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Dosimetric characterization of CVD diamonds irradiated with 62 MeV proton beams

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Abstract

Diamond is potentially a very suitable material for use as on-line radiation dosimeter. Recent advances in the synthesis of polycrystalline diamond by chemical vapor deposition (CVD) techniques have produced material with electronic properties suitable for dosimetry applications. In this work the possibility to use a segmented commercial CVD detector in the dosimetry of proton beams has been investigated. The response as function of dose, dose rate, the priming and the rise time have been investigated thoroughly. This study shows the suitability of CVD diamond for dosimetry of clinical 62 MeV proton beams.

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Keywords: Proton beams; Diamond; CVD; Dosimetry

1. Introduction

Synthetic diamond is one of the more interesting materials among the choices of detectors applicable to dosimetry. It is, in fact, tissue equivalent (its atomic number $Z = 6$ is very close to the effective atomic number of the tissue, $Z = 7.5$). Moreover, it is not toxic and shows a high resistance to radiation damage, a high sensitivity and stability of response, a low leakage current and a good time resolution. It is an electrical insulator, is chemically stable, robust and can be

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produced in a variety of sizes. Considering these features, the possibility to use synthetic diamond as on-line dosimeters is very high [1]. Diamond can be used in on-line dosimetry by directly measuring the change of current due to the energy deposition of the impinging particles when a constant bias is applied to the film in a transverse-electrode configuration. In this work the current–voltage characteristic, the pre-irradiation effect, the linearity with absorbed dose, the dose rate, energy dependence and the dynamic of the response have been studied irradiating a commercial chemical vapor deposited chemical vapor deposition (CVD) diamond detector [2,3] with a 62 MeV therapeutical proton beam.

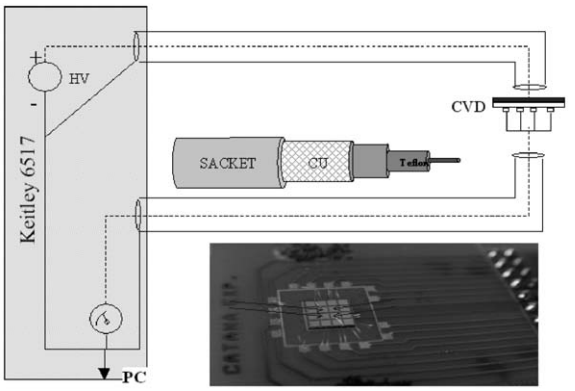

Fig. 1. Diagram to the readout electronics of CVD diamond detector and real detector,

2. Materials and methods

In this work a detector-grade CVD diamond film purchased in 1999 from De Beers [2,3], with thickness 300 μm and area 0.25 cm^2 has been studied. Surfaces were polished by the manufacturer and material was removed from the nucleation side to increase its detection performances. Electrodes were performed by Drukker, Netherlands, on the front and back surfaces of the film. The front contact is composed by 16 squared pixels each with 4 mm^2 active area. The over-metal used for electrodes is gold, further information on electrode composition is withheld because it is considered proprietary by the manufacturer.The front-end electronics, the board to supply the bias and the readout has been assembled by the electronic division of the Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare (INFN-LNS) and is shown in Fig. 1. The main operational characteristics of the detector employed are summarized in Table 1.

Table 1
Operational characteristics of CVD diamond used for the experiment

Thickness of sensitive volume (mm)	0.3
Sensitive volume (mm^3)	6.4
Sensitive surface (mm^2)	16
Dark current at 400 V (pA)	15
Operating bias (V)	400

For the irradiation, the CVD diamond is positioned in a polymethylmethacrylate (PMMA) holder shielded with adhesive copper deposited on the outside walls. The signals coming from the 16 squared pixels, acquired simultaneously, are transferred to the readout via a multipolar, low noise, cable. The bias is applied using a SHV connector. The low-noise cable was made of teflon, made conductive with addition of graphite . It has the characteristics to reduce the triboelectrical noise, guarantees a complete shielding and improves the efficiency of filtering out low-frequency noise. The bias voltage is applied by a Keithley 6517 electrometer. Fig. 1 shows the detector assembled and ready for the measurement with a simple diagram of the readout electronics. The irradiation is performed using modulated and unmodulated 62 MeV therapeutical proton beams, delivered by the superconducting cyclotron installed and operating at INFN-LNS. The diamond detector is placed along the proton beam axis with the phantom surface at isocenter (8.5 cm from the last collimation). For reference dosimetry a plane-parallel Markus ionization chamber was chosen. In order to study the dependence of the diamond response versus radiation with different linear energy transfer (LET), beams of various energies are used. For the non-modulated beam, the diamond is placed at three different depths in the PMMA: 2.59, 15.59, 24.89 mm corresponding to

