Radiation hardness issues in diamond

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Motivation

Review of existing data on diamond radiation hardness in different operative conditions in view to develop a model of radiation damage in diamond.

Outline

- Applications of diamond in radiation environments.
- The diamond as a sensor: advantages and limits.
- Background: from the CCE to the comparison between scCVD and pCVD.
- Radiation hardness respect to:
  - γ-rays
  - Electrons.
  - Neutrons.
  - Protons.
  - Pions.
  - Alphas.
  - MeV energy ions.
- Summary.

Applications of diamond in radiation environments

Diamond application is currently foreseen in many fields from fundamental to high energy physics experiments and dosimetry:

- Tracking detectors:
  - Strip and pixel detectors to reconstruct particle track with high spatial and energy resolution.
  - A full diamond pixel module has been built for the ATLAS experiment.
- Beam Condition Monitors (BCM) [1]:
  - To avoid detectors damage from beam instabilities, beam condition monitoring detectors should abort safely and quickly the beam.
  - Diamond has been selected for BCM at Babar, Belle, CDF, ATLAS and CMS.
- Fission reactor flux monitors [2]:
  - To detect neutron emitted from reactor plasmas, operating at temperatures above ambient temperature.
  - Diamond sensors are developed for the International Tokamak Experimental Reactor (ITER).

[1] Wallny et al., NIM A, 2007, Status of diamond detectors and their high energy physics application.
[2] Angelone et al., NIM A, 2008, Development of single crystal diamond neutron detectors and test at JEK tokamak.

Diamond as a sensor

- **Advantages:**
  - **Large band-gap:**
    - ⇒ **Low intrinsic charge carrier density, high resistivity: low leakage current.**
  - **Low dielectric constant (≈1/2 of Si and GaAs):**
    - ⇒ **Low capacitance: low noise.**
  - **High breakdown field:**
    - ⇒ **Operation at high voltages: fast charge collection.**
  - **High mobility:**
    - ⇒ **Fast charge collection.**
  - **Large thermal conductivity:**
    - ⇒ **Operation without cooling.**
  - **High binding energy:**
    - ⇒ **Radiation hardness.**
- **Limits:**
  - **High energy required to create an electron-hole pair:**
    - ⇒ **Low signal.**
  - **High density of defects:**
    - ⇒ **Charge trapping and recombination: unable to collect all the produced ionization signal.**
    - ⇒ **Polarization effect.**

Background

- Parameters characterizing performances:
  - Charge Collection Efficiency (CCE): $CCE = \frac{Q_{measured}}{Q_{deposited}}$
  - Charge Collection Distance (CCD):

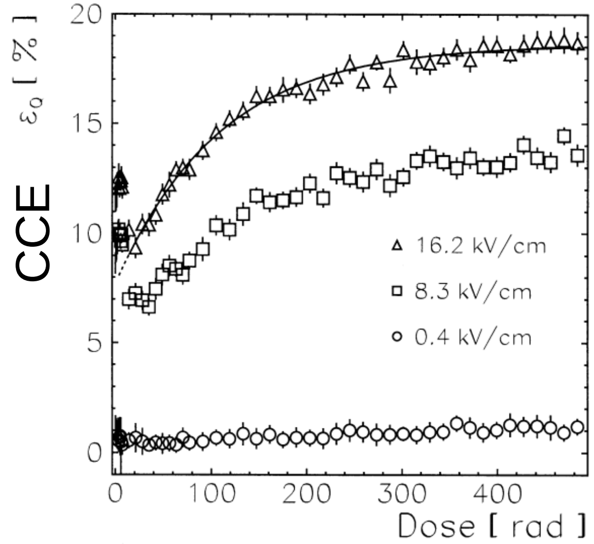
$$CCD = (\mu_n \tau_n + \mu_p \tau_p)E = \frac{Q_{measured}}{Q_{deposited}} * thickness = \frac{Q_{measured}[e]}{36[e/\mu m]}$$

- Short-time radiation effects (especially for pCVD):
  - Priming or pumping: increase of the CCE (CCD) during the irradiation with ionising particles due to the filling of vacant trap sites (passivation) [3]:

$$CCE(D) = CCE(D=0) + (R_p - 1)CCE(D=0)\left(1 - e^{-\frac{D}{D_0}}\right)$$

    - R_p: priming ratio; D_0: priming dose.

  - Polarization effects: building of a non uniform electric field due to the localized filling of the traps.



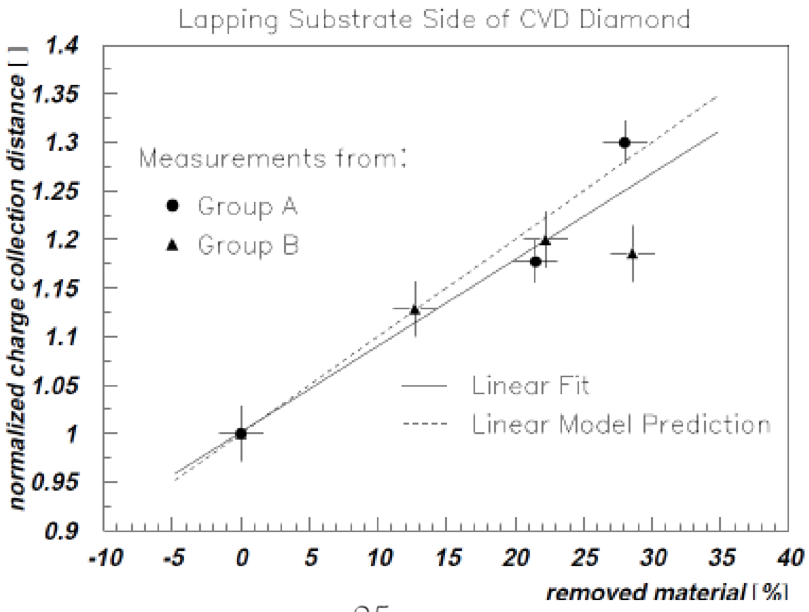
[3] Oh et al., DRM, 2000, Neutron irradiation studies with detector grade CVD diamond.

Background

- Properties vs. depth:
  - pCVD pristine material [4]:

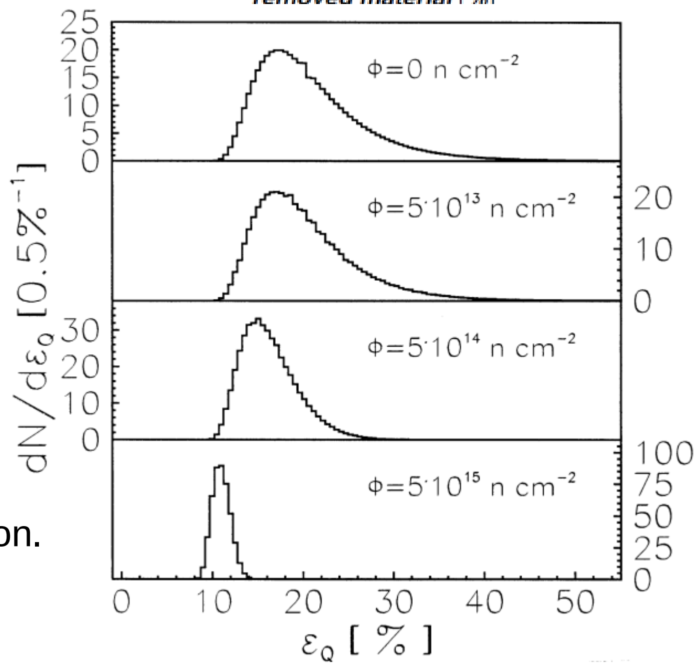
$$CCD(x) = cx$$

$$\Rightarrow \quad CCD = CCD_{original}\left(1+\frac{thickness_{removed}}{thickness_{original}}\right)$$



  - Irradiating the sample [3]:

    The introduction of radiation induced defects will change the CCE more in regions with initially lower defect concentration: the mean <CCE> decreases and the CCE distribution after irradiation is narrower.



- Model [4] prediction.
- ε_Q=CCE.

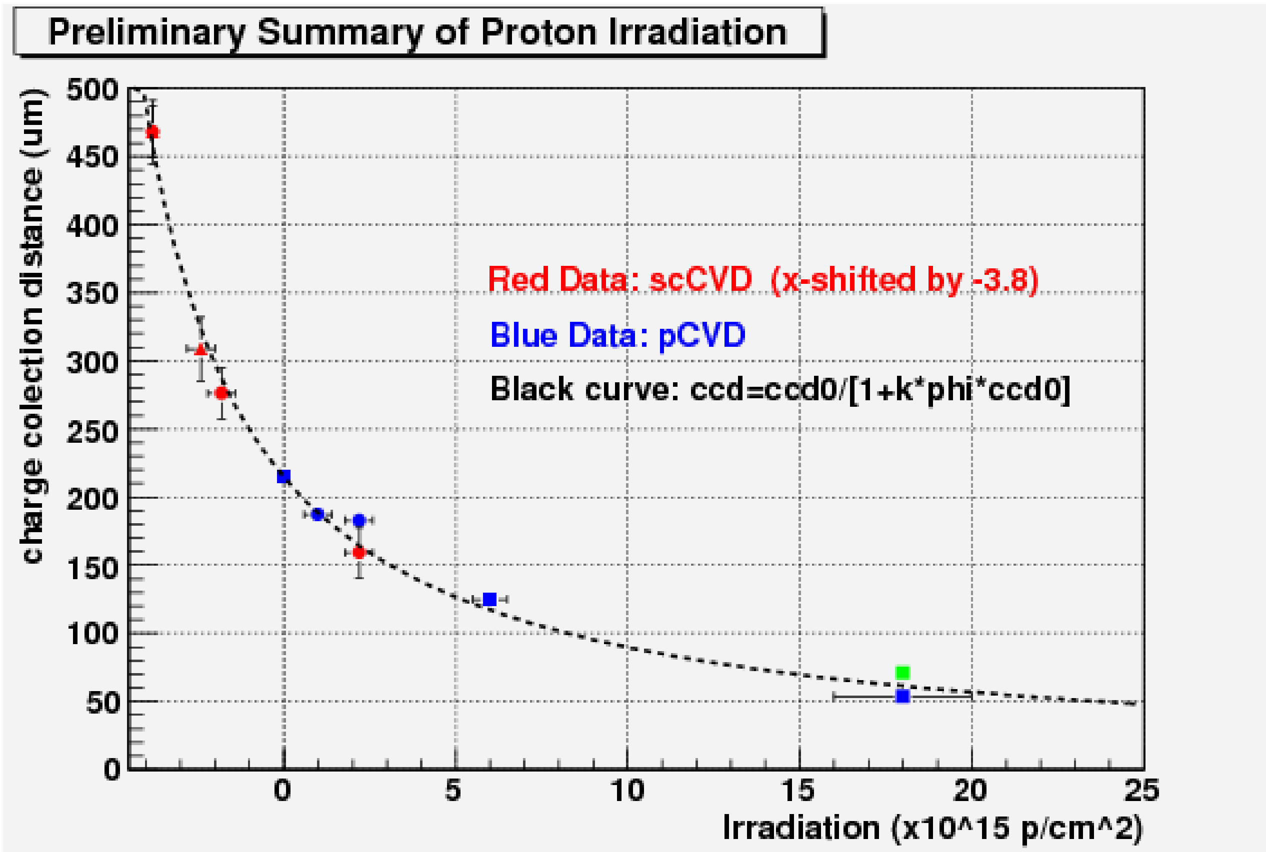
[4] RD42 collaboration, CERN EP, 1998, Development of CVD diamond radiation detectors.
[3] Oh et al., DRM, 2000, Neutron irradiations studies with detector grade CVD diamond.

