Understanding (and mitigating) radiation damage in diamond detectors at CMS

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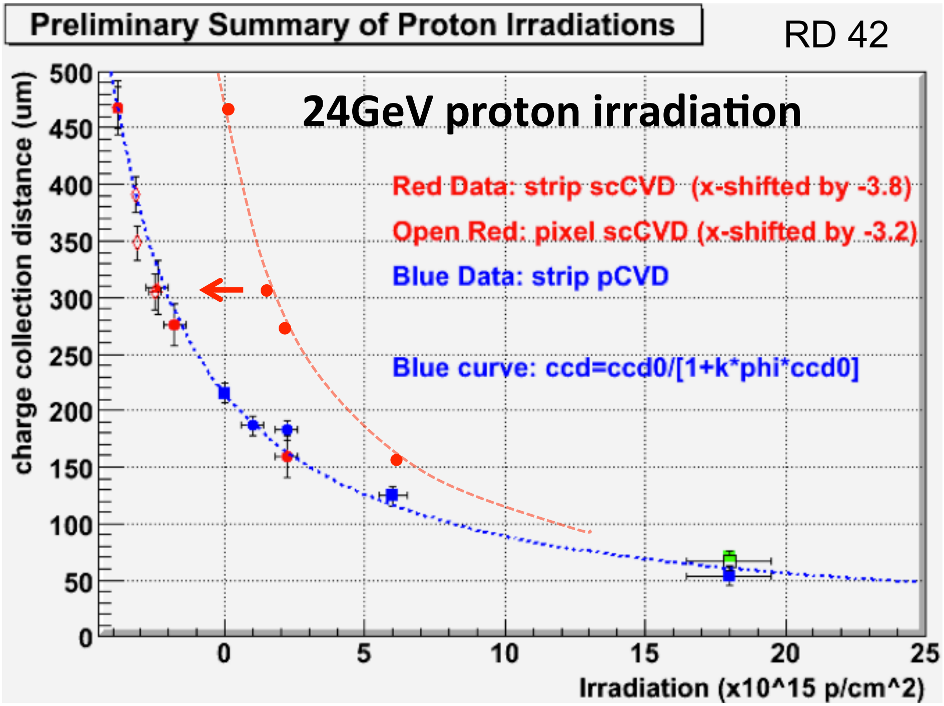
19th November 2014
3rd ADAMAS workshop, Trento

Overview

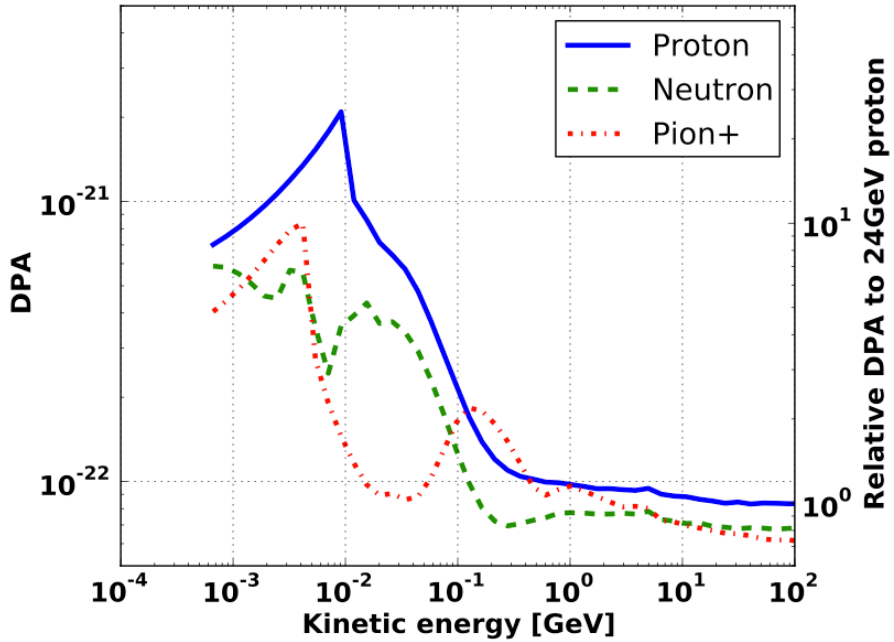
- Radiation damage to diamond, expected and observed.
- The polarization effect
- Electric field measurements with the Transient Current Technique
- Modeling the electric field and simulating the TCT pulse
- Preparations for irradiation campaign
- Requirements on un-irradiated sCVD diamonds

Radiation damage in diamond



- **Irradiation tests of RD42 collaboration.**
- **Collected charge decreases hyperbolically**

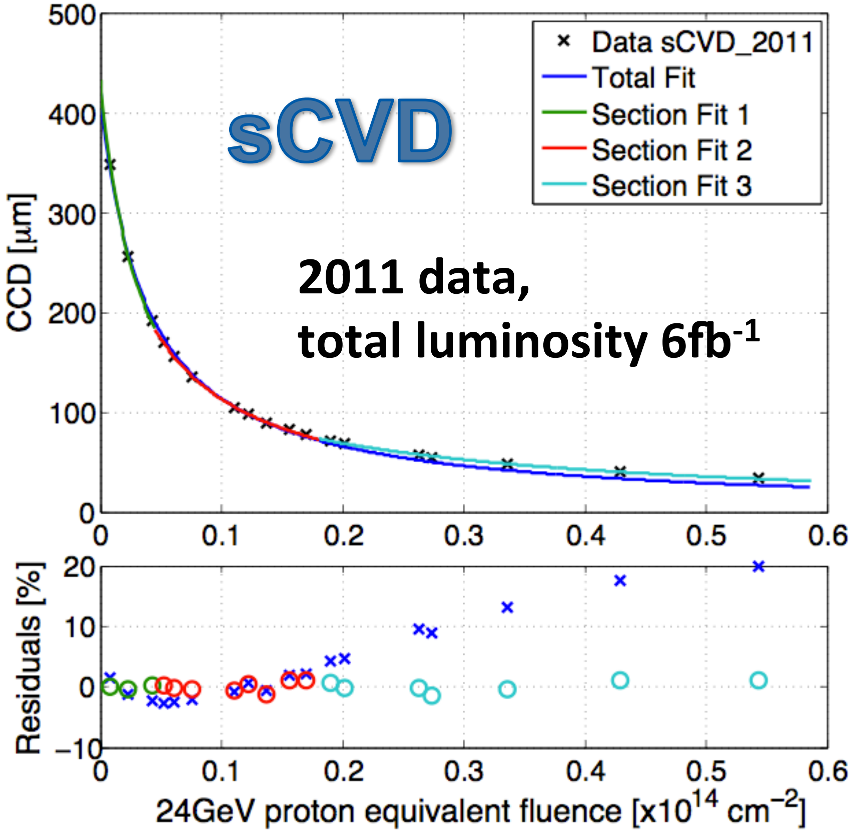
DPA model



M. Guthoff, W. de Boer, S. Müller: **Simulation of beam induced lattice defects of diamond detectors using FLUKA**, arXiv:1308.5419, NIM A: Vol.735, Pages 223-228, 2014.

