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PARTICLE INTERACTIONS WITH DIAMOND DETECTORS

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Abstract

Chemical vapor deposition (CVD) diamond as radiation detector material has a wide range of applications, in particular for harsh radiation environments and at high temperatures. The sensitivity of diamond is exploited in measurements with charged particles, neutrons and photons.

Diamond detectors are used as beam loss monitors in particle accelerators, for photon detection in Synchrotron Light Sources, for neutron diagnostics in thermal neutron fields and for Deuterium-Deuterium (D-D) fusion and Deuterium-Tritium (D-T) fusion plasma neutrons.

In this paper we present the simulated and measured response functions of single-crystal (sCVD) diamond detectors to charged particles, heavy ions, thermal neutrons, fast neutrons, X-rays and gamma radiation. All measurements were performed with CIVIDEC diamond detectors and related electronics [1] at various research facilities.

CHARGED PARTICLES

Stopping Power

The interaction of charged particles with diamond sensors is based on the Bethe-Bloch formalism and was simulated with GEANT4 [2]. The minimum ionizing particle (MIP) energy for protons is 3 GeV, with a stopping power of 600 eV/µm in diamond. The MIP energy of electrons is 1.5 MeV with 570 eV/µm. The simulated stopping power in diamond is shown in Fig. 1, with examples for electron and proton facilities.

Electron facilities: DLS = Diamond Light Source (3 GeV), SP8 = Spring 8 (8 GeV), SLC = SLAC Linear Collider (47 GeV), LEP = Large Electron Positron Collider (105 GeV).

Proton facilities: MED = Medical Proton Therapy Facilities (250 MeV), SPS = CERN Super Proton Synchrotron (450 GeV), TVT = Tevatron (1 TeV), LHC = Large Hadron Collider (7 TeV).

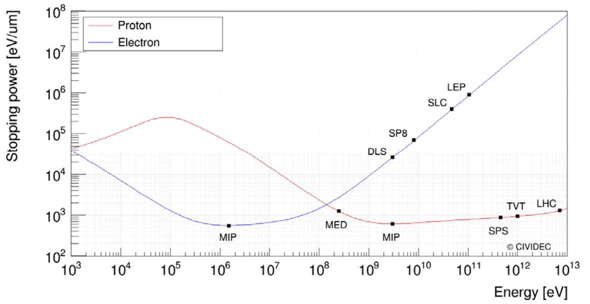

Figure 1: Bethe-Bloch function for electrons (blue) and protons (red) indicating the MIP energy and references of accelerator facilities.

Landau Distribution

The deposited energy spectrum by charged particles in diamond has a characteristic shape of a Landau distribution. The simulated most probable value (MPV) for MIP particles is 2.8 fC in 500 µm diamond, which corresponds to 17’500 electron-hole pairs, and to 35 eh-pairs/µm with the ionization energy of 13 eV/eh-pair in diamond.

The response of a diamond detector to a ^{90}Sr source, 0.5 MeV electrons (Fig. 2), is similar to the spectrum of MIP particles, with an MPV of 3.8 fC.

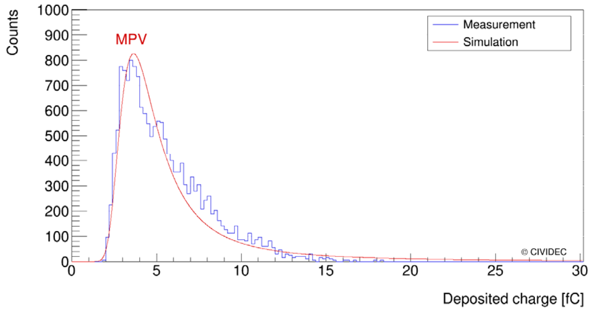

Figure 2: Deposited charge spectrum of ^{90}Sr β-particles in 500 µm diamond. The measured (blue) and the simulated Landau distribution (red).

Heavy-Ion Spectroscopy

The deposited energy spectrum from a ^{238}Pu α-source (Fig. 3), emitting 5499 keV (71%) and 5456 keV (29%) α-particles, was measured in vacuum [3]. The simulated spectrum with GEANT4 includes ionization fluctuations of 5.6 keV FWHM, the electronic noise of 14.1 keV FWHM and energy straggling of 9.4 keV FWHM in the electrodes of the diamond sensor.

