Recent studies of Diamond detectors radiation hardness

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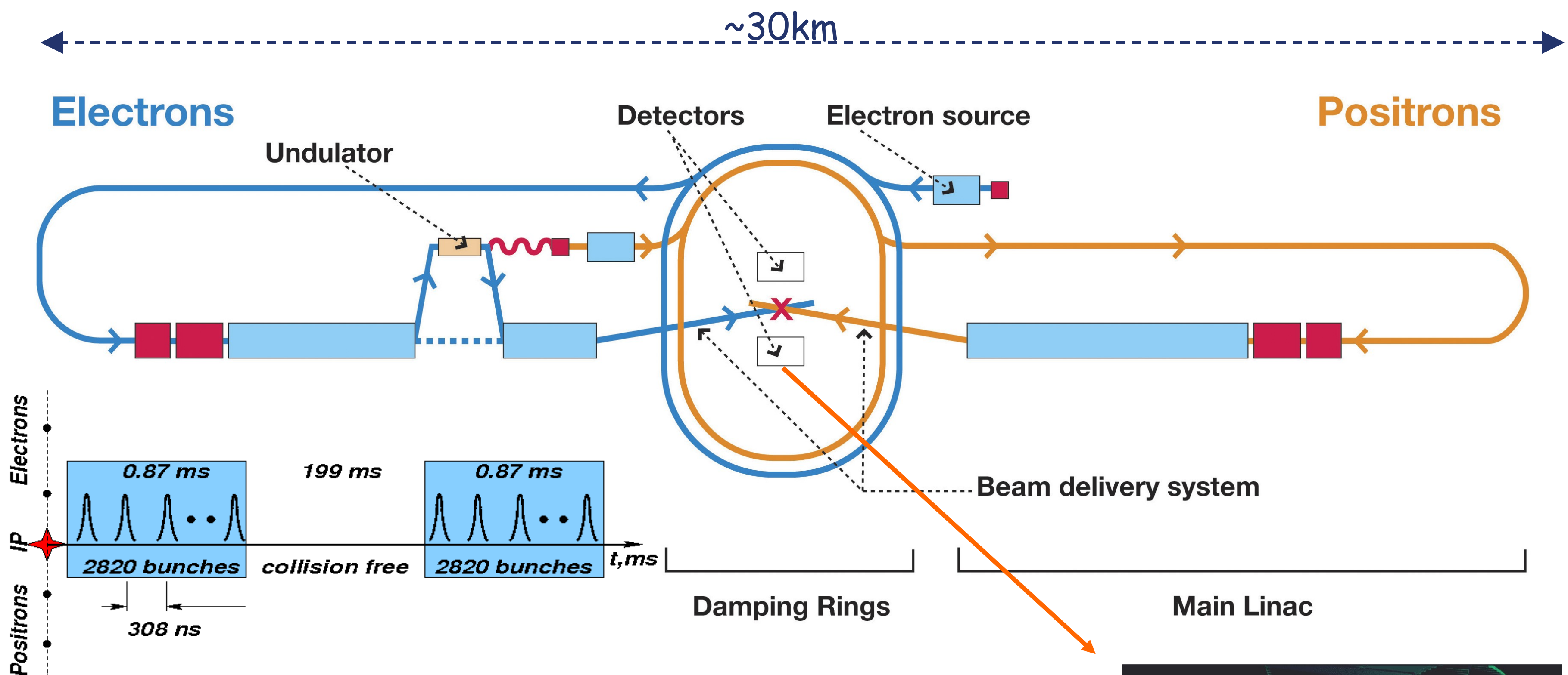
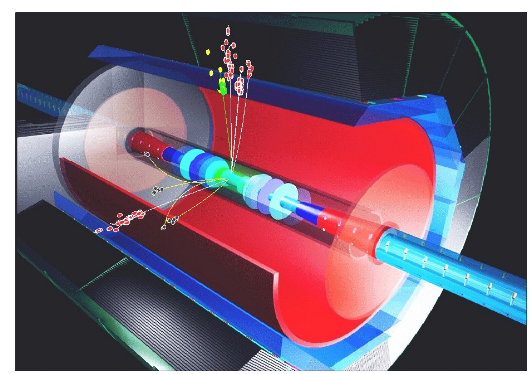
Hamburg University seminar

Outline

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

The International Linear Collider





Parameters:

500 GeV (1 TeV upgrade possible)

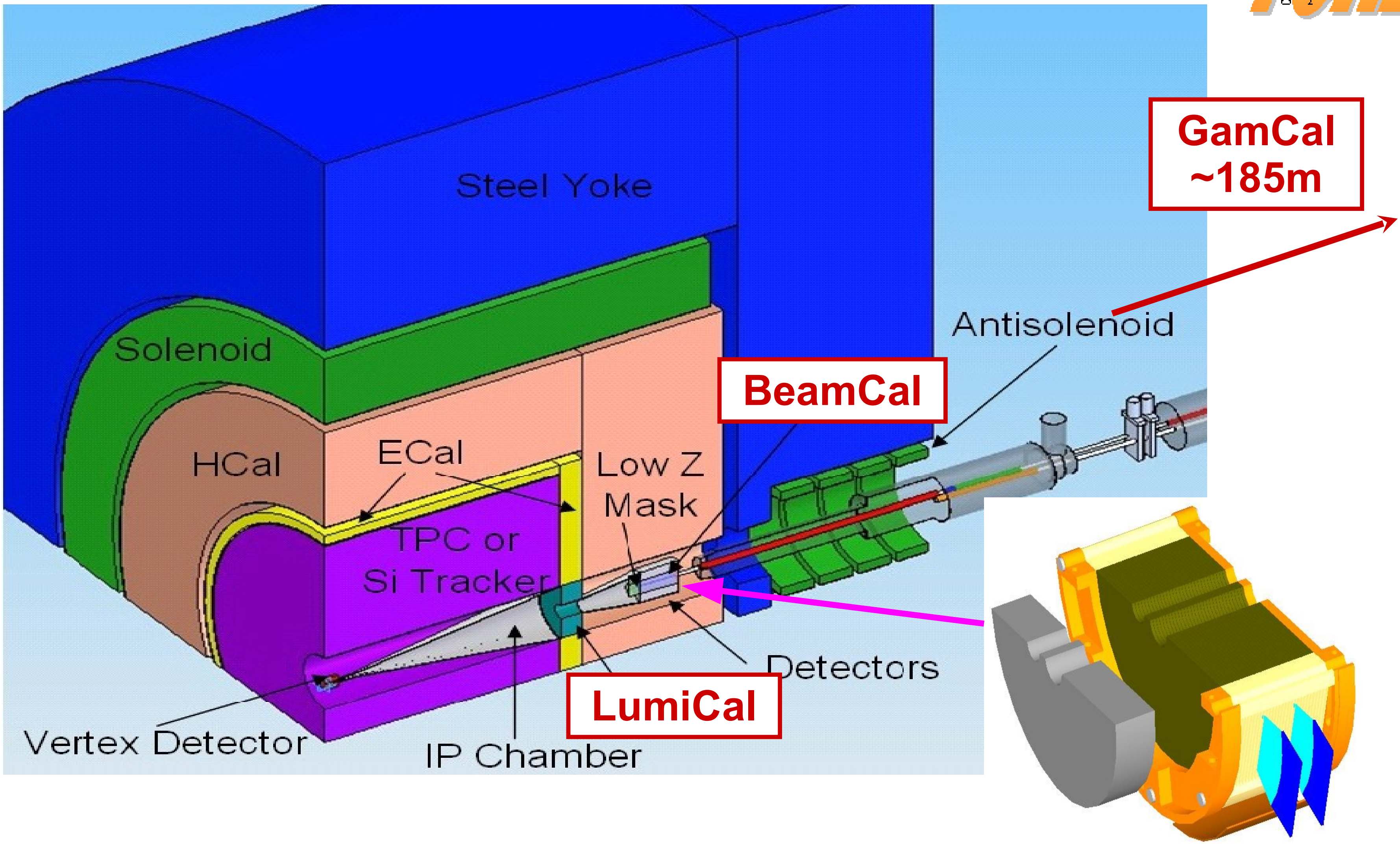
2×10^{34} $cm^{-2}sec^{-1}$

electron polarization ~80 %

positron polarization ~30 % (60 %)

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

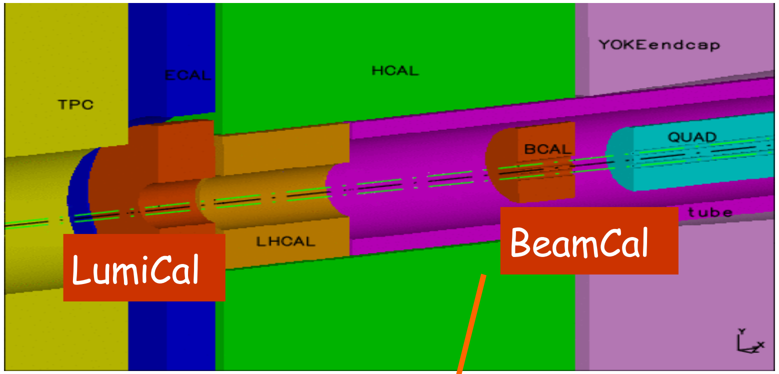
Design of the Forward Region

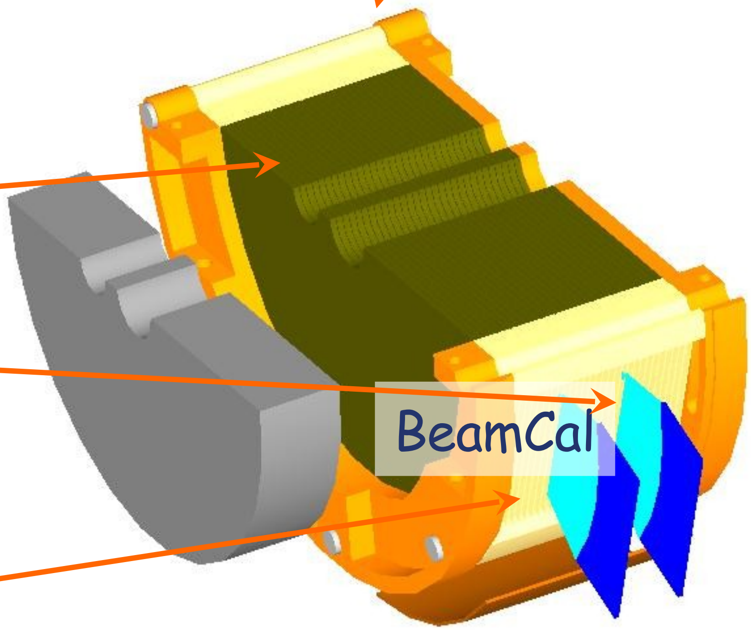


BeamCal Design

- 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 $R_M \approx 1$cm
- Segmentation between 0.5 and 0.8 x R_M





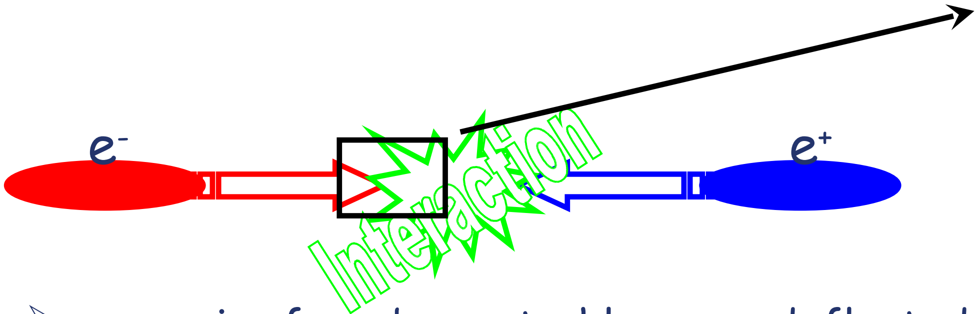
W absorber layers

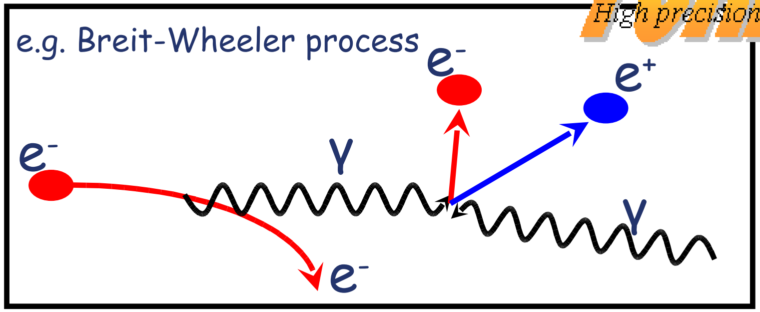
Radiation hard sensors with thin readout planes

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.

