First Applications of CVD-Diamond Detectors in Heavy-ion Experiments

E. Berdermann*, K. Blasche, P. Moritz, H. Stelzer*, B. Voss, F. Zeytouni

Gesellschaft für Schwerionenforschung (GSI), Planckstraße 1, 64291 Darmstadt, Germany

* Members of the RD42 Collaboration

Abstract

Test measurements with ^{241}Am-α-particles, ^{12}C, ^{20}Ne, ^{58}Ni, ^{208}Pb and ^{238}U projectiles are performed. It is shown that the most important charactristics of heavy-ion diamond detectors are described by the shaping parameters of the detectors single pulse. Distributions of rise and decay times of the signals as well as of the associated charge amplitudes are discussed. An intrinsic time resolution well below 100 ps and a single-pulse width of 1 ns are achieved. First applications of CVD-diamond detectors in heavy-ion accelerator beam diagnostics, in heavy-ion experiments and a promising first test in the GSI's heavy-ion tumor-therapy project are presented.

1. INTRODUCTION

The development of radiation hard and ultra-fast detectors for the use in heavy-ion measurements at low and intermediate energies up to 2 GeV/amu is continued [1][2]. Data taken with different diamond samples and various projectiles at different energies confirm the expectation that polycrystalline CVD diamond is most suitable for heavy-ion time measurements and for the precise counting of very high heavy-ion rates. The high ionisation density produced by heavy particles in matter balances the incomplete charge collection in the todays material. The possibility to apply low-noise, broad-band electronics to the diamond detectors and therefore to take advantage of the rather high velocities of the charge carriers in the diamond bulk open a wide field of applications. Beam diagnostics can be performed in the whole accelerator area from the low-energy region behind the RFQ-IH structure with particle energies of a few hundred keV/amu to the highest energies above 2 GeV/amu from the Schwer-Ionen-Synchrotron (SIS). Due to the low nuclear charge and mass a low background implementation in heavy-ion experiments e.g. as radiation hard and fast start detectors or beam monitors is possible. The similarity of carbon with human tissue is a particular advantage of CVD diamond to be used for the dosimetry of carbon ions in the tumor-therapy project at GSI [3].

2. CHARACTERISATION

The charge-collection distance and its radiation hardness are the most important parameters characterizing the quality of CVD-diamond detectors developed for the tracking of minimum ionizing particles in high-luminosity collider experiments [4] [5]. The quality of diamond detectors for heavy ion experiments described above has to be discussed in a different way. Although the specific energy transfer of heavy projectiles to the target atoms is dramatically higher, the requirements on the radiation hardness of detectors applied in fixed-target experiments at the SIS is much more relaxed [1]. Further irradiations are necessary to define the heavy-ion fluence which starts damaging CVD diamond. However, up to 5x10^{10} ^{238}U ions/cm^2 the detector characteristics remain unchanged [2].

2.1. Voltage-Dependent Dark Current

Due to the high band gap of 5.45 eV the intrinsic carrier density of CVD-diamond is negligible. A measurable leakage current contains therefore information about the chemical purity of the material, the distribution of the recombination centers in the bulk and about the quality of the metallic contacts [2].

A high electric field is always needed to operate the detectors at saturated charge-carrier velocities (s. 2.2.). Break-down fields from ± 1 V/μm to ± 6 V/μm are measured. Although a wide bias range implies a high chemical purity the corresponding charge-collection efficiency of such samples is not always good. This observation indicates that the incomplete charge collection in diamond detectors must be on account of the polycrystalline structure of CVD diamond.

2.2. Charge-Collection Properties

In a solide-state detector in thermal equilibrium the continuously produced charge carriers are balanced by the recombination processes [5] in which electrons and holes annihilate each other. Traversing charged particles ionize the detector material and produce excess carriers along their tracks. The amount of charge initially generated is estimated from the energy loss of the heavy particle in the detector assuming a value of 13 eV to produce an e-h pair in diamond (1).

$$Q_G = \left(\frac{\Delta E}{w_D}\right)\cdot q_e \propto \frac{Z^2}{(E/A)}\cdot\frac{q_e}{w_D} \qquad (1)$$

where w_D is the energy needed to create an e-h pair in diamond, q_e the electron charge, and ΔE, Z, A, E the energy loss, the nuclear charge, the mass and the kinetic energy of the particle impinging the detector.

The excess e-h pairs separate and the electrons and holes move apart guided by the externally applied electric field. The detector material relaxes towards the equilibrium state and the concentrations of electrons and holes decay to their equilibrium values. As long as the excess charge carriers are not trapped an increasing signal appears on the elctrodes.

