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Characterization of miniature RAD-HARD silicon diodes as dosimeters for small fields of photon beams used in radiotherapy

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HIGHLIGHTS

- Dosimetric response characterization of FZ Si diodes for photon beams was studied.
- Beam data acquisition performance of FZ diodes for photon beams was investigated.
- The FZ diode presented good short term repeatability operating in short-circuit mode.
- The results of the penumbra profiles confirmed the good spatial resolution of the FZ.
- Output factor study of the FZ matched with different detectors.

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ABSTRACT

The dosimetric response characterization and beam data acquisition performance of a miniature Float Zone (FZ) silicon diode for photon beams was investigated using Novalis TX linear accelerator (Varian Medical Systems®). In all measurements the unbiased diode operated in a short-circuit mode, connected to the input of a Keithley 6517B electrometer using a water phantom. For photon beams of the 6 and 15 MV the results presented good repeatability (coefficient of variation $\leq$1.6%), measured through switching on/off the photon beams. Moreover, the diode showed a quite linear response, given by the charge versus absorbed dose, with charge sensitivities higher than 6.9 nC/Gy. The output factor, percentage depth dose profile (PDD) and transversal dose profile (TDP) were also measured in a water phantom. For small field sizes, the output factor values using the FZ diode were compared with measurements obtained with a SFD (Stereotactic Field Diode) commercial diode and the differences were 5.4%, 2.5% and 1.3% for the field sizes of 1×1, 2×2 and 3×3 cm^2. For larger field sizes ($\geq 4 \times 4$ cm^2), the maximum difference found was 0.7% in comparison with values obtained with a CC13 ionization chamber. Thus, the result demonstrates that the unshielded FZ diode has the potential to be used for measuring of, as it performed acceptably well for both small and large field sizes. The TDP experimental results obtained with the FZ diode for field sizes of: 1×1 cm^2, 2×2 cm^2 and 4×4 cm^2 are in agreement with experimental results acquired with several commercial detectors. Through the TDP study, the comparison of the field penumbra size confirmed the excellent spatial resolution of the miniature diode. However, the PDD study, requires further investigation.

1. Introduction

The commissioning of small fields (typically $\leq$ 4 cm^2) used in radiotherapy often consists in measurements of output factors, lateral and depth dose profiles (Podgorsak, 2005; TG 106, 2008; TG 120, 2011). Nevertheless the choice of appropriate detectors for this task is still a challenge due to (i) lack of lateral charged particles equilibrium, (ii) partial occlusion of the x-ray source focal spot by

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the collimators and (iii) energy spectrum differences between small and regular field sizes (Almeida, 2012; Aspradakis et al., 2010). Effects (i) and (ii) lead to a rapid reduction in the beam output at central axis as well as a widening of its penumbra (Mecalfe et al., 1993).

The accurate assessment of dosimetric properties of such narrow fields strongly depends on the size of the detectors (volume averaging effect)(Garcia-Vicente et al., 2005; Santos et al., 2011), requiring high spatial resolution devices such as micro (0.007 cm^3) and mini (0.05 cm^3) ionization chambers (Alashrah et al., 2010), semiconductor diodes and diamond based detectors (Alaei et al., 2009; Bruzzi et al., 2002; Talamonti et al., 2011, 2007; Djouguela et al., 2008; Rosenfeld et al., 2011). However, many of them have materials of high atomic number in their construction (e.g. steel central electrodes in small volume ion chambers and silicon in diode dosimeters) which leads to an over-response to low energy photons due to the increased photoelectric interaction relative to water and, as a consequence, field size dependence as a result of effect **(iii)** (Alfonso et al., 2008; Das et al., 2008). In this work we report the development and dosimetric characterization of a waterproof dosimeter based on a miniature unshielded FZ diode envisaging its particular application to the commissioning of small megavoltage fields.

