

Dosimetric measurements and Monte Carlo simulation for achieving uniform surface dose in pulsed electron beam irradiation facility

V C PETWAL^{1,*}, J N RAO¹, JISHNU DWIVEDI¹, V K SENECHA¹
and K V SUBBAIAH²

¹Raja Ramanna Centre for Advanced Technology, Indore 452 013, India

²Safety Research Institute, Indira Gandhi Centre for Atomic Research,
Kalpakkam 603 102, India

*Corresponding author. E-mail: vikash@rrcat.gov.in

MS received 6 April 2009; revised 21 August 2009; accepted 9 October 2009

Abstract. A prototype pulsed electron beam irradiation facility for radiation processing of food and medical products is being commissioned at our centre in Indore, India. Analysis of surface dose and uniformity for a pulsed beam facility is of crucial importance because it is influenced by various operating parameters such as beam current, pulse repetition rate (PRR), scanning current profile and frequency, scanning width and product conveying speed. A large number of experiments are required to determine the harmonized setting of these operating parameters for achieving uniform dose. Since there is no readily available tool to set these parameters, use of Monte Carlo methods and computational tools can prove to be the most viable and time saving technique to support the assessment of the dose distribution. In the present study, Monte Carlo code, MCNP, is used to simulate the transport of 10 MeV electron beam through various mediums coming into the beam path and generate an equivalent dose profile in a polystyrene phantom for stationary state. These results have been verified with experimentally measured dose profile, showing that results are in good agreement within 4%. The Monte Carlo simulation further has been used to optimize the overlapping between the successive pulses of a scan to achieve $\pm 5\%$ dose uniformity along the scanning direction. A mathematical model, which uses the stationary state data, is developed to include the effect of conveyor speed. The algorithm of the model is discussed and the results are compared with the experimentally measured values, which show that the agreement is better than 15%. Finally, harmonized setting for operating parameters of the accelerator are derived to deliver uniform surface dose in the range of 1–13 kGy/pass.

Keywords. Food irradiation; electron accelerator; Monte Carlo; dose uniformity.

PACS Nos 87.66.-a; 87.53.Wz

1. Introduction

The use of electron accelerators for food irradiation and medical sterilization has enjoyed great interest in the last decade as they can be used for preservation,

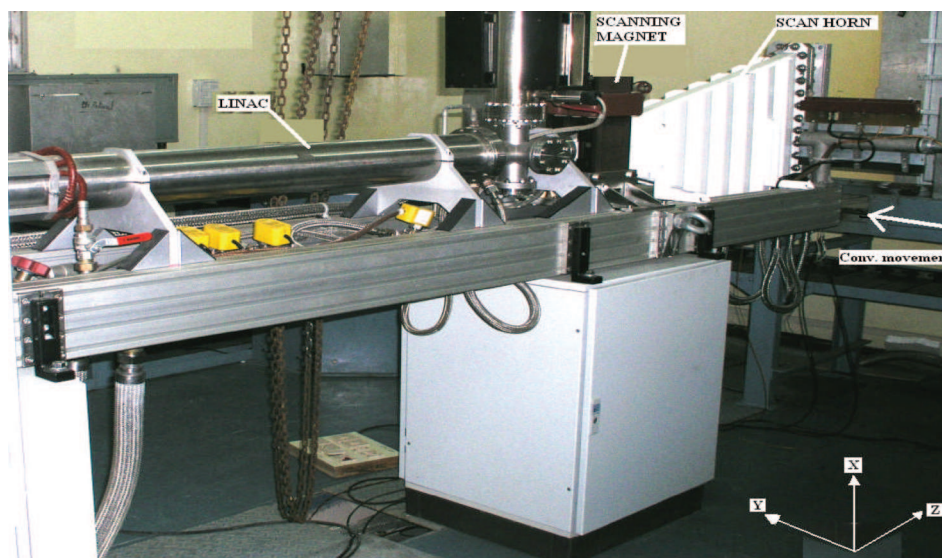


Figure 1. MeV Linac-based prototype irradiation facility.

