Electric field deformation in diamond sensors induced by radiation defects

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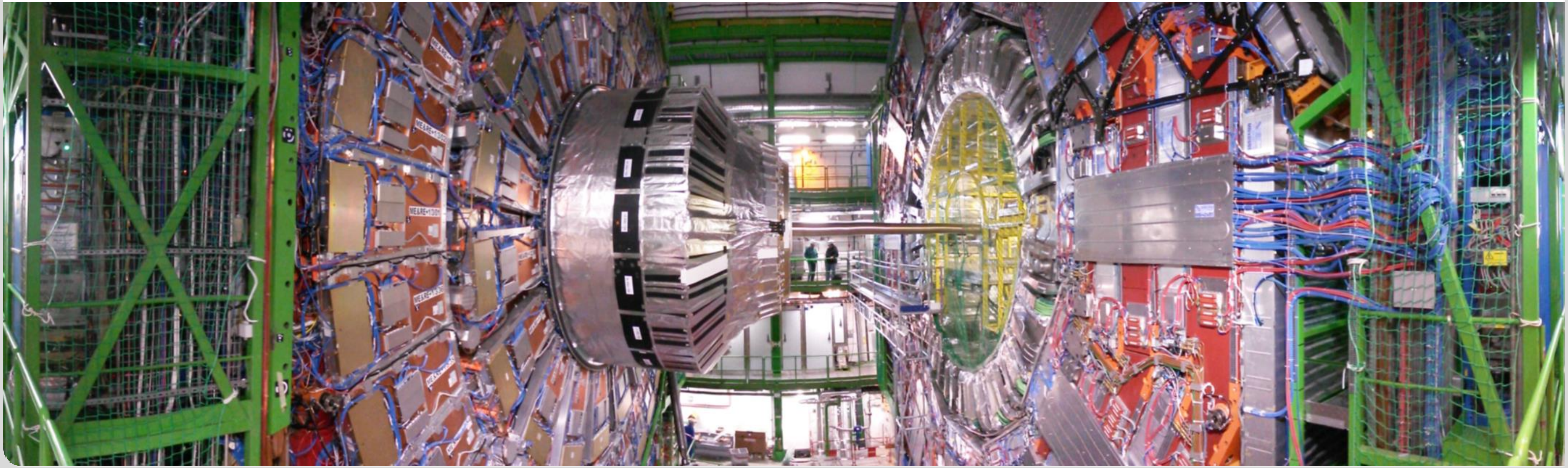
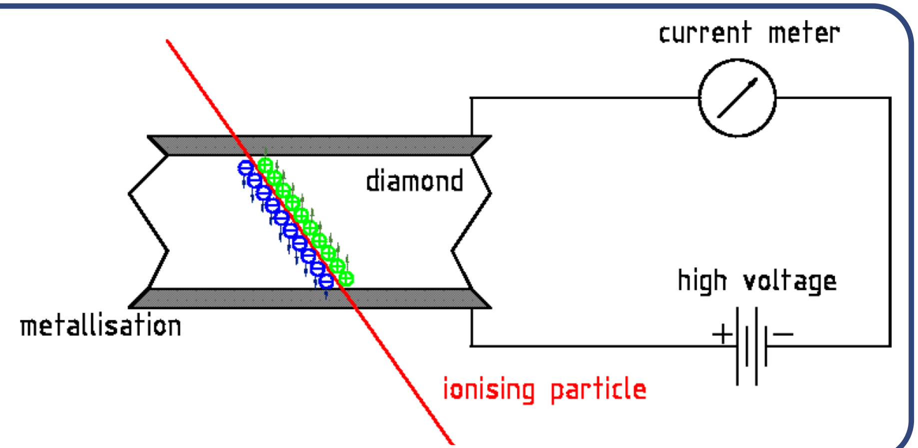


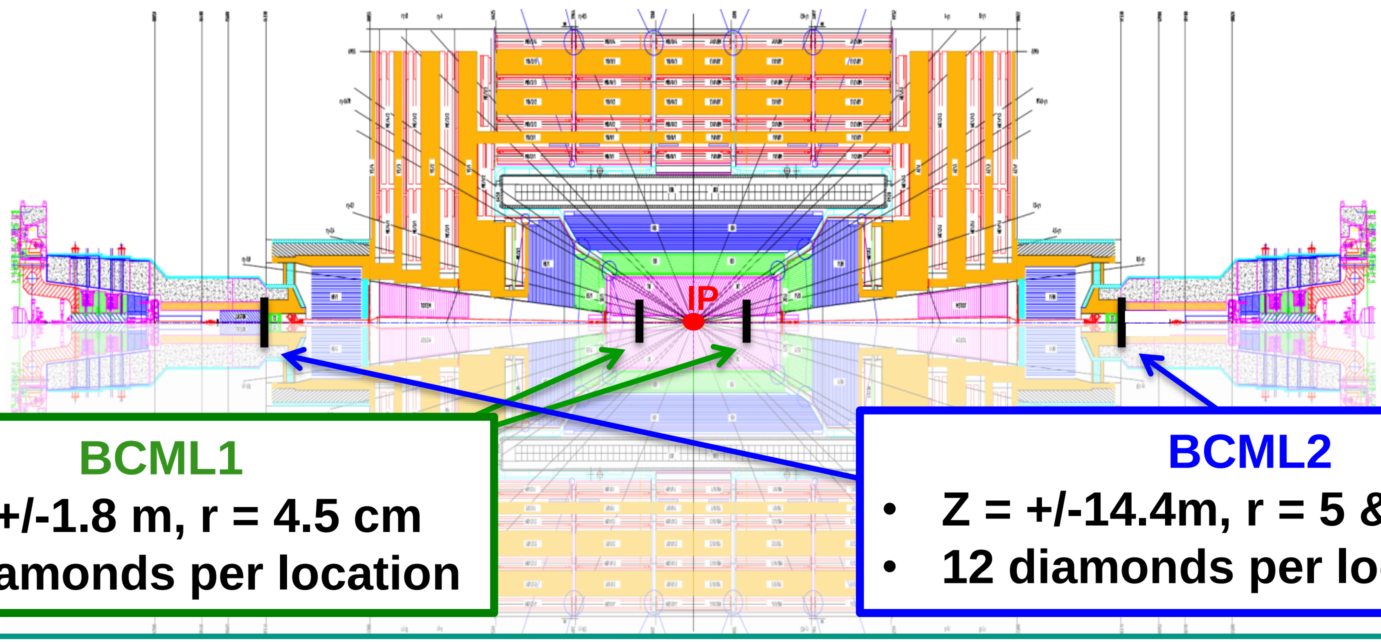
The beam abort system at CMS (BCML)

Working principle of diamond detectors

- High voltage applied to metallized surfaces of diamond
- Ionization creates e/h-pairs
- Measurement of charge carrier drift



Positions of diamond detectors at CMS



BCML1

- Z = +/-1.8 m, r = 4.5 cm
- 4 diamonds per location

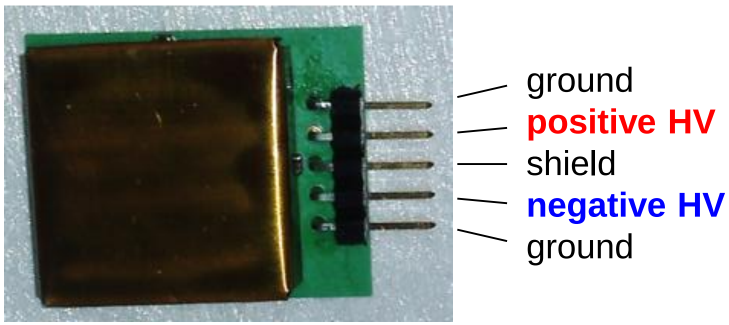
BCML2

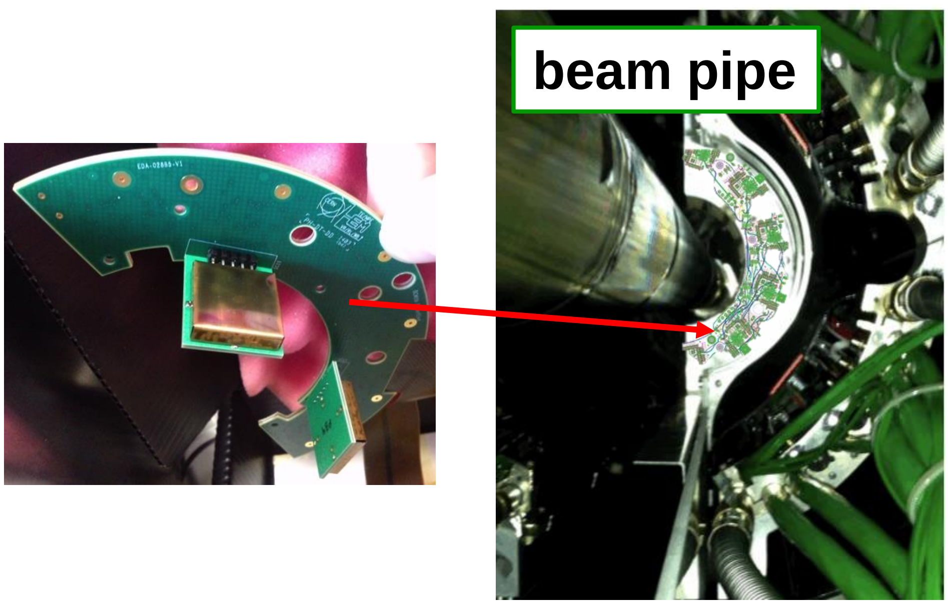
- Z = +/-14.4m, r = 5 & 28 cm
- 12 diamonds per location

The beam abort system at CMS (BCML)

