Polarization effects in radiation damaged scCVD Diamond detectors

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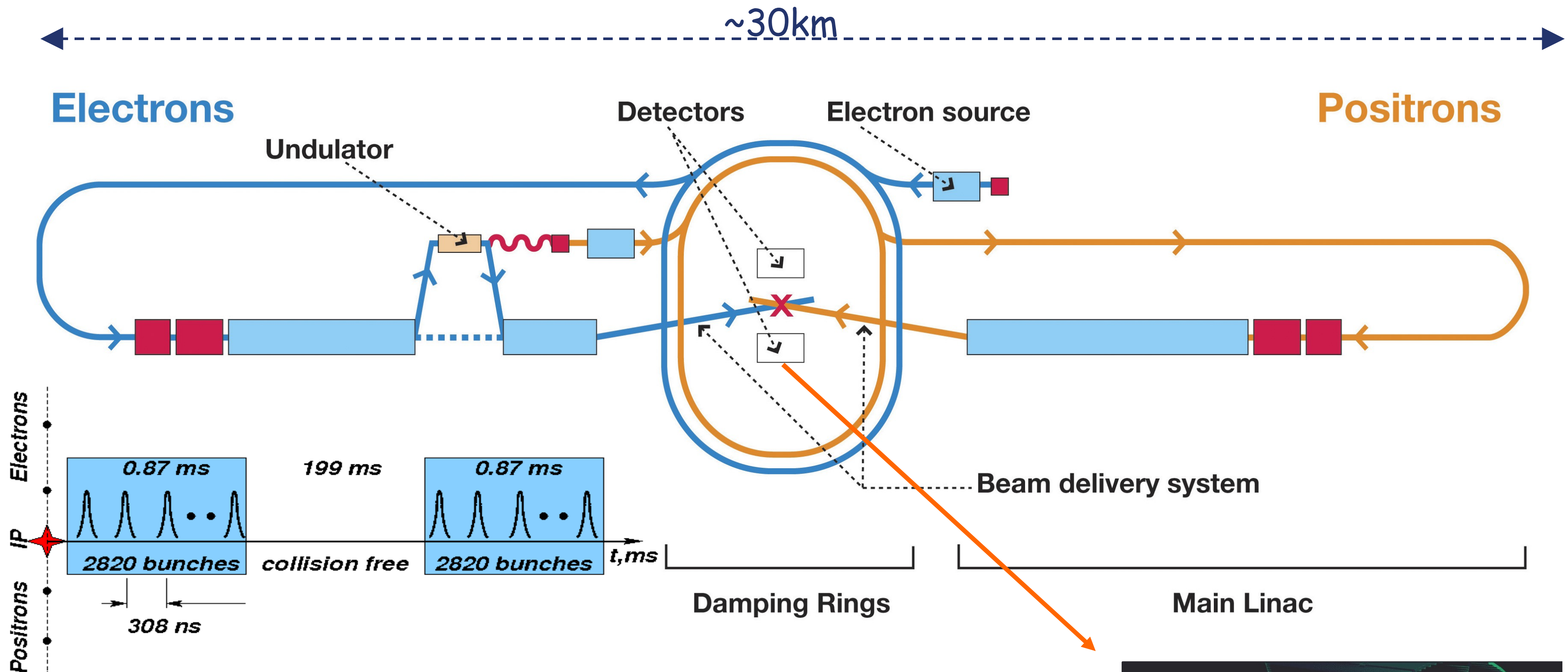
4th NoRHDia Workshop @ GSI

Contents

- Why do we need Diamond Detector @ ILC?
- BeamCal challenge
- Diamond properties
- Charge collection
  - **Ideal crystal, Radiation damaged crystal**
- Polarization creation, model
- Experimental studies:
  - **CCD vs Dose, CCD time dependence**
  - **Future plans**
- Summary

The International Linear Collider



<u>Parameters:</u>

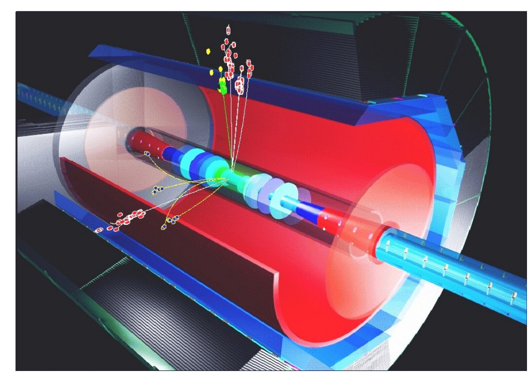
500 GeV (1 TeV upgrade possible)

2×10^{34} cm^{-2}sec^{-1}

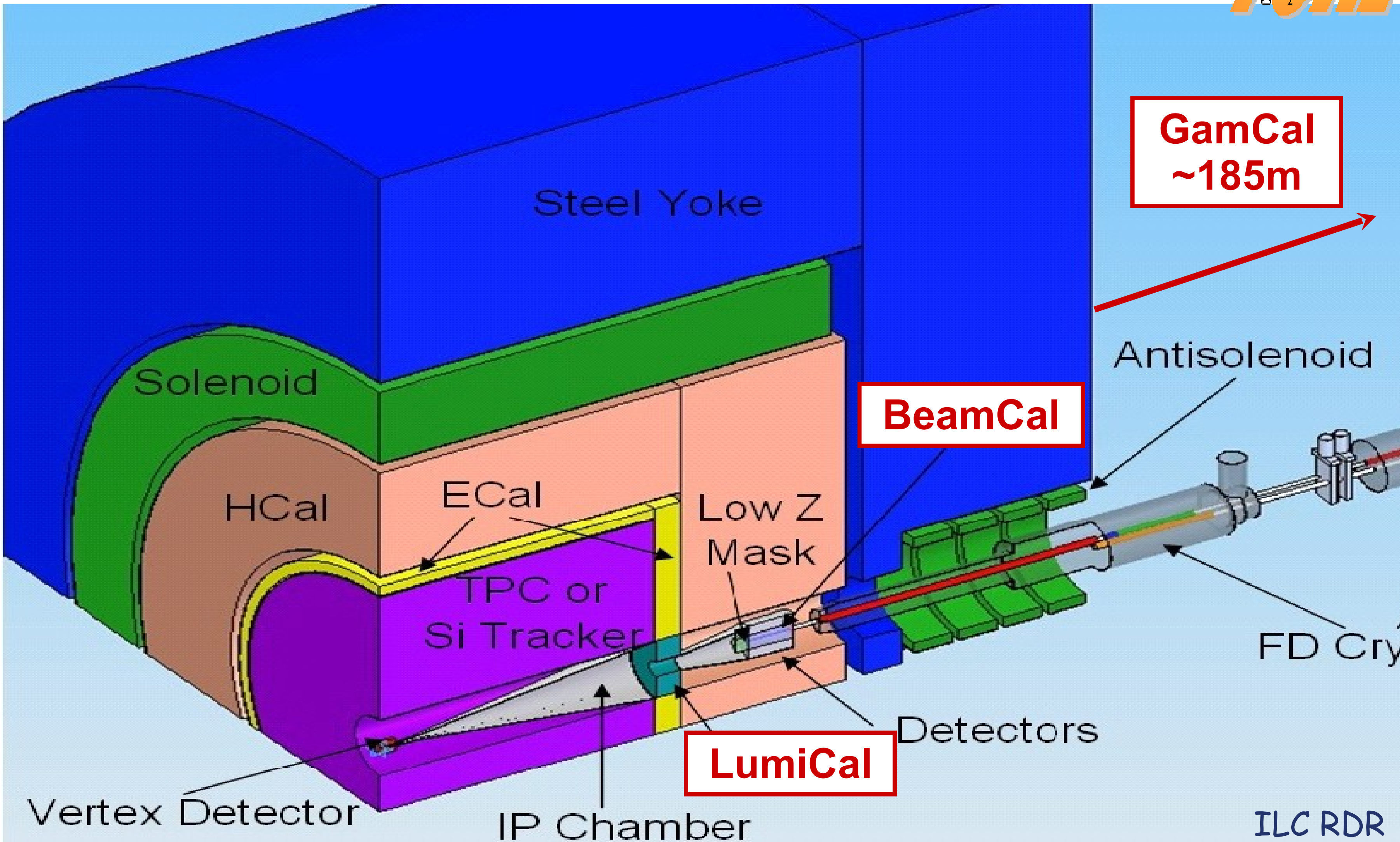
electron polarization ~80 %

positron polarization ~30 % (60 %)

beam sizes: $\sigma_x \approx 600$nm, $\sigma_y \approx 6$nm, $\sigma_z = 300\mu$m