hygienization, shelf-life extension, quarantine or sterilization of food and medical products [1–3]. The doses required to achieve the desired effect in different products are usually based on experimentally arrived values. Since absorbed dose is the quantity of energy used to achieve the desired effect, it is necessary to ascertain that the product is irradiated suitably. The lowest acceptable dose is the dose required to achieve the desired effect in the product, while the highest dose that is permitted for a given process is specified by the regulatory body giving legal permission for the operation [4]. The actual minimum dose (D_{\min}) and maximum dose (D_{\max}) in the product must be within these limits. The ratio D_{\max}/D_{\min} , termed as dose uniformity ratio (DUR), is of vital importance and should be close to unity for maximum throughput [5]. Surface dose uniformity for Rhodotron-type machine (CW accelerator) generating continuous electron beam has been studied and reported by Ziaie *et al* [6] for high dose application. Surface dose uniformity in pulsed electron accelerator is influenced by various operating parameters such as pulse repetition rate (PRR), scanning current profile, scanning frequency, scan width, product conveying speed etc. Uniformity over the surface can be achieved by proper harmonization of these parameters. Once the uniformity over the surface is achieved, variation of dose along the depth can be determined with the help of depth dose profile, which is mainly beam energy and product density dependent. Hence, in this paper more emphasis is given to achieve dose uniformity over the surface. Judiciously, we have used Monte Carlo simulations and experimental dosimetry data to optimize these operating parameters for pulsed electron beam irradiation facility.

2. Description of the facility

Figure 1 shows the snapshot of the prototype irradiation facility, based on 10 MeV Linac at Raja Ramanna Centre for Advanced Technology, Indore, India. The Linac generates electron beam pulses in the range 1–300 Hz PRR, each with 10 μ s duration. The beam scanning system consists of a scanning magnet and a trapezoidal shape vacuum chamber (scanning horn) used for scanning the electron beam (along x -axis) over the full width of a product.

The scanning horn is attached with a thin Ti foil (50 μ) to transmit electrons from vacuum to atmosphere. The scanning magnet is energized by a sawtooth-type current profile to produce a time varying magnetic field for sweeping the beam in an angular width of $\pm 15^\circ$. A product conveying system, whose speed can be varied in the range 0.5–4.7 m/min is used to transport the products (along y -axis) in front of the scanning horn.

3. Dose uniformity and modelling algorithm

Dose uniformity along the scanning direction can be achieved by partial superimposition of successive beam pulses by deflecting the beam across the product. The pulse repetition rate (PRR), limited to ≤ 300 Hz, places limit on the scan frequency that can be used. From dose and uniformity point of view, this, in turn, imposes limit on conveyor speed. Proper harmonization of scan frequency, scan width, pulse repetition rate and the conveyor speed is necessary to achieve optimum contiguity of successive pulses for uniform dose delivery. For a given scan frequency (f), surface dose uniformity is achieved at a high dose level, in situations, when conveyor speed (v) is low and the beam spot diameter (d) is large. Further, when $v/f > d$, the consecutive beam scan will not overlap sufficiently, and impose a limit on the minimum dose that can be delivered in low dose, high throughput applications [7]. Since there is no comprehensive model available for optimization of these parameters, we have judiciously used the Monte Carlo simulations and experimental dosimetry data to develop such a model for achieving uniform surface dose.

The model is developed in three steps. In the first step, the radial dose profile of the electron beam from Linac is simulated with the Monte Carlo code MCNP [8] and validated with experimental measurements for stationary state (both beam and product are stationary). In the second step, Monte Carlo simulation is extended to optimize the scanning frequency by optimizing the overlapping between the successive beam spots (beam scanned over stationary product), to achieve $\pm 5\%$ variation in dose uniformity along scan direction. In the third step, numerical calculations through MATLAB have been performed to include product movement (conveyor speed) and determine the harmonized setting of the parameters to achieve uniform surface dose and then compared with dosimetric measurements.

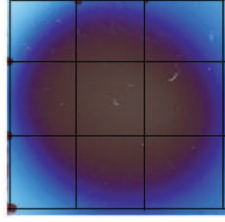


Figure 2. Electron beam cross-section measured at the exit of the scanner.