BCML1

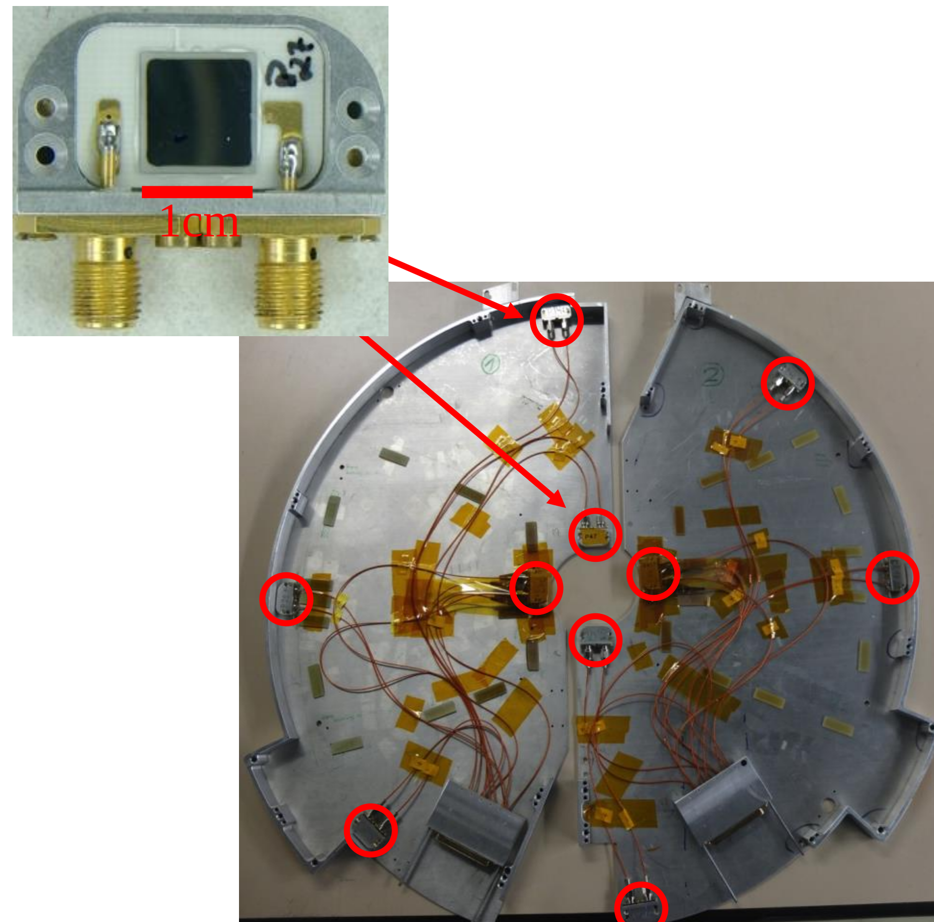
➢ **Mounted on BCM carriage**





BCML2

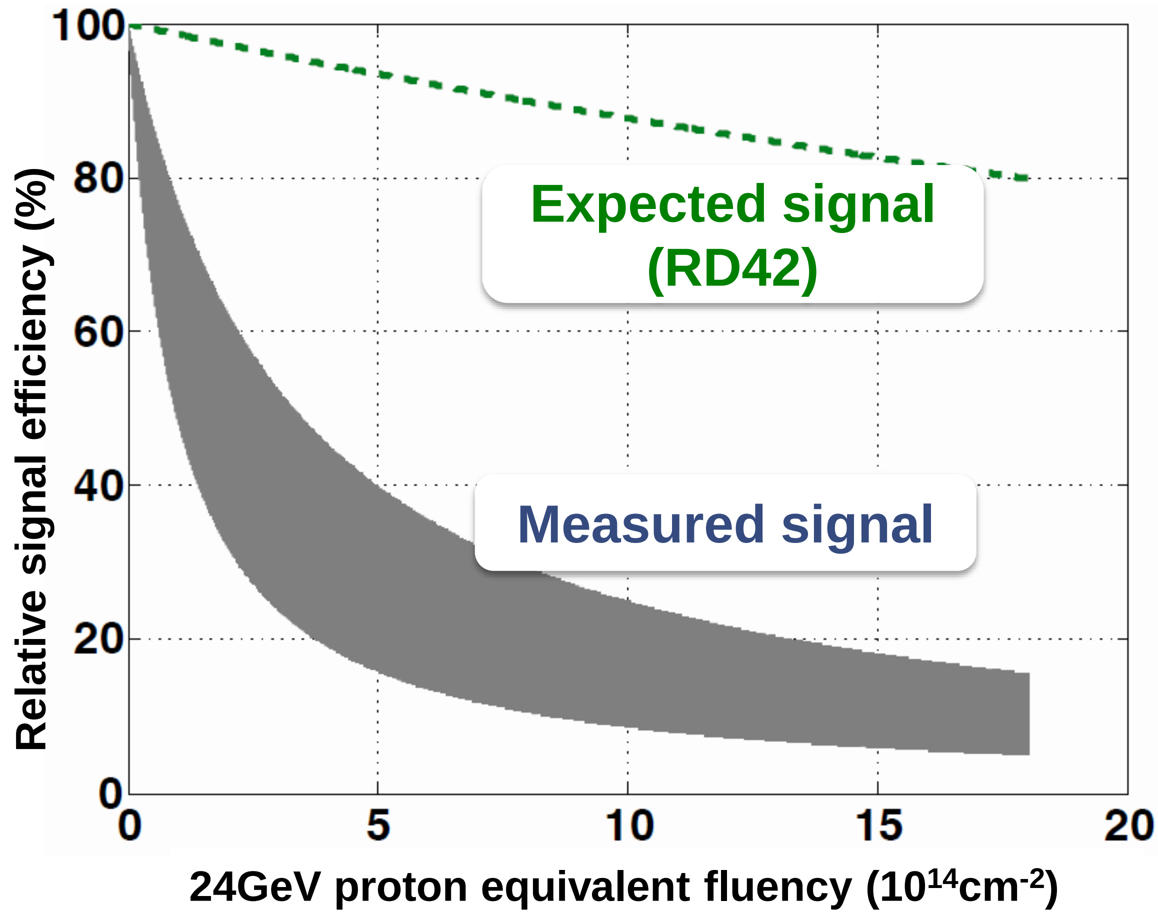
➢ **Mounted on wheel structure around the beam pipe**



Unexpected strong radiation damage at LHC

Decrease of detector efficiency was higher than expected in comparison to lab measurements (RD42)

- **caused by reduced electrical field in a high rate particle environment (‘polarization’)**



This talk:

- **Detailed simulation and irradiation studies to understand this plot**

Source of graph: M.Guthoff, “Radiation damage to the diamond based Beam Condition Monitor of the CMS Detector at the LHC ", Ph.D. thesis, 2014

Outline

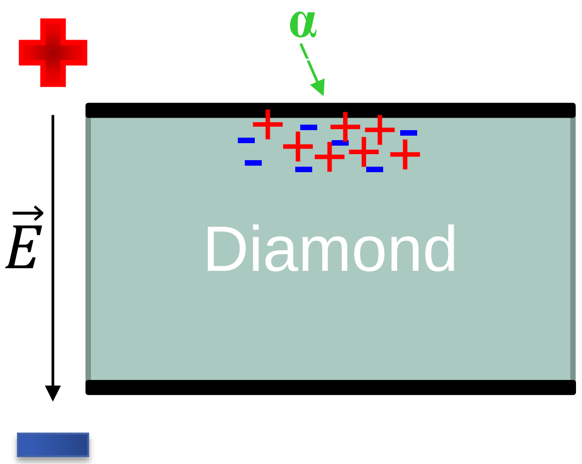
1. **Measuring the electrical field of a diamond sensor**

2. **Irradiation campaign**
   - **TCT measurements at KIT**
   - **CCE measurements at DESY**

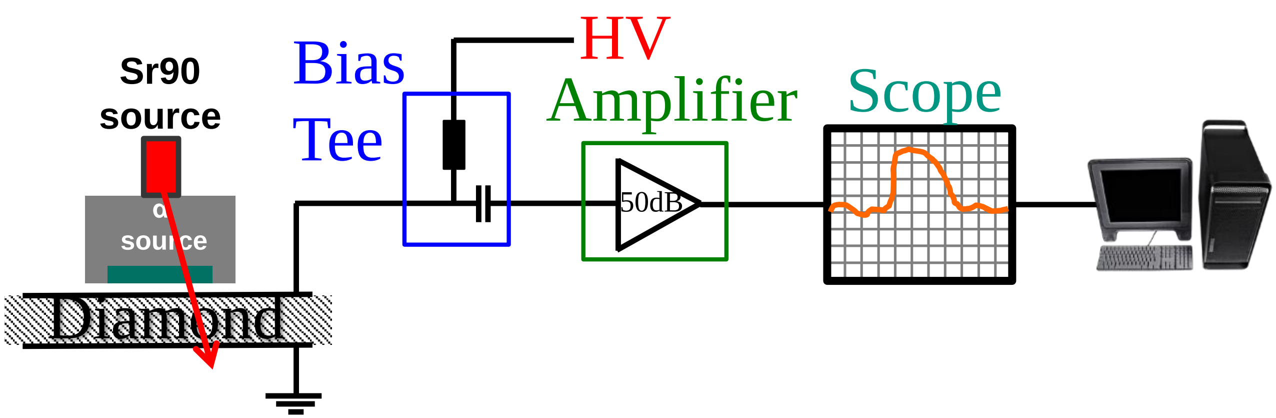
3. **Simulation of an irradiated diamond detector with SILVACO TCAD**

2. Measuring the electrical field with the Transient Current Technique (TCT)

Measurement idea



Measurement setup



Ramos theorem:

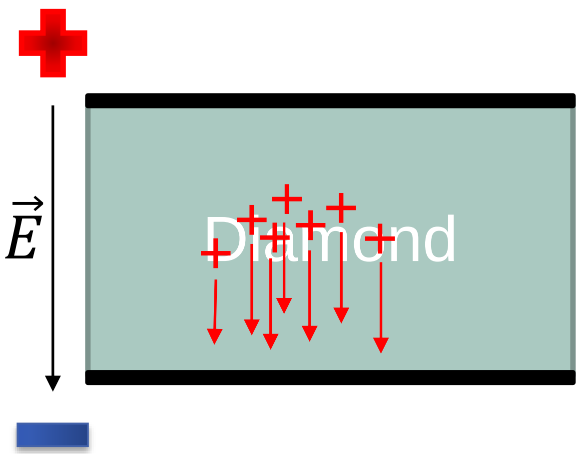
$$i = q\, v\, E_V$$

with *i* as induced current, *q* as charge, *v* the velocity of the charge drift and with E_V the weighting field

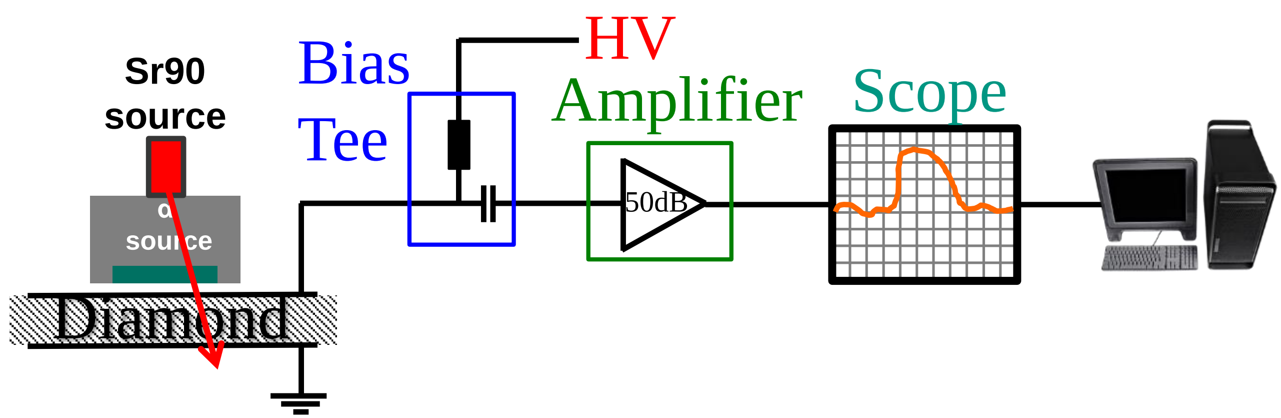
- **Alpha particles are used to introduce charge carriers at the diamond surface.**