Background

- scCVD and pCVD – Results of the RD42 collaboration
  - Radiation hardness with respect to 24GeV/c proton irradiation:

$$\frac{1}{CCD} = \frac{1}{CCD_0} + k\phi$$

- $k \approx 10^{-18}$ cm
- scCVD shifted by $3.8 \times 10^{15} cm^{-2}$



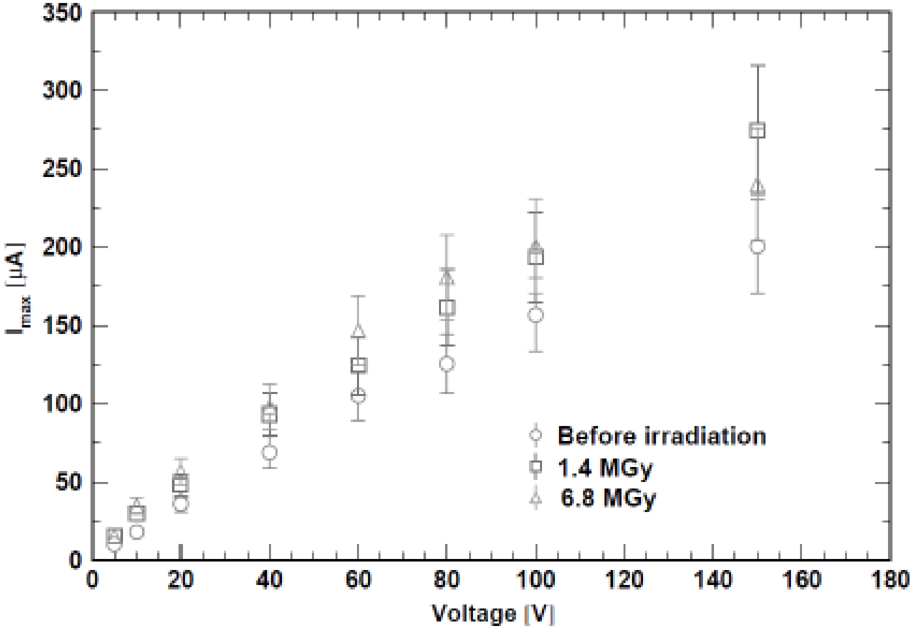
γ-rays

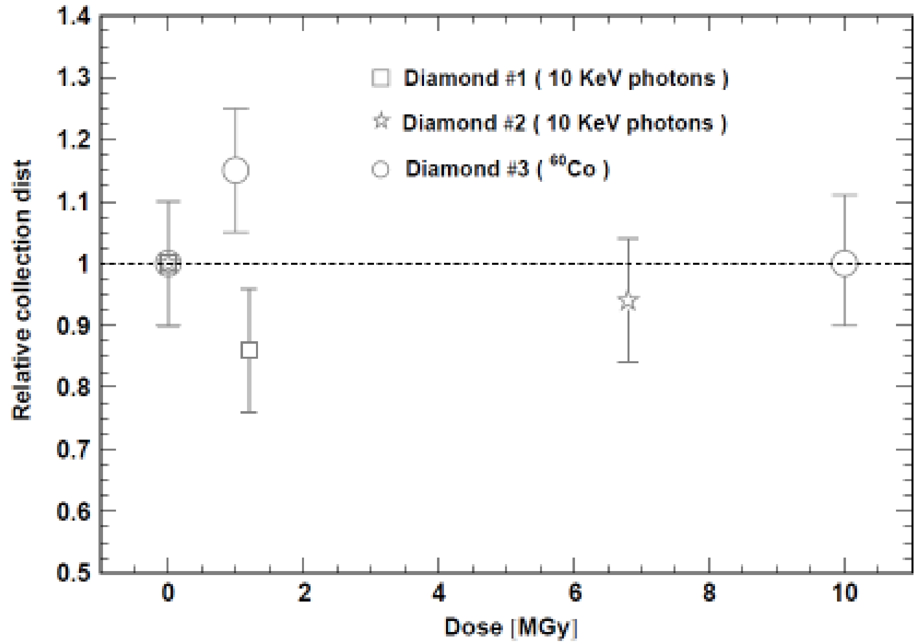
- Motivations:
  - Low-angle detectors for TESLA linear accelerator project [6]: detector at 1.2 cm from the beam line, dose of as much as 1 MGy per year.
- Materials and methods:
  - pCVD diamond from DeBeers, with Ti-Pt-Au contacts.
  - Irradiations: 10 keV photon beam and ^{60}Co source (1.17 and 1.33 MeV).
  - CCD and TSC measurements before and after radiation (primed samples, voltage for maximum carrier velocity).
  - Measurement of the TSC peak and of the CCD respect to the non irradiated samples.

[5] Behnke et al., NIM A, 2002, Electromagnetic radiation hardness of diamond detectors.
[6] Behnke et al., R. Settles (Eds.), 2001, TESLA technical design report, Part IV: A detector for TESLA.

10 keV γ-rays on pCVD

- ## Results: TSC and CCD





- **TSC peak increase with the bias accordingly to the increasing mobility.**
- **No effect of the irradiation on the TSC: same concentration of induced defects.**
- **No degradation of the CCD for any energy and dose.**
- **No radiation damage problem in diamond for applications like TESLA.**

[5] Behnke et al., NIM A, 2002, Electromagnetic radiation hardness of diamond detectors.

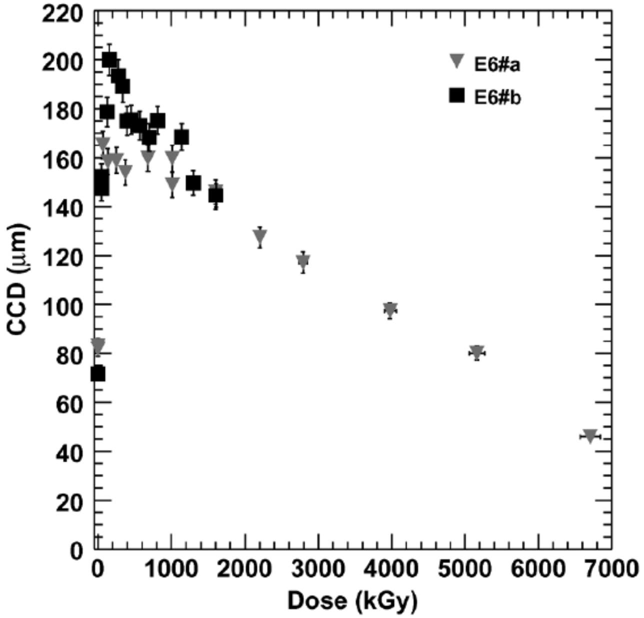
Electrons

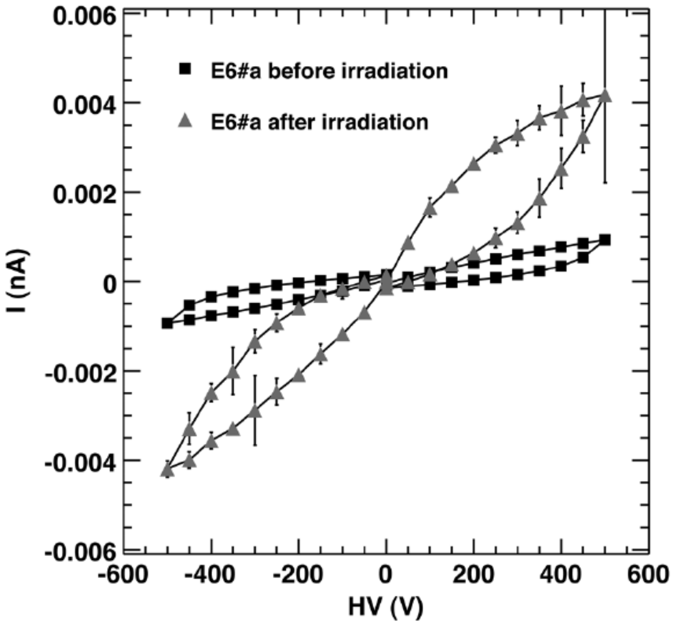
- Motivations:
  - At the International Linear Collider (ILC), the innermost calorimeter, the BeamCal, is hit by a huge amount of electron-positron pairs. Sensors are interspersed between the absorber planes to obtain information about the collision and provide a feedback for the steering.
  - The Total Ionizing Dose (TID) can accumulate to several MGy/year: radiation hardness is mandatory.
- Materials and methods:
  - pCVD diamonds from two manufacturers with Ti-Pt-Au contacts.
  - Irradiation with 10 MeV electrons up to a TID of several MGy (S-DALINAC, Darmstadt) and comparison with 4 GeV hadrons (PS, CERN) .
  - Measurement of the CCD before and after irradiation.
  - Comparison with silicon detector (3-5 kΩcm resistivity).

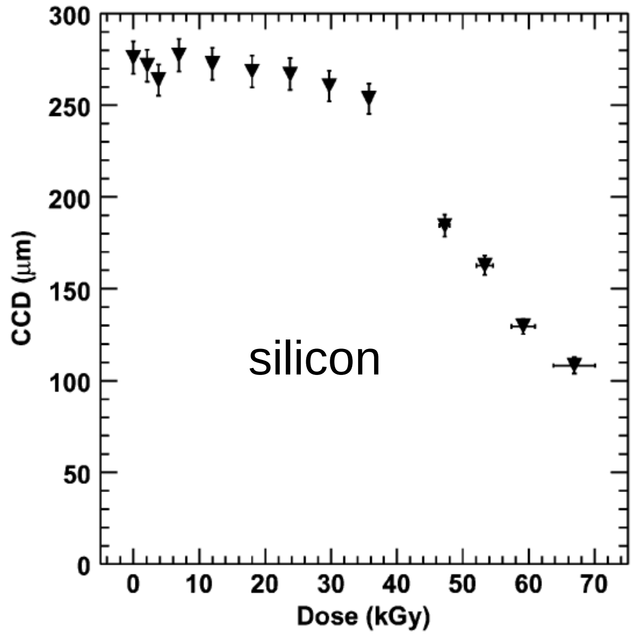
[14] Grah et al., IEEE TNS, 2009, Polycristalline CVD diamonds for the beam calorimeter of the ILC.

