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Radiation induced signal degradation in diamond sensor

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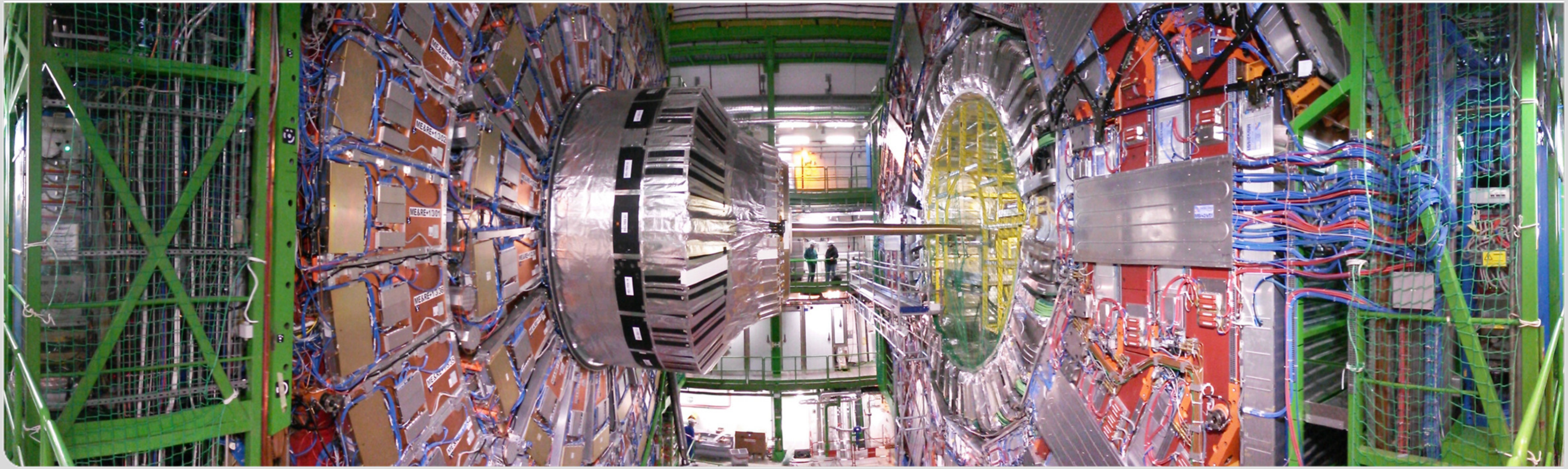
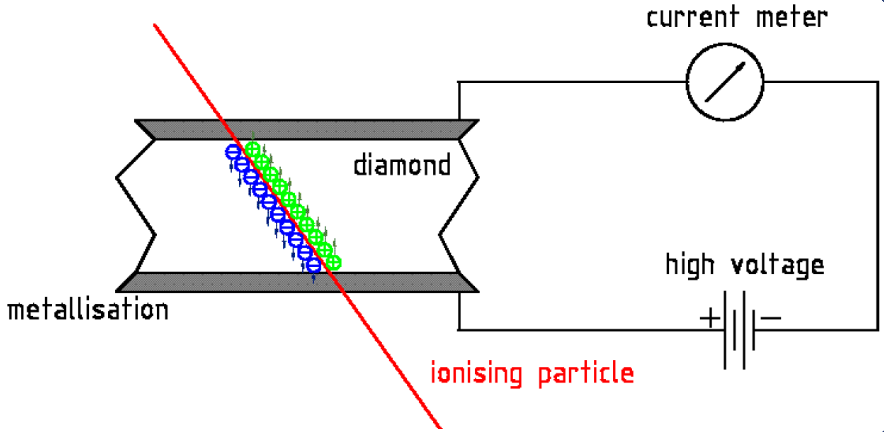


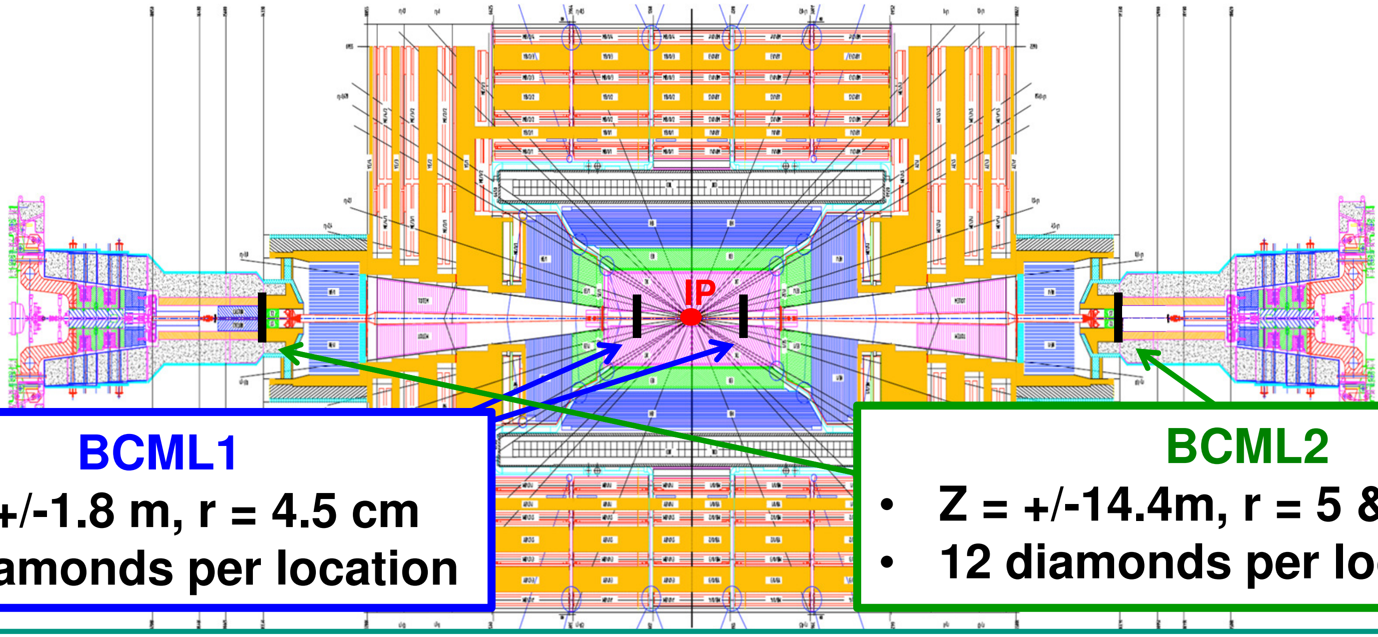
The beam abort system at CMS (BCML)

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



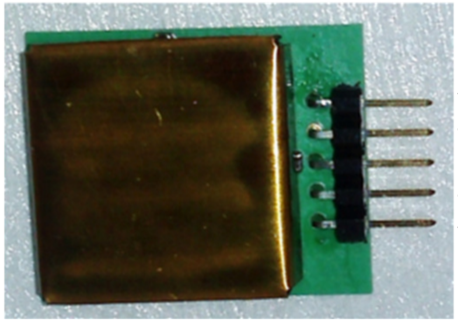
BCML1
- Z = +/-1.8 m, r = 4.5 cm
- 4 diamonds per location

BCML2
- Z = +/-14.4m, r = 5 & 28 cm
- 12 diamonds per location

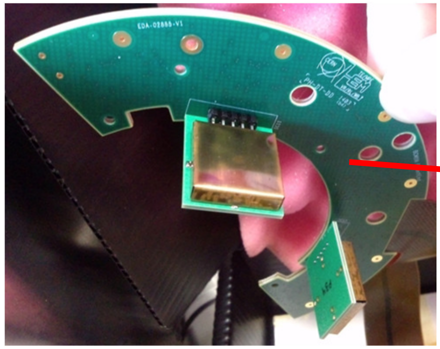
The beam abort system at CMS (BCML)

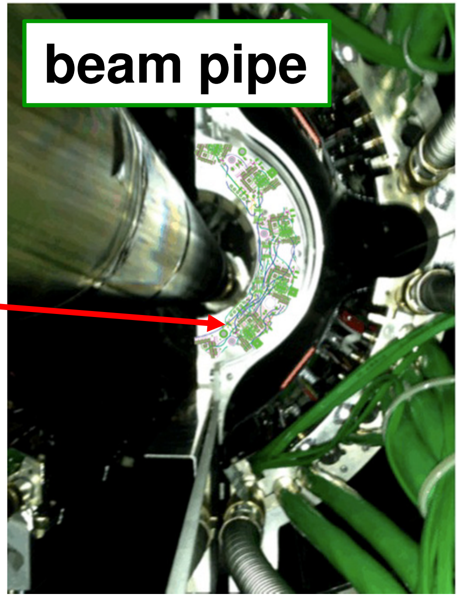
BCML1

➢ Mounted on BCM carriage



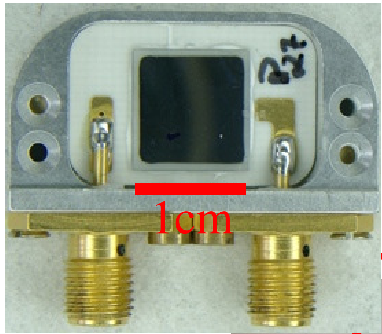
ground
positive HV
shield
negative HV
ground

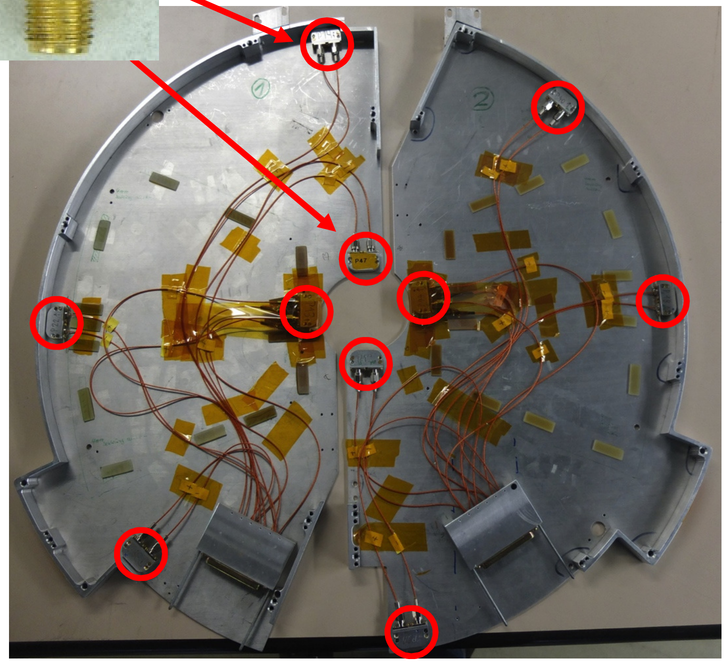




BCML2

➢ Mounted on wheel structure around the beam pipe





Unexpected strong radiation damage at LHC

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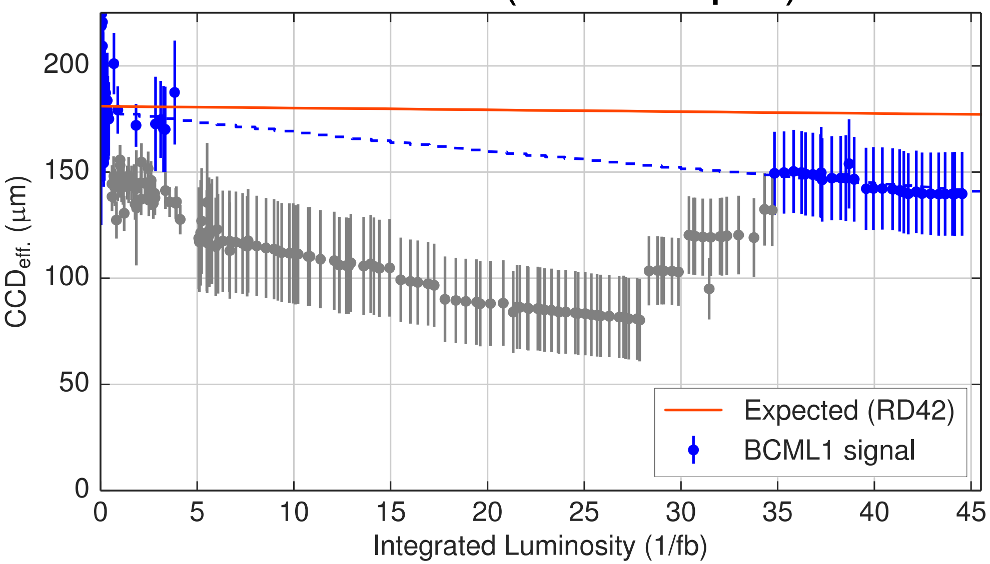
Decrease of detector efficiency was higher than expected in comparison to lab measurements (RD42)

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

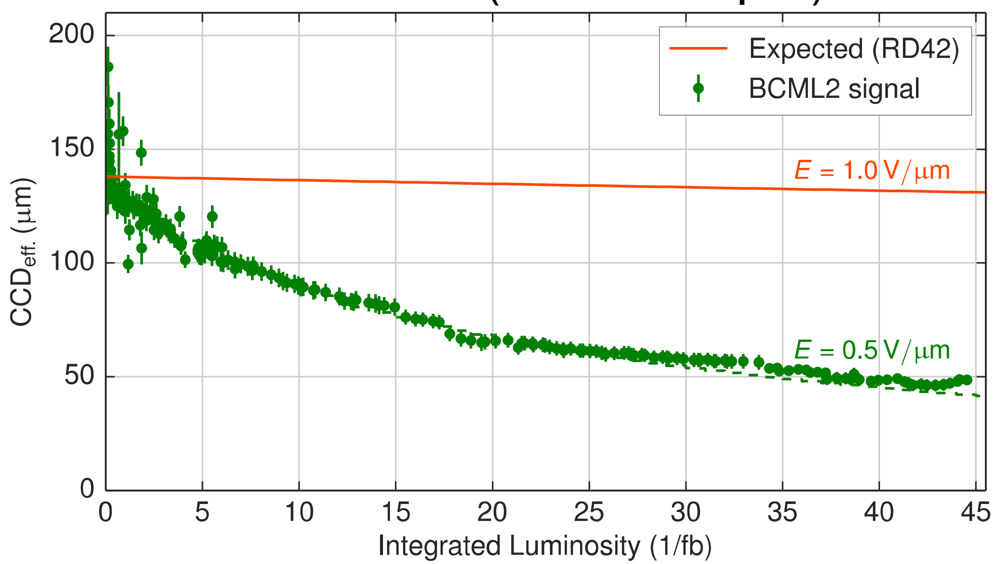
This talk:

- ➢ **Detailed simulation and irradiation studies to understand these plots**

BCML1 (E ~ 1 V/µm)