- **Displacements per Atom in diamond.**
- **Number of displacements calculated for different particle types and energies.**
- **Possibility to scale mixed field fluence to normalized particle**

Radiation Damage to single crystal, observations in CMS



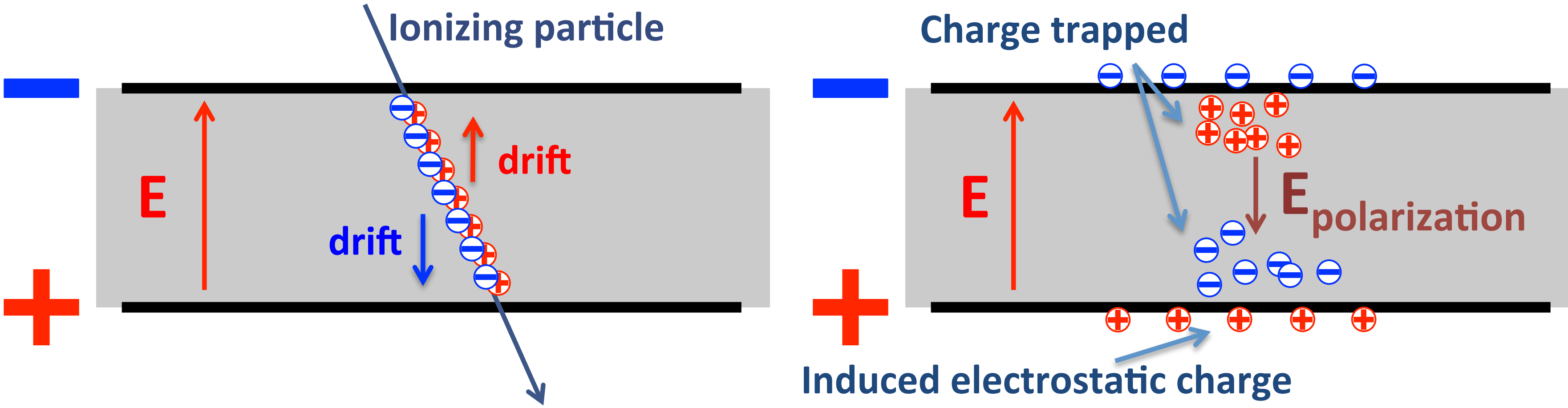
CCD calculated by:
- **Measured signal is detector current**
- **Compare signal with luminosity**
- **Assume full CCD at zero fluence.**

FLUKA simulated equivalent fluence
- **Data from 2011, corresponds to ~6fb^{-1}**
- **In HL-LHC expect ~300fb^{-1} per year**

Signal decrease not perfectly hyperbolic

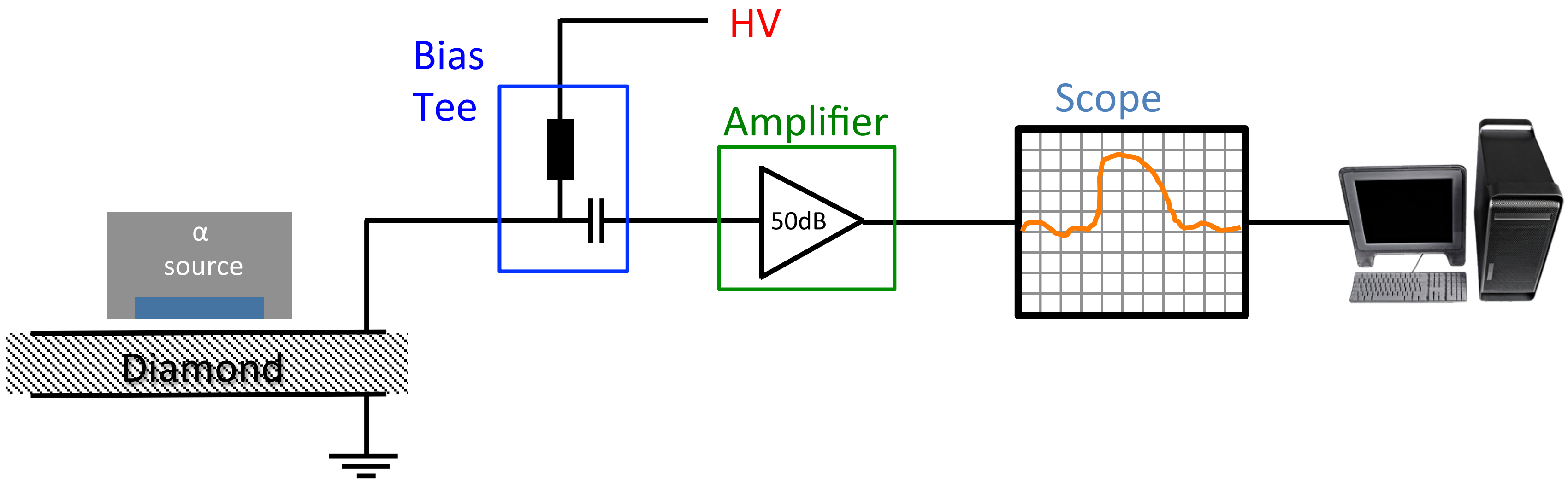
- **Decrease of signal with relatively low fluences.**
- **Space charge trapped at defects deform electric field and decrease signal efficiency. So called: Polarization**

Polarization model



- Positive charge trapped at cathode
- Negative charge trapped at anode.
- Deformation of electric field creates low/zero-field regions.
  - Reduced sensor efficiency
- Measurements of electric field required.