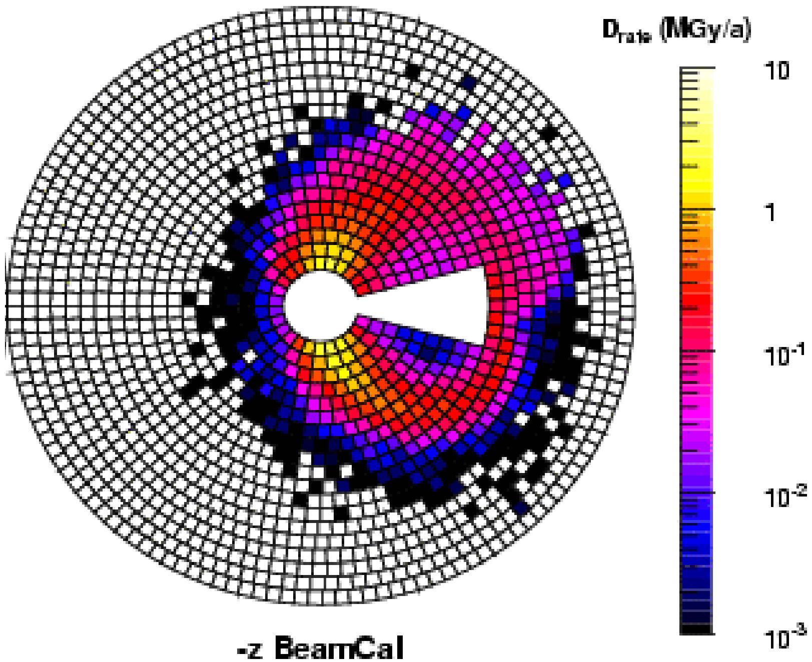
- **~ 10 MGy per year** strongly dependent on the beam and magnetic field configuration

  => radiation hard sensors

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

  => high dynamic range/linearity

Up to 10 MGy/a



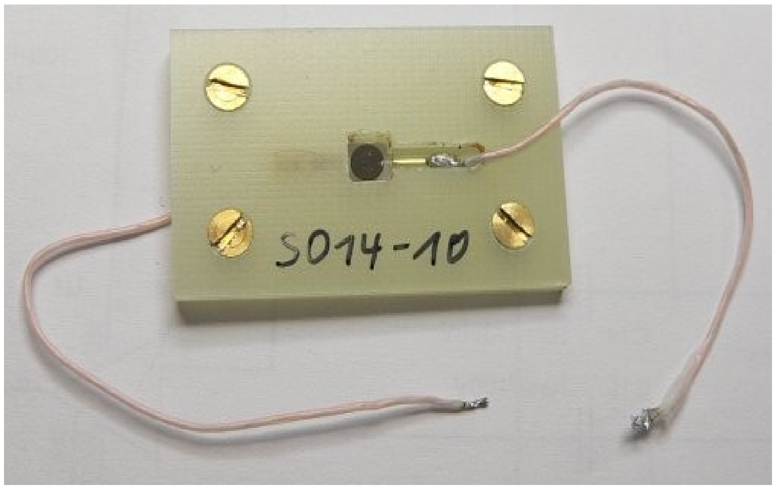
Diamond properties

- 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



Charge collection efficiency:

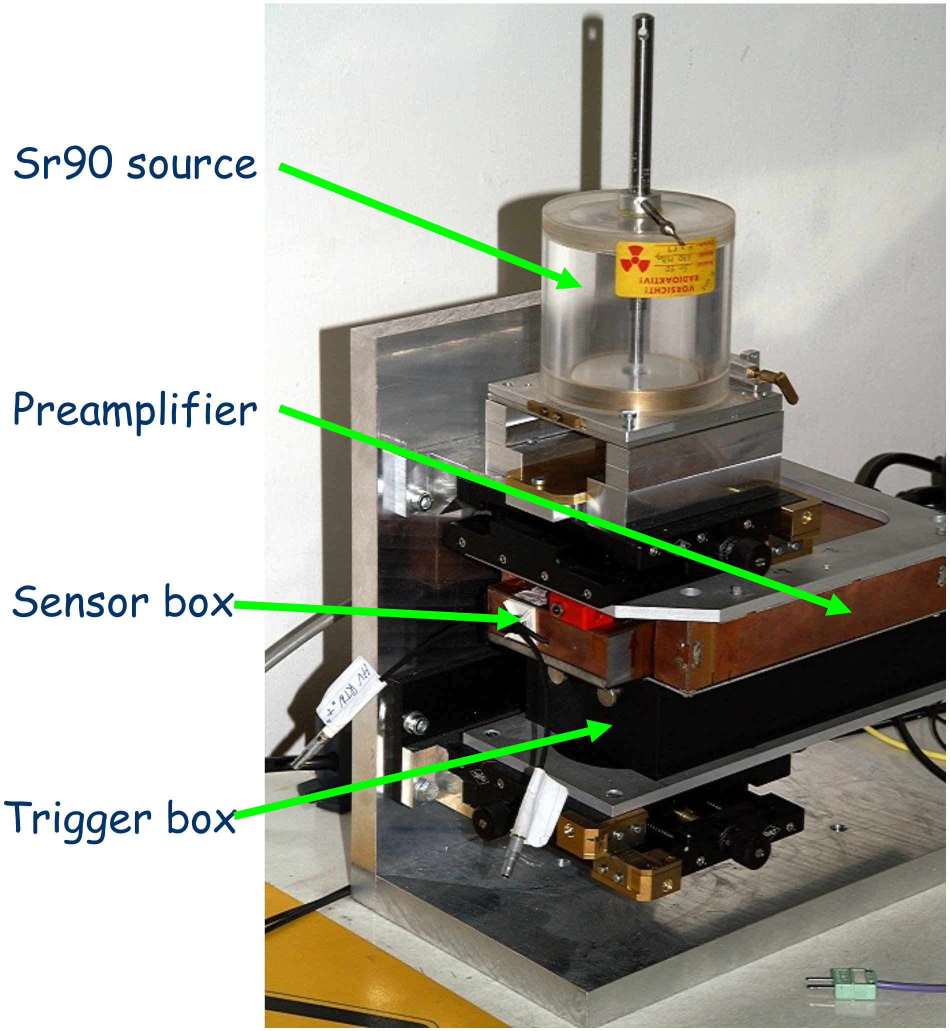
$$CCE = \frac{Q_{collected}}{Q_{induced}}$$

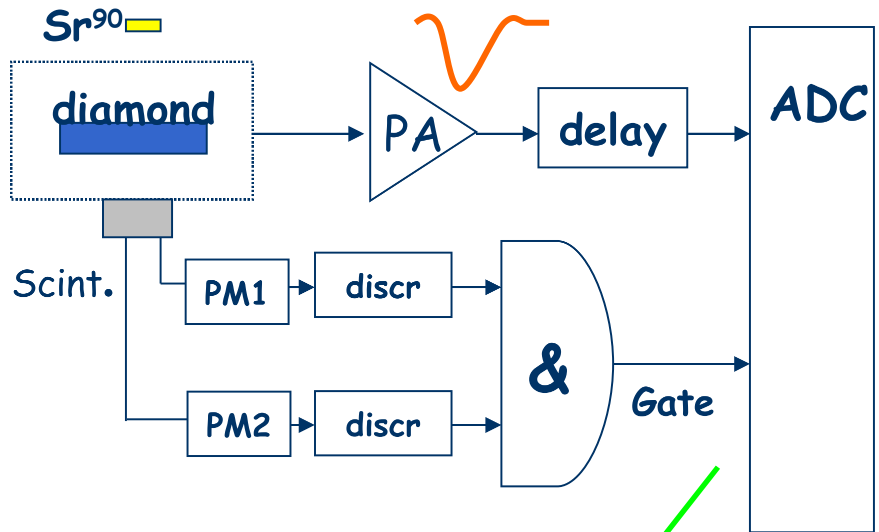
Charge collection distance:

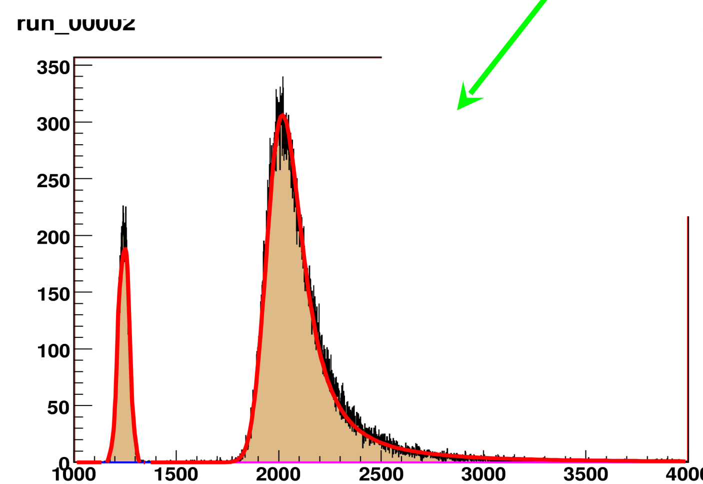
$$CCD = d \cdot \frac{Q_{collected}}{Q_{induced}}$$

2 sensors, one is irradiated up to 5 MGy dose at the 10 MeV electron beam in 2007 and then up to 10 MGy in Dec 2008