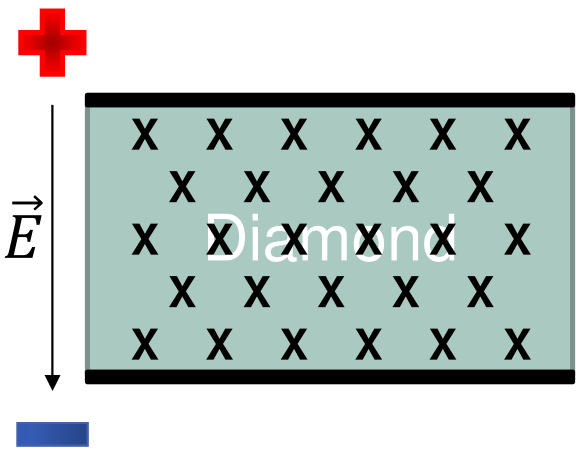


BCML2 (E ~ 0.5 V/µm)

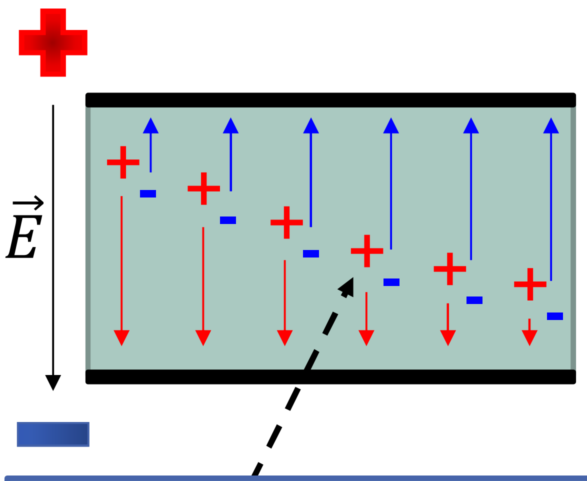


Irradiated diamond sensors - *Polarization*

1. Homogeneous trap distribution

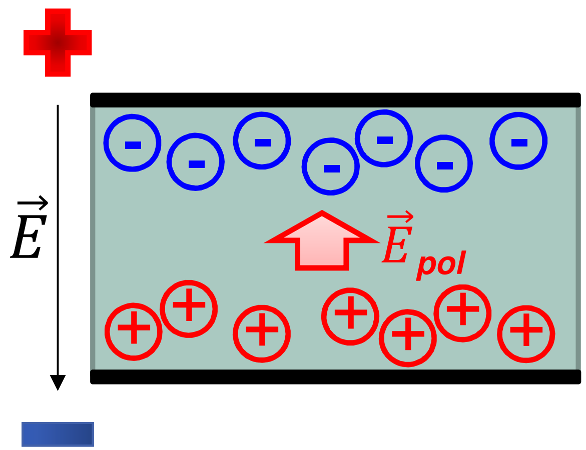


2. Asymmetrical charge carrier density



Homogeneous creation of charge carriers by MIPs

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



Diamond polarization a stable configuration?

Depends on trap properties influencing trapping and de-trapping rates.

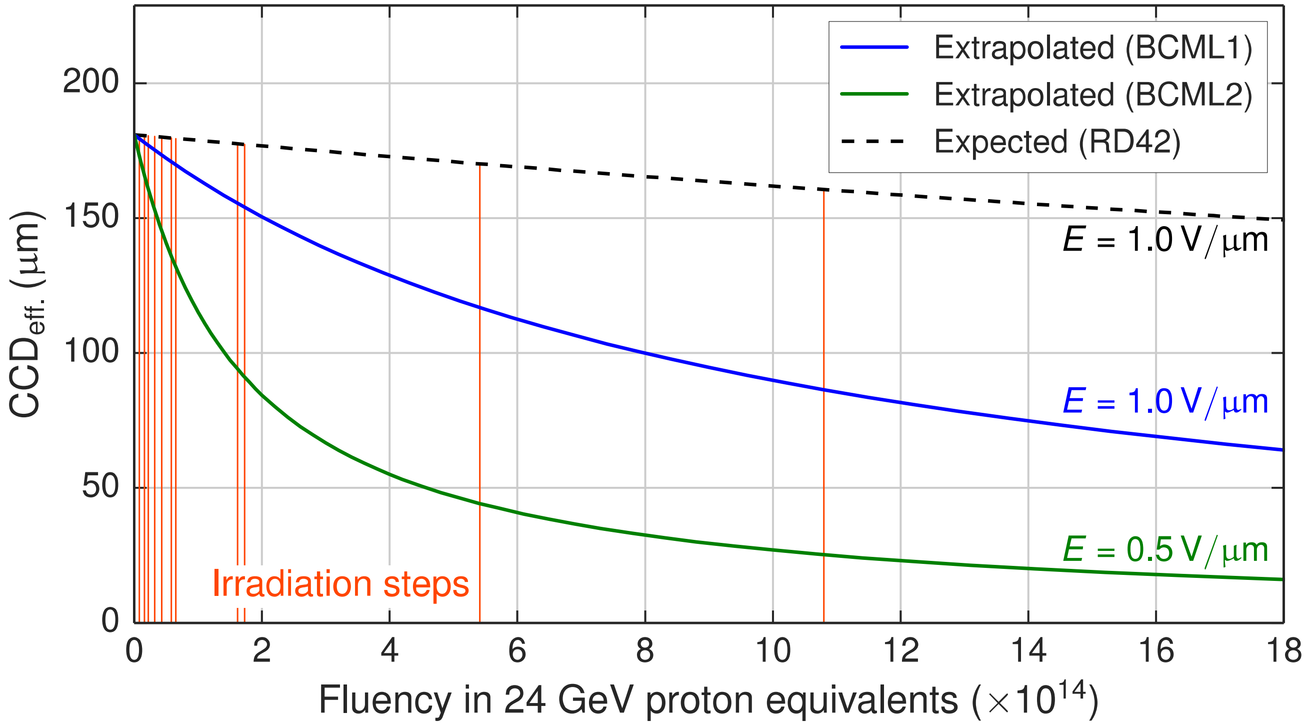
New approach to understand the severe radiation induced signal degradation by:

Creation of an effective defect model to describe the radiation induced signal degradation of diamond sensors as function of:

a) **Radiation Damage.**
b) **Particle Rate environment.**
c) **Electric field at which diamond is operated.**

Creation of Effective Defect Model based on

- Stepwise irradiation of high quality sCVD diamonds with proton or neutron particles
- Regularly measurements of the diamond polarization in a particle rate environment created by a ^{90}Sr source**:**
  - ➢ Modification of the internal electric field as function of exposure time ($T_{exp.}$) via the TCT technique.
  - ➢ Modification of the charge collection efficiency as function of $T_{exp.}$.



Standard radiation model

$$\frac{1}{\mathrm{CCD}(\Phi)} = \frac{1}{\mathrm{CCD}_0} + k \times \Phi.$$

Measurement procedure for TCT/CCE measurements to measure build up space charge as function of exposure time T_{exp}

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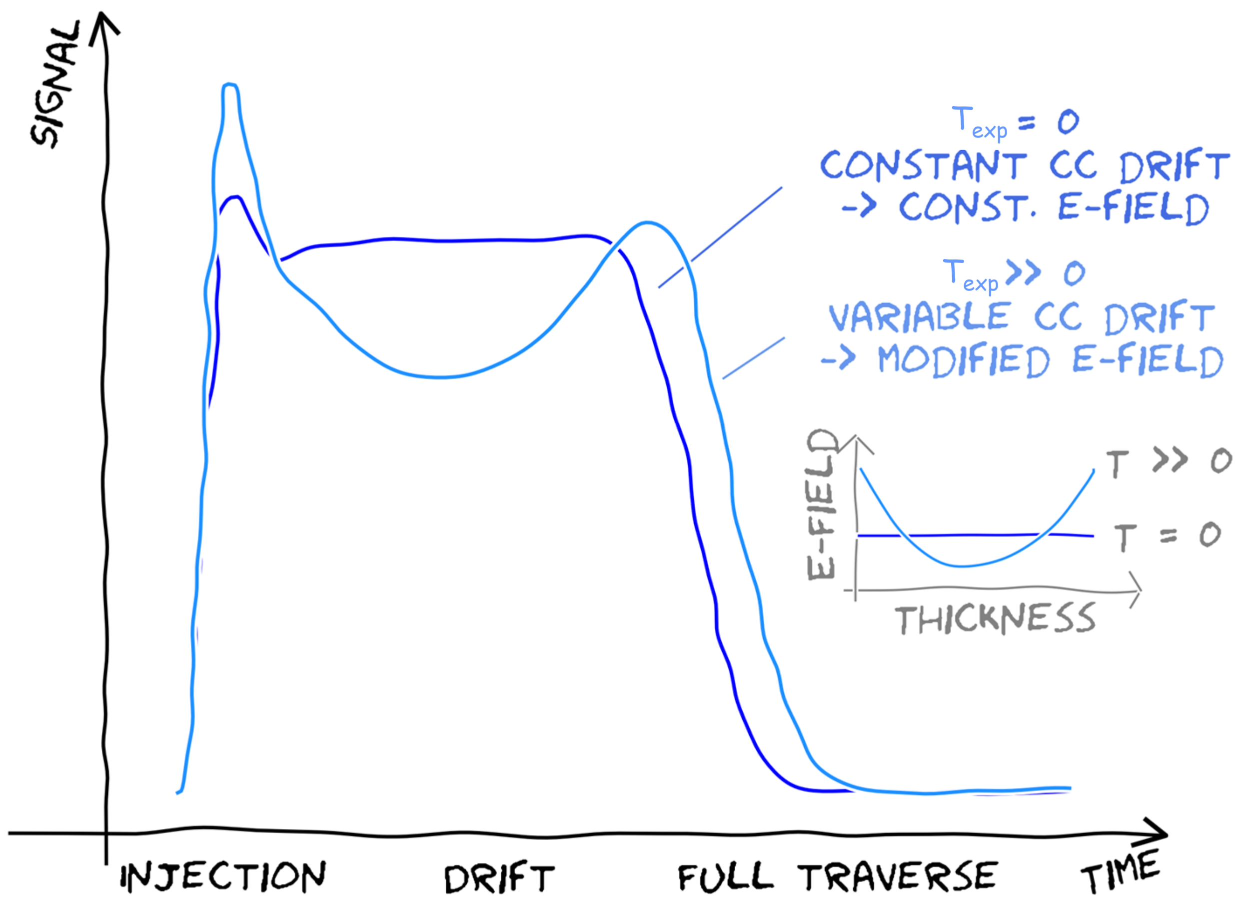
Measurement procedure:

1. Exposing diamond to ^{90}Sr source without HV (pumping)
2. Fast ramping up of HV and immediately start of TCT measurement **(T_{exp}=0)**
3. Data taking over extended time period **(T_{exp} > 3000s)**
4. Analyze deformation of TCT pulse as function of exposure time T_{exp}



Diamond Irradiation campaign:
TCT modification as function of radiation damage

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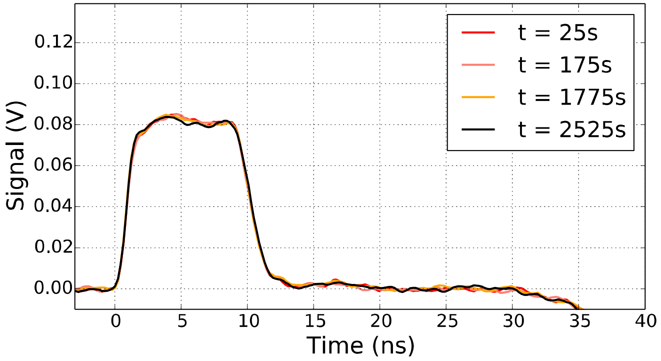
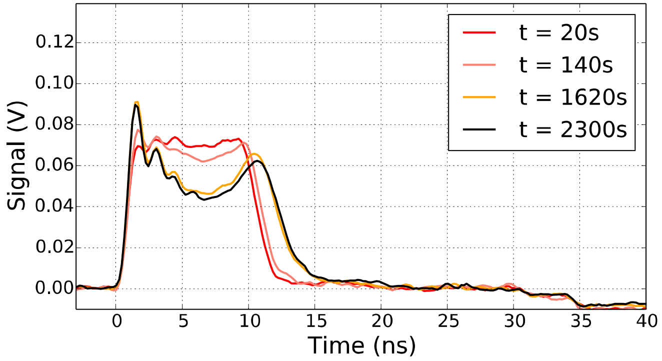
Diamond operated at an electric field of E = 0.36 V/µm
(**hole** drift)