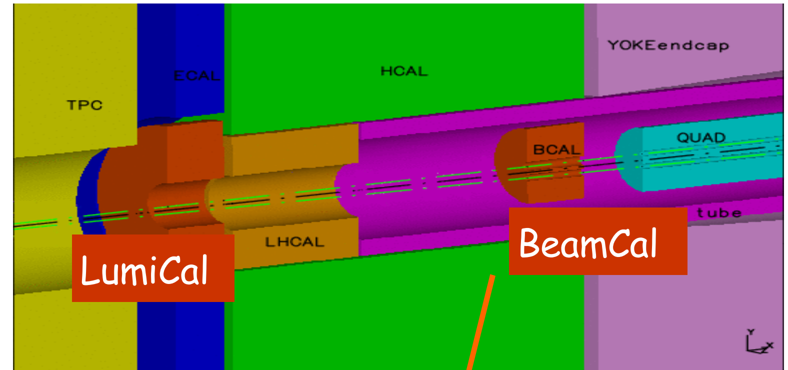


Design of the Forward Region



BeamCal Design

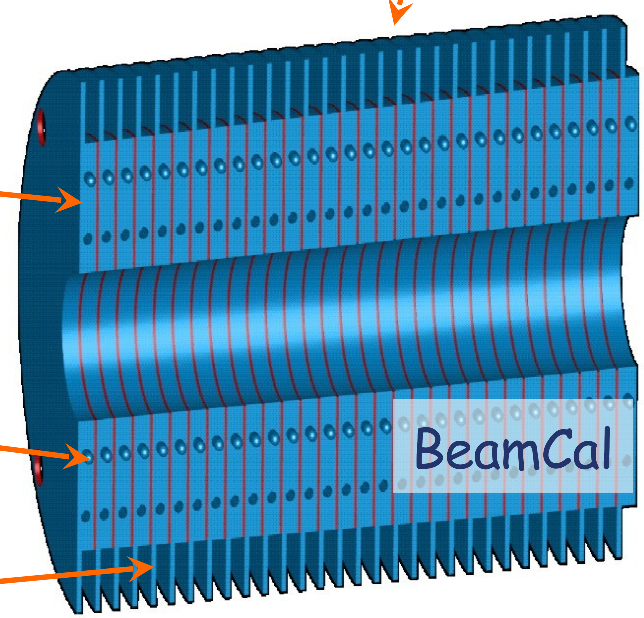
- Compact em calorimeter with sandwich structure:
  - 30 layers of 1 X_0
  - 3.5mm W and 0.3mm sensor
- Angular coverage from ~5mrad to ~45 mrad
- Moliére radius $R_M \approx$ 1cm
- Segmentation between 0.5 and 0.8 x R_M



W absorber layers

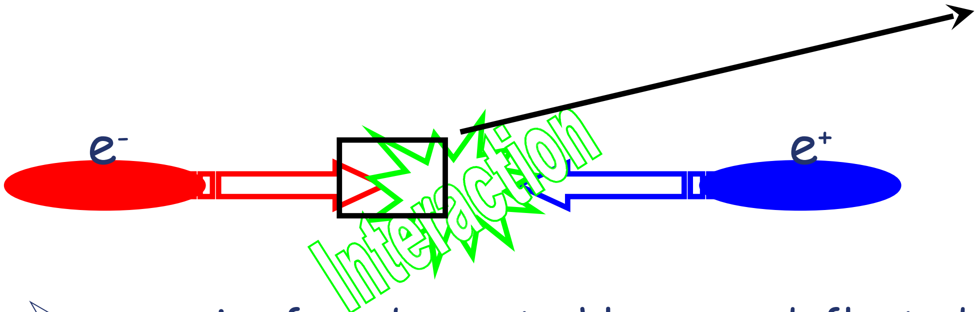
Radiation hard sensors with thin readout planes

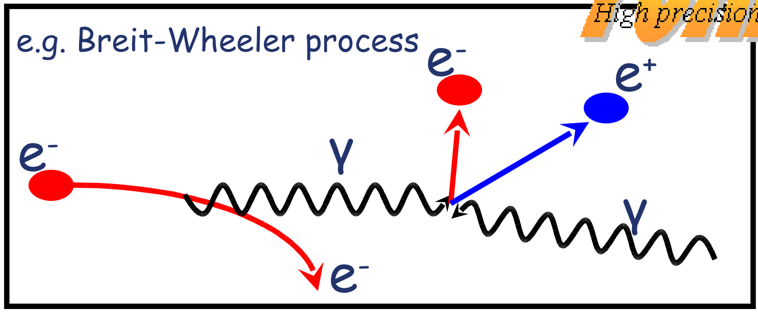
Space for readout electronics



The Challenges for BeamCal

Creation of beamstrahlung at the ILC





- e+e- pairs from beamstrahlung are deflected into the BeamCal
- 15000 e^+e^- per BX

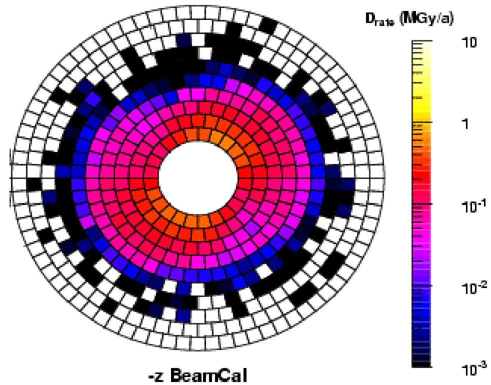
  => 10 – 20 TeV total energy dep.

- **<u>~ 10 MGy per year</u>** strongly dependent on the beam and magnetic field configuration

  => <u>radiation hard sensors</u>

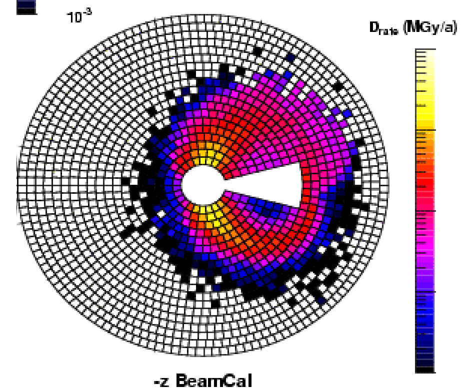
- Detect the signature of single high energetic particles on top of the background.

  => <u>high dynamic range/linearity</u>



≈ 1 MGy/a

≈ 5 MGy/a



Diamond properties

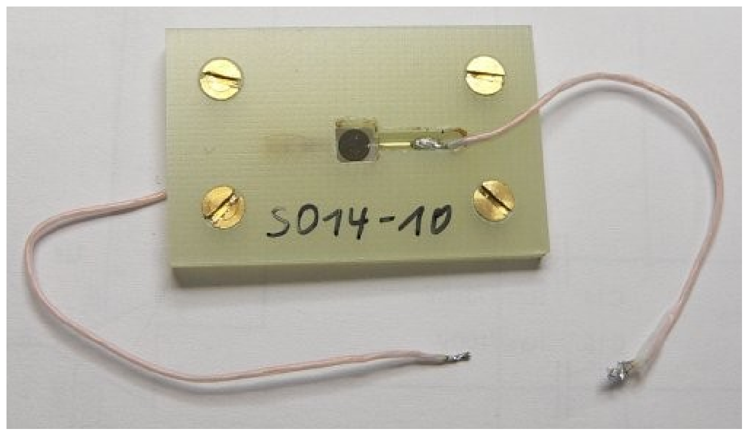
- Density 3.52 g cm^{-3}
- Dielectric constant 5.7
- Breakdown field 10^7 V cm^{-1}
- Resistivity $>10^{11}$ Ω cm
- Band Gap 5.5 eV
- Electron mobility 1800 (4500) cm^2 V^{-1} s^{-1}
- Hole mobility 1200 (3800) cm^2 V^{-1} s^{-1}
- Energy to create e-h pair 13.1 eV
- Average signal created 36 e μm^{-1}

