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Diamonds for Beam Instrumentation

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Abstract

Diamond is perhaps the most versatile, efficient and radiation tolerant material available for use in beam detectors with a correspondingly wide range of applications in beam instrumentation. Numerous practical applications have demonstrated and exploited the sensitivity of diamond to charged particles, photons and neutrons. In this paper, a brief description of a generic diamond detector is given and the interaction of the CVD diamond detector material with protons, electrons, photons and neutrons is presented.

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1. Introduction

Diamond detectors are currently exciting a lot of attention. Their high radiation tolerance, their rapid response of the order of nanoseconds, and their low dark current of the order of pico-amperes make them excellent particle detectors for applications in beam instrumentation devices [1]. It has long been known that diamonds fluoresce and generate electrical signals when irradiated. The emergence of single-crystal and poly-crystalline CVD diamond made it possible to provide detector material with precise shapes, and uniform and predictable properties, while modern electronics make it possible to fully exploit the pico-second structure of the diamond response. These basic ingredients provide all that is needed for an extremely wide range of high-energy particle monitors and counters. The development of diamond

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detectors is a field where the basic physics is known, but technology is constantly pushing the boundaries outwards.

- Photons can be monitored above 5.5 eV, which corresponds to the conduction band, using a diode configuration in which the photo-excitation current is measured. In the range of 2 keV up to 50 keV diamond fluorescence monitors are widely used. Above 50 keV, the photo-ionized electrons ejected from the diamond start to create ionization in their own right and detectors configured as ionization chambers can be used, even for single-photon detection.
- For neutrons, a diamond monitor configured as an ionization chamber can be used with a converter from thermal energies up to 6 MeV and above this energy there is no need for the converter. Recent tests at n_TOF (CERN) have gone up to 1 GeV neutrons.
- For electrons, diamond is used in the ionization mode and is frequently configured as a quadrant monitor in synchrotron light sources.
- Possibly the main advance in diamond detectors is currently in the detection of protons and ions. Giga-particle counting up to 3.5 TeV has been demonstrated at the LHC (CERN) and carbon ions have been calorimetrically measured in the energy range of 30 MeV at ISOLDE (CERN).

1.1. Principle of operation

Figure 1 shows the operating principle of a diamond detector. Diamond is a semiconductive material. Particles traversing the detector ionize electrons and holes, which drift in the externally applied electric field and induce a current signal in the preamplifier. The ionization energy for CVD diamond is 13 eV/eh-pair and the stopping power for minimum ionizing particles (MIP) is 615 eV/ μm .

Fig. 1. Principle of a diamond detector.

In a single crystalline detector with a thickness $d = 500 \mu\text{m}$, the drift time t_d is of the order of 6 ns with an applied electric field of $1 \text{ V}/\mu\text{m}$. The corresponding drift velocity v_d is 10^5 m/s at a bias voltage $U_B = 500 \text{ V}$. The loading resistor R is $1 \text{ M}\Omega$ and the coupling capacitance $C = 1 \text{ nF}$.

There are two modes of operation: Particles traversing with high energy will use only a part of their energy for ionization. In this case of uniform ionization across the detector they generate a triangular output pulse shape. Particles with lower energy will be absorbed and they deposit all their energy in the diamond. In the case of a point-like ionization they produce a rectangular output pulse shape. The first mode is dubbed the “counting mode” and the second the “calorimetric mode”. See Figure 2.

Fig. 2. Theoretical pulse shapes: (a) counting mode: a linear charge density is ionized which induces the triangular pulse shape; (b) calorimetric mode: a point-like charge density is ionized, causing a rectangular pulse shape. The opposite ionized particles are immediately absorbed by the adjacent electrode and cause the Dirac-like initial current peak, which can hardly be detected by up-to-date readout electronics.