4. Results and discussion

4.1 Radial dose profile: Simulation and measurement

Monte Carlo simulation is carried out using MCNP to determine the radial dose profile on product surface. In order to obtain the input parameters of electron beam for Monte Carlo simulation, the cross-section of the beam was measured with FWT radiochromic film. The film is placed 5 mm away from Ti foil and exposed by a single pulse of 10 MeV beam at 200 mA peak current. Density pattern developed on the film is shown in figure 2. The beam spot has circular cross-section with 15 mm diameter. The spatial density distribution within the beam diameter could not be derived due to the saturation of the film. However, the beam dynamics study of the Linac suggests that electrons have Gaussian distribution within the beam envelope. Hence for Monte Carlo simulation, it is considered that almost all the electrons (>95%) are contained within 15 mm diameter and they possess Gaussian distribution within the envelope. The Gaussian profile of the envelope can be derived by a characteristic parameter σ_e , such that $4\sigma_e = 15$ mm (in Gaussian distribution, 95% particles are contained within $\pm 2\sigma$). Further, electron sampling from the above distribution is carried out by dividing the beam envelope into annular rings of increasing radius in 1 mm interval and probability of electron density in the annular rings for Monte Carlo simulation is considered as proportional to the differential area lying under the Gaussian curve.

In order to determine the radial dose profile, the electron beam is considered to incident normally on a polystyrene phantom located 40 cm away from Ti foil. The phantom is divided into an array of small cells of 1 cm^3 for dose scoring and *F8 tally of MCNP is used to score the energy deposited in each cell. Cut-off energy of electron is set to 20 keV and 10^6 histories are run to reduce the statistical error to less than 3%.

Figure 3 shows the simulated radial dose profiles for two cases, beam 1: diameter 15 mm ($\sigma_e = 3.75$) and beam 2: diameter 16.5 mm ($\sigma_e = 4.125$). The FWHM of the dose profile from beam 1 and beam 2 is found to be 49.2 mm and 51 mm.

Although, the incident electron beam had 10% difference in their σ_e , no significant difference in the radial dose profile is observed. It reveals that the radial dose profile is less sensitive to σ_e provided the distribution of electrons within the envelope does not change.

The functional dependence of the dose variation on radial distance can be approximated by a parametric equation:

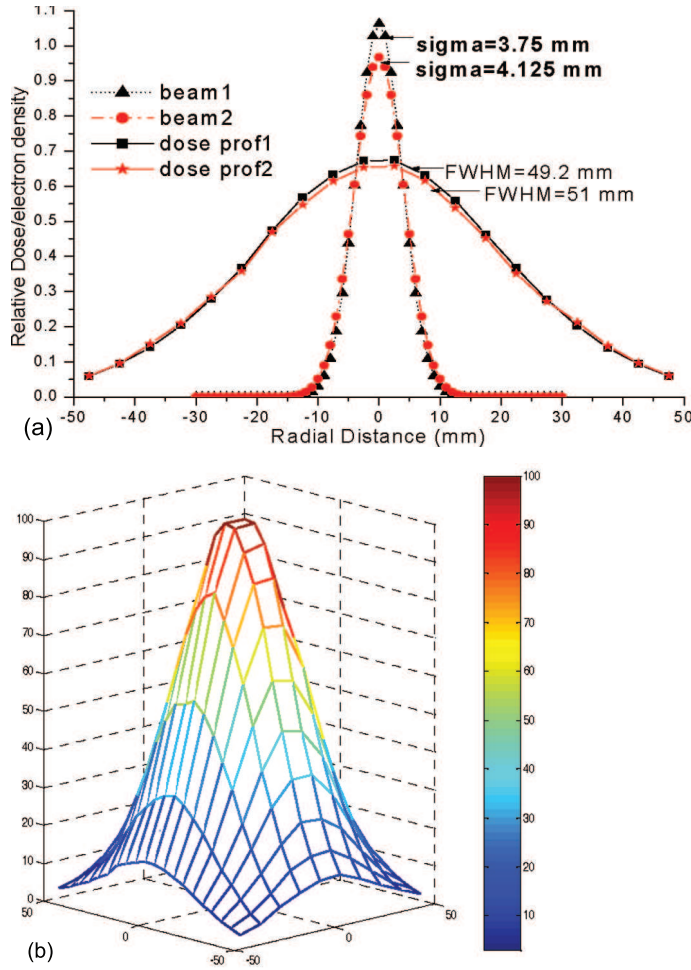


Figure 3. (a) Comparison of the radial dose profiles for beam 1 ($\sigma_e = 3.75$) and beam 2 ($\sigma_e = 4.125$). (b) Three-dimensional dose profiles for beam 1 ($\sigma_e = 3.75$).

