Dose response of selected solid state detectors in applied homogeneous transverse and longitudinal magnetic fields

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Purpose: MR-Linac devices under development worldwide will require standard calibration, commissioning, and quality assurance. Solid state radiation detectors are often used for dose profiles and percent depth dose measurements. The dose response of selected solid state detectors is therefore evaluated in varying transverse and longitudinal magnetic fields for this purpose.

Methods: The Monte Carlo code PENELOPE was used to model irradiation of a PTW 60003 diamond detector and IBA PFD diode detector in the presence of a magnetic field. The field itself was varied in strength, and oriented both transversely and longitudinally with respect to the incident photon beam. The long axis of the detectors was oriented either parallel or perpendicular to the photon beam. The dose to the active volume of each detector in air was scored, and its ratio to dose with zero magnetic field strength was determined as the “dose response” in magnetic field. Measurements at low fields for both detectors in transverse magnetic fields were taken to evaluate the accuracy of the simulations. Additional simulations were performed in a water phantom to obtain few representative points for beam profile and percent depth dose measurements.

Results: Simulations show significant dose response as a function of magnetic field in transverse field geometries. This response can be near 20% at 1.5 T, and it is highly dependent on the detectors’ relative orientation to the magnetic field, the energy of the photon beam, and detector composition. Measurements at low transverse magnetic fields verify the simulations for both detectors in their relative orientations to radiation beam. Longitudinal magnetic fields, in contrast, show little dose response, rising slowly with magnetic field, and reaching 0.5%–1% at 1.5 T regardless of detector orientation. Water tank and in air simulation results were the same within simulation uncertainty where lateral electronic equilibrium is present and expectedly differed at the beam edge in transverse field orientations only. Due to the difference in design, the two detectors behaved differently.

Conclusions: When transverse magnetic fields are present, great care must be taken when using diamond or diode detectors. Dose response varies with relative detector orientation, magnetic field strength, and between detectors. This response can be considerable (~20% for both detectors). Both detectors in longitudinal fields exhibit little to no dose response as a function of magnetic field. Water tank simulations seem to suggest that the diode detector is better suited to general beam commissioning, and each detector must be investigated separately. © 2014 American Association of Physicists in Medicine. [http://dx.doi.org/10.1118/1.4893276]

Key words: Monte Carlo, Monte Carlo methods, linac-MR, longitudinal and transverse linac-MR, linear accelerators, biomedical MRI, magnetic field, dosimetry, solid state detectors, diamond detector, diode detector

1. INTRODUCTION

The ART² (Advanced Real Time Adaptive RadioTherapy) team at the Cross Cancer Institute (CCI) in Edmonton, Canada, is working on a hybrid magnetic resonance imager (MRI) and linear accelerator (Linac) device capable of delivering radiation whilst imaging the irradiated volume.¹ The group at UMC Utrecht in the Netherlands is also investigating such a device.² These are the only two known groups to possess working prototypes of a system capable of concurrent Linac irradiation and MR imaging. Our group at the CCI uses a rotating biplanar magnetic design in which the Linac and
the magnet rotate together. This design is unique in that it allows for the photon beam from the Linac to be oriented either longitudinally (parallel) or transversely (perpendicular) to the direction of the static magnetic field in the MRI device. At UMC Utrecht, a standard solenoidal magnet is combined with a rotating Linac in the transverse configuration.2

It has been shown previously that the introduction of a magnetic field has a negligible effect in both longitudinal and transverse orientations in a relatively dense homogeneous medium. The introduction of air cavities disturbs equilibrium, and the Lorentz force acting on the secondary electrons gives rise to the so called electron return effect (ERE).3,6,7 Radiation detectors introduce in-homogeneities, and it cannot be assumed that a magnetic field will not introduce appreciable changes in dose response of detectors. To date, much work has been done in characterizing the dose response, and use of ion chambers in MR-Linac devices.8–12

Solid state detectors, such as diamond and diode detectors, can be used for the measurement of PDDs (percent depth doses) and beam profiles, as well as dosimetric measurements in small fields, such as those encountered in radiosurgery.13,14 These detectors may be attractive for use since they offer near water equivalence and a small active volume. They can be used in conjunction with ion chambers for the full characterization of a linear accelerator or patient specific quality assurance. According to information readily available by their various manufacturers, their small active volume is conducive to highly spatially sensitive dose profile measurements, IMRT verification, and for general use in regions of steep dose gradients. Work characterizing the various solid state detectors has been investigated briefly, but has not been done in the same, relatively comprehensive fashion as for ion chambers.12