* High-purity single crystal CVD

Sensors

sc CVD diamond from Element 6
(provided by GSI, Darmstadt)

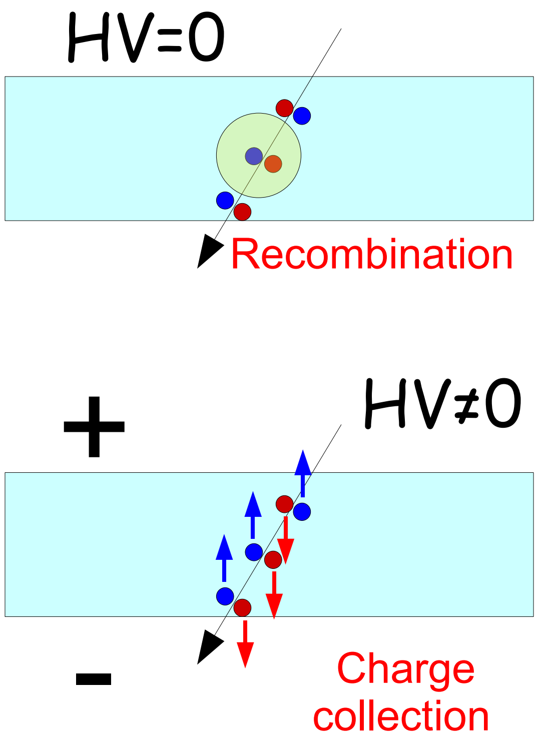
Thickness 326 μm, active area 3mm in diameter

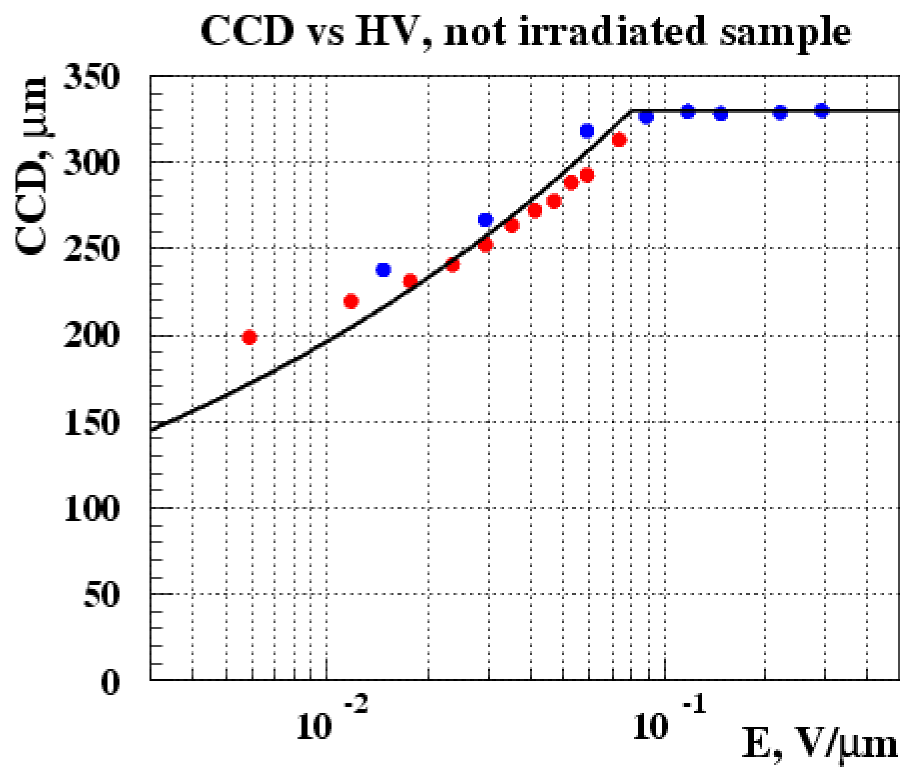


2 sensors, one is irradiated up to 5 MGy dose
at the 10 MeV electron beam in 2007

'Ideal' crystal charge collection

- Charge collection efficiency depends on E

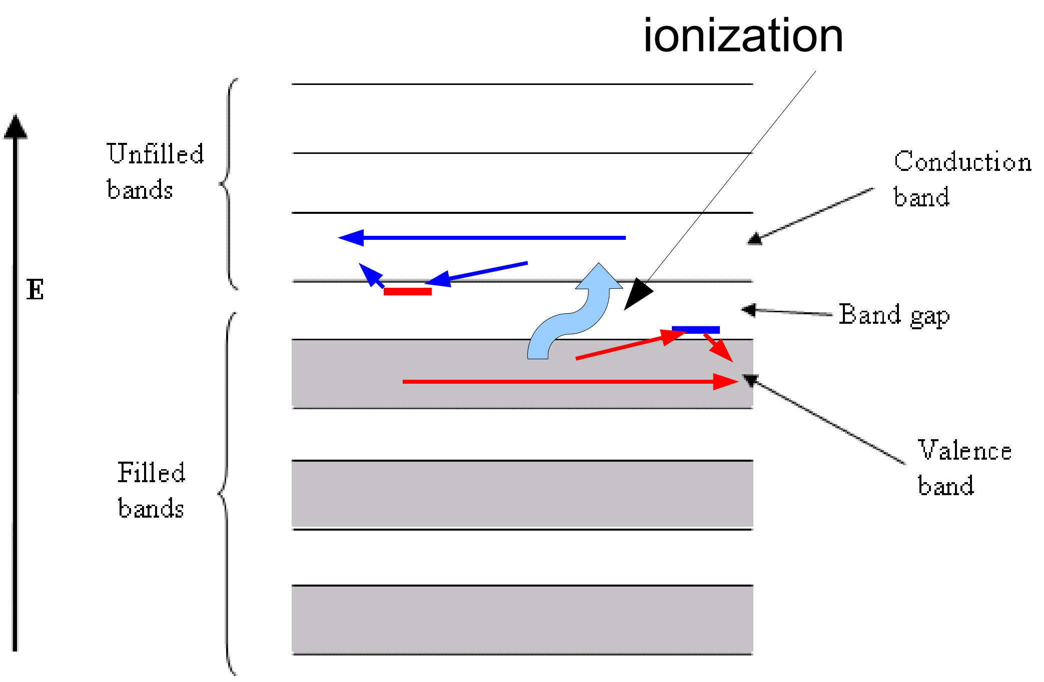




Radiation damaged crystal

- Radiation causes local damages of the lattice structure.
- These local damages (traps) are able to capture free charge carriers and release them after some time

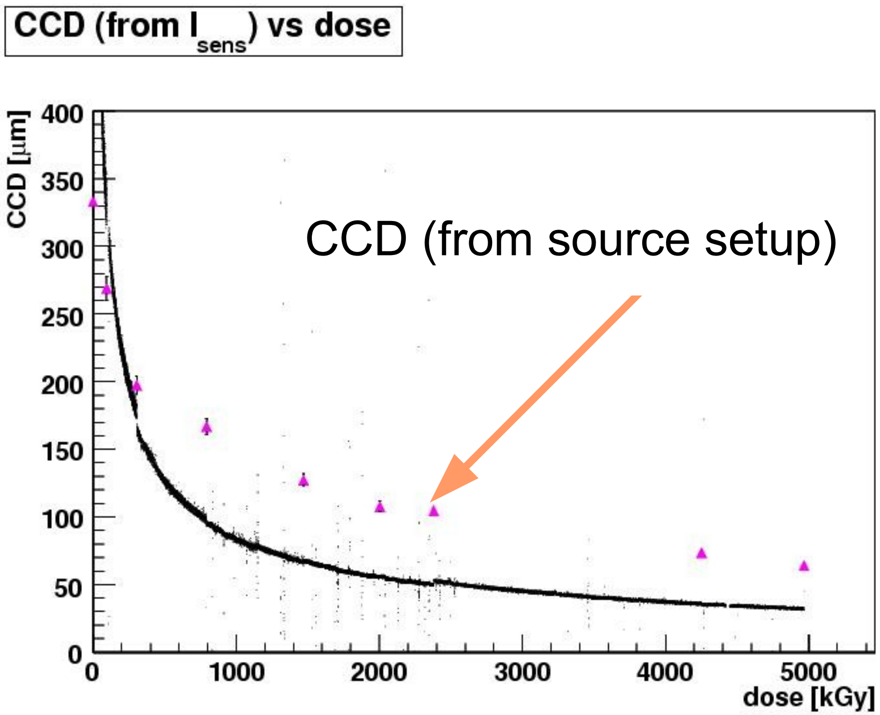
- Assumptions:
- Trap density is uniform (bulk radiation damage)
- Traps are created independently (linearity vs dose)

