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Impact of the change in the mean excitation energy of diamond on energy deposition in different beam qualities

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INTRODUCTION

The use of synthetic diamond detectors has surged in small-field photon and electron beam dosimetry during the recent years. The detector's absorbed-dose energy dependence and perturbation of radiation fluence caused by extra-cameral components and non-water equivalence of the cavity itself has been investigated using Monte Carlo (MC). However, there is no consensus on which mass density (ρ) and mean excitation energy (I-value) should be adopted for mass electronic stopping power (S_{el}/ρ) calculations and MC simulations.

The confusion arises because graphite and diamond are carbon allotropes (atomic number Z = 6) but they have different crystalline structures and mass densities (ρ = 2.265 g/cm^3 for crystalline graphite, ρ = 3.515 g/cm^3 for diamond). Moreover, Fernández-Varea et al (2008) pointed out that diamond and graphite differ in their optical and dielectric properties. Based on the dielectric formalism, the I-value of diamond would be 88 eV instead of 81 eV for graphite. It is clear from the Bethe formula for the mass electronic stopping power of light charged particles that the density-effect correction term (δ) and energy deposition in diamond medium would be affected

$$\frac{S_{el}}{\rho}(E) = \frac{2\pi r_e^2 m_e c^2}{m_u}\frac{1}{\beta^2}\frac{Z}{A}\left[\ln\left(\frac{E^2}{I^2}\frac{\gamma+1}{2}\right) + F^{\pm}(\gamma) - \delta\left(\rho\frac{Z}{A}, I^2, \gamma\right)\right]$$

However, the International Commission on Radiation Units and Measurements (ICRU) has not made any distinction between graphite and diamond.

AIM

Given the increasing use of diamond detectors and an ongoing discussion on the cause of its over-response relative to water in small-field dosimetry (Scott et al 2012, Andreo and Benmakhlouf 2017), this study investigated what implications the use of an I-value of 88 eV would have in terms of energy deposition in diamond for different beam qualities where diamond dosimeters have potential applications.

METHODS

The main program penEasy (v. 2019-09-21) for the PENELOPE (v. 2018) general-purpose MC code was used to calculate energy deposited ε in a cylindrical diamond cavity (r = 1.1 mm, t = 1 µm (mimicking a commercial diamond detector), 10 µm, and 30 µm. The statistical uncertainties were up to 0.3 % (k = 2).

The investigated beams were:

1. Kilovoltage photon beams (25-180 kV) corresponding to the CCRI x-ray beam qualities.
2. Brachytherapy (BT) sources: ^{106}Ru (average beta energy 1.4 MeV, ^{125}I (average photon energy 28 keV), ^{169}Yb (average photon energy 93 keV with major emissions at 50 and 200 keV), ^{192}Ir (average photon energy 350 keV).
3. Calibration beam ^{60}Co (two major gamma emissions at 1.17 and 1.33 MeV)
4. 6 MV photon beam (0.5 × 0.5 cm^2 and 10 × 10 cm^2 fields).

The density-effect correction term and the mass electronic stopping power values were obtained using the PENELOPE MC code.

RESULTS AND DISCUSSION

1. MC results of energy deposition in diamond

Table 1. % change in energy deposited ε in different thickness diamond cavities (r = 1.1 mm) when the I-value was changed from 81 to 88 eV. The mass density was 3.515 g/cm^3.

Beam		Cavity thickness		
		1 µm	10 µm	30 µm
25 – 180 kV		-1.0 %	negligible	
^{125}I, ^{169}Yb, ^{192}Ir		-1.0 %	negligible	
^{106}Ru		-0.7 %	-0.7 %	-0.7 %
^{60}Co		-0.6 %	-0.6 %	-0.6 %
6 MV	0.5 × 0.5 cm^2	-	-	-0.7 %
	10 ×10 cm^2	-	-	-0.5 %

- Kilovoltage beams and BT sources

The negligible change in ε for 10 and 30 µm cavities is due to the short continuous slowing down range of electrons compared to the cavity dimensions. For instance, the average fluence-weighted electron energy ranges from 10 to 29 keV for 25 -180 kV beams corresponding to the continuous slowing down range of electrons from 0.8 to 5 µm, respectively, in diamond cavity. Therefore, the I-value is no longer useful to describe energy deposition. In the case of the beta emitter ^{106}Ru, ε decreased by 0.7 % when the I-value increased, and the change was independent of cavity thickness.