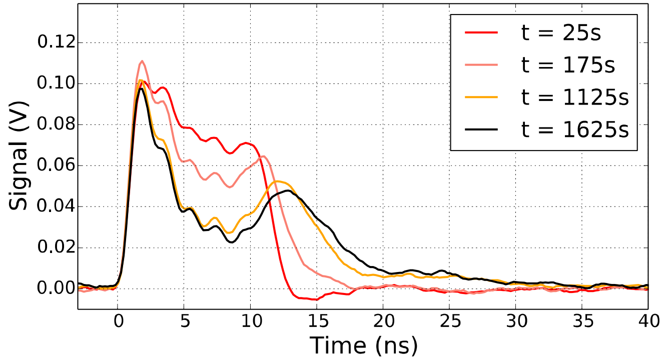
unirradiated



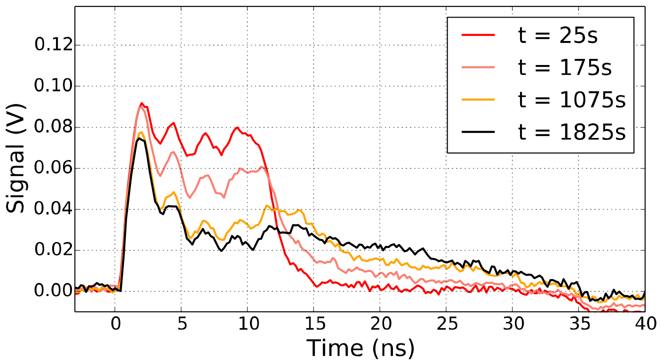
f = 0.6 x 10^{13} $p_{24GeV}cm^{-2}$



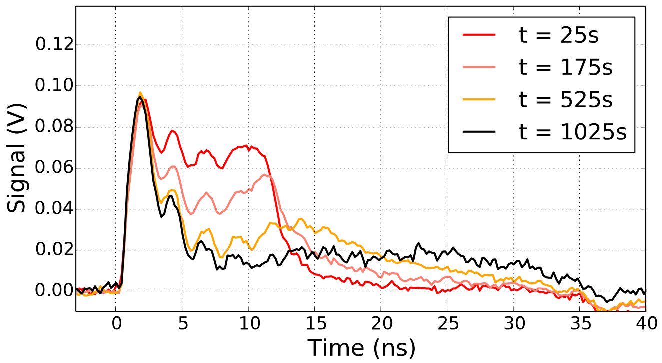
f = 1.2 x 10^{13} $p_{24GeV}cm^{-2}$



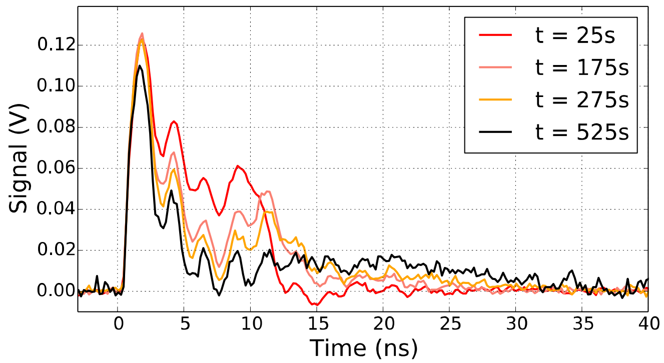
f = 1.8 x 10^{13} $p_{24GeV}cm^{-2}$



f = 4.8 x 10^{13} $p_{24GeV}cm^{-2}$



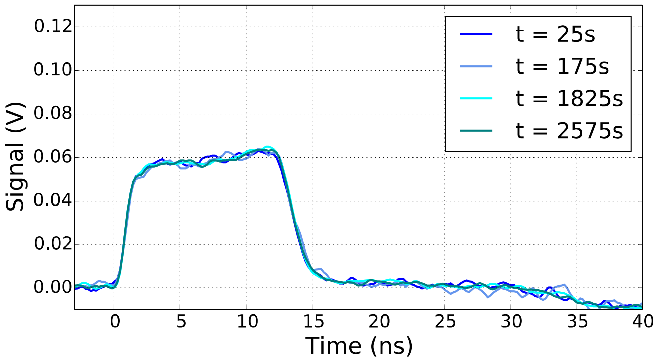
f = 15.1 x 10^{13} $p_{24GeV}cm^{-2}$



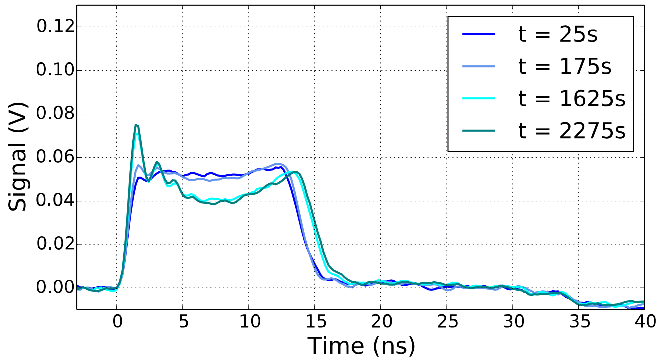
Diamond Irradiation campaign:
TCT modification as function of radiation damage

Diamond operated at an electric field of E = 0.36 V/µm
(**electron** drift)

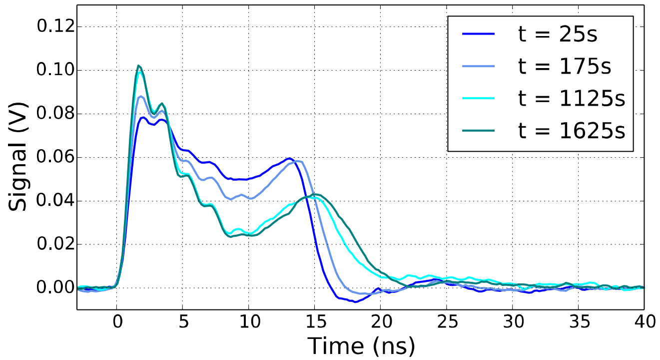
unirradiated



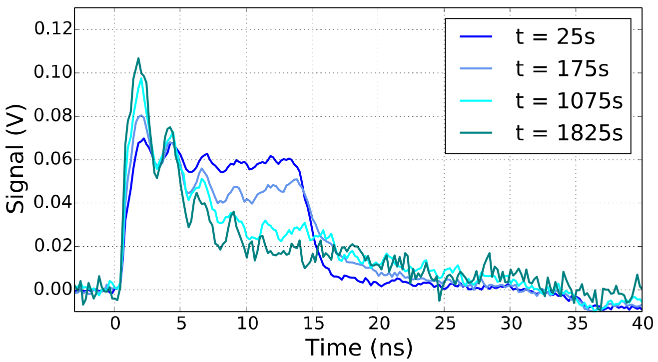
f = 0.6 x 10^{13} $p_{24GeV}cm^{-2}$



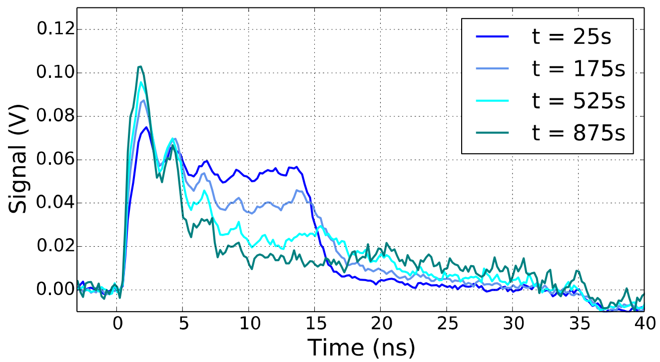
f = 1.2 x 10^{13} $p_{24GeV}cm^{-2}$



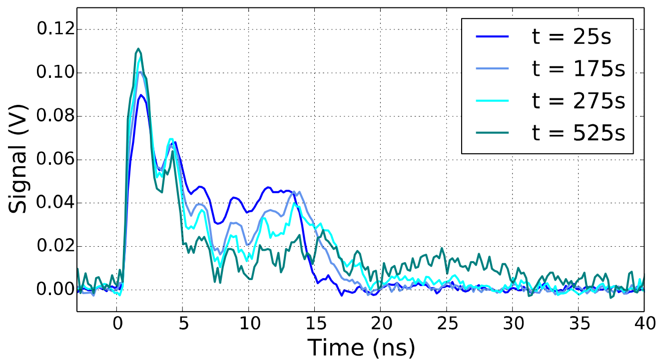
f = 1.8 x 10^{13} $p_{24GeV}cm^{-2}$



f = 4.8 x 10^{13} $p_{24GeV}cm^{-2}$

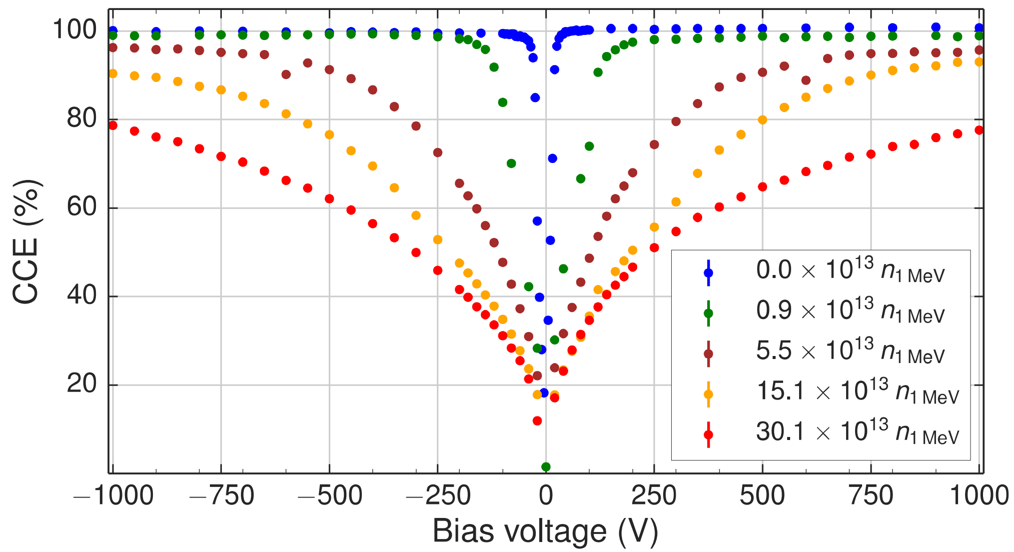


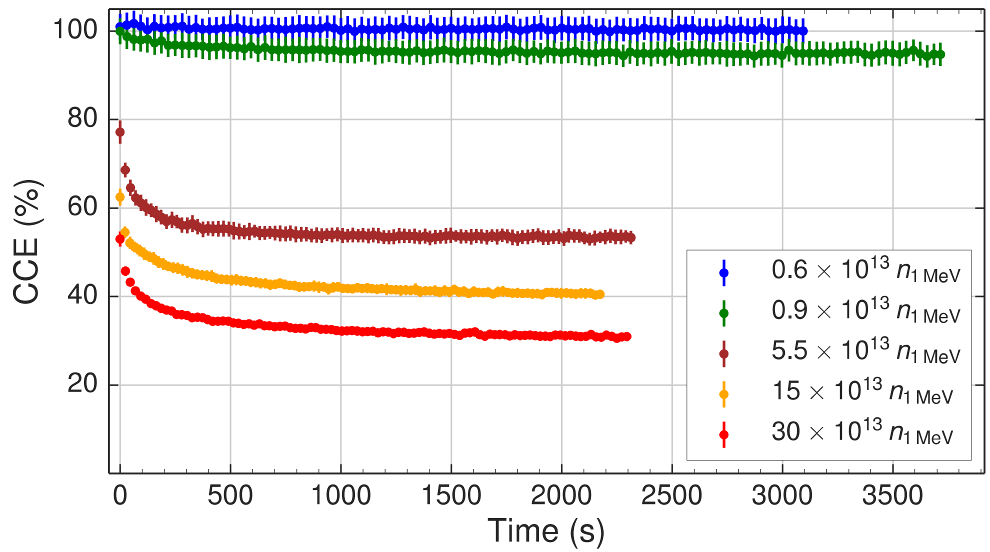
f = 15.1 x 10^{13} $p_{24GeV}cm^{-2}$



Diamond Irradiation campaign:

CCE measurements for different irradiation damages





CCE as function of bias voltage

Measured just after bias voltage ramp
(minimize polarization effects)

CCE as function of $T_{exp.}$

(E = 0.36 V/µm)

3. Simulation of a diamond detector with SILVACO TCAD

3. Simulation of a damaged diamond detector
Input parameters – Quasi 3D simulation

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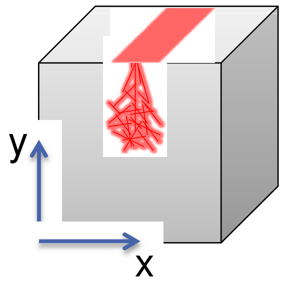
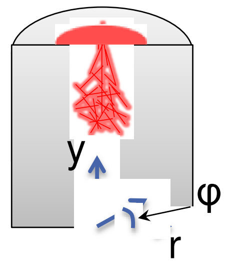
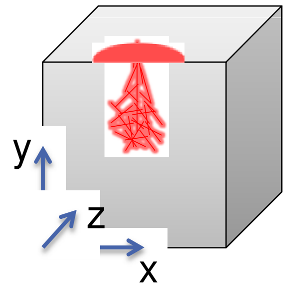


Two Dimensional:
Correct charge density
or
Correct total charge
Incorrect geometry

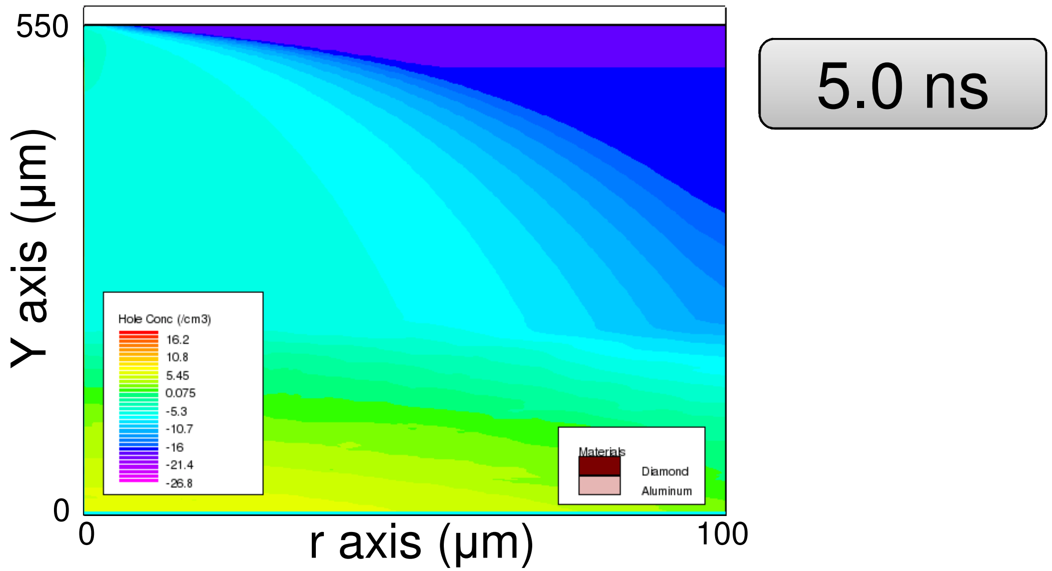


Quasi 3D:
Correct charge density
Correct total charge
Incorrect geometry



Three Dimensional:
Correct charge density
Correct total charge
Correct geometry

Simulation of TCT signal:
- **Alpha particle hit on top side**
- **charge carrier drift through diamond bulk**



3. Simulation of a damaged diamond detector
Input parameters –Simulated energy depositions

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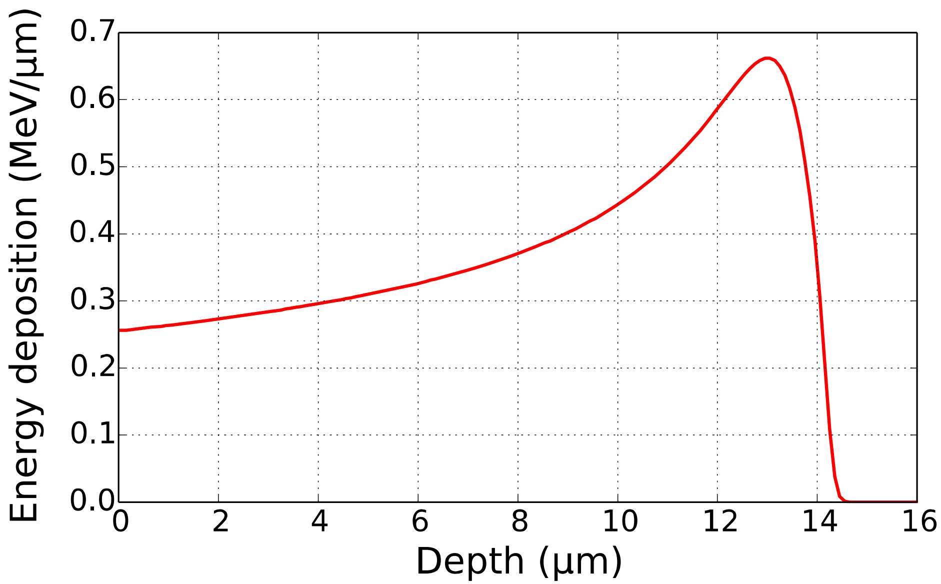
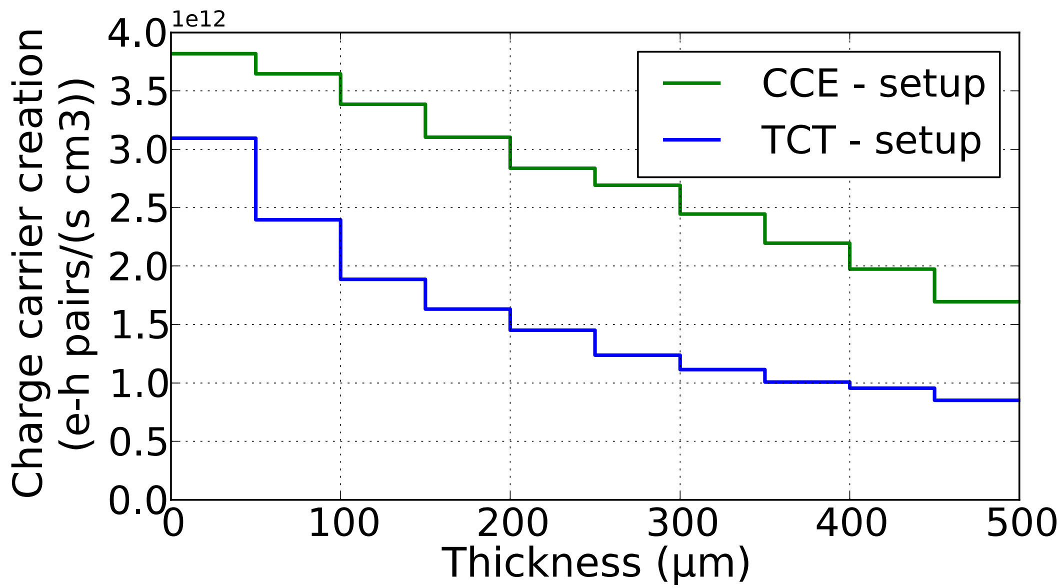
- TCT & CCE hardware setup geometry implemented in Fluka
- Simulation of ^{90}Sr and ^{241}Am energy deposition in diamond sensor

