Radiation Safety Studies

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Dosimetric Characterization of 10 MeV Electron Accelerator Developed by BARC for Food Irradiation

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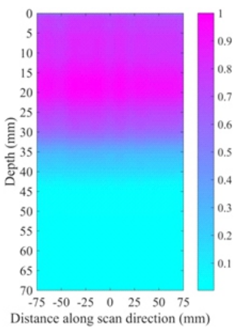

2D-Dose plane for 10 MeV EBC LINAC

ABSTRACT

This article delves into the dosimetry of food irradiation from a 10 MeV radiofrequency (RF) electron linear accelerator (LINAC) developed by BTDG, BARC. The investigation aims to assess the uniformity of the electron beam, evaluate Percentage Depth-Dose (PDD) distribution and Beam Quality Index, and verify the reproducibility of the beam. The study also includes dose uniformity verification of chili powder irradiation. Radiochromic B3 films have been employed as routine dosimeters. Results demonstrate ~8% variation in absorbed dose along the scan and conveyor directions. Comparison reveals that the dosimetric characteristics of the EBC LINAC is in agreement with a 9 MeV medical LINAC. Recommendations for adjusting product thickness based on dose uniformity ratios (DUR) of 2.3 for single-sided exposure are made with 3.3 cm for homogeneous water equivalent materials and 8 cm for chili powder packets. Recommendations emphasizing the need for case-specific analyses for heterogeneous materials and different DUR values are also presented.

KEYWORDS: *Electron beam irradiation, Food irradiator dosimetry, Film dosimetry*

Introduction

Food irradiation refers to the process of subjecting food products like bulbs, roots, vegetables, fruits, seafood, meat, spices, animal feed etc. to ionizing radiation. This process entails the transfer of energy from ionizing radiation source into the treated product. Purpose of irradiation are sprouting inhibition, shelf life extension, insect disinfestation, reduction in pathogenic micro-organisms etc. [1]. The quantity of irradiated food is increasing, predominantly in the Asia-Pacific region and the Americas [2]. Studies performed by U.S. Food and Drug Administration (FDA) and the World Health Organization (WHO) confirmed the safety of food irradiation [3, 4, 5].

Gamma radiation from ^{137}Cs and ^{60}Co electron beams up to 10 MeV energy and X-rays with maximum 5 MeV energy are used to treat food [1, 2]. The benefits of electron beam primarily stem from its clean and room temperature processing, minimal or complete elimination of additional chemicals, simple ON/OFF type machine operation [6], high throughput, safe radiation handling [7] and no chance of recontamination [8]. A radio frequency (RF) 10 MeV electron linear accelerator (LINAC) has been indigenously developed in India by Beam Technology Development Group, Bhabha Atomic Research Centre (BARC) for multi-product irradiation, including food, and is operational at Electron Beam Centre (EBC), Kharghar, Navi Mumbai.

As per design, thermoionically generated 50 keV electrons from electron gun are accelerated to 10 MeV beam in 1 m long coupled-cavity LINAC. Electromagnetic wave at RF range, generated from a 2856 MHz and 6 MW Klystron, is used for acceleration inside the LINAC. Electron beam is passed to the scan horn through the magnetic sweep scanner and comes out in the atmosphere through a Titanium exit window while sweeping a distance of 1m. A vacuum of 10^{-7} torr is maintained in the accelerating system. Cooling mechanisms and ozone removal system are in place to carry away excess heat and ozone (from scan horn area) [9]. Products to be irradiated are placed on conveyor system that can move with speeds varying from 0.1 – 10 m/min, equipped with metallic product rack. Distance between the exit window and the top surface of product boxes is approximately 45 cm [6]. The current operational characteristics of the irradiator include a beam energy of 10 MeV, an average beam power of 5 kW, a scanning

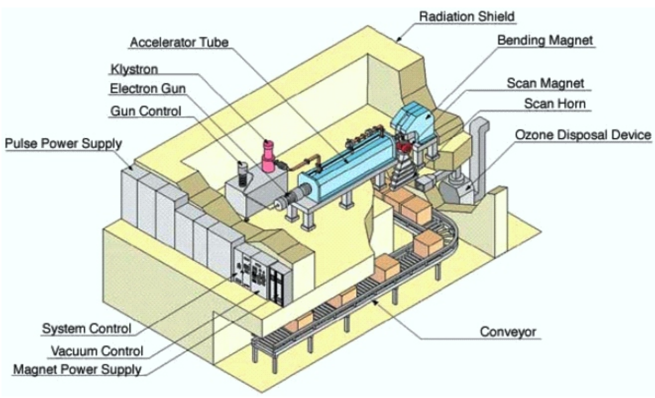

Fig.1: A standard electron beam irradiator (IAEA TRS 481).

