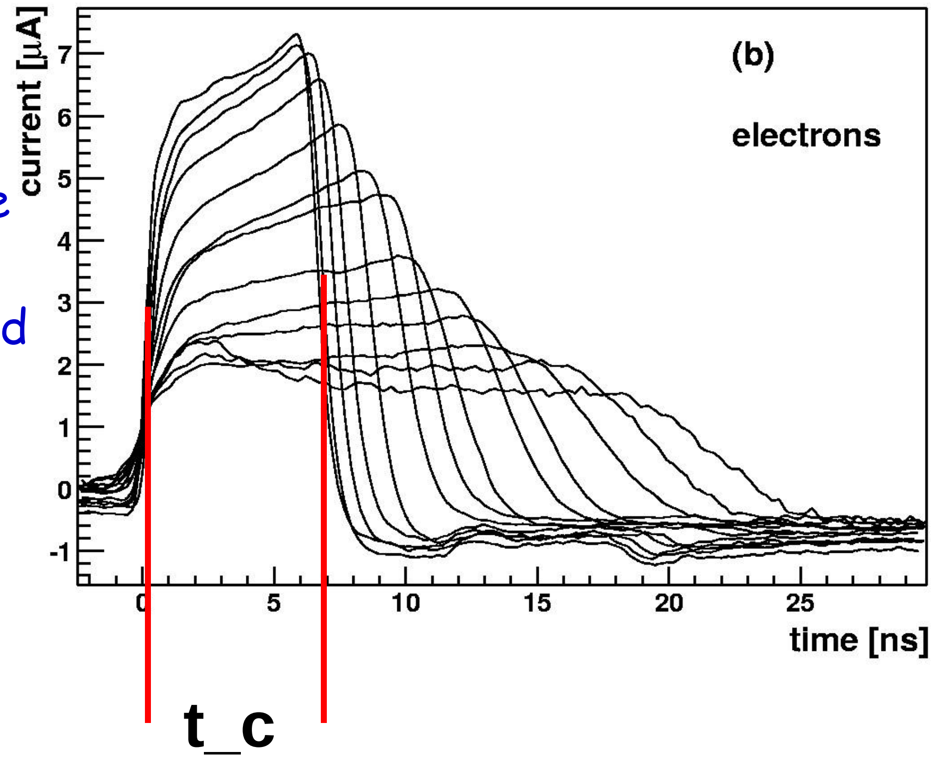
$$\tau_{eff_{e,h}} = \frac{\epsilon\epsilon_0}{e_0\mu_{e,h}|N_{eff}|} \approx \frac{\epsilon\epsilon_0 t_c V}{e_0 d^2|N_{eff}|}$$

- Two effects
  - Charge trapping during drift
  - Space charge : decrease of current for holes / increase for electons

The parameters

- Extracted parameters

- Transit time of charge cloud
  - Signal edges mark start and arrival time of drifting charge cloud
  - Error-function fit to rising and falling edge
- Total signal charge
  - Integral of curves
  - $$Q_{e.h}(V) = \int_{t_s}^{t_e} i_{m_{e,h}}(V,t)dt$$



$$Q_{c_h}(V) \quad = \quad \int_{t_s}^{t_e} i_{m_h}(V,t)e^{+\frac{t}{\tau_h}}dt$$