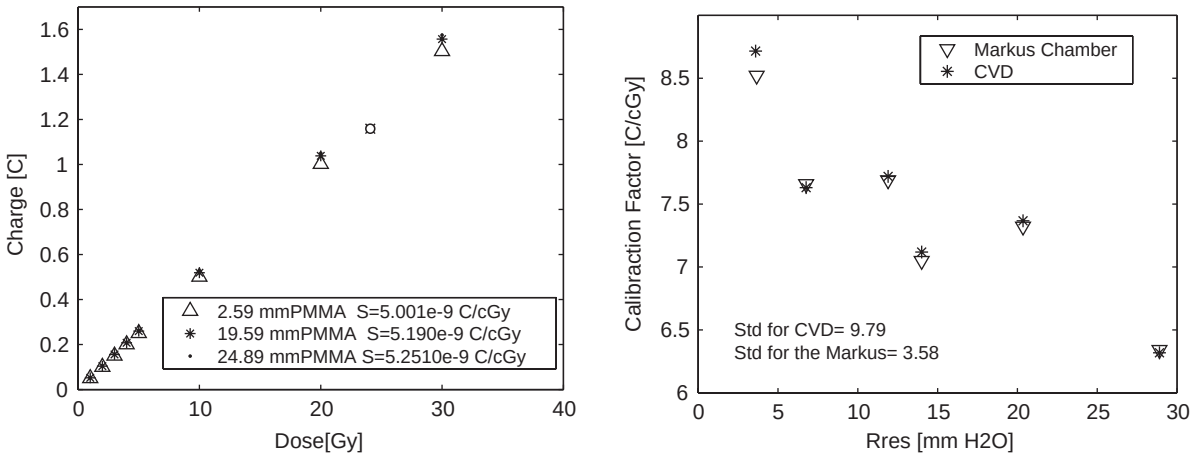

Fig. 2. Collected charge as a function of the adsorbed dose and sensitivity factors of diamond at three different depths in PMMA corresponding to three different energies and at various R_{res}.

58.84, 33.07 and 20.80 MeV, respectively. For modulated beams, the Markus chamber was placed at the middle of different spread out Bragg peaks (SOBPs) corresponding to various values of the quality index residual range R_{res}[1] [5].

3. Experimental results

3.1. Dark current, I–V characteristic, priming, sensitivity and LET dependence

The dark current of the CVD diamond was studied polarizing it with a bias varying between 0 and 400 V. The polarization chosen for all dosimetric measurements was 400 V. Under this condition the dark current is ~40 pA for the 16 mm^2 area. The current–voltage characteristic was measured also under irradiation, to evaluate the electrical quality of the CVD detector in the range ±400 V. The I–V curve appears quite similar for negative and positive bias and shows no saturation up to 400 V. An important aspect of a CVD diamond film is related to the fact that its radiation-induced current usually does not stabilize with time if the diamond is not sufficiently pre-irradiated. The pre-irradiation effect is also known as "priming" and its extent depends on the previously delivered dose. Our CVD diamond shows an initial increase in response with dose, which saturates after ≃ 15 Gy. When the radiation is switched off, the current returns to the dark current value within a few seconds [9]. The knowledge of the diamond response, when beams of different stopping power values are used (LET effects), is necessary for its use in clinical dosimetry. For this reason we irradiated our detector both with mono energetic (pure Bragg peak) and modulated (clinical SOBP) proton beams of different energies. In the first case (mono energetic beam) the energy was varied inserting different thicknesses of PMMA along the beam path. Fig. 2 (left side) shows the response of the diamond detector versus the absorbed dose for three different energies obtained with 2.59, 15.59 and 24.89 mm of PMMA, respectively. The slope of the curves represents the calibration factor of the detector (in C/cGy) that are reported inside the legend: they are 5.001×10^{-9}, 5.190×10^{-9} and 5.251×10^{-9} C/cGy. The calibration factor, for any detector to be used in dosimetry, permits to correct its response to a value expressing an absorbed dose. Usually such a detector must be calibrated against an "absolute" detector able to measure the total ionizing dose. The absolute

[1] In the dosimetry of modulated proton beams, residual range is chosen as the beam quality index. R_{res} is defined as the difference between practical range [6] and measuring depth (where the diamond is positioned during the irradiation).

detector we used is the Markus-type ionization chamber. A maximum variation of the calibration factor of 4.7% is found. Similar values were found for the same detector under electron and photon beam irradiation [10]. The calibration factors obtained for modulated beams of different energies are listed in Fig. 2 (right side). In the same plot, the factors obtained with the reference dosimeter (Markus chamber) are reported. A maximum difference of 2.8% between the two detectors was found. A decrease of the calibration factors by 34% with increasing LET values is evident.