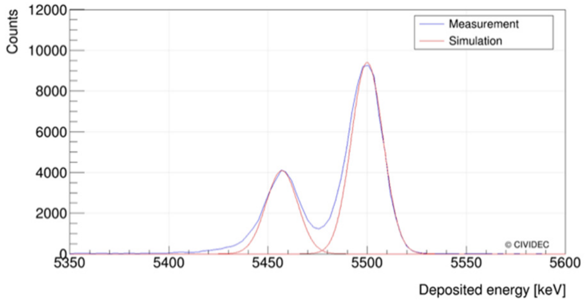

Figure 3: Deposited energy spectrum of ^{238}Pu α-source in diamond. The main measured peak with 21 keV FWHM compares well to the expected theoretical value of 19 keV.

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PHOTONS

X-Ray Interaction

The X-ray interaction with diamond is dominated by Compton scattering and the photoelectric effect. As an example, for 80 keV photons (Fig. 4) the characteristic Compton edge is at 19 keV energy deposition. The photoelectric effect appears at the initial photon energy minus the binding energy of the material, which is 288 eV for Carbon [4,5].

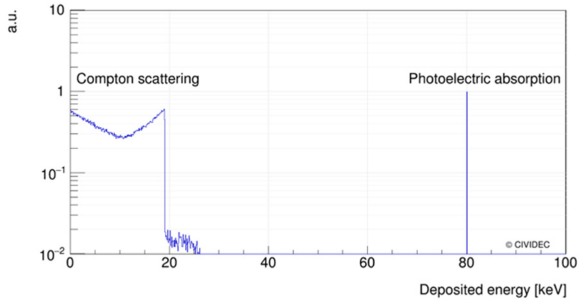

Figure 4: Deposited energy spectrum of 80 keV X-rays in 500 µm diamond.

The interaction probability of photons depends on the photon energy. The deposited charge per interacting photon is shown below (Fig 5.). The simulations were performed using GEANT4.

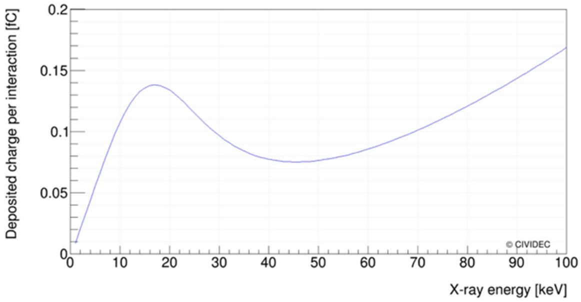

Figure 5: Distribution of the deposited charge per interacting photon for X-rays in 500 µm diamond.

γ-Ray Interaction

Compton scattering is the dominant effect for γ-rays up to 20 MeV. Pair production occurs for γ-ray energies above 1.022 MeV. The GEANT4 simulated spectrum for 2 MeV γ-rays is shown in Figure 6.

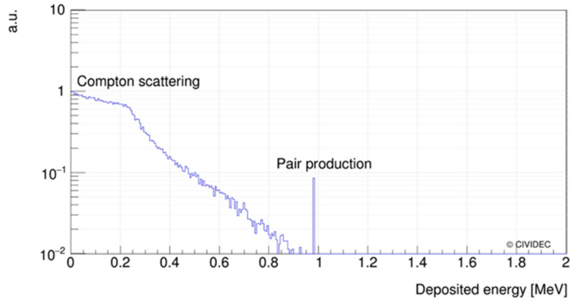

Figure 6: Deposited energy spectrum of 2 MeV γ-rays in 500 µm diamond.

The mean deposited energy by γ-rays is close to the MPV of MIP particles in diamond. The simulations are in good agreement with measurements performed at a γ-ray facility with sCVD diamond detectors published in [6].

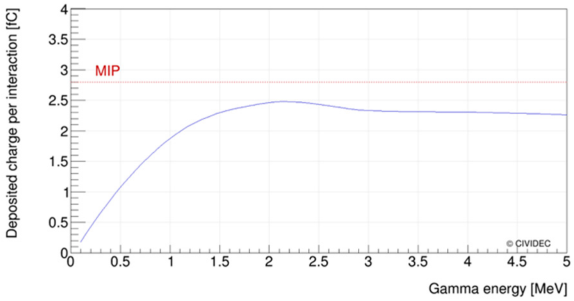

Figure 7: Deposited charge per interacting γ–ray in 500 µm diamond, compared to the deposited charge of MIP particles.