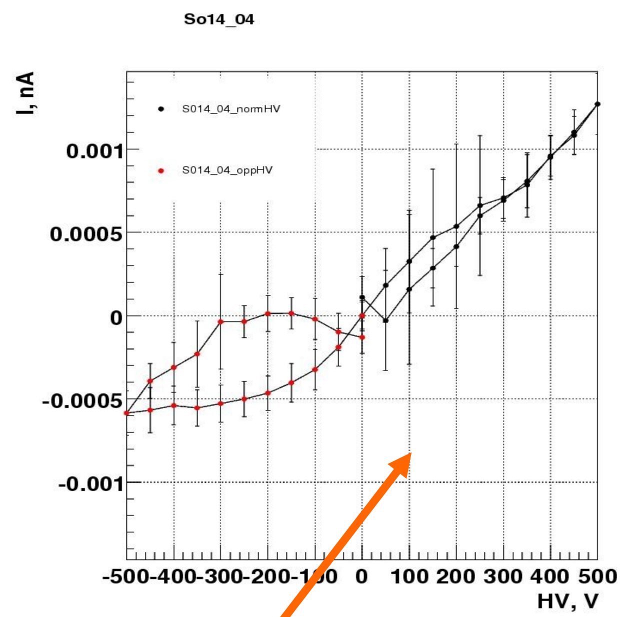


Irradiation of single crystal CVD Diamond

After absorbing 5 MGy:

CVD diamonds still operational.

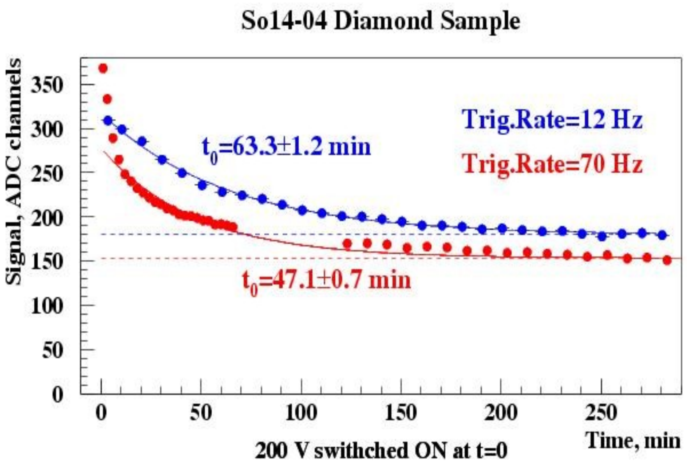


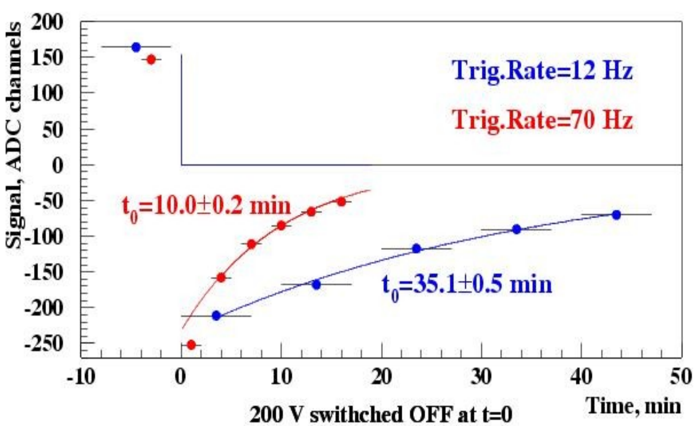


- Very low leakage currents (~pA) after the irradiation.
- Decrease of the charge collection distance with the dose.
- Generation of trapping centers due to irradiation. Traps release?
- Strong polarization effects !!!

Irradiation of single crystal CVD Diamond

After absorbing 5 MGy:





Measurements at ^{90}Sr-source setup:

After switching HV on signal drops with time

Switching HV off after signal stabilization: strong signal of opposite polarity is observed

Signal time behavior depends on the MIPs rate

Dynamic polarization !

Model of sCVD Diamond Polarization

Polarization Model

Radiation damage – uniformly produced traps

MIP signal – uniformly produced e–h pairs

+Electric field → *NONUNIFORM space charge*

↓

Change of the electric field

e–h Recombination if the field is low

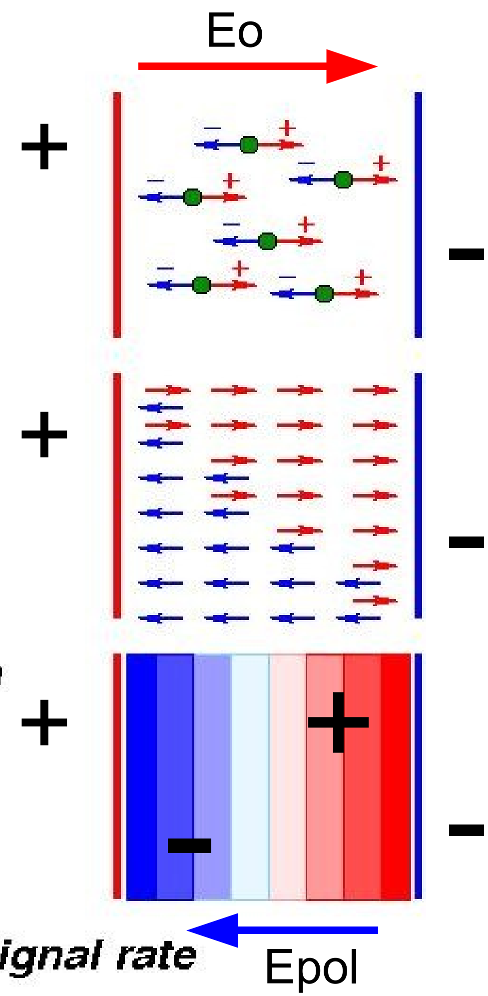
Release of trapped charges (decay time)