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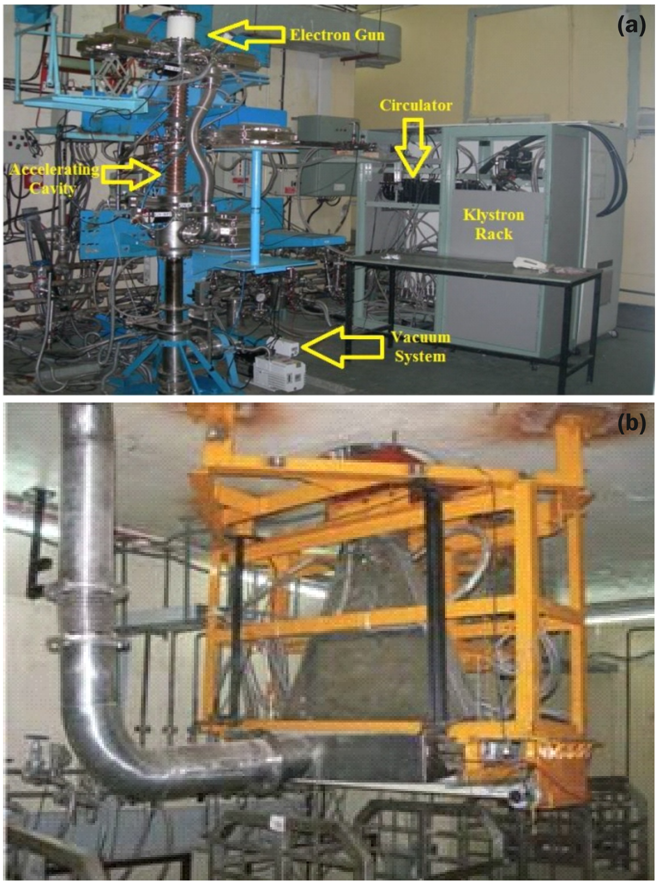

Fig.2: (a) Overview, (b) Scan horn of RF LINAC at EBC, Kharghar [9].

length of 1000 mm and a dose rate per unit area of 3.3 kGy per pass at a conveyor speed of 1 m/min [7]. A standard electron beam accelerator and the accelerator situated at EBC are shown in Fig.1 and Fig.2, respectively.

Stable, repeatable and reliable operation of such high power accelerators are quite challenging tasks [8]. The goals of the current investigation are to examine uniformity of the electron beam, evaluation of the Percentage Depth-Dose (PDD) distribution and Beam Quality Index and verify the reproducibility of the beam. Chili powder was also irradiated for further confidence in the experiments performed.

Material and Methods

Dosimeters

Routine dosimetry systems are used for absorbed dose assessments like dose mapping and process monitoring for quality control [1, 2, 10]. Radiochromic films are frequently used as routine dosimeters because of long shelf life, low atomic number and thus food product equivalence, stable response, simple readout procedure etc. [1]. In this study, radiochromic B3 films have been used. These are thin polyvinyl butyral films containing the leucocyanide of pararosaniline. The colorless film changes to deep pink color when exposed to radiation and the intensity of color is directly related to the amount of dose received. Practically measurable dose range with these films is 1-150 kGy [11]. Spectrophotometric measurements, which are non-destructive, can be performed with maximum sensitivity at 552 nm [6]. In this study, optical density of the films was measured using Genesys-20 portable spectrophotometer (Thermo Electron Corp., USA). The measurements have been performed after a gap of 48 h, post irradiation. Un-irradiated films are also measured to get the net absorbance due to exposure.