10 MeV electrons on pCVD

- ## Results: CCD and I-V







- **Initial pumping, then CCD down to a level comparable with the initial unpumped state.**
- **The current is still in the order of few pA after irradiation, thus is uncritical for operations as a detector. (In the Si detector it increases up to more than 6 uA.)**
- **The silicon detector is much less radiation hard.**

[14] Grah et al., IEEE TNS, 2009, Polycristalline CVD diamonds for the beam calorimeter of the ILC.

Neutrons

- Motivations:
  - Test radiation hardness and predict the radiation induced damage with a model.
- Materials and methods:
  - pCVD diamond compared to Si.
  - Neutrons from 10 keV to 20 MeV up to 1.6×10^{16} n/cm^2.
  - Measurement of the leakage current in time during the exposure and of the CCD after irradiation. Measurement of the maximum CCE in the primed state.
  - CCE vs. fluence empirical model [3]:

$$CCE(\phi) = CCE(\phi = 0)\left[r_n \left(1 - \frac{\phi}{\alpha_{n1}} \right) + (1 - r_n) e^{-\frac{\phi}{\alpha_{n2}}} \right]$$

- r_n: ratio of the CCE loss due to the linear part to the total.
- α_{n1}, α_{n2}: damage constants.

[3] Oh et al., DRM, 2000, Neutron irradiation studies with detector grade CVD diamond.

1 MeV neutrons on pCVD

- **Results:**

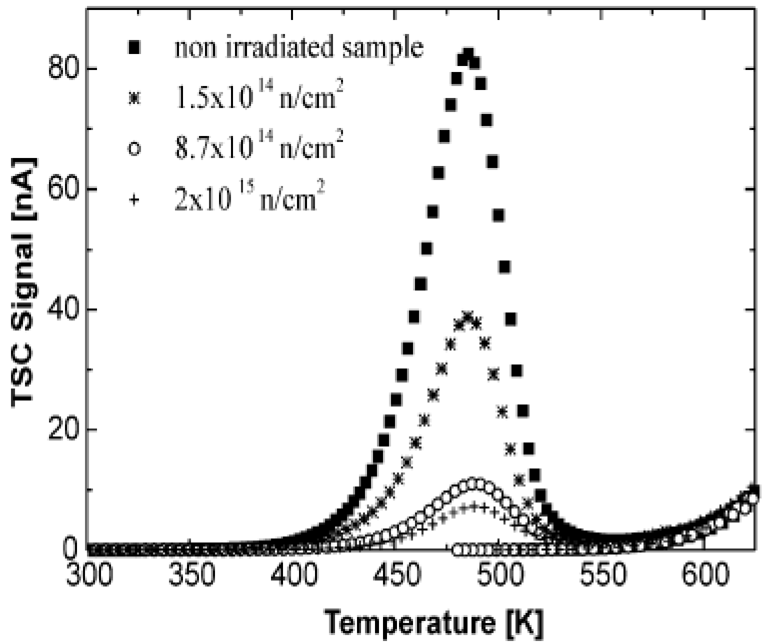


Fig. 1. TSC signal vs. temperature for non-irradiated and irradiated samples, after filling with UV xenon lamp for 20 min. The samples are biased with 100 V. The heating rate is 0.15 K/s. The neutron fluences are indicated in the legend.

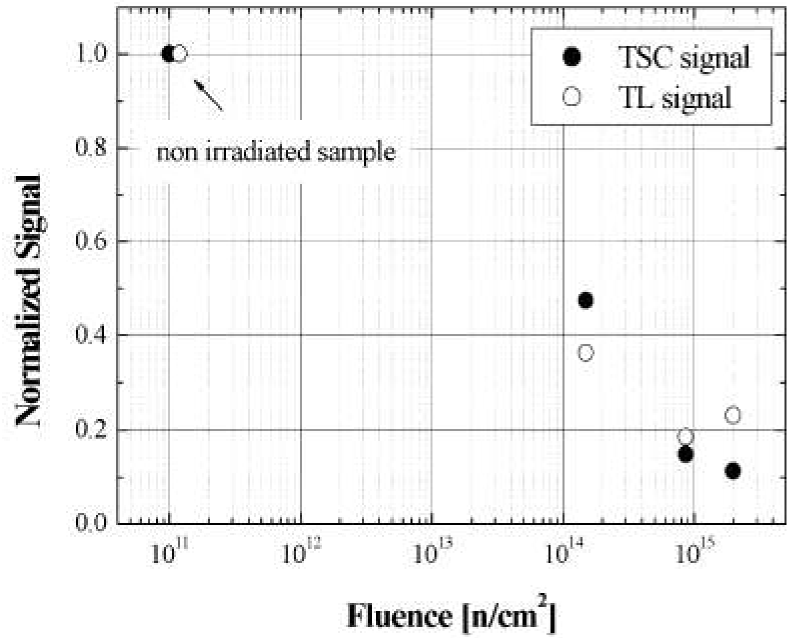


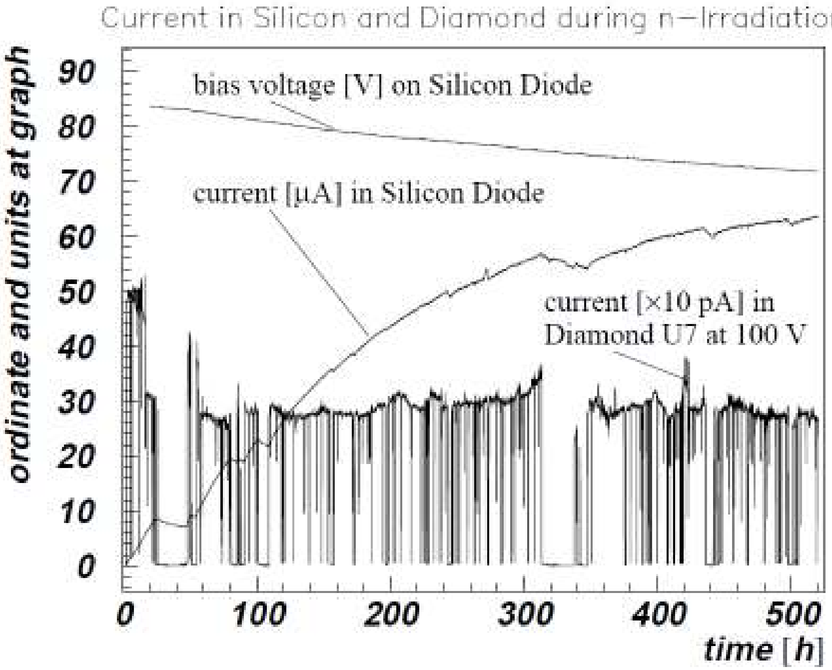
Fig. 5. Normalised TSC and TL signal vs. fluence obtained by the integral of the TSC and TL signal as a function of the temperature, dividing by the heating rate and normalising to the value corresponding to the non-irradiated sample.

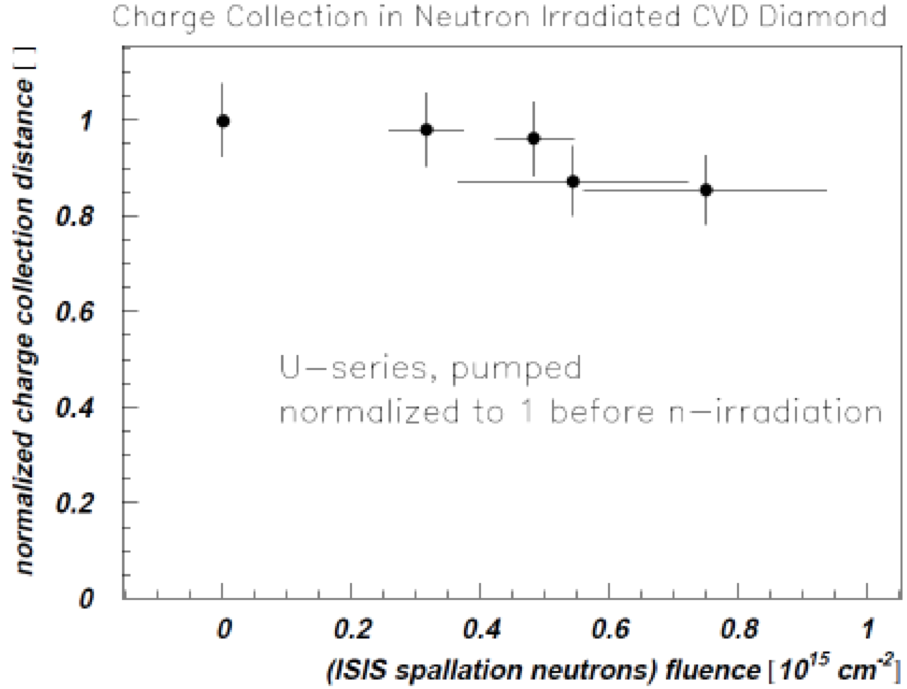
- **1 MeV neutrons deactivate high temperature electrically active defects.**
- **This corresponds to have faster dynamics in dosimetry (see M. Bruzzi talk).**

[7] Bruzzi et al., DRM, 2001, Electrical properties and defect analysis of neutron irradiated undoped CVD diamond films.

Spallation neutrons on pCVD

- **Results (from 10 keV to 10 MeV peaked at 5 MeV)**





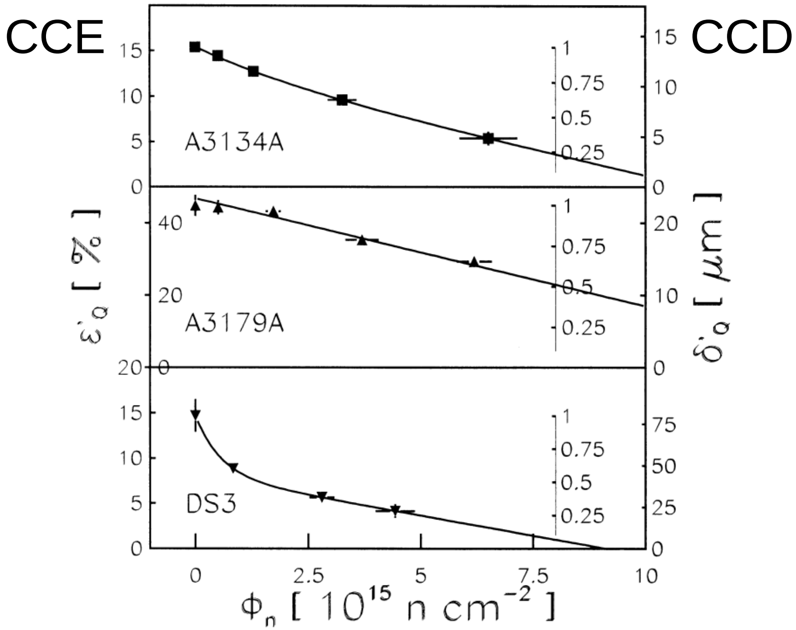
- **In diamond, very low and stable leakage current (≈300 pA) correlated to the neutron (or γ-background) flux. In silicon, the current increases (up to ≈10 uA) due to radiation induced defects creation.**
- **The CCD of diamond slightly decrease before 10^{15} n/cm^2.**