About half of the charge Q_G expected from formula (1) can be collected [1][2]. Q_C rises with increasing electric field proportional to the charge-collection distance d_{CD} [5] as described in relation (2)

$$Q_C = Q_G\cdot\frac{d_{CD}}{d_D} = Q_G\cdot\frac{v(E_D)\cdot\tau}{d_D} \qquad (2)$$

with $v(E_D)$ the velocity, τ the lifetime of the charge carriers, d_D the detector thickness and E_D the electric field applied to the detector.

Due to the finite lifetime of the carriers the collected charge stays constant at saturated carrier velocities above a certain electric field E_s. For minimum ionizing particles with Z=1 an electric field of ± 0.8 to ± 1 V/μm is sufficient to achieve a constant amplitude [4].

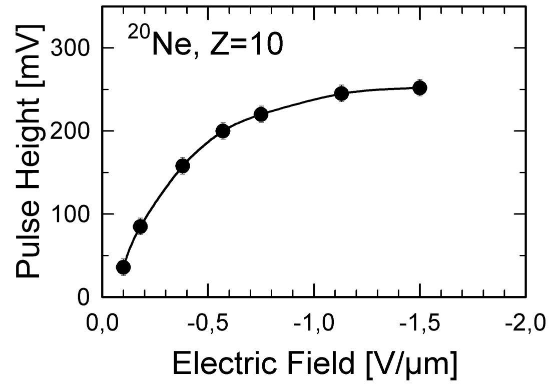

Figure 1. Electric field dependence of the charge amplitudes of ^{20}Ne ions with Z=10.

In order to compare our data with the results of the RD42 Collaboration [4] the detectors are operated at an electric field of ± 1 V/μm. However, since the rise of the pulse heights observed relates to the ionisation density in the detectors a higher bias is required to avoid a screening of the electric field due to the space charge produced by the heavy ions. Figure 1 shows that an electric field of at least E_S = 1.5 V/µm is required even for light ions as ^{20}Ne with Z=10.

2.2.1. Single-Pulse Shape

The movement of the separated electrons and holes causes a recharging of the electrodes and can be observed as a time variant voltage pulse. The time interval in which the amplitude decreases to its 1/e value is defined by the lifetime of the charge carriers and by the RC$_D$ constant given by the detectors capacitance and the impedance of the readout electronics used.

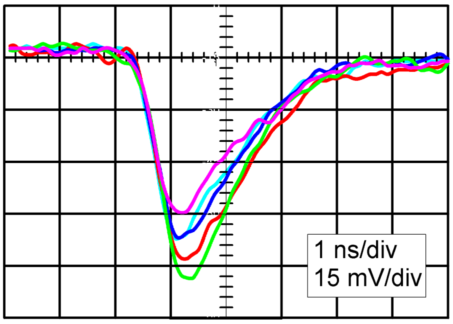

Figure 2. Signals from ^{208}Pb ions at 300 MeV/amu measured with a detector with a capacitance of 8 pF. No amplifier is used.

Signals from heavier projectiles can be measured without amplification. They are the pure response of a diamond detector with a capacitance C_D to the passage of the ionizing charged particles. They offer therefore the unique opportunity of a direct measurement of the charge-carrier lifetime in the bulk of the diamond sample.

Figure 2 shows signals produced from single ^{208}Pb ions at 300 MeV/amu in a 330 µm thick diamond detector. The signals are recorded with a 1.5 GHz, digital-storage sampling oscilloscope with a single-shot resolution of 10 GS/s. The parameters measured are the rise time (10%-90%), the decay time (1/e) and the pulsewidth (FWHM). About 1000 signals are analyzed for this sample. The rise time and the decay time distributions of those signals are plotted in Figure 3. The mean value of the rise-time distribution of 570 ps is given by the bandwidth of the oscilloscope and of the measurement system. The width of the distribution is determined by the range of the measured pulse heights and the electronic noise. The mean value of the decay-time distribution is 1.5 ns. By taking into account the contributions of the RC$_D$ constant and of the measurement system a rough estimation of the charge-carrier lifetime in this sample gives 1.3 ns. However, the width of the decay time distribution reflects the variation of collection distances appearing and therefore the pulse-height resolution of this detector.