Energy deposition of *α* and *β* particles



^{241}Am: *α* particle



^{90}Sr source: *β* particles

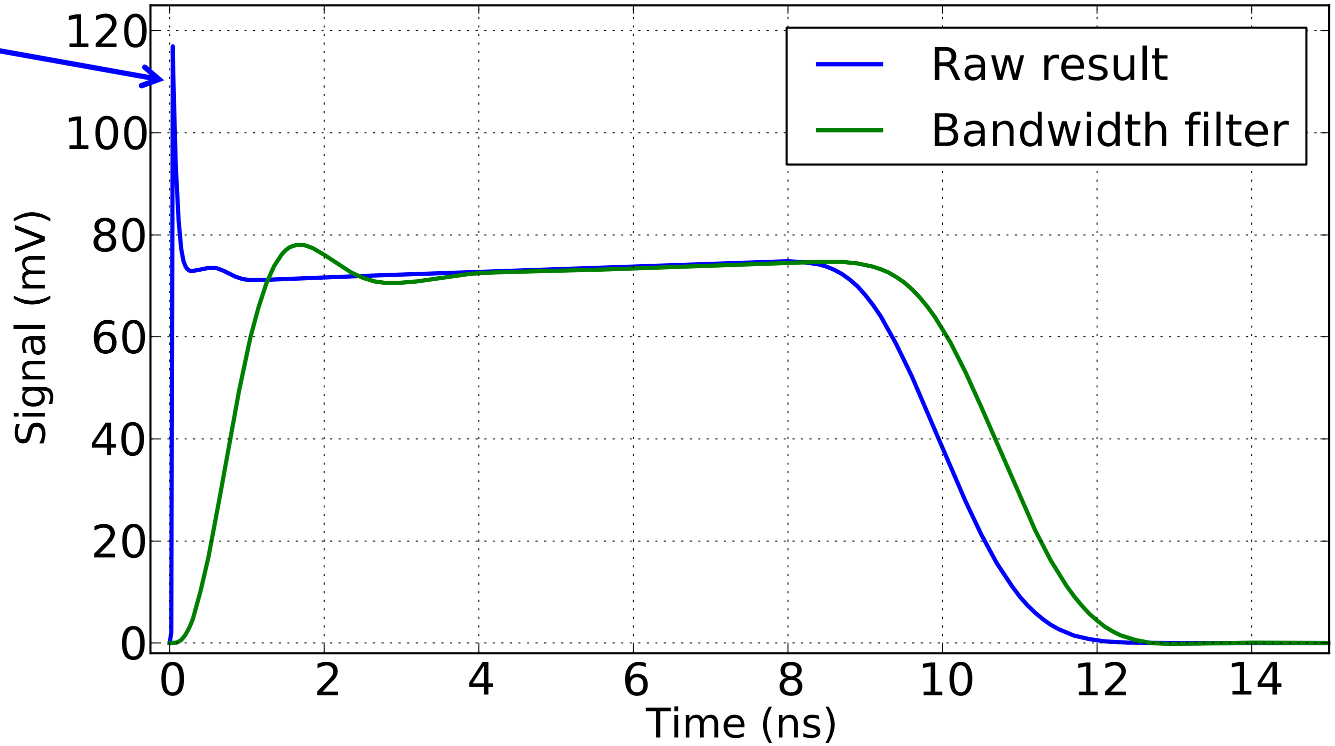
Thanks to M.Guthoff & L.Gloggler

3. Simulation of a damaged diamond detector
Input parameters – Limitation of Hardware

Limited bandwidth of the TCT measurement setup taken into account:

- Limiting component is oscilloscope with a bandwidth of 1GHz
- Simulation results manipulated with Bandwidth filter

Charge carrier drift in both directions



3. Simulation of a damaged diamond detector
Input parameters

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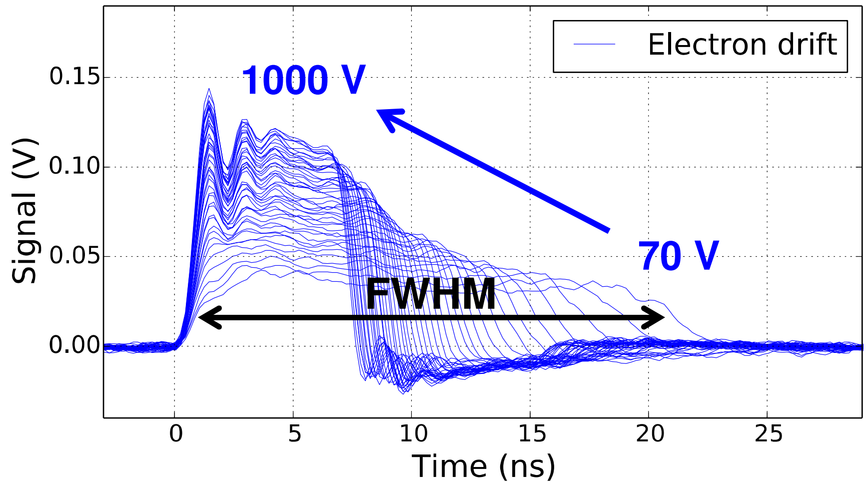
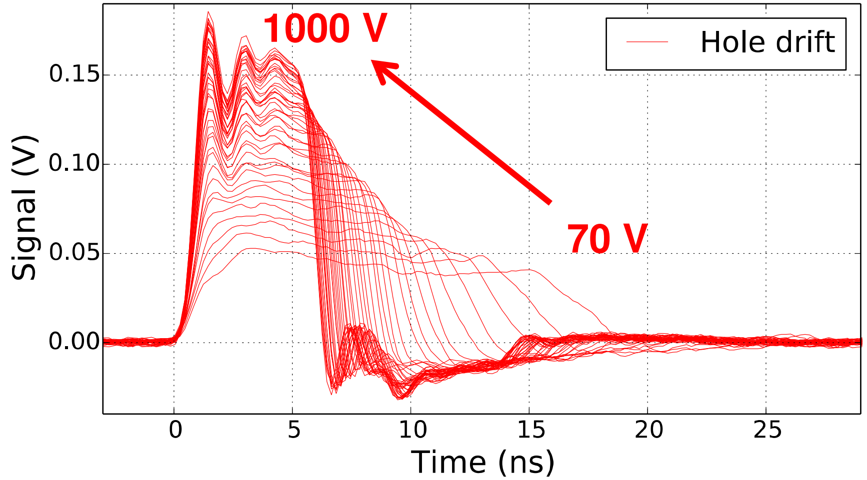
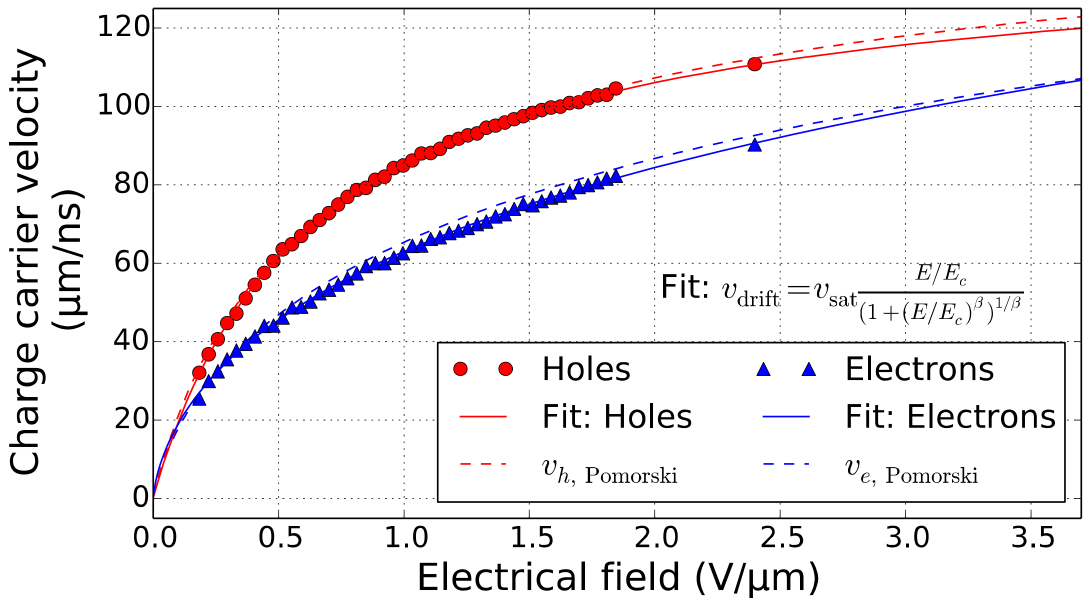
TCT measurement of e/h drift





Parameterization of charge carrier drift

- Drift velocity calculated via: $\mathbf{v_{e,h} = d/t_{FWHM}}$ with **d** as diamond thickness
- In agreement with measurement results of M.Pomorski
- Parameterization with Saturation Velocity Model (Caughey and Thomas mobility model)

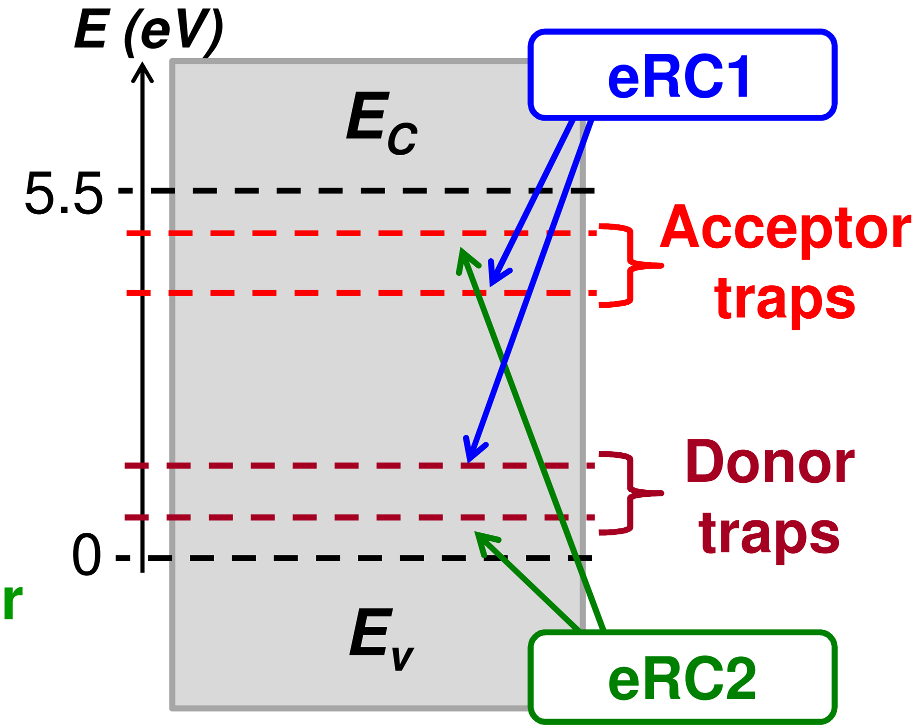


Definition of traps (recombination centers)

- Radiation damage causes plutoria of defects
- Energy levels and properties of defects poorly known

Creation of an effective defect model:

- **2 deep traps as acceptor and donor (effective recombination center 1)**
- **2 Shallow traps as acceptor and donor (effective recombination center 2)**



Symmetric properties of effective traps:

- Acceptor and donor energy levels of **eRC1** and **eRC2** identical
- Electron and hole capture cross section ($\sigma_{e,h}$) of **eRC1** identical
- σ_h of **eRC2** is 2x increased compared to σ_e

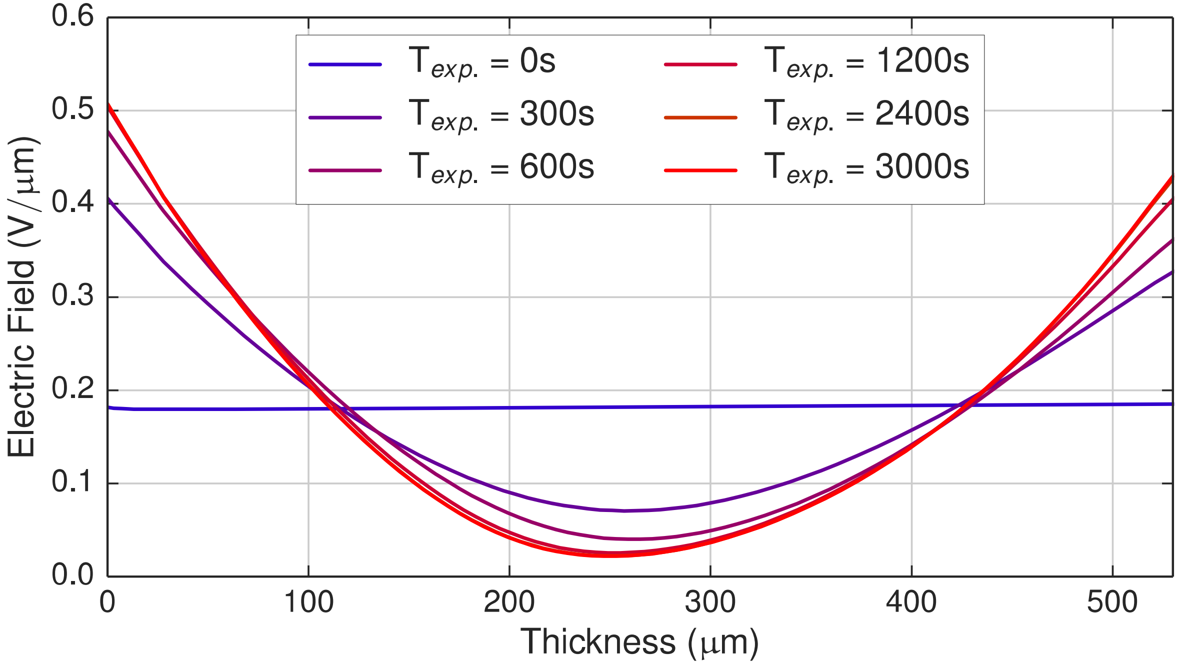
Simulation of the electric field using effective trap model

Simulation follows the measurement procedure:

1. Diamond exposed the entire simulation to an ionizing current created by a ^{90}Sr source.
2. *Pumping:* Diamond exposed to ^{90}Sr source for 20min without bias voltage applied.
3. Quick ramp up of bias voltage (t<1s) and start of TCT/CCE measurement simulation.
4. Probing of electric field, TCT and MIP pulse at different time steps 0s, 300s, …, 3600s.