2. Materials and methods

The n-type FZ wafer was produced by the company Okmetic Oyj (Finland) and processed by the Microelectronics Center of Helsinki University of Technology (Härkönen et al., 2004 Väyrynen et al., 2011). The device has a p^+-n-n^+ structure with a p^+ electrode of 6.5 mm^2 surrounded by a guard ring structure and an n^+ electrode with an area given by the outer dimension of the device (≈ 16 mm^2). The diode was covered with a thin layer of black epoxy resin (Technical Data Sheet, 2011) to make it waterproof and for light shielding. The FZ diode received a pre dose of 200 kGy.

In all measurements the unbiased diode operated in a short-circuit mode with the planar pad (p+) connected to the input of a Keithley® 6517B electrometer. The irradiation was performed with 6 MV and 15 MV photon beams from a Novalis TX linac (Varian Medical Systems®) at Sírio Libanês Hospital. The dosimetric parameters, namely linearity between current-dose rate and charge-dose, output current repeatability and both energy/dose rate dependence were determined under the experimental conditions: diode submerged in a 30 cm × 30 cm ×30 cm water phantom at 5.0 cm depth and centered in a 10 × 10 cm^2 field size at a source-to-surface distance (SSD) of 100 cm.

The linearity between output current and dose rate was investigated within the ranges from 100 to 1000 MU/min (1.43–14.29 cGy/s) for 6 MV and 100–600 MU/min (1.57–9.43 cGy/s) for 15 MV. The repeatability parameter was investigated recording output current wave forms (signals) as a function of the exposure time, switching the beam on and off. Each signal was measured with constant dose (100 MU–85 cGy) and dose rate (500 MU/min: 7.14 cGy/s for 6 MV and 7.86 cGy/s for 15 MV). After each step of irradiation, when the beam was switched off, the dark currents were measured to calculate the signal-to-noise ratio (SNR) as well as to foresee possible radiation damage effects.

The dose–response curve given by the charge (achieved through the integration of the photoinduced current from the radiation field) as a function of the dose was studied for both energies, with a constant dose rate of 500 MU/min, in the range from 1 to 1000 MU (0.86 cGy–8.57 Gy for 6 MV and 0.94 cGy–9.43 Gy for 15 MV).

The dependence on the LINAC pulse repetition rate (dependence in MU/min) was evaluated by irradiating the diode with 6 MV photon beam in the range 100–1000 MU/min and measuring the charge to a constant dose of 100 MU. Similar studies were also performed for 15 MV beam with dose rates from 100 to 600 MU/min.

The beam data acquisition performance was studied for 6 MV photons and the obtained results compared with those from the commissioning of the Novalis TX® carried out with several detectors. The main characteristics relevant to radiation dosimetry of these detectors are presented in Table 1.

The output factor was measured with the FZ centered in field sizes from 1 × 1 cm^2 to 40 × 40 cm^2 and placed at 5.0 cm depth. The transversal dose profiles (TDP) and percentage depth dose profiles (PDD) were measured in the water phantom with the FZ diode centered in radiation fields of size 1 × 1 cm^2, 2 × 2 cm^2 and 4 × 4 cm^2 and face on orientation. The dose rate was 500 MU/min and SSD = 100 cm. In both studies, for each position, two signals were consecutively registered. Transversal dose profile measurements were carried out with the diode placed at 5.0 cm depth and moving the treatment table across the whole irradiation field crossplane axis. From these results it was evaluated the penumbra size and compared with those obtained with diodes and ionization chambers. For PDD measurements the dosimeter depth was changed from 0 (phantom surface level) to 200 mm.

3. Results and discussion

3.1. Dosimetric response characterization

The linearity between output photoinduced current and dose pulse repetition rate, within the range 1.43–14.29 cGy/s for a 6 MV radiation field and 1.57–9.43 cGy/s for 15 MV radiation field, is

Table 1
Characteristics of all detectors used in beam data acquisition performance studies.