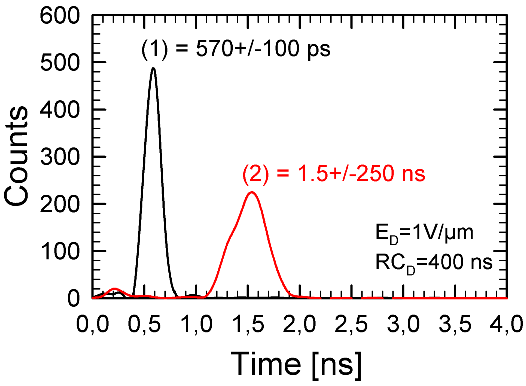

Figure 3. Rise time (1) and decay time (2) distribution of 1000 ^{208}Pb signals of a diamond sample with C_D = 8 pf.

2.2.2. Collected-Charge Distributions

The energy loss of heavy ions in solid-state detectors is well defined. The ΔE distribution of ^{208}Pb ions at 300 MeV/amu e.g., measured with a silicon pin-diode is a sharp gaussian line with a width in the order of 1‰ of the total kinetic energy loss.

The ^{208}Pb signals shown in Figure 2 correspond to a ΔE of 1.6 GeV. The charge Q_C collected from each single lead ion is evaluated from the area of every single pulse and is plotted in Figure 4. Although the electric field of 1 V/μm is by far to low for the saturation of the pulse heights caused by particles with Z=82 the charge distribution is well separated from the electronic noise. Applying a higher bias to the diamond detectors a rise of the collected charge is expected and a significant improvement of the pulse-height resolution as well.

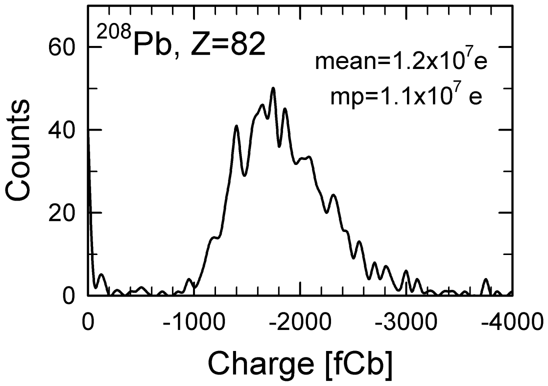

Figure 4. Charge distribution of ^{208}Pb ions at 300 MeV/amu measured with a 330 μm thick diamond detector. E_D=1 V/μm. No amplifier is used.

3. ELECTRONICS

The investigations of diamond detectors at GSI are focused on the development of radiation-hard detection devices for the use in measurements in which either a good time resolution below 100 ps or a very high counting-rate capability is required.

The parameter restricting the excellent timing results of heavy-ion diamond detectors is the bandwidth of the available electronics. The fast but weak pulses are a challenge for the readout components. Double-Threshold Discriminators (DTD) developed for the Pestov Spark Counters [6] and the GSI's low-noise Diamond Broadband Amplifiers (DBA) [7] are used in all measurements presented in this report. The performance of the above described electronics is demonstrated in the next two pictures. Figure 5 shows signals of ^{241}Am-α-particles amplified by a DBA. The α-particles with an energy of 5.5 MeV are stopped in 12 μm diamond material. No significant change of the pulse shape is found comparing these signals with the pure, non amplified ^{208}Pb signals shown in Figure 2. The lowest energy measured with a DBA is 3.6 MeV produced from stopped ^{12}C ions with a kinetic energy of 300 keV/amu. The associated signal-to-noise ratio is 10/1.

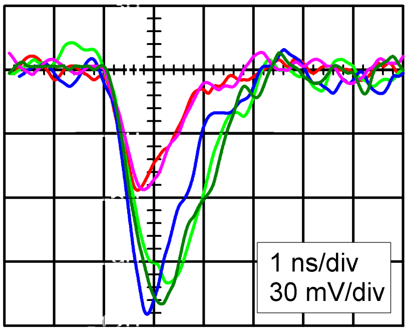

Figure 5. ^{241}Am-α-signals from a 330 μm thick diamond detector amplified with a DBA.

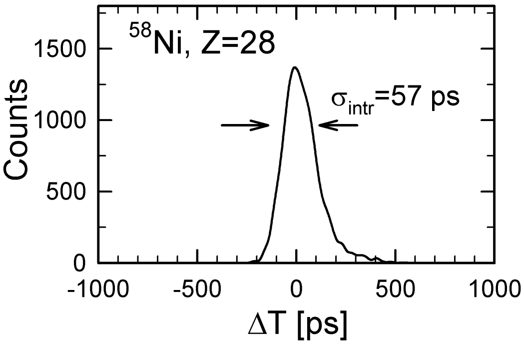

Figure 6: Time spectrum measured with ^{58}Ni ions at 600 MeV/amu. The samples used are 80 μm respectively 1.2 mm thick.