Simulation of the electric field modification caused by the effective traps:

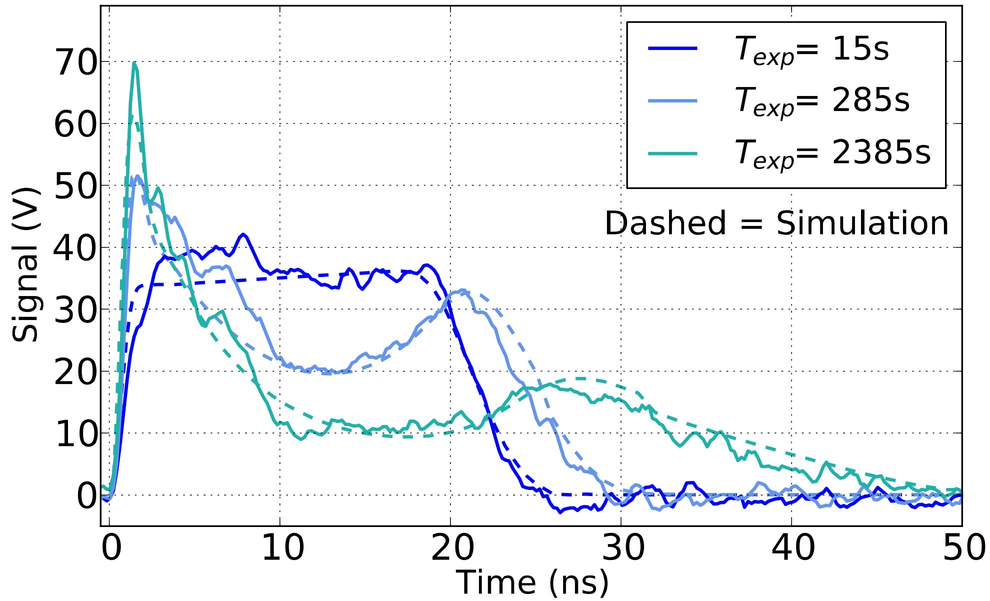
- Build up of space charge
- Diamond polarization



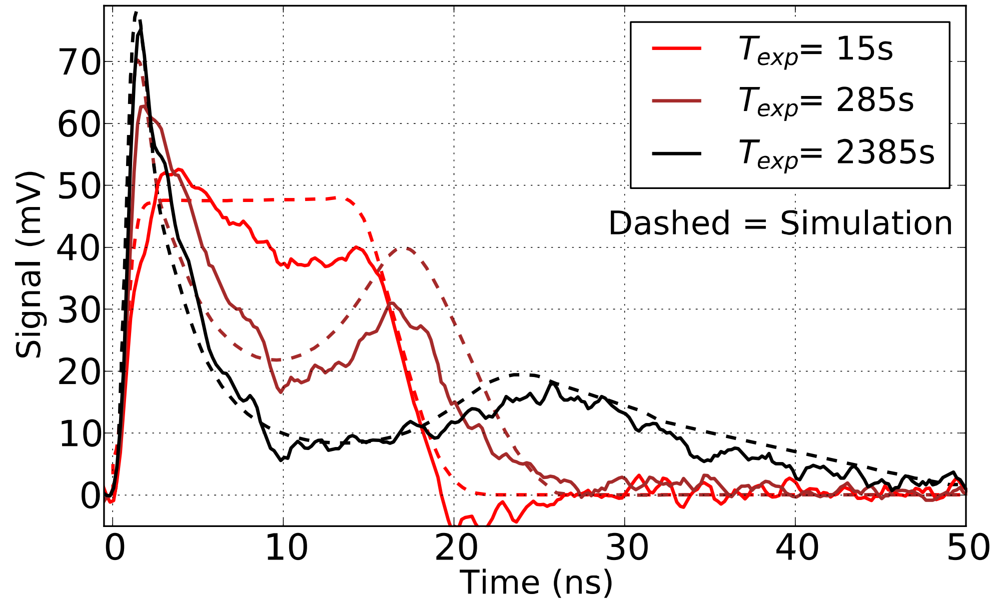
3. Simulation of TCT pulse and comparison to measurement result

Diamond operated at an electric field of ***E* = 0.18 V/µm**

electron drift



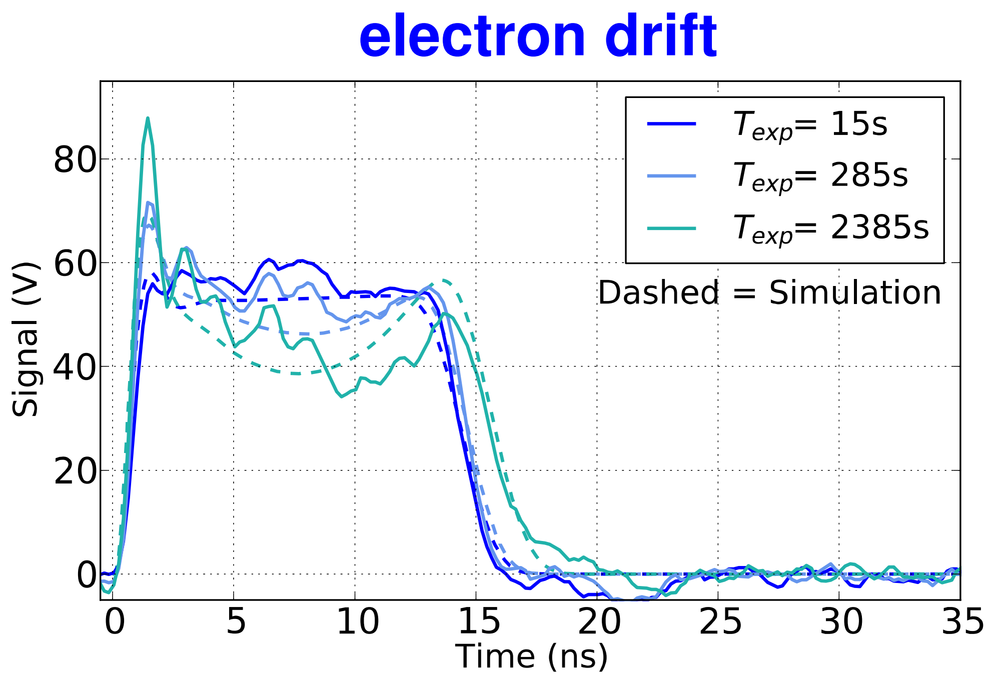
hole drift

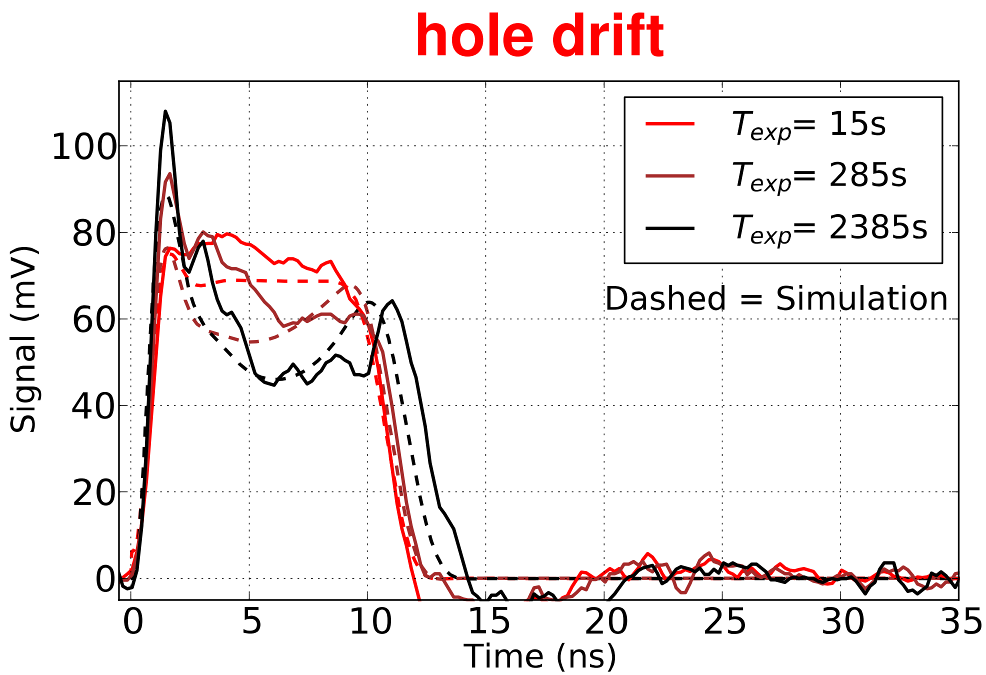


Radiation damage: $\Phi = 0.9 \times 10^{13}\ n_{1MeV}\ cm^{-2}$

3. Simulation of TCT pulse and comparison to measurement result

Diamond operated at an electric field of ***E* = 0.36 V/µm**



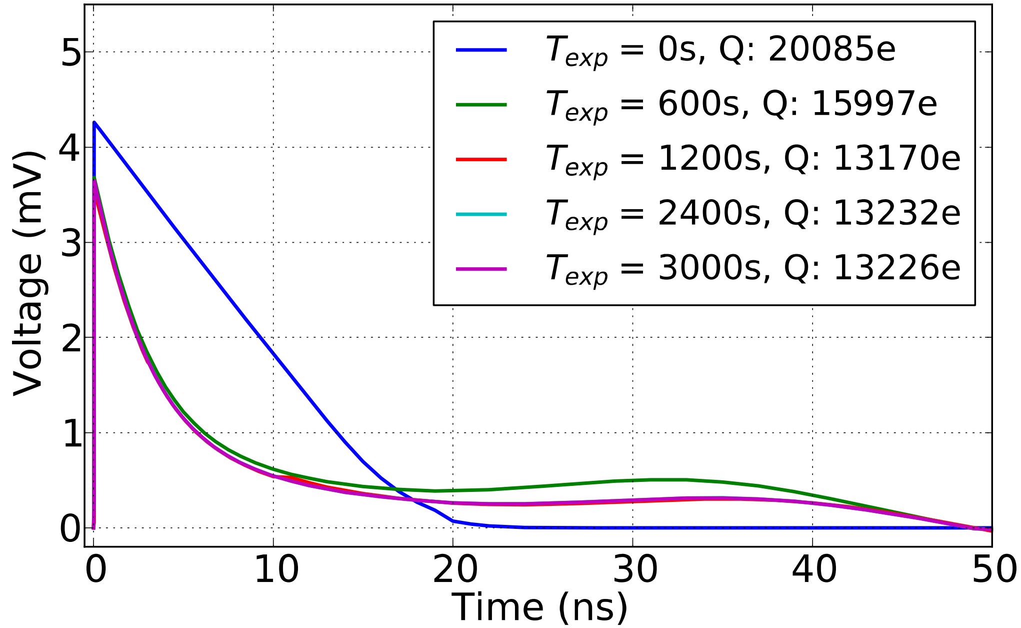


Radiation damage: $\Phi = 0.9 \times 10^{13}\ n_{1MeV}\ cm^{-2}$

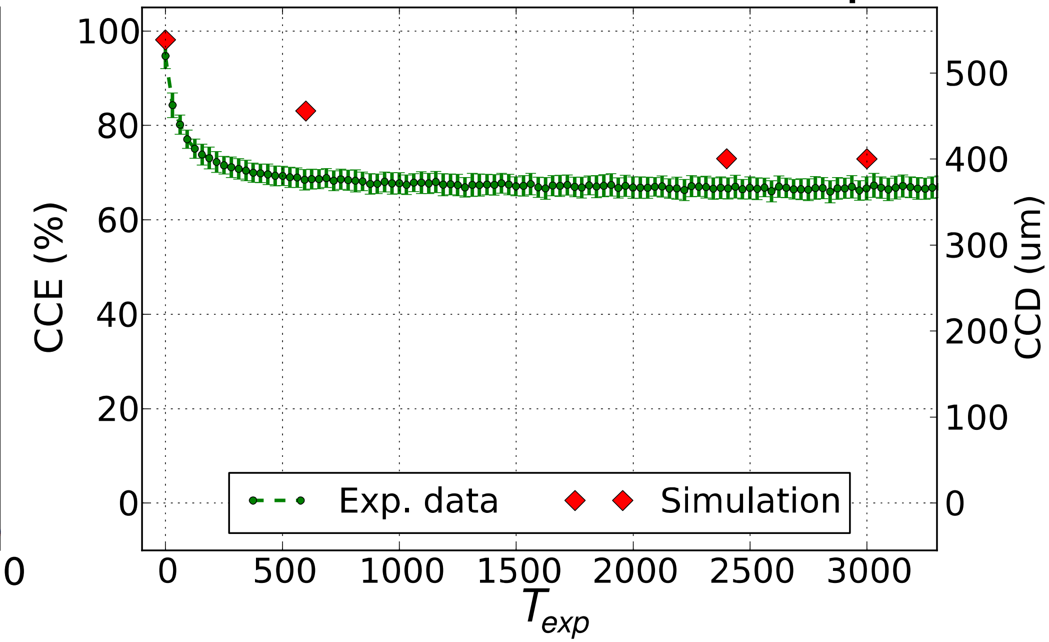
3. Simulation of MIP pulse and comparison of calculated CCE to measurement result