Detector	Manufacturer	Characteristics		Additional information	
		Dimension		Pre-dose	Sensitivity
SFD (Stereotactic Field Diode)	IBA Dosimetry®	Chip Size (side/thickness) 0.95/0.5 mm Diameter of active area 0.6 mm	Geometric form of active area circled Thickness of active volume 0.06 mm	0 Gy	4.0 nC/Gy
PFD (Photon Field Diode)	IBA Dosimetry®	Chip Size (side/thickness) 2.5/0.5 mm Diameter of active area 2.0 mm	Geometric form of active area circled Thickness of active volume 0.06 mm	0 Gy	30.0 nC/Gy
CC13 (Compact Chamber) Ionization Chamber_Cylindrical	IBA Dosimetry®	Volume 0.13 cm^3	Electrode Diameter 1.0 mm		0.083 nC/cGy
NACP (Nordic Association of Clinical Physicists) Ionization Chamber_ Parallel Plate	IBA Dosimetry®	Volume 0.16 cm^3	Electrode Diameter 10 mm		
A1SL – Thimble Ionization Chamber	Standard Imaging®	Volume 0.057 cm^3	Electrode Diameter 1.0 mm		1.818 nC/Gy
A16 – Micro Ionization Chamber	Standard Imaging®	Volume 0.007 cm3	Electrode Diameter 0.4 mm		0.286 nC/Gy
PinPoint – Ionization Chamber_ Cylindrical	PTW®	Volume 0.015 cm^3	Electrode Diameter 0.3 mm	2 Gy	400 pC/Gy

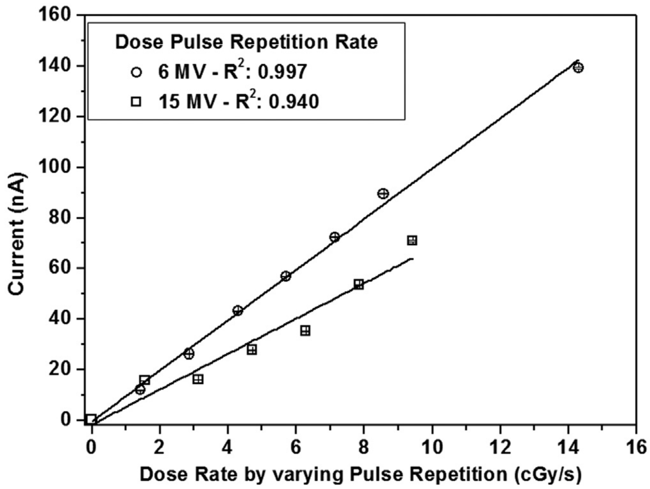

Fig. 1. Output current signals delivered by the FZ diode as a function of dose rate obtained by varying LINAC pulse repetition rate (MU/min) for 6 MV and 15 MV beam qualities. Experimental uncertainties (0.3%) are smaller than the symbols size.

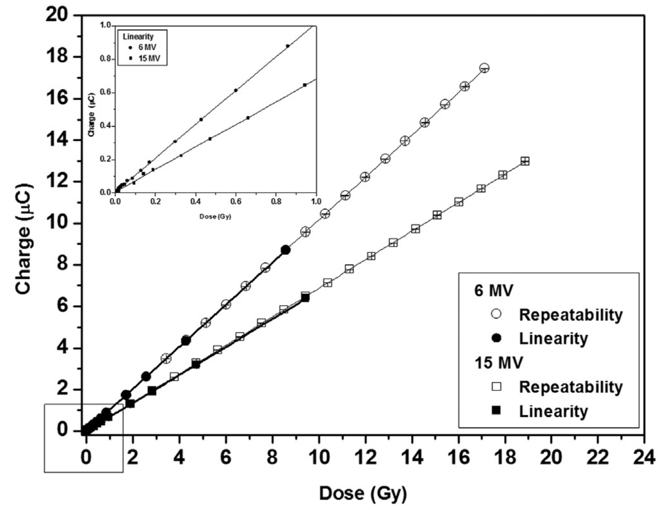

Fig. 3. Dose response curves of the FZ diode obtained from repeatability studies (open dots) and linearity studies (full dots). Experimental uncertainties (0.3%) are smaller than the symbols size.