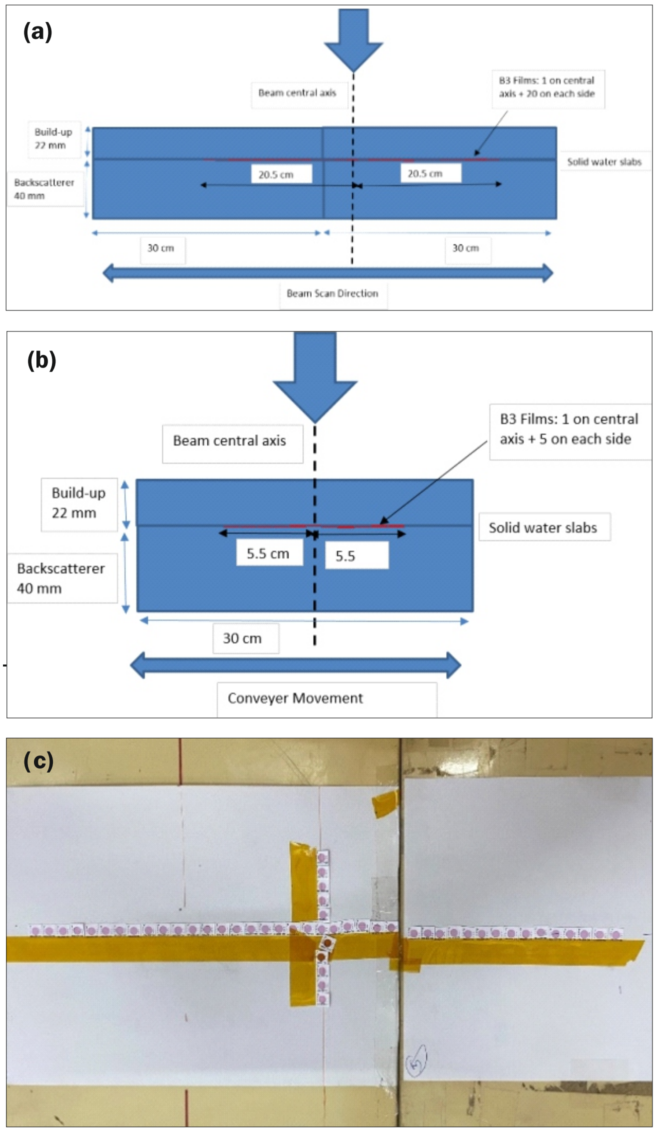

Fig.3: Measurement set-up for beam uniformity: (a) along beam scan direction, (b) along conveyer movement direction, (c) photograph of irradiated samples arranged as exposed.

Beam uniformity

On a 60 x 30 x 4 cm^3 solid water slab, forty-one B3 films were placed along the beam scan direction and eleven B3 films along the conveyer movement direction. The films were kept at depth of 2.2 cm. Centre-to-centre distance between two films was 1 cm. The exposure set-up is as shown in Fig.3. Radiation was delivered at 45 mA beam current and 1.4 kW beam power through 15 passes at 1 m/min conveyer speed.

Percentage Depth-Dose (PDD) distribution and beam quality index in terms of R_{50}

Solid water slabs,30 x 30 cm^2, of varying thicknesses were arranged in several combinations and B3 films positioned so that the films were at different thicknesses during irradiation. Four sets of these combinations were created to facilitate measurements at all necessary depths. One such experimental set up is shown in Fig.4. Radiation was administered with a beam current of 45 mA and a beam power of 1.4 kW, utilizing 15 passes at a conveyor speed of 1 m/min.

The beam quality index R_{50}, which is the half-value depth in water and R_p, which is the practical range in water of the measured electron beam are calculated using the empirically derived relationships given in ICRU Report 35 [12]:

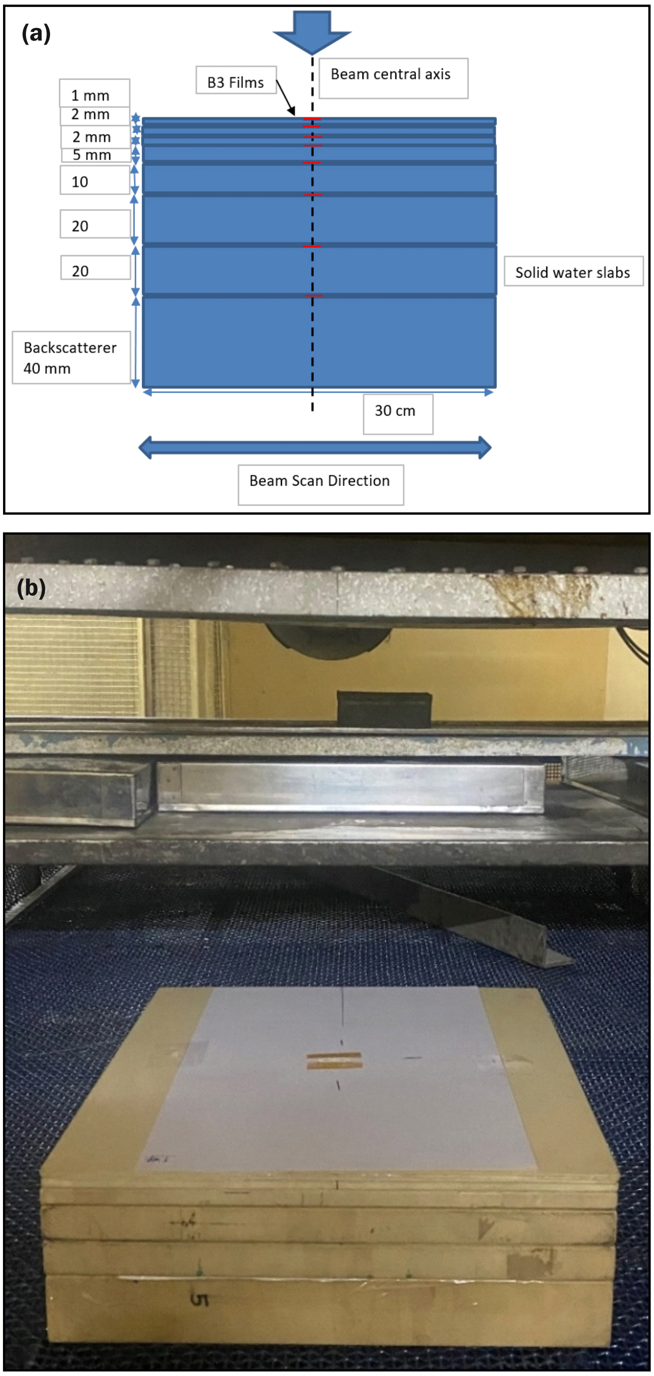

Fig.4: Measurement set-up of PDD (a) Layout (b) photograph.

E_a (MeV)= 2.33 R_{50} (cm) if 5 MeV < E_a < 35 MeV

Ep (MeV)= 0.22 + 1.98 R_p + 0.0025 R_p^2 (R_p in cm)

if 1 MeV < E_a < 50 MeV

where E_a is the average electron beam energy at the entrance surface of water and E_p is the most probable electron beam energy.

Dose uniformity during chilli powder irradiation

A 60 x 35 x 16 cm^3 cardboard box is filled with chili powder packets placed in the central volume 50 x 35 x 8 cm^3 in two layers. In each layer, 8 packets are kept in two rows. B3 films were placed on top of each packet and also at the bottom packets. The measurement arrangement is depicted in Fig.5. Radiation with beam current of 45 mA and beam power of 1.4 kW was given through 15 passes at 1 m/min conveyor speed.

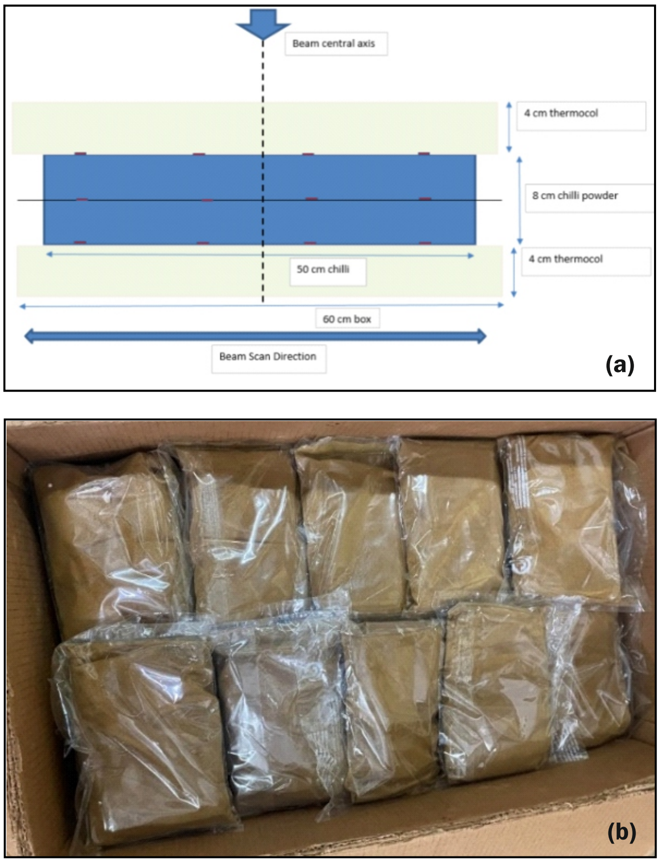

Fig.5: Measurement set-up of dose uniformity in chilli powder irradiation (a) Layout (b) photograph.