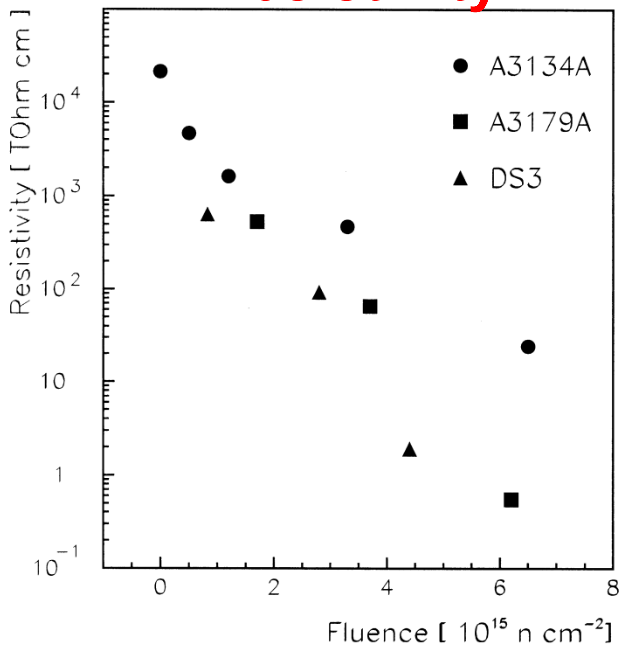
[4] RD42, CERN EP, 1998, Development of CVD diamond radiation detectors.

5 MeV neutrons on pCVD

$$CCE(\phi) = CCE(\phi=0)\left[r_n \left(1-\frac{\phi}{\alpha_{n1}}\right) + (1-r_n)e^{-\frac{\phi}{\alpha_{n2}}}\right]$$

- **Results: CCE** **resistivity**



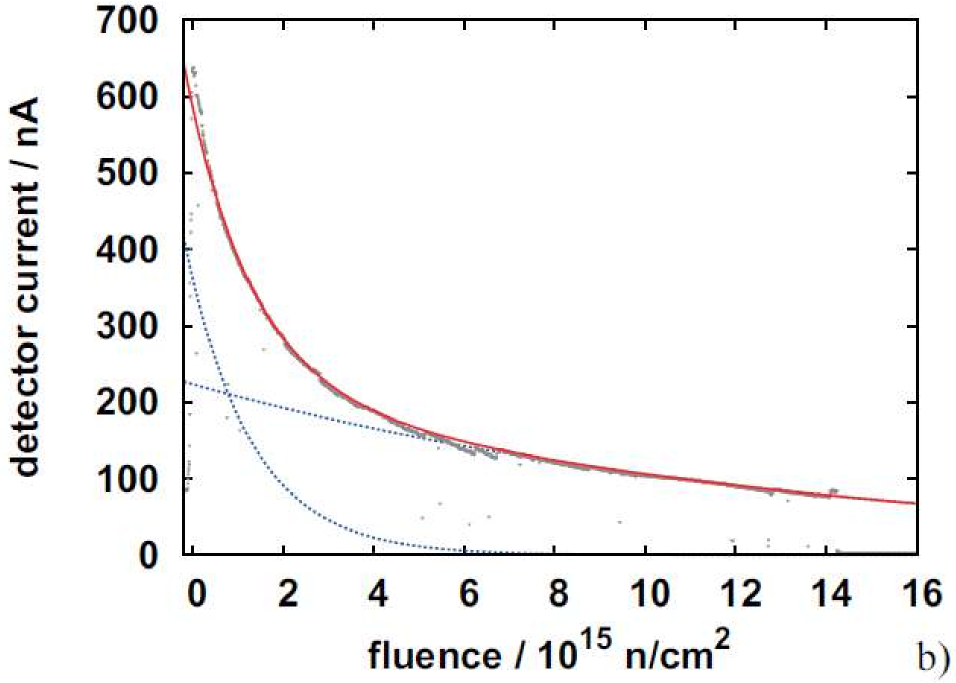


- **CCE decrease (as modelled) due to increasing defect concentration. Resistivity decreases because defects increases the free carrier concentration (but not a severe problem: >5x10^{11} Ωcm!!!).**
- **Samples behave differently: explained by different defects introduction rate.**
- **[3] model also priming, introduction rate, depth dependence.**

[3] Oh et al., DRM, 2000, Neutron irradiation studies with detector grade CVD diamond.

20 MeV neutrons on pCVD

- **Results: ionization signal**



- **The signal decrease of 50% after $(1.25\pm0.25)\times10^{15}$ n/cm^2.**
- **Twofold exponential decay (see [9]).**

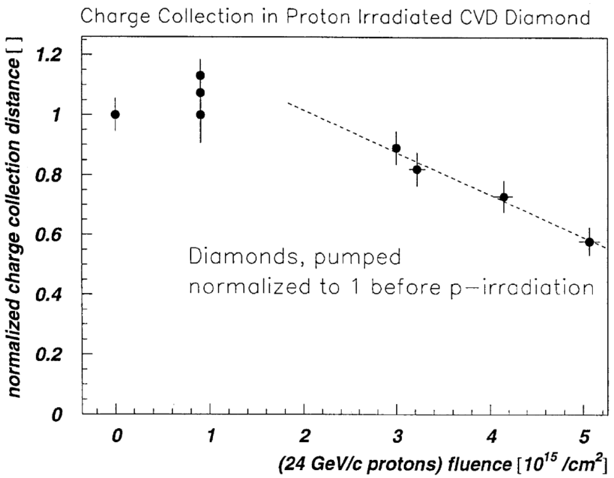
[8] de Boer et al., PSS, 2007, Radiation hardness of diamond and silicon sensors compared.
[9] Muller, Diploma thesis, 2006, University of Karlsruhe.

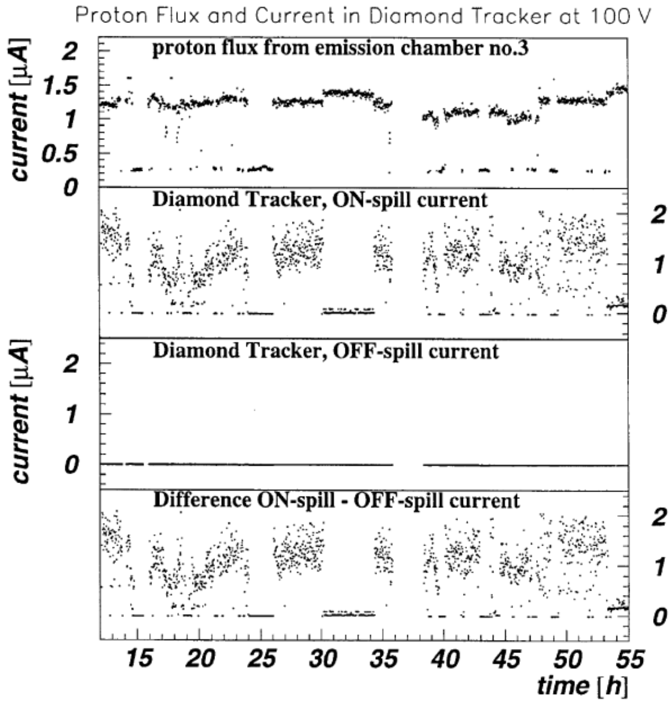
Protons

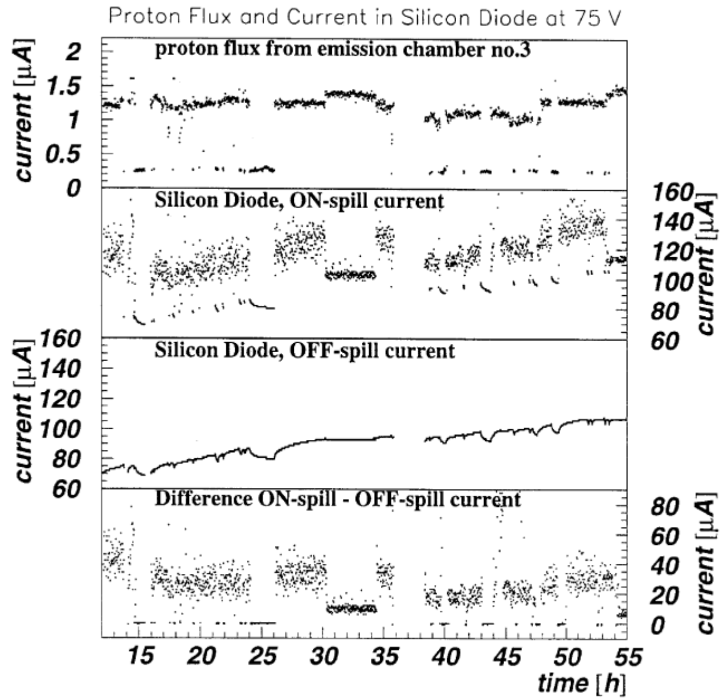
- Motivations:
  - Test the radiation hardness for LHC experiments.
  - Compare diamond with silicon performance with respect to proton irradiation.
- Materials and methods:
  - pCVD diamond samples with Cr-Au contacts and scCVD with Au contacts.
  - Irradiation with protons with 500 MeV kinetic energy (TRIUMF, Canada), 24 GeV/c momentum (PS, CERN), 26 MeV, 2.6 MeV (40 um penetration depth), up to 18×10^{15} p/cm^2.
  - Measurement of charge signal distribution, CCD and of particle-induced current during irradiation. IBIC (Ion Beam Induced Charge) on scCVD to measure the CCE with 2.6 MeV protons.