MIP Response of scCVD Diamond



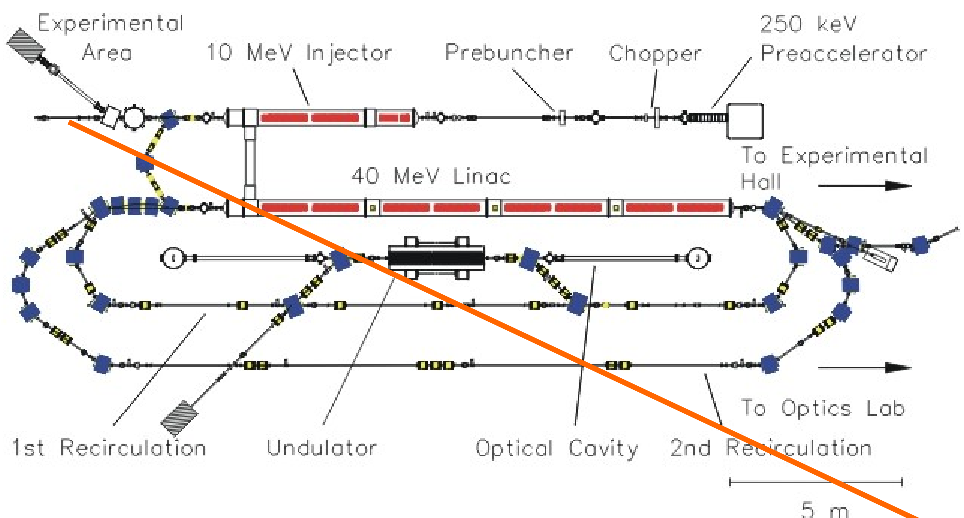


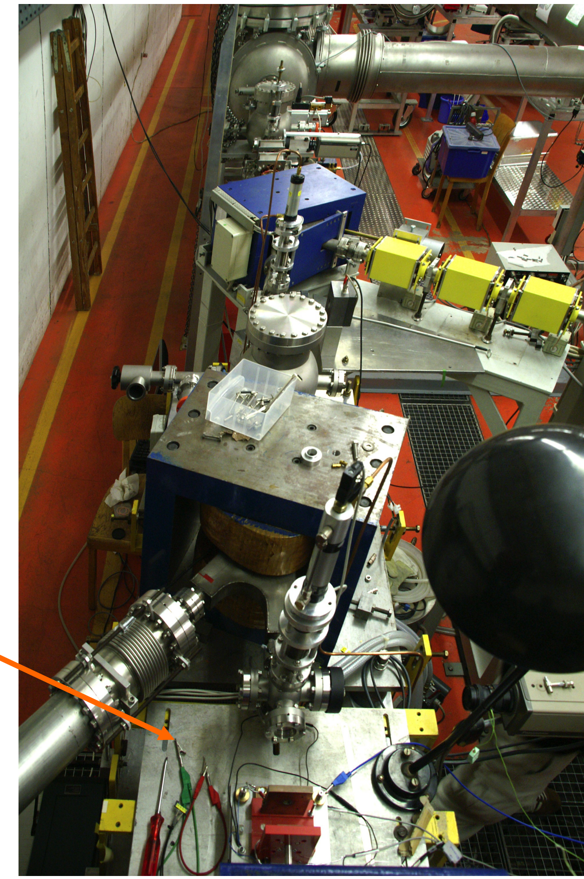


High statistics Diamond spectrum

High Dose Irradiation

Superconducting DArmstadt LINear ACcelerator
Technical University of Darmstadt

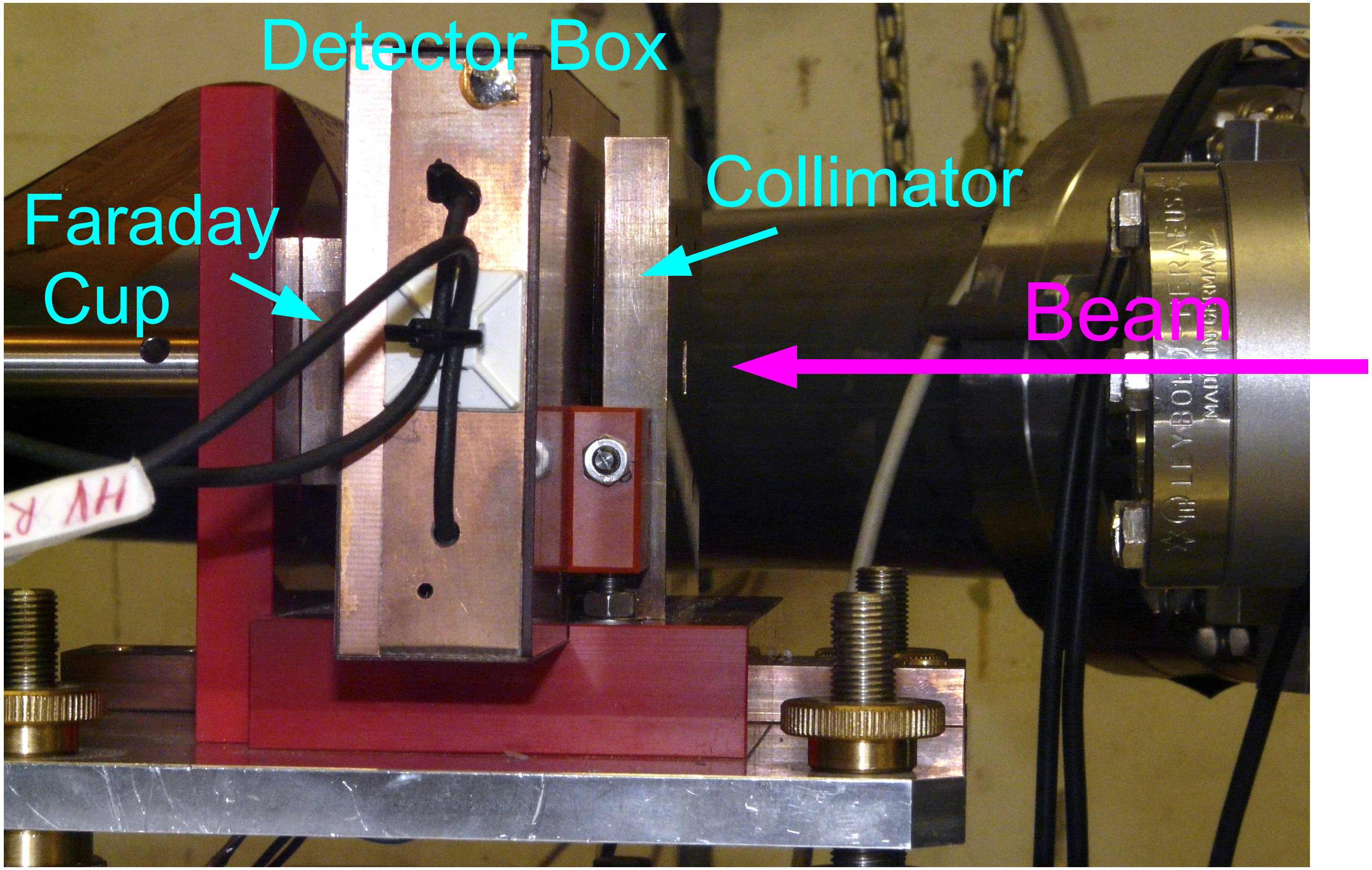




- Irradiation up to ~12 MGy:
  8.5 - 8.6 MeV electrons and beam currents from 10 to 250 nA
  (corresponding to 60 to 1800 kGy/h.)
- Keeping the sensor under bias (100 V) permanently.
- This is a much higher dose rate compared to the application at the ILC (~1 kGy/h)

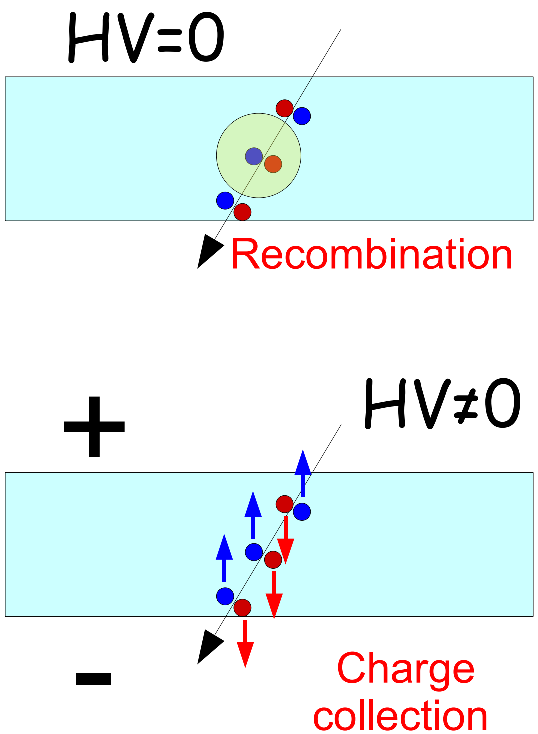
(1 MGy = 100 Mrad is deposited by about 4 x 10^{15} e^-/cm^2)

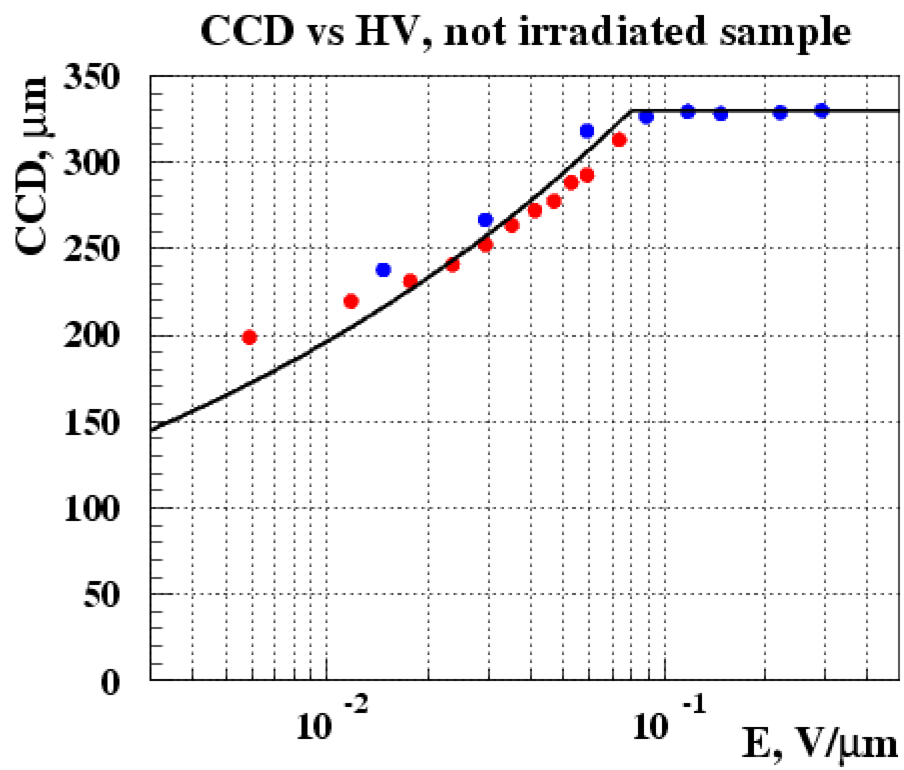
High dose irradiation at TU-Darmstadt



'Ideal' crystal charge collection

- Charge collection efficiency depends on E

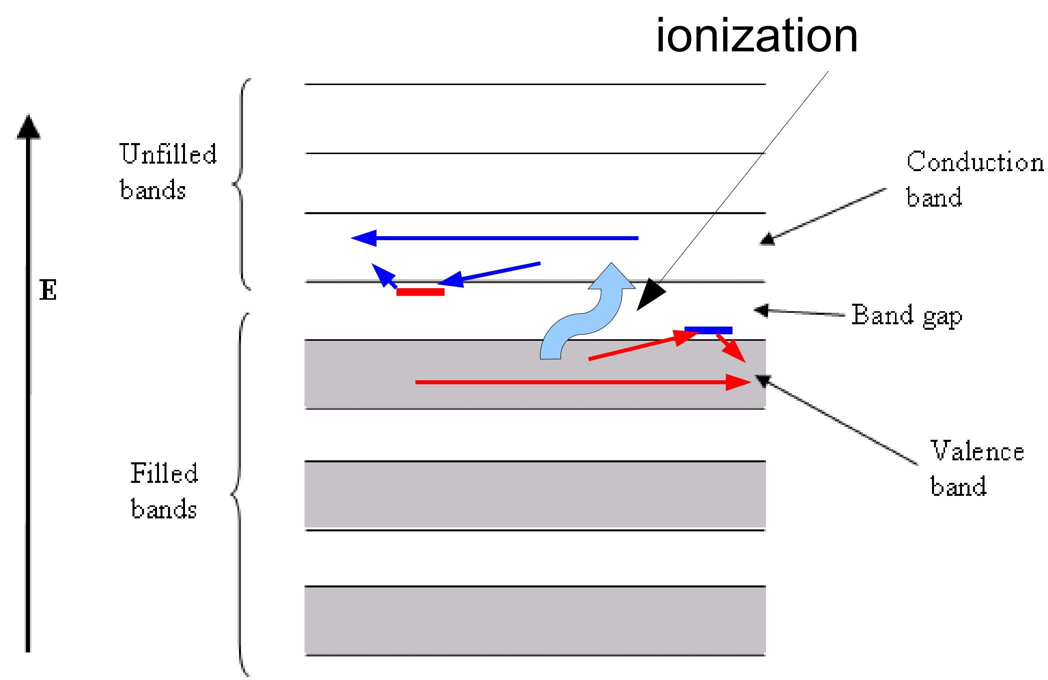




Radiation damaged crystal

- 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

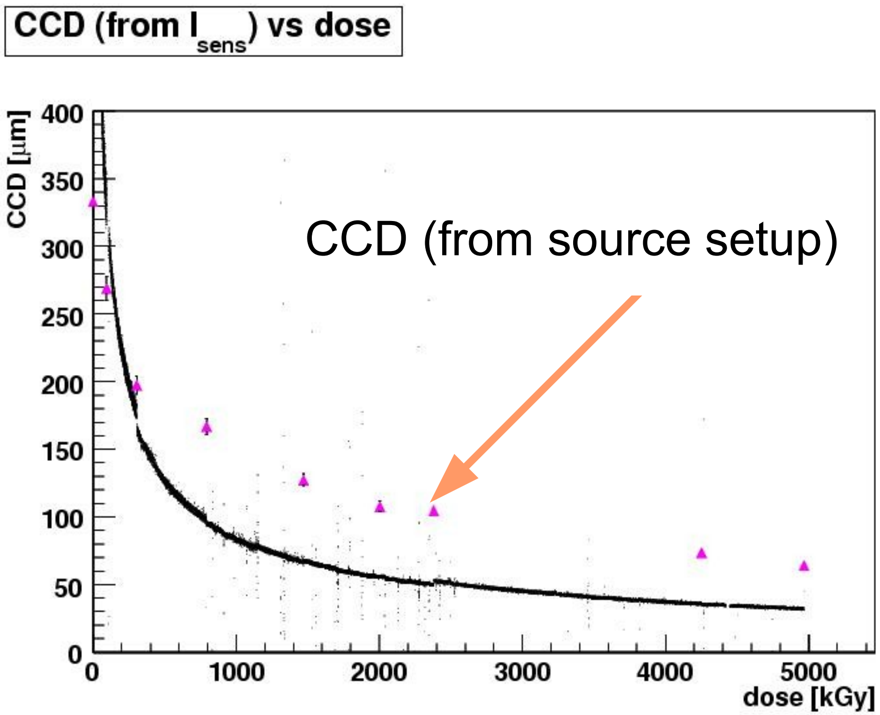
- Assumptions:
- Trap density is uniform (bulk radiation damage)
- Traps are created independently (linearity vs dose)

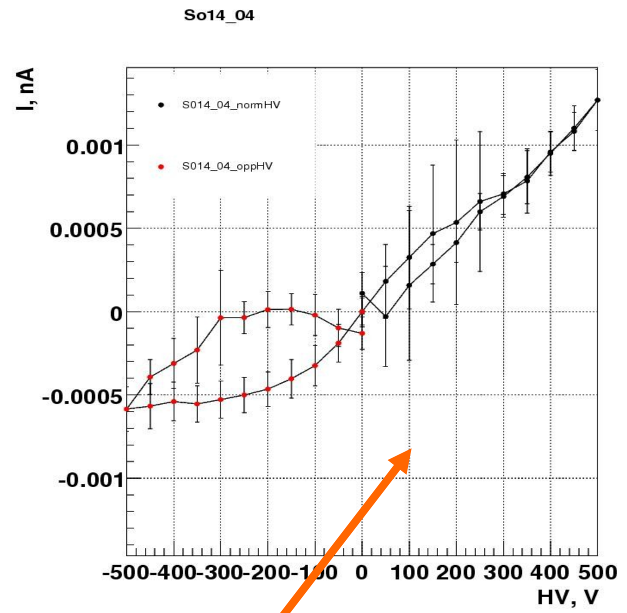


Irradiation of single crystal CVD Diamond

After absorbing 5 MGy:

CVD diamonds still operational.