Herein we present a study of dose response to magnetic fields of the PTW 60003 diamond detector, and the IBA PFD Diode detector. Details of these detectors can be found on the manufacturer websites, or data sheets provided with the detector (as for the PTW60003). Physical dimensions of the two detectors are presented in Table I. Both the diamond in the PTW 60003 and the silicon in the PFD exhibit a band gap structure, with forbidden gaps of 5.5 and ~1.1 eV (as per NIST database), respectively. It should be noted that the energy required to create an electron hole pair is larger than the energy of the forbidden gap.15 Irradiation excites electrons from the valence band to the conduction band. In the PTW60003, an externally applied electric field (100 V) collects the charge produced. The IBA PFD contains a p-n junction operating without bias (passive mode), forming a depletion region. Charges freed in this region diffuse and are collected via the passive electric field created by the differences in n and p type silicon.15 The methods of determining the dose response are similar to our previous investigation of the ion chambers, considering both longitudinal and transverse magnetic field configurations.8 These detectors were chosen as both were available for experimental use, and both types are used regularly for relative dose measurements. We also investigate dose response in typical use scenario, i.e., a scanning geometry at a depth in water, in order to evaluate feasibility of use of these detectors. The investigation is done using both Monte Carlo simulations, and experimental measurements to validate the simulations wherever possible owing to equipment limitations.

2. MATERIALS AND METHODS

2.A. Description of geometry

There are four standard relative orientations of the photon beam, magnetic field, and radiation detectors’ long axis that have been previously investigated.8,9 These orientations are presented in Fig. 1. The long axis of the detector can be oriented either parallel [Figs. 1(I) and 1(III)] or perpendicular [Figs. 1(II) and 1(IV)] to the incident photons. The magnetic field strength is varied in this investigation, and its orientation can be either longitudinal with the photon beam (Figs. 1(III))

<table>
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<tr>
<th>Detector</th>
<th>Active volume radius (mm)</th>
<th>Active volume thickness (mm)</th>
<th>Depth of active volume setting (mm)</th>
<th>Detector encapsulation length (mm)</th>
<th>Detector encapsulation diameter (mm)</th>
<th>Detector encapsulation material</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTW 60003 Diamond Detector</td>
<td>1.47</td>
<td>0.25</td>
<td>1.0</td>
<td>20</td>
<td>7.3</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>IBA PFD Diode detector</td>
<td>2.5</td>
<td>0.5</td>
<td>0.3</td>
<td>17</td>
<td>7.2</td>
<td>ABS/epoxy/tungsten</td>
</tr>
</tbody>
</table>

FIG. 1. Various geometrical orientations for radiation detector’s long axis (central cylinder) magnetic field (arrow) and radiation beam (transparent rectangular prism) as used in Monte Carlo simulation and experimental measurements.
and I(IV)), or transverse to the photon beam [Figs. 1(I) and 1(II)]. It should be noted that the magnetic field is also perpendicular to the long axis of the detector in orientations 1.I and 1.II. The electric field direction in the detectors does not change with respect to the detector long axis, and thus the relative orientation of electric and magnetic fields changes as we rotate the long axis through orientations I–IV.

These permutations of orientation seem to yield four cases to investigate. In fact, the solid state detectors investigated (PTW 60003 diamond and IBA PFD diode detectors) are asymmetric along the long axis of the detector (see Fig. 2 for detailed detector schematics), more specifically, the materials encountered in front, and behind the face of the cylindrical detector disc differ. This is in contrast to the relatively symmetric design of farmer chambers used in similar studies.8, 9 As a result, orientation 1.II was additionally investigated under a 180° rotation of detectors in the plane of the long axis of the detector. This geometry is termed as orientation II-2 in this work. This brings the total number of orientations under consideration to 5 for each of the two detectors. It should be noted that orientation I.IV does not require investigation under 180° rotation. This is because the electron’s trajectory as influenced by the magnetic field will remain relatively forward in direction, making lateral electron contribution increasingly inconsequential with magnetic field strength.

One final unique orientation of magnetic field, chamber, and radiation beam orientation still exists. Where the long axis of the detector is parallel to the magnetic field, and both are perpendicular to the incident radiation beam. This orientation is not explicitly presented in Fig. 1, but it can be visualized by rotating the chamber in orientation II by 90°. This final orientation will be referred to as orientation V henceforth.

2.B. Simulation setup

All Monte Carlo simulations used the thoroughly benchmarked code system PENELOPE.16–18 PENELOPE was used in part because it is capable of low cut-off energies; this allows for the possibility of tracking lower energy particles, which may have a significant effect on the dose deposited in the active volumes of the detectors. This becomes increasingly important as the range of lower energy electrons approaches the scale of the small detection volumes of these solid state detectors, necessitating explicit tracking down to lower energies. PENELOPE also benefits from a simple and powerful geometry construction approach. Geometries can be built and viewed in 2D by slice, or in 3D with or without a cutaway, in a short period of time. This helps to ensure completeness of geometries that are error free. After each geometry is constructed, the viewer application allows the user to scroll through cross sectional planes along the three cardinal axes, or to rotate a 3D representation in space to check for inconsistencies. The geometry can be viewed by material type, or by body type, where a body is a defined subvolume in the entire geometry (e.g., the diamond disc in the diamond detector). Moreover, PENELOPE contains a main file which implements a rigorous treatment of electromagnetic fields, as presented in the user manual;19 PENELOPE methods in conjunction with magnetic field have been used previously by the ART5 team.3, 8, 20 The free to use main program pmfield.f (available from the OECD/NEA databank) was used with minimal modifications to eliminate electron track logging. Namely, all lines that wrote electron trajectory to file were commented out.