Measurement of velocity

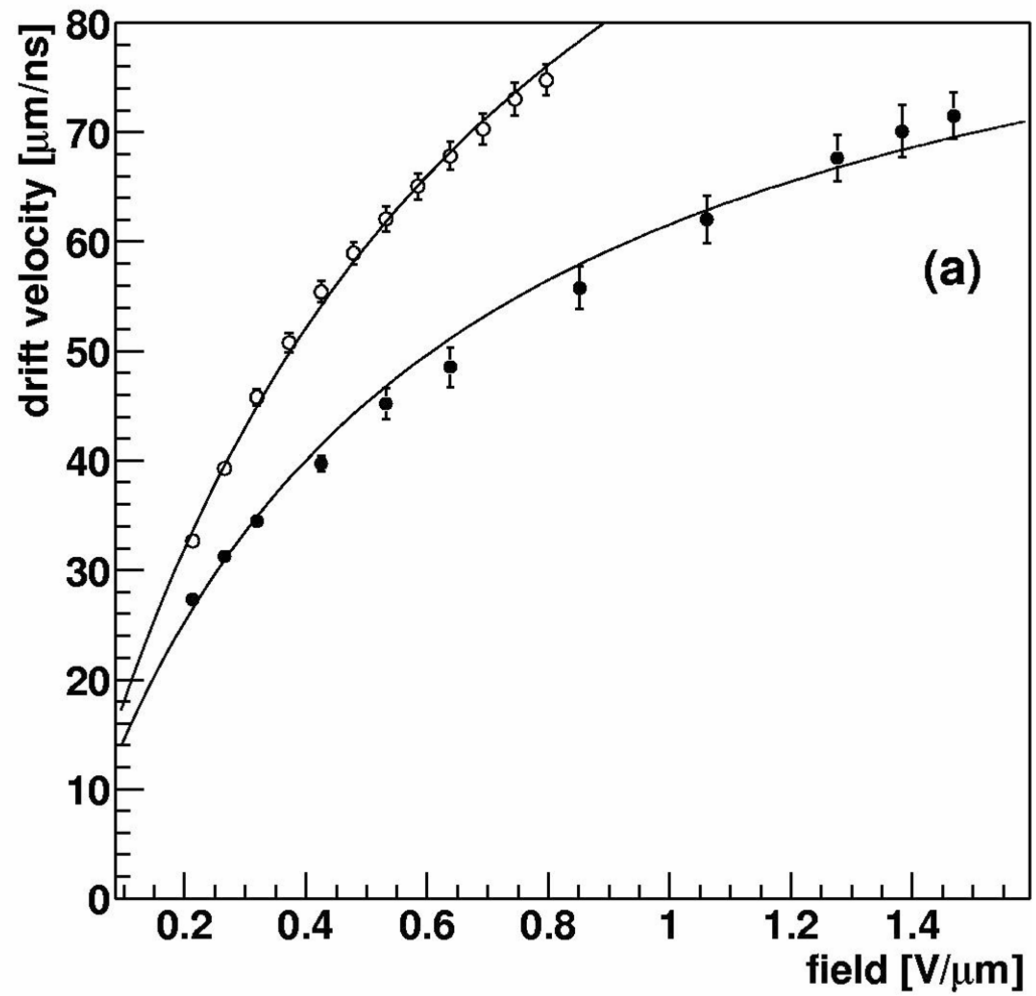
- Average drift velocity for electrons and holes

$$v_{dr_{e,h}}(E) = d/t_c$$

- Extract μ0 and saturation velocity

$$v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_s}}$$

- μ0:
  - Electrons: 1714 cm2/Vs
  - Holes: 2064 cm2/Vs
- Saturation velocity:
  - Electrons: 0.96 10^7 cm/s
  - Holes: 1.41 10^7 cm/s



… and "effective mobility"