$$D(r) = \frac{A}{\sigma_d \sqrt{2\pi}} e^{-(r^2/2\sigma^2)}, \quad (1)$$

where $D(r)$ is the dose at radial distance r from the beam centre, A (area under the curve) and σ_d are the characteristic parameters describing the radial dose profile.

In order to validate the simulation results, an experiment was carried out to measure the radial dose profile on the surface of polystyrene phantom placed 40 cm away from the Ti window, with an array of FWT radiochromic films (size: 5 mm \times 10 mm each). Dosimetry has been carried out as per the procedure described in ISO/ASTM standards [9] and necessary precautions have been taken to reduce the measurement uncertainties (combined type A and type B) within $\pm 5\%$ at 95% confidence level. Figure 4a shows the darkening produced in the exposed films.

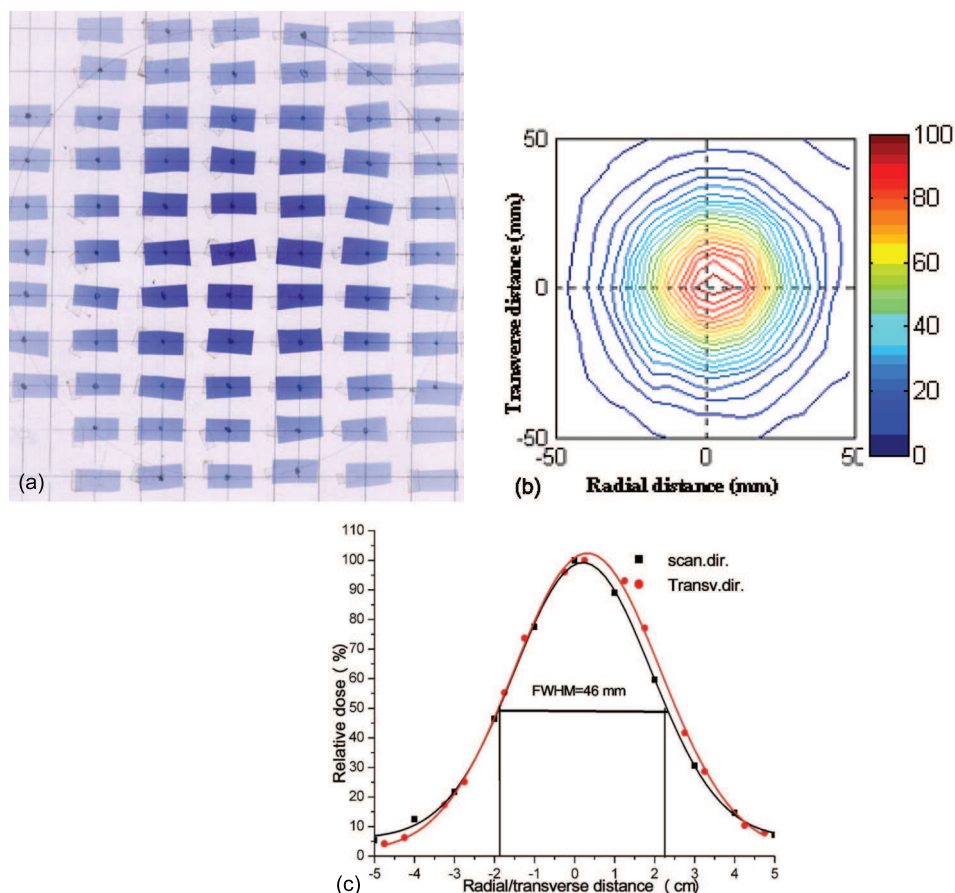


Figure 4. Electron beam cross-section measured with FWT films. (a) Exposed array of FWT films, (b) measured isodose lines and (c) radial dose profiles.