2. Measuring the electrical field with the Transient Current Technique (TCT)

Measurement idea



Measurement setup



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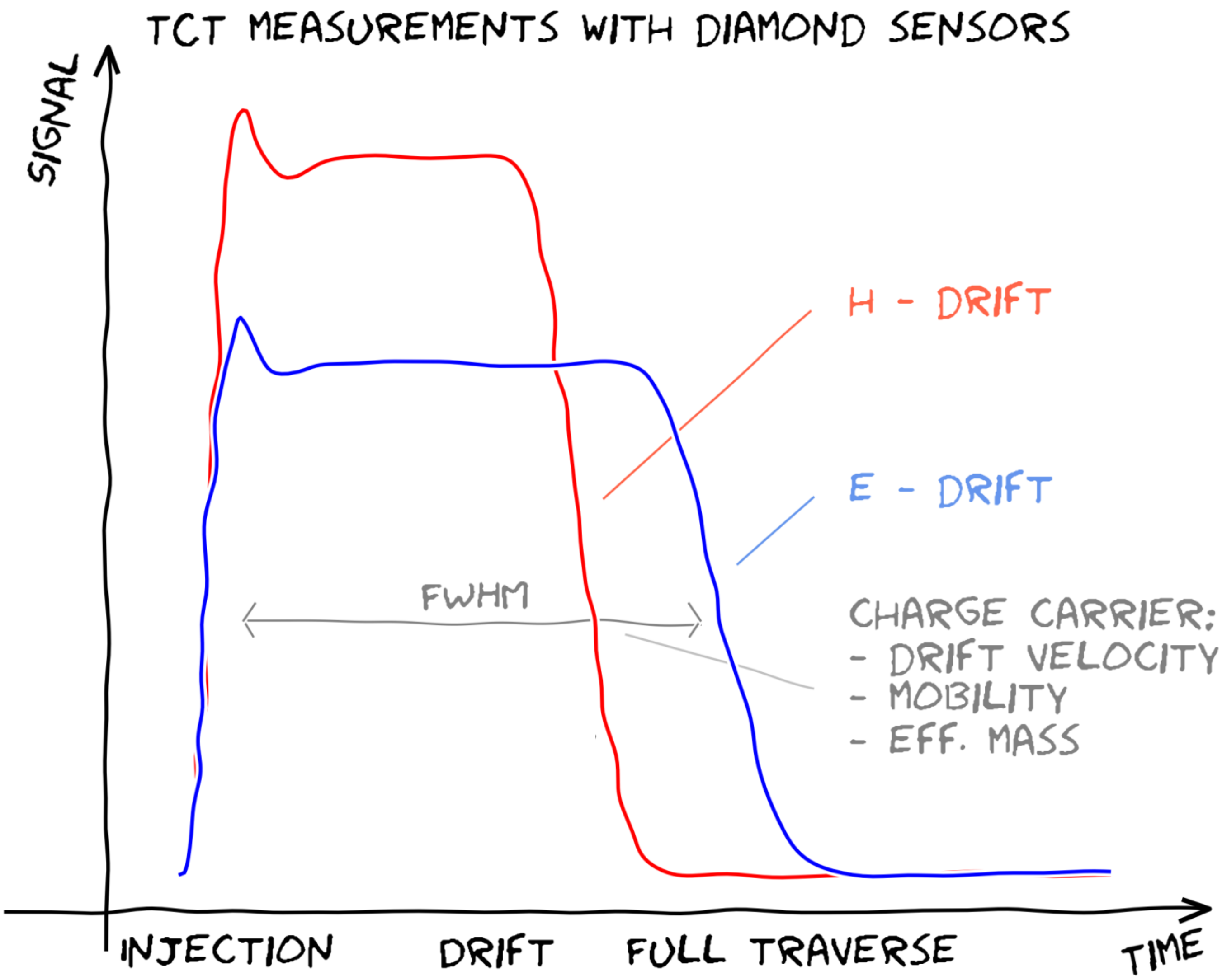
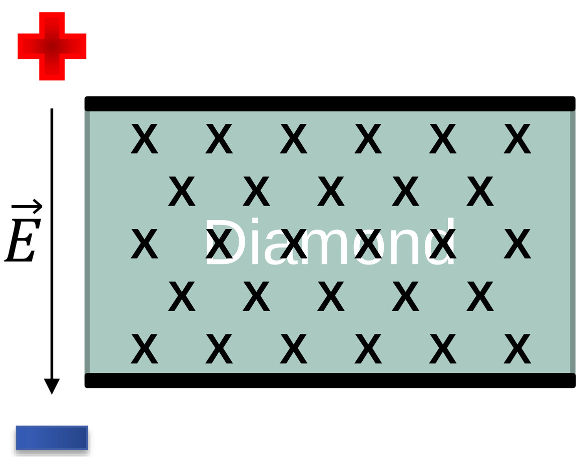
Intermezzo:
TCT measurement, polarization and electrical field



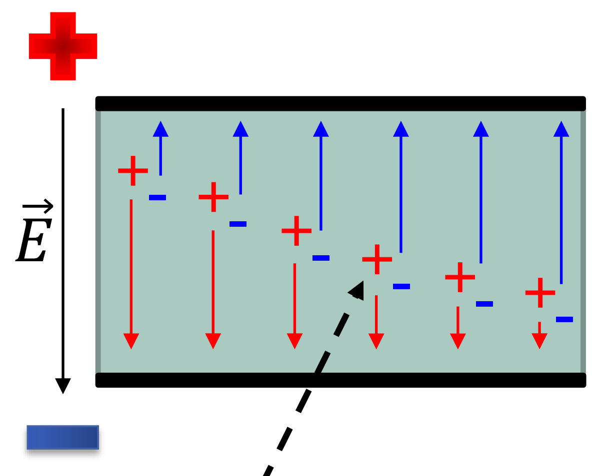
Intermezzo:
TCT measurement, polarization and electrical field

Polarization of an irradiated diamond in a high particle rate environment

1. Homogeneous trap distribution

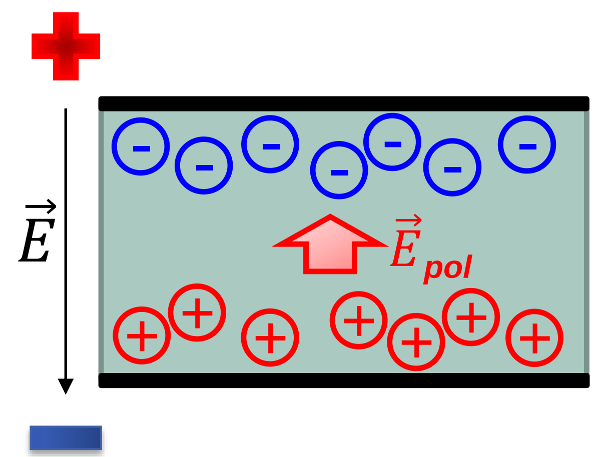


2. Asymmetrical charge carrier density



Homogeneous creation of charge carriers by MIPs

3. Asymmetrical trap filling -> locally reduced E-field



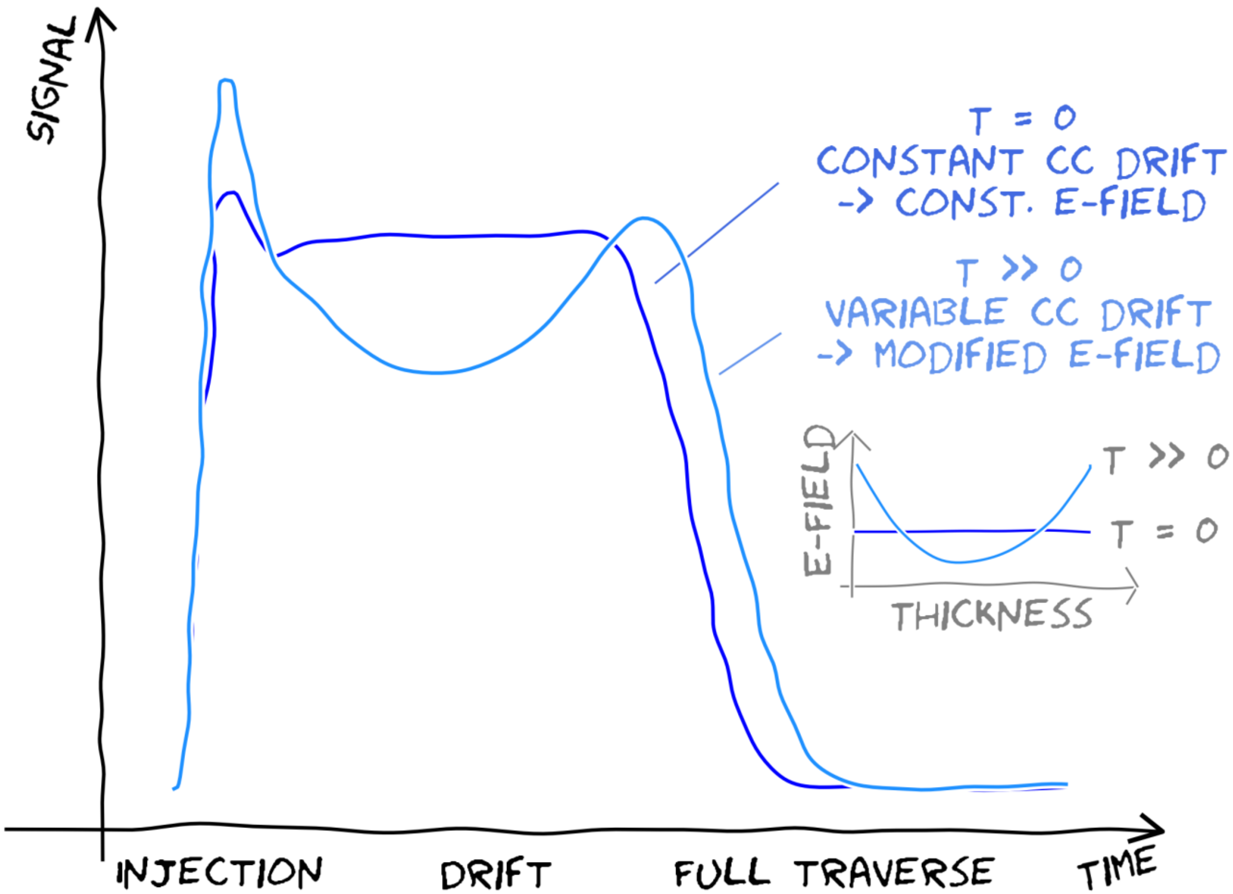
Intermezzo:
TCT measurement, polarization and electrical field

Polarization of an irradiated diamond in a high particle rate environment

Measurement procedure:

1. Exposing diamond to ^{90}Sr source without HV (pumping)
2. Fast ramping up of HV and immediately start of TCT measurement (t=0)
3. Data taking over extended time period
4. Analyze deformation of TCT pulse as function of time (t>>0)