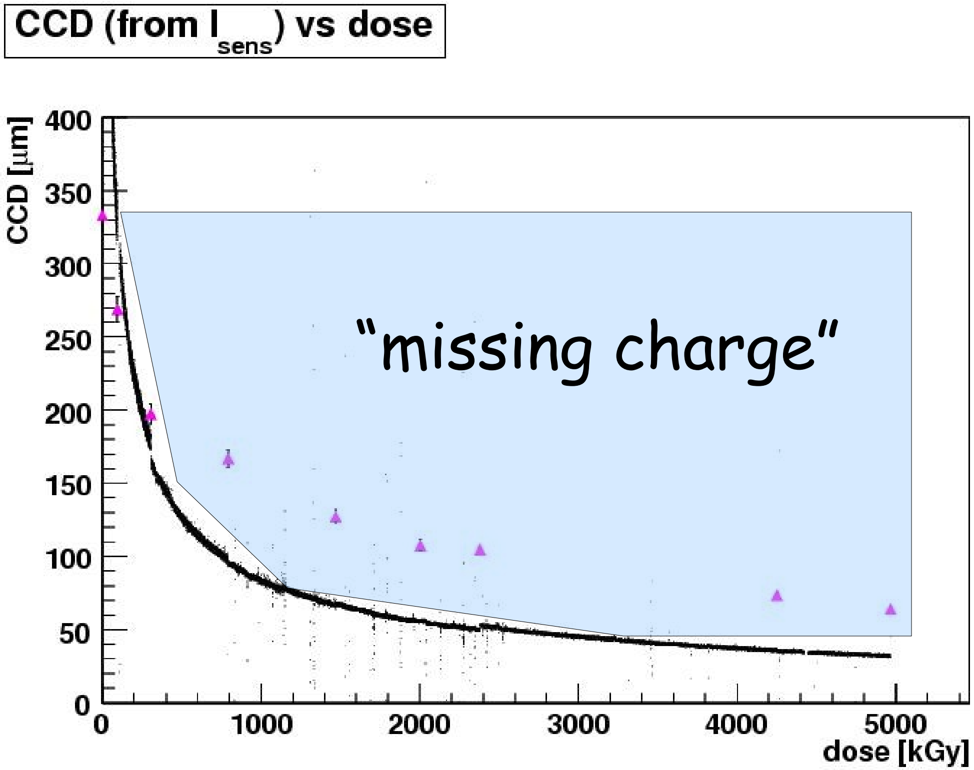




- Very low leakage currents (~pA) after the irradiation.
- Decrease of the charge collection distance with the dose.
- Generation of trapping centers due to irradiation. Traps release?

Pure trapping/detrapping mechanism is contradictory :

- expected $CCD_{I\ detector}$ > CCD_{MIP} (not the case)
- too high "missing charge" $n_{Traps} \sim n_{Atoms}$ at 5 MGy?
- too high cross section for defects creation $dN_{traps}/dt > N_{eh}$



Example:

$Beam_{det}$ – 5×10^{10} e/sec

1.2×10^{4} eh pairs/particle

Irradiation time 3.6×10^{4} sec

Detector volume 2.3×10^{-3} cm^3

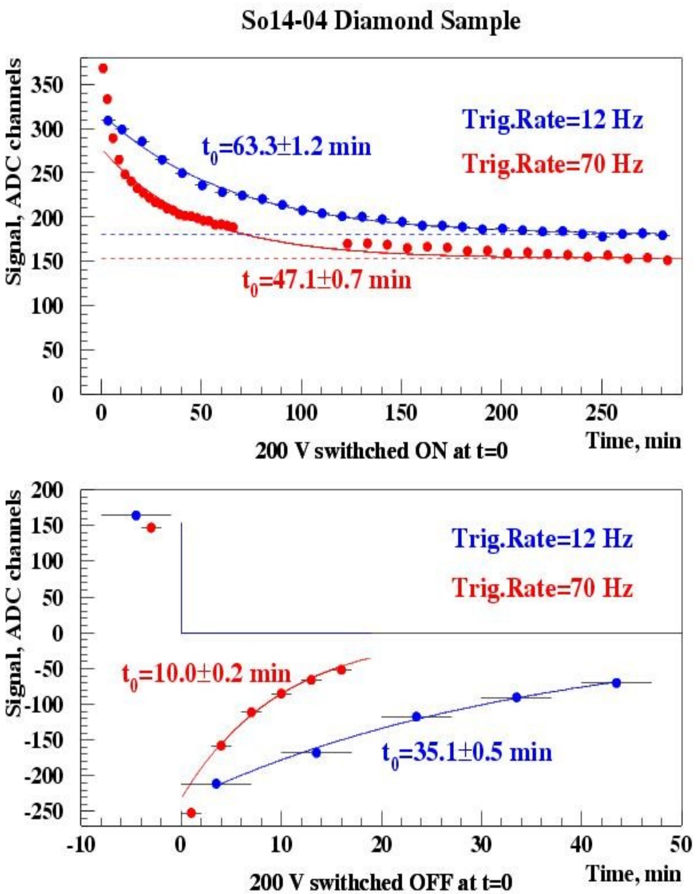
Pairs produced $\sim10^{22}$ cm^{-3}

Atom density 1.77×10^{23} cm^{-3}

Recombination!

Labtest of damaged 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 vs 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

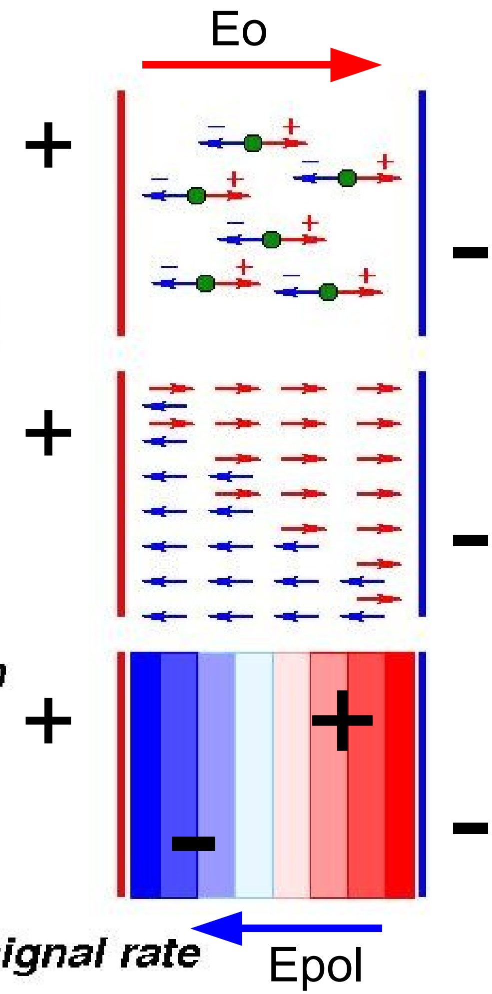
Release of trapped charges (decay time)

Change of the space charge distribution

↓

Steady state POLARIZATION

Dependent on trap density, applied voltage and signal rate



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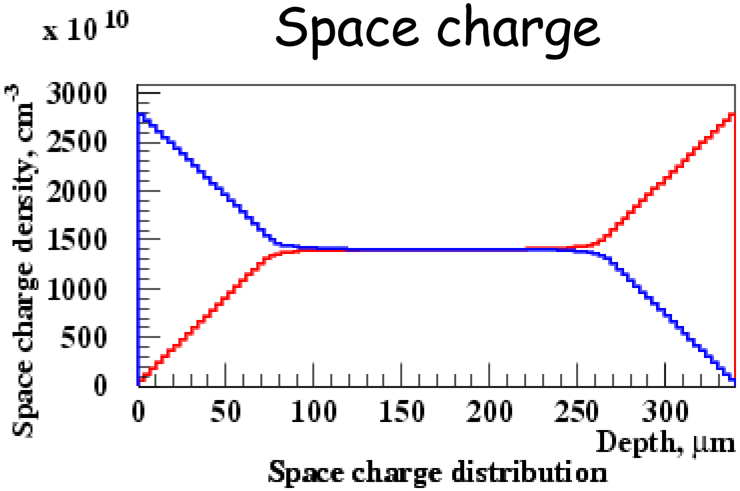
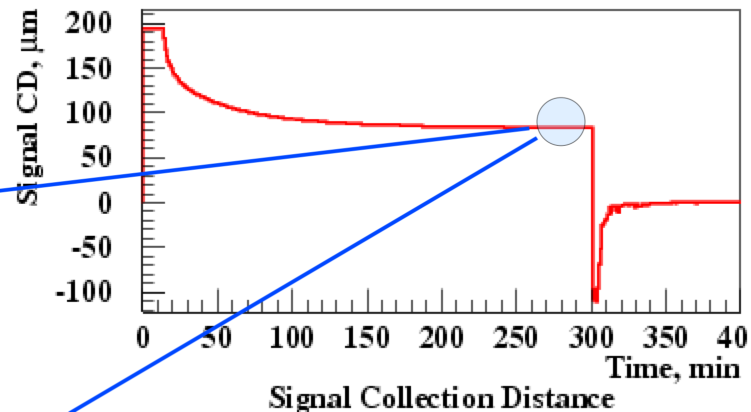
Model of sCVD Diamond Polarization - 1