Optical density of each film is measured with a spectrophotometer at 510 nm, which is directly proportional to the dose absorbed by the film. Figure 4b shows the measured isodose lines, showing circular symmetric pattern. Figure 4c shows the dose profiles along the two diameters parallel to x -axis and y -axis. Both profiles have Gaussian shape with a FWHM of 46 ± 2 mm, which has close agreement (within 5%) with the simulated results.

4.2 Dose profile under beam scanning

As explained earlier, during irradiation the electron beam needs to be scanned over the entire width of the product. There have been several approaches to dissipate the energy content over the extended area. The approach in which a single pulse

is scanned over the full width has never worked reliably for low-dose applications (0.1 to 1 kGy), because homogeneity of dose in scan direction is always achieved at higher dose with multiple overlap of subsequent pulses [10]. Further, to sweep the 10 MeV beam over a typical width of 50–100 cm within 10 μ s (pulse width), the magnetic field should be varied in the range ± 600 G within the same time period. Such requirement poses many practical difficulties on magnet lamination, chamber wall thickness, eddy currents and magnet power supply. We have adopted a scheme of multiple beam spot overlapping in forward scanning and quick fly back in reverse direction. In this way scanning is carried out in one direction in time T_s (scan time) and electron beam returns quickly to the starting position in a short time ($< 1/\text{PRR}$) and keep on repeating this scan procedure. Dose uniformity along scanning direction is achieved by partial overlapping between the successive pulses. Monte Carlo simulations are performed to optimize the extent of the overlapping of pulses. The simulation is carried out for monoenergetic 10 MeV electron beam having a diameter of 15 mm ($\sigma_e = 3.75$ mm) and scanned within an angular width of $\pm 10^\circ$. The total angular width is divided into N equally spaced angular widths and their centre is designated as the emerging direction of different pulses coming during the scan. Dose uniformity on product surface located 40 cm away from Ti foil is shown in figure 5. For $N = 27, 23, 19$ and 15 , variation in dose uniformity along the scanning direction is found to be $\pm 0.2\%$, $\pm 0.6\%$, $\pm 1.2\%$ and $\pm 7.3\%$ respectively. Now, for a given PRR, the beam scanning frequency, f , can be derived from N , such that $f = 1/T_s$ and $T_s = N/\text{PRR}$ (T_s is the scan time for N number of beam pulses in one direction). Dose uniformity variation within $\pm 5\%$ is achieved for $N = 17$, which corresponds to a maximum scanning frequency of 5.8 Hz at 100 Hz PRR. The study reveals that, when scanning frequency $f > 5.8$ Hz, overlapping between the successive pulses is not sufficient, causing poor dose uniformity. However, for scanning frequency $f < 5.8$ Hz the dose uniformity improves at the cost of dose accumulation. Hence scanning frequency should be less than 5.8 Hz to restrict the variation in dose uniformity within $\pm 5\%$.

4.3 Harmonization of beam scanning and conveyor movement

Dose uniformity calculations as mentioned above have been performed by considering the product in stationary state. However, in actual practice the products are transported in front of scanning beam using a product conveying system. Consequently, both product and beam position keep on changing with time. Under such a dynamic situation, simulation with MCNP is not feasible. Therefore, a mathematical model has been developed which uses the stationary state data generated from MCNP to derive the harmonized setting of scanning frequency, scan width, PRR and conveyor speed in dynamic situation. The algorithm of the model, which is developed in MATLAB is described below:

The radial dose profile on the product surface has circular symmetry with Gaussian shape as described by eq. (1). Let the electron beam be scanned along x -axis, over a width w ($-w/2$ to $w/2$), on the product surface with scanning frequency f . Due to the scan, the centre of successive pulses will be shifted by a constant displacement Δx given by