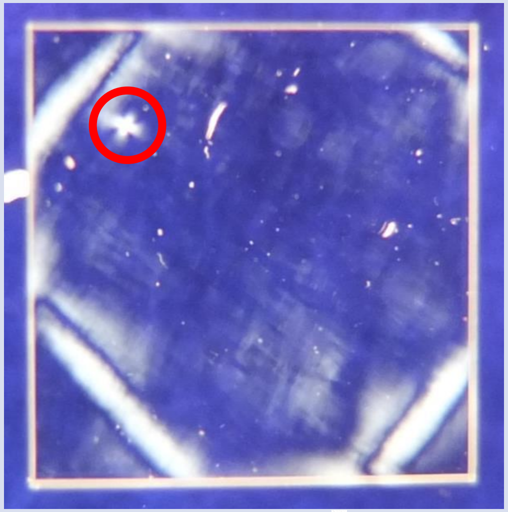
TCT measurement



2. Irradiation campaign

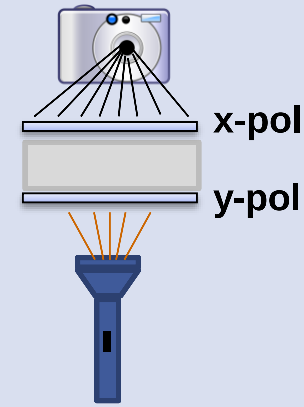
- Four single crystalline diamonds bought from E6
- Stepwise irradiation of diamond detectors with neutrons and protons
  - TCT measurements after each irradiation step
  - CCE measurements at DESY (Zeuthen)

2. Irradiation campaign: Diamond samples from E6



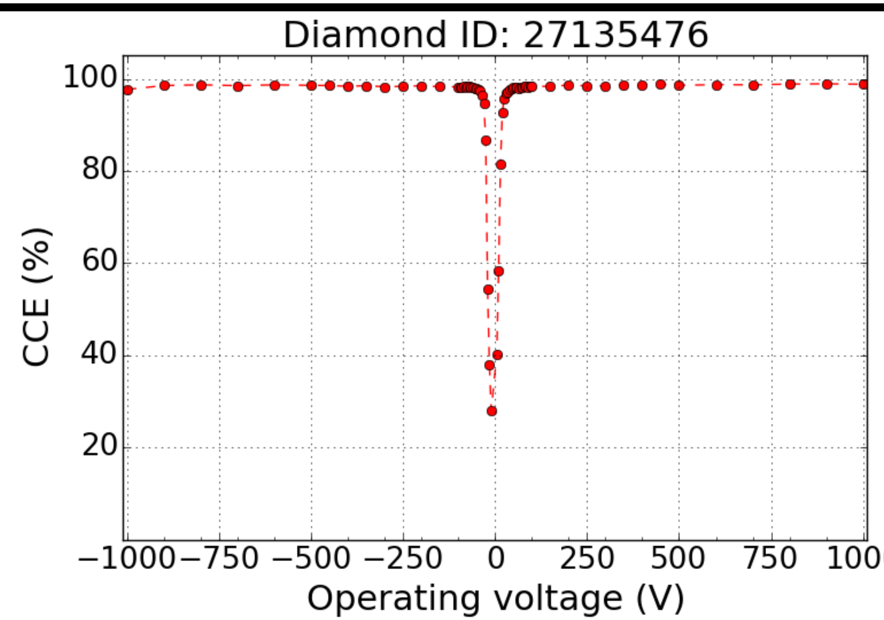
X-polarized pictures

- Defects can change the polarization of light.
- Two or less damage centers found on each diamond sample
- At the cutting edges surface tensions visible on all samples

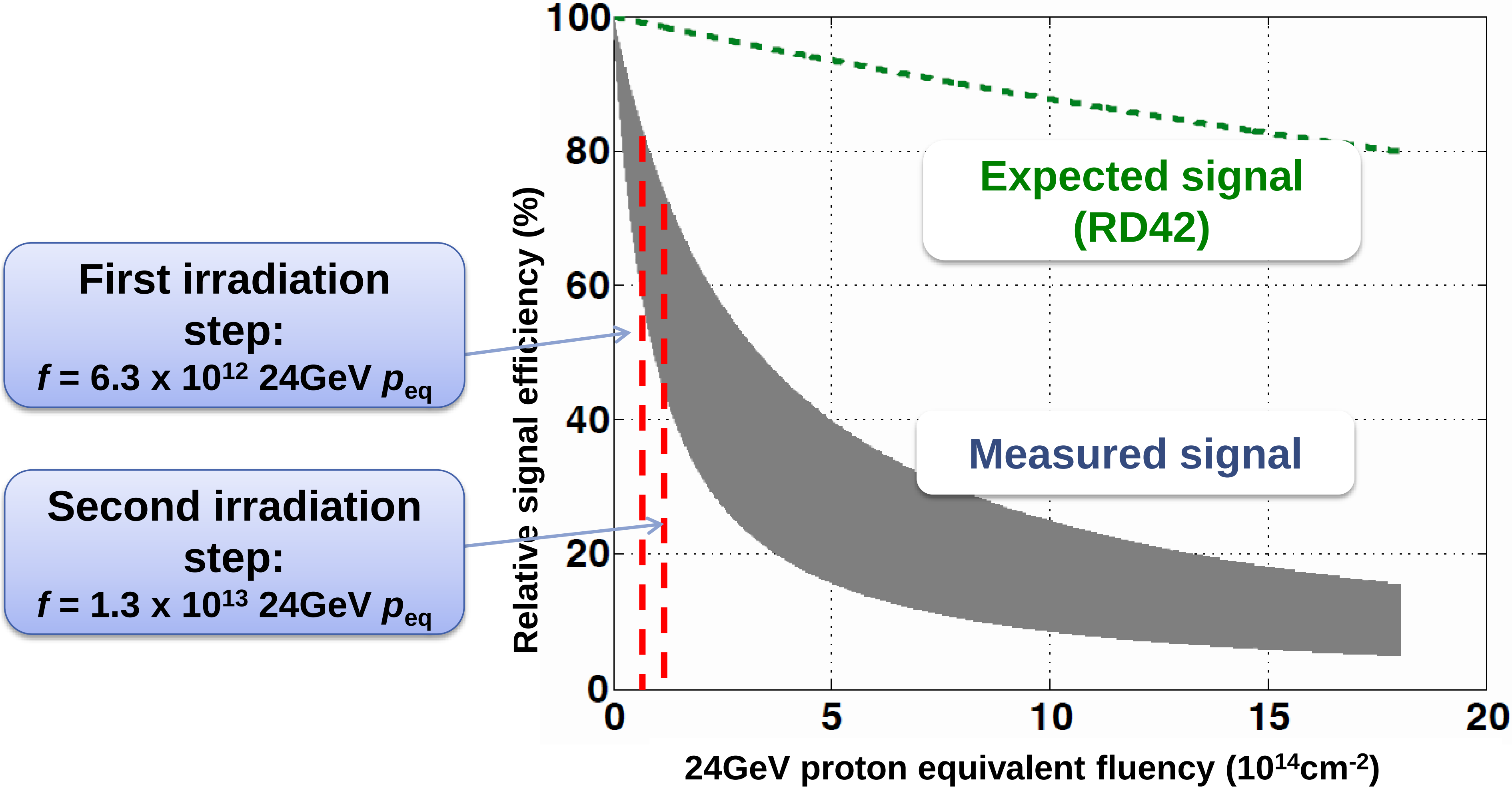


Charge Collection efficiency (CCE)

- All samples reaching an efficiency of CCE > 94%
- Maximal CCE already at low voltages (+/- 50V)
- All diamonds are stable up to 1000V (at least one polarity)



2. Diamond irradiation campaign: Irradiation steps

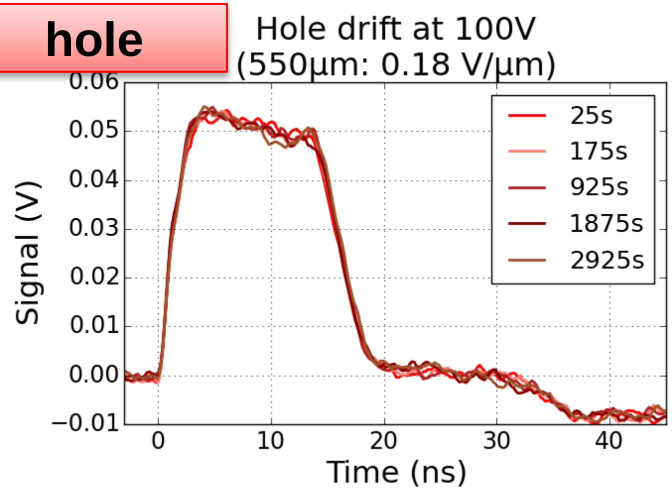


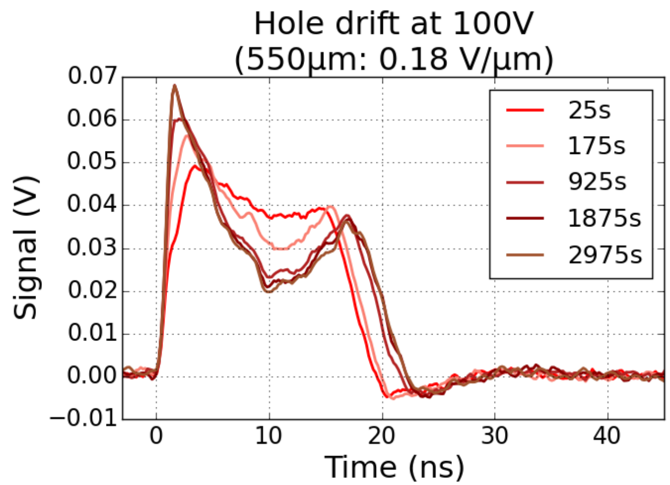
Source of graph: M.Guthoff, "Radiation damage to the diamond based Beam Condition Monitor of the CMS Detector at the LHC ", Ph.D. thesis, 2014

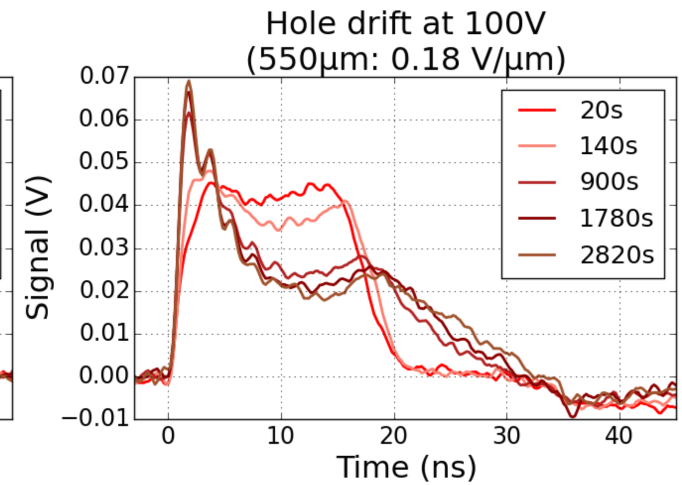
TCT pulse modification with increased radiation damage