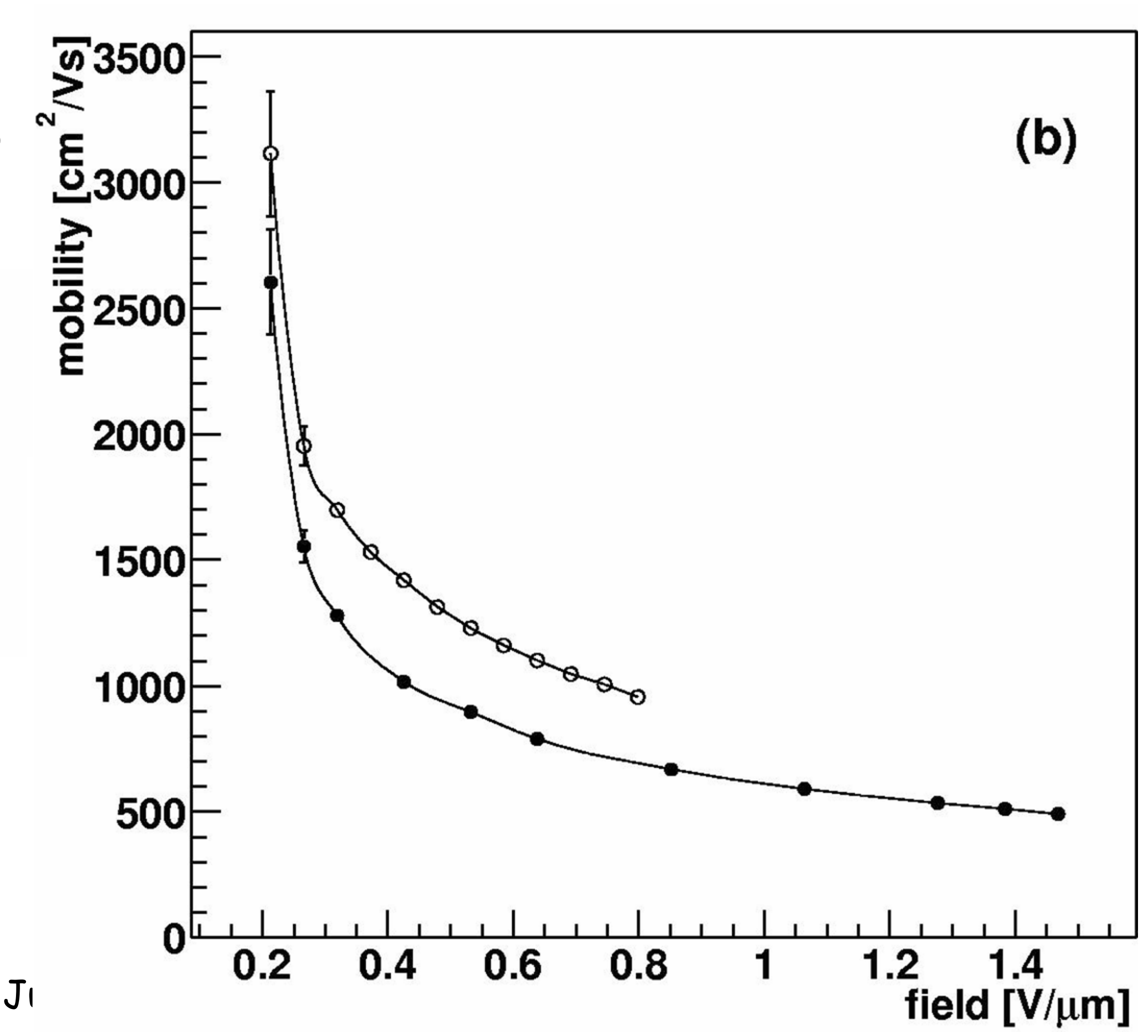
- Deduce a calculated mobility from the measured velocity (normaly mobility is defined only at low fields with linear relation between field and velocity)

- Taking space charge into account:

$$\mu_h = -\frac{d^2}{2t_cV_c}\ln\left(\frac{V+V_c}{V-V_c}\right)$$

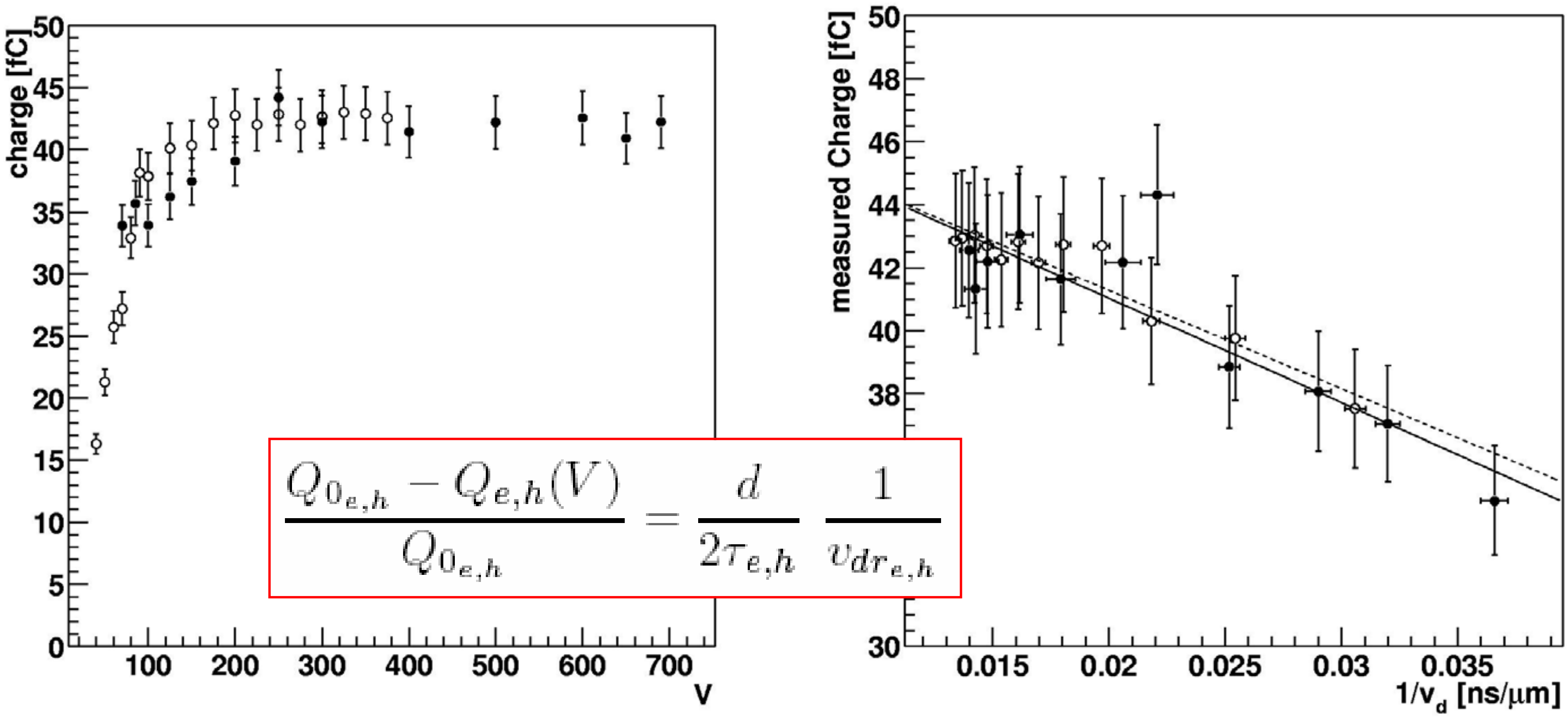
$$\mu_e = -\frac{d^2}{2t_cV_c}\ln\left(\frac{V-V_c}{V+V_c}\right)$$