Change of the space charge distribution

↓

Steady state POLARIZATION

Dependent on trap density, applied voltage and signal rate



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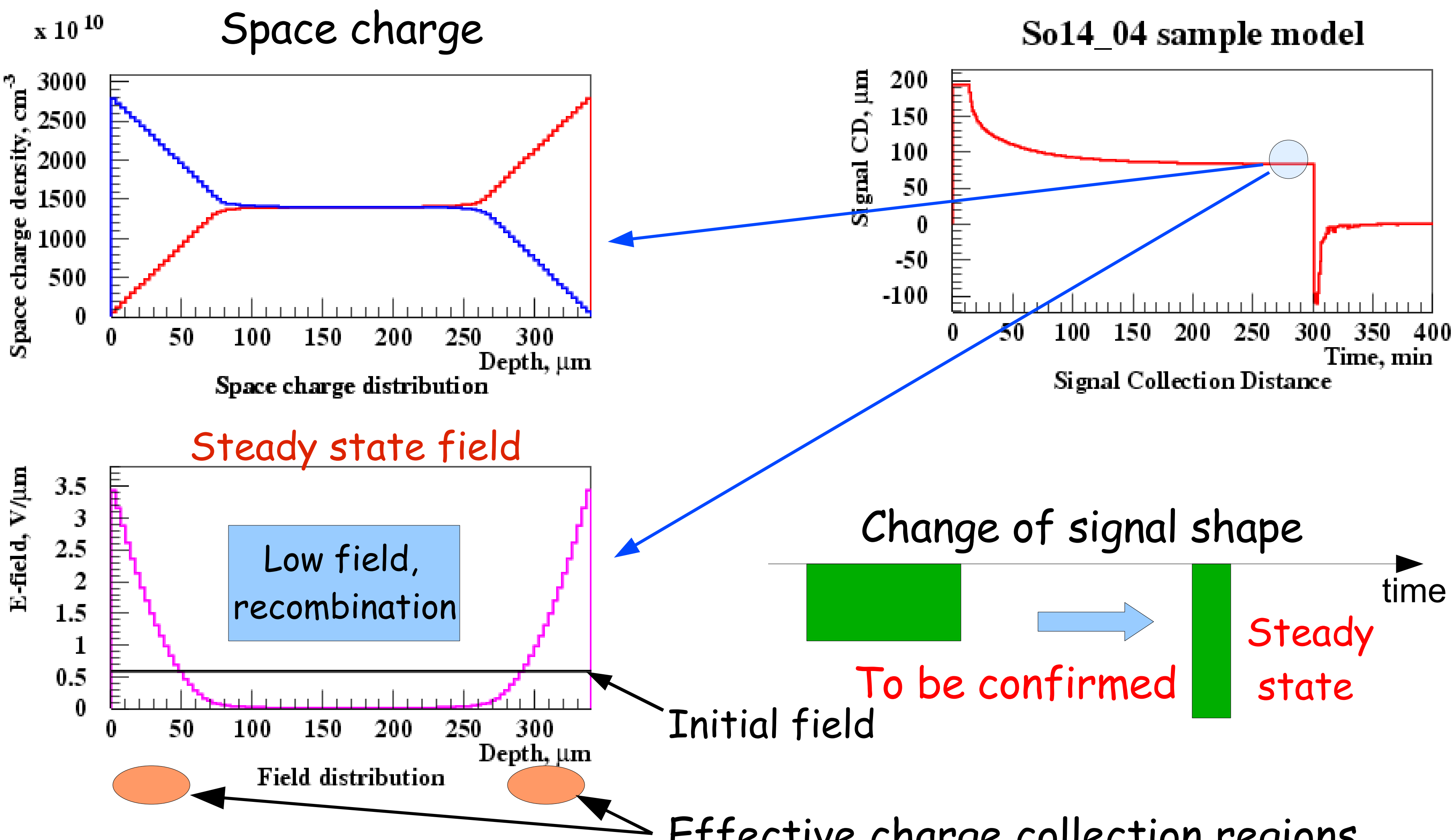
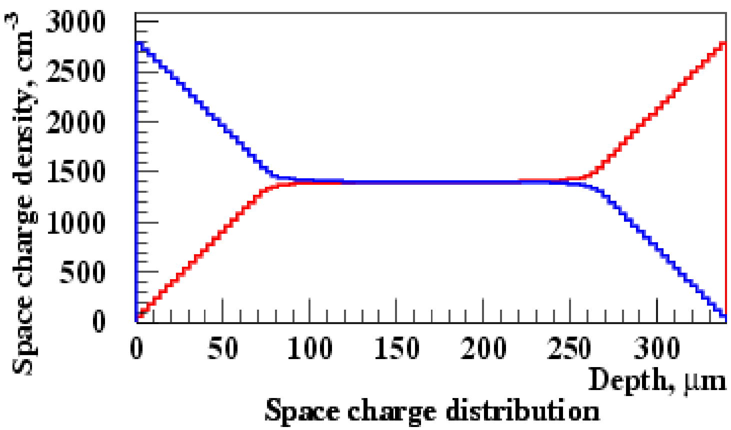
Model of sCVD Diamond Polarization - 1



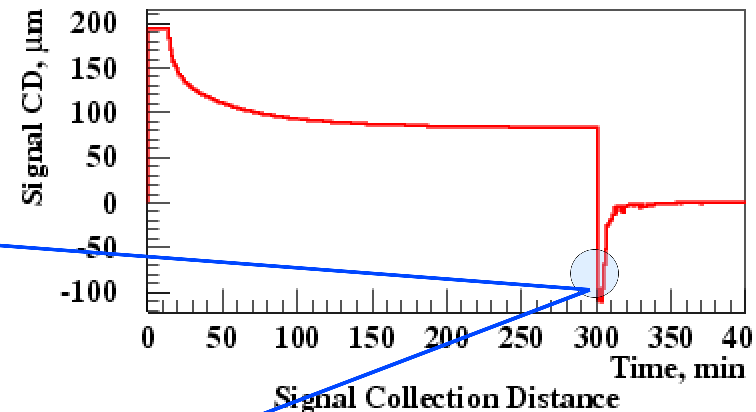
Model of sCVD Diamond Polarization - 2

HV -> 0 !

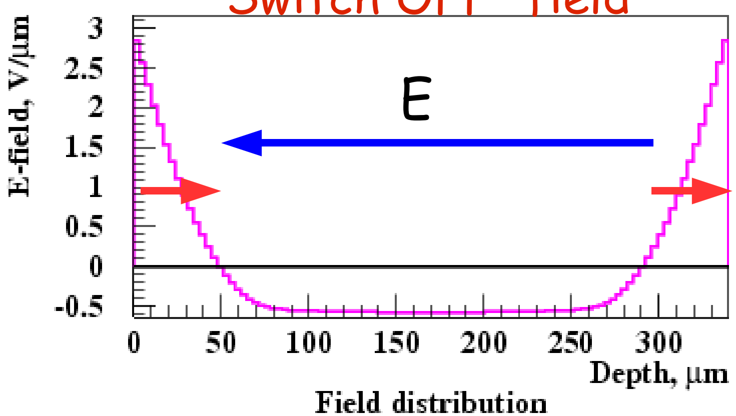
Space charge

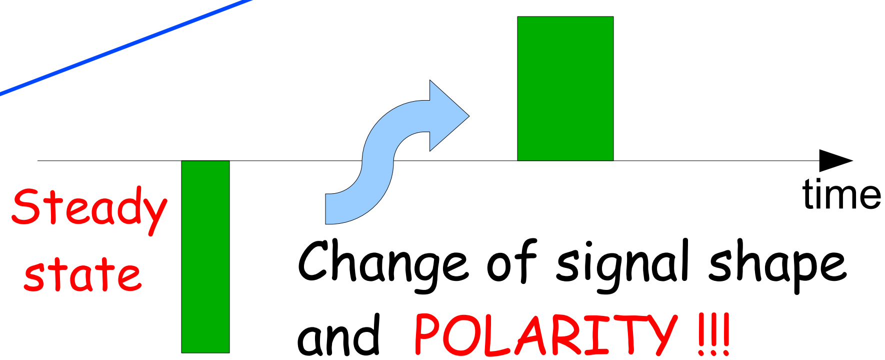


So14_04 sample model



'Switch OFF' field



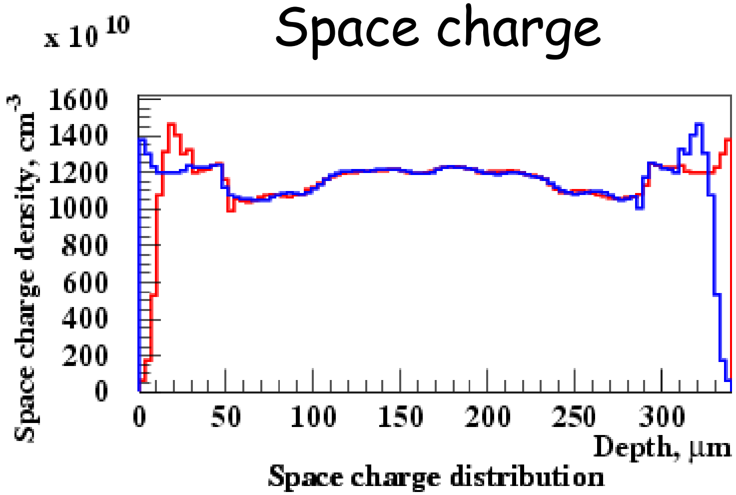


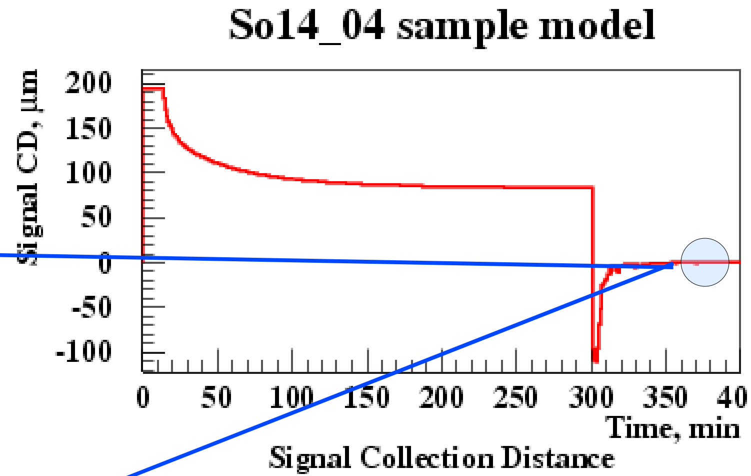
Change of signal shape and POLARITY !!!

