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DEPTH-DOSE DISTRIBUTION DEPENDENCE ON THE ENERGY PROFILE OF LINEAR AND LASER WAKEFIELD ACCELERATOR ELECTRON BEAMS*

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Abstract

The depth-dose distributions of 10 MeV electron beams used for food irradiation and sterilization purposes at Research and Development Center for Radiation Technology, HCMC, Vietnam are measured and the results are well reproduced by the MCNP simulations. We extend the simulations to predict the dose depth distribution for 10 MeV electron beams with the energy profiles of a model Laser Wake Field accelerator (LWFA). The dosimetry and simulation results show that the maximum dose of the depth-dose curve inside the product are 1.4 times surface dose with an area density limit of 8.6 g/cm^2 for two-sided irradiation with nearly mono-energetic beams from linear accelerator and the corresponding parameters for LWFA are 1.2 times surface dose and 13.0 g/cm^2, respectively.

INTRODUCTION

Electron beams are widely used for food irradiation to induce structural changes in polymer materials, to dispose of environmental pollutants and handling of semi-precious stones [1]. In case of the direct irradiation without X-ray converter, the depth-dose distribution inside the product depends on electron energy spectrum, density and homogeneity of the material distribution in the product. Earlier, we reported our results of the depth-dose distribution of 10 MeV electron beam in inhomogeneous media [2]. In this article, we report the experimental and simulation results of depth-dose profiles in homogeneous media in products irradiated by electron beam from the 10 MeV linear accelerator. We extend the simulations to laser wakefield accelerator (LWFA) in view of their prospects as food irradiation tools. In order to apply LWFA to radiation processing, the electron spectrum has to be modulated so that it has a peak or at least a bump around 10 MeV [3]. For the resultant spectrum, the dose distribution in irradiation products has to be established to determine the dose uniformity ratio (DUR) for each product and electron energy [4, 5]. For quantitative assessment, the ranges of electron beam are defined: r_{opt1} is the depth at which the dose is equal to the surface dose, r_{50} is the depth at which the dose is equal to the half of the maximum dose, and r_{opt2} is the depth at which the dose is equal to the half of the surface dose [6]. The area density [5, 6] limit (ADL) for one side and double side irradiations are defined as ADL_1 (g/cm^2) = $\rho \times r_{opt1}$, ADL_2 (g/cm^2) = $2\rho \times r_{opt2}$, where ρ is the density of the irradiated product.

EXPERIMENT AND SIMULATION

The Experiment of Dose Distribution Inside Dummy Using Film Dosimeter

The depth-dose distribution in the irradiated products was measured at the UELR-10-15S2 (LINAC) of Research and Development Center for Radiation Technology, Vietnam Atomic Energy Institute. The film dosimeter B3000 (manufacturer: GEX Co., USA) was used. The film dosimeter is of large dynamic range of 0.55 to 86.0 kGy with a 95% confidence level [7]. The electron beam energy was measured to be of 9.92 ± 0.48 MeV as determined through the depth-dose distribution by using the aluminum wedge device [1].

The homogenous dummy is made of polypropylene (PP) of size 24 × 20 × 1 cm^3, a density of 0.95 g/cm^3, and without air in the PP stack. The film dosimeter is put in the center of plates and the dummy box is irradiated with electron beam of scanning width of 50 cm, at a conveyor speed of 0.5 m/min, and repetition frequency of 140 Hz.

Simulation and Dose Calculation Using MCNP Code

The modeling simulation MCNP4c2 [8] was used. We validated our simulation by reproducing the dosimetry experiment [9] results. The MCNP modeling was then applied to calculate depth-dose distribution of our experimental data with the linear accelerator and extended to the irradiation with LWFA.

The MCNP simulation parameter includes the average electron energy of 10.0 MeV, the scanning width of 50.0 cm, the product box size of 24 × 20 × 10 cm, the conveyor belt speed of 0.5 m/min, and the distance from the beam window to the surface of the box of 30.0 cm. Figure 1 shows MCNP modeling simulation geometry. The average electron energy is 10 MeV for both LINAC and LWFA but the energy profiles are different. As mentioned above, the electron energy spectrum from LINAC was determined by measurement of the most probable electron beam energy

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and the average electron beam energy by aluminum wedge device [1] and combined with MCNP simulation.