- Normal operation in region close to velocity saturation



Carrier lifetime measurement

- Extract carrier lifetimes from measurement of total charge



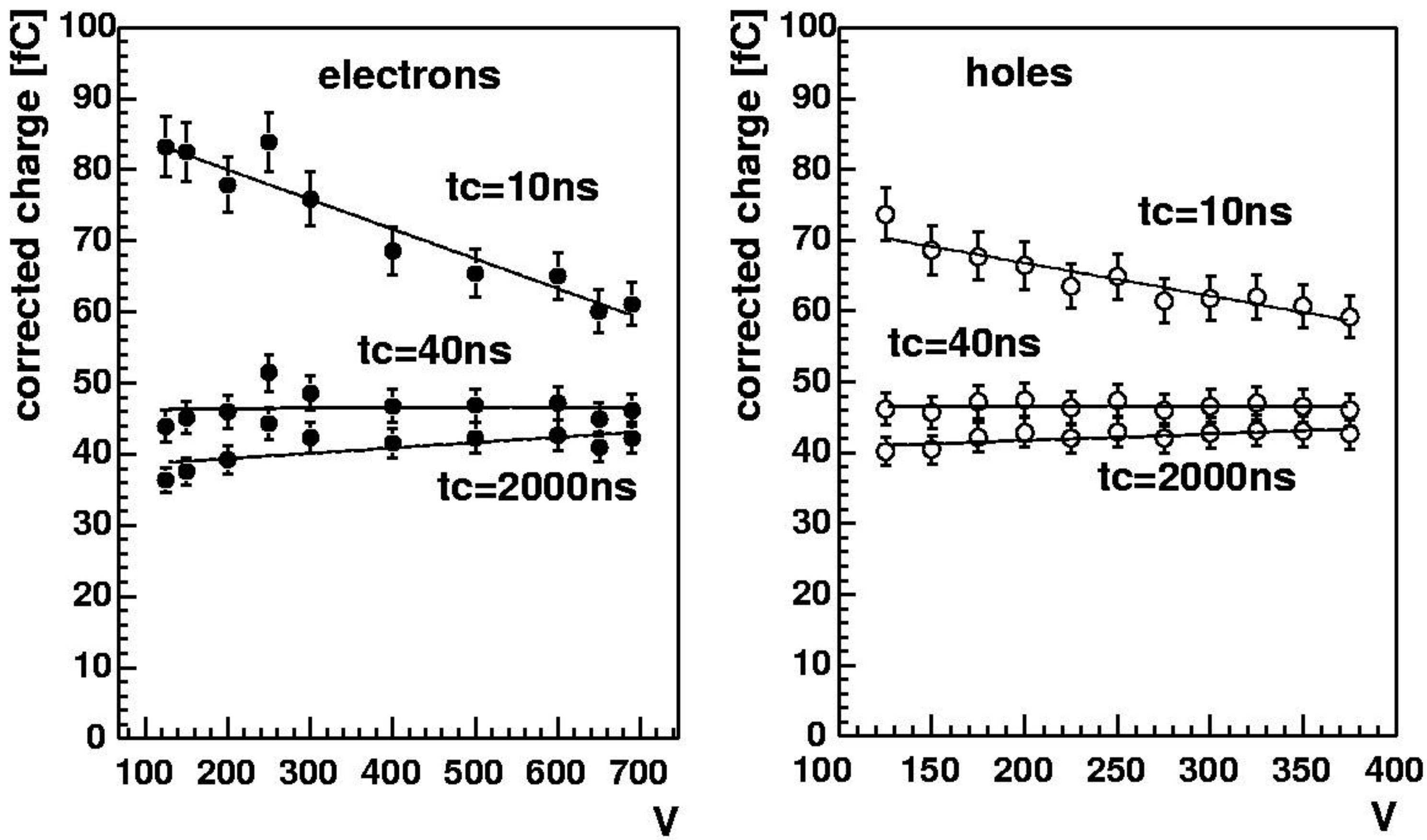
$$\frac{Q_{0_{e,h}} - Q_{e,h}(V)}{Q_{0_{e,h}}} = \frac{d}{2\tau_{e,h}} \frac{1}{v_{dr_{e,h}}}$$

- Total ionization charge (from extrapolation) : 47.6 (e) & 47.5 (h) fC
- Lifetime: 34ns (+10/-6ns) for electrons & 36ns (+20/-9ns) holes

Lifetime measurement by charge correction

- Correct the measured charge

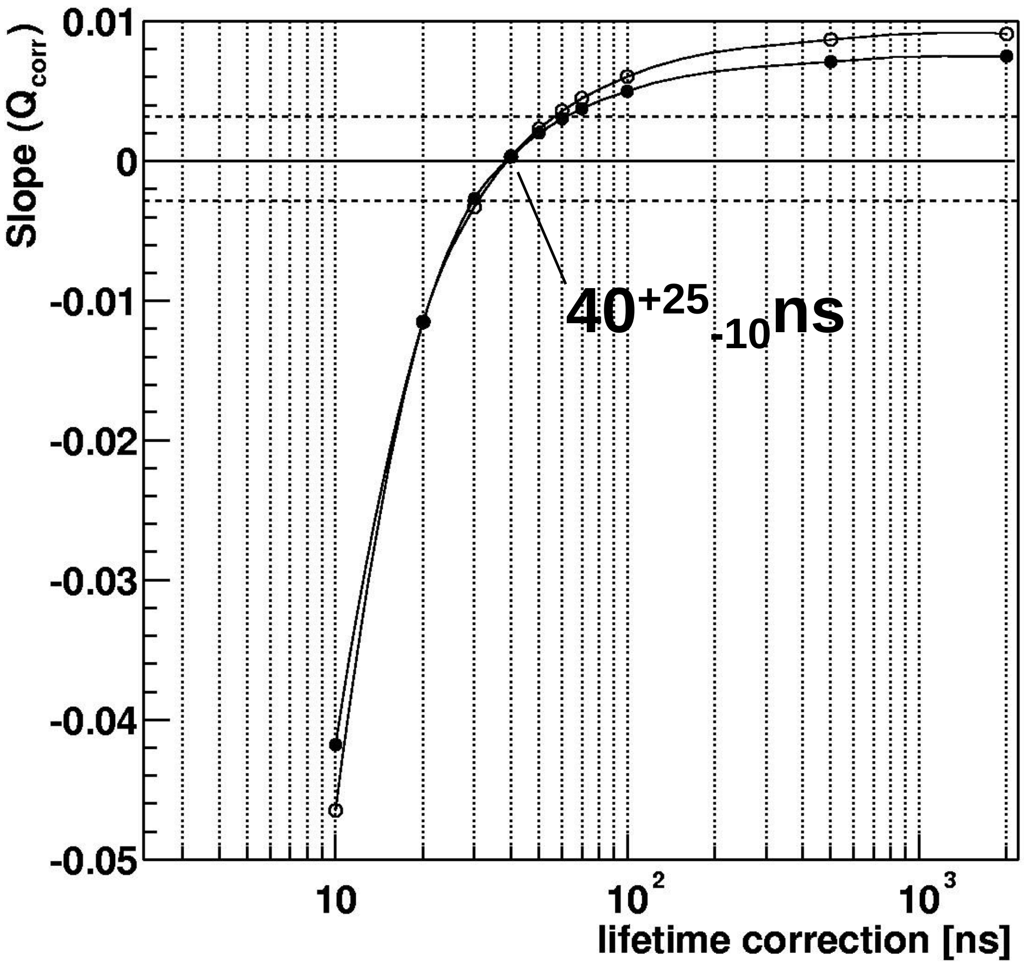
$$Q_{c_h}(V) = \int_{t_s}^{t_e} i_{m_h}(V,t)\, e^{+\frac{t}{\tau_h}}\, dt$$