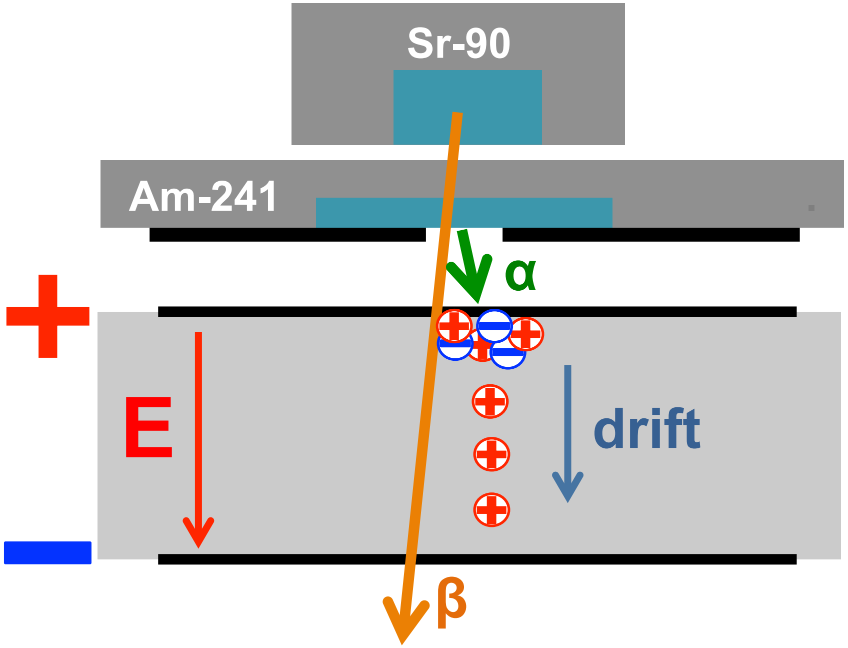
Transient Current Technique



- **Alpha particles are used to introduce charge carriers at the diamond surface.**
- **Charge carriers drift along the electric field with v_{drift} ~ E-field.**
- **Measure signal with high bandwidth amplifier and scope. I_{Signal} ~ v_{drif} ~ E-field.**

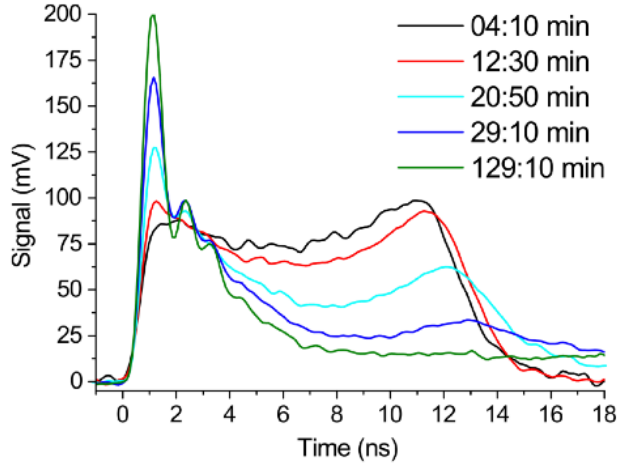
TCT measurement procedure

- Apply Sr90 at zero HV.
  - All remanent electric field is removed
- Apply Sr90 and Alpha source simultaneously
- Start measurement and fast HV switch on.
  - Initial state of detector is completely polarization free.
- Continuously measure single traces
  - Deformation of electric field with time.
- Comparative study requires well defined conditions.

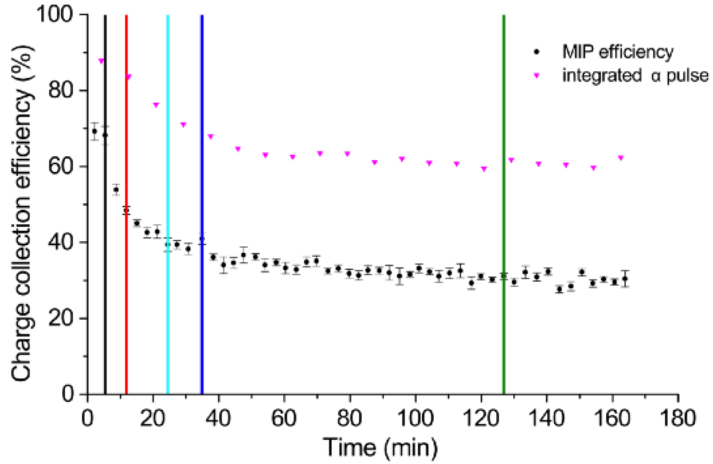


TCT pulse polarizing

TCT
(hole drift)



CCE



- **Change in pulse shape over time**
  - **Reduction of collected charge due to E-field deformation.**
- **Qualitative understanding of E-field**
- **De-convolution of drift effects impossible**
  - ➢ **No quantitative understanding.**
- **Simulate E-field and TCT carrier drift to reproduce measurement.**
  - ➢ **Quantitative understanding of E-field and space charge.**