There are a handful of parameters of interest for the user to define in PENELOPE. WCR and WCC define the energy thresholds for the radiative and hard inelastic collisions, respectively. These parameters define the lower cutoff energies for hard inelastic collisions and radiative events, in a mixed random hinge simulation hard interactions do not occur with energies below these values. Eabs is the energy absorption criteria in particle transport. Below this energy a particle is assumed to deposit its energy in place, and is no longer tracked. In the simulation flow the energy and positional information of such particles are tallied, and then the particles are removed from the stack. The WCC, WCR, and Eabs values are set at 1 keV kinetic energy for both detectors. This value gives a good balance between simulation speed, and simulation accuracy, considering the size and composition of the detectors. The maximum step size parameter pertains to the simulation only in the active volume of the detector. This value limits the maximum step size of particle transport, which becomes an important parameter as the thickness of a volume of interest decreases. The value is set to 1 μm for each detector to help ensure particles are modeled appropriately in the volume of interest. The degree by which the mean free path between hard elastic events can be determined by the first transport mean free path is affected by the C1 parameter. The maximum fractional energy loss between hard elastic events (governed by C1) is in turn governed by the C2 parameter. These define the degree of mixed simulation by the random hinge method in PENELOPE.16 They can be varied from 0 (full simulation) to 0.2 (maximum allowed mixed simulation value). The C1 and C2 parameters were set to favor simulation accuracy over speed, and were more stringent for the PTW 60003 (C1 = C2...
The active volume of each detector as a function of magnetic field strength was scored. The data presented (i.e., the dose response) is the ratio of energy deposited in the presence of the magnetic field, to the energy deposited under identical circumstances without any magnetic field. A previously published photon spectrum from a 6 MV Varian 600C Linac was used in all of the simulations. This spectrum was used because, at the time, a Varian 600C Linac was available for experiments. All orientations outlined in Sec. 2.A were simulated for both detectors. Both detectors were simulated at isocenter, 100 cm from the radiation source in air. The field size in the simulation was set at 2 × 4 cm to match the experimental field size that is limited by the open space between the poles of the magnet used. This field size is not expected to invalidate the use of the spectrum from reference 20, where the spectrum is specified for a larger field size, since the measurements are relative in nature. Additionally, this matter has been investigated previously with ion chambers, and was found to have no discernible change (within simulation uncertainty) in dose response at various field sizes at the field strengths investigated.

The diamond detector’s simulation geometry was constructed using a combination of schematics from the manufacturer, and a previously published simulation geometry, it is pictured in Fig. 2(a). The main body of the detector was a cylinder of 7.3 mm diameter and 20 mm length. The active volume of the detector was a diamond, 1.47 mm in radius, and 0.25 mm in thickness. The edge of the active volume was positioned at 1 mm below the top surface of the detector’s housing. The air cavity positioned behind the active volume of the detector was modeled as being 2.65 mm in radius, and 5 mm in length, its face was positioned 1.75 mm below the end of the active volume of the detector. With exception of the air gap and diamond itself, the detector materials were all simulated as polystyrene, as the exact composition of the epoxy setting is unknown.

The diode detector, as seen in Fig. 2(b), was modeled with similar dimensionality and materials as other Monte Carlo work with the IBA PFD diode detector. The active volume (silicone) was a disc 0.5 mm thick and 2.5 mm in diameter, set 0.3 mm below the surface of the detector. The 2.5 mm diameter region behind the active volume was modeled as epoxy through the remainder of the 17 mm length of the detector. The tip of the detector (0.3 mm in thickness above the silicone) was modeled as ABS plastic. The remainder of the detector is a series of 3 annuli around the central 2.5 mm diameter central region. The first annulus extends from 2.5 to 4.4 mm thickness, and is ABS plastic through the 17 mm length of the detector. The second annulus extends from 4.4 to 5.8 mm in thickness. It is composed of tungsten for the first 10 mm in detector length, and epoxy for the remaining 7 mm of detector length. The final annulus extends from 5.8 mm in thickness to 7.2 mm, and is ABS plastic for the entire 17 mm length of the detector.

The mean energy per history deposited in the active volume of each detector as a function of magnetic field strength was scored. The data presented (i.e., the dose response) is the ratio of energy deposited in the presence of the magnetic field, to the energy deposited under identical circumstances without any magnetic field. A previously published photon spectrum from a 6 MV Varian 600C Linac was used in all of the simulations. This spectrum was used because, at the time, a Varian 600C Linac was available for experiments. All orientations outlined in Sec. 2.A were simulated for both detectors. Both detectors were simulated at isocenter, 100 cm from the radiation source in air. The field size in the simulation was set at 2 × 4 cm to match the experimental field size that is limited by the open space between the poles of the magnet used. This field size is not expected to invalidate the use of the spectrum from reference 20, where the spectrum is specified for a larger field size, since the measurements are relative in nature. Additionally, this matter has been investigated previously with ion chambers, and was found to have no discernible change (within simulation uncertainty) in dose response at various field sizes at the field strengths investigated.