3.2. Dose rate effect and dynamic of the response

The dose rate dependence of diamond was studied with the 62 MeV non-modulated proton beam. The dose rate variation (in the range 1–80 Gy min^{-1}) was achieved by changing the beam current at the accelerating stage. The obtained results show a lower tendency to saturate when the dose rate increases. The dose rate effects were also studied by us irradiating the same sample with electron and photon beams [9]. The modern radiotherapeutic techniques (stereotactic radiotherapy, intensity modulated radiation therapy (IMRT), proton and ion therapy) require, in most cases, detectors either with a high spatial resolution, or with very fast response time. This permits the use of such detectors even in the case when irradiated with radiation fields which vary strongly in time. In order to verify the possibility to use our CVD detector in such conditions, we started a more accurate study of its time response. If $I(t)$ is the photoinduced current measured with our acquisition system, we define the *rise time* as the time in which diamond signal grows from 10% to 90% of its stable value. The diamond *rise time* represents a quantity useful to express the ability of the detector to follow the current beam variations. In our investigation we compared time responses of CVD diamond in therapeutical 62 MeV proton beams with that of a reference beam monitor. The reference is a secondary emission monitor (SEM) chamber, installed along the proton therapy beam line and directly connected to an ADC converter. The dependence of the SEM signal on the irradiation time is an ideal way to obtain information on the proton beam current variations. Fig. 3 (left side) shows the simultaneous response in current of the SEM and of the CVD diamond film. The two signals are acquired with a sample rate of 200 ms.

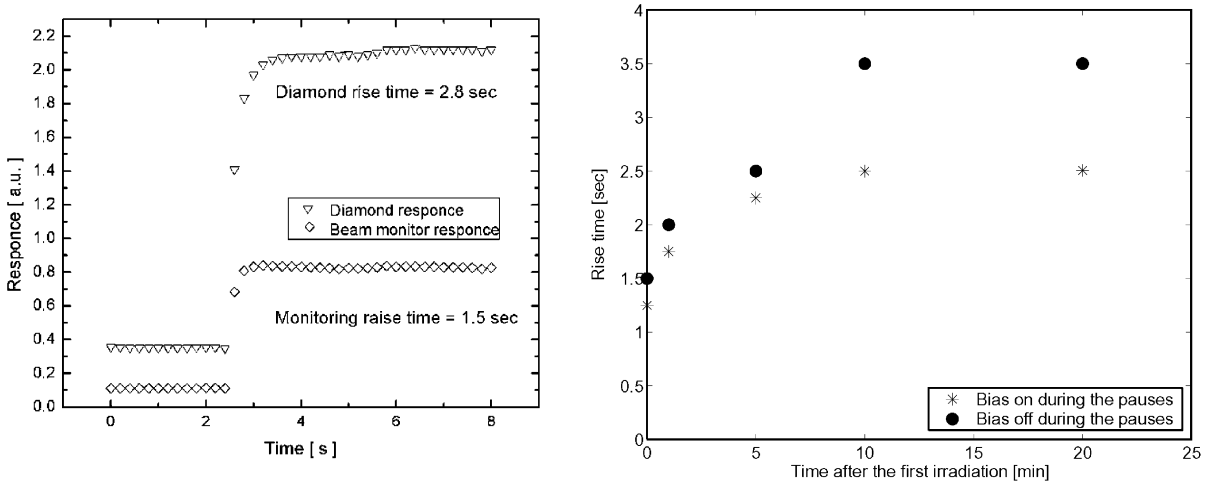

Fig. 3. Diamond and beam monitor (SEM) currents contemporarily acquired for an irradiation with protons. Beam dose rate was 20 Gy/min. Signals are acquired with a sample rate of 200 ms. Right side: the *rise time* values for CVD diamond detector measured as function of different no-irradiation periods. The measure is performed keeping both the bias on (stars) and off (dots) during the pauses in between the beams.