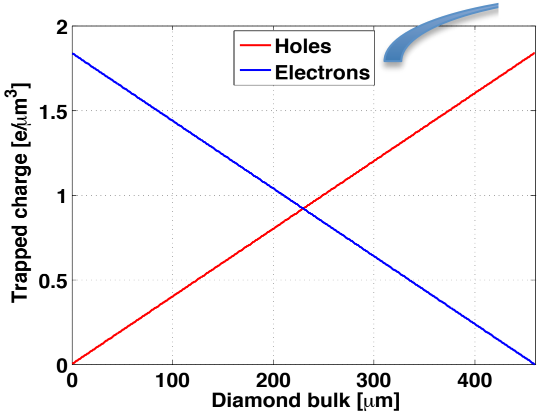
Polarization model

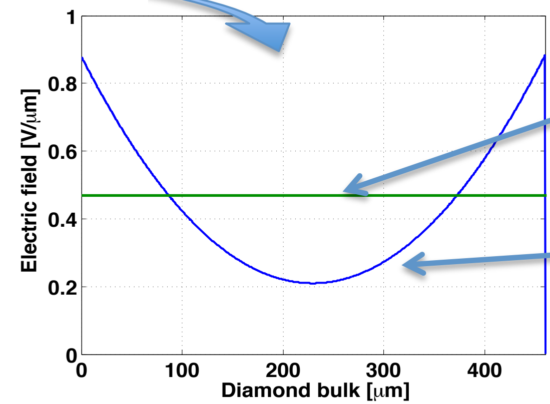
Fixed space charge

Electric field

integrate

Assume linear increase of space charge

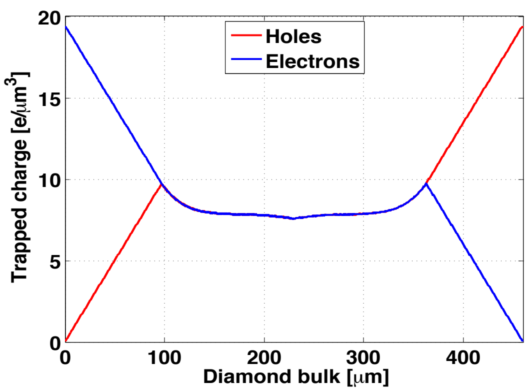


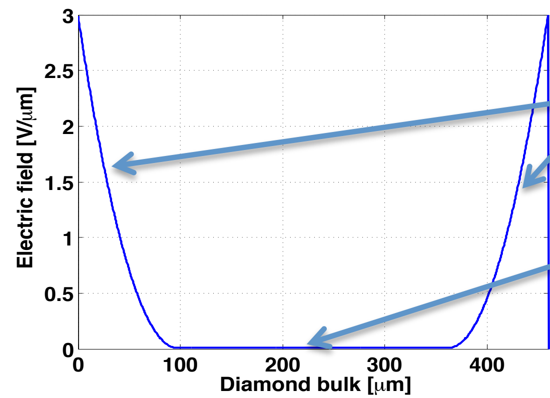


Field with no space charge

Integral has to be constant

No effective space charge at zero field

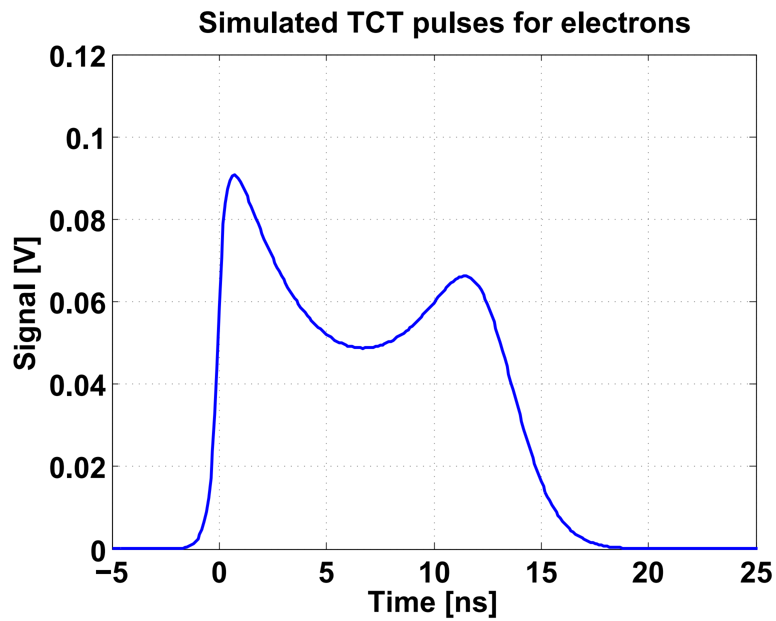


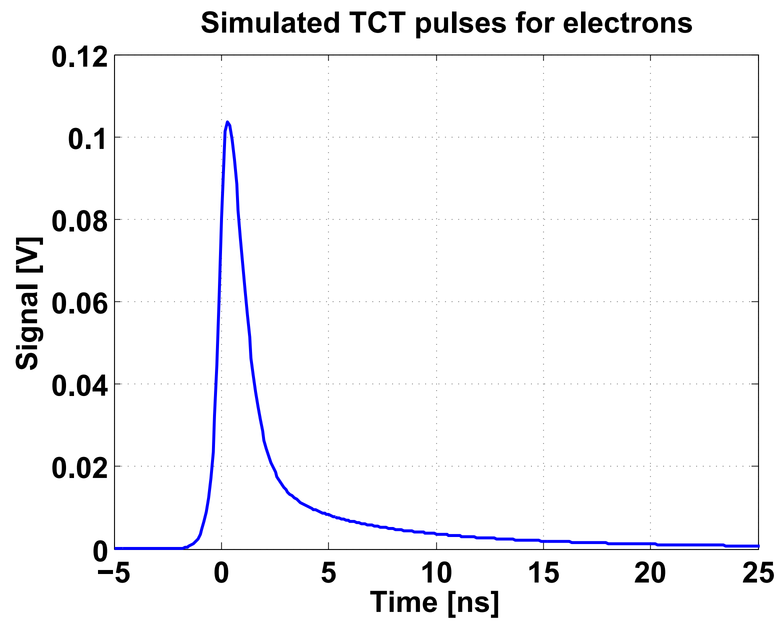