If a particle traverses the detector, a linear charge density is ionized which will move to the collecting electrodes. As a result, a triangular current will be induced in the electrodes (see Figure 2a). In the case where a heavy ion is stopped directly after an electrode, a point-like charge will be induced. One part will be immediately absorbed by the adjacent electrode and cause a Dirac-like induction current. The opposite charged ionized particles will move to the second electrode and induce a rectangular pulse shape (see Figure 2b). The type of ionization can be derived by the shape of the induced current [9], as long as a fast current amplifier is used. It is important to see that in both of these modes only 50% of the generated charge Q contributes to the current signal.

2. Types of operation

2.1. Proton interaction

Protons ionize the CVD diamond on their passage through the material with an efficiency of essentially 100%. The stopping power represents the energy loss of the particles in the detector in $\text{eV}/\mu\text{m}$. The function of energy loss versus particle energy corresponds to the Bethe-Bloch function (see Figure 3). The stopping power shows a maximum at 100 keV and a minimum at 3 GeV.

The values of dE/dx can easily be converted into the deposited charge by division of the ionization energy of 13 eV/eh pair. Figure 4 shows the ionization charge in fC for the example of a 500 μm thick detector.

Fig. 3. Bethe-Bloch function representing the stopping power of protons in CVD diamond.

For detecting single particles the level of ionization must be higher than the noise of the preamplifier. In Figure 4 the limit is drawn at 1 fC. Above this threshold, single particles can be detected. Below this threshold particle bunches are required to generate a signal that exceeds the threshold.

Fig. 4. Ionization characteristics of protons in 500 μm sCVD diamond.

At energies below 100 keV protons are absorbed and proton bunches are required in order to generate a detectable signal above 1 fC. At energies below 10 MeV protons are absorbed (calorimetric mode) but they generate a signal above threshold, which makes single-particle detection possible. Above 10 MeV protons traverse the detector (counting mode) and generate signals where single particle detection is possible.

Heavier ions create more ionization, which can be estimated from Figure 4 by multiplying the charge created by a proton by a) the mass number of the incident ion in the calorimetric mode and b) the square of the charge number of the incident ion in the counting mode.

Diamond detectors were used for calorimetric and spectroscopic applications with 23 MeV carbon ions at ISOLDE [2]. At LHC single-particle detection is currently applied in the Diamond Beam Loss Monitors for 3.5 TeV protons [3]. In particular, the time resolution of 1 ns is interesting for this application, as the bunch separation at LHC is 25 ns, making measurements of ghost bunches feasible. For medical applications with proton energies in the range of 70 MeV to 250 MeV diamond detectors are used for phase measurements and beam profile monitoring [4].

2.2. Electron interaction

The same approach can be applied to quantifying the electron interaction. Figure 5 shows the charge generation of electrons in a diamond detector.

Above 400 keV, electrons traverse the detector and are individually detectable (counting mode). Between 80 keV and 400 keV, electrons will be absorbed by the detector, but they are still individually detectable (calorimetric mode). Below 80 keV only electron bunches generating over 1 fC can be resolved from the noise.

Diamond detectors are used in electron accelerators for synchrotron light sources as beam loss monitors where the sub-nanosecond time resolution is needed.

Fig. 5. Ionization characteristics of electrons in 500 µm sCVD diamond.

2.3. Photon interaction

Figure 6 shows the three interaction processes in diamond in the range of 10 keV to 1 TeV that contribute to the ionization left by photons in the detector. As mentioned in the introduction, photons can also be detected at much lower energies (from 5.5 eV using a diode configuration in which the photo-excitation current is measured and, in the range of 2 keV up to 50 keV, using diamond fluorescence monitors). However, these low energy examples are not considered here.

Fig. 6. Cross section of photon interaction in 500 μm sCVD diamond. The photo-electric effect is drawn in red, Compton scattering in green and pair production in blue. The black line indicates the total cross section. The photo-electric effect dominates in the region up to 20 keV where Compton scattering takes over. Pair production becomes important from 2 MeV onwards and becomes the dominant process at 20 MeV. These three effects create secondary ionization.