HV = 100V

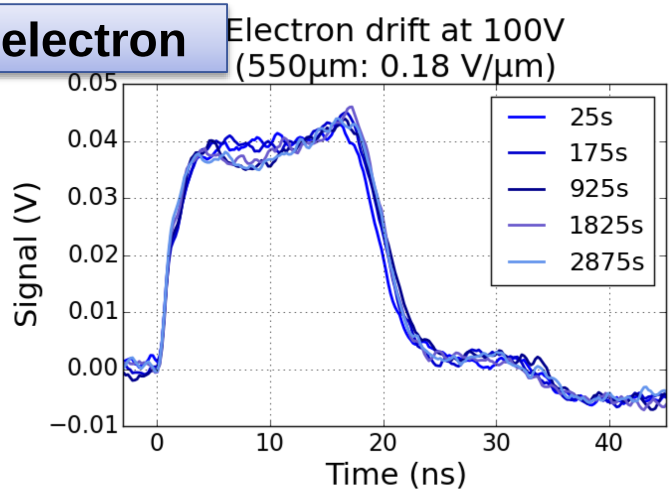
hole

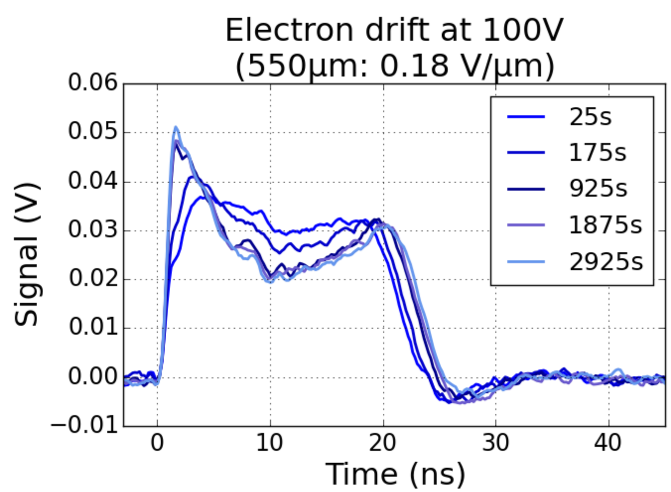


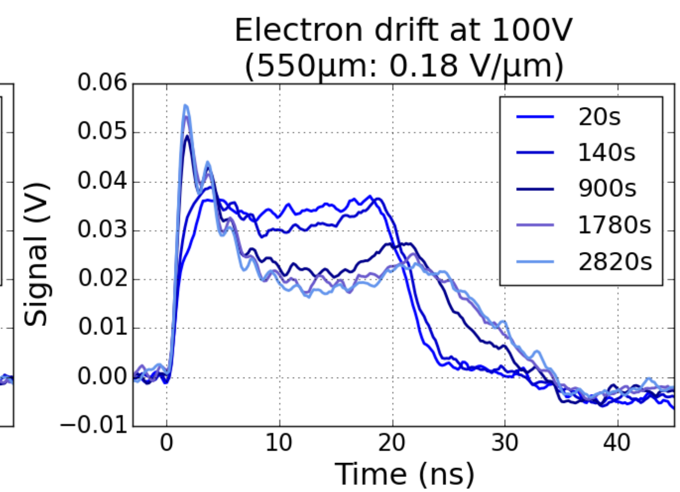




electron



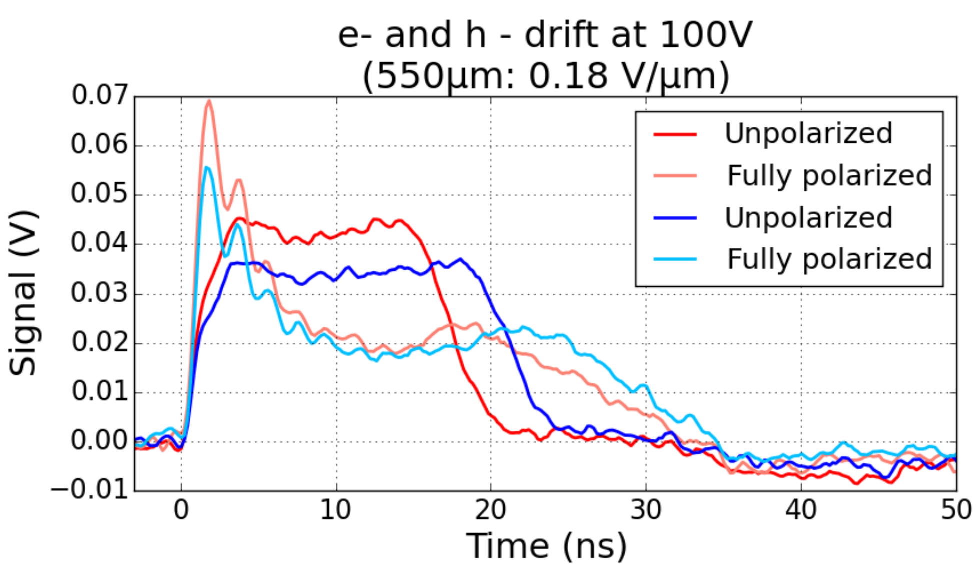


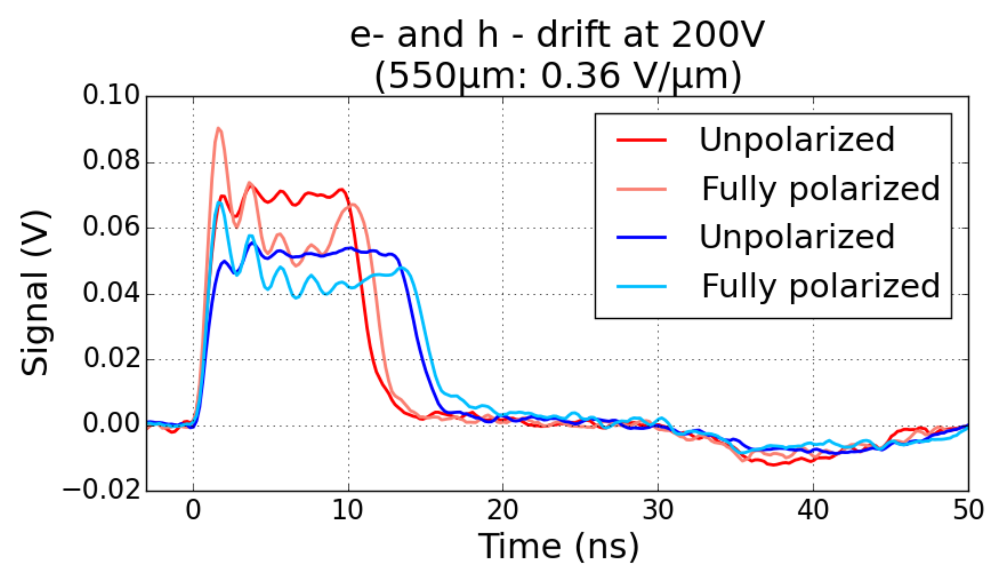


unirradiated | **f = 6.3 x 10^{12} 24GeV p_{eq}** | **f = 1.3 x 10^{13} 24GeV p_{eq}**

TCT measurement at KIT
100V vs 200V of irradiated diamond

- **Polarization effect reduced for increased bias voltage!**
- **For HV > 400V almost no polarization is visible (stable TCT pulses over time)**
- **Electron drift in blue, hole drift in red**



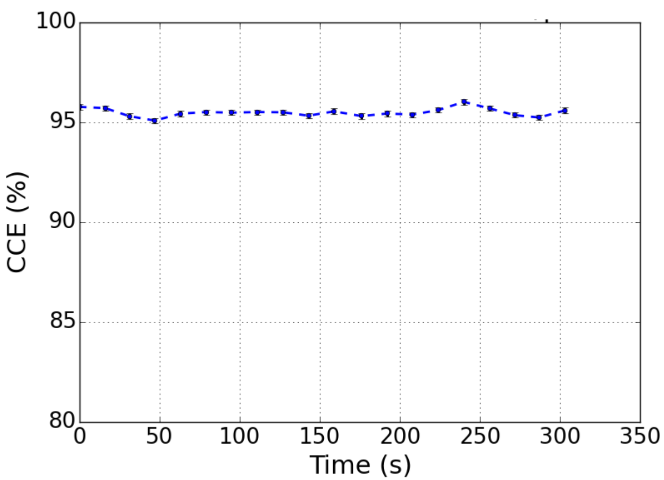


Irradiated diamond at 100V → **Increased HV** → **Irradiated diamond at 200V**

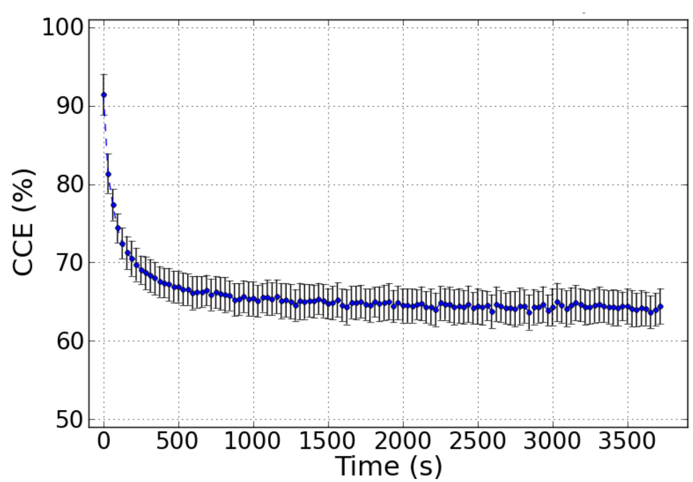
CCE measurements done at DESY (Zeuthen)

CCE measurement over time

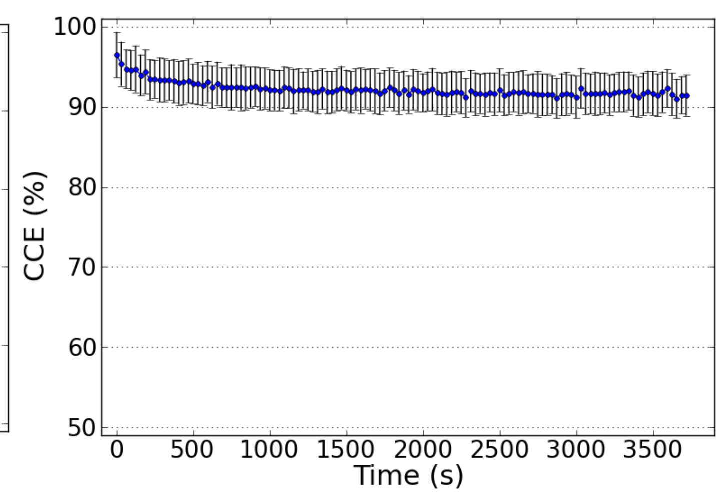
1. **Unirradiated diamond stable over time**
2. **Strong polarization for irradiated diamond (100V)**
   - ➢ **Reduction of CCE from 92% -> 65% (loss of 27%)**
3. **Reduced polarization for irradiated diamond (200V)**
   - ➢ **Reduction of CCE from 95% -> 91% (loss of 4%)**



1. Unirradiated at 100V



2. Irradiated at 100V



3. Irradiated at 200V

3. Simulation of a diamond detector with SILVACO TCAD

- Radiation effects can be taken into account by introducing effective traps
  - ➢ Development of a trap model that describes diamond performance with respect to the radiation damage and the particle rate environment.