shown in Fig. 1. Fig. 1 also indicates that there is a significant difference in sensitivity of the FZ diode by the change in slope of the response between the 6 MV and 15 MV beam quality. This may be related to the fact that the amplitude of dose pulses are different between these beams and further studies on dose rate dependence (in terms of dose per pulse) are needed in order to clarify this behavior. These results are in agreement with those obtained during the repeatability tests where twenty current signals were consecutively registered, at the same dose rate of 500 MU/min, for 6 MV and 15 MV. Five of them are displayed in Figs. 2 (a) and (b) where oscillations in the current wave forms are quite evident for 15 MV photon beam. This instability might be due to the linac output dose rate control (Fuduli et al., 2014), but further investigation needs to be done to clarify the origin of it. From the Fig.2(b), because of the log scale, it is also possible to see some intrinsic noise on the dark current, but this effect can be neglected since the signal/noise ratio (350–6 MV and 170 to 15 MV) is very high.

In Fig. 3, the dose–response curves given by the integrated charge generated in the sensitive volume of the diode as a function of the prescribed dose delivered (obtained from both repeatability and linearity studies) are presented. These results are in excellent agreement and evidence the linearity between charge-dose with correlation coefficients of about 0.999. The charge sensitivities of 10.2 nC/Gy (6 MV) and 6.9 nC/Gy (15 MV) may possibly be related to dependence on the dose rate since de dose per pulse are different between the two beams. Further studies on dose rate dependence (in terms of dose per pulse) are needed in order to clarify this behavior. It is important to note that the photoinduced current oscillations (Fig. 2(b)) are accounted for in the integration of the current signal to obtain the average charge. Fig. 4 presents the normalized charge versus dose of the diode irradiated with a 6 and 15 MV photon beam, at a dose rate of 500 MU/min. The repeatability parameters given by the coefficient of variation in charge (CV), calculated as suggested by ISO/ASTM 51276, are 1.0% (6 MV) and 1.6% for 15 MV.

The use of 15 MV radiation beam implies on the photoneutrons production. Although the presence of neutrons in photon beams is low, their damage coefficient on silicon is much higher (Shi et al., 1998). Nevertheless, the reported sensitivity decreases are in the order of 16% per kGy in 21 MV photon beams for commercial diodes (AAPM 87, 2005), while Jornet et al., 2000, reported decreases ranging from 3.4% to 0.2% per 0.1 kGy for different varieties of diodes. In the present experiment, the total accumulated dose due to the 15 MV beam was less than 60 Gy. Thus, we consider that possible changes in diode's sensitivity due to photoneutrons were

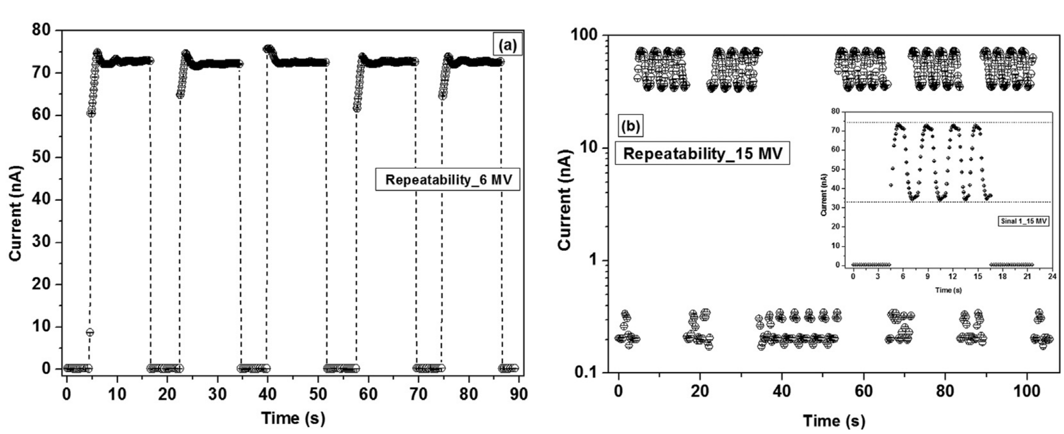

Fig. 2. The output current signals from the FZ diode consecutively irradiated with 6 MV (a) and 15 MV (b) photon beams. In detail, an expanded view of one of these current signals to 15 MV photon beam (b). Dose rate of 500 MU/min. Experimental uncertainties (0.3%) are smaller than the symbols size.