high field

zero field

Simulation model

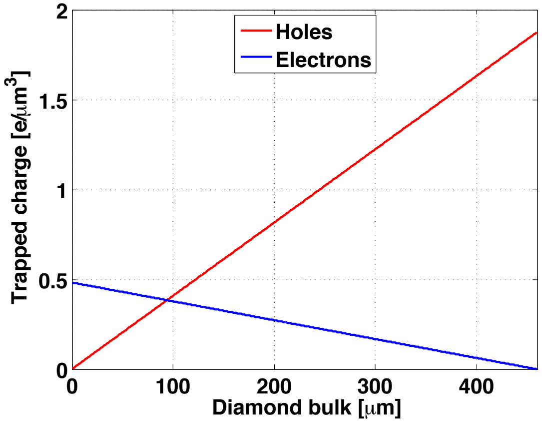


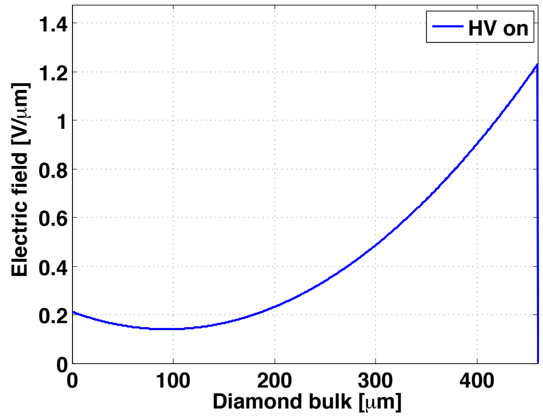


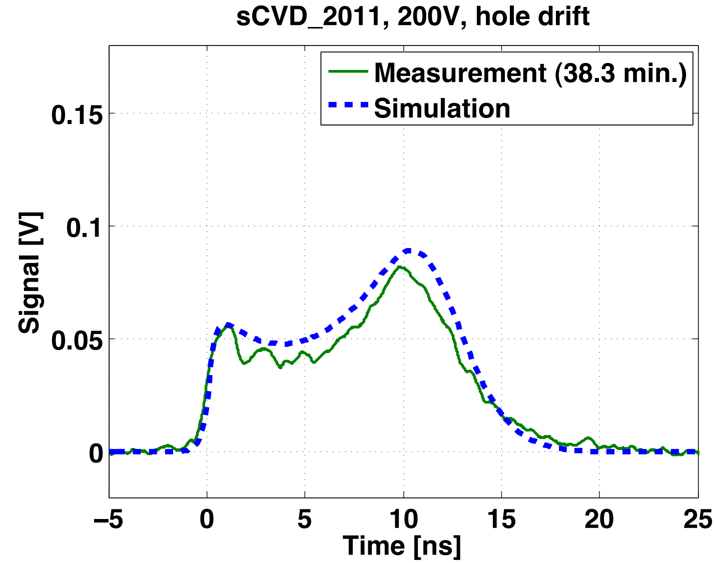
- **Estimation of TCT pulse for given electric field.**
- **Inject charge created by alpha and transport through E-field.**

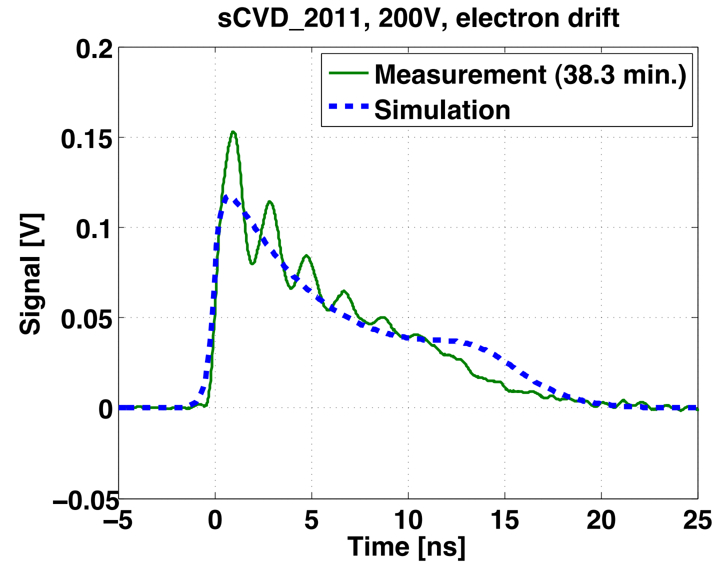
➢ **Match simulation to measured pulse to understand electric field distribution during measurement.**