H. Pernegger, NoRDHia workshop , GSI, July 2004

Extract the lifetime

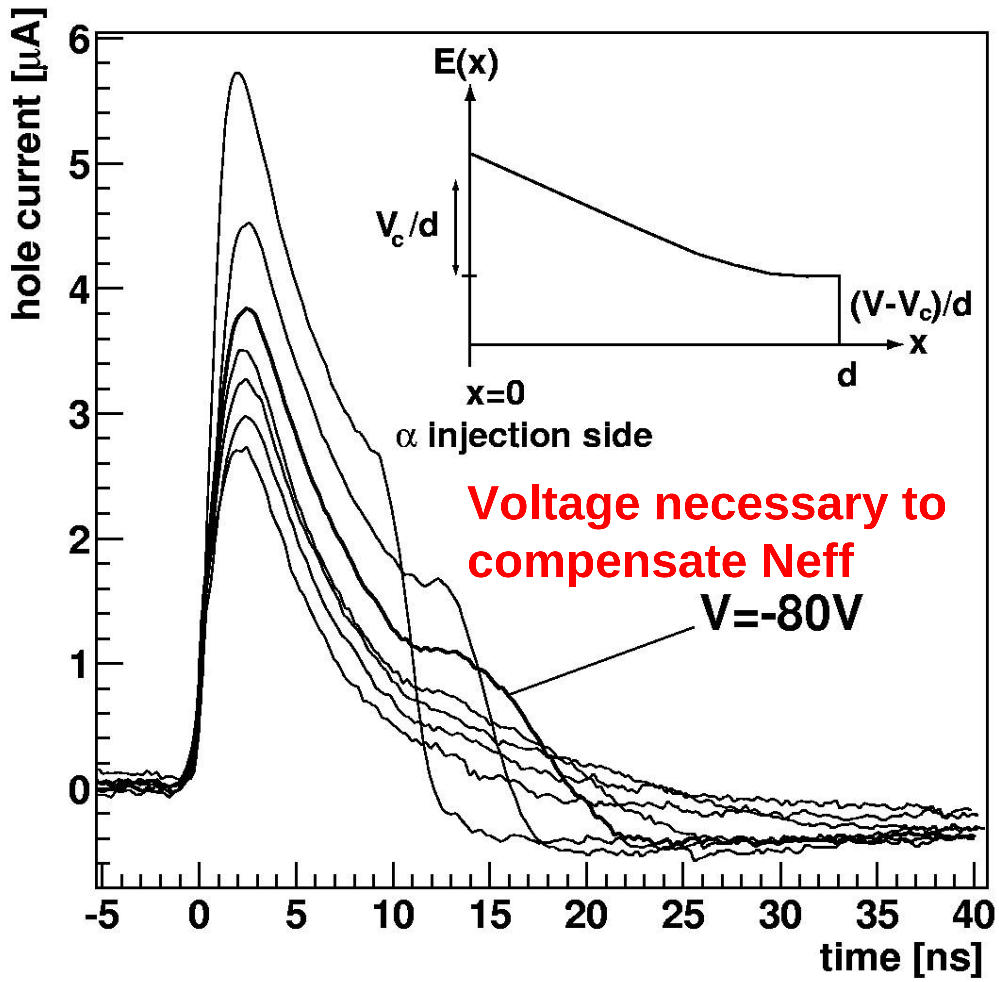
- For the correct choice of the correction time, slope becomes zero