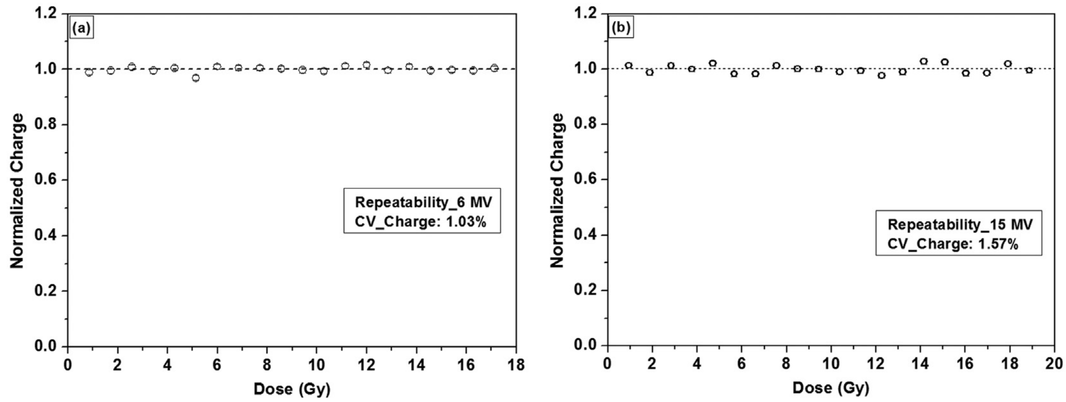

Fig. 4. Normalized charge as a function of accumulated dose for the twenty current signals for 6 MV (a) and 15 MV (b). Experimental uncertainties (0.3%) are smaller than the symbols size.

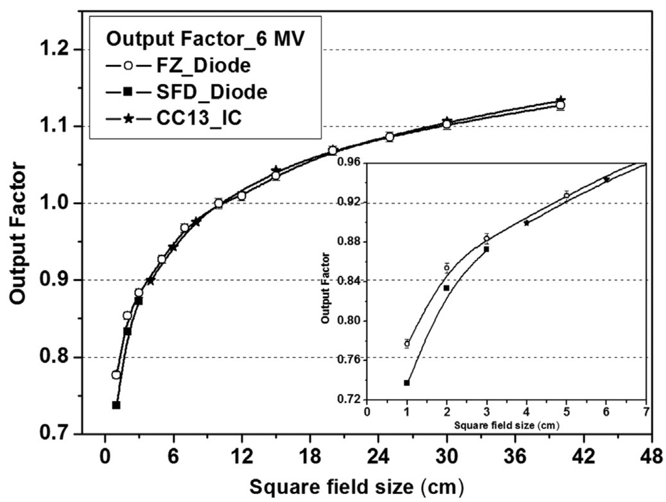

Fig. 5. Output factor study for the FZ diode. Measurements of output factor with SFD commercial diode and CC13 ionization chamber are presented for comparison. Experimental uncertainties (0.3%) are smaller than the symbols size.

not sufficient to affect the results, although specific tests regarding damage effects from neutrons are still lacking.

3.2. Beam data acquisition performance

To evaluate the beam data acquisition performance, we investigated the use of the FZ diode to measure the output factors of a 6 MV photon beam irradiation using field sizes from 1 × 1 cm^2 to 40 × 40 cm^2. The results obtained are presented in Fig. 5. For small field sizes (≤3 × 3 cm^2), the of values were compared with those gathered by a SFD commercial diode and the differences were 5.4%, 2.5% and 1.3% for the field sizes of 1 × 1, 2 × 2 and 3 × 3 cm^2 respectively. For larger field sizes (≥4 × 4 cm^2), the maximum difference found was 0.7% in comparison with values obtained with a CC13 ionization chamber (used to measure the of from 4 up to 40 cm square field size) (Fig.5).