- ^{60}Co and 6 MV photon beams

The change in energy deposited did not depend on cavity thickness because the fraction of photon interactions inside the cavity was low in these beam qualities. In 6 MV photon beams, the shape of electron fluence in diamond is similar in small and large fields, hence the change in ε was of the same magnitude within the statistical uncertainties.

CONCLUSIONS

In practice, currently used MC-calculated small-field output correction factors would not change if a larger I-value for diamond would be adopted. However, Figures 1 and 2 indicate that the mass electronic stopping power and the density-effect correction term are affected to a non-negligible degree in this energy range and this should be taken into account when energy deposition in diamond is investigated not as a ratio (for instance, determining whether the I-value or the mass density influence energy deposition) or when electron spectra differ in the compared cases.

2. Mass electronic stopping power

Figure 1 shows that when the I-value increases, the mass electronic stopping power for electrons in diamond decreases by up to 1.8 %. Use of the currently adopted I-value and crystalline density of graphite for S_{el}/ρ calculations for diamond gives a more varying change (blue curve). Hence the use of different quantities of (I-value, ρ) for S_{el}/ρ calculations than those for MC simulations, i.e. (81 eV, 2.265 g/cm^3) and (81 eV, 3.515 g/cm^3), respectively, (Andreo and Benmakhlouf (2017)) does not give a coherent view of electron interactions in diamond and does not allow for estimation of how energy deposition would change as a function of electron energy.

That being said, the change in S_{el}/ρ averaged over electron fluence in the diamond cavity may not always directly indicate the change in energy deposited if the cavity cannot be assumed as small or intermediate size compared to the electron range as Table 1 indicates.

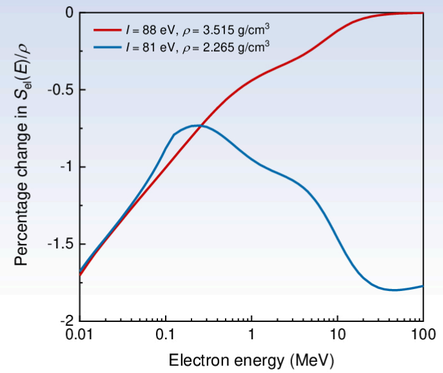

Figure 1. % change in the mass electronic stopping power S_{el}/ρ of diamond as a function of electron energy compared to the case when I = 81 eV and ρ = 3.515 g/cm^3.

3. Density-effect correction term

Although the density-effect correction term plays a role at high energies, the differences between diamond and graphite material properties affect the term mostly at lower energies since the effect depends on the dielectric properties of media. Furthermore, most of the electrons produced by 6 MV photon beams have energies below 1 MeV and the density-effect correction term contribution to S_{el}/ρ is up to 5 % in this energy range and cannot be neglected.

As Figure 2 indicates, diamond (88 eV, 3.515 g/cm^3) and graphite (81 eV, 2.265 g/cm^3) have different density-effect correction terms. The former approaches zero faster due to its energy band gap of 5.5 eV (40 meV for graphite). Additionally, even if the same I-value of 81 eV and diamond mass density of 3.515 g/cm^3 is used in MC calculations, diamond is an insulator and should not be treated as a graphite-like material (conductor). Therefore, changing only the mass density in the MC material definition files, as it is currently done, is not enough to have a proper description of diamond medium.

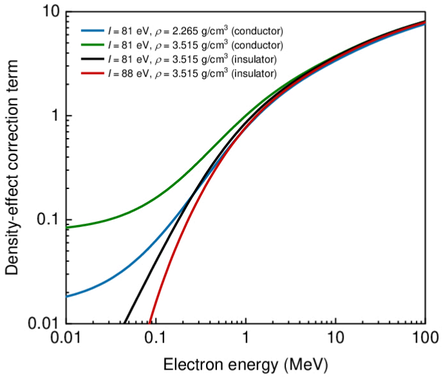

Figure 2. Density-effect correction term as a function of electron energy for different media with graphite and diamond properties. *Conductor* means that 1 conduction electron was assumed for the medium, as currently recommended for graphite by ICRU 90.

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