- The photo-electric effect creates one primary electron per photon (with the full energy of the photon) and this electron creates secondary ionization according to the graph in Figure 5.
- Scattered photons produce both a primary electron and a scattered photon that share the incident photon energy. The primary electron will create secondary ionization according to Figure 5 and the scattered photon can, in principle, participate in further scattering or the photo-electric effect. However, this potentially complicated situation is largely avoided because the low interaction rate for photons in diamond ensures that the majority of the scattered photons escape from a 500 μm thick detector without further interaction.
- In pair production, the primary electron and positron share equally the energy of the incident photon and both particles create secondary ionization according to Figure 5

Diamond detectors are used as dosimeters in medical X-ray applications [5]. For future applications in synchrotron light sources like XFEL diamond detectors are under investigation as intensity monitors and to measure the position and the timing of photon bunches [6].

2.4. Neutron interaction

Diamond detectors were tested at the n_TOF facility at CERN. The interaction between neutrons and CVD diamond is shown in Figure 7 over an energy range from eV to GeV neutrons [7].

Fig. 7. Measurement with a 500 μ m pCVD diamond in a neutron beam (red) and with a B-10 converter foil (black).

Neutron detection is based on the measurement of the products of nuclear reactions and the efficiency is dependent on the corresponding cross-section. Neutrons can directly be measured through nuclear reactions on the C-12 nuclei of the diamond. Above neutron-energies of 6 MeV $n \rightarrow$ charged particle reactions are dominant, which can be detected with an efficiency of practically 100%. At energies higher than a few 100 keV neutrons can directly be measured through the $n \rightarrow$ elastic reaction. At lower energies, the direct measurement of neutrons is based on the $n \rightarrow$ gamma reactions with a gamma-energy dependent efficiency.

To increase the interaction probability of neutrons, especially in the energy-range below 1 keV, a converter material with a high cross-section for $n \rightarrow$ charged particle reactions can be used. In the case that a neutron hits the converter foil, like B-10 in the above example of Figure 7, the neutron can either be absorbed by the B-10 foil, producing a charged particle which causes a signal in the detector on entry (black curve in Figure 7). The neutron might as well pass through the converter foil without any interaction, and penetrate the detector material. In this case, a nuclear interaction between the neutron and the C-12 atoms might take place, and cause a signal in the detector, which is qualified as background event in Figure 7 (red curve).

Neutrons can directly be measured at energies higher than a few 100 keV through $n \rightarrow$ elastic and $n \rightarrow$ charged particle reactions. At lower energies, neutrons can be directly be measured by the $n \rightarrow$ gamma reactions with an energy dependent and reduced efficiency. At energies higher than 6 MeV $n \rightarrow$ charged particle reactions are dominant, which can be measured with an efficiency of practically 100%.

Neutrons have a small interaction probability with matter. In the case that a neutron hits the converter foil, like B-10 in the above example of Figure 7, the neutron can either be absorbed by the B-10 foil, and a nuclear reaction will be provoked and cause a signal in the detector (black curve in Figure 7). The neutron might well pass through the converter foil without any interaction, and penetrate the detector material. In this case, a nuclear interaction between the neutron and the C-12 atoms might take place, and cause a signal in the detector, which will usually be qualified as background events (red curve in Figure 7).

Diamond detectors are used for spectroscopic applications in combination with high-resolution digitizers. Neutron flux monitors are under investigation for nuclear fusion at ITER [8] for the detection of 14 MeV neutrons. The use of a boron converter essentially increases the interaction probability of neutrons in the low-energy range below 1 keV.

3. Conclusion

Diamond detectors have a wide range of proven and potential applications as beam instrumentation devices. Charged particles, photons and neutrons can all be detected over a large energy range that is basically unlimited at the top end and limited by the noise in the detector at the lower end. The detection efficiency depends on the energy and in the case of charged particles it is close to 100%. Photons and neutrons can be measured directly, but at lower energies the detection efficiency can be increased by the use of conversion foils.

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