

Radiation Field Assessment of an Electron Beam Irradiation Facility under Beam Misalignment Conditions Using PHITS

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1. Introduction

High-energy electron accelerators are widely used for sterilization, food processing, and materials modification because they provide high dose rates, enable efficient processing, and can be switched off when irradiation is not required [1]. Despite these operational advantages, interactions of high-energy electrons with irradiated products and structural components can generate secondary bremsstrahlung photons. In particular, for electron energies around 10 MeV, these secondary photons may contribute to radiation fields beyond the primary irradiation region, making appropriate shielding design and assessment essential for radiation protection.

The radiation field in an electron beam irradiation facility depends not only on the primary beam characteristics but also on interactions with the beam stop, irradiation components, surrounding structures, and shielding materials. Under normal operation, the electron beam follows its intended irradiation path and the shielding configuration is designed accordingly. However, deviations from the intended beam direction may alter the locations of electron interactions and secondary radiation production. Assessment of such beam-misalignment conditions is therefore useful for examining the robustness of the radiation-field distribution against small deviations from normal beam operation. Monte Carlo radiation transport calculations are particularly suitable for this purpose because they can represent complex facility geometry, material interactions, electron transport, and secondary photon production [2].

The Thailand Institute of Nuclear Technology (TINT) electron beam facility supports research and irradiation services in Thailand [3]. Radiation shielding is required to protect personnel in nearby accessible areas during routine operation and credible abnormal beam conditions. In this study, the Particle and Heavy Ion Transport Code System (PHITS) was used to investigate radiation-field variations under normal operation and three beam-misalignment conditions. The effects of beam misalignment on the lateral electron distribution and central dose distribution were evaluated, and calculated radiation levels at selected accessible locations were examined together with area dose-rate measurements obtained during normal operation. The results provide a basis for understanding how small angular deviations