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For in air simulations of the diamond and diode detectors, a tight fit PMMA buildup cap was included. The cap was simulated with a cylindrical body and flat tip, each extending 1.27 cm from the detector to provide sufficient 6 MV buildup. This cap has been excluded from Fig. 2 in order to highlight detector compositions, but it was included in the simulation geometry.

All material compositions used in the construction of the simulation geometries were generated within the PENELLOPE code system. PENELLOPE allows the user to either create new materials with defined elemental abundances or use the default predefined materials whose compositions are well known. The material files used in this investigation were all generated from a predefined database of known materials using a companion program contained in the PENELLOPE code.

In air simulations, of the four previously studied orientations, for the two detectors were additionally repeated with a change in detector composition implemented. The PTW 60003 was simulated with the air gap replaced by polystyrene, and the IBA PFD was simulated with all materials, including the tungsten shield, set to polystyrene. This was done to investigate the probable cause of the recorded dose responses. Models of the modified PTW 60003 diamond and IBA PFD diode detectors are pictured in Figs. 2(c) and 2(d), respectively.

Simulations for each detector were also done in a 20 × 20 × 20 cm water tank, using the aforementioned photon beam at source to surface distance (SSD) of 95 cm, and a 10 × 10 cm field size defined at 100 cm from the source. Each simulation was done both without a magnetic field, and with either a transverse [Figs. 1(I) and 1(II)], or longitudinal [Figs. 1(III) and 1(IV)] magnetic field, with a field strength of 0.5 T. The detectors were simulated as above, without the buildup caps, in dose at depth, and beam profile geometries. The dose at depth geometry used the parallel detector orientation [Figs. 1(I) and 1(III)]. Dose at depth simulations was done with the active volume of each detector at Dmax (1.5 cm) and again at a depth of 5 cm. The beam profile geometry used the perpendicular detector orientation [Figs. 1(II) and 1(IV)]. The beam profile geometry was simulated with each detector in four different positions. The centers of the active volumes of the detectors were positioned at Dmax, at 5 cm depth on the CAX (central axis), and then at the left and right edges of the collimated photon field dimensions (5 cm from CAX in either direction). The dose response in each case was evaluated as the ratio of the simulation result with magnetic field to that without a magnetic field in the same geometry. Although the charge collected by the detector in a magnetic field is affected by the change in the intrinsic response of the detector and the alteration of the secondary electron fluence (i.e., the real change in dose deposited at a point), this investigation does not separate the two effects and presents a gross change in the energy deposited in the sensitive volume of the detector due to the presence of magnetic field.

In order to further validate the simulated behavior of the detectors in a water tank, the dose to water at that point in the
absence of any detector was also simulated. The dose to water along the central axis (a percent depth dose), and the dose to water at the periphery of the fields at 5 cm depth, and 5 cm left and right of the central axis (beams eye view) were scored. The ratio of the doses to water with and without a magnetic field applied as per above was taken for comparison. The simulation parameters used for the dose to water were identical to the simulation parameters above. The size of the scoring volume of water was set equal to the size of the active volume of the diode detector. The detectors’ behavior in the water tank can be compared to both the dose to water at that point, as well as in in air simulations and measurements to assess any changes of the in air magnetic field dose responses when the detectors are used in a phantom. We can also evaluate the potential use of these detectors in beam scanning situations.

2.C. Measurement setup

The physical size of the electromagnet available did not allow for the water tank measurements to be done. The experimental results for the PTW 60003 diamond detector were obtained using a 6 MV beam from a Varian 600C Linac (Varian Medical Systems, Palo Alto, CA). The IBA PFD detector experiments were conducted using the 6 MV beam from a Varian 23EX, as the last 600C is no longer available for use. Both Linacs are produced by Varian and will have small spectral differences. The differences in spectra are expected to be of the order of, or less than, the differences seen between manufacturers. This intermachine variability is small in magnitude and will have little overall impact, especially compared to the mechanisms described further on. Measurements were made in air with the aid of a 0.2 cm thick brass buildup cap to ensure electronic equilibrium in the detector. The detectors with buildup caps were placed at the center of the two poles of a small electromagnet (EEV M4261, Chelmsford England) in configurations I and II. Measurements in configuration II were taken twice, with the detector rotated 180° in the plane of the long axis in the second set. The poles of the magnet measure 7.5 cm in diameter and are separated by a distance of 7.5 cm. In the experiments involving these solid state detectors, the magnetic field strength was varied from 0 T to ~0.18 T. The field strength of the electromagnet in the central region between the poles was verified using a three-dimensional hall probe (SE-NIS GmbH C-H3A-2m_E3D-2.5 kHz-1%-0.2 T), the manufacturer claims the probe has an accuracy of 1%. Longitudinal magnetic field orientations (Configurations III and IV) have presently not been investigated experimentally. The physical shape and dimensions of the electromagnet do not allow for a photon beam parallel to the magnetic field without irradiating the magnet itself. The active volumes of the detectors were set at the isocenter, at 100 cm from the source of radiation. The field size used was 2 × 4 cm at isocenter, which was sufficient to encompass the entire detector volume.