- Both measurements yield consistent results:
  - Electrons and holes of identical lifetime between 35 to 40ns
- The charge lifetime is much larger than the transit time (at typical detector operation voltes)
- Charge trapping doesn't seems to be a limiting issue for scCVD

Net effective space charge

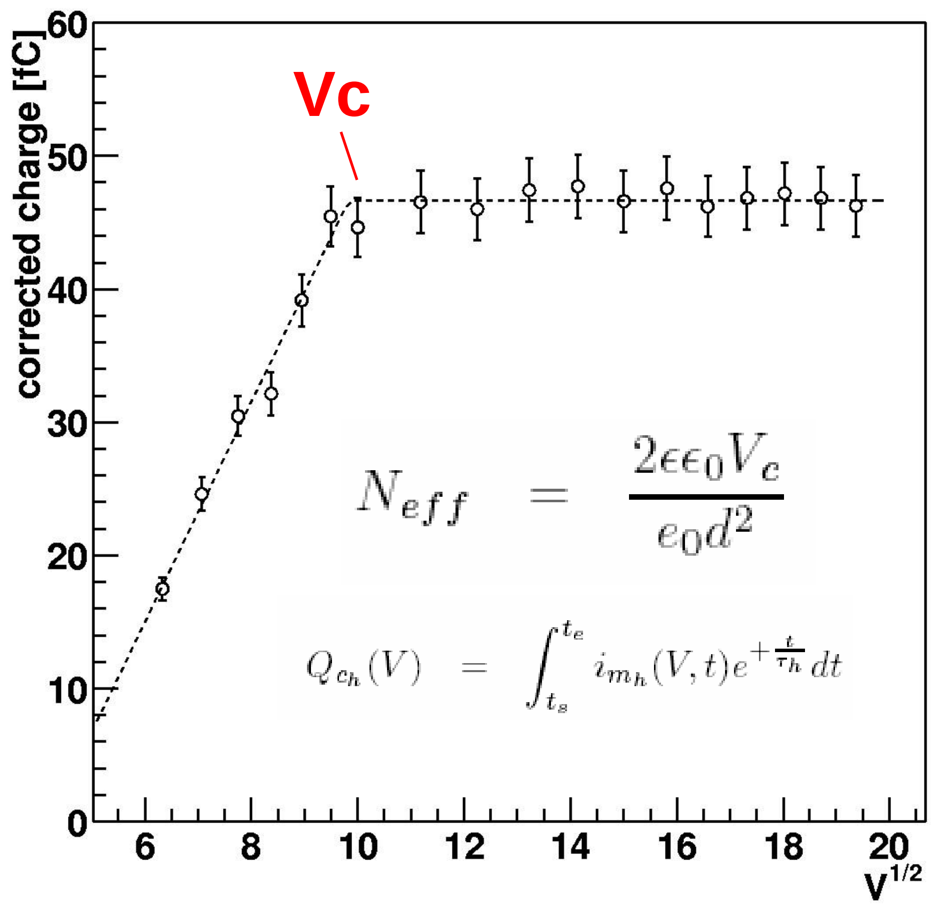
- Shape of current pulses can be explained by net effective space charge in diamond bulk
- Signal decrease due to decreasing electrical field
- In the simpliest model of a uniform space charge: linear field ->exponential current decrease
- Further considerations on field distribution:
  - See Vladimir's talk



Linear Model Determination of N effective

- Non-zero field region increases with $V^{1/2}$
- For V=Vc : holes cloud arrive
- No electron signal below Vc (for this injection configuration)
- Sign of increase/decrease -> NEGATIVE space charge