The agreement is according to what is observed in literature (Das et al., 2008; Haryanto et al., 2002): higher differences for smaller fields and lower differences for field sizes larger than 4 × 4 cm^2. For small fields dosimetry, still there is no gold standard detector (Aspradakis et al., 2010), especially for field sizes of 1 × 1 cm^2 and below. Difference between measurements with various detectors of about 5% are commonly reported in literature. For example Bassinet et al., 2013 reported a 6.2%, 3.5% and 6.1% difference respectively for a PTW 60016, 60017 and a Sun Nuclear EDGE diodes in comparison with a SFD diode on the determination of the of a 1.2 × 1.2 cm^2 field defined by a microMLC of a 6 MV Novalis linear accelerator Pantelis et al., 2010 reported up to 9% difference between several high resolution detectors (small volume ion chambers, alanin, EBT film, TLD, diodes and polymer gel) on the determination of the of 1 cm diameter circular field from a 6 MV Cyberknife radiosurgery unit.

Thus, our result presented above that the FZ diode has a potential to be used for measuring of, performing acceptably well for both small and large field sizes. It is interesting to point out that the current commercially available unshielded diodes present strong energy dependence (Aspradakis et al., 2010; IBA Dosimetry®, 2010;

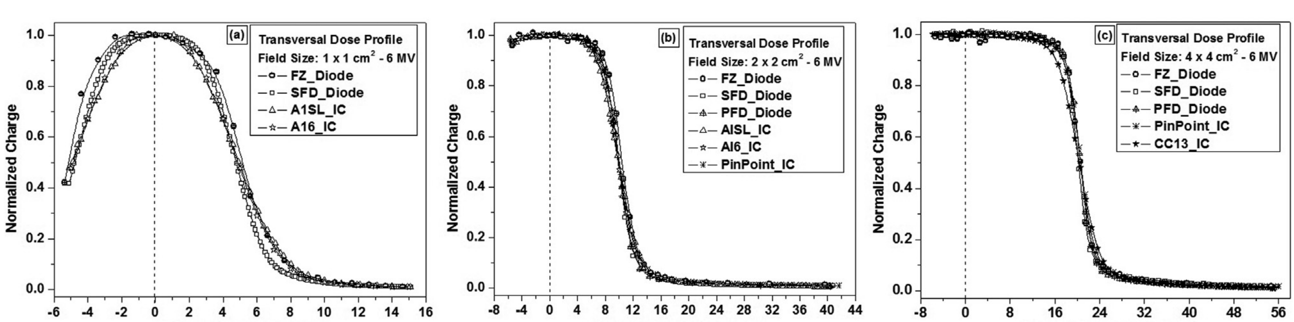

Fig. 6. Transversal dose profile measurements performed with FZ diode for 6 MV photon beam irradiation. Measurements with several commercial detectors are presented for comparison. (a) field size: 1 × 1 cm^2; (b) field size: 2 × 2 cm^2; (c) field size: 4 × 4 cm^2. Experimental uncertainties (0.3%) are smaller than the symbols size.