24 GeV/c protons on pCVD

- **Results: CCD and current for 24 GeV/c protons**





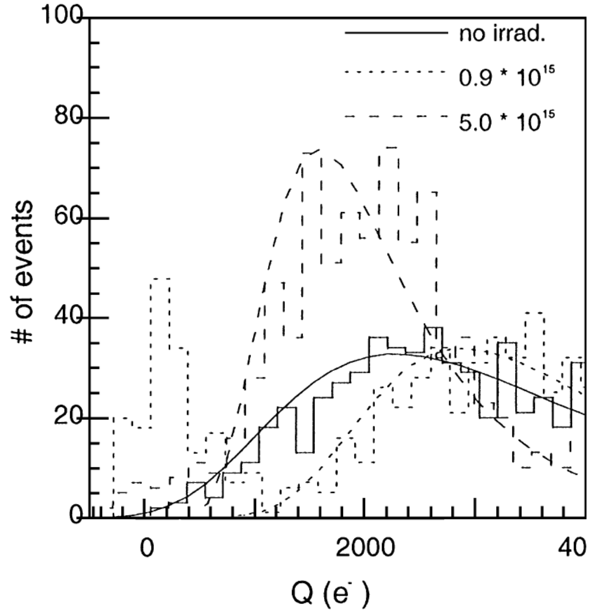


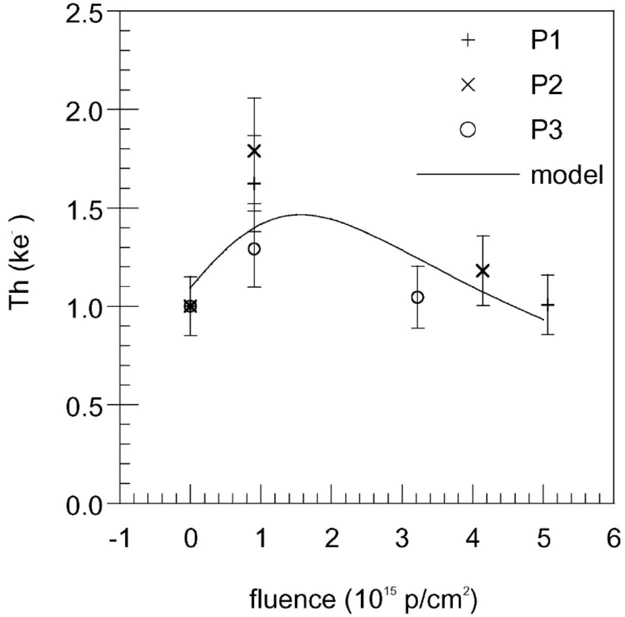
- **Diamond is radiation hard up to $2x10^{15}$ p/cm^2.**
- **Particle-induced current in diamond doesn't change in time.**
- **The OFF-spill current in diamond is negligible, while in silicon increases over 100 uA indicating radiation damage.**

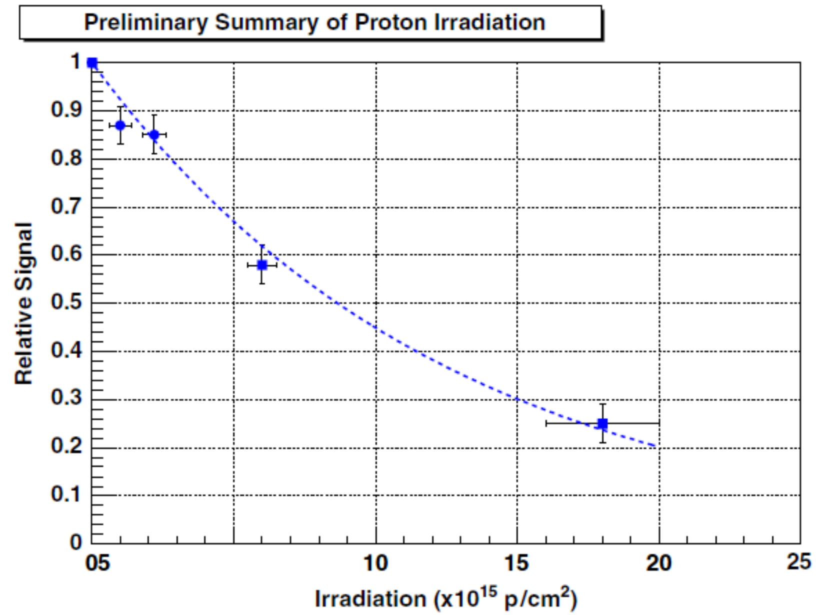
[10] RD42, NIM A, 1999, Proton irradiation of CVD diamond detectors for high-luminosity experiments at the LHC.

24 GeV/c protons on pCVD

- ## Results: signal distribution for 24 GeV/c protons





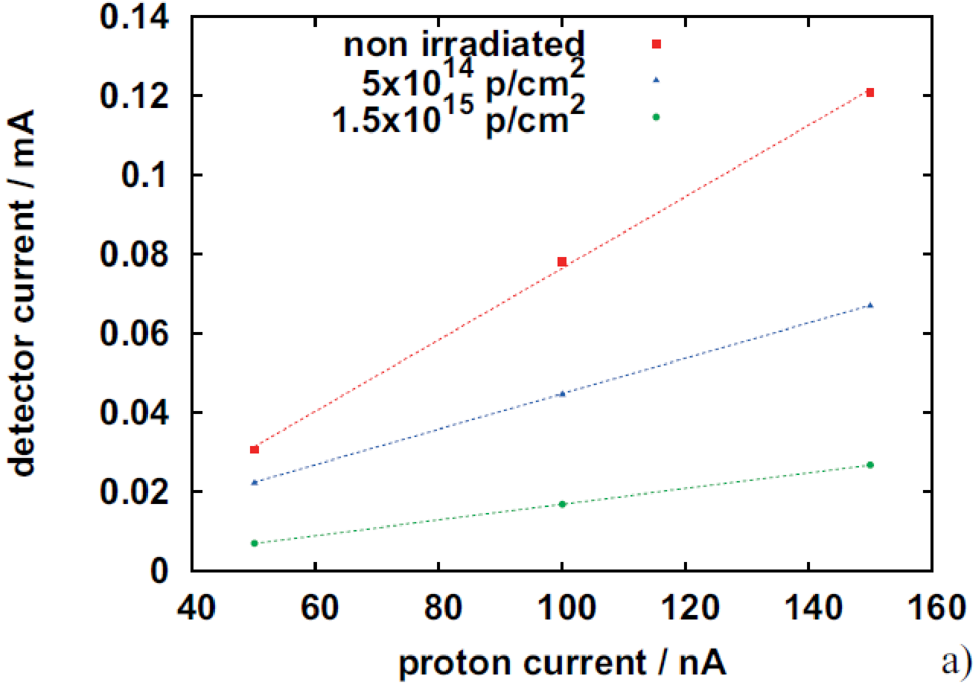


- **MPV decrease of 20% only at $5x10^{15}$ p/cm^2. Exponential decay of the signal with irradiation. “Radiation lifetime” is $12.5x10^{15}$ p/cm^2.**
- **Pumping effect for $0.9x10^{15}$ p/cm^2, radiation damage dominate over $3x10^{15}$ p/cm^2.**
- **The pulse height distribution agree with a model [12] accounting for the pumping and the radiation damage.**

[11] RD42, NIM A, 2000, Pulse height distribution and radiation tolerance of CVD diamond detectors.
[12] Adam et al., NIM A, 2006, Radiation hard diamond sensors for future tracking applications.

26 MeV protons on pCVD

- **Results: 26 MeV protons**



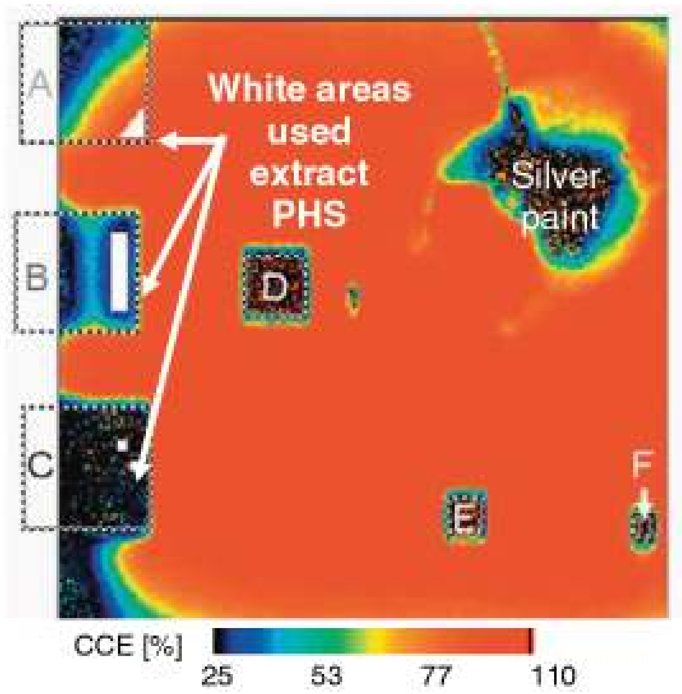
- **Signal decrease more rapidly respect to higher energetic protons and neutrons.**

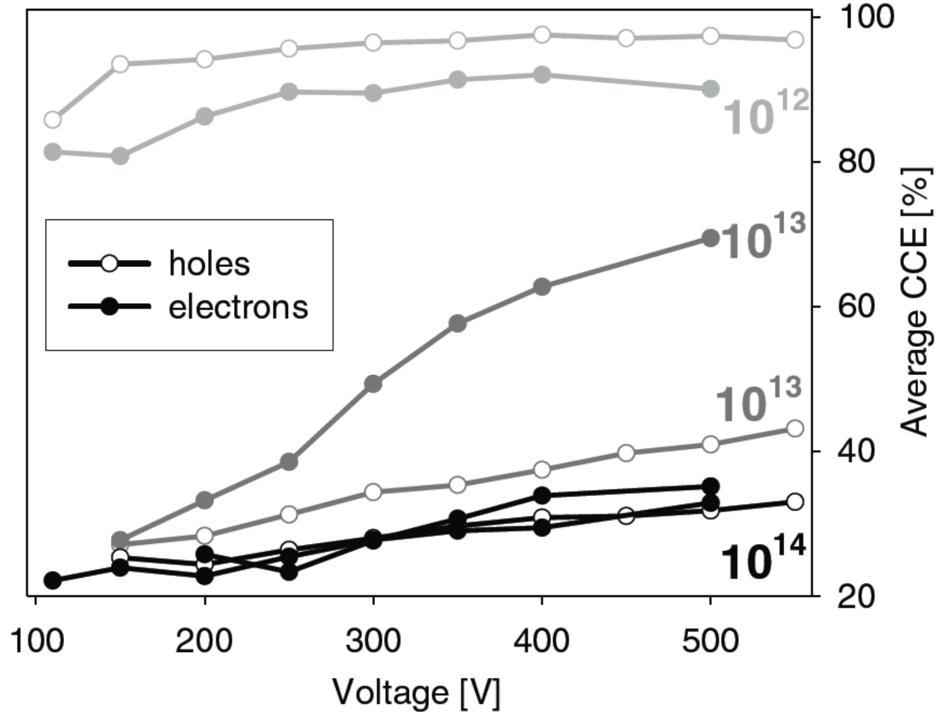
[8] de Boer et al., PSS, 2007, Radiation hardness of diamond and silicon sensors compared.

2.6 MeV protons on scCVD

- **Results: 2.6 MeV protons**

CCE map after irradiation of the areas A-F





- **Reduction of 50% of the CCE already at 10^{13} p/cm^2.**
- **2.6 MeV protons (Bragg peak at about 40 um) leave localized damage which influence the CCE, by trapping charges and reducing the field strength in the undamaged material for polarization effects.**

[13] Lohstroh et al., PSS, 2008, Ion beam induced charge (IBIC) irradiation damage study in synthetic single crystal diamond using 2.6 MeV protons.