Diamond operated at an electric field of ***E* = 0.18 V/µm**

MIP pulse

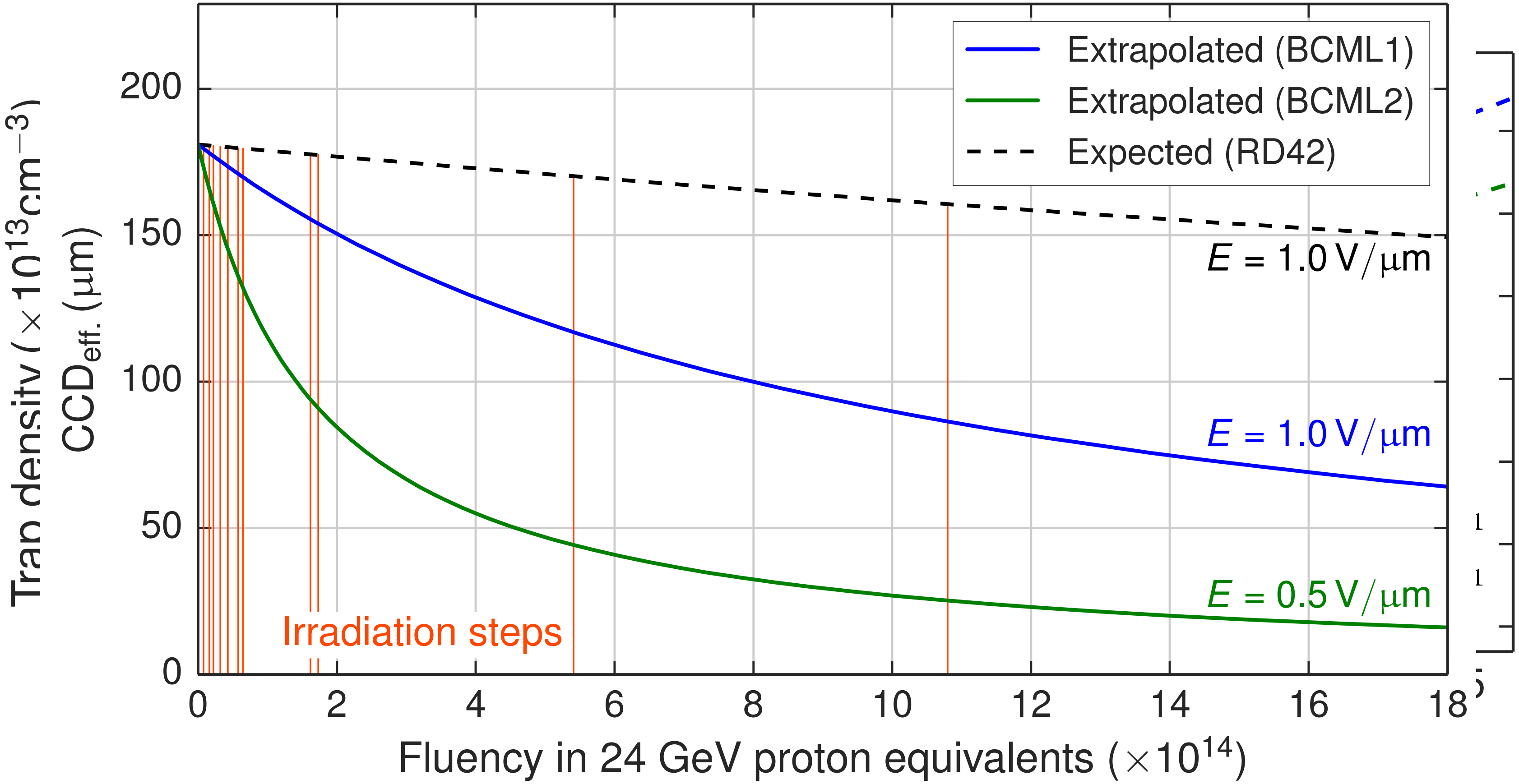


CCE as function of T_{exp}



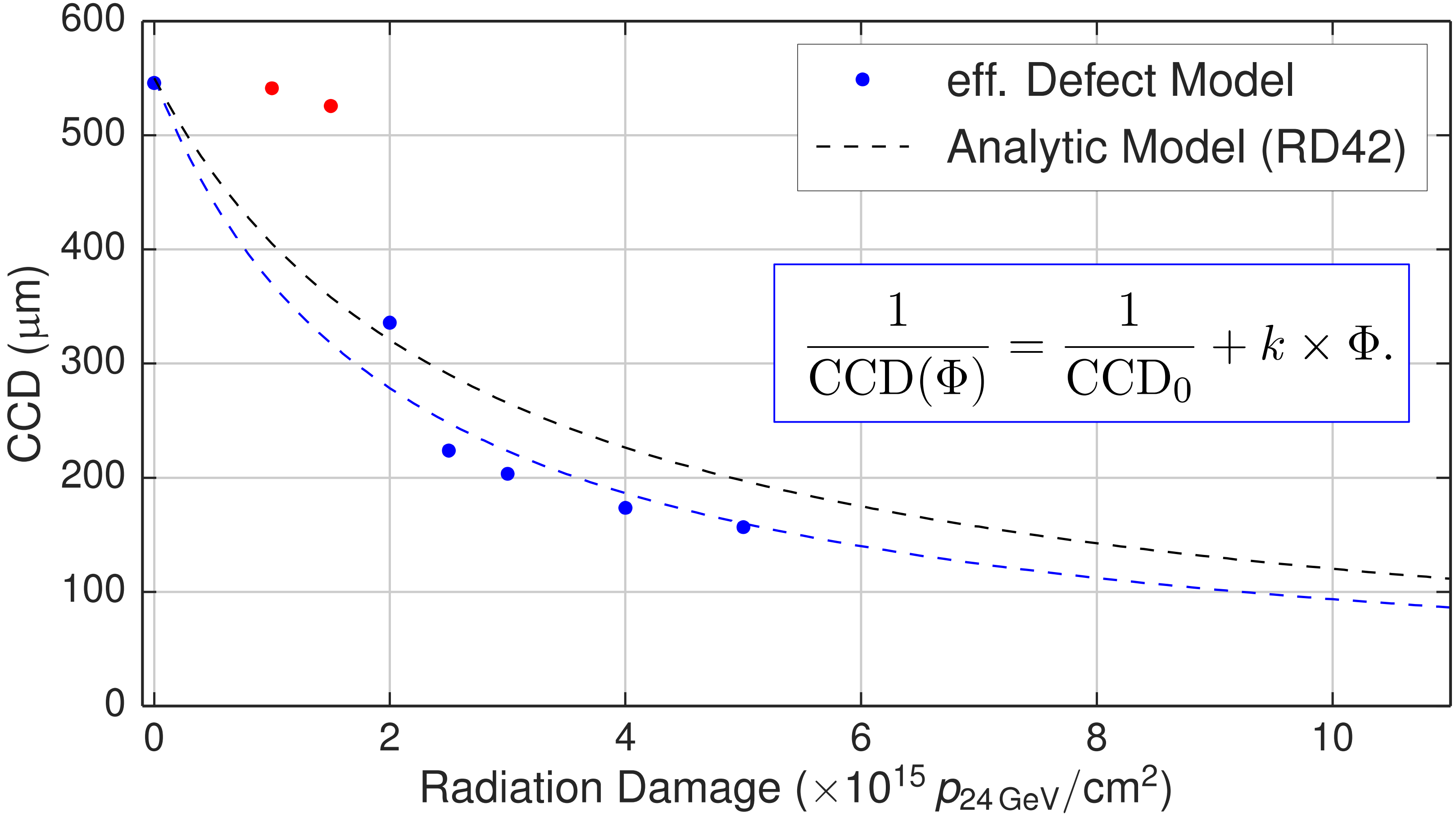
Radiation damage: Φ = 0.9 x 10^{13} n_{1MeV} cm^{-2}

3. Effective Defect Model as function of Radiation Damage



- For each radiation step the trap densities ρ of **eRC1** & **eRC2** were optimized to the TCT/CCE measurement results.
- Trap properties like $\sigma_{e,h}$ and energy levels remain unchanged.
- Proton irradiated (#73 and #74) and neutron irradiated (#76) sample in agreement.

Effective Defect Model (eRC) vs. RD42 radiation damage model

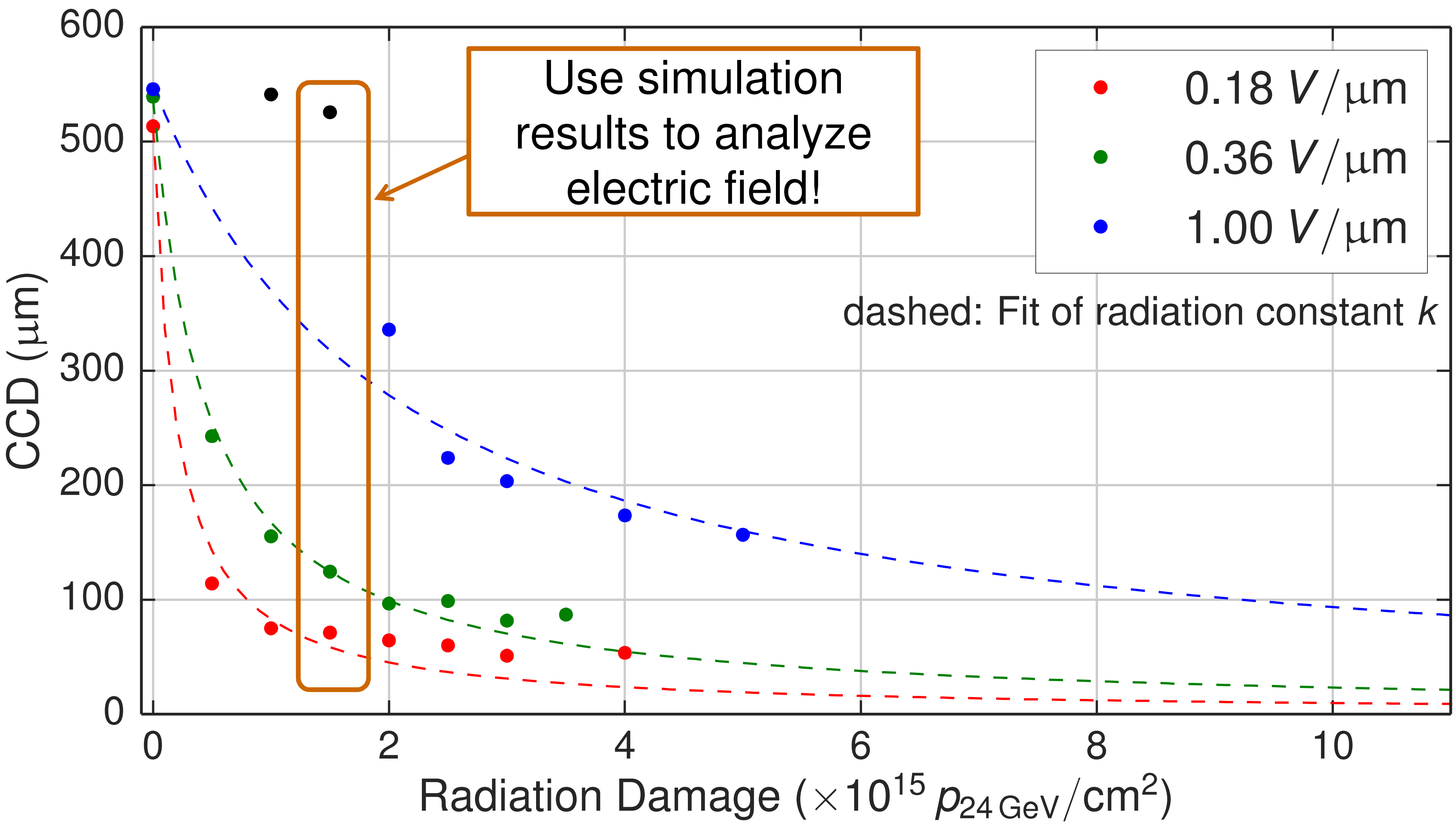


$$\frac{1}{\mathrm{CCD}(\Phi)} = \frac{1}{\mathrm{CCD}_0} + k \times \Phi.$$

- Diamond sensors simulated/operated at an electric field of 1V/µm.
- Simulation results fitted to analytical RD42 radiation damage model results in:

$\boldsymbol{k_{eRC} = 8.9 \times 10^{-19}\ cm^2 \mu m^{-1}}$ vs. $\boldsymbol{k_{RD42} = 6.5 \times 10^{-19}\ cm^2 \mu m^{-1}}$.

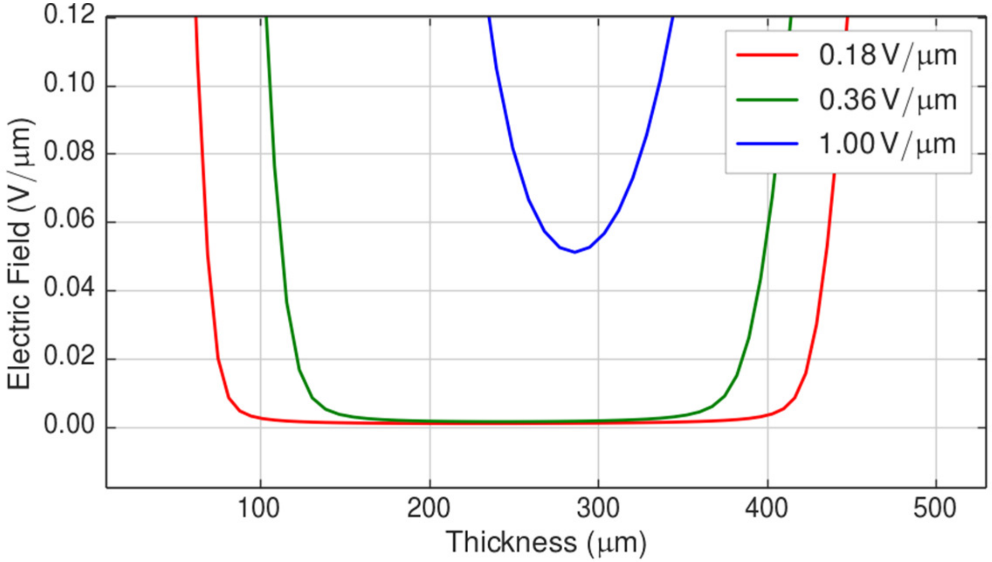
Effective Defect Model: Simulation of different electrical fields at which diamond is operated



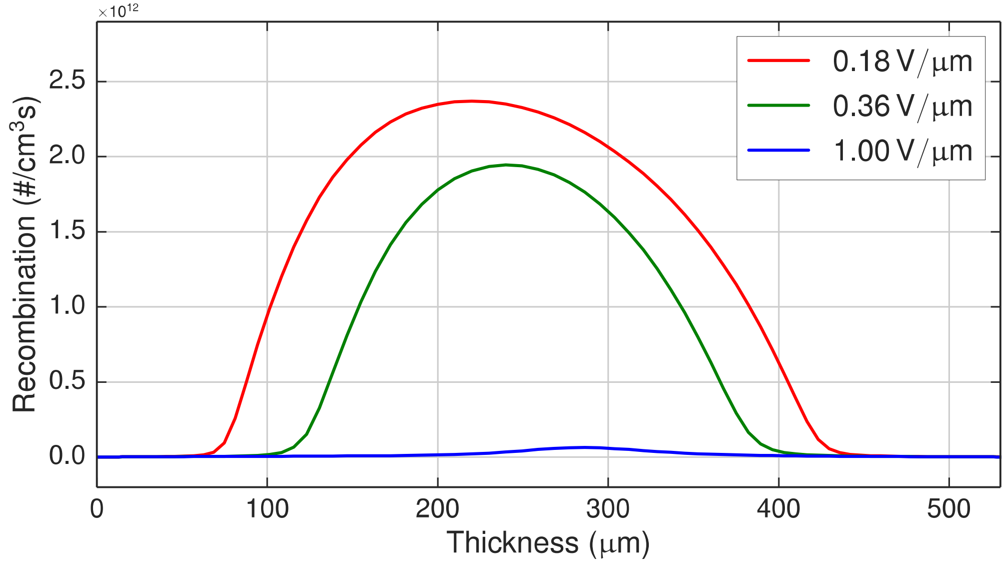
Effective Defect Model: Simulation of different electric fields at which diamond is operated