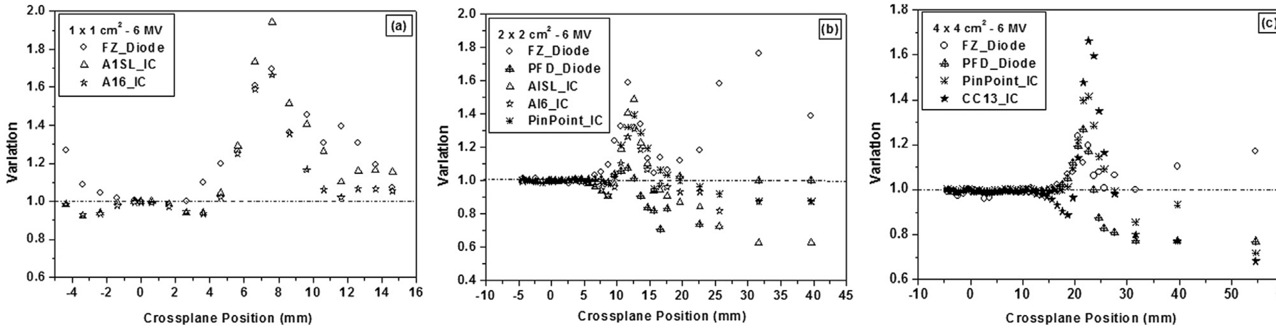

Fig. 7. Variation of detectors in relation to the SFD diode used as a reference in the TDP study.

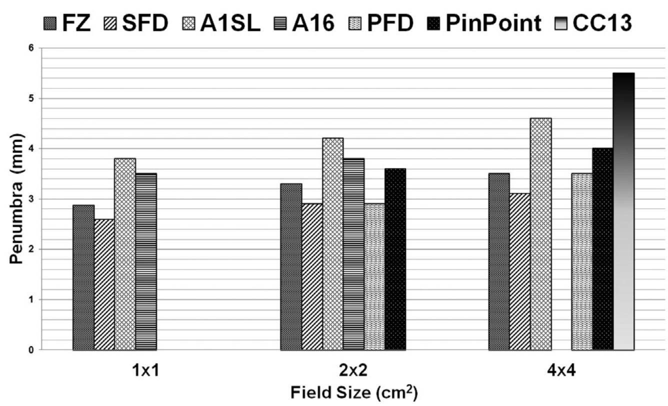

Fig. 8. Comparison the penumbra size modifying the field size for several devices. FZ diode is represented by the first bar to each field size.

PTW®, 2013) which limits its use to small field sizes only (where low energy scattered photons are insignificant).

The measurements of the TDP for 6 MV photon beam in water are presented in Fig. 6 together with several commercial detectors for comparison. The experimental results obtained with the FZ diode for field sizes of: 1×1 cm^2 (Fig.6(a)), 2×2 cm^2 (Fig.6(b)) and 4×4 cm^2 (Fig.6(c)) are in agreement with experimental results acquired with several commercial detectors. Furthermore, as analysis of the TDP study, in Fig. 7 are showed the variation of detectors in relation to the SFD diode used as a reference. The major differences on profiles measured with the different detectors relative to the SFD diode are, as expected, on the high gradient penumbra region.

In addition to this, by the TDP curves, the size of the field penumbra resulting from each measurement was calculated for each detector. Fig. 8 presents this comparison which confirms the excellent spatial resolution of the miniature FZ diode. The broader penumbra obtained with the FZ diode compared to the SFD is due to volume averaging (Wong et al., 2011) effect since the FZ is larger than the SFD (chip size side of 4 mm against 0.95 mm, respectively).

Fig. 9 depicts the percentage depth dose profile (PDD) measurements with the FZ diode performed in water for the 6 MV photon beam and field sizes of 1×1 cm^2 (Fig.8(a)), 2×2 cm^2 (Fig.8(b)) and 4×4 cm^2 (Fig.8(c)) together with several commercial detectors measurements for comparison. Although the shape of the PDD obtained with the FZ diode is according to what would be expected, the curve diverges from the other detectors by 4.0% after 50 mm depth. Moreover, to the PDD study, in Fig. 10 are presented the variation of detectors in relation to the SFD diode used as a reference.

More studies will be carried out in order to better evaluate the diode in PDD measurements.

4. Conclusions

The dosimetric response characterization of the miniature FZ diode was evaluated for 6 MV and 15 MV photon beams. The results presented good repeatability (CV $\leq$ 1.6%) of the device, operating in photovoltaic mode. The charge generated in the sensitive volume of the diode as a function of the absorbed dose obtained by repeatability study showed agreement with that from linearity the study. Despite the dose response curves being quite linear, the charge sensitivities varied significantly ($\approx$33%) for each photon beam used. Furthermore, as a first investigation, the charge-dose response of the FZ diode is not dependent on the dose rate within the range from 1.43 to 14.29 cGy/s (6 MV) and 1.57–9.43 cGy/s (15 MV) based on changing of MU/min while distance between source - diode was constant. Research on intrinsic dose rate dependence in term of dose per pulse will be investigated further.