3. Simulation of a damaged diamond detector
Input parameters

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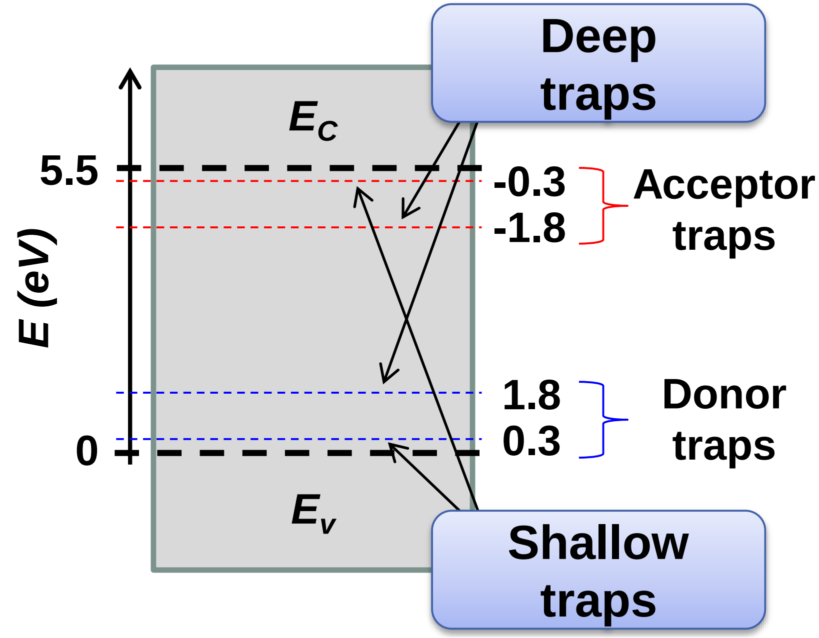
Effective 4 trap model:

- Two deep traps
  - Energy level (eV): 1.8
  - Density (cm^{-3}): 1e12
  - Cross section$_{e,h}$ (cm^2): 3e-15
- Two shallow traps
  - Energy level (eV): 0.3eV
  - Density (cm^{-3}): 7e13
  - Cross section$_{e,h}$ (cm^2): 1e-14



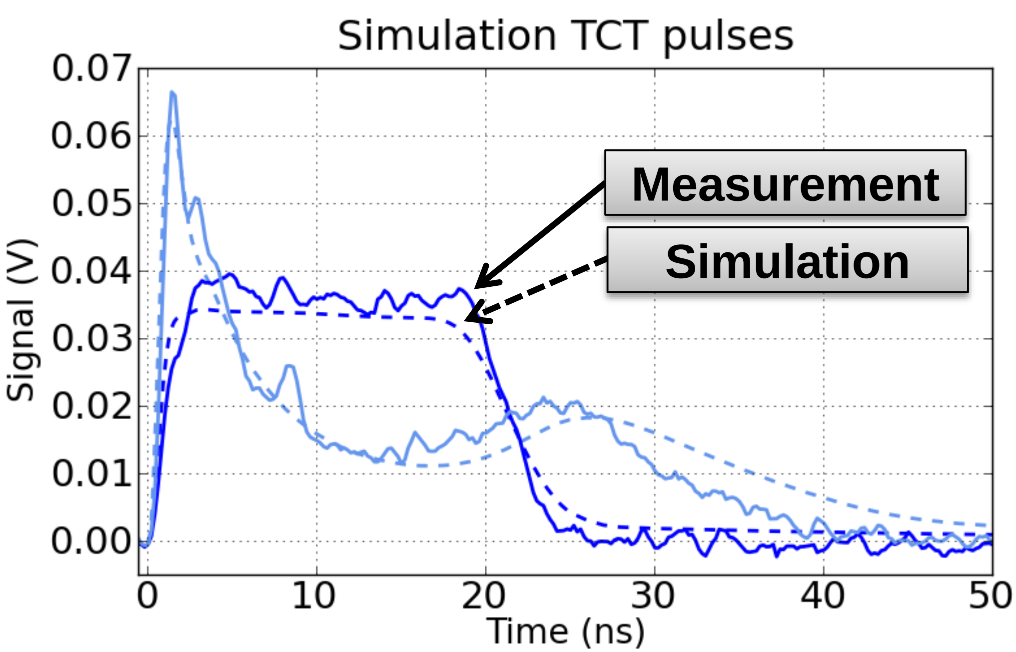
Other input parameters:

- Measured mobility and drift parameters
- Hardware setup
  - ^{90}Sr source
- Experimental limitations
  - e.g. bandwidth of amplifier

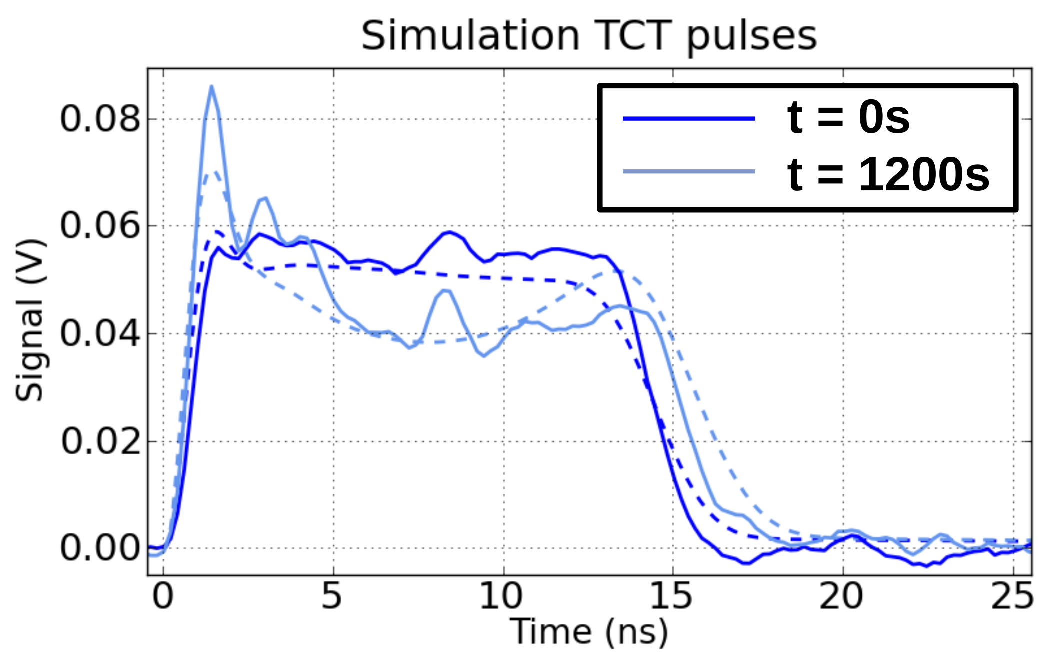
All following results are obtained with this trap model

3. Simulation of the polarization of a damaged diamond detector: electron drift

- **Comparison between measurement (*solid*) and simulation (*dashed*) results**
- **Trap model optimized to the 100V TCT measurement results**
- **Good agreement also for simulation of 200V**



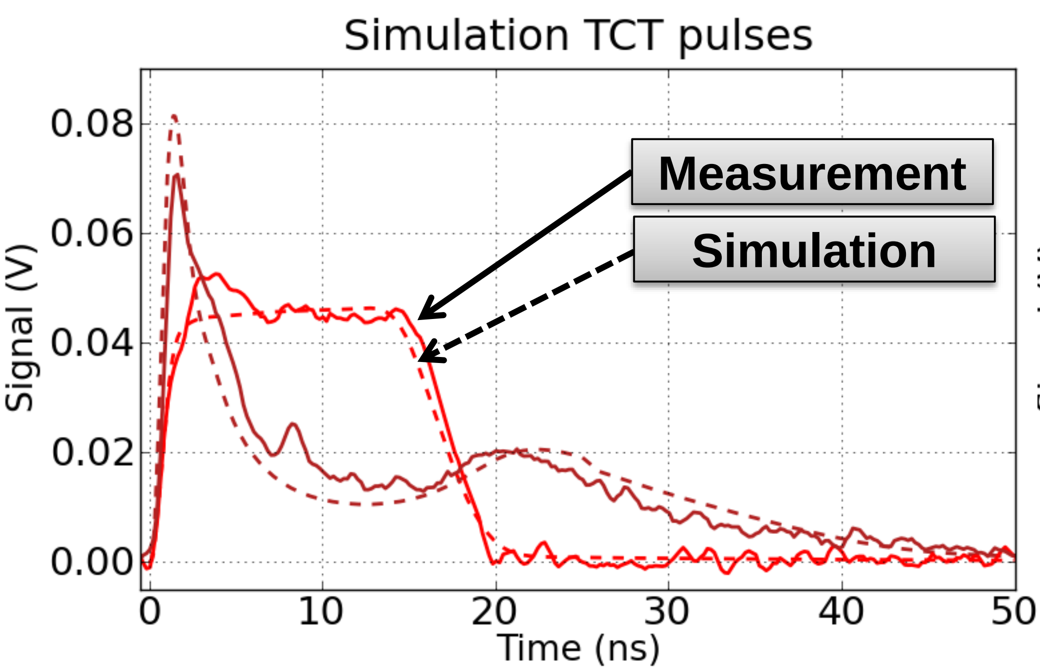
HV = 100V



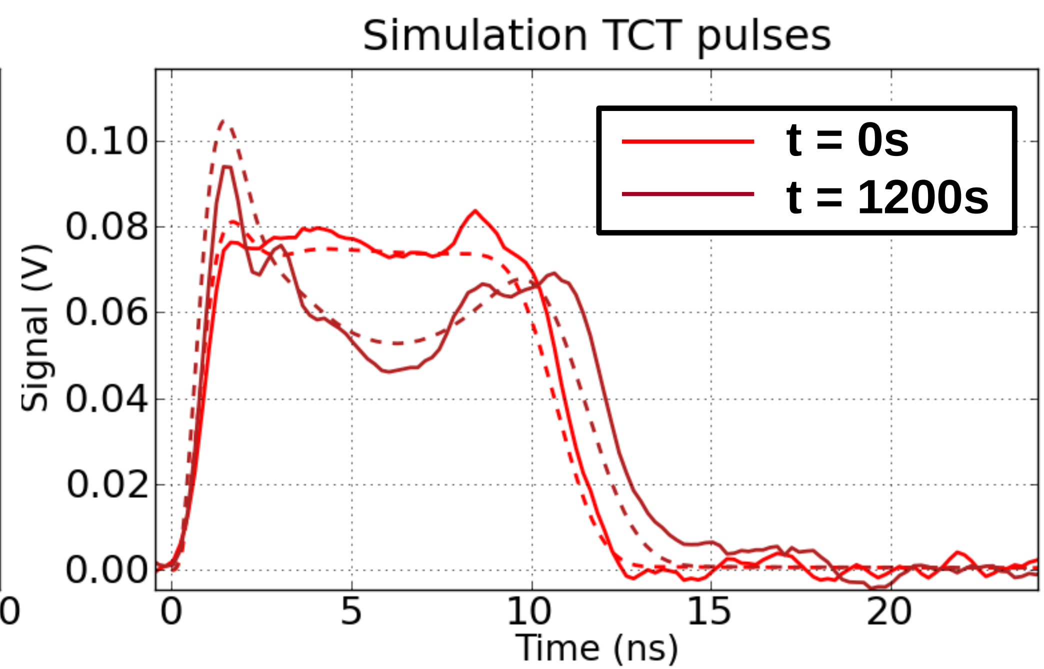
HV = 200V

3. Simulation of the polarization of a damaged diamond detector: hole drift

- **Good agreement between simulation and measurements of the hole drift for both voltages**