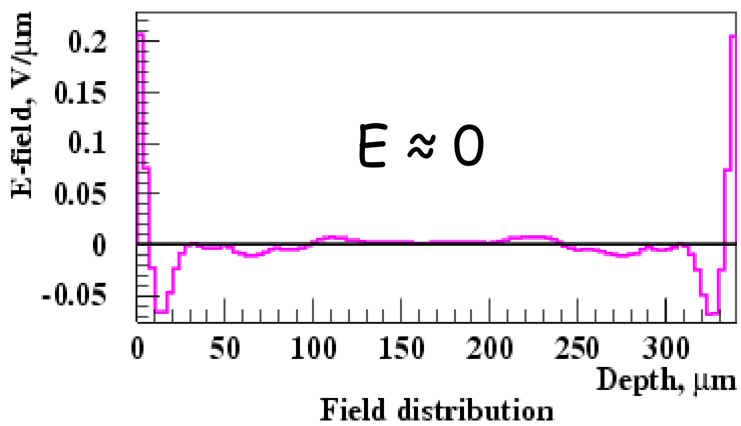
Model of sCVD Diamond Polarization - 3

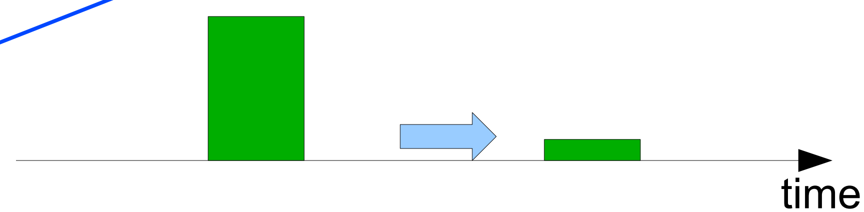
HV = 0

Space charge









Change of signal size

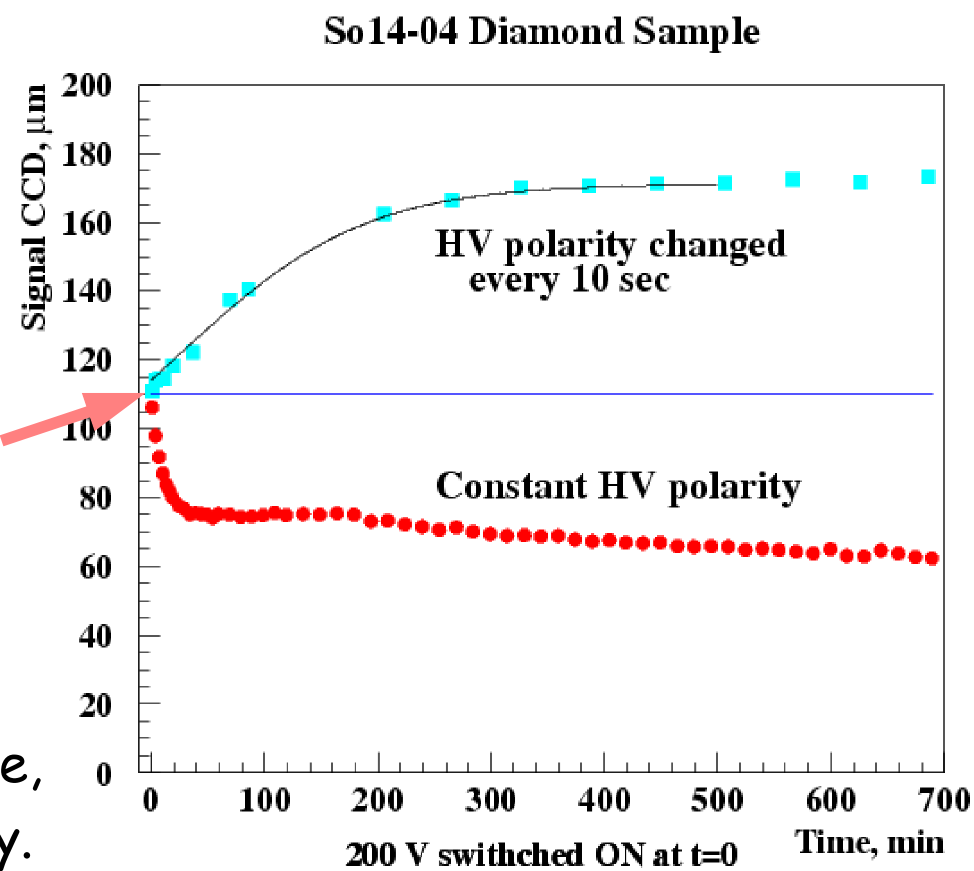
^{90}Sr setup: CCD time dependence

- Diamond sCVD sensor after 5 MGy

$$CCE_0 = \frac{2}{aD} \cdot \left(1 - \frac{1-\exp(-aD)}{aD}\right)$$

$$a = \frac{\pi R^2_{trap}}{l_0} \cdot \frac{n_{free}}{N}$$

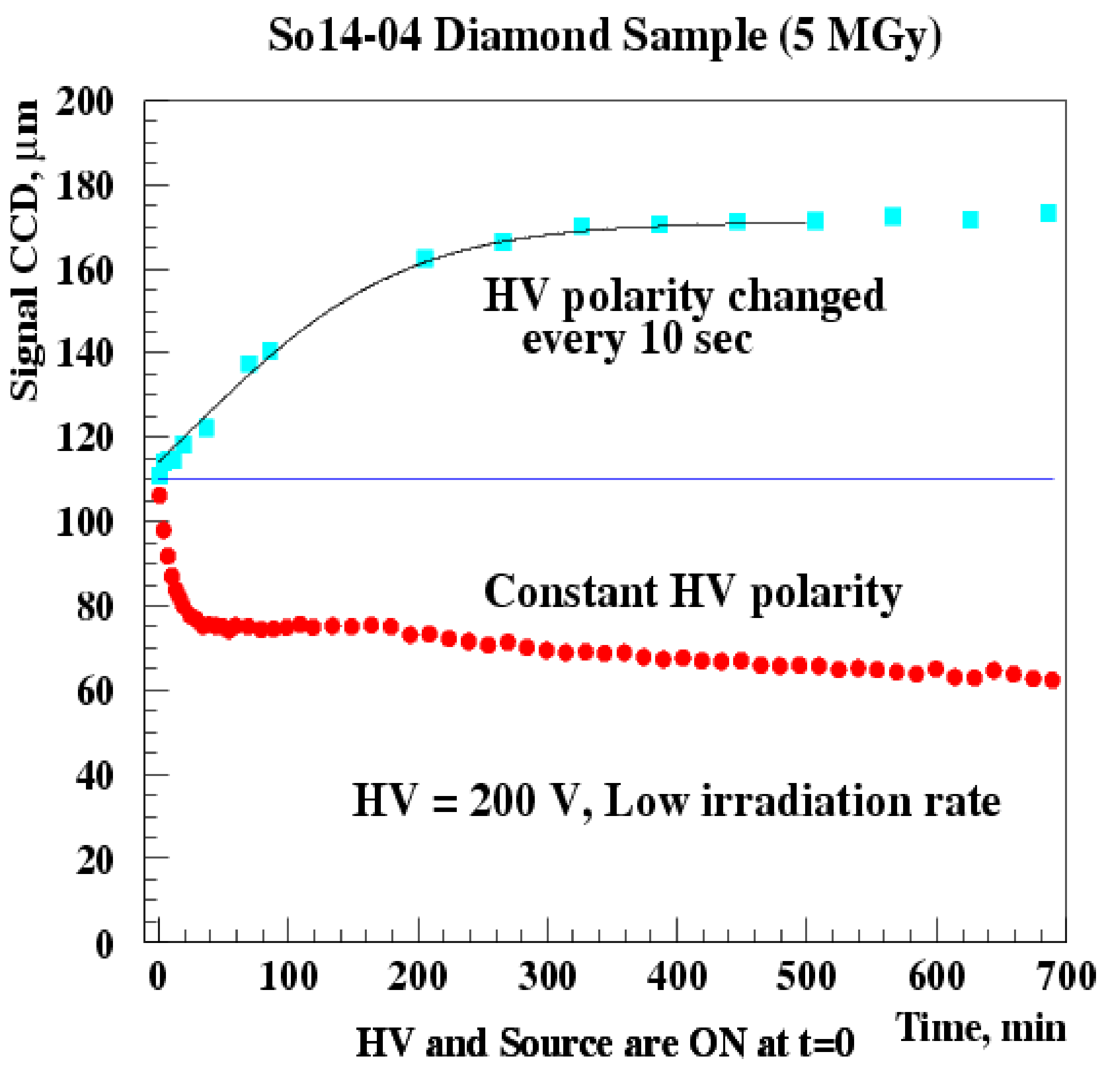
CCD at t=0 allows to extract $n_{trap} R^2_{trap}$ value