The results are presented as the ratio of charge collected in the presence of a magnetic field to the charge collected in the absence of a magnetic field as a function of magnetic field strength. Using a ratio allows us to isolate the factor attributed to dose response in the magnetic field and compare the results with the simulations that are presented as the ratio of energy deposited in the sensitive volume. The similar ratio of energy deposited in the active volume of the detector with and without magnetic field was calculated from simulations, and thus the experimental the simulation results are directly comparable (except for the buildup cap material). It is true that the buildup cap material will alter the composition and spectrum of incident radiation on the active volume of the detector; however, this change is expected to be small and will differ depending on the exact composition of the brass in the cap, which is unknown. It is also worth noting that the spectrum used in the simulations will differ slightly from that produced by the Linac itself, as well as from Linac to Linac. These spectrum perturbations will be small and are expected to be inconsequential to the relative nature of this work. The detectors were preirradiated according to manufacturer recommendations before use. A set of three 100 MU readings was taken at each magnetic field strength for both detectors. The average of these three measurements was taken as the data point for the associated magnetic field. To verify the stability of the measurements, once the data set was complete, the baseline (no magnetic field) and readings for three intermediate field strengths were remeasured to ensure they were unchanged.

3. RESULTS AND DISCUSSION

3.A. PTW60003 in air

Figure 3 depicts the Monte Carlo simulated dose response for the PTW 60003 Diamond Detector in all orientations. Figure 4 depicts the simulations and measurement dose responses for three transverse field orientations (orientations I, II, and II-2). Figure 5 shows the difference in simulations with and without the air gap [Fig. 2(a) as compared to Fig. 2(c)] to illuminate mechanisms of the observed dose response. It should be noted that orientations III and IV are excluded from Fig. 5. The orientation III and IV results with and without the air gap are nearly identical and their removal aided readability of the figure.

The PTW60003 detector simulations have an average standard deviation of uncertainty of ±0.65% for all orientations. The simulated dose responses for orientations III and IV as presented in Fig. 3 are nearly the same; both orientations exhibit a slight upward trend with the relative response approaching 1.005 (0.5%) at 1.5 T, which is less than one standard deviation of simulation uncertainty. A similar response in these orientations was also found for ion chambers. Orientation V also exhibits slight change as a function of magnetic field strength, showing a possible slight increase in dose response (1.006) towards 1.5 T. This was expected, as the regions surrounding the detection volume are radially symmetric in the direction of curvature in this orientation, meaning electrons will see little to no difference with and without a magnetic field.

The dose response in orientation I does not change much up to 0.5 T transverse magnetic field; however, thereafter it
increases slowly to 1.06 at 1.5 T. The mechanism for this behavior is likely the electron return effect, where above 0.5 T, electrons entering the polystyrene curve back and re-enter the diamond and deposit energy in the active volume of the detector. Replacing air gap with polystyrene does not appear to be of consequence to this dose response, as is evident in Fig. 5. In Fig. 4 we see that the measurements made in all orientations follow the simulated results, staying near 1.0 in orientation I, rising to near 1.01 in orientation II and falling to near 0.99 in orientation II-2 at ∼0.18 T. The measured data points generally do not stray far from the simulated data. There is a clear rise, fall, or null result through low field strengths in the measured data, depending on the orientation considered. The error in the measured data points is on average ±0.5%. It can be seen that the measurements agree with the simulations within 0.5% through all measured field strengths. Given the good comparison between results, it could be suggested that the simulations accurately model the detector, and had higher magnetic fields been possible, the agreement between the measured and simulated values would remain.

The orientation II and II-2 responses are opposite of each other. The orientation II simulation shows a sharp rise in dose...
response as a function of magnetic field, reaching higher than 1.20 at 1.5 T. In this orientation the electrons incident on the active volume are first curved through the internal detector components situated nearer the stem [from left to right in Fig. 2(a)]. The active volume of the diamond detector is a thin circular slab, and as secondary electrons are curved via the Lorentz force, those incident on the active volume see a larger, more circular cross section of the active volume, rather than a thin disc of diamond on edge leading to an increased dose response. Additionally, electrons entering the air gap are able to freely follow their curved trajectories, and are bent towards the active volume of the detector increasing electrons incident. As seen in Fig. 5, these electrons originating from the air gap region contribute to the increased dose response, but are not the sole cause of the response, as evidenced by the rise in dose response as a function of magnetic field without the air gap present.

The diamond detector orientation II-2 case exhibits a different response than the orientation II results. Where in orientation II there is a sharp rise in dose response, the orientation II-2 trend is a slow decrease in dose response, trending towards 0.97 at 1.5 T. The orientation of the detector in the II-2 case is actually mirrored to that shown in Fig. 2(a). Although the curving of electrons due to magnetic field is in the same direction with respect to the magnetic field as in orientation II, the electrons will appear to curve from right to left with respect to the internal structure of the diamond shown in Fig. 2(a). It is true that in this orientation the electrons incident on the active volume of the detector see an increasing cross sectional area as was the case for orientation II. This increase in cross sectional area seen would tend to increase dose response as more electrons are incident on the detection volume, but this is not what the simulations would suggest. It appears that the effect of air pocket in the detector structure dominates the observed response. Figure 5 shows that the decrease in response is due to the electrons in this orientation entering the air gap and curving away from the active volume of the detector via the Lorentz force, thus decreasing the energy deposited in the active volume. It is evident that the bending away of the electrons due to the presence of the air gap has a larger impact on the total dose response than the initial effect, yielding an overall decrease in dose response as a function of magnetic field strength. When the air gap is replaced by the polystyrene [Fig. 2(c)], the dose response increases slightly due to the increase in the apparent cross-section of the active volume. Measurements in this orientation are seen to follow the simulation results within 0.3%.