- Vc = 96V
- $N_{eff} = 2.8 \times 10^{11}$ cm^{-2}

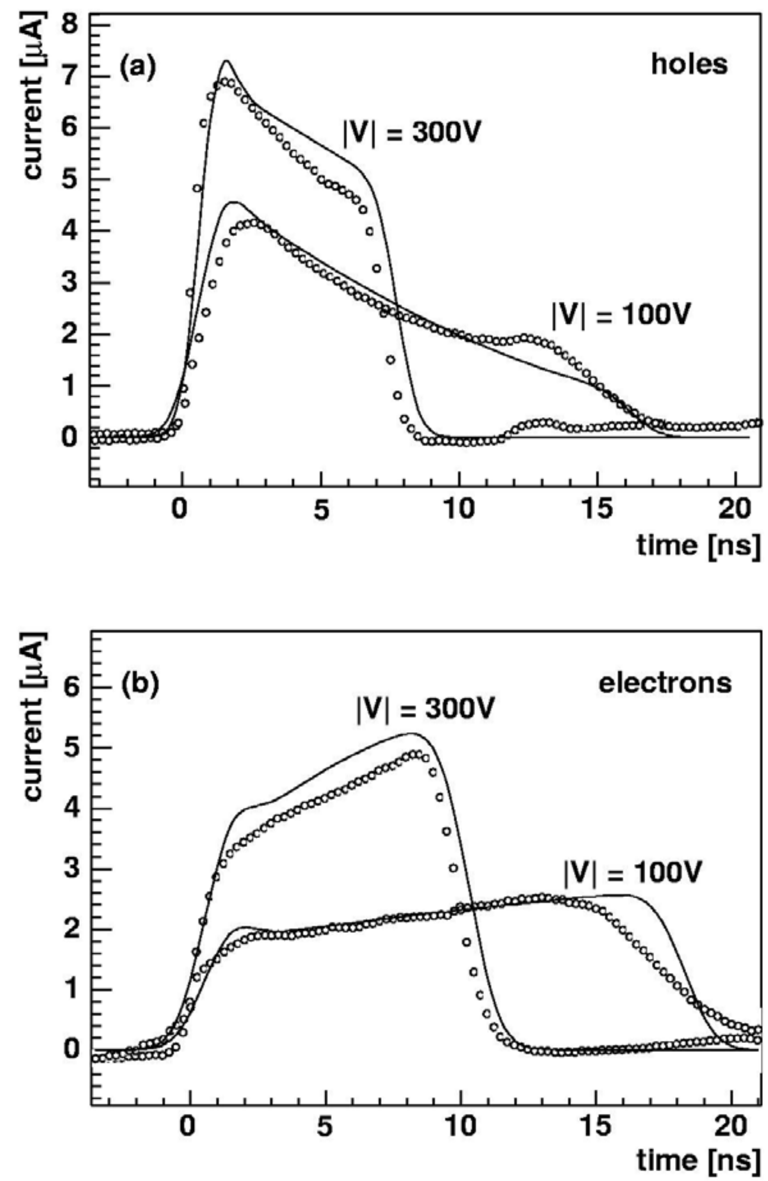


Further considerations regaring space charge

- Linear field maybe a good approximation for high fields but not at low fields (near Vc)
  - Flat region in current curve at end
  - Extrapolation for Q=0 yields 25V
- At V close to Vc the field may e.g. depend on combination of generation current and trapping center density which can lead to a non-uniform space charge
- Space charge may depend on detector bias voltage
  - Electron current increase stronger at higher voltages

Comparion with Simulation:

- Simulation
  - Uses charge drift through detector
  - Electronics transfer function
  - Material parameters as measured (lifetime, velocity)
- Can achieve good approximation of data
- Vary N_{eff}



Conclusion

- TCT allows to measure several charge transport properties in a single characterization and seems (to me) ideally suited for further additional studies of CVD properties.
- It allows to measure
  - Drift velocity
  - Lifetime
  - Space charge & characterize the field configuration inside the diamond
- We measure
  - Lifetimes of approx. 40ns >> transit time at typical detector operation
  - Saturation velocity of 1 (e) to 1.4 (h) x 10^7 cm/s
- Propose to continue measurements with
  - Further scCVD samples in the next future (sample comparison)
  - Study other dependence's (e.g. surface and contact preparation)