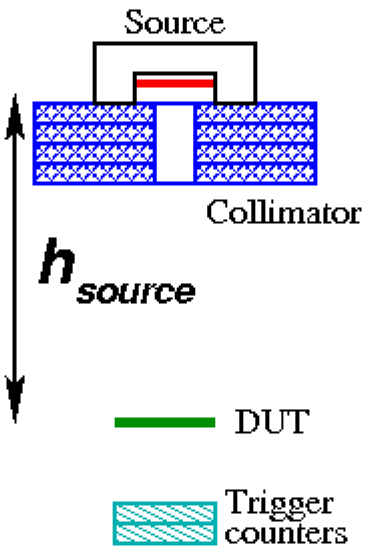
Steady state CCD is sensitive to n_{trap}, T_0 and signal rate

Curve shape depends on the rate, trap properties and trap density.

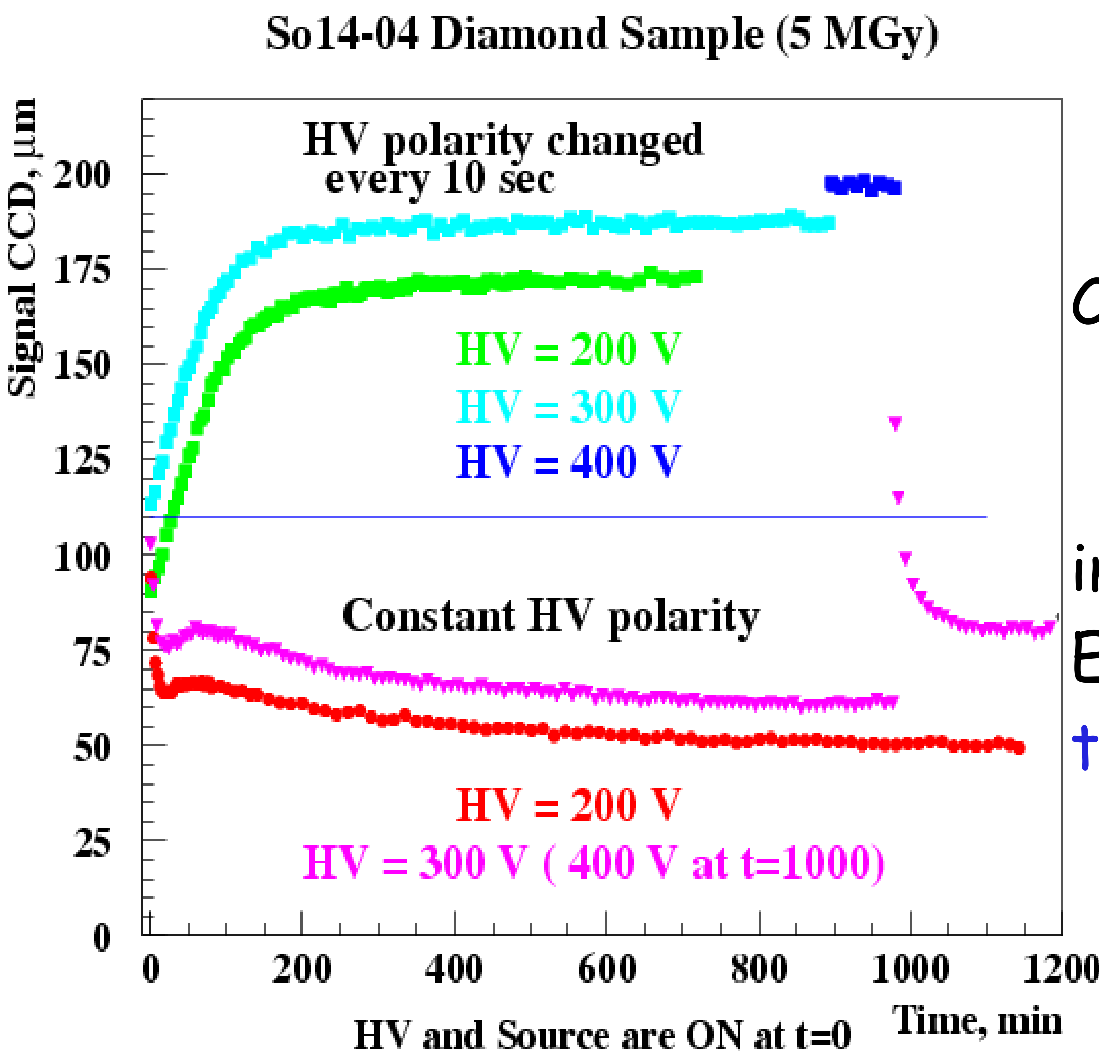
CCD vs time dependence, low rate



Trigger rate about 12 Hz, old trigger counters, h_{Source} ~ 36 mm



CCD vs time, different HV

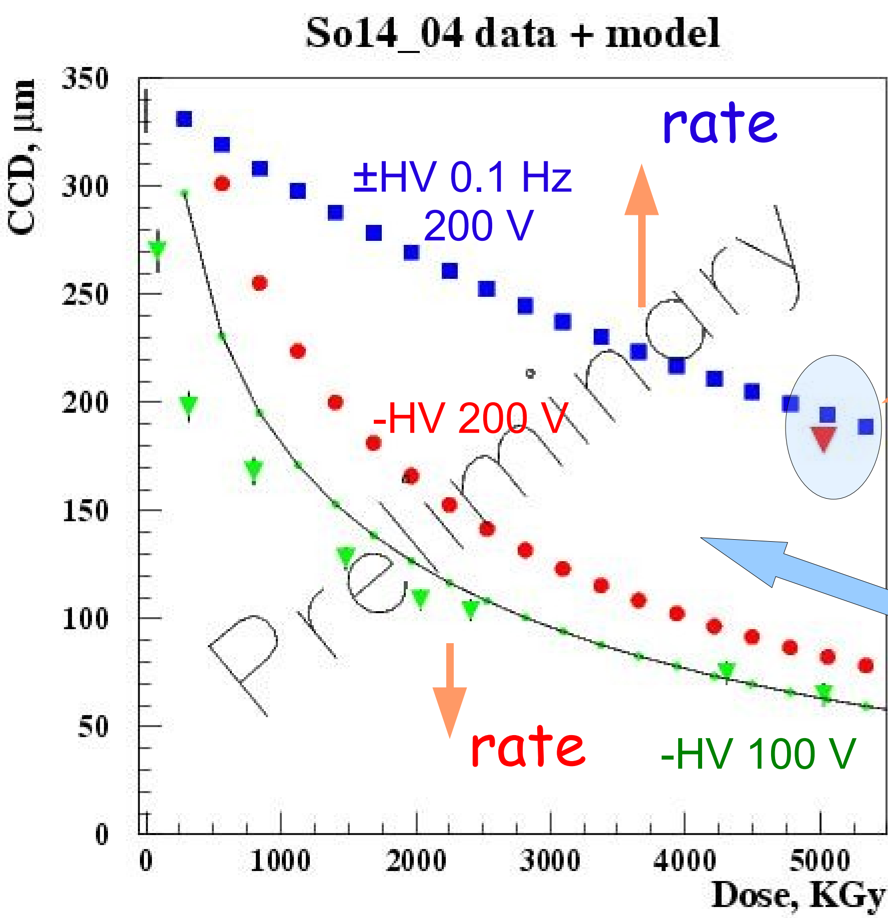


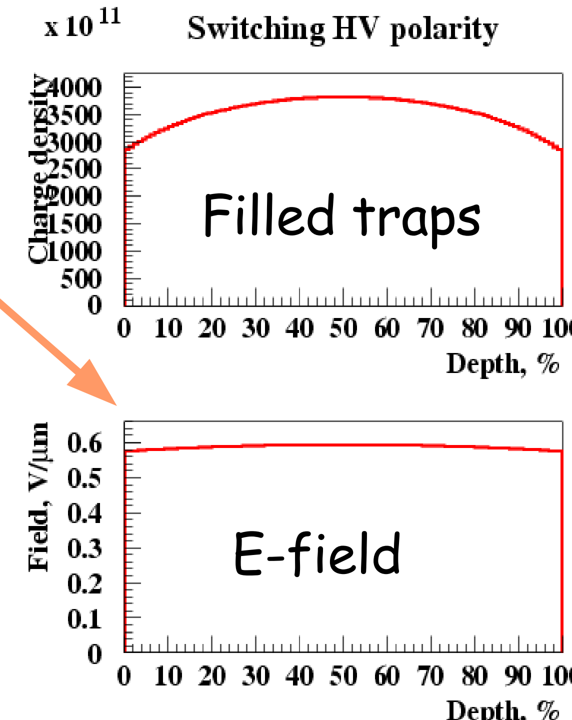
"High rate" data

CCD dependence on HV in case of switching polarity is NOT yet in the model. What is E-field dependent: trap release time, capture probability?

Irradiated single crystal CVD Diamond

Regular change of HV polarity to avoid polarization: almost uniform E-field





cross-check

$n_{ntraps} = k\ Dose + n_0$?

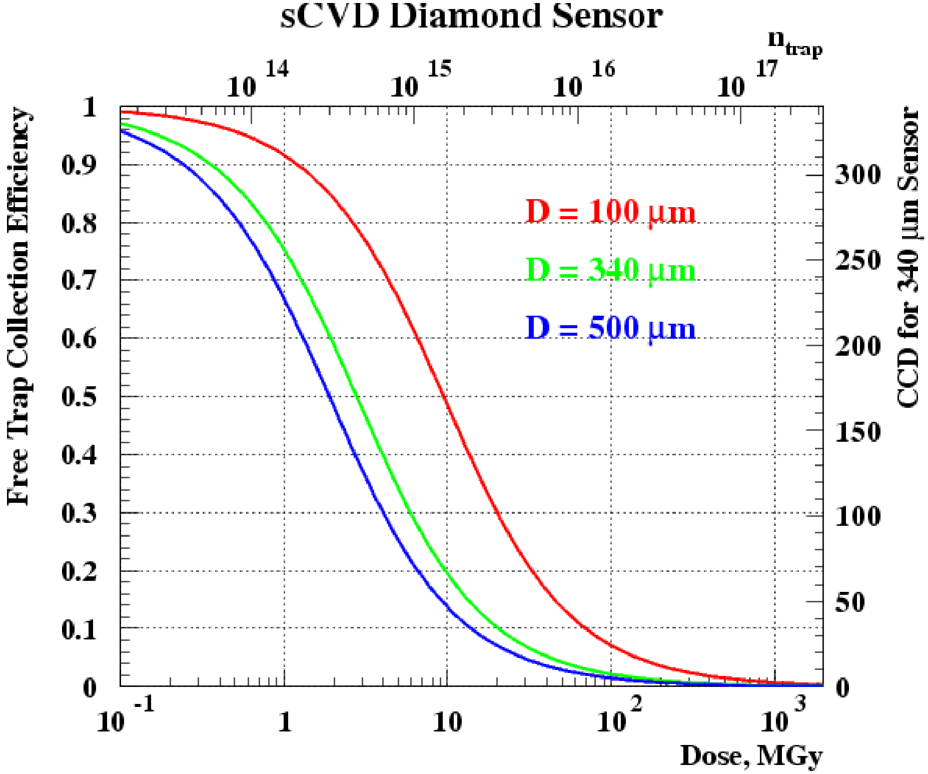
More experimental studies needed

Uniformly distributed free traps

Charge absorption probability for the thin layer:

$$P_l = 1 - \exp\left(-\pi R_{trap}^2 \cdot \frac{l}{l_0} \cdot \frac{n_{free}}{N}\right) = 1 - e^{-al}$$

$$a = \frac{\pi R_{trap}^2}{l_0} \cdot \frac{n_{free}}{N}$$



In case when free traps are uniformly distributed:

Charge collection efficiency could be calculated analytically. For the detector of thickness D:

$$CCE_0 = \frac{2}{aD} \cdot \left(1 - \frac{1 - \exp(-aD)}{aD}\right)$$