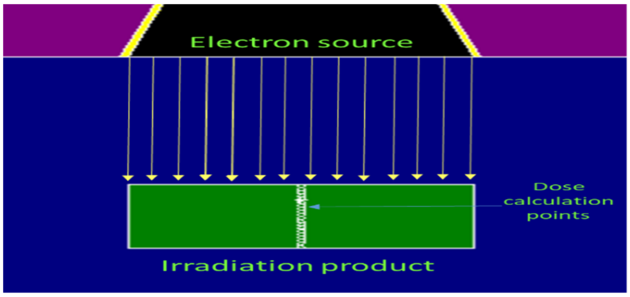

Figure 1: MCNP simulation modeling for irradiation products by electron beam.

The electron energy spectrum of LWFA is that of the GEKKO Petawatt laser system at the Institute of Laser Engineering (ILE) at Osaka University [3]. The electron energy spectrum from LINAC and LWFA are shown in Fig. 2. As seen there, the LWFA energy spectrum has a broad peak at 10 MeV, extending up to 30 MeV and a long tail up to 50 MeV, whereas the LINAC spectrum is nearly mono energetic with a sharp peak at 9.92 MeV. These distinctions of energy spectra between that of LINAC and LWFA strongly influence the depth-dose distribution and food irradiation homogeneities.

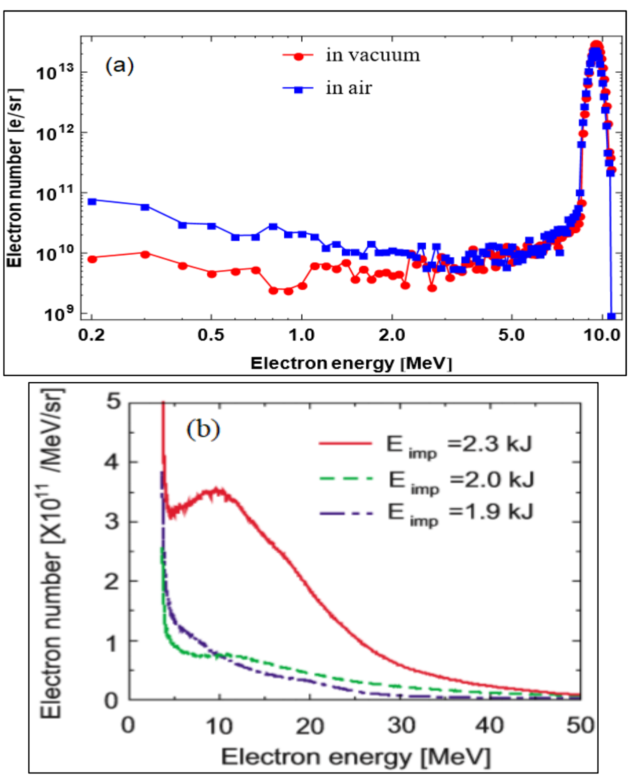

Figure 2: The electron energy spectrums of accelerator, (a) LINAC and (b) LWFA [3].

In the simulations, the electron spectrum from LINAC was a Gaussian of peak energy of 9.92 MeV and of FWHM of 0.5 MeV was used. For the LWFA, the pulse energy (E_{imp}) of 2.3 kJ (red color in Fig. 2b) was used.

RESULTS AND DISCUSSION

Comparison Between MCNP and Dosimetry

For the LINAC experiment, the MCNP result is compared to measurement result with the same of the electron beam parameters and the same of PP stack dummy.

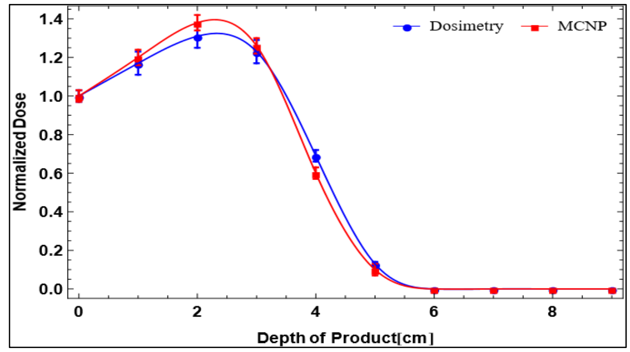

Figure 3: Depth-dose distribution inside the PP dummy irradiated by UELR-10-15S2 accelerator.