Using two diamond detectors with a thickness of 170 μm and DTDs an intrinsic time resolution of 39 ps is achieved with ^{238}U ions at 1 GeV/amu [2]. Figure 6 shows a recent measured time spectrum with ^{58}Ni ions at 600 MeV/amu. Two diamond samples of different thicknesses of 80 μm respectively 1.2 mm are used. The intrinsic width is again 57 ps the tail is not understood yet.

Due to the 20 ns width of the output signal DTDs are not able to measure very high particle rates. Using a 500 MHz scaler and a detector with a capacitance of 9 pF rates of $3\text{x}10^8$ ^{20}Ne ions/s are counted in a single-particle mode [7]. By dividing the active area of the samples in broad strips or pixels an increase of the counting-rate capability by a factor of 10 can be achieved. A more suitable discriminator for this purpose has recently been developed by the University of Giessen for the diamond start detector of the HADES [8] spectrometer. This fast leading-edge discriminator is able to cope with rates up to 10^9 particles/s [9].

4. APPLICATIONS

The properties of CVD-diamond exploited for heavy-ion detectors are summarized as follows:

1 Fast Collection of Charge
2 Low Dielectric Constant εr
3 High Break-Down Field
4 Low Mass and Nuclear Charge
5 Large Band Gap
6 Radiation Hardness
7 Large Areas up to 80 mm in diameter
8 Photo-Lithography and Laser-Cutting possible
9 Frontend-Electronics connected with 50 Ω strip-lines to the detectors. No damaging and no disturbance of the electronics are expected.
10 Easy Handling

In the previous sections the influence of the parameters listed in 1-6 on the signal performance is discussed in detail. For the construction of real and feasible detector devices however, the facts mentioned in 7-10 are of particular importance.

4.1. Beam Diagnostics

The most powerful tool developed for these applications is the DBA amplifier mentioned above. Due to the bandwidth of 3 GHz and a noise figure of 2.5 dB the shaping parameters of the original diamond signal remain short and a low-noise readout is guaranted.

Several designs of beam-intensity and beam-profile monitors are currently under construction. A 30x30 mm² detector with 9 strips with a pitch of 3.1 mm and a 20 x 20 mm² pixel detector with a pixel size of 4.5 x 4.5 mm² are the first large-area CVD-diamond detectors to be installed at the SIS in the spring 1999. The detectors are operated in air separated from the vacuum chamber of the SIS by a thin window made of stainless steel.

For the high-frequency structure analysis of the SIS spill a pulsewidth of less than 1 ns is needed [7]. Figure 7 shows ^{12}C ions at 200 MeV/amu passing a diamond detector in a time interval of 2 ms (upper trace). The three lower traces are zooms of it. Bottom trace indicates single particles.
Further detectors under development are designs with various single or double-sided interdigital electrodes. The aim is to count high particle rates with large and very thin detectors without destruction of the beam characteristics. The capacitance of such structures is not determined by the number of strips or pixels but by the interstrip

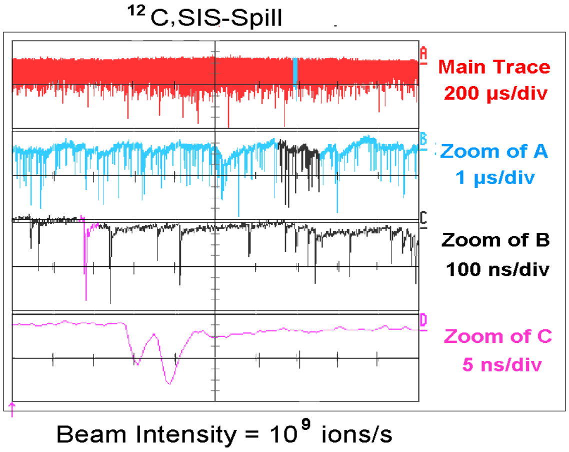

Figure 7. ^{12}C ions at 200 MeV/amu passing a 260 µm thick diamond detector. The lower traces are zooms of the upper-trace time interval of 2 ms.

distance. The amount of electronic channels decreases extremely.

4.2. Heavy-Ion Dosimetry

Diamond detectors to be used in the framework of the heavy-ion tumor-therapy project have similar characteristics as the beam-diagnostic detectors.