Dose uniformity in the chili powder box is quantified by Dose Uniformity Ratio (DUR), which is the ratio of maximum to minimum dose in the product box. While irradiators are typically engineered to achieve a low DUR, such as ≤ 1.5, numerous food products can accommodate a higher uniformity ratio of 2 or even 3 [1]. In practice, DURless than 2.3 for food is considered acceptable.

Reproducibility of delivered dose

On 30 x 30 x 4 cm^3 solid water slab, 3 B3 films were placed along the beam scan direction. Centre-to-centre distance between two films was 1 cm. A solid water phantom of dimensions 30 x 30 x 2 cm^3 was placed on the films to act as build-up. The exposure set-up is shown in Fig.6. Films were changed and this experiment was repeated thrice. Radiation beam current of 33 mA and 1.4 kW power was delivered through 20 passes at 1 m/min conveyor speed.

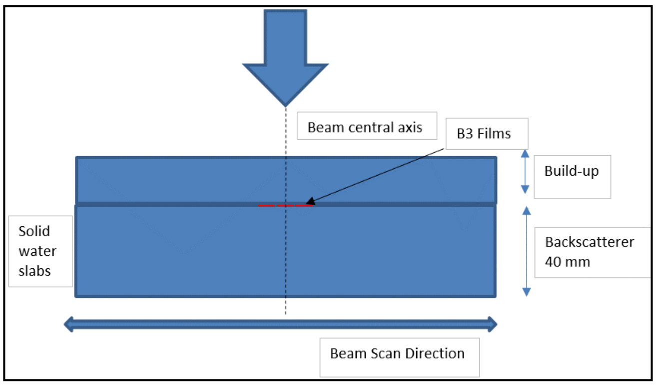

Fig.6: Measurement set-up of repeatability.

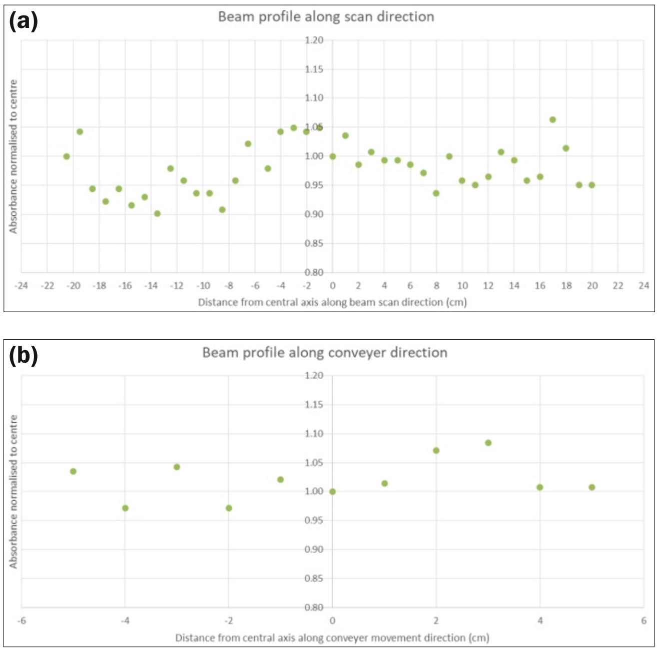

Fig.7: Beam profile (a) along beam scan direction, (b) along conveyer movement direction.

Results and Discussion

Beam uniformity

Normalized to the centre, the absorbed dose varies between 0.90-1.06 along scan direction and 0.97-1.08 along conveyer direction. Beam profiles in both scan and conveyer directions are shown in Fig.7.

Percentage Depth-Dose (PDD) distribution and beam quality index in terms of R_{50}

PDD in solid water slabs is shown in Fig.8.