As seen in Fig. 3 the MCNP4c2 simulation is in good agreement with the results of depth-dose measurement with the film dosimeter. The exact simulation result proved to be a reliable simulation method for depth-dose profile problems on electron beam accelerators.

Depth Dose Profile from LINAC and LWFA

As next step, the MCNP simulation was carried out to calculate the depth-dose profile inside the products irradiated by LINAC and LWFA. The calculation results are shown in Figs. 4a and 4b. The maximum dose of the depth-dose curve in the product irradiated by electron beam from LINAC (Fig. 4a) with the Gaussian electron energy spectrum is 1.4 times the surface dose. The penetration (at half-surface dose) is 4.25 cm and r_{opt1} is 3.7 cm with a product density of 1.0 g/cm^3 so ADL_1 is 3.7 g/cm^2 for irradiating one side. The depth-dose profile in the irradiation by electron beam from LINAC with the Gaussian electron energy spectrum is similar to its from mono energy electron beam 10 MeV [4, 5]. In the case of irradiation with LWFA beam, the depth-dose curve is not as steep as that of 10 MeV mono- energetic beams and the maximum dose varies from 1.1 to 1.2 times the surface dose. The difference in comparison to the LINAC beams is understood as due to the broad energy spread of the LWFA beam. As seen in Fig. 4b r_{opt1} is 3.0 cm with a product density of 1.0 g/cm^3 so ADL_1 is 3.0 g/cm^2 for irradiating one side also. However, the penetration (at half-surface dose) or r_{opt2} is 6.5 cm so ADL_2 is 13.0 g/cm^2 for irradiation double sided. The results of the depth-dose curve inside the products irradiated double sided by LINAC and LWFA are shown in Figs. 5a and 5b.

ADL_2 of the double sided irradiation by mono energy 10 MeV electron beam is 8.6 g/cm^2 for the homogenous products [5]. ADL_2 depends on r_{opt2} and depth-dose curve of LINAC (Fig. 5a) shows that ADL_2 is 8.5 g/cm^2 as the case of the mono energy 10 MeV. The optimization product density of 0.4 g/cm^3 for 20 cm depth of irradiation product

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and density product above 0.5 g/cm^3 is not possible to irradiate by electron beam from LINAC. The results of one side (Fig. 4a) and double sided (Fig. 5a) irradiations show that the ADL_1 and ADL_2 of LINAC with Gaussian energy spectrum and mono energy 10 MeV electron beam are not different. ADL_2 of the product irradiated by LWFA is

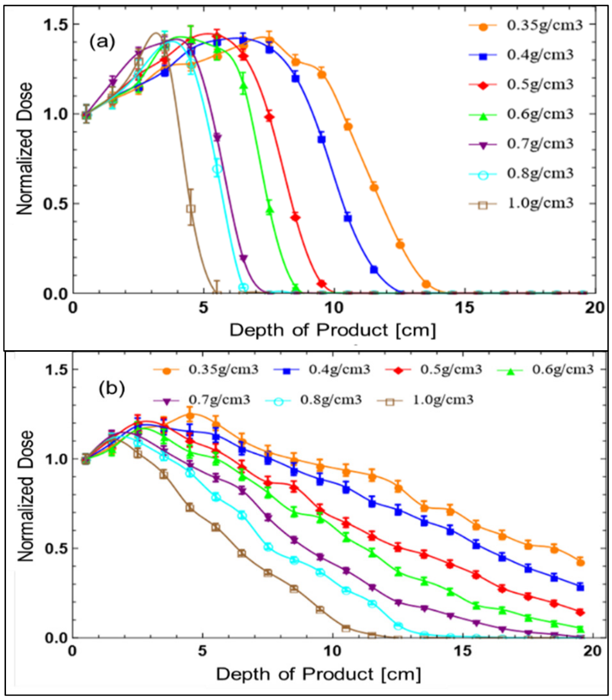

Figure 4: The depth-dose curve inside products irradiated one side by electron beam (a) LINAC and (b) LWFA.