Simulated TCT measurement



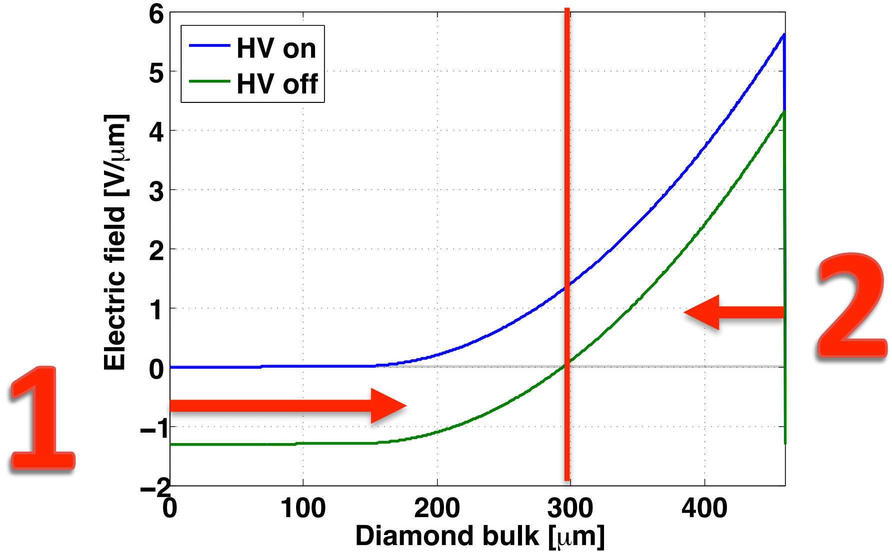


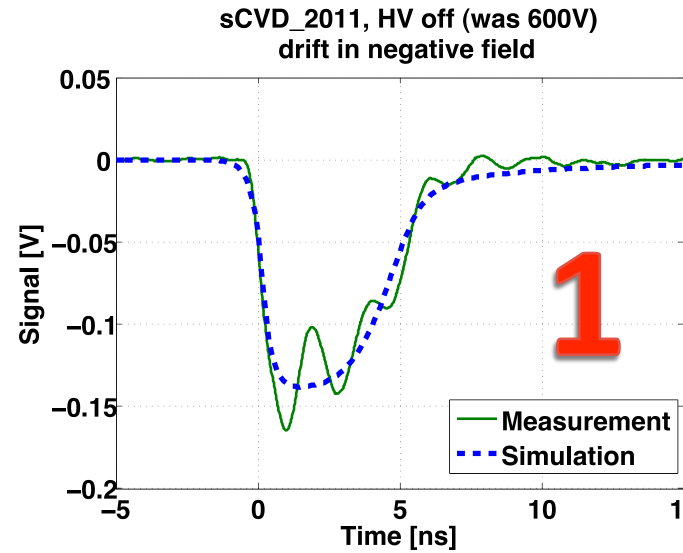


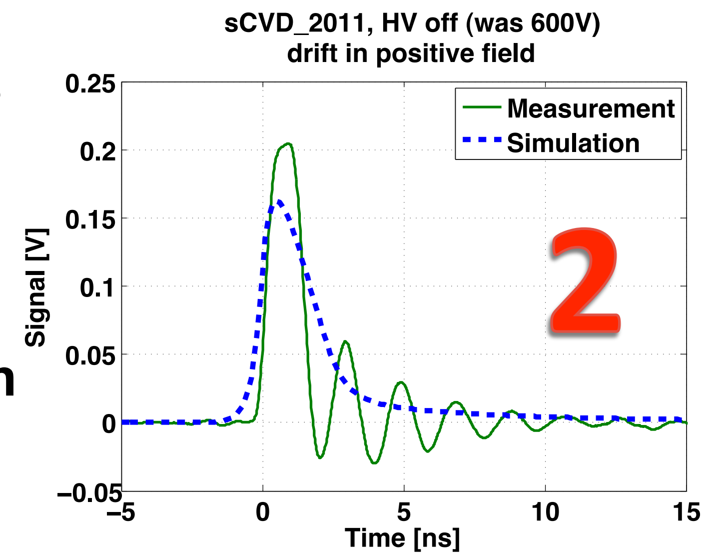


- **Space charge distribution needs to be asymmetric to explain data. (asymmetric E-field)**
- **Implies stronger trapping of holes.**
- **TCT simulation reproduces well the measurement.**

Highly polarized state, HV off experiment



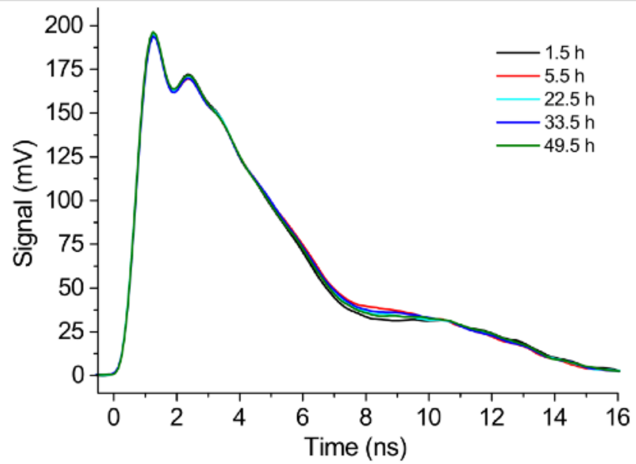




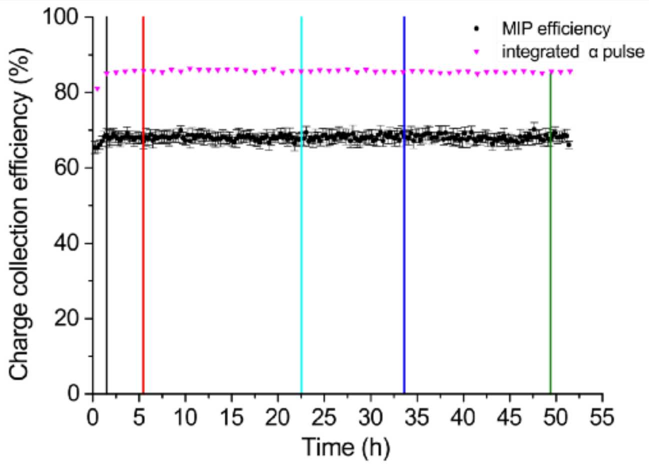
1. Apply Sr90 source under HV for some time.
   - Diamond is fully polarized
2. Remove Sr90, and then switch off HV.
   - Field due to space charge persists.
3. Measure with alpha on side 1 and then on side 2.
   - Positive and negative field regions found.

Alternating polarity TCT

TCT
(hole drift)

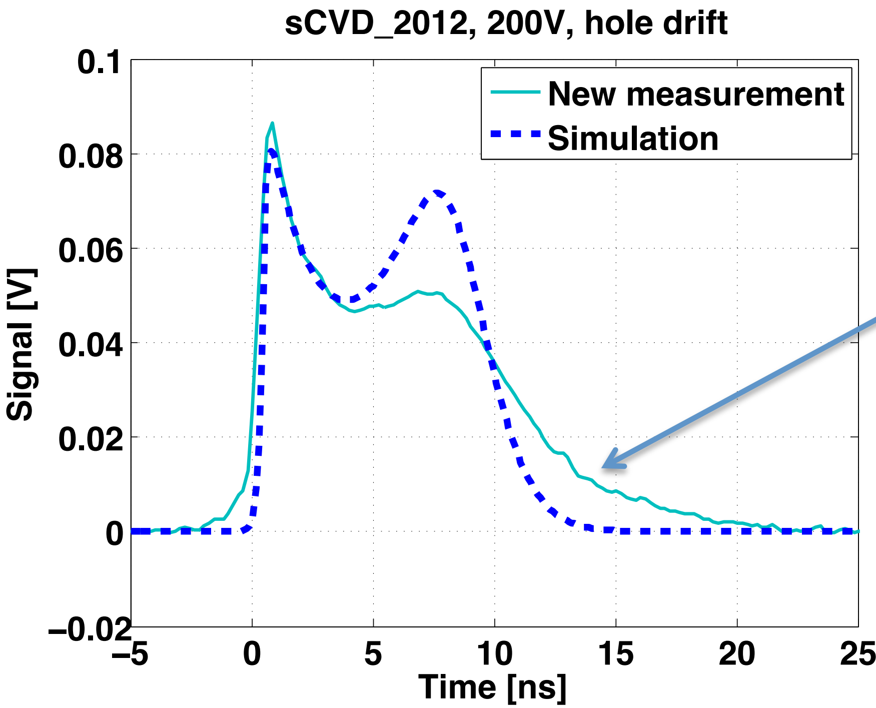


CCE
(Charge Collection Efficiency)