3.B. IBA PFD in air

Figure 6 depicts the Monte Carlo results for the IBA PFD Diode Detector in all orientations. Figure 7 depicts the simulations and measurement quantities for three transverse field orientations (orientations I, II, and II-2). Figure 8 shows the difference in simulations with the change in detector materials implemented [Fig. 2(b) as compared to Fig 2(d)] to illuminate mechanisms of the observed dose response. It should be noted that orientations III and IV are excluded from Fig. 8. The orientation III and IV results for both detector material compositions are nearly identical and their removal aided readability of the figure.

The IBA PFD diode detector simulations have an average standard deviation of ±0.85% for all orientations. The simulated responses for orientations III and IV as presented in Fig. 5 nearly lie on top of one another and exhibit a slight upward trend with a relative response approaching 1.01 (1%)
at 1.5 T. This kind of response was not unexpected, and was found to be the same for the PTW 60003 diamond detector, and selected ion chambers. Again, a similar response to orientations III and IV was found for orientation V, which is the same behavior as was found for the PTW 60003. The largest change in the response of 1.017 occurs at the largest magnetic field strength of 1.5 T. This was expected as the diode detector is also radially symmetric about the detection volume in the direction of electron curvature in this orientation.

The relative dose response of the diode detector in orientation I decreases at an increasing rate as magnetic field strength is increased. In this case the Lorentz force tends to curve electrons laterally from the buildup material through the internal detector components, namely the tungsten shielding, towards the active volume of the detector (through the plane of the page in Fig. 2(b)). The diode detector’s response is predominantly affected (as seen in Fig. 8) by the presence of the cylindrical tungsten shield along the long axis of the detector. The curved electrons encounter the encapsulating tungsten and are removed from the beam, thus resulting in lower dose. When the tungsten shield is replaced by polystyrene, the dose response is increased slightly, as electrons are no longer being attenuated by the tungsten shield (Fig. 8). Measurements shown in Fig. 7 hover around the 1.0 relative response mark.
for orientation I, rise to near 1.03 in orientation II-2, and fall to near 0.99 in orientation II, at \( \sim 0.18 \) T. The measurement points follow the simulated data closely at these low magnetic field strengths for orientations I and II. Measurements in orientation II-2 start out 0.5% low until near 0.1 T, where they match more closely (0.2%) through the higher field strengths. Although there is a difference in the agreement of the measurements and simulations below and above 0.1 T, all measurement points are within simulation uncertainty. The average error in the measurements was \( \pm 0.5\% \), and their values match the response seen in the simulations within 0.2% up to the highest measured field strength. From the measured data, it is clear that in these low field strengths the simulation accurately models the dose response. It is not unreasonable to assume that measurements done at higher field strengths would also agree with the simulations.

In orientation II-2 electrons incident on the active volume of the diode detector will be curved via the Lorentz force through the laterally situated buildup material, from left to right in Fig. 2(b) [as presented with the Lorentz Force from left to right, Fig. 2(b) is orientation II-2]. Unlike in the same orientation with the PTW 60003 diamond detector, there is a monotonic rise in dose response as a function of magnetic field strength, up to a relative response of 1.2 at 1.5 T seen in Fig. 5. This is because the active volume of the diode detector is a thin disc, geometrically similar to the diamond detector. As the magnetic field increases, the electrons curve more, and the detection volume cross section seen by the curved electrons incident increases as it becomes more and more circle-like, leading to an increased dose response. This differs from the diamond detector in that there is no air gap giving rise to a dominating loss of scattered radiation from the stem side of the detection volume. Figure 8 shows that upon removal of the tungsten shield, the relative response is somewhat lower than with the shield. This can be easily explained by looking at the zero magnetic field cases of both detector constructions. In the zero field case, electrons still must travel through tungsten to reach the active volume in the original design; where in the modified design the tungsten is absent (giving a larger zero field reading). Because the results are normalized to this measurement in each case, it is clear that without the tungsten shield, the larger baseline measurement (no magnetic field) will decrease relative response with increasing field strengths.