Summary

- Strong polarization effect is observed in the radiation damaged scCVD Diamond detector.
- It was shown that the polarization significantly decreases the detector charge collection efficiency.
- A simple model is developed in order to understand and describe observed phenomena.
- Method of routinely switching HV polarity is proposed to suppress polarization. Large improvement of CCE is observed experimentally.
- More work is needed to understand CCD dependence on the signal rate and details of polarization development.
- It is desirable to continue test beam studies up to higher doses (approx 50 MGy) and measure sensor CCD @ ILC-like conditions.

Thank you...

Special thanks to GSI team:

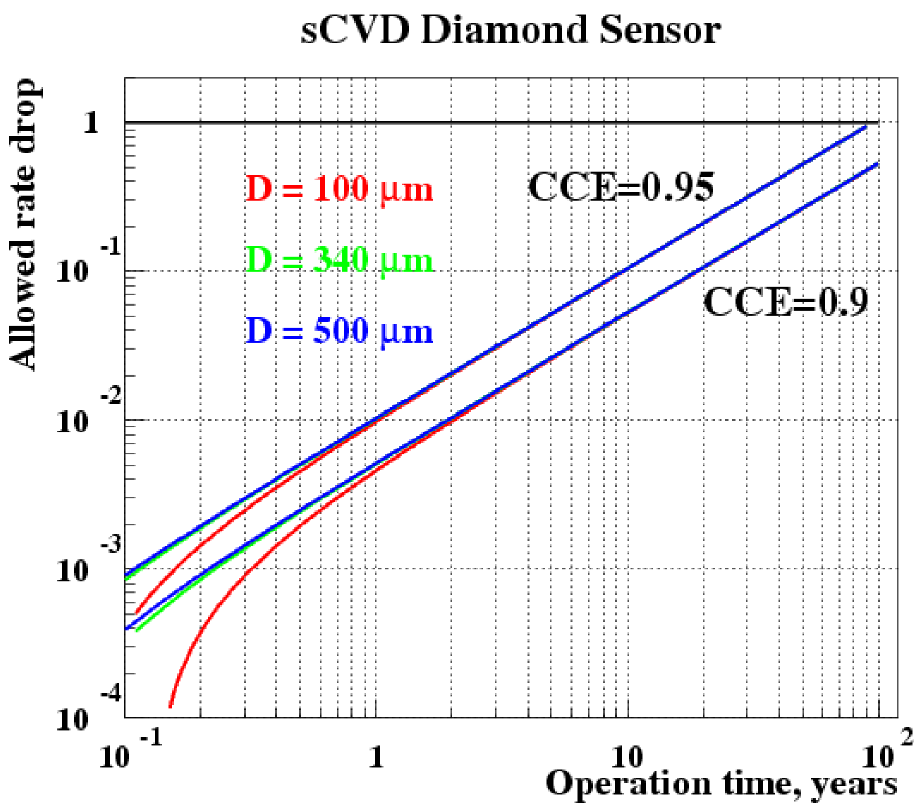
CVDD sensors, test beam etc.

Uniformly (partly) filled traps

Allowed reduction of the flux keeping ε efficiency:

$$r = \frac{\Phi_\epsilon}{\Phi_{nom}} = \frac{1}{R^q_{nom}} \cdot \frac{Q}{T_0 \cdot Q_{absorb}} \cdot \left(t - \frac{n^\epsilon_{free}}{R_{trap}} \right)$$

; t – detector operation time



Alternating HV polarity +
+ stable particle flux =
= XXL radiation hardness

Charge collection efficiency could be kept at high level for a very long time if particle flux is maintained stable.

Leakage current ???
Crystal destruction ???