Natural and CVD type diamond detectors as dosimeters in hadrontherapy applications

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Diamond is potentially a suitable material for use as radiation dosimeter; the wide band gap results in low dark currents and low sensitivity to visible light, the high carrier mobility can give rapid response, the very high density of strong bonds in the crystal structure make diamond very resistant to radiation damage; moreover it is tissue equivalent. The more recent advances in the synthesis of polycrystalline diamond by chemical vapour deposition (CVD) techniques have allowed the synthesis of material with electronic properties suitable for dosimetric application. In this paper we will report the results obtained in the study of the response of a natural diamond dosimeter and a CVD one irradiated with 62 AMeV proton beams to demonstrate their possible application in protontherapy.

1. INTRODUCTION

The outstanding properties of diamond as a radiation detector material have been deeply investigated in the past [1,2]. The appealing properties of diamond make it an attractive alternative to currently used ThermoLuminescence (TL) dosimeters for off-line dosimetry[3]and to ionization chambers for on-line dosimetry[4] in the cases where a high spatial resolution is required. It is non toxic, nearly tissue equivalent, robust, radiation-hard and highly sensitive. Otherwise synthetic diamond prepared with controlled amounts of impurities are expected to give reproducible inter-sample response and high sensitivity. Moreover, Chemical Vapour Deposited (CVD) diamond films can be grown in small sizes with potential low cost for applications in dose distribution measurements and in vivo dosimetry in radiotherapy. Natural and CVD diamond detectors gained the general attention as very suitable dosimeters for high-energy photon and electron therapy beams [4–7,9]. On the contrary the study of diamond response in the hadrontherapy field is scarce and limited to natural diamond (see for istance [10,11].The purpose of this work is to demonstrate the suitability of synthetic CVD diamonds as on line dosimeters in protontherapy treatments, comparing results with a PTW natural diamond detector. The detectors were tested in the proton beam line of the CATANA (Centro di AdroTerapia Applicazioni Nucleari Avanzate) at the Laboratori Nazionali del Sud in Catania (Italy) were proton beams from a superconducting cyclotron are used for the treatment of ocular melanomas. CATANA is actually the first Italian protontherapy center. The current - voltage characteristics, the pre-irradiation effect, the energy dependence and the response of the detectors versus dose and dose rate for a 62 AMeV proton beam will be presented. The differences in the behavior between natural and CVD diamond will be shown.

2. MATERIAL AND METHODS

2.1. The Detectors and the electrometer

In the last years more and more interest is grown around the use of high-energy proton beams for the treatment of tumors. In particular protons are used for high conformal radiotherapy when clinical targets are close to critical structures. The main advantages in the use of protons in stead of conventionally radiation like photons or electrons, are mainly in the useful physical characteristics of the beam. These include the sharp fall-off (1 mm) after the Spread Out Bragg Peak (SOBP), the good peak to plateau ratio (about 4,5) and the very small (1 mm) lateral penumbra. Moreover protons show an higher relative biological effect (RBE) than photons and electrons. The rapid development of new protontherapy centers induced nuclear and medical physics to study and develop new detectors for their specific use in protontherapy. These detectors have to satisfy the need of the conventional dosimetry (linear dose dependence, dose-rate independence and stability of response, tissue equivalence) but has to show additional features. These include, in particular, the high spatial resolution (to perform an accurate dose measurement also high gradient dose region) and the radiation hardness. We focused our attention in the study and characterization of diamond detectors. Diamond has physical and chemical features that make it a potentially useful material for use as radiation dosimeters in proton beams. The wide band gap of diamond (5.5 eV) reduces the sensitivity to visible light compared with silicon and results in a very low dark current allowing high signal-to-noise ratio. In addition diamond is more resistant to radiation damage than silicon [4]and therefore does not need frequent calibration. Diamond also shows radiation interaction and absorption that is very similar to that of soft tissue because of their similar atomic numbers (6 and 7.4 respectively).Moreover the mobility of charge carriers produced in diamond is very high (about 1800 cm$^2 V^{-1} s^{-1}$).