As seen in Fig. 6, the relative dose response of orientation II decreases slowly to 0.95 at 1.0 T then rises slowly to 0.97 at 1.5 T. Although the increasing detection volume cross section seen by the curved electrons [electrons travel from right to left in Fig. 2(b)] is true for orientation II, we must also consider the materials the electrons incident on the detector must travel through. As seen in Fig. 8, the tungsten encapsulation again has a noticeable effect on dose response, as was the case for orientation I. This encapsulation will remove more of the electrons that traverse it compared to the other materials present, so fewer are available to interact with the detection volume. This removal of electrons tends to decrease the dose response and is initially a larger effect than the increasing cross sectional area seen by the curved electrons. After 1.0 T the individual response of the increasing cross sectional area begins to increase relative to the removal of beam by the tungsten, and the total relative response increases from a minimum. This response differs from the sharp rise seen in the diamond detector due to the differences in construction materials, namely the tungsten shielding of the diode, and air gap in the diamond detector.

3.C. Beam scanning simulations

Figures 9 and 10 profile the water tank simulations of the diamond and diode detectors, respectively, as compared to the relevant simulation results in air and water. It should be noted
FIG. 9. PTW60003 diamond detector simulations in air and a water tank, presented as the ratio of dose with to dose without magnetic field (0.5 T). Water tank simulations are done in dose at depth (labeled DD, corresponding to orientations I and III depending on magnetic field direction) and profile scanning (labeled Profile, corresponding to orientation II-2 and IV depending on magnetic field direction) geometries, at Dmax, 5 cm depth on the CAX, and 5 cm depth at beam left (LE) and right (RE) edges (beams eye view). Ratio of dose to water, i.e., in the absence of detector, at all these points in the phantom are also presented.

that only one of the orientation II (orientation II-2) geometries was simulated, orientation V was also omitted. It is expected that the same trends with respect to the in air measurements will be observed in the remaining orientations while not near the periphery of the field. For reference, as discussed previously, secondary electrons in orientation II-2 (the simulated orientation) tend to curve from the tip of each detector towards the active volume and stem region, namely from right to left in Fig. 2(a) and from left to right in Fig. 2(b). It should be noted that not all detector positions were investigated for each orientation (i.e., beam profile simulations were not completed in orientations I or III). This is because the detector positions omitted are not typically used in the respective orientation. As such, the reader should be aware that a water tank simulation done in a particular detector position and orientation may not have a corresponding simulation in another orientation.

The uncertainty in the water tank simulations was ±3.5% on average for the PTW60003 diamond detector simulations. The uncertainty for the IBA PFD diode detector was an average of ±4.0%. The average uncertainty in the ratio of dose (with and without magnetic field) in water was 2.75% along the central axis, and 6.0% at the beam periphery. These uncertainties at the left and right edges are larger than the uncertainties for the in air simulations due to the simulation geometry. The water tank itself is much larger than the active volumes of

FIG. 10. IBA PFD diode detector simulations in air and a water tank, presented as the ratio of dose with to dose without magnetic field (0.5 T). Water tank simulations are done in dose at depth (labeled DD, corresponding to orientations I and III depending on magnetic field direction) and profile scanning (labeled Profile, corresponding to orientation II-2 and IV depending on magnetic field direction) geometries, at Dmax, 5 cm depth on the CAX, and 5 cm depth at beam left (LE) and right (RE) edges (beams eye view). Ratio of dose to water, i.e., in the absence of detector, at all these points in the phantom are also presented.
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Each detector scored for dose. Each particle shower therefore takes much longer to track through the geometry, and is less likely to interact with the volume of interest. While the simulation uncertainty in the ratio of dose to the medium at the beam periphery is large, it is less than the difference between the dose response in water (with and without magnetic field), and dose response in the radiation detector in orientation II-2 where it is of importance.

As can be seen in Fig. 9, the water tank and in air simulations for the diamond detector differ by up to 3% in all orientations when not at the edge of the beam. This could suggest a slight depth dependence on dose response; however, this deviation is still close to one standard deviation of the simulations, making an exact postulation impossible. We see that the dose response to water differs to that of the diamond detector in the water tank, as was expected. The dose response of the diamond detector for a given orientation at the water tank field strength (0.5 T) is represented by the difference between the normalized dose to the detector, and the normalized dose to water at this point. The dose response simulations at the left and right edge of the beam in the water tank with transverse magnetic fields (orientation II-2) vary drastically from the in air result (∼20%), which was expected, and do not seem to accurately represent the ratio of dose to water in the region. Lateral electronic equilibrium does not exist in these regions, so the introduction of transverse magnetic fields (those which guide electrons across the active volume asymmetrically at either edge of the beam) drastically alters the dose deposited in the detector, as well as in the phantom generally. At the left edge of the beam, electrons that would have reached the scoring volume tend to curve towards the central axis, and are not replaced, leading to lost dose contributions and a lower magnetic field dose response in both the water, and detector. It is clear from Fig. 9 that the amount by which the dose to water is altered by the magnetic field at the left edge is not modeled accurately by the detector, differing by ∼7%. At the right edge of the beam electrons tend to curve towards the scoring volume. As per previous discussion, these electrons see an increasing cross section of the active volume, leading to an increased dose response in the detector. The dose to water also increases in this case due to electrons curving towards the scoring volume. However, the increase to dose in water is again not accurately modeled by the detector, their responses in fact differ. The left and right edge responses of the water and diamond detector suggest that a combination of dose to water and intrinsic detector response are factors in the overall dose response at these positions. The beam periphery cases differ from the in air simulations, which were done in the center of the field encompassing the entire detector. The difference arises because in this water tank case there is no electronic equilibrium.