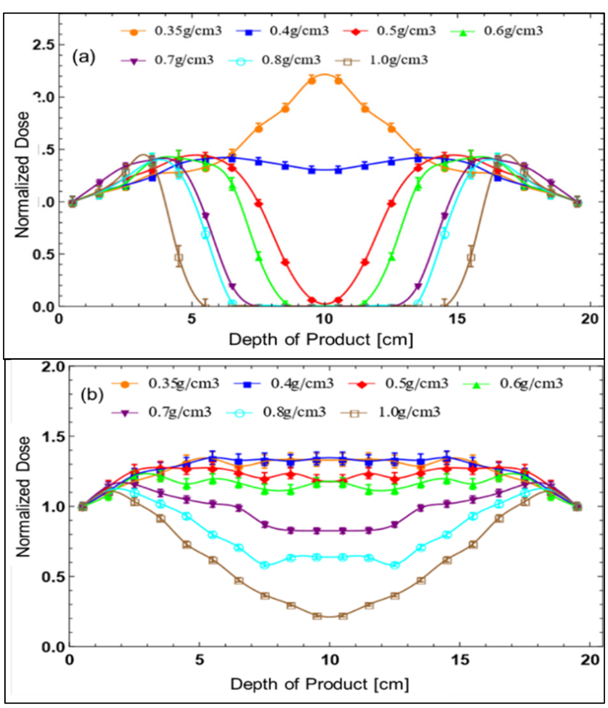

Figure 5: The depth-dose curve inside products irradiated double sided by electron beam (a) LINAC and (b) LWFA.

13.0 g/cm^2 and the optimization product density is under 0.65 g/cm^3 for the product depth of 20 cm. In the low dose level, the product density of 0.8 g/cm^3 can be irradiated by LWFA. At the center of the product, the dose is not too high nor too low compared to surface dose and DUR is better than in the case of the irradiation by LINAC. All penetrations and ADLs for irradiating one side and double sided on electron beam 10 MeV from LINAC and LWFA are presented in Table 1.

Table 1: Penetrations and ADL Values for Products Irradiated by Electron Beam 10 MeV from LINAC and LWFA

Parameters	Mono energy 10 MeV	LINAC	LWFA
r_{opt1}, cm	3.5	3.7	3.0
ADL_1, g/cm^2	3.5	3.7	3.0
DUR_1	1.4	1.4	1.2
r_{opt2}, cm	4.3	4.25	6.5
ADL_2, g/cm^2	8.6	8.5	13.0
Optimal area density, g/cm^2	$\rho_A \leq 3.5$; $7.5 \leq \rho_A \leq 8.6$	$\rho_A \leq 3.7$; $7.5 \leq \rho_A \leq 8.5$	$\rho_A \leq$ 13.0

The results of the MCNP calculation and the film dosimeter measurement inside irradiated products by LINAC and LWFA show that the penetration depends on electron energy spectrum. The penetration (at a half surface dose), r_{opt2}, of average energy 10 MeV electron beam from LINAC is 4.25 cm in irradiation product with a density of 1.0 g/cm^3 and it is the equivalent to the mono energy 10 MeV electron beam (4.3 cm). Thus, the optimal area density for the product irradiated by LINAC is in the range ($\rho_A \leq 3.7$; $7.5 \leq \rho_A \leq 8.5$) and it is same as for the mono energetic 10 MeV electron beam. However, LWFA with electron spectrum energy with a bump around 10 MeV can irradiate the product of an area density of 13.0 g/cm^2 due to the less steep depth-dose distribution. Figure 5b also shows that the depth-dose curve inside the product irradiated by LWFA is nearly a flat distribution at the center of the product. We may thus conclude that the product irradiated double sided by electron beam from LWFA has DUR is more uniform in the interior than mono energetic LINAC beams.

CONCLUSION

In this work, we presented the results of our measurements and MCNP simulations of depth-dose distribution of homogeneous materials of food irradiation interest with a 10 MeV electron beams from our linear accelerator. We also presented our simulation results for model LWFA electron beams with a broad peak at 10 MeV. The broad energy spectrum of LWFA renders the depth-dose distribution less steep and offers a more uniform dose in the interior of materials. This might prove to be an advantage for irradiating bulk quantities of food, when the technology becomes available.

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