HV on

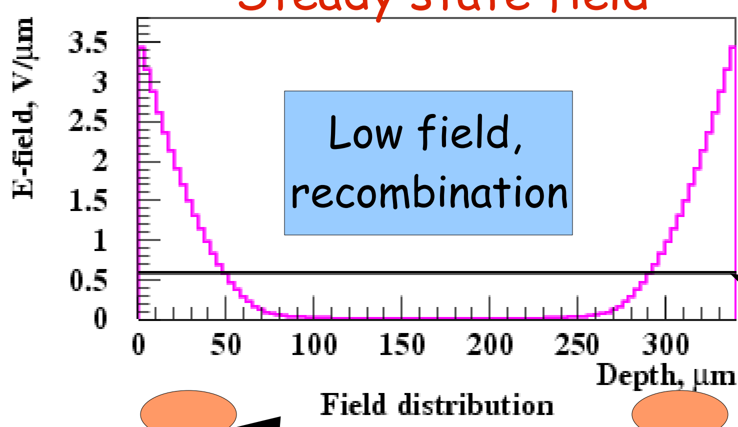
Space charge



So14_04 sample model

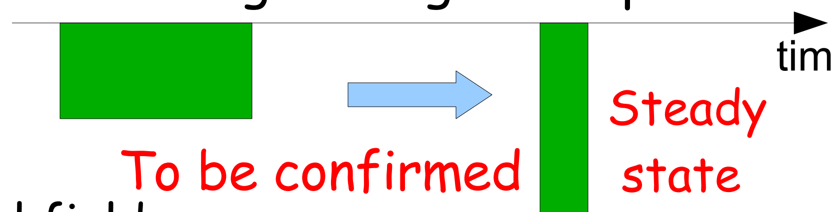


Steady state field



Initial field

Change of signal shape

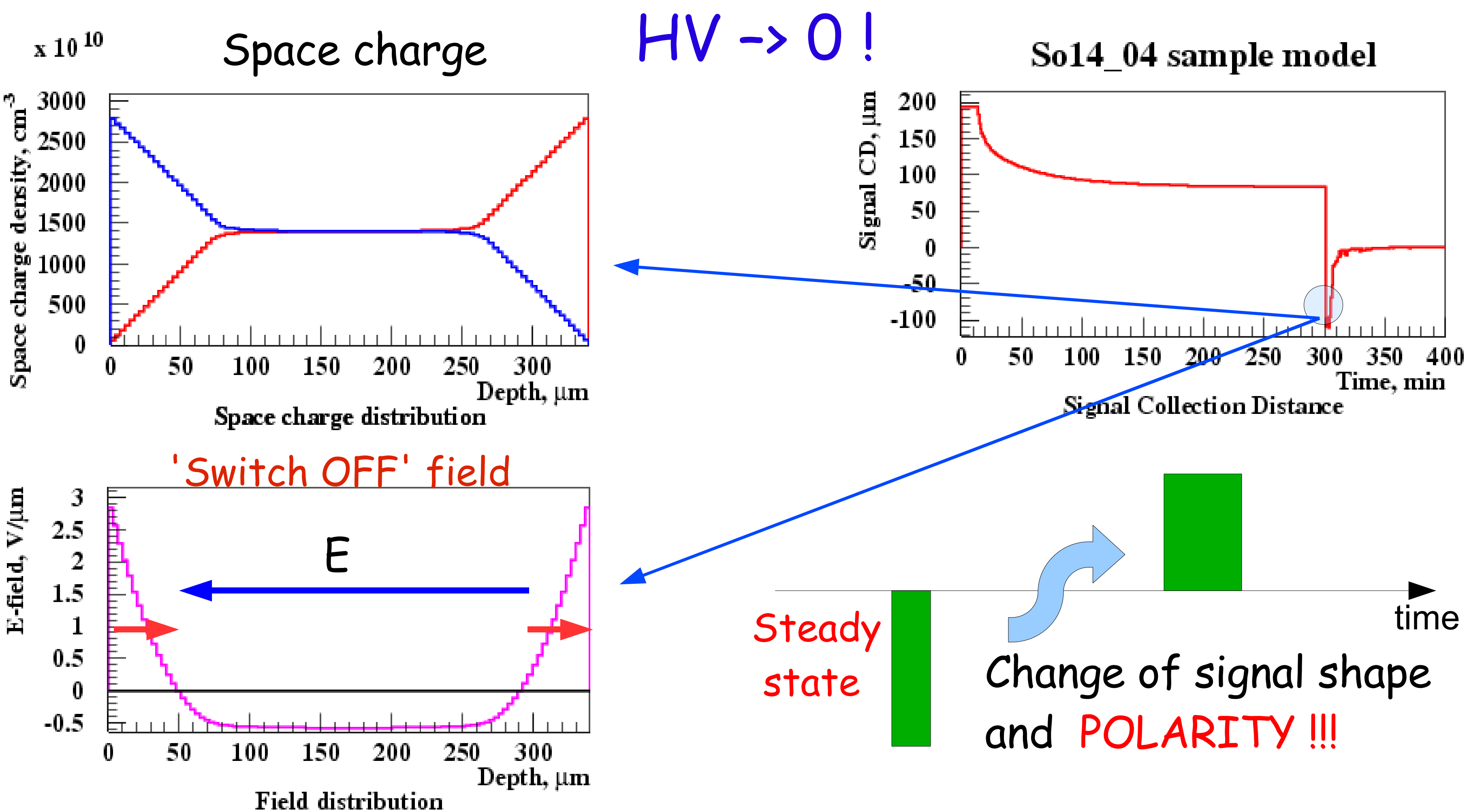


To be confirmed

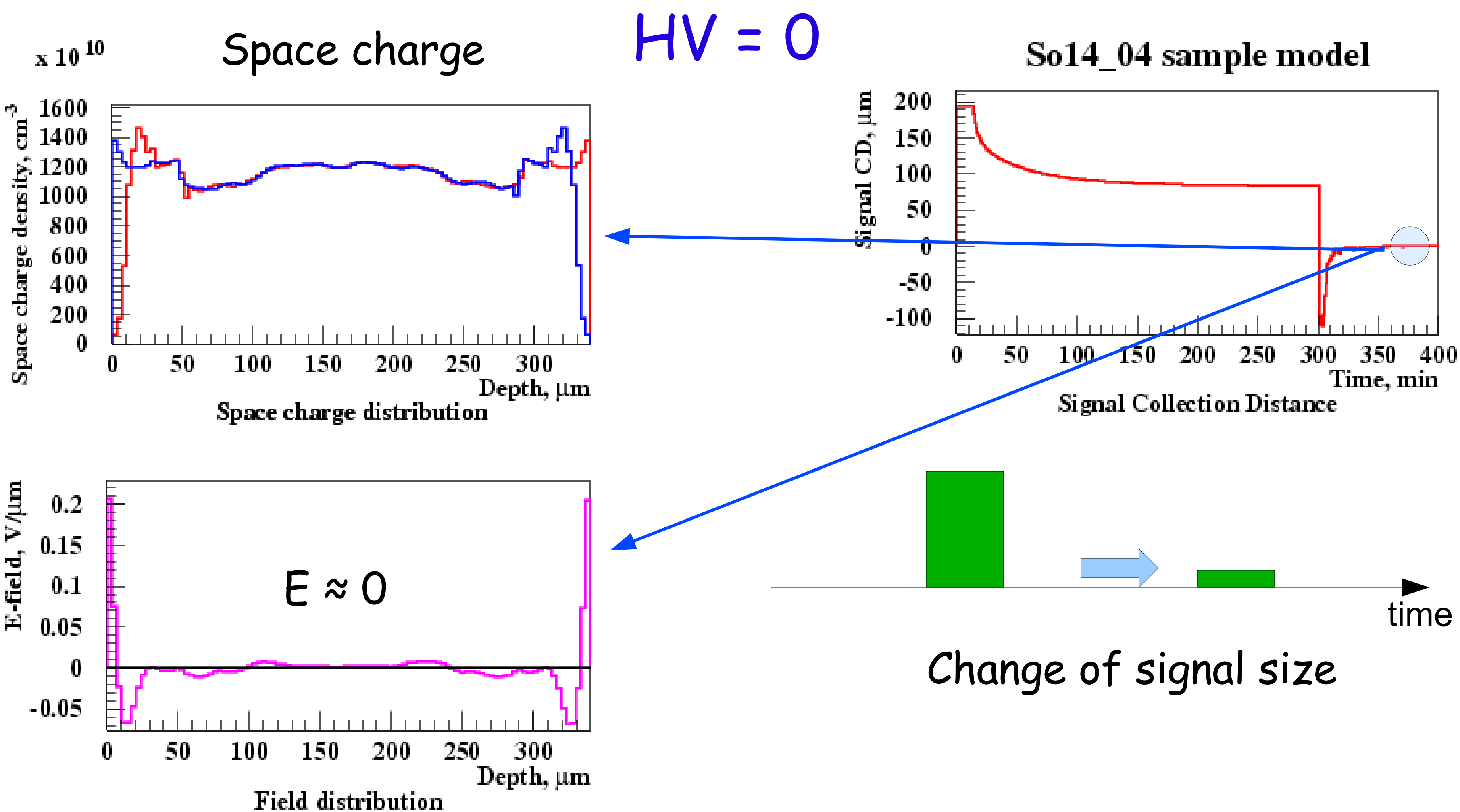
Steady state

Effective charge collection regions

Model of sCVD Diamond Polarization - 2



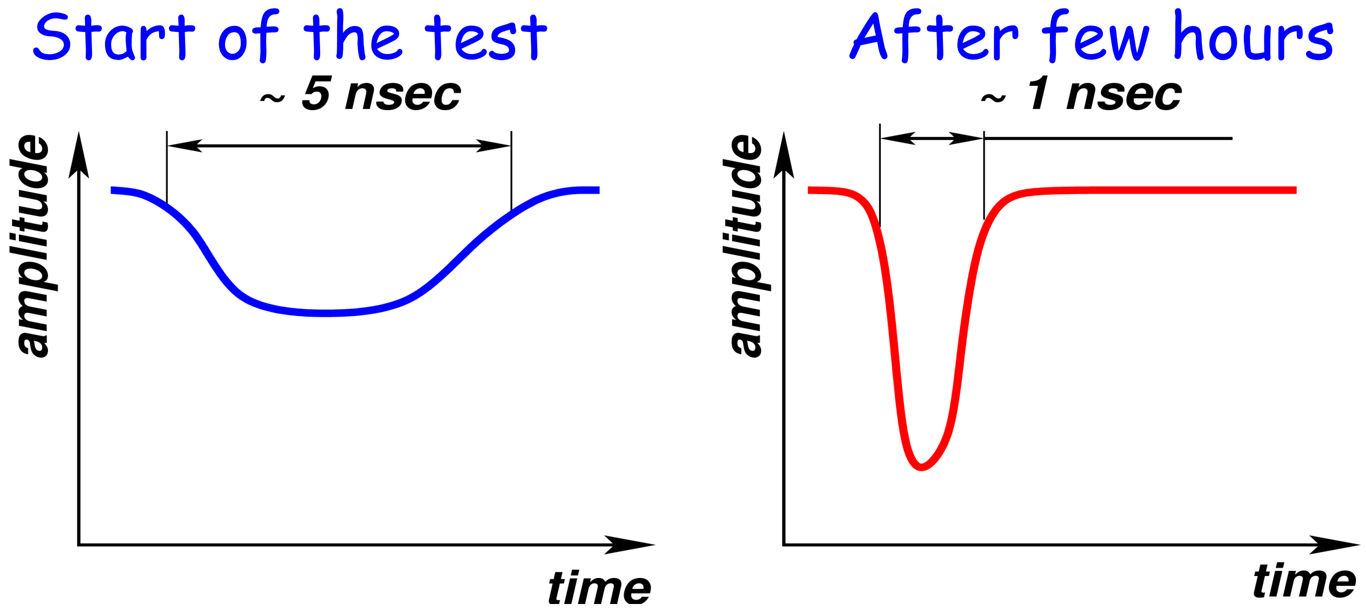
Model of sCVD Diamond Polarization - 3



Polarization model prediction:

- Detector signal shape is changing with the polarization development:

Radiation damaged crystal under ^{90}Sr source



Collected charge drops, but amplitude rises

To be confirmed !!!

^{90}Sr setup: CCD time dependence

- Diamond sCVD sensor after 5 MGy

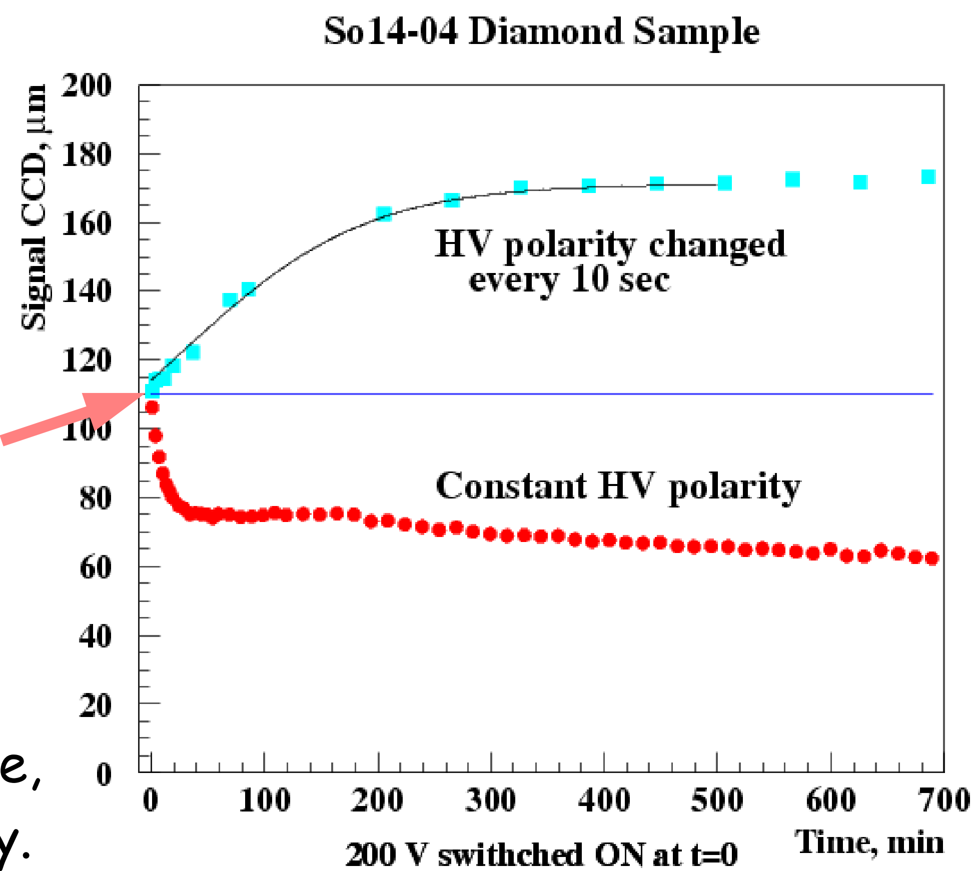
$$CCE_0 = \frac{2}{aD} \cdot \left(1 - \frac{1-\exp(-aD)}{aD}\right)$$