Radiation damage: $\Phi = 1.5 \times 10^{15}\ p_{24GeV}\ cm^{-2}$

Electric field (zoom)



Recombination rate



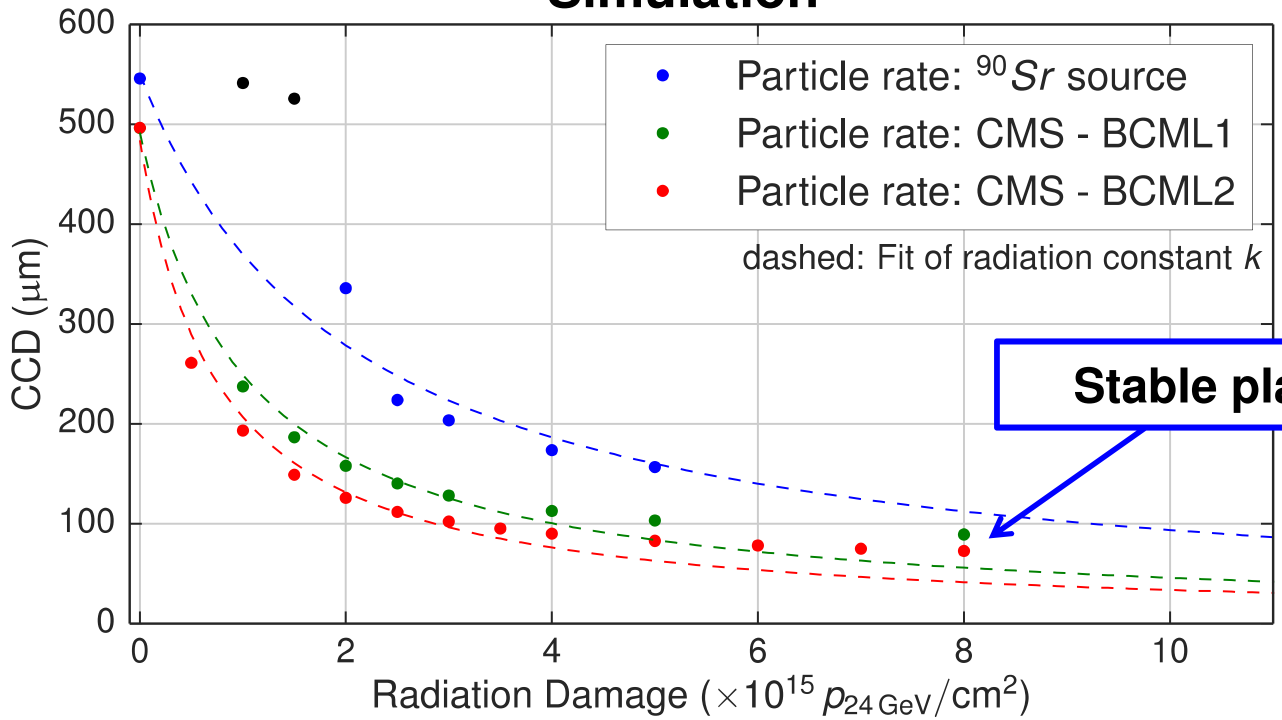
- 42x increased charge carrier recombination (0.36 V/μm)
- 70x increased charge carrier recombination (0.18 V/μm)

..explains the severe reduction in CCD

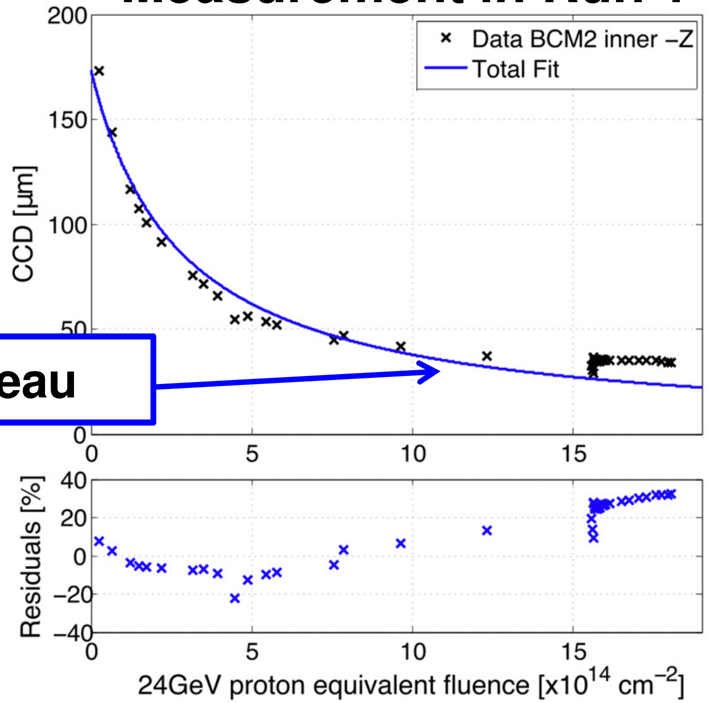
Effective Defect Model: Different particle rate environments

- Simulation for different particle rate environments: **^{90}Sr = 0.15 GHz/cm³, BCML1 = 2.04 GHz/cm³, BCML2 = 20.4 GHz/cm³**
- Equilibrium of stable polarized diamond state depends on particle rate environment.

Simulation



Measurement in Run 1



Stable plateau

Rate dependency of diamond signal !

Conclusion

Effective Defect Model is based on:

- **2 deep traps as acceptor and donor (eRC1)**
- **2 shallow traps as acceptor and donor (eRC2)**
- **Trap density of these 4 effective recombination centers determined as function of radiation damage (n_{1MeV} cm^{-2}) by:**

$$\rho_{eRC1}\,(\mathrm{cm}^{-3}) = \Phi \cdot (2.52 \pm 0.13) \times 10^{-2} + (9.40 \pm 1.11) \times 10^{11}$$
$$\rho_{eRC2}\,(\mathrm{cm}^{-3}) = \Phi \cdot (2.15 \pm 0.04) \times 10^{-2} + (6.67 \pm 0.38) \times 10^{11}$$

Effective Defect Model successfully describes:

- **CCD as function of radiation damage**
- **CCD as function of electric field at which the diamond is operated**
- **CCD as function of particle rate environment (Rate dependency!)**

Detailed analysis of intrinsic diamond parameters possible like:

- **Internal electric field configuration, space charge distribution, charge carrier recombination rates and more..**

THANK YOU!

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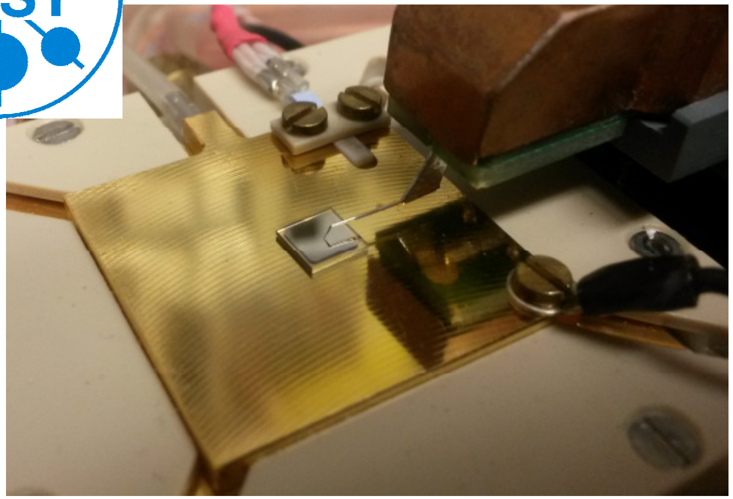


- To Prof. Lohmann and the CMS group at DESY!
- To Moritz, Anne and Wim!

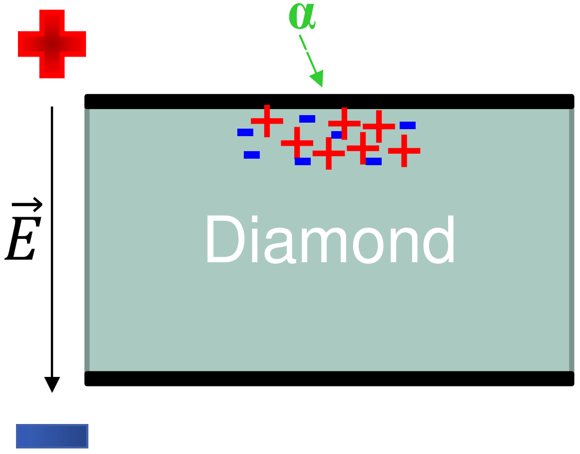
sponsored by the:

Federal Ministry of Education and Research

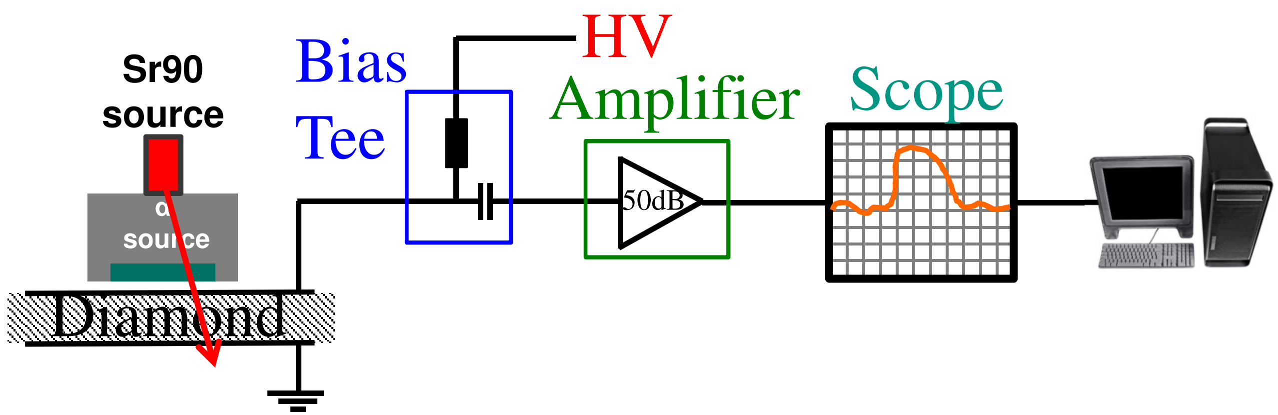
BACKUP

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

Measurement idea



Measurement setup



Ramos theorem:

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

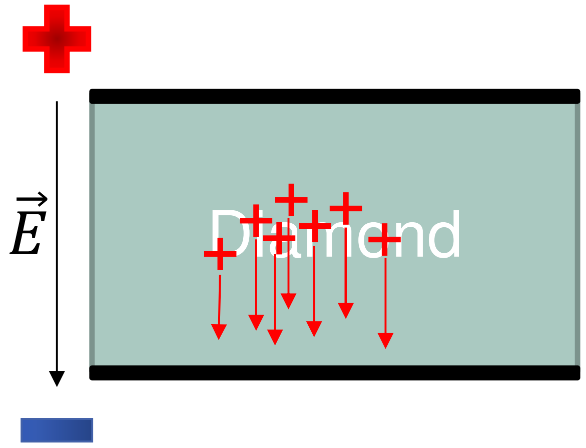
with i as induced current, q as charge, v the velocity of the charge drift and with E_v the weighting field

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

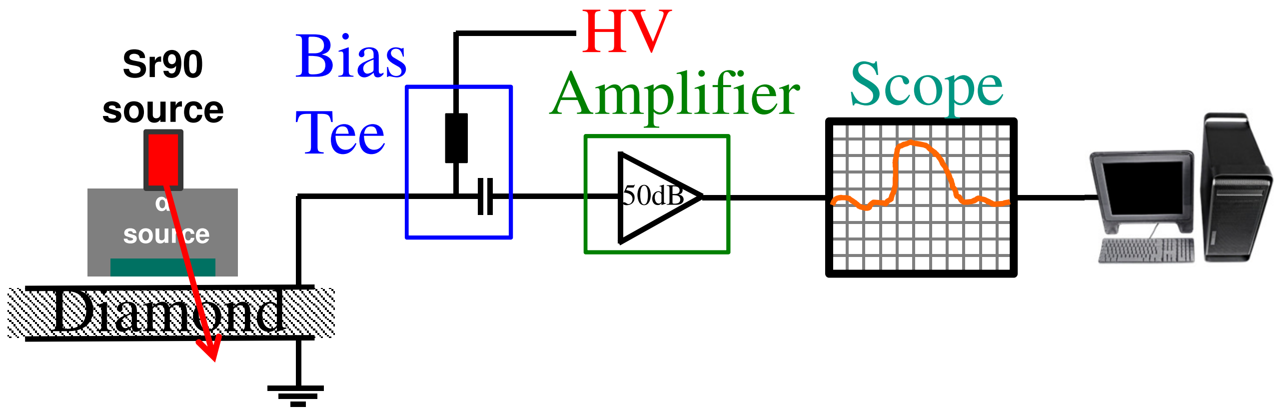
2. Measuring the electric field with the Transient Current Technique (TCT)

Karlsruher Institut für Technologie

Measurement idea



Measurement setup



Ramos theorem:

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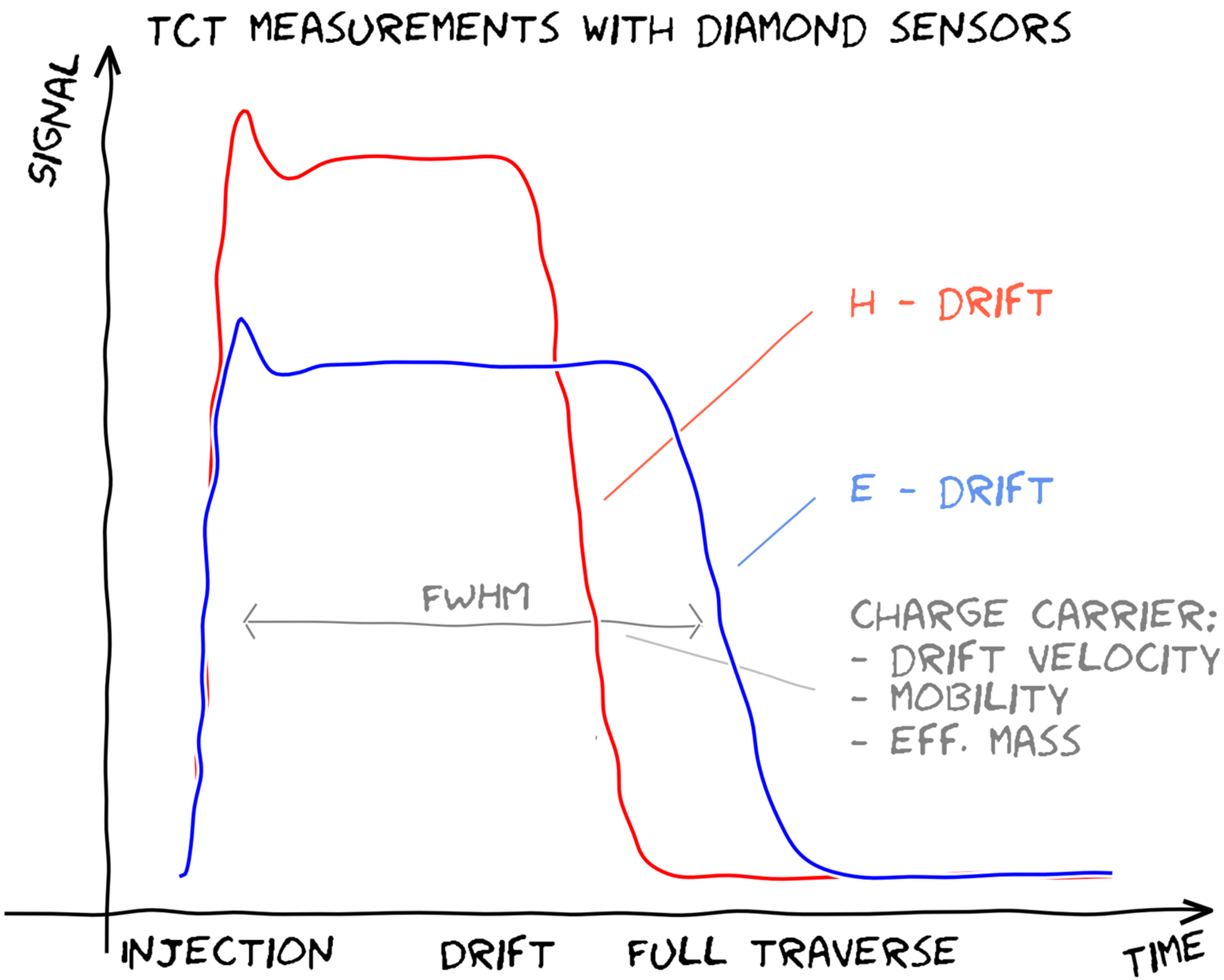
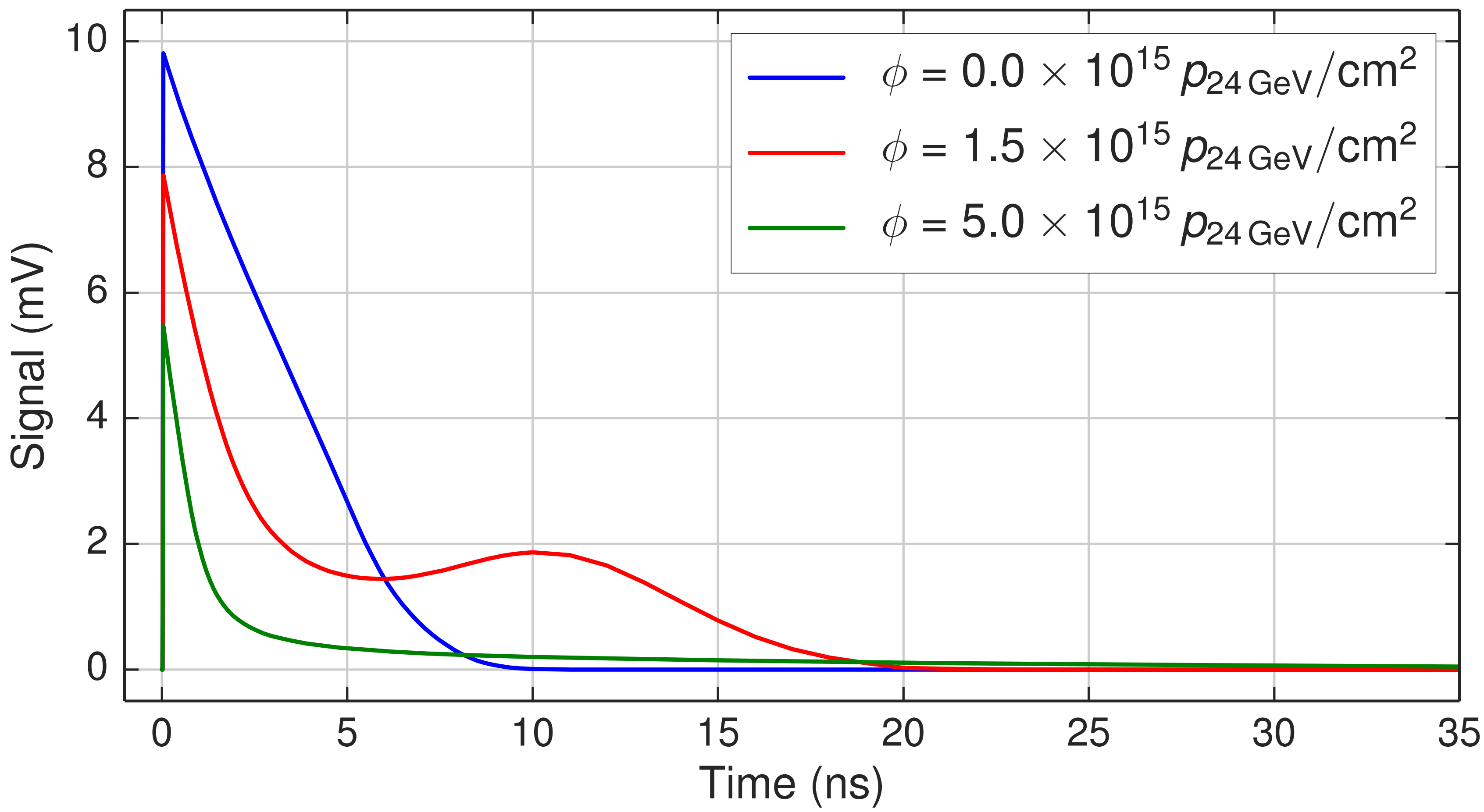
Intermezzo:
TCT measurement, polarization and electric field

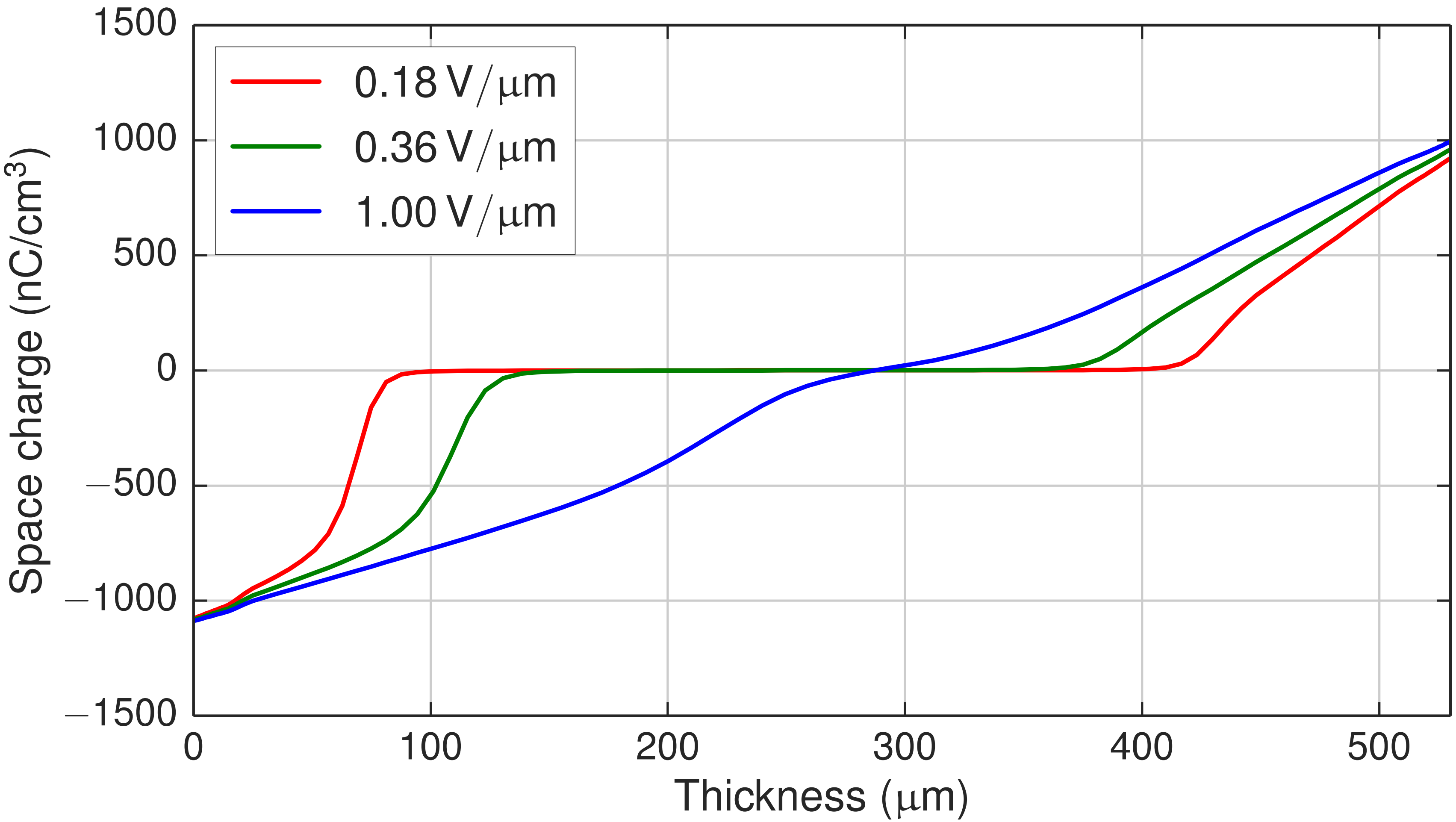


MIP signal for diamond operated at an electric field of *E* = 0.18 V/µm for different radiation damages



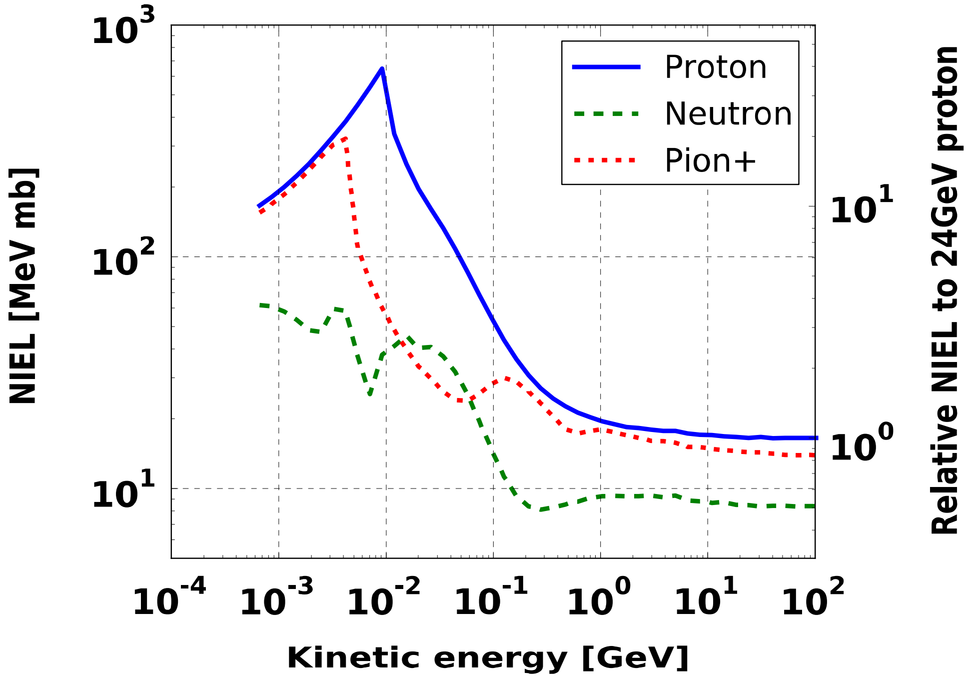
Effective Defect Model: Space charge for different electric fields

Radiation damage: Φ = 1.5 x 10^{15} p_{24GeV} cm^{-2}

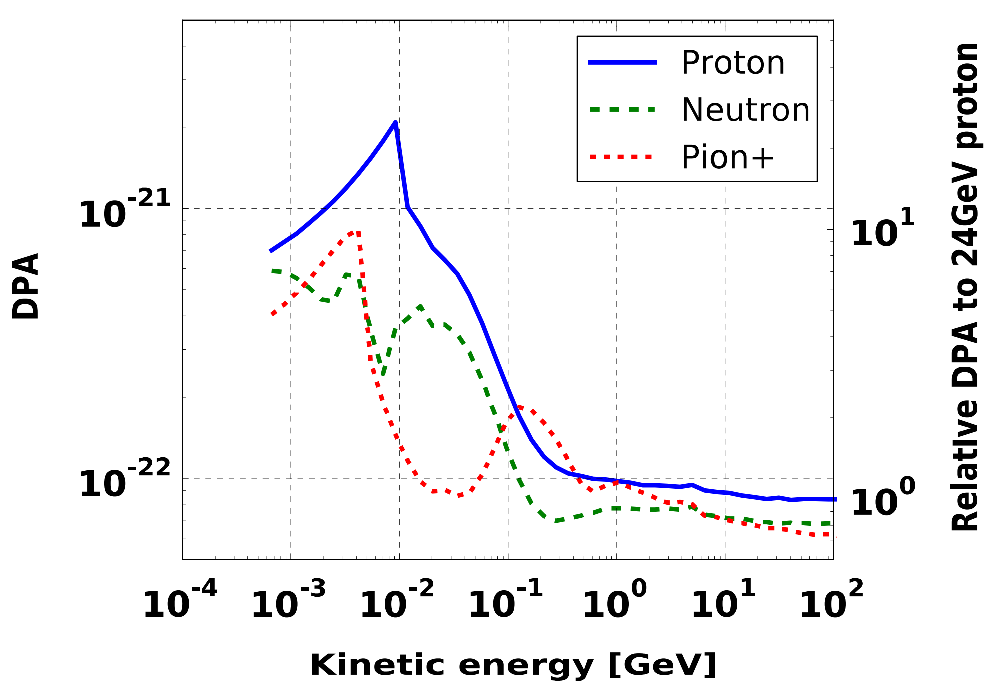


NIEL and DPA model

NIEL model



DPA model



Taken from:

M. Guthoff et al., *Simulation of beam induced lattice defects of diamond detectors using FLUKA*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **735** (2014) 223–228.