The objective is the measurement of the deposed dose within the volume of the irradiated tumor. Dosimetry is performed using conventional gasfilled ionisation chambers. Recombination effects in the detector gas have an impact on such measurements. The exact determination of w-values and of their energy dependence are necessary to calibrate the data. It is expected that precise counting of the impinging particles and the calculation of their energy loss lead to a higher accuracy of the dose measurements and make an examination of known w-values possible.

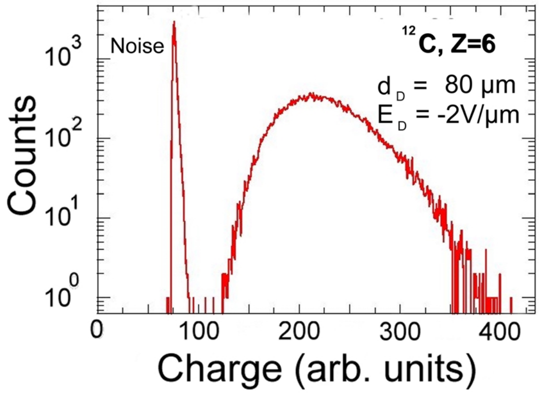

Figure 8. ^{12}C ions at 11.5 MeV/amu in a 80 µm thick diamond detector. Two DBA's with a total gain of 380 are used.

It is essential that the detectors are able to measure online particle fluences with an efficiency of 100 %. In some cases they have to be position sensitive. An encouraging first result with a 80 µm thick selftriggered detector is shown in Figure 8. The ^{12}C ions at 11.5 MeV/amu are clearely separated from the electronic noise. However, further experience with CVD-diamond detectors is needed since the security requirements of the therapy program can be fulfilled.

4.3. The HADES Start-Veto Device

Since slow extraction lead to SIS-spill lengths up to 10 s fast and radiation-hard detector systems have to define the “start” i.e. the “time zero” of a reaction of interest.

Two CVD-diamond strip detectors are placed in a distance of 75 cm upstream respectively 75 cm downstream the HADES target. The detectors are of octogonal shape with outer dimensions of 25 mm respectively 15 mm matching the beam spot at this position. To keep multiple scattering and secondary reactions low the detectors have a thickness of 100 µm.

The downstream detector shall veto all particles with no reaction with target nuclei to provide a start signal with a rate of < 10^7 particles/s. To optimize the veto efficiency and the count rate per readout channel several layouts are discussed [10]. Detectors with identical design are choosen. Each detector has 8 strips of variable width ranging from 5.4 mm for the outer strips to 1.55 mm for the inner strips. The widths are optimized such that a coincidence of one start strip with 3 veto strips is sufficient for a veto efficiency of 96.5%. In addition the count rate per strip is nearly constant. The first beam test of HADES is started in December ‘98 with ^{209}Bi ions of 800 MeV/amu kinetic energy.

5. CONCLUSIONS

Heavy-ion beams are found to be a powerful tool for the investigations of CVD diamond as a new detector material. Pulse-shape analysis of non-amplified diamond signals of the heavier ions allow a direct measurement of the charge-carrier lifetime and therefore of the quality of the material. The extreme suitability of CVD-diamond detectors for heavy-ion measurements makes real applications possible in a short time of research. Even common material without any post treatment is well suited. An intrinsic time resolution between 38 ps and 65 ps is achieved with several ion species and different diamond samples. Diamond detectors are able to measure precisely heavy-ion rates from single particles beyond 10^8 particles/s in one readout channel.

REFERENCES

[1] E. Berdermann et al., 5th International Conference of Advanced Technology and Particle Physics, Como (1996)

[2] E. Berdermann et al, XXXVI Int.Winter Meeting on Nucl. Physics, Bormio 1998

[3] G. Kraft et al., Hadron in Oncology, U. Amaldi and B. Larsson (eds.)

[4] D. Meier for the RD42 Collaboration, ”5. Symposium on Diamond Materials”, Electrochemical Society, Paris (1997)

[5] S. Zhao, Ph.D. Thesis, The Ohio State University (1994)

[6] Y. Pestov, Timing below 100 ps with Spark Counters, XXXVI Int.Winter Meeting on Nucl. Physics, Bormio1998

[7] P. Moritz et al., ”Diamond Detectors for Beam Diagnostics in Heavy Ion Accelerators”, DIPAC III,Frascati (1997)

[8] R. Schicker et al., NIM A380 (1996) 586

[9] Carsten Lichtblau, priv.communication

[10] W. Koenig, internal draft (HADES).