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

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

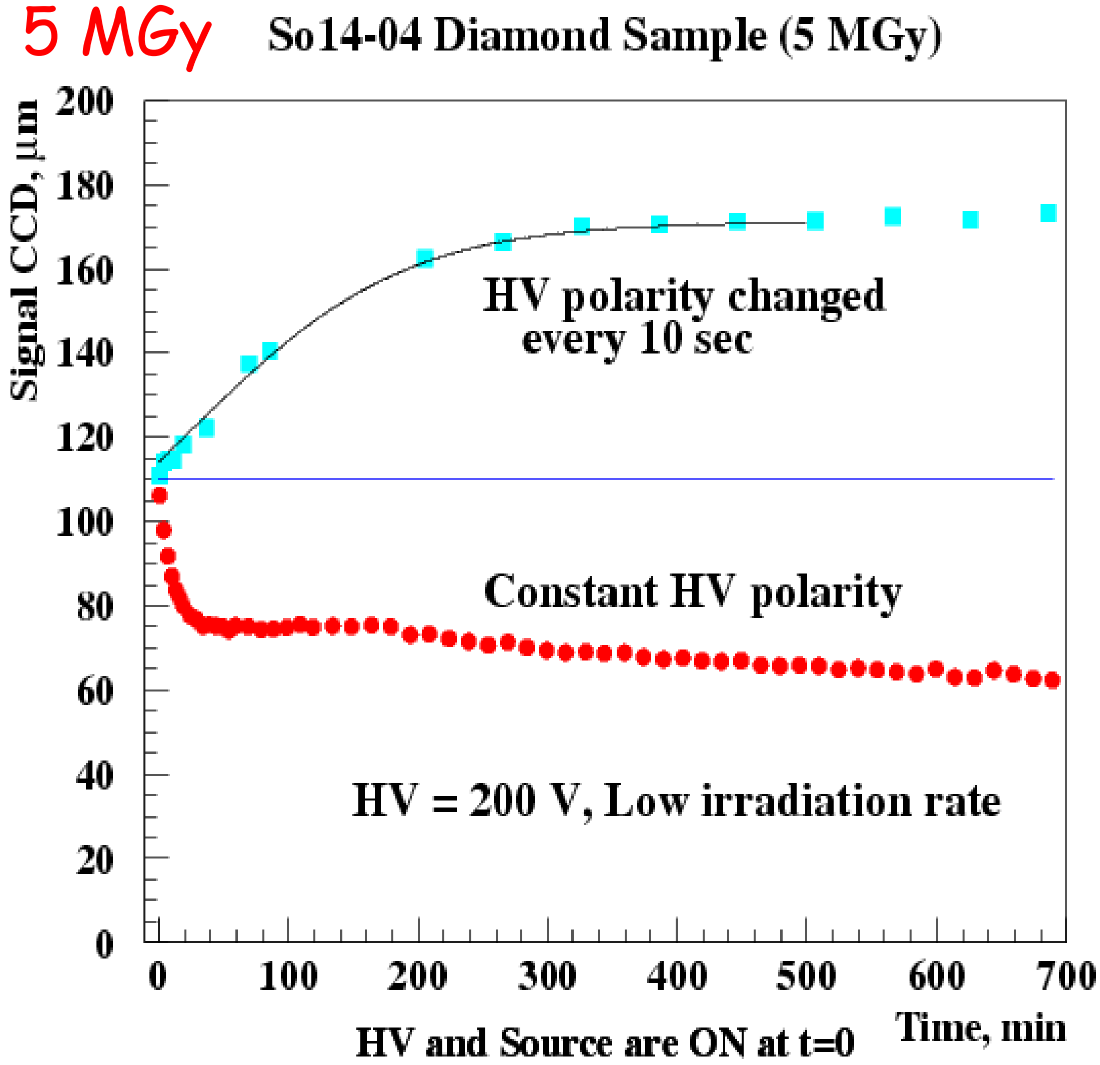
Steady state CCD is sensitive to n_{trap}, T_0 and signal rate

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

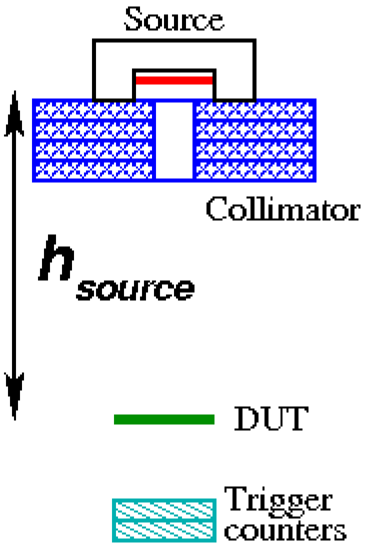


CCD vs time dependence, low rate

5 MGy

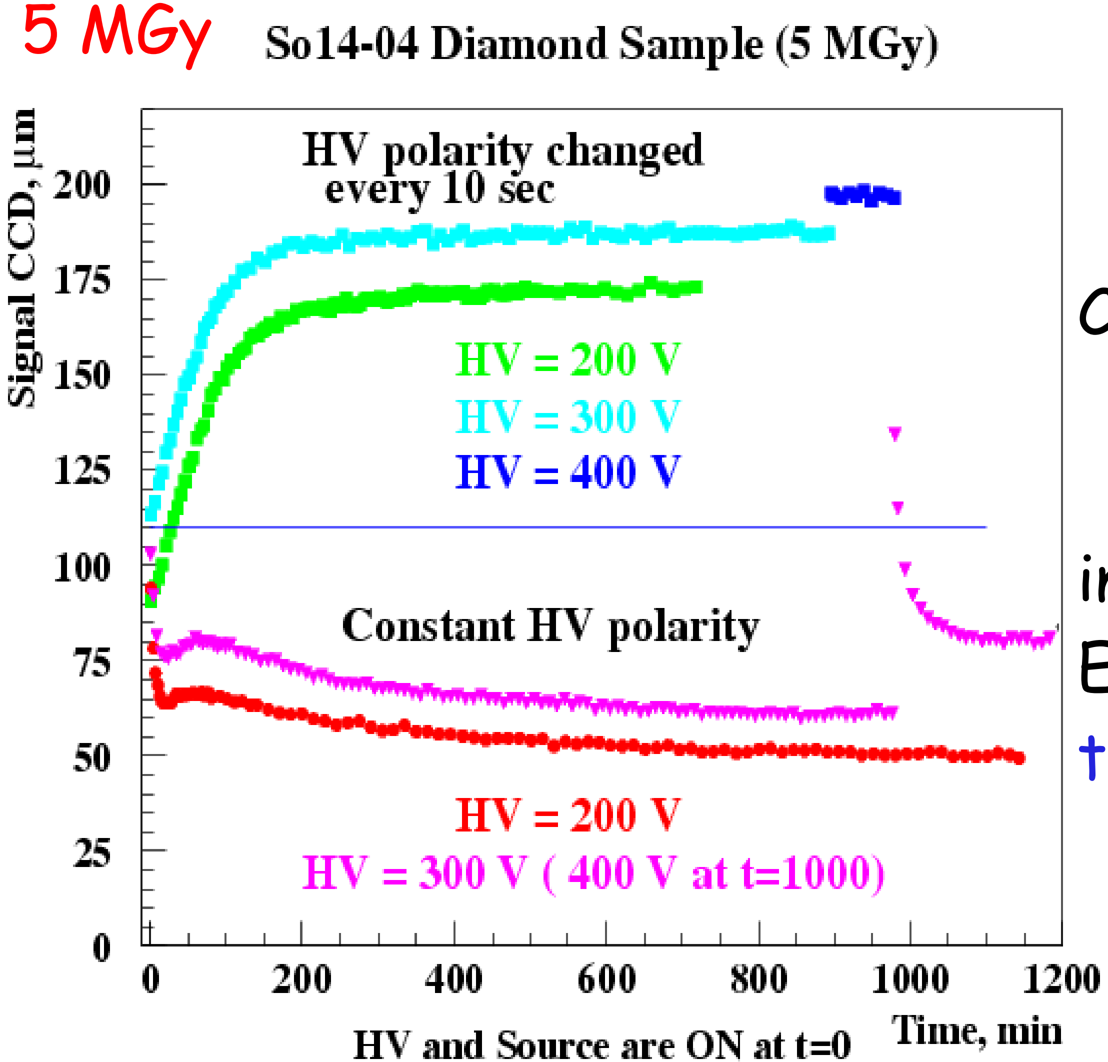


Trigger rate about 12 Hz, h_{Source} ~ 36 mm



CCD vs time dependence, high rate

5 MGy



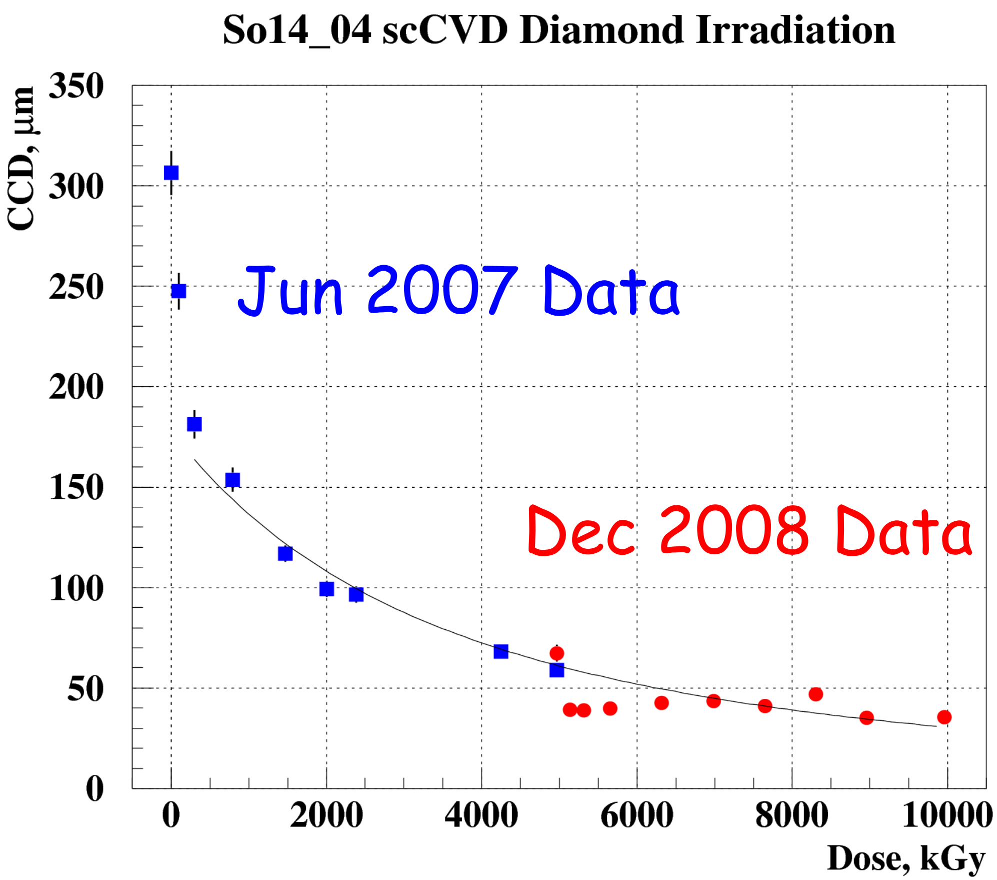
"High rate" data

h_{Source} ~ 20 mm

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

Frenkel effect?

So14-04 scCVDD additional irradiation Dec 2008



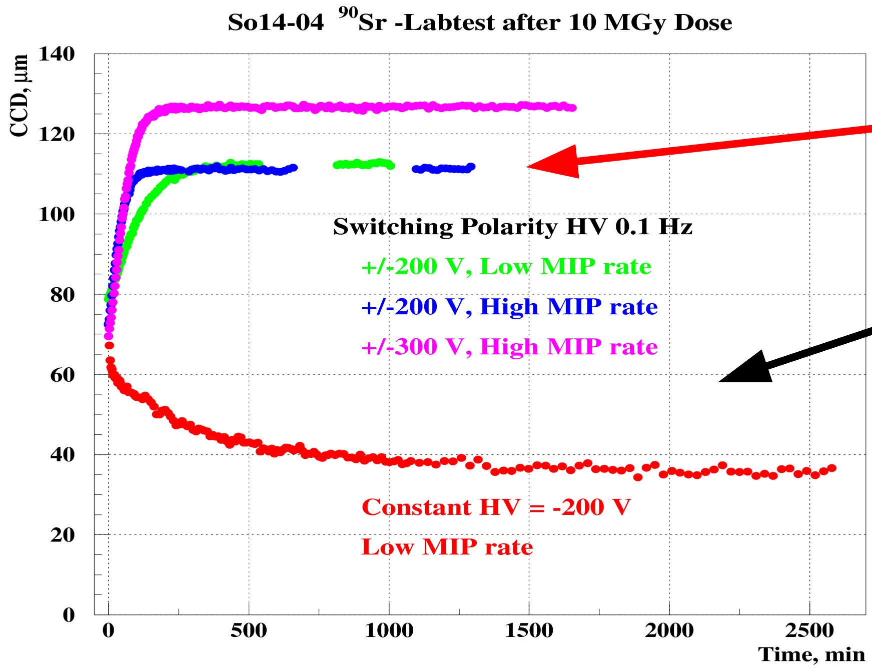
No annealing!