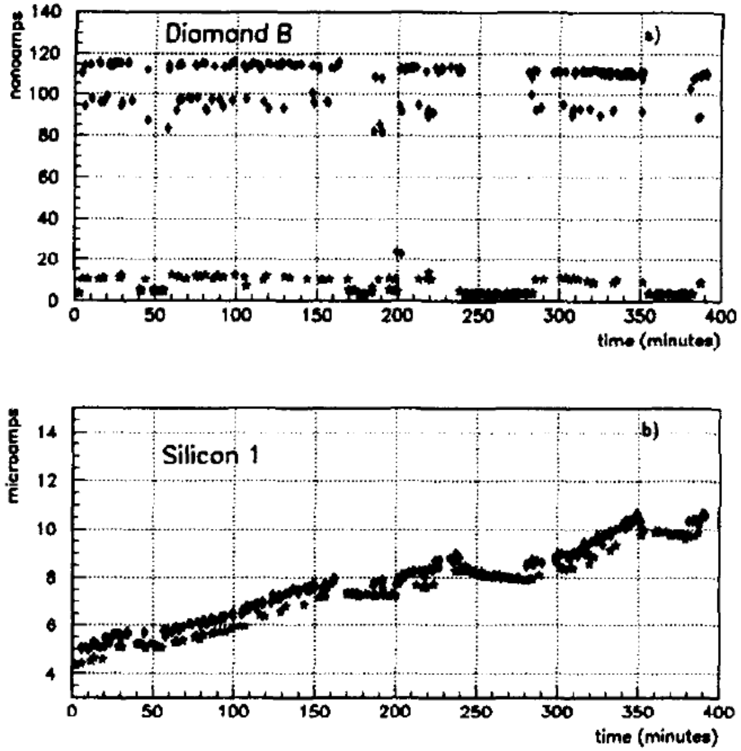
Pions

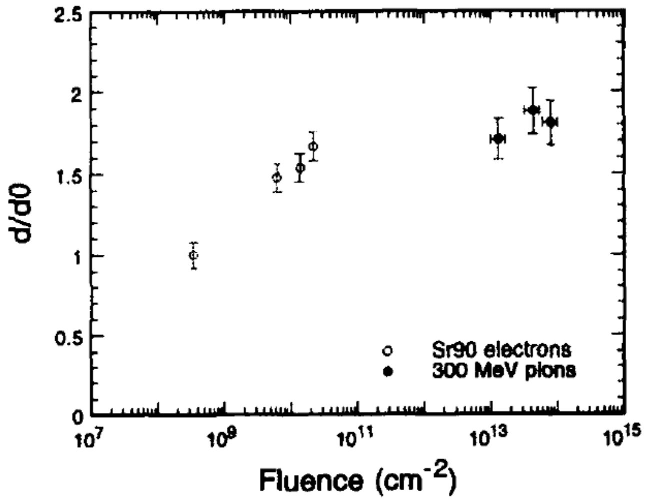
- Motivations:
  - Study the radiation hardness for the LHC.
- Materials and methods:
  - pCVD diamonds with Cr-Au contacts.
  - Irradiation with 300 MeV/c pions (correspondingly to the peak of the pion-nucleon cross section) up to 1.7×10^{15} π/cm^2.
  - Measurement of the particle-induced current and CCD.
  - Comparison with silicon detector.

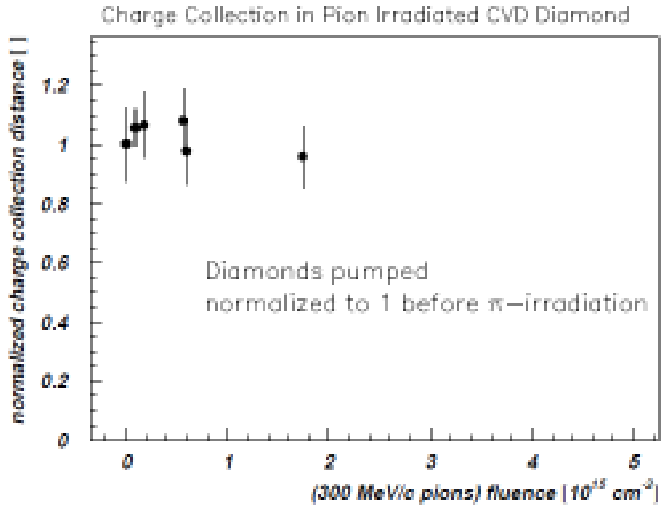
[4] RD42, CERN EP, 1998, Development of CVD diamond radiation detectors.
[15] Bauer et al., NIM A, 1996, Recent results from the RD42 diamond detector collaboration.

300 MeV/c pions on pCVD

• Results:







- **Diamond doesn't show increase of the leakage current after irradiation.**
- **Pumping effect for low fluences.**
- **Detector performances unchanged up to 1.7x10^{15} π/cm^2.**

[4] RD42, CERN EP, 1998, Development of CVD diamond radiation detectors.
[15] Bauer et al., NIM A, 1996, Recent results from the RD42 diamond detector collaboration.

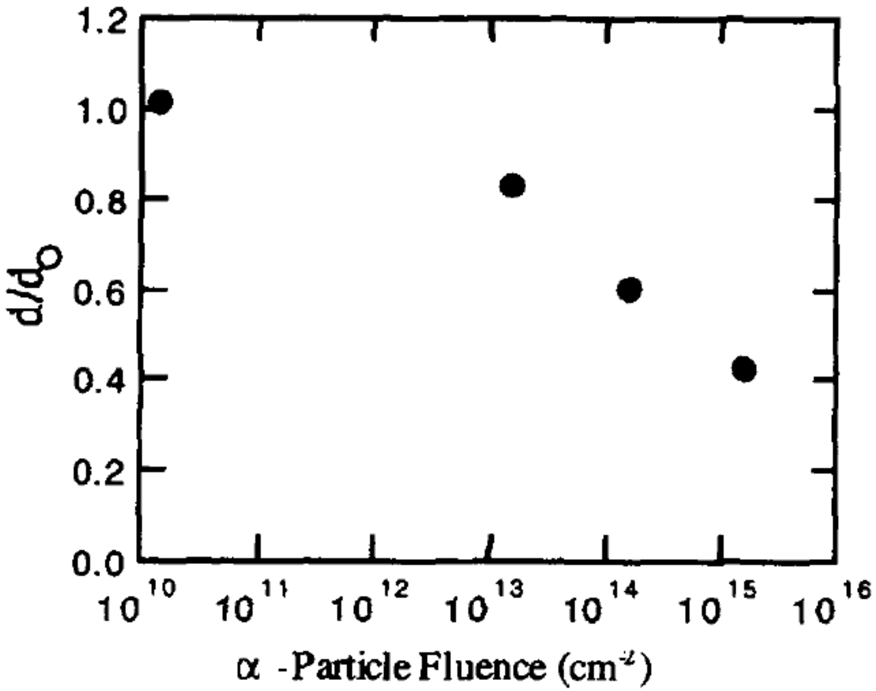
Alphas

- Motivations:
  - Study of the radiation hardness.
- Materials and methods:
  - pCVD diamonds with Cr-Au contacts.
  - Irradiation with 5 MeV alpha particles (12 um penetration depth) up to 2×10^{15} α/cm^2.
  - Measurement of the CCD by means of surface photo-induced conductivity measurements.

[15] Bauer et al., NIM A, 1996, Recent results from the RD42 diamond detector collaboration.

5 MeV alphas on pCVD

- **Results:**



- **20% CCD decrease after only $2x10^{13}$ α/cm^2.**

[15] Bauer et al., NIM A, 1996, Recent results from the RD42 diamond detector collaboration.

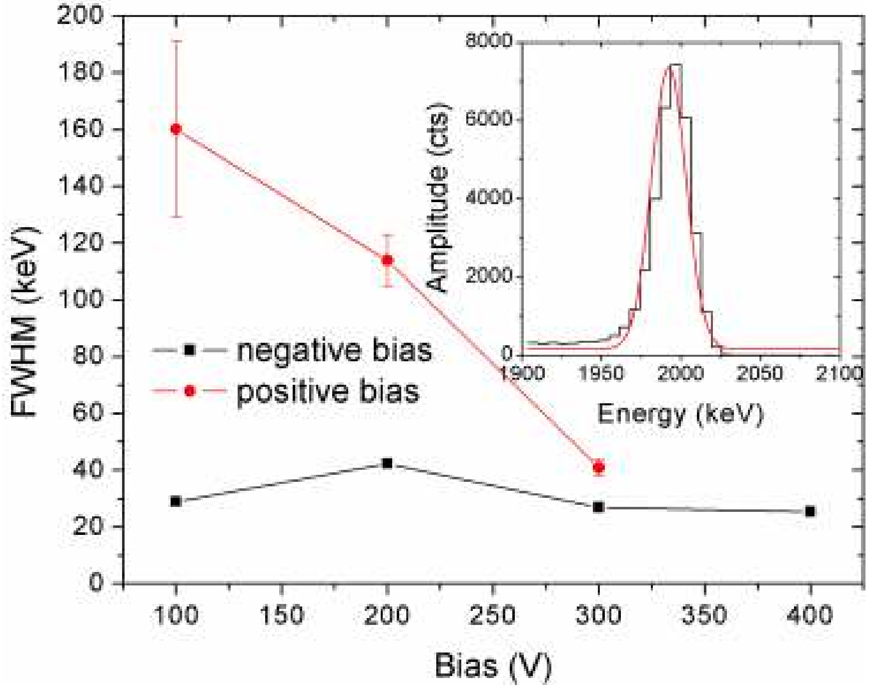
MeV-energy ions

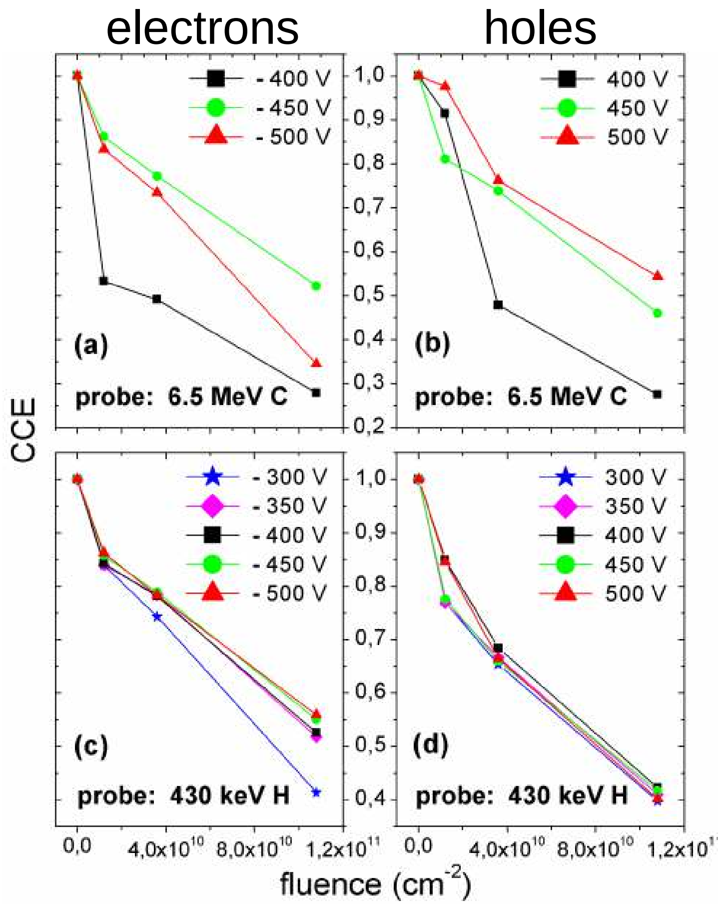
- Motivations:
  - At high energy hadron colliders, secondary interactions produce a significant fraction of particles in this range.
  - Reducing the range result in an increase of defect concentration, which is no longer homogeneous.
  - The radiation hardness cannot be simply extrapolated from the higher energy range.
- Materials and methods:
  - scCVD diamonds with diamond-like carbon film plus Pt-Au contacts and silicon PIN diode.
  - Carbon ions as damaging particles (avoid the implantation of foreign atoms).
  - Microprobe single ion technique IBIC (Ion Beam Induced Charge) to measure the CCE.