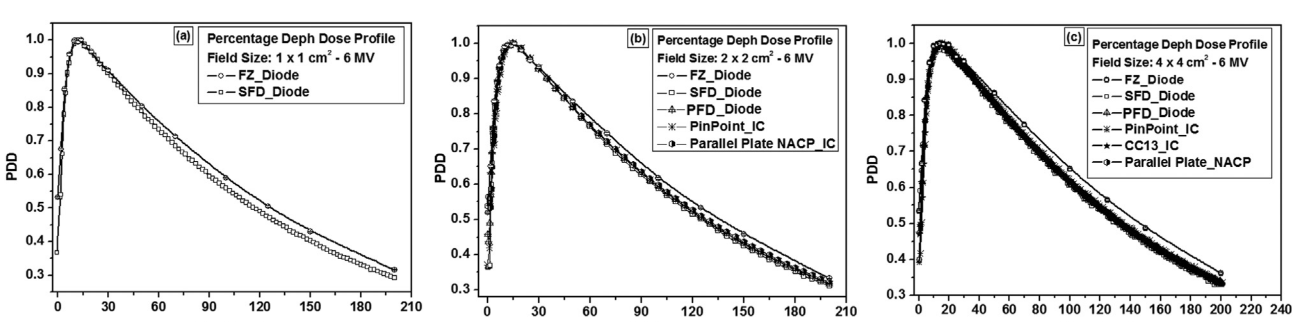

Fig. 9. Percentage depth dose profile measurements performed with the FZ diode for 6 MV photon beam irradiation. Measurements with several commercial detectors are presented for comparison. (a) field size: 1×1 cm^2; (b) field size: 2×2 cm^2; (c) field size: 4×4 cm^2. Experimental uncertainties (0.3%) are smaller than the symbols size.

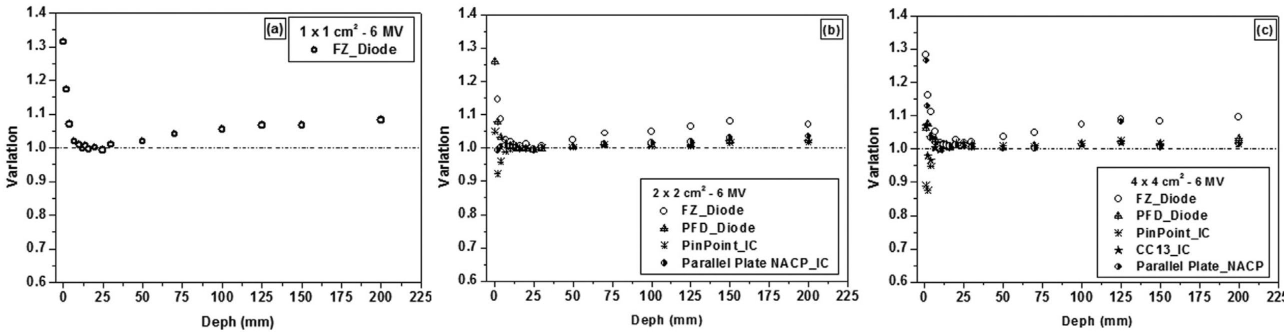

Fig. 10. Variation of detectors in relation to the SFD diode used as a reference in the PDD study.

The beam data acquisition performance studies were evaluated in a 6 MV radiation field and, the results were compared with beam data acquired during commissioning procedures of the linear accelerator Novalis TX® with several detectors. The results demonstrated that the penumbra profiles, obtained by transversal dose profile and output factors measurements agreed with those from the SFD for small fields and CC13 for large fields – a unique property for an unshielded high resolution diode.

Accordingly, these preliminary results on the use of the miniature FZ diode for commissioning of small fields is promising.

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