(1.5 years, a lot of tests with ^{90}Sr source, UV-light, several TSC measurements)

Strange drop of CCD at the very beginning of the Dec 2008 irradiation

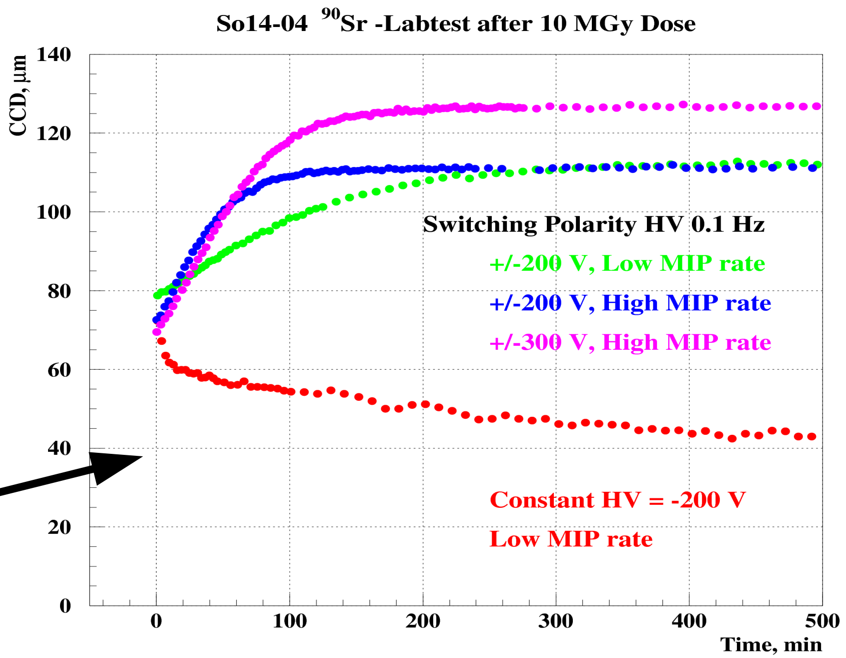
Tests at Zeuthen 2009: CCD vs time

After 10 MGy



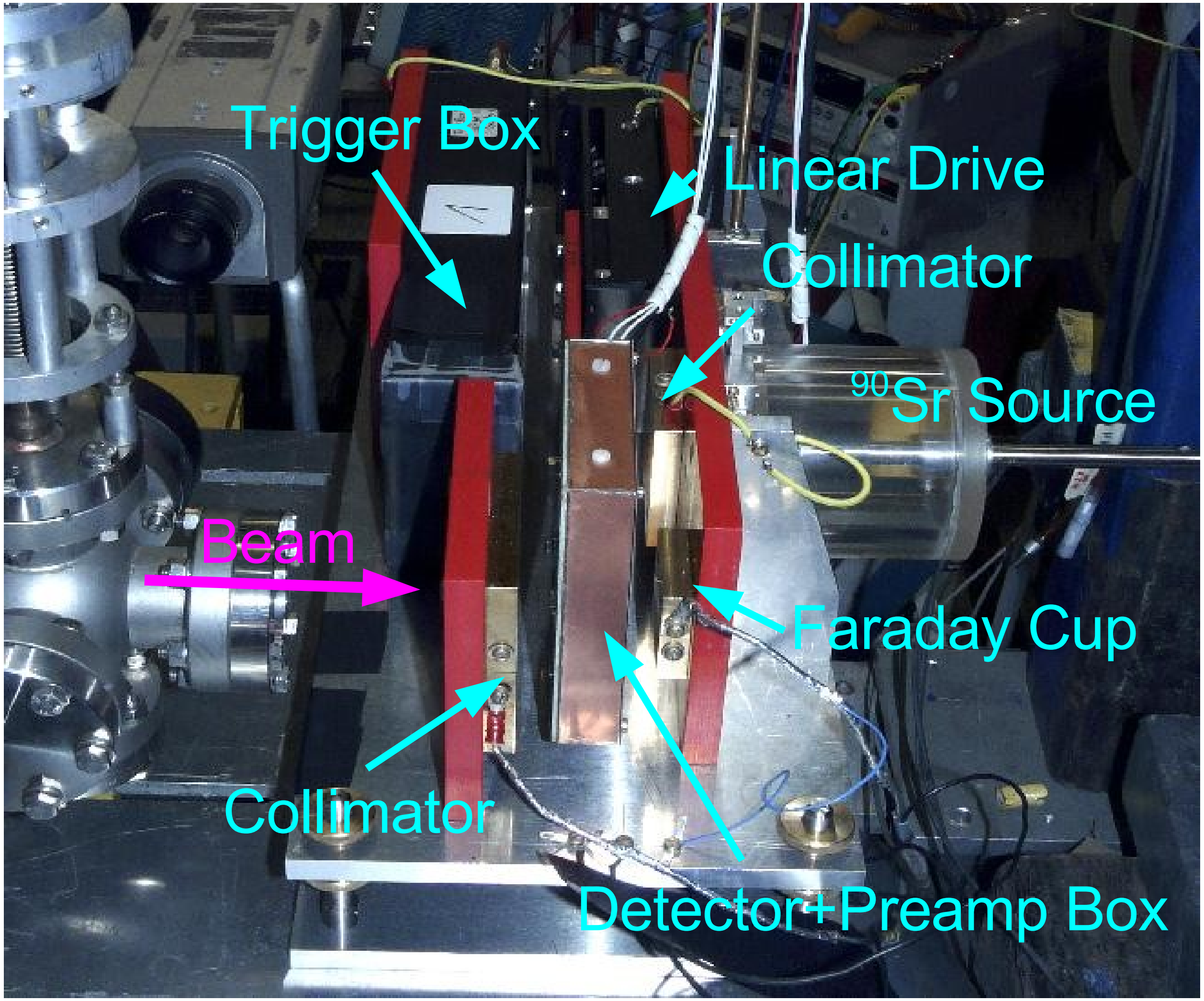
Same steady state CCD?
Short living traps?

All data



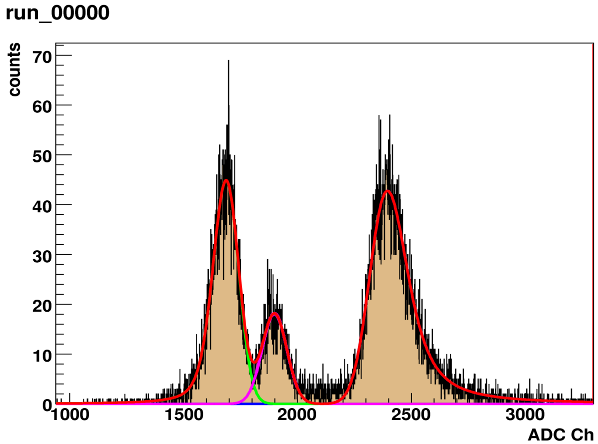
First 500 min data taking:

Beam Pumping Test

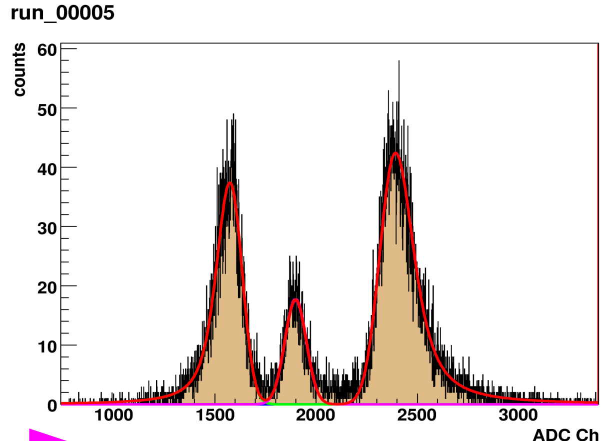


Beam pumping test at 5 MGy

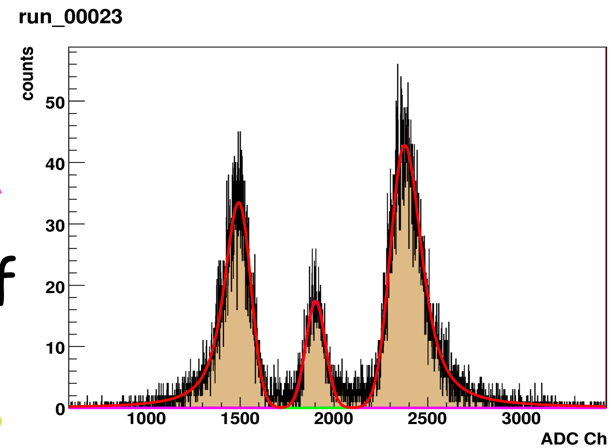
- Pumping dose rate ~50 kGy/hour (~50 x ILC)
- Example of spectra evolution: +/-200 V, 0.1 Hz:



t = 20 sec



t = 100 sec

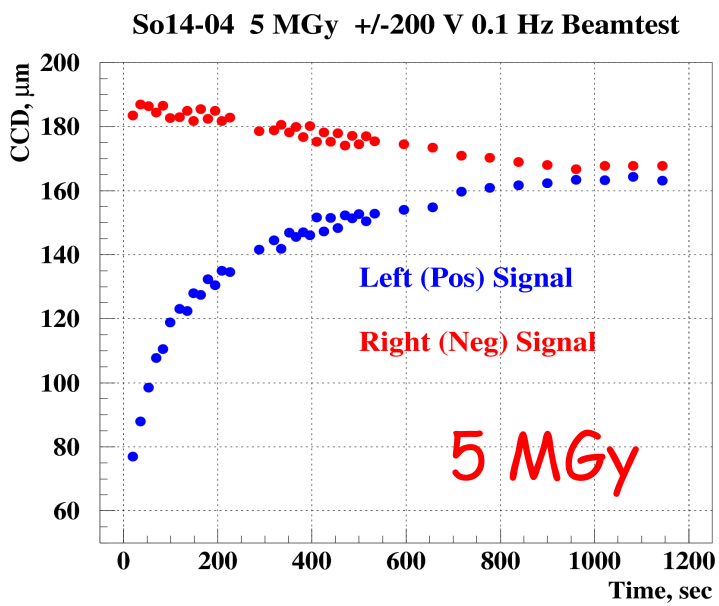


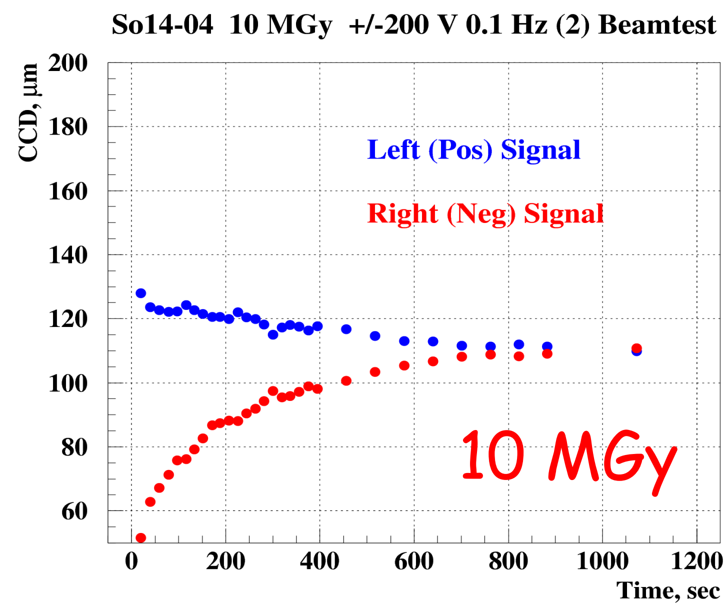
t = 440 sec

Strong spectrum asymmetry, which depends on time left from the beam-off

Beam pumping test at 10 MGy

➢ Examples of CCD time evolution:





Data available:HV frequency: from 0.1 to 3 Hz + constant polarity
HV value: from 50 V to 300 V, in total 19 sets

Clear indication to the presence of fast decaying traps

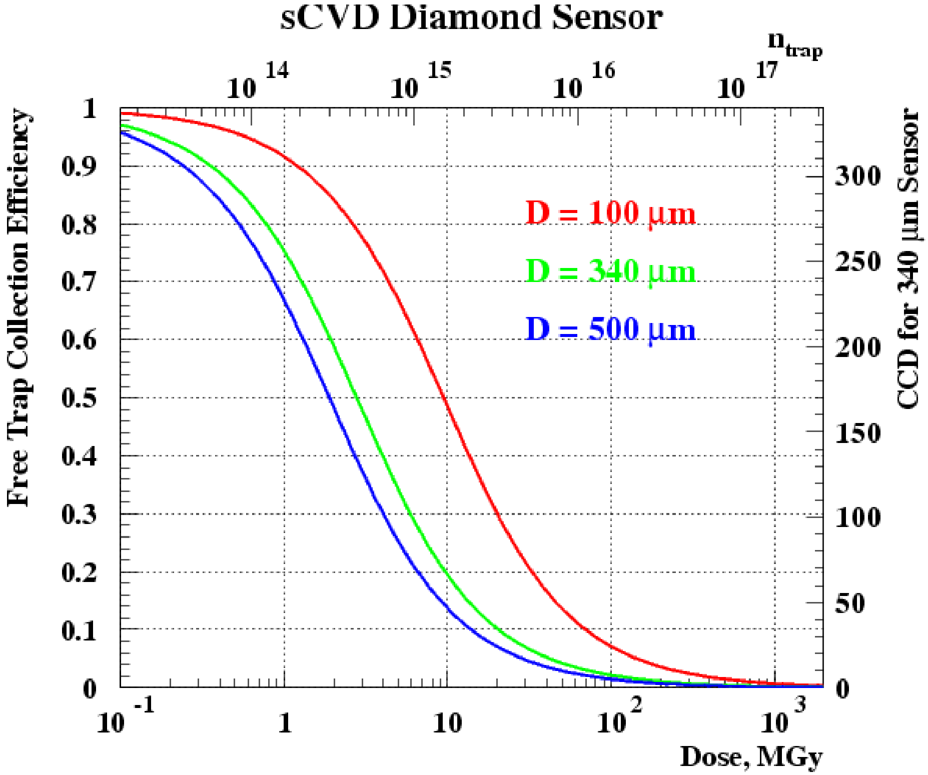
Uniformly distributed free traps case

CCE vs detector thickness

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:

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

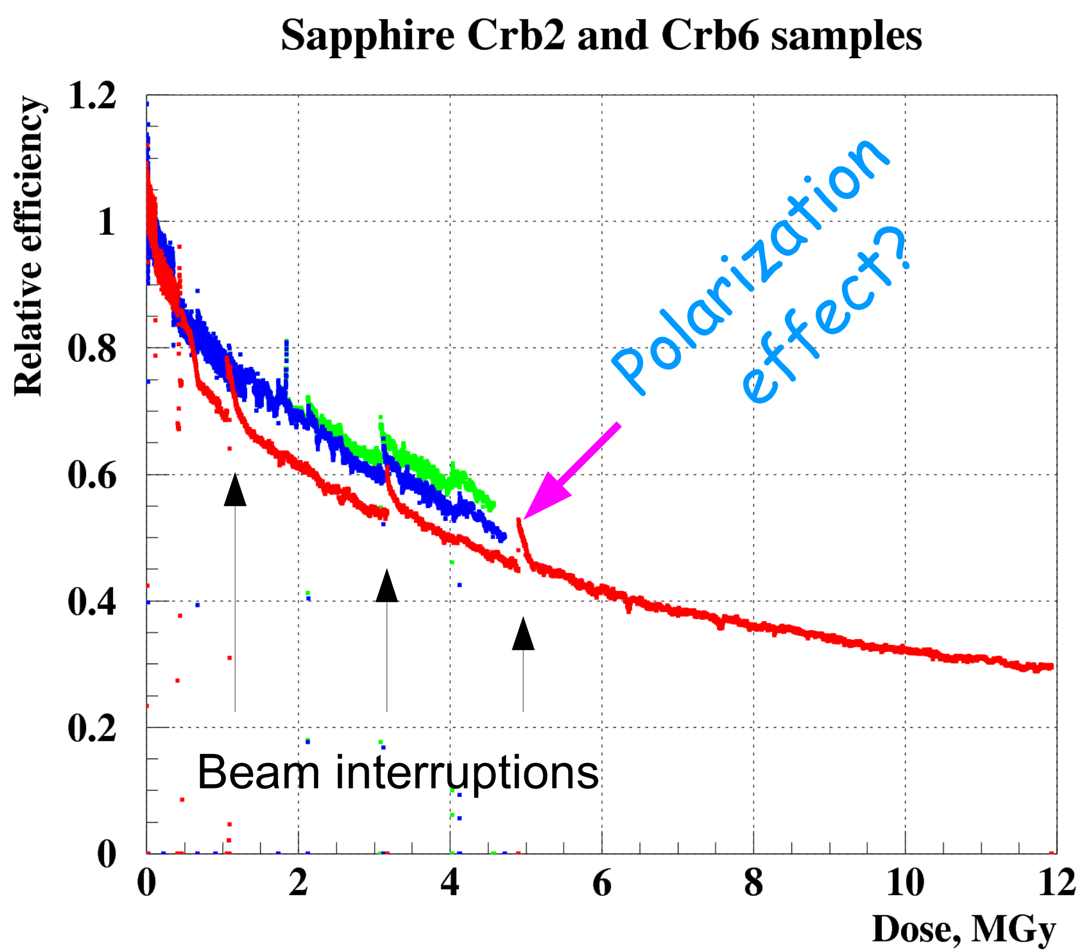
Summary

- The performance of scCVD Diamond sensor was studied as a function of absorbed dose up to 10 MGy.
- 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 in addition to pure trapping/detrapping mechanism.
- 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.
- Data obtained show the way for better understanding of solid state detectors radiation hardness problem.

Thank you...

Special thanks to GSI team for CVD Diamond sensors and TU-Darmstadt for the test beam

Sapphire - preliminary results

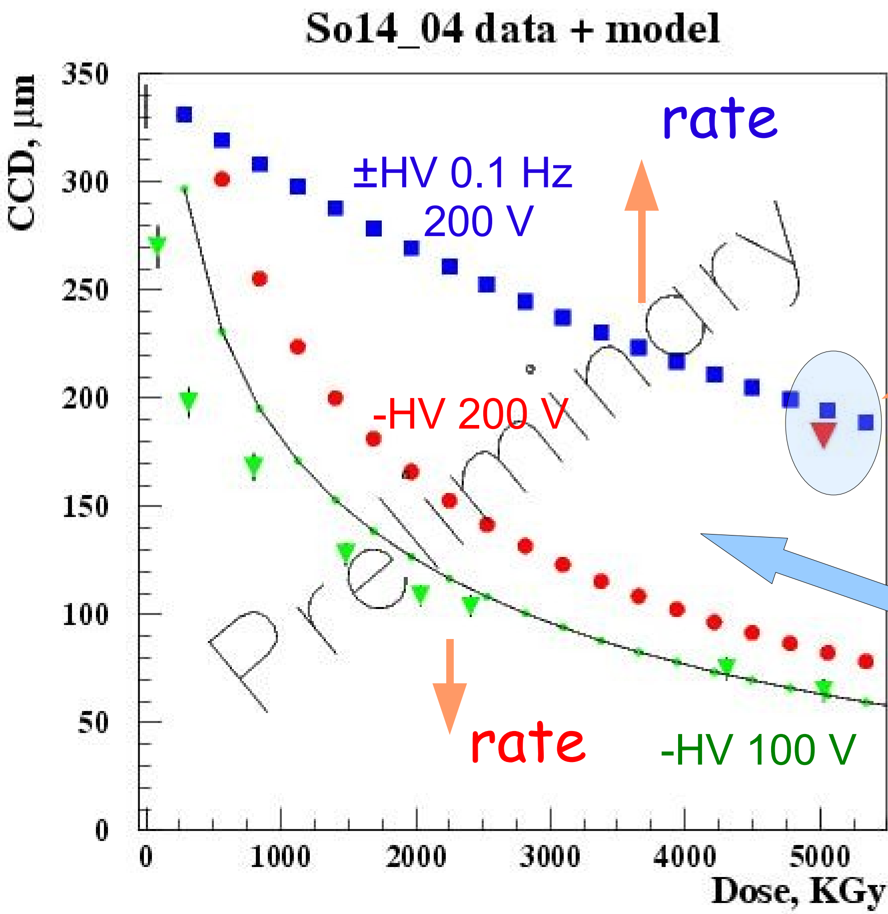


Ratio between Detector current and Faraday Cup current was used as a measure of sensor efficiency

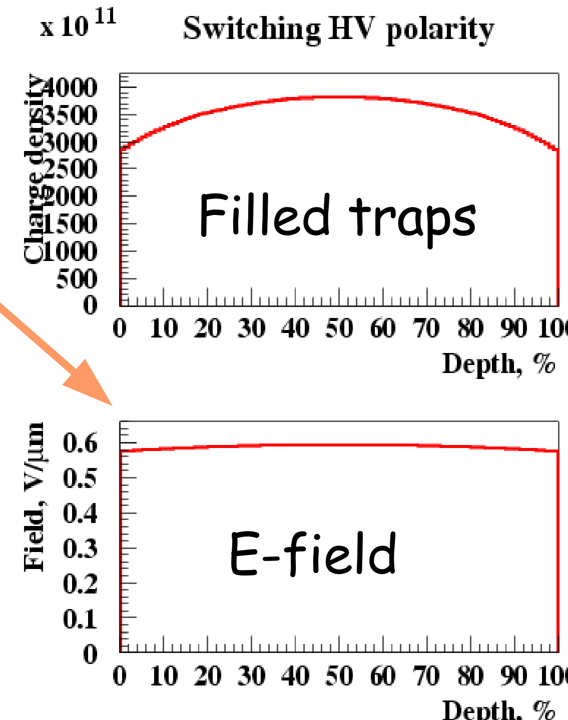
~30% of initial efficiency after 12 MGy - not bad!

Irradiated single crystal CVD Diamond

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



cross-check



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

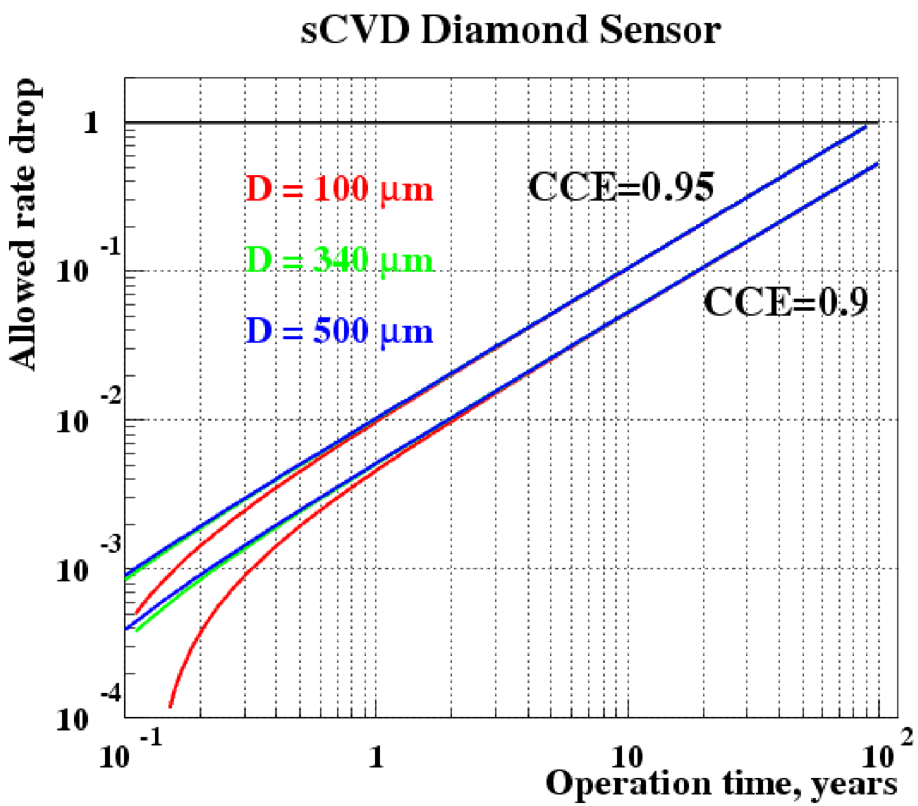
More experimental studies needed

Uniformly (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 ???