- Polarization filed counteracts Electric field. Changing E-field polarity with a few Hz avoids polarization field.
- Bulk still charges up, but with a more flat distribution.
- No “zero field” regions, charge carrier transport in whole bulk.
- Recover charge collection efficiency (compared to constant HV)

Limitations of simulations model

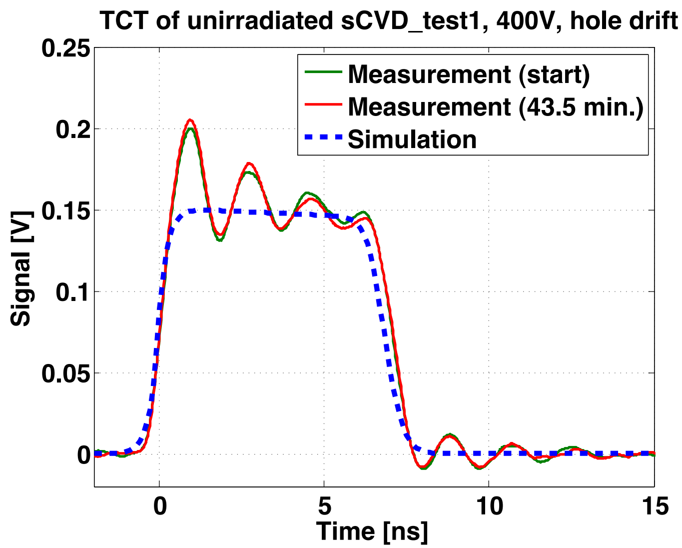


Long extension of pulse. Underestimation of diffusion in model.

- Long tails of TCT pulses in polarized state
- Charge carrier distribution influences electric field
- Charge carrier density cannot be simulated in 1-D
  - In the future T-CAD simulations (see talk F. Kassel)

Irradiation campaign

- Neutron and proton irradiations in small steps.
  - Aim at ~5×10^{12} cm^{-2} per step.
- TCT measurements in between steps.
  - Controlled radiation environment for comparative results.
- Require perfect diamond at the start
  - CCE = 100%, no electric field deformations at low E fields.
- Potential follow-up study: Find temperature for trap mobility with annealing study.