Approximately 2.5 s after the acquisition is started, the proton beam is switched on. This corresponds to the time the signals keep growing. It is evident that the diamond reaches its stable value in a longer time than the monitor, even at higher intensity. Consequently, the rise time appears longer for diamond (2.8 s to reach its maximum) than for the monitor (1.5 s to reach its maximum). Once the *slower* behavior of the diamond detector was verified, we decided to investigate in detail the dynamic of its response, in order to understand the applicability of the CVD in case of very rapid beam current variations. We noted that the *rise times* depend strongly on the time diamond remains un-irradiated. Moreover, they behave differently depending if the bias is switched on or off during the pauses in between beams. Fig. 3 (right side) shows how the *rise times* change when the detector is non-irradiated for a defined period (stars for bias on and dots for bias off). The *rise times* shown in the plot are measured after fixed pauses of no irradiation. The first value (either for stars and dots), correspondent to the time zero, is measured immediately after that CVD diamond was irradiated with the pre-irradiating dose (15 Gy). The second point is measured after a pause of 1 min, during which proton beam is off, the third point corresponds to a pause of 5 min and so on. During each irradiation, a large enough dose was administered to let the diamond current reach a stable value.

4. Conclusion

Thanks to its specific physical and chemical characteristics, diamond can be considered a very interesting material for dosimetry. The synthetic CVD one, moreover, presents additional advantages (possibility of specific shapes, small dimensions, possibility to control the amount of impurities, relative low cost, etc.) to make it very attractive to the medical physicist community. Thus, it is of great importance to characterize the response of CVD diamond films from a dosimetric point of view. In this work we studied the response of a commercial CVD diamond film by irradiating it with clinical high-energy proton beams and followed up on some of the experimental results we obtained. The diamond response versus absorbed dose and dose rate is very good and its stability (in terms of calibration factors over many weeks of use) stays within low values of reproducibility (under 3%). On the other hand, some problems we encountered must be mentioned and solved before the use of CVD diamond for dosimetry can be envisioned. The first, and less important, is the need for priming. This can be easily overcome by pre-irradiating the diamond before its use: the same procedure is done for the commercial natural diamond, produced by PTW [11], and currently used by medical physicists. A second, and more significant problem is that time responses of our detector are very far from being stable: the rise time changes drastically if the diamond detector is not exposed to irradiation, even for a few seconds, or if the beam intensity changes with time, and they show differences if bias is maintained off or on during some pause between irradiation. Moreover, the rise time of diamond appears to be longer than that of a conventional dosemeter. These latter limitations do not permit, at the moment, the use of diamond in the applications where rapid beam current variations are involved, like IMRT or intensity modulated proton therapy (IMPT) and where fast responses in time are required. On the contrary, from previous studies [10] of CVD diamond, we can assert that it may be a good dosimeter when is used in photon and electron therapy beams. Our initial study indicates that a future use of CVD diamonds as on-line dose monitors in rapidly changing beams will require both further study of the dynamic response as well as an improvement of the material quality.

References

[1] H. Pernegger, et al. (RD42 Collaboration) Radiation Hardness Studies of CVD Diamond Detectors, The Vienna Wire Chamber Conference, Vienna, 1995.

[2] A.J. Whitehead, R. Airey, C.M. Buttar, J. Conway, G. Hill, S. Ramkumar, G.A. Scarsbrook, R.S. Sussmann, S. Walker, Nucl. Instr. and Meth. A 460 (2001) 20.

[3] S. Ramkumar, C.M. Buttar, J. Conway, A.J. Whitehead, R.S. Sussman, G. Hill, S. Walker, Nucl. Instr. and Meth. Phys. Res. 460 (2001) 401.
[5] International Atomic Energy Agency (IAEA), Absorbed dose determination in external beam radiotherapy: an international code of practice for dosimetry based on standards of absorbed dose to water, Vienna, Technical Report Series No. 398, 2001.
[6] International Commission on Radiation Units and Measurements, Clinical proton dosimetry, Part I: beam production, beam delivery and measurement of absorbed dose, Bethesda, ICRU Report No. 59, 1999.
[9] G.A.P. Cirrone, G. Cuttone, L. Raffaele, M.G. Sabini, C. De Angelis, S. Onori, M. Pacilio, M. Bucciolini, M. Bruzzi, S. Sciortino, Nucl. Phys. B (Proc. Suppl.) 125 (2002) 178.
[10] G.A.P. Cirrone, G. Cuttone, S. Lo Nigro, V. Mongelli, L. Raffaele, M.G. Sabini, Dosimetric characterization of CVD diamonds in photons, electrons and proton beams, Official paper of the ''9th Topical Seminar on Innovative particle and Radiation Detectors'', Siena, 2004.
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