Using the empirical relationships from ICRU 35, the following parameters were estimated.

Half-value depth R_{50} = 3.3 cm

Mean electron beam energy (E_a) = 7.7 MeV

Practical electron range (R_p) = 4.2 cm

Most probable energy (E_p) = 8.6 MeV

Dose Uniformity during chilli powder irradiation

Considering all the of chili powder packets, the DUR is found to be 2.22, with maximum dose at bottom plane of first layer or top plane of second layer and minimum at bottom plane of lowest layer. Therefore, if chili powder is filled till 8 cm below 4 cm of thermocol and exposed from a single side, the DUR value is 2.22 which is within the acceptable limit of 2.3.

Reproducibility of delivered dose

Maximum 14% variation from grand mean is observed.

Comparison with electron beam from 10 MeV Medical LINAC

Parameters of medical LINAC are stable and well established. To compare the PDD of 10 MeV EBC electron beam, dose distribution in a water phantom for electron beam of field size 20 x 20 cm^2 and energies 6, 9, 12, 15 and 18 were computed using a radiotherapy treatment planning system. Medical LINAC used in the study, does not have option to produce 10 MeV electron beam. Hence, the calculated PDD values for the mentioned energy levels were used to establish the PDD for 10 MeV using the interpolation method. Fig.9 shows the comparison of PDD of EBC and Medical LINAC. It is evident from Figure 9 that the energy of EBC LINAC is less than 10 MeV medical LINAC. Fig.10 shows the PDD curve of 9 MeV electron beam from a Medical LINAC and 10 MeV EBC LINAC. Table-1 shows the comparison of different dosimetry parameters. It can be inferred that measured EBC data is in good agreement with 9 MeV Medical LINAC data.

A 3D dose cube of dimension 40 x 40 x 40 cm^3 was computed based on the measured PDD and dose along the scan direction for EBC LINAC. From this, a 2D-Dose distribution plane for field size of 15 x 15 cm^2 were compared with data obtained for 10 MeV medical LINAC. Both the dose distributions are shown in Fig.11, which shows that DUR= 2.3 can be achieved till about 3.3 cm in 10 MeV EBC LINAC, whereas the same can be obtained till approximately 3.9 cm in 10 MeV Medical LINAC.

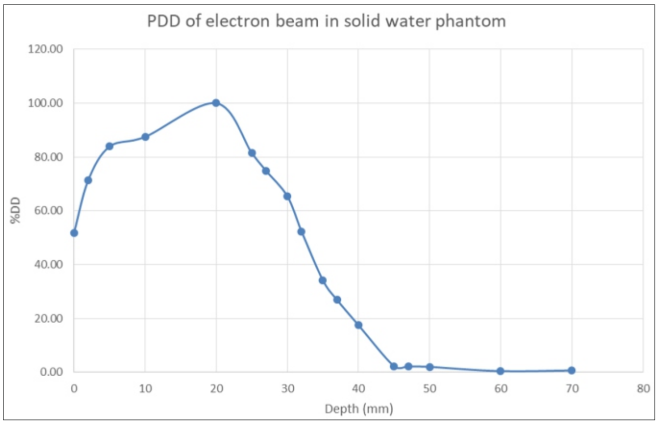

Fig.8: Measured PDD of electron beam in solid water phantom.

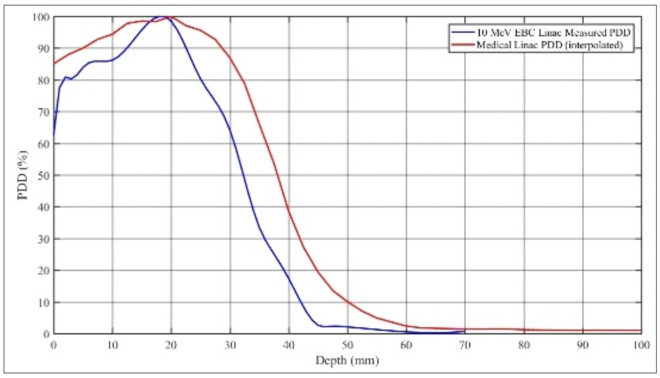

Fig.9: Measured PDD of EBC LINAC and computed PDD of Medical LINAC for 10 MeV.