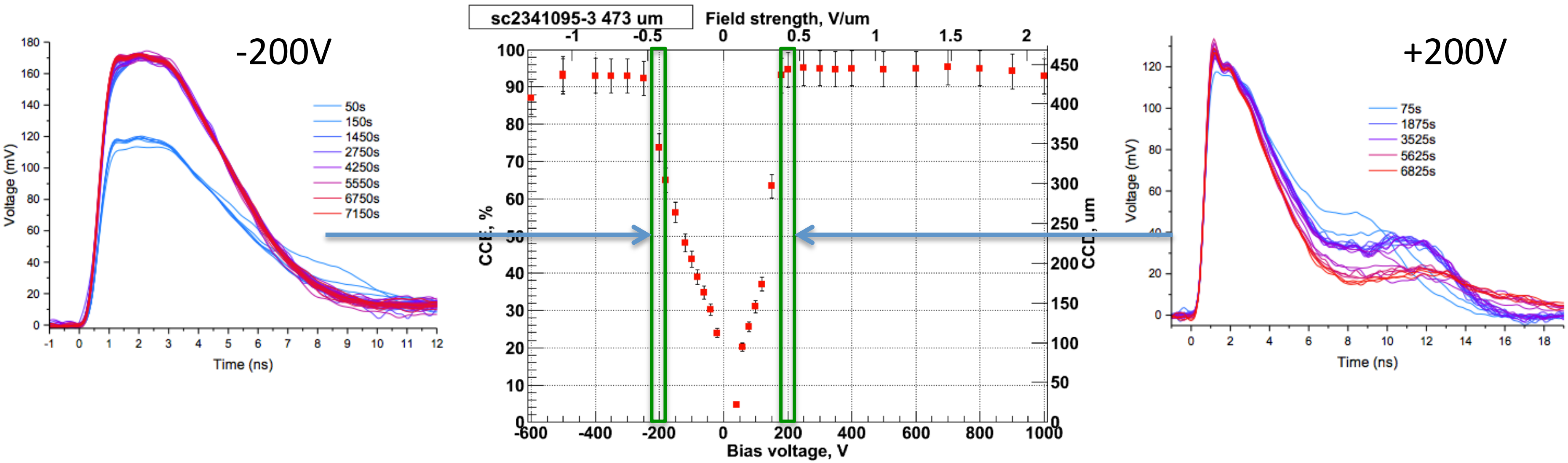


TCT example of perfect non polarizing diamond

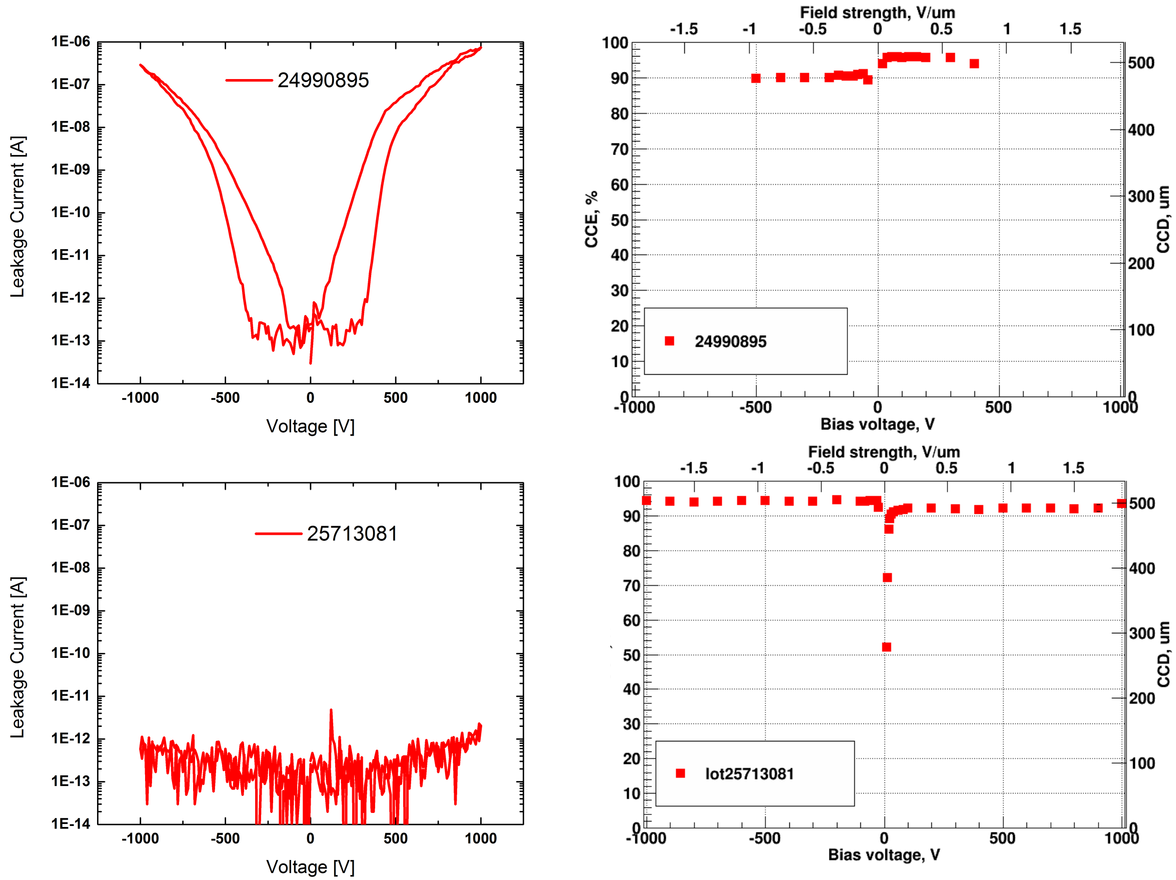
New sCVD diamond quality

- Many new sCVD diamonds bought by CMS and DESY for new BCM1F detector (see talk W. Lohmann).
- Few new sCVD diamonds purchased for irradiation campaign.
- Diamonds are of varying quality

Example of unirradiated sCVD showing E-field deformations



New sCVD - IV & CCE



Measurements by DESY Zeuthen

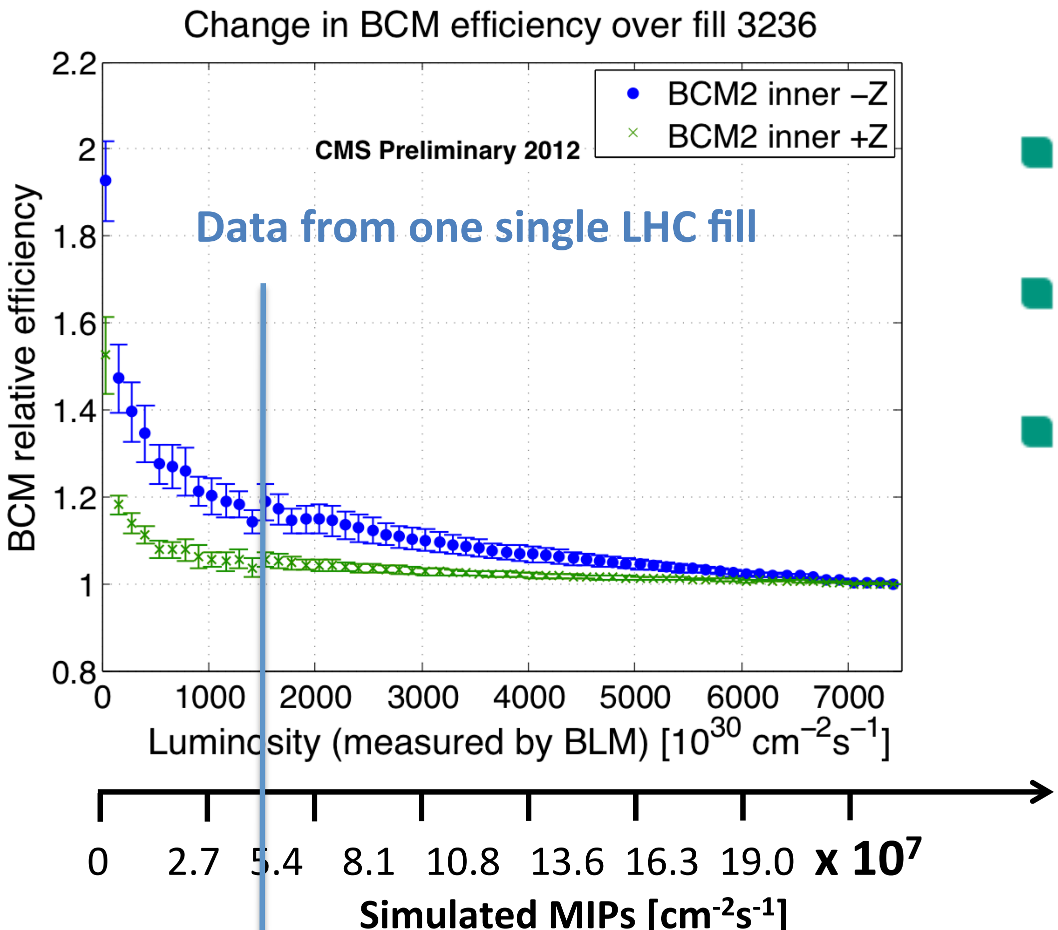
- To overcome polarization, need diamonds that can hold more than 2 V/um.
- Some show high currents.
  - Could be surface issue. Re-metalizing can lower leakage, but not remove it.
- Several new diamonds with full charge collection at extremely low fields.

Summary

- Searching for ways to ensure radiation hardness of diamond.
- TCT measurements as presented are the key to understand performance of diamond after irradiations.
  – Simple 1-D model limited to reproduce charge drift.
  ➢ Silvaco TCAD simulations by F.Kassel in next talk.
- Diamond quality of high importance.
  – Study radiation damage effects requires high purity.
  – Overcoming polarization requires high field stability.

BACKUP

Rate dependency of efficiency



Luminosity scan at end of fill

Normal luminosity span of this fill. (starts with highest luminosity.)

- Leakage current readout (E~0.5V/um)
- Signal efficiency lower at high rates.
- Possible explanation: Polarization less strong at low rates.

M. Guthoff