HV = 100V



HV = 200V

Simulation result: Electrical fields

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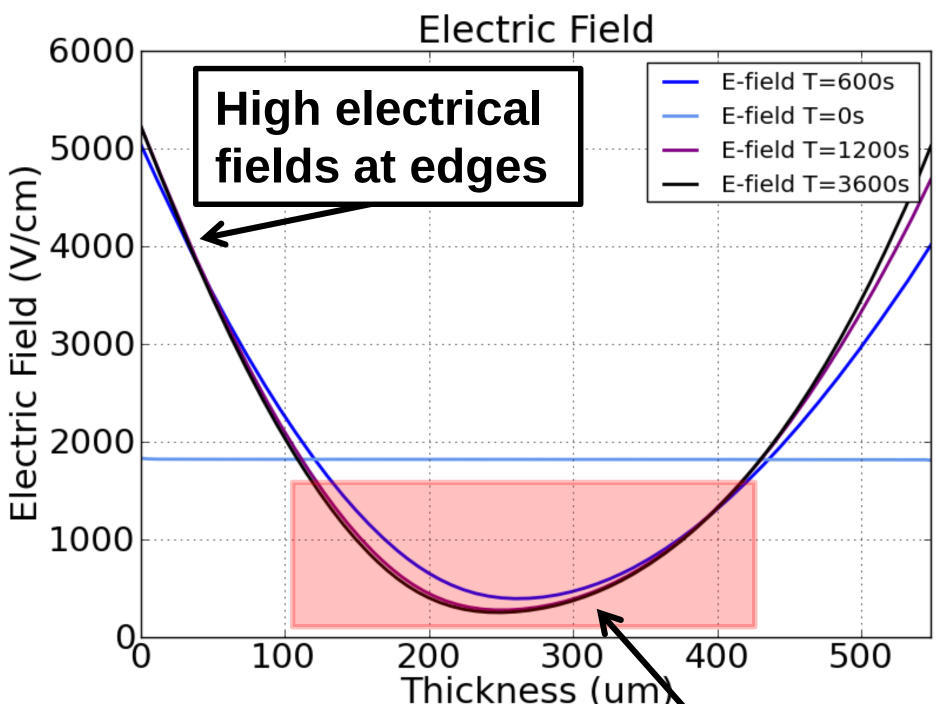
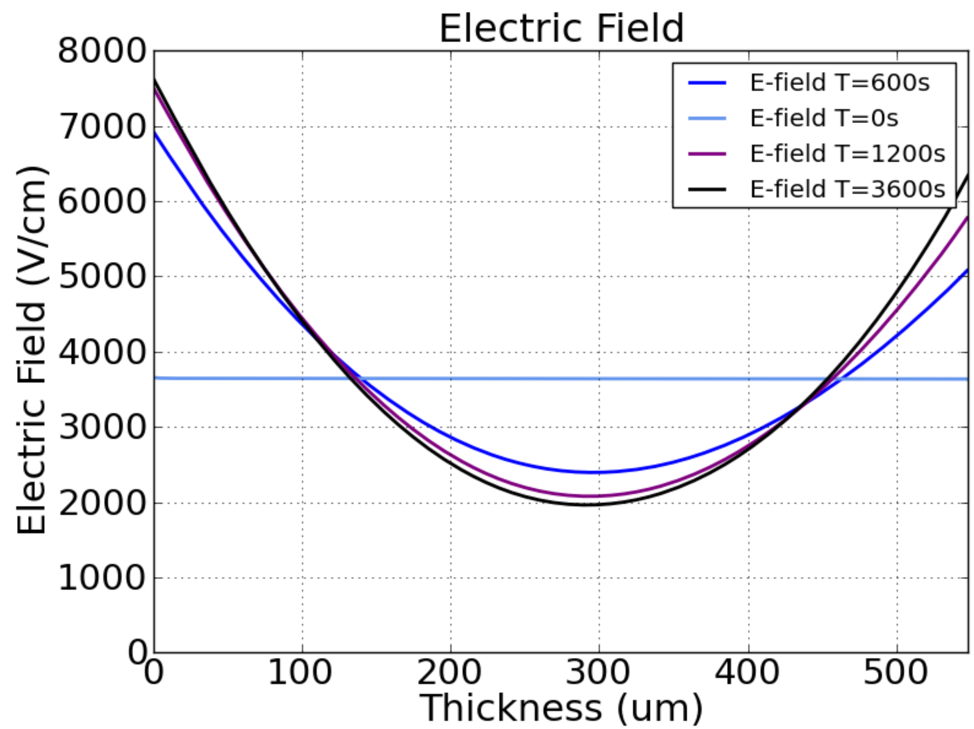
HV = 100V



HV = 200V

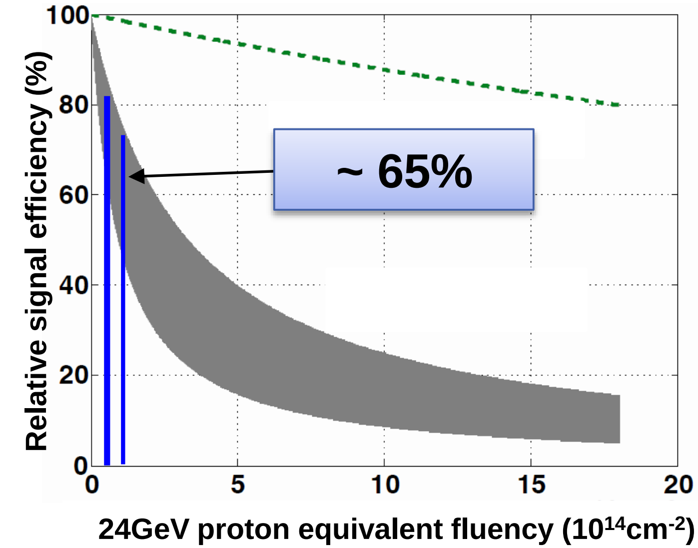


Low electrical field supports recombination of charge carriers -> reduced CCE!

First approach to simulate a high particle rate environment

CCE measurements of irradiated diamond at 200V:

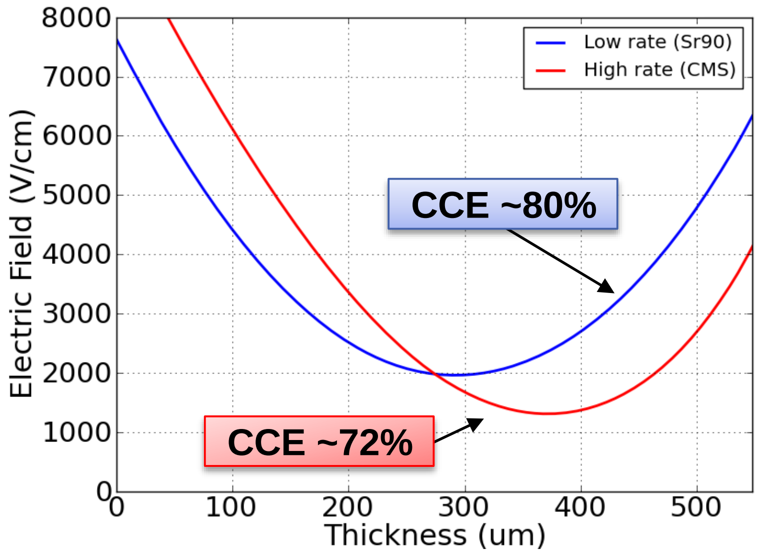
- **^{90}Sr particle rate: ~91%**
- **CMS particle rate (15x^{90}Sr): ~65%**



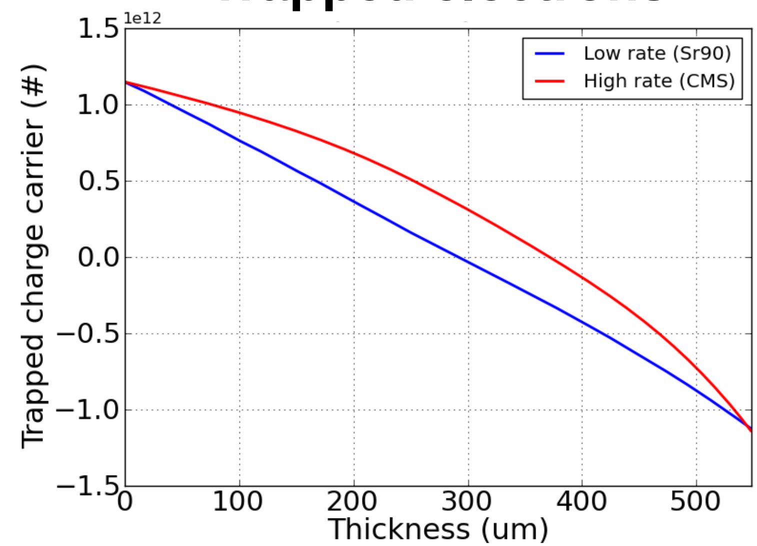
Simulation of the maximal polarization with respect to the particle rate:

- **low rate (^{90}Sr)**
- **high rate (CMS)**
- **CCE estimations based on MIP simulations**

Electrical field



Trapped electrons



Conclusion

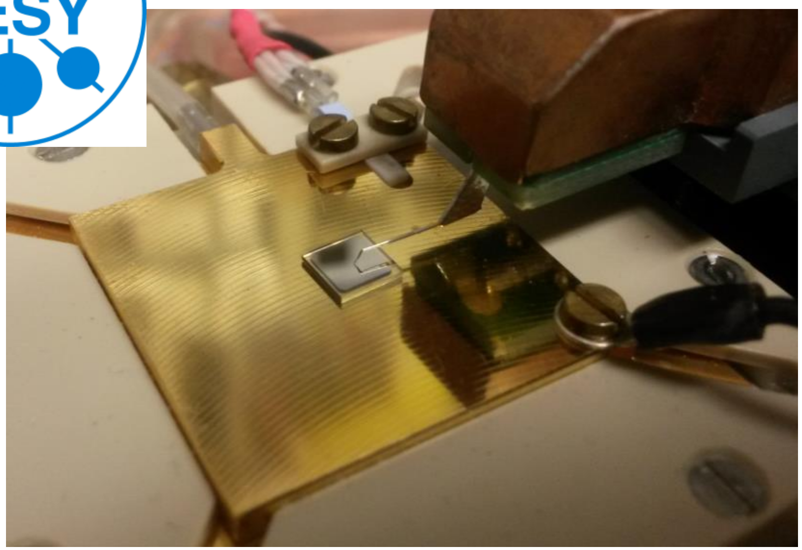
- **TCT Measurements:**
  - ➢ **No polarization for unirradiated diamond sensors**
  - ➢ **Increased radiation damage leads to an increasing polarization.**
- **CCE Measurements:**
  - ➢ **Unirradiated sCVD diamonds show CCE close to 100%**
  - ➢ **A decrease of the CCE for irradiated diamond samples measured.**
- **Simulation of diamond polarization:**
  - ➢ **TCT measurement can be simulated with an effective 4 trap model.**

Next steps:

- ➢ **Optimizing simulation for a correct CCE calculation**
- ➢ **Adapting the trap model to describe influence of particle rate correctly**

➢ **Prediction of the diamond CCE with respect of the irradiation damage and the particle rate environment!**

THANK YOU!