[16] Zamboni et al., DRM, 2012, Radiation hardness of single crystal CVD diamond detector tested with MeV energy ions.

MeV energy ions on scCVD

- **Results: hole and electron CCE**



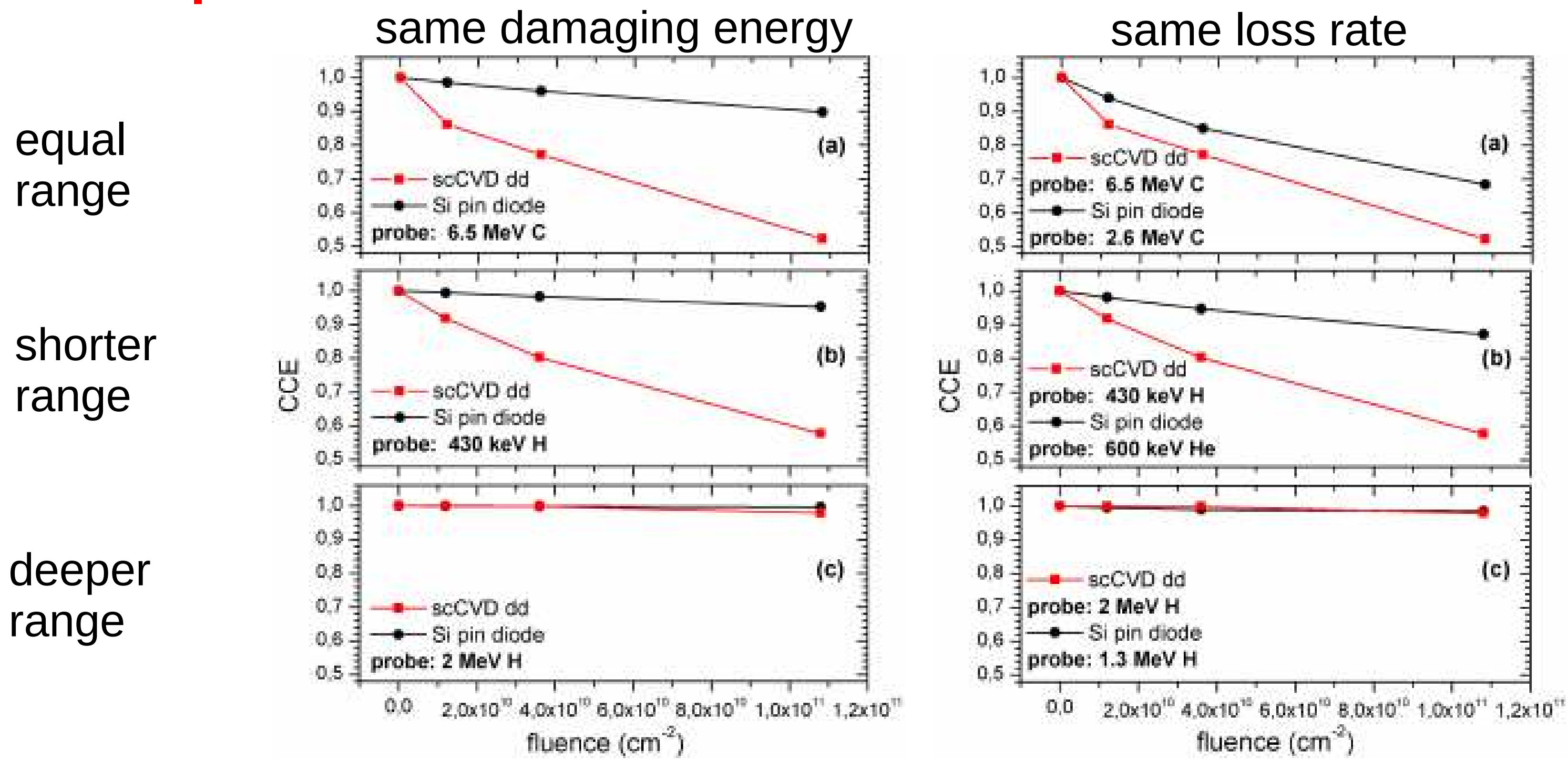


- **The detector energy resolution increase with the applied bias.**
- **Hole CCE deteriorate faster due to the more efficient hole trapping by carbon ion produced stable defects or less efficient electron trapping due to additionally produced donor centers.**

[16] Zamboni et al., DRM, 2012, Radiation hardness of single crystal CVD diamond detector tested with MeV energy ions.

MeV energy ions on scCVD

- **Results: comparison with silicon**



- **Same energy: over the entire carbon fluence range, silicon CCE is higher than diamond CCE.**
- **Same loss rate: higher CCE deterioration rate for silicon but still better than diamond.**

[16] Zamboni et al., DRM, 2012, Radiation hardness of single crystal CVD diamond detector tested with MeV energy ions.

MeV energy ions on scCVD

- Irradiation with C ions produce more hole traps or donor centers, as suggested by the higher hole CCE deterioration.
- Radiation at MeV energies produce higher defect concentration in a small volume, decreasing local lifetime by increasing trapping probability. It influences the overall CCE more respect to an homogeneous irradiation.
- For 6.5 MeV C ions, the simulations give four times more vacancies in silicon than in diamond, but results show lower radiation hardness of diamond:
  - Much higher mobility and recombination of defects in silicon at RT that reduce the net concentration.
  - Stronger influence of polarization effects in damaged regions of diamond.

[16] Zamboni et al., DRM, 2012, Radiation hardness of single crystal CVD diamond detector tested with MeV energy ions.

Summary

- Diamond is currently planned for fundamental and high energy physics experiments as a tracking detector, beam condition monitor, fission reactor flux monitor, etc..
- It should withstand an high radiation environment maintaining its unique properties such as fast response, collection efficiency, energy resolution. Radiation hardness is a fundamental property.
- In the last 15 years, diamond radiation damage has been tested with γ-rays, neutrons, protons, electrons, pions, alphas and low energetic ions.
- Results show diamond is radiation hard up to several MGy of photons and electrons, up to 10^{15} (neutrons and high energetic protons)/cm^2 and >10^{15} pions /cm^2. In such conditions, leakage current remains negligible and CCD decreases only slightly.
- Apart for low energetic ions, silicon detectors appear to be much less radiation hard than diamond in terms of CCE.
- Radiation damage in diamond is more significant for low energetic protons, neutrons, alphas and MeV ions.
- Most of the studies are for pCVD due to historical reasons, more tests on scCVD are required!
- A model on radiation hardness should account for different particles and energy (NIEL) .
- More systematic studies on radiation induced defects and simulations are required to get to it.

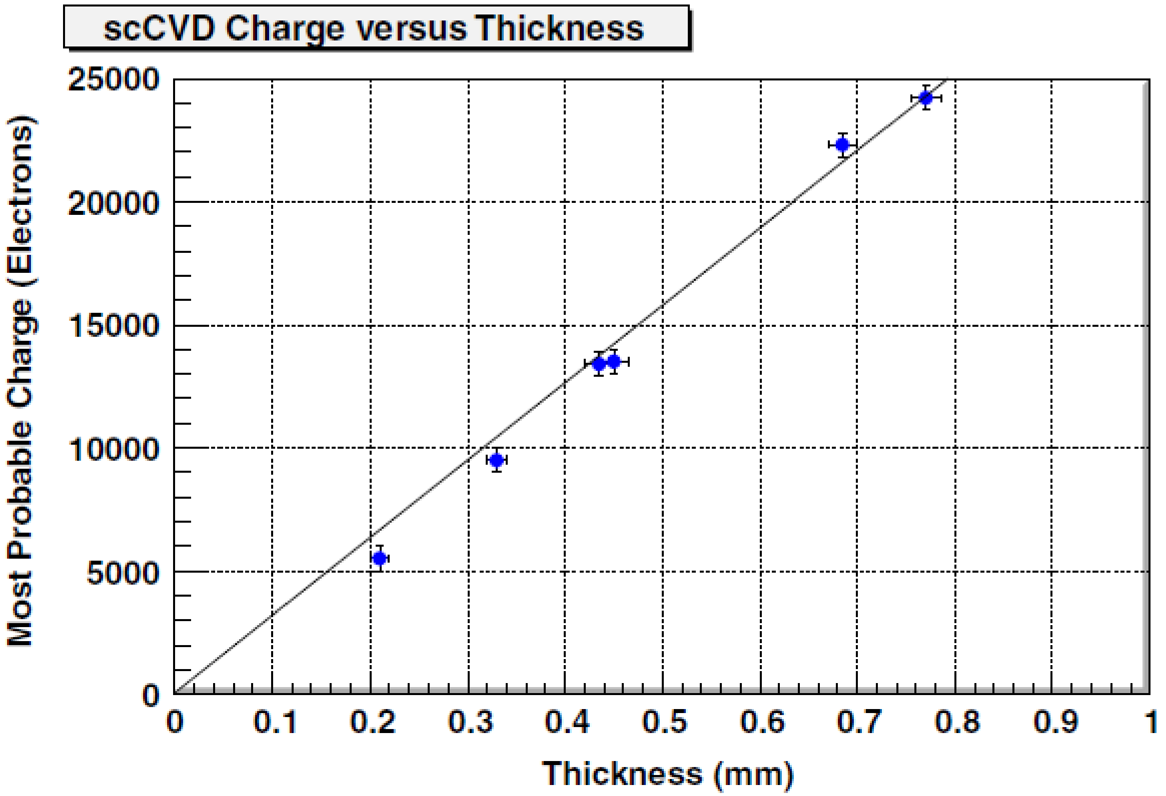
Thank you for your attention!!!

Spares

- Properties of the scCVD vs. thickness.
- Modeling of the CCD with pumping effect.
- MeV energy ions: penetration.
- NIEL damage cross section.
- Particles damage on silicon.