Those water tank simulations completed in orientations III and IV using the diamond detector show relatively similar results to the corresponding in air simulations, as is the case in orientations I and II-2 when not at the edge of the beam. However, at the periphery of the beam in orientation IV we do not see the large deviations in dose response that we saw in orientation II-2. The dose response instead is relatively stable. This was again expected, since the electrons are focused downstream homogeneously throughout the beam, which would tend to lead to a stable response across the beam. The detector does seem to under-report the dose to water at the periphery slightly in orientation IV, but the water tank simulation uncertainty is still larger than the difference between simulations, so exact conclusions are impossible.

The water tank and in air simulations for the diode detector appear to lay nearly on top of one another when not at the edge of the beam for all orientations (beam edge simulations only completed in orientations II-2 and IV), they differ by an average of 0.75%. This differs from the diamond detector results, in that the simulation results in the water tank are closer to the corresponding simulation results in air. However, it must be noted that the water tank simulation error is still larger than the average difference between simulations. The dose response to water differs to that of the diode detector in the water tank, similarly to the diamond detector, as was expected. In the same manner as the diamond detector, the dose response of the diamond detector for a given orientation at the water tank field strength (0.5 T) is represented by the difference between the normalized dose to the detector, and the normalized dose to water at this point. Again, similar to the case for the diamond detector, the diode detector simulation results at the periphery of the beam for transverse magnetic fields in the water tank vary from the in air simulations a great deal (∼10%–20%), and vary from the dose to water simulations, but to a lesser extent (∼10%–14%). At the left edge of the beam, as was the case with the diamond detector, electrons tend to curve towards the central axis of the beam, and are not replaced, leading to the large decrease in dose response seen in the diode detector, as well as in the dose to water (but by different amounts). In contrast, at the right edge of the beam, there is a large increase in dose response. In the diode detector this is again mainly to the increasing cross section of the active volume seen by the incident electrons, where the difference in the dose to water is due to the increased number electrons directed towards the scoring volume by the magnetic field. This again differs from the in air simulations, where electron equilibrium existed. It is clear that the diode detector does not accurately measure dose in the penumbra regions presented, the observed response is some combination of the actual change in dose to water with magnetic field and the intrinsic response of the diode detector to the magnetic field.

The diode detector simulations completed in orientations III and IV show the same relative response (to the in air simulations) as those simulations completed in orientations I and II-2 when not at the periphery of the beam. The large deviations at the periphery of the beam seen in orientation II-2 are not seen in orientation IV, where instead the dose response is relatively stable through all detector locations. This is again due to the nature of the focused electrons downstream. The electrons in this case are focused symmetrically throughout the entire beam (including the beam edges), and are not preferentially curved in one direction. It is therefore not unexpected that we see the same dose response throughout all areas of the beam. However, we again see that the detector
does seem to under-report the dose to water at the periphery slightly in orientation IV. Exact conclusions are still impossible here due to the size of the simulation uncertainty in this case.

4. CONCLUSION

In air simulations of the PTW60003 diamond detector and IBA PFD diode detector suggest that measurements require a multiplicative correction factor when a magnetic field is introduced. This correction factor, like that postulated for ion chambers, is the reciprocal of the dose response (i.e., 0.935 for a response of 1.07). This correction factor is of grave importance for ensuring the accuracy of radiotherapy deliveries in a hybrid MR-Linac device. The correction factor itself has a strong dependence on the relative orientations of magnetic field, detector long axis, and incident photon beam, and is dependent on the type of detector used. It is evident that any detector used will have to be characterized independently for its individual magnetic field dose response. Measurements made at low fields follow the same trends, and generally agree quite closely, and are within simulation uncertainty compared to the simulation results. This leads us to conclude that the simulations are likely correct for higher field strengths.

Transverse field orientations appear to have the largest dose responses and the longitudinal orientations show little response as a function of magnetic field. In the presence of a longitudinal magnetic field, minimal correction is needed at 1.5 T, and no correction appears to be required below a field strength of 1.0 T for both detectors investigated. This is in contrast to the cases with transverse magnetic fields, where complete characterization of detectors on an individual basis is required as a function of relative orientations and field strengths.

The water tank simulations suggest that in air characterization of these solid state detectors gives a general trend of dose response with magnetic field. The accuracy of the in-air results compared to the water tank results appears to differ between detectors, but is within simulation uncertainties in both cases; however, the diode detector displays a closer match between the in-air simulations and water tank simulations. It is again shown that each detector must be investigated individually in the field geometry of interest before use. In the penumbra region, both detectors failed to accurately measure the change in dose to water in transverse magnetic fields. In the presence of transverse magnetic fields, beam scanning measurements must therefore be taken with care, so that the beam profile at the beam periphery is measured without artifacts introduced by the detector itself. Longitudinal magnetic field geometries appear not to suffer from this issue to the same degree, if at all, and thus, it is easier to scan the photon beams in the presence of longitudinal magnetic field.

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