To Prof. Lohmann and the CMS group at DESY, especially to Martin Stegler!

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

BACKUP

Measurement of charge carrier drift velocities

Fit parameter used in simulation

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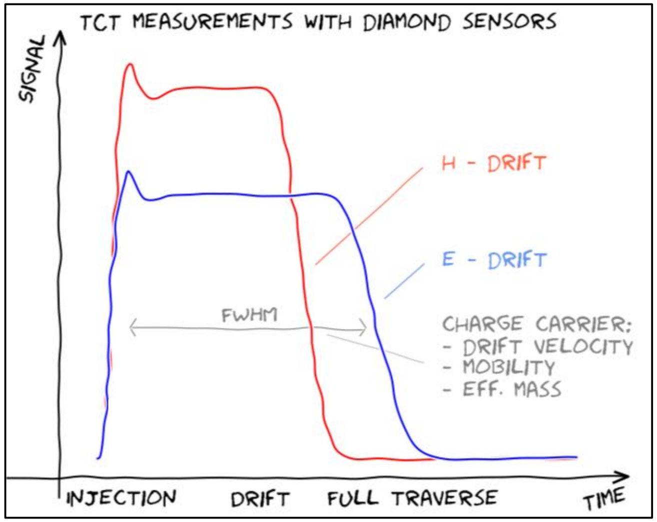
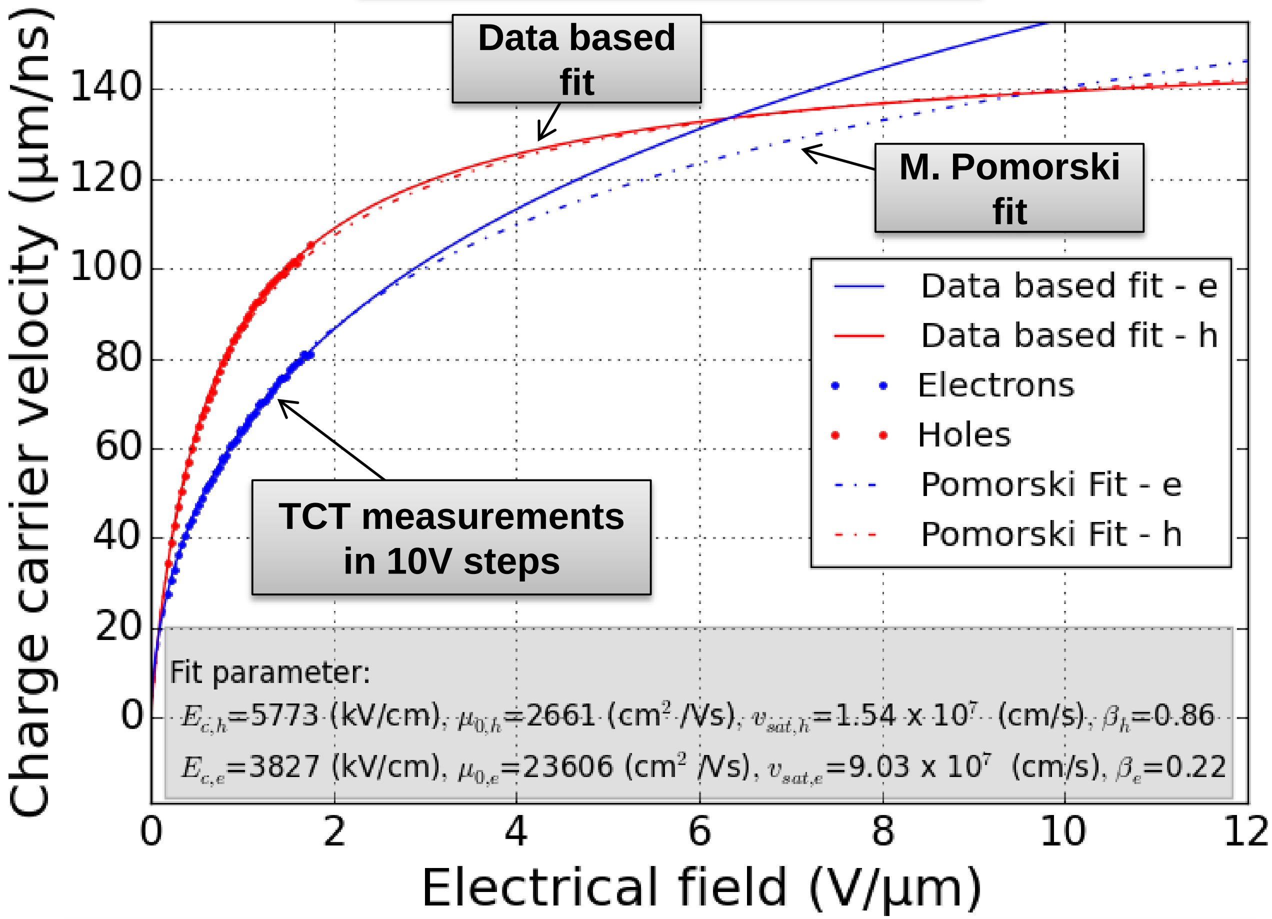
- Drift behavior of charge carrier is changing with increased radiation damage?
- Drift behavior can be described by:

$$v = v_{sat}\frac{E/E_c}{\left[1+(E/E_c)^{\beta}\right]^{1/\beta}},\ \text{with}\ v = \mu E$$

Reminder



Unirradiated diamond



- **Good agreement with measurements done by M.Pomorski**

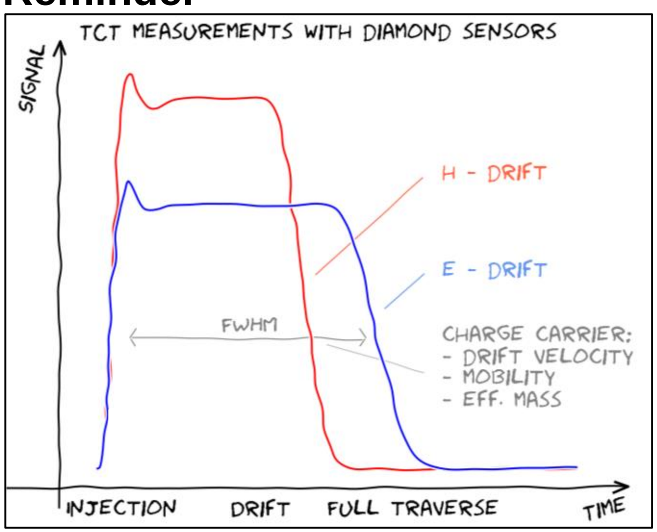
Measurement of charge carrier drift velocities

Fit parameter used in simulation

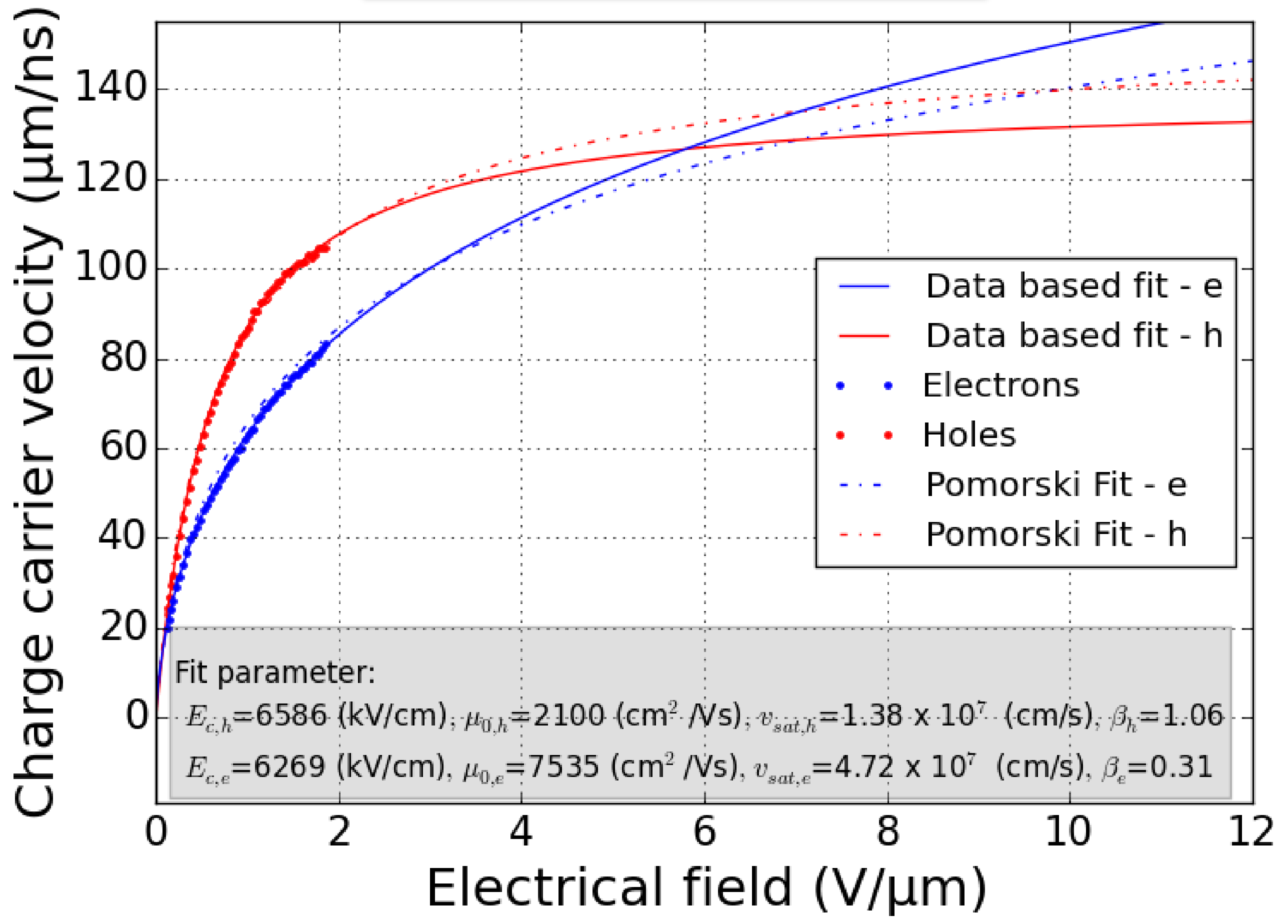
- **Drift behavior of charge carrier is changing with increased radiation damage?**
- **Drift behavior can be described by:**

$$v = v_{sat}\frac{E/E_c}{\left[1+(E/E_c)^{\beta}\right]^{1/\beta}}, \text{ with } v = \mu E$$

Reminder



Irradiated diamond



- **No reduced drift velocity measured so far!**