NEUTRONS

In neutron measurements the contribution of background to the detector response function has to be considered. The diamond detector is matched to the neutron environment, to suppress, for instance, strong γ-background in reactor environments.

Thermal Neutrons

To detect thermal neutrons with diamond sensors, a neutron converter foil, emitting heavy charged-particles, such as ^{6}Li, ^{10}B or fissile materials like ^{235}U, is used.

The reaction products of ^{6}Li(n,α)t are α-particles with an energy of 2.05 MeV and triton with 2.73 MeV. Measurements were performed at the TRIGA MARK-II reactor of TU Wien [7]. The strong γ-background from the reactor is well separated in the measurement.

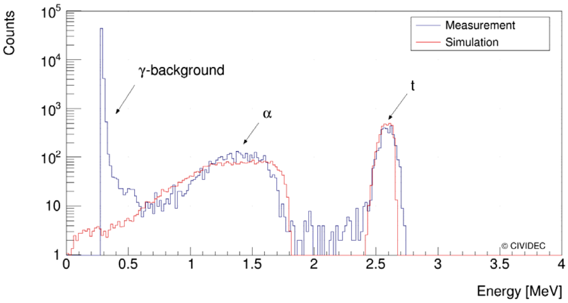

Figure 8: Deposited energy spectrum of thermal neutrons, using a ^{6}Li(n,α)t neutron converter. The γ-background is efficiently suppressed.

D-D Fusion Neutrons

Deuterium-Deuterium Fusion neutrons have 2.45 MeV energy and interact via elastic scattering on the Carbon nuclei in the diamond sensor, depositing maximum 0.8 MeV in the diamond sensor.

Measurements with D-D fusion neutrons were performed at the HiSPANoS facility of CNA Seville, Spain. The spectrum from a ^{22}Na source, emitting 1.3 MeV γ-rays is shown in comparison to judge the contribution of the γ-background in the experiment. The γ-background does not contribute significantly to the response function. The measurement agrees well with the simulated spectrum.

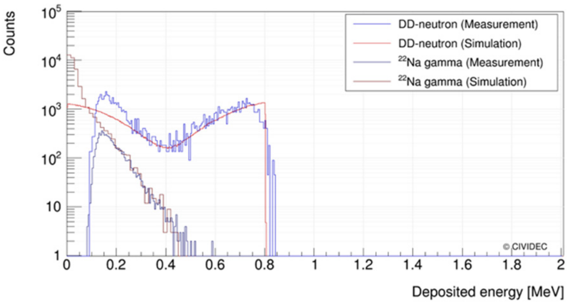

Figure 9: Diamond detector response function for DD-fusion neutrons and for γ-rays from a ^{22}Na source, compared to simulated spectra.

D-T Fusion Neutrons

Deuterium-Tritium (D-T) fusion neutrons have 14 MeV energy. Various nuclear interactions with the Carbon nuclei in diamond are identified in the response function of the diamond sensor to D-T fusion neutrons.

Measurements with 14 MeV neutrons were performed at the Van De Graaf accelerator facility at EC-JRC, Geel, Belgium [8]. Data was analysed using the method of pulse-shape discrimination, described in [9], for efficient background rejection.

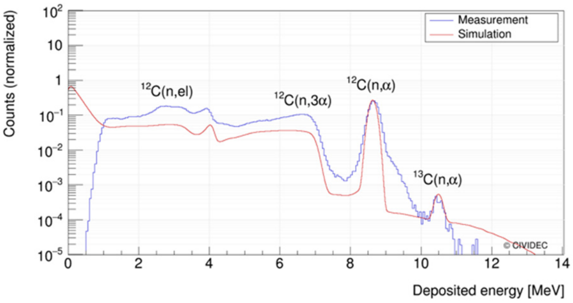

Figure 10: Detector response function for DT-fusion neutrons. The ^{12}C(n,a)^{9}Be peak is the most pronounced structure in the spectrum.

CONCLUSION

The simulated response of diamond detectors to charged particles, heavy ions, thermal neutrons, fast neutrons, X-rays and γ-rays is described in this paper. GEANT4 simulations are compared to measurements which were performed at various research facilities. Very good agreement between Monte-Carlo models and practical measurements is demonstrated. The wide range of possible applications of diamond detectors as radiation sensors is emphasized in this article.

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