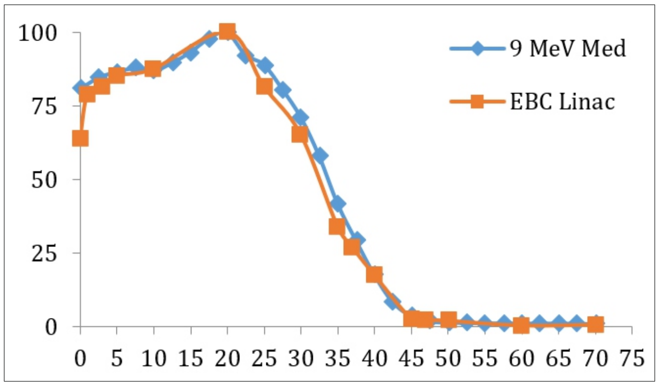

Fig.10: Measured PDD of EBC LINAC and computed PDD of 9 MeV Med LINAC.

Table 1: EBC and 9 MeV medical LINAC dosimetric parameters.

Parameters	9 MeV Medical LINAC	10 MeV EBC LINAC
R_{50} (cm)	3.4	3.3
R_p(cm)	4.3	4.2
E_p(MeV)	8.8	8.6
E_a(MeV)	7.9	7.7

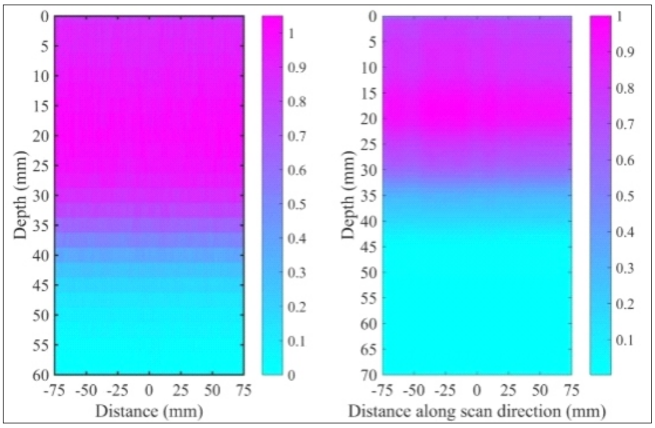

Fig.11: 2D-Dose plane along depth and beam scan direction for (a) 10 MeV Medical LINAC (b) 10 MeV EBC LINAC.

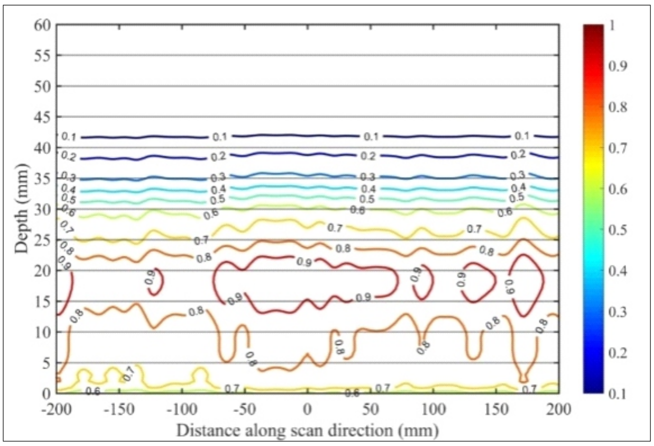

Fig.12: Isodose contour of 10 MeV EBC LINAC.

Isodose contours of measured dose drawn along depth and beam scan direction are shown in Fig.12. DUR= 2.3 is attained till approximately 3.3 cm of homogeneous solid water material.

Conclusion

Dose mapping in homogeneous material is used for operational qualification and that in routine product is necessary for performance qualification of an irradiation facility [2]. Determination of electron beam parameters like R_{50}, R_p, surface dose etc. are required to determine the geometry of product box to be irradiated. As per our study, the dosimetric characteristics of the electron beam in EBC facility matches closer to that of 9 MeV beam of a medical LINAC. Accordingly, for this energy, for single-sided exposure of water equivalent materials, DUR = 2.3 value can be achieved by irradiating 3.3 cm of homogeneous water equivalent product/medium. For any other DUR limit, product thickness can be adjusted accordingly. For example, Up to 8 cm thick chili powder packets placed under 4 cm thermocol can be exposed from one side to be within the acceptable DUR limit of 2.3. For any other product, or heterogeneous material, case-specific detailed study is recommended to achieve the acceptable performance.

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