For this reason diamond show a fast time response to ionizing radiation. We tested two different diamond dosimeters: a commercial natural PTW Riga diamond and a synthetic CVD diamond produced by De Beers and electronically assembled by us. The main operational characteristics of the detectors are summarized in Table 1. In our experiments natural diamond detector was connected to an UNIDOS PTW electrometer while the CVD detector to a Keihley 6517 high precision electrometer. The configuration was different just for the depth dose curve measurements for which both dosimeters were connected to a National Instrument acquisition board directly interfaced with LabView software.

2.2. The irradiation

Diamonds response and all their dosimetric characteristics were studied under irradiation with 62 AMeV protons accelerated by the superconducting cyclotron of Laboratori Nazionali del Sud - INFN of Catania (Italy). At LNS 62 AMeV protons are used for the treatment of ocular melanomas. The beam, extracted from the cyclotron, is modified in term either of its lateral and energy distribution in order to permit the irradiation of tumors with lateral dimension ranging from 5 mm up to 25 mm. For the irradiation diamonds were placed inside a PMMA phantom with the center of their sensitive volume set at the point corresponding to the position of the tumor (isocenter). The dose was changed from 2 Gy up to 20 Gy and dose rate from 2 Gy/min up to 15 Gy/min. The dose is released in terms of monitor units using two monitor chambers calibrated, according to the IAEA TRS 398 protocol [8], with respect to a parallel plate Markus ionization chamber. For the depth dose curve reconstruction, the energy of the beam was decreased using PMMA absorbers of known thickness.

3. RESULTS AND DISCUSSION

The dosimetric characterization of the detectors was carried out focusing the attention on dark current, Current - Voltage(C-V) characteristic, the preirradiation effects, dose linearity, dose rate effects, relative dose distributions and LET dependence. Each of these aspects was studied and analyzed and a comparison between two de-

Table 1
Operational characteristics of natural and CVD diamond used for the experiment

MeV	$Naturaldiamond$	$CVDdiamond$
Thickness of sensitive volume [mm]	0.3	0.4
Sensitive volume [mm^3]	1.3	6.4
Sensitive surface [mm^2]	4.3	16
Dark current at 100 V [pA]	2.5	9
Operating bias [V]	100	400

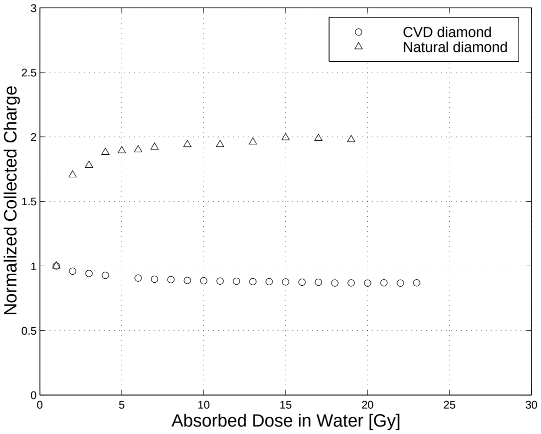
tectors is shown.
Dark currents is 2,5 pA and 9 pA at 100 Volt bias applied for natural and CVD detector, resulting in a specific resistance of 11,3*10^{14} Ω·cm and 2,7*$10^{14}\Omega$·cm respectively. We found however a very big difference in the C-V of two diamonds. For the natural one a plateau is found for an applied voltage higher than 80 V while the signal of the CVD one grows and grows with voltage never reaching a level for a complete trapping of carries. Another difference was also found regarding the preirradiation effects. Natural diamond, when irradiated for the first time, or after a long period of no irradiation, shows a response decreasing with absorbed dose. Opposed is the behavior of the CVD diamond. In fact its response increases with the absorbed dose. Anyway it is necessary to irradiate both detector with a dose of 15 Gy at least to obtain a stable response. Figure 1 shows the preirradiating effects for the two samples.

These effects are related to the competitive effects of shallow trapping centers and space charge effects inside the forbidden gap. Both diamonds show a very good response with absorbed proton dose with a perfect linearity up to 15 Gy. The 15 Gy level is the typical dose prescription for a single fraction for a protontherapy session of the ocular melanoma treatment. Dependence with dose rate can be observed for both detectors as expected from theory [12]. Dose rate dependence of diamond detectors was determined at a depth 2 cm in a PMMA phantom by changing the proton beam current directly at the accelerating stage. Each dose rate was measured using the ionization Markus chamber. For a change in dose rate from 0,9 Gy/min to 10 Gy/min a decrease of 4,0% and 13% is observed for natural and CVD diamond, respectively (Figure2). A constant value of 1 represents the condition of a perfect linearity. Detector response decrease can be ascribed to the very short electron-hole recombination time. The relationship of induced conductivity with increasing dose rate is given by [12]. The detector current, I, can be approximated by the empirical expression:

$$I(D_r) = I_{dark} + R_r^{\Delta} \tag{1}$$

where D_r is the dose rate (Gy/min) The parameter I_{dark} indicates dark-current influences. R is the fitting parameter for the response of diamond detector and Δ is the parameter accounting for sub-linearity of response. For the investigated detectors I_{dark} was within the range of 2,5 pA - 9,0

Figure 1. Preirradiation effects are opposed for the two diamonds



pA and Δ was 0.977 and 0.807 for natural and CVD samples, respectively this showing a better dose rate independence for the first detector. In Figure 2 is reported diamonds response versus dose rate normalized at the value of lower dose rate (1 Gy/min). The value of 1 corresponds to a perfect linearity ($\Delta = 1$).
Depth dose distribution profiles for the unmodulated Bragg Peak of 62 AMeV proton beams were performed for both detector (Figure 3) and they show the presence of a big LET dependence of the diamond. Peak to plateau ratio results 40% for natural diamond and 20% for CVD lower with respect to the reference unmodulated Bragg peak acquired with the Markus chamber dose distribution.

Knowledge of the LET correction factor is necessary for the use of diamond in the estimation of the depth dose distribution. Lateral dose profiles acquired with diamond detector are, on the other hand, in good agreement with the lateral distributions measured with our reference dosimetric systems (silicon diode and radiographic films). This means diamonds studied have a sufficient spatial resolution to follow the high dose gradients typical of proton beams.

4. CONCLUSION

The study of the dosimetric behavior of two diamond detectors, here reported has confirmed the favorable properties of those detectors also in proton beam. After the pre-irradiation, diamond detectors had an excellent time stability of sensitivity.CVD dosimeter shows a higher highest sensitivity with respect to the natural diamond and a lower LET dependence while it shows an higher dose rate dependence. Probably, further improvements of CVD diamonds will permit to improve the dose rate and LET dependence of the response making them an ideal dosimetric system for application in the protontherapy field.

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Figure 2. Response of diamond samples increasing dose rate of proton beam

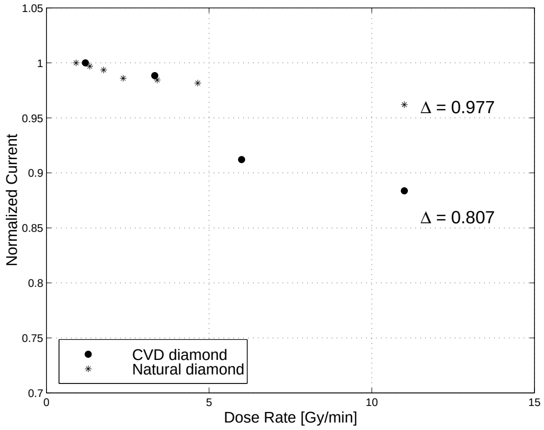
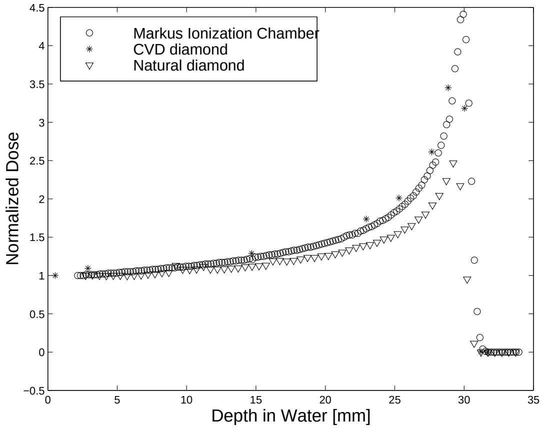


Figure 3. Bragg peak for the 62 AMeV proton beam measured with an ionisation Markus chamber and with the two studied diamonds



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