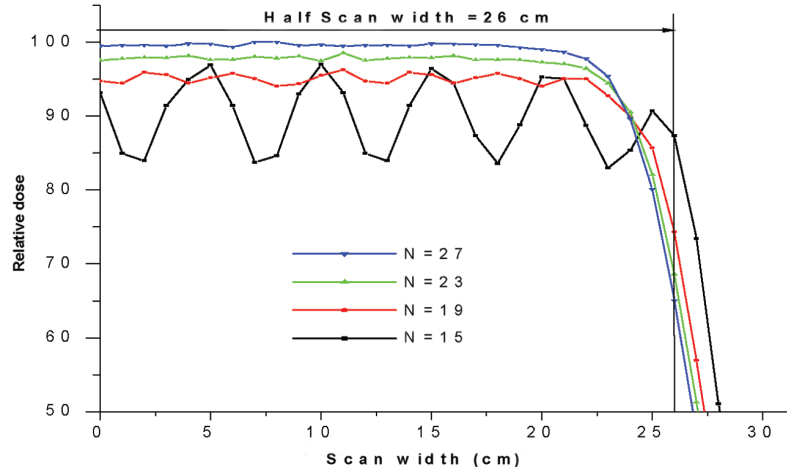


Figure 5. Dose profile along scanning direction for different number of angular bins.

$$\Delta x = \frac{wf}{\text{PRR}}. \quad (2)$$

The position of successive pulse centres along the scanning line on product surface can be calculated as

$$C_n = -w/2 + (n-1)\Delta x, \quad n = 1, 2, 3, \dots, N. \quad (3)$$

$-w/2$ is the lower bound of the scan (position of first pulse centre) and N is the maximum number of beam pulses per scan. The distance of a point lying on the scanning line, from n th beam centre is given by

$$d_n(x) = \text{Mod}[x - \{-w/2 + (n-1)\Delta x\}], \quad n = 1, 2, 3, \dots, N. \quad (4)$$

x is the x -coordinate of the point of interest where dose is to be calculated. Total dose at the point in a scan is calculated by integrating the incremental dose due to all the N pulses coming during the scan, i.e.

$$D(x) = D_1(d_1) + D_2(d_2) + D_3(d_3) + \dots + D_N(d_N)$$

or

$$D(x) = \frac{A}{\sigma_d \sqrt{2\pi}} \sum_{n=1}^{n=N} e^{-d_n^2/2\sigma^2}. \quad (5)$$

Now, let the conveyor system be transporting the products along y -axis, with a uniform speed v . The displacement of a product point along transverse direction within a time gap of two successive pulses is given by

$$\Delta y = \frac{v}{\text{PRR}}. \quad (6)$$

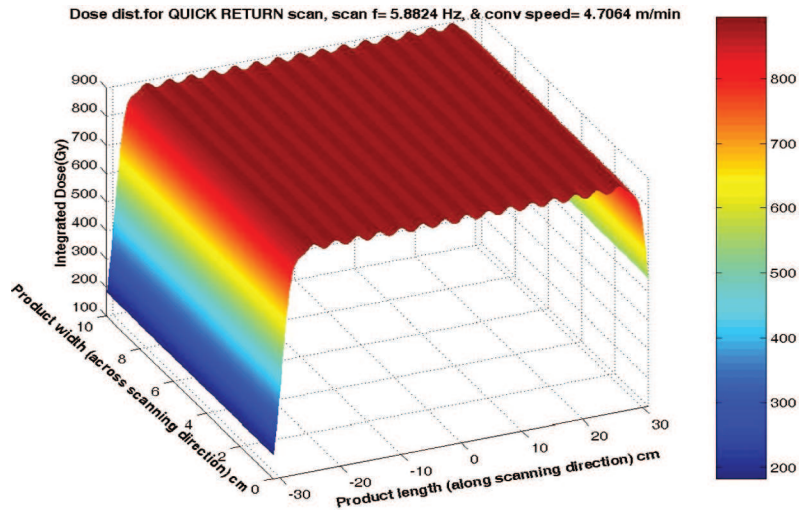


Figure 6. Surface dose profile for harmonized setting at a conveyor speed of 4.7 m/min.

Let us assume that when the first pulse falls on the product, the transverse distance of a sample point $P(x, y)$ from the beam scanning line is $-s$. As the product is transported, the x coordinate of the sample point remains constant while the y coordinate keeps on changing with time, which can be determined by

$$y_k = -s + (k - 1) \frac{v}{\text{PRR}}, \quad k = 1, 2, 3, \dots, j, \quad (7)$$

where $k = 1, 2, 3, \dots$ represents incident beam pulse number.

The radial distance of the product point $P(x, y)$ from the centre of the k th pulse is given by

$$r_k = (d_k^2 + y_k^2)^{1/2}. \quad (8)$$

d_k is given by eq. (4). When $k = N, 2N, 3N, \dots$, beam scanning cycle completes and value of k resets to 1. Dose for different r_k 's is calculated using eq. (5).

Overall integrated dose at the point of interest $P(x, y)$ is calculated by adding the incremental dose due to all j pulses coming during the product movement under the electron beam field of width $2s$ (extended along y -axis from $-s$ to $+s$), which is calculated as

$$D(x) = \frac{A}{\delta_d \sqrt{2\pi}} \sum_{k=1}^{k=j} e^{-r_k^2/2\sigma^2}. \quad (9)$$

Numerical integration of eq. (9) has been carried out for a typical scan width of 52 cm and experimentally measured values of A and σ . It is found that to achieve surface dose uniformity variation within 5% under the above-mentioned conditions, the conveyor speed should be less than 12.7 m/min. Figure 6 shows the simulation results corresponding to a conveyor speed of 4.7 m/min (max. set value).

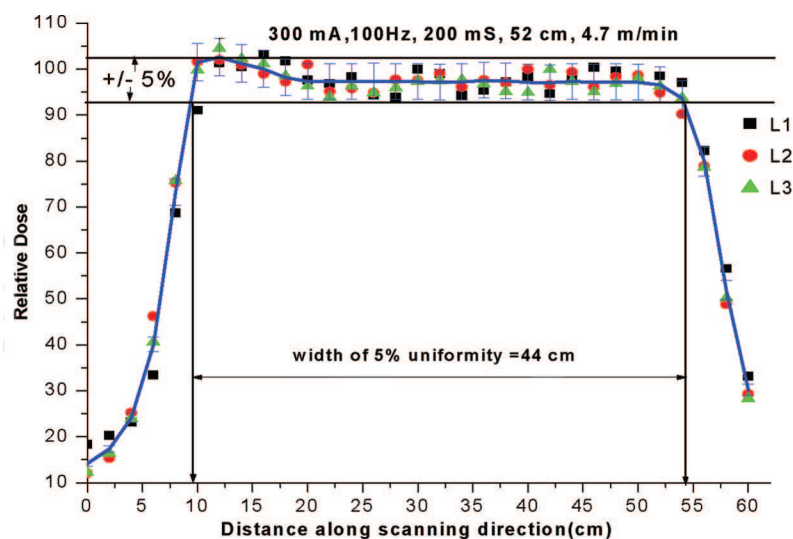


Figure 7. Measurement of uniform field width.

Experimentally, the dose uniformity along scanning direction was measured in accordance with ISO/ASTM [11], using FWT films (size: 1 cm \times 1 cm). The films were placed on a polystyrene phantom (60 cm \times 25 cm \times 5 cm) at regular interval of 2 cm in three lanes L_1 , L_2 , L_3 , each separated by 5 cm. Current in the scanning magnet was adjusted to achieve a scanning width of 52 cm on phantom surface located 40 cm away from Ti foil. The physical width of the beam scanning on phantom surface was measured with a fluorescent screen and CC TV camera. The electron beam creates diffused image on the fluorescent screen, causing an uncertainty of ± 1 cm in locating the position of the beam centroid. Hence, the actual physical width of scanning is 52 ± 1 cm. The beam scanning frequency was kept at 5 Hz, marginally less than the value worked out from the above study, keeping in view the inherent uncertainty of $\pm 5\%$ in dosimetry system. The conveyor was operated at a maximum speed of 4.7 m/min. The measured dose profile for 300 mA beam current is plotted in figure 7. The exploitable width of uniform dose is found to be 44 cm, in which variation in dose is within $\pm 5\%$. A small hump at one end is observed, due to the contribution made by the electrons scattered from the metallic conveyor system used for transportation.

The absolute absorbed dose for harmonized setting of operating parameters has been measured with polystyrene calorimeter calibrated and supplied by RNL Denmark. Calorimeter is passed to and fro in front of the radiation field at the optimized operating parameters. Uncertainty associated with the calorimetric measurements is less than 3% at 95% confidence level. Table 1 compares the simulated and measured results for optimized parameters at 100 Hz PRR and 200–300 mA peak current. The measured and calculated nominal dose rate per pass are in good agreement, within 2–8%, while a difference of 13% is found in dose uniform field width. The large difference is anticipated due to the uncertainty in locating the beam centroid while measuring the physical scanning width. The study reveals that

Table 1. Comparison of results for 10 MeV electron beam.

Beam current (mA)	Scan current (A)	Physical scan width (cm)	Scan frequency (Hz)	Conveyor speed (m/min)	Simulated values		Measured values	
					Uniform field width (cm)	Surface dose rate (kGy/pass)	Uniform field width (cm)	Surface dose rate (kGy/pass)
300	6	52	5.8 (5)	2.35	50	2.85	44	2.80±3%
300	6	52	5.8 (5)	4.70	50	1.32	44	1.37±3%
200	6	52	5.8 (5)	4.70	50	0.90	44	0.98±3%

at a maximum conveyor speed of 4.7 m/min, minimum dose of 0.98 kGy/pass is achievable and at a minimum speed, the maximum dose per pass will be 13.1 kGy.

5. Conclusion

Monte Carlo simulations have been carried out to simulate the radial dose profile of electron beam in stationary state of the product and the beam. The results have been verified by dosimetry measurements performed with FWT radiochromic films. Simulations were further extended to optimize the overlap of successive beam pulses to achieve the uniform dose along the scan direction. In order to consider the dynamic mode of irradiation (the situation when the product as well as the e-beam is in motion) a mathematical model has been developed to calculate the harmonized setting of beam irradiation parameters. At 100 Hz PRR, the maximum scanning frequency for achieving 5% dose uniformity is found to be 5.8 Hz using a $\pm 15^\circ$ scan angle and the corresponding maximum conveyor speed is found to be 12.7 m/min, which delivers a minimum dose of 0.35 kGy/pass using 10 MeV electron beam. The operating parameters of the existing prototype facility are optimized to deliver uniform surface dose in the range 0.98–13.1 kGy/pass.

Though the present methodology described in the paper has been applied to our specific facility, it can be applicable to other similar e-beam irradiation facilities having different operating parameters such as beam current, scan width, PRR, conveyor speed etc. These calculations are being further extended to find out the volumetric dose distribution within the irradiated product and will be reported in a separate paper.

References

- [1] J McKeown and R T Jones, *Nucl. Instrum. Methods* **B24–25**, 976 (1987)
- [2] T Watanabe, *Radiat. Phys. Chem.* **57**, 609 (2000)
- [3] Aikawa Yasuyuki, *Radiat. Phys. Chem.* **57**, 635 (2000)
- [4] IAEA, Manual of food irradiation dosimetry, Technical report series No. 178, 1977
- [5] IAEA, Dosimetry for food irradiation, Technical report series No. 409, 2002
- [6] F Ziaie, H Afarideh, S M Hadji-saeid and S A Durrani, *Radiat. Measure.* **34**, 609 (2001)

- [7] J McKeown, S T Craig, N H Drewell and D L Smyth, *Radiat. Phys. Chem.* **46**, 1363 (1995)
- [8] J Briesmeister, MCNP – A general Monte Carlo N-Particle Transport Code, Los Alamos National Laboratory, Los Alamos, New Mexico, USA, 1997
- [9] ISO/ASTM 51275:2002(E), Standard practice for use of radiochromic film dosimetry system.
- [10] D A E Ehlermann and D Morriseau, *Radiat. Phys. Chem.* **63**, 609 (2002)
- [11] ISO/ASTM 51649:2002(E), Standard practice for dosimetry in an electron beam facility for radiation processing at energies between 300 keV and 25 MeV.