Properties of the scCVD vs. thickness

- Properties vs. thickness:



[12] Adam et al., NIM A, 2006, Radiation hard diamond sensors for future tracking applications.

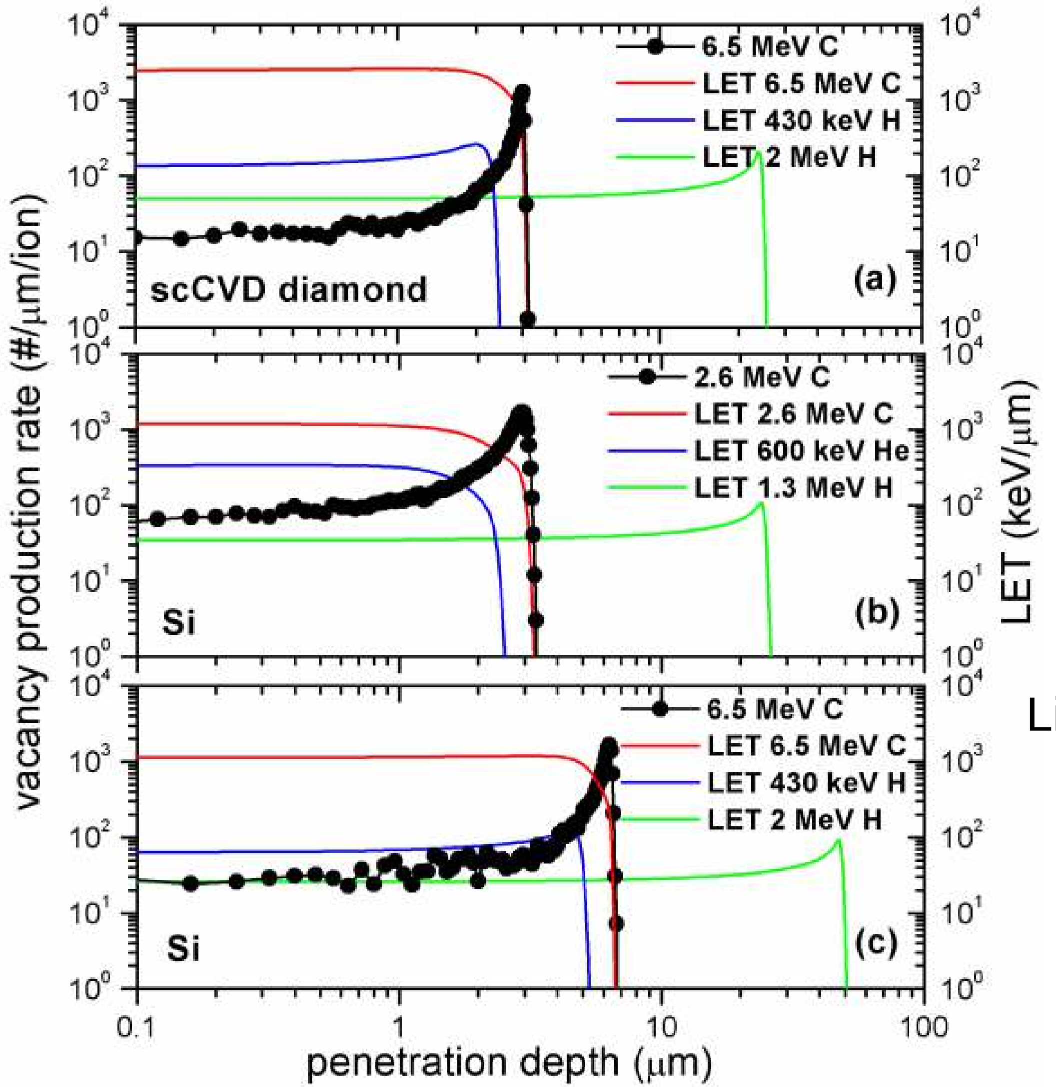
Modeling of the CCD with pumping effect

$$\frac{1}{CCD(\phi)} = \frac{1-\delta+\delta e^{-\gamma\phi}}{CCD(0)} + k\phi$$

- δ: fraction of the traps which can be passivated.
- γ: passivation constant.

[11] RD42, NIM A, 2000, Pulse height distribution and radiation tolerance of CVD diamond detectors.

MeV energy ions: penetration



Linear energy transfer

[16] Zamboni et al., DRM, 2012, Radiation hardness of single crystal CVD diamond detector tested with MeV energy ions.

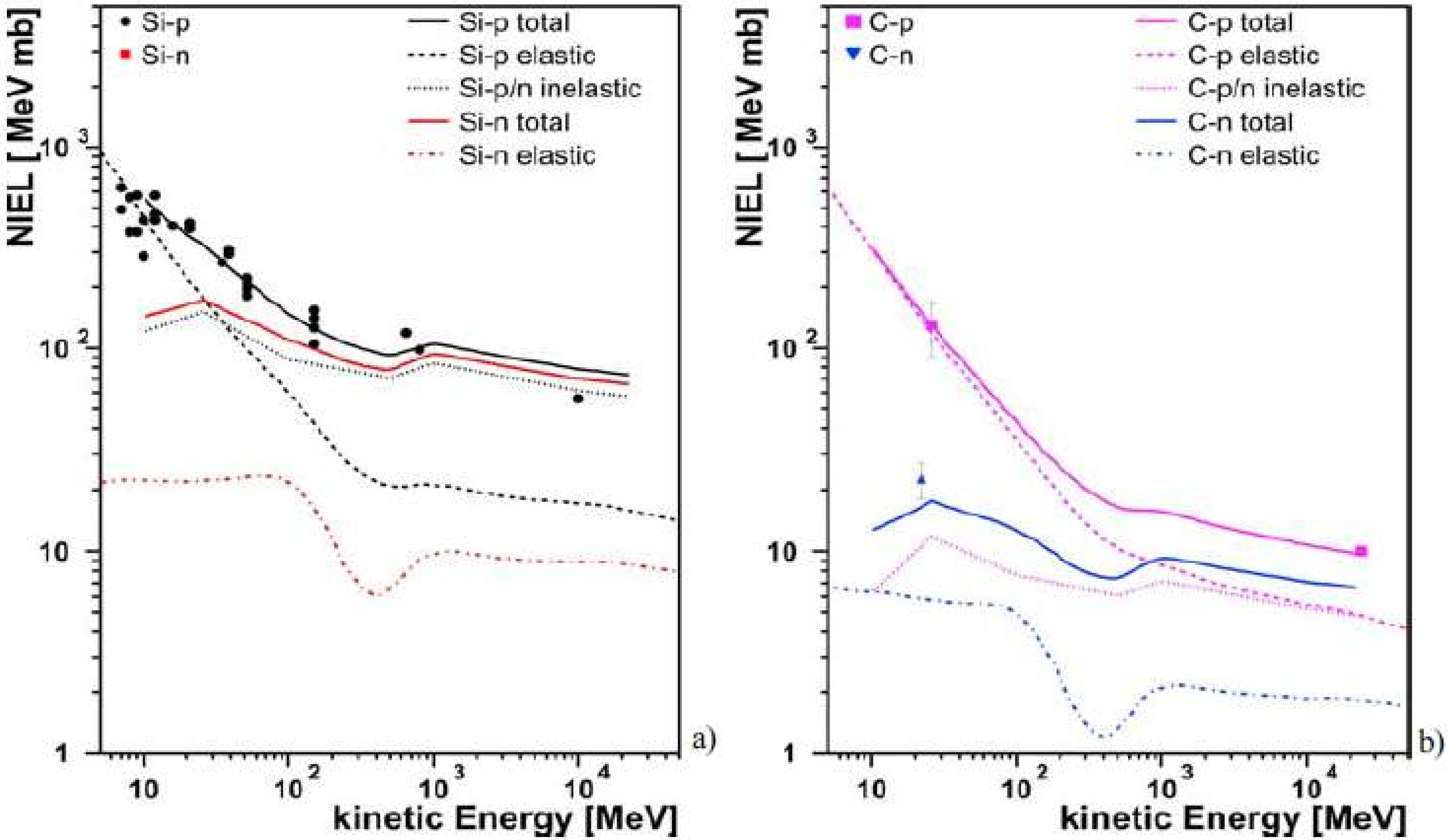
NIEL damage cross section

The NonIonizing Energy Loss (NIEL) express the rate of energy loss due to atomic displacement as a particle transverses the material.

The Kinetic Energy Released in MAtter (KERMA) is expressed by:

KERMA (keV)=NIEL(keV*cm^2/gm)* ϕ(cm^{-2})*mass(gm).

Here it is shown the Displacement damage cross section (in Si 100 MeVmb=2.144 keV*cm^2/gm).

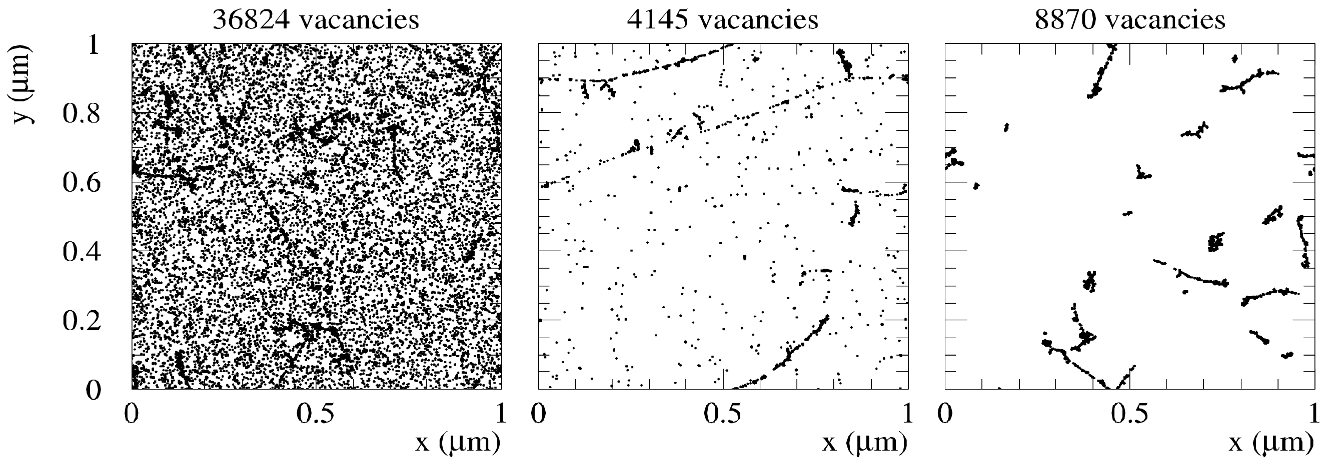


[8] de Boer et al., PSS, 2007, Radiation hardness of diamond and silicon sensors compared.

Particles damage on silicon

Initial distribution of vacancies in (1μm)^3 after 10^{14} particles/cm^2

10 MeV protons **24 GeV/c protons** **1 MeV neutrons**



[17] Huhtinen, NIM A, 2002.