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Dosimetric characterization of CVD diamonds in photon, electron and proton beams

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The purpose of this work is the characterization, in an *on line* configuration, of the dosimetric response of a commercial CVD diamond. The study shows the possibility of using CVD diamond for dosimetric purposes with clinical , high-energy electron (4-15 MeV), photon (6-15 MV) and proton (62 MeV) beams.

1. INTRODUCTION

Synthetic diamond is potentially one of the more interesting materials in the field of detectors applicable in dosimetry. It is, in fact, tissue equivalent (its atomic number, Z = 6, is very close to the actual atomic number of a biological 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, chemically stable, robust and realizable in small size. Considering these features, there is a very high motivation to characterize synthetic diamond as an *on line* dosemeter. The diamond can be used in *on line* dosimetry studying the change of conductivity induced during the exposure to an ionizing radiation. The current-voltage characteristic, the preirradiation effect, the linearity of response with dose, dose rate effects, and the LET dependence have been studied for a commercial CVD diamond by De Beers [1], [2] in order to verify its applicability for dosimetry in the radiotherapy field.

2. MATERIALS AND METHODS

2.1. Diamond detector

We focused our attention in the study and "on line" characterization of a CVD diamond detector produced by De Beers and electrically assembled by us. The main operational characteristics of the detectors are summarized in Table 1. Both

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

Thickness of sensitive volume [mm]	0.4
Sensitive volume [mm^3]	6.4
Sensitive surface [mm^2]	16
Dark current at 100 V [pA]	9
Operating bias [V]	400

surfaces of the detector have been metalized realizing the two contacts necessary to apply the bias, and to acquire the output signal. The voltage has been applied using a Keithley 6517 electrometer. The diamond current is measured with the same device for the "in charge measurements" and with a National Instrument Acquisition Board [3] for the "in current" measurements. The software developed by us using the LabVIEW[1] programming language, permits the acquisition from both the K6517 and the NI board, and displays the plots and the analysis results during the measurement.

[1] *Laboratory Virtual Instrument Engineering Workbench*, by National Instrument

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2.2. The irradiation

All the dosimetric characteristics of the CVD diamond were studied irradiating it with high-energy electrons (4, 6, 9, 12, 15 MeV) and photons (6, 15 MV) produced by a linear accelerator at REM Radioterapia in Catania, and with 62 MeV protons delivered by the superconducting cyclotron installed and working at INFN-LNS since 1995. For the irradiation, diamond was placed inside a PMMA phantom and, in order to facilitate the tests, was connected to a printed circuit board giving the possibility to read out the signal. The dose interval studied was 2÷40 Gy. The radiation beam was, in all the cases, perpendicular to the surface of the diamond. In the irradiation with photons, the dosimeter was placed at 4.4 cm depth of PMMA with the phantom surface at isocenter[2]. When irradiating with electrons, the dosimeter was placed at different depths depending on the beam energies.

3. RESULT AND DISCUSSION

3.1. Dark current, I-V characteristic and Priming

The dark current of the CVD diamond was studied in the range 0-400 V for the polarization field. For a polarization of 400 V (that was chosen as bias for all the measurements, the dark current is $\sim 40pA$ resulting in a specific resistance of $2 * 10^{13}$ $\Omega{\cdot}cm$, lower than that reported in the literature [4], [5], [6]. The current voltage characteristics has been measured, under irradiation, to evaluate the electrical quality of the CVD detector in the range $\pm 400V$. In Figure 1 the current-voltage characteristics of the CVD sample is shown. The I-V curve appears to be quite similar for negative and positive bias and shows no saturation up to 400 V.

An important aspect that must be studied in a CVD diamond is related to the fact that the current induced by the radiation does not reach a stable value, unless the diamond has been pre-irradiated. The effect of pre-irradiation is also known as "priming" and its importance is dependent on the dose deliveerd previously. In figure 2

[2]point in the space where, ideally, the tumoral mass is centered

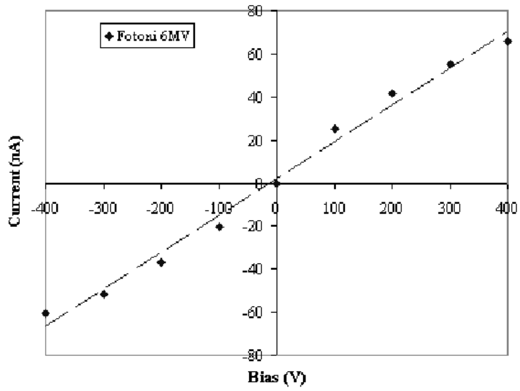

Figure 1. Current-Voltage characteristics of the CVD diamond during irradiation with 6 MV photon beam and a dose rate of 3.4 Gy$\backslash min$

is reported the value of the CVD charge response versus the dose during an irradiation by 6 MV photon beam with a dose-rate of 3.4 Gymin and a 400 V bias applied. The CVD diamond showed an initial increase in response with dose, which saturates after $\simeq 15Gy$. When the radiation is switched off, the current returns to the dark current value within a few seconds. We have calculated the values of the standard deviation over a pre-dose of 9 Gy, 11 Gy and 15 Gy. These values were, respectively, in percentage, 1.62, 1.03, 0.97. The induce current of CVD diamond reached the stable value of 1.32 μC after a preirradiation with 15 Gy. The same kind of measurements has been repeated with 62 MeV proton beams, obtaining a stable charge value of 1.19 μC after 15 Gy pre-dose, with a standard deviation of 4.22%. For clarity only the 6 MV photon beam is shown in Figure 2.

3.2. Dose linearity and sensitivity

If R_s is the response in charge of the CVD dosimeter under irradiation, then R_s must be proportional to the total dose delivered D.

The R_s versus dose graph must be linear and the $m = \frac{R_s}{D}$ coefficient expresses the sensitivity of the device. We measured R_s as a function of the absorbed dose for all the available radi-

Table 2
Values of sensitivities

	CVD DETECTOR			
Beam	Energy	Sensitivity $[\frac{nC}{cGy}]$	Specific Sensitivity $[\frac{nC}{cGy.mm^3}]$	σ^2 %
Photons	6 MV	11.93	7.45	5
	15 MV	12.52	7.82	5
Electrons	15 MeV	11.63	7.27	2.5
	9 MeV	11.92	7.45	2.5
	4 MeV	11.68	7.30	2.5
Protons	62 MeV	11.98	7.48	6
		Δ% Sensitivity		
Photons	6-15 MV	4.9		
Electrons	15-9 MeV	2.5		
	9-4 MeV	2		
	15-4 MeV	0.4		
Protons-electrons	62-15 MeV	2.9		
	62-9 MeV	0.5		
	62-4 MeV	2.5		
Protons-photons	62 MeV-6 MV	0.4		
	62 MeV-6 MV	4.5		

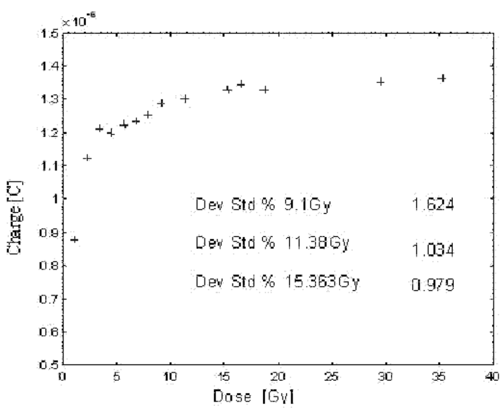

Figure 2. Linearity with dose for CVD diamond during "priming" for 6 MV photons e dose rate of Gy$\backslash min$

ation beams: it turned out to be linear in every case, with a regression coefficient never lower than 0.997. The sensitivities and the specific sensitivities of the CVD detector for all the radiation beams used, are summarized in Table 2. In the same table we report the percentage differences of the diamond response to different beams and to different energies of the same beam. All the differences turn out to be lower than 5%. These values show a consistent difference with respect to those reported in the literature by other authors [7].

It is clear that CVD diamond has sufficient sensitivity to be used as a dosimeter, when compared with other commercially available devices.

3.3. Dose Rate effect

The dose-rate dependence of diamond was studied for proton, electron and photon beams. In the case of protons the variation of the dose rate (in the range $1 - 10Gymin$) was realized by changing the beam current at the accelerating stage. The results are reported in reference [9]. For electron and photon beams the dose rate was varied from 1 to 8 Gymin using the assumption that the dose rate varies as $1d^2$, where d is the distance between the source and the dosimeter.

The results obtained show a low tendency to saturation when the dose rate increases. This effect has been observed by other authors [5] [8] for natural diamond detectors. The detector current, I, versus the dose rate can be fitted with the semi-empirical expression [4]:

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

where D_r is the dose rate. The parameter I_{dark} expresses the contribution of the dark-current. R is the fitting parameter for the response of diamond detector and Δ is the parameter accounting for the dose rate dependence of diamond. For the detector investigated, Δ was 0.874 and 0.870 for 6 MV photon and 15 MeV electron beams, respectively. These values are consistent with those reported in the literature by other authors [7], [8], [2] and with that obtained with proton beams for the same sample [9].

3.4. Let dependence

The knowledge of the different stopping power effects (LET effects) in the diamond response is necessary for its use in the clinical dosimetry. The results of Table 2 demonstrate that these effects are below 5% for electron and photons. In order to investigate the LET effects also for the proton beams, we studied the response of diamond placing it at different depths (2.59, 19.59 and 24.89 mm PMMA) in a full energy proton Bragg peak. In this way each point corresponds to a different proton beam energy. Figure 3 shows the sensitive factors (in n$CcGy$) as function of the depth in a PMMA phantom. It is evident a small energy dependence of diamond also when proton beams of different energies are used.

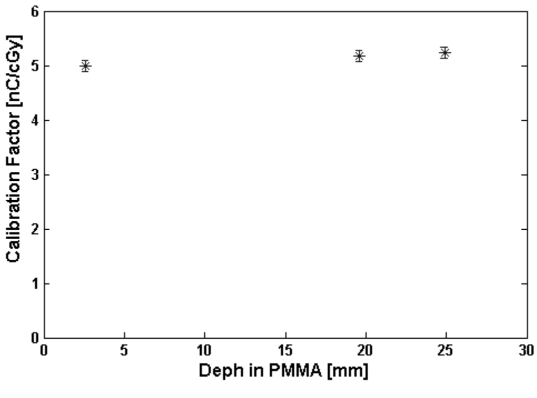

Figure 3. Sensitivity factors of diamond at three different depth in PMMA corresponding to three different energies

3.5. Conclusions and future

The performance of a CVD device has been investigated in the *on line* configuration. This study confirmed the favorable properties of such a detector for its use in conventional beams (electron and photon) and also in proton beams. After preirradiation, the diamond detector response shows a good stability, a linear response with absorbed dose and a very small LET dependence (for different energies of the same type of radiation). Moreover its response appears almost independent of different types of radiation beams employed (see Table 2.

The results obtained encourage us to continue the investigation of this detector. In the next future we will study its dynamic response in order to verify the possibility of its application also with a time-dependent radiation beam (like IMRT), where a good time resolution is needed.

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