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
- $Z = +/-1.8 \text{ m}$, $r = 4.5 \text{ cm}$
- 4 diamonds per location

BCML2
- $Z = +/-14.4 \text{ m}$, $r = 5 \& 28 \text{ cm}$
- 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 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
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 ($T_{\text{exp.}}$) via the TCT technique.
  - Modification of the charge collection efficiency as function of $T_{\text{exp.}}$.

![Graph showing the behavior of CCD efficiency with fluency](image)

**Standard radiation model**

$$\frac{1}{\text{CCD}(\Phi)} = \frac{1}{\text{CCD}_0} + k \times \Phi.$$
Measurement procedure for TCT/CCE measurements to measure build up space charge as function of exposure time $T_{\text{exp}}$

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

Diamond operated at an electric field of $E = 0.36 \text{ V/µm}$

(hole drift)

unirradiated

$f = 0.6 \times 10^{13} \text{ p}_{24\text{GeV}} \text{cm}^{-2}$

$f = 1.2 \times 10^{13} \text{ p}_{24\text{GeV}} \text{cm}^{-2}$

$f = 1.8 \times 10^{13} \text{ p}_{24\text{GeV}} \text{cm}^{-2}$

$f = 4.8 \times 10^{13} \text{ p}_{24\text{GeV}} \text{cm}^{-2}$

$f = 15.1 \times 10^{13} \text{ p}_{24\text{GeV}} \text{cm}^{-2}$
Diamond operated at an electric field of $E = 0.36 \text{ V/}\mu\text{m}$

(\textit{electron drift})

- **unirradiated**
- $f = 0.6 \times 10^{13} \text{ p}_{24\text{GeV}}\text{cm}^{-2}$
- $f = 1.2 \times 10^{13} \text{ p}_{24\text{GeV}}\text{cm}^{-2}$
- $f = 1.8 \times 10^{13} \text{ p}_{24\text{GeV}}\text{cm}^{-2}$
- $f = 4.8 \times 10^{13} \text{ p}_{24\text{GeV}}\text{cm}^{-2}$
- $f = 15.1 \times 10^{13} \text{ p}_{24\text{GeV}}\text{cm}^{-2}$
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 $T_{\text{exp.}}$
($E = 0.36 \text{ V/µm}$)
3. Simulation of a diamond detector with SILVACO TCAD
3. Simulation of a damaged diamond detector

*Input parameters – Quasi 3D simulation*

<table>
<thead>
<tr>
<th>Two Dimensional:</th>
<th>Quasi 3D:</th>
<th>Three Dimensional:</th>
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<td>Correct charge density</td>
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<td>or</td>
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<td>Incorrect geometry</td>
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**Simulation of TCT signal:**
- Alpha particle hit on top side
- charge carrier drift through diamond bulk

![Graph](image)
3. Simulation of a damaged diamond detector

*Input parameters – Simulated energy depositions*

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

**Energy deposition of $\alpha$ and $\beta$ particles**

$^{241}\text{Am}$: $\alpha$ particle

$^{90}\text{Sr}$ source: $\beta$ 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

![Graph showing signal vs time with raw result and bandwidth filter comparison]
3. Simulation of a damaged diamond detector

*Input parameters*

**TCT measurement of e/h drift**

Parameterization of charge carrier drift

- Drift velocity calculated via: $v_{e,h} = \frac{d}{t_{\text{FWHM}}}$
  - 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
- $\sigma_h$ of eRC2 is 2x increased compared to $\sigma_e$
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

Radiation damage: $\Phi = 0.9 \times 10^{13}$ n$_{1\text{MeV}}$ cm$^{-2}$
3. Simulation of TCT pulse and comparison to measurement result

Diamond operated at an electric field of $E = 0.36 \text{ V/µm}$

**electron drift**

**hole drift**

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

Radiation damage: $\Phi = 0.9 \times 10^{13} \text{n}_{1\text{MeV}} \text{cm}^{-2}$
3. Effective Defect Model as function of Radiation Damage

- For each radiation step the trap densities $\rho$ 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.
Diamond sensors simulated/operated at an electric field of 1V/µm.

Simulation results fitted to analytical RD42 radiation damage model results in:

\[ k_{\text{eRC}} = 8.9 \times 10^{-19} \text{cm}^2\mu\text{m}^{-1} \text{ vs. } k_{\text{RD42}} = 6.5 \times 10^{-19} \text{cm}^2\mu\text{m}^{-1}. \]
Effective Defect Model: Simulation of different electrical fields at which diamond is operated

Use simulation results to analyze electric field!

Radiation Damage ($\times 10^{15} p_{24\text{GeV}/\text{cm}^2}$)

CCD ($\mu$m)

- 0.18 V/μm
- 0.36 V/μm
- 1.00 V/μm

dashed: Fit of radiation constant $k$
Effective Defect Model: Simulation of different electric fields at which diamond is operated

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

- 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:
  - $^{90}\text{Sr} = 0.15 \text{ GHz/cm}^3$, BCML1 = 2.04 GHz/cm$^3$, BCML2 = 20.4 GHz/cm$^3$
- Equilibrium of stable polarized diamond state depends on particle rate environment.

Simulation Measurement in Run 1

Rate dependency of diamond signal!
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 \(n_{1\text{MeV} \text{ cm}^{-2}}\) by:

\[
\begin{align*}
\rho_{eRC1} \text{ (cm}^{-3}\text{)} &= \Phi \cdot (2.52 \pm 0.13) \times 10^{-2} + (9.40 \pm 1.11) \times 10^{11} \\
\rho_{eRC2} \text{ (cm}^{-3}\text{)} &= \Phi \cdot (2.15 \pm 0.04) \times 10^{-2} + (6.67 \pm 0.38) \times 10^{11}
\end{align*}
\]

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

Measurement idea

Diamond

\[ \vec{E} \]

\[ \alpha \]

Measurement setup

Sr90 source

Bias Tee

HV Amplifier

Scope

Ramos theorem:

\[ i = q \nu E_v \]

with \( i \) as induced current, \( q \) as charge, \( \nu \) 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)

Measurement idea

\[ \vec{E} \]

Measurement setup

Ramos theorem:

\[ i = q \nu E_v \]

with \( i \) as induced current, \( q \) as charge, \( \nu \) 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.
Intermezzo:
TCT measurement, polarization and electric field

TCT MEASUREMENTS WITH DIAMOND SENSORS

H - DRIFT
E - DRIFT
FWHM

CHARGE CARRIER:
- DRIFT VELOCITY
- MOBILITY
- EFF. MASS
MIP signal for diamond operated at an electric field of $E = 0.18$ V/µm for different radiation damages

\[ \phi = 0.0 \times 10^{15} \text{ } p_{24\ GeV/cm^2} \]
\[ \phi = 1.5 \times 10^{15} \text{ } p_{24\ GeV/cm^2} \]
\[ \phi = 5.0 \times 10^{15} \text{ } p_{24\ GeV/cm^2} \]
Effective Defect Model: Space charge for different electric fields

Radiation damage: $\Phi = 1.5 \times 10^{15} \text{ p}_{24\text{GeV}} \text{ cm}^{-2}$
NIEL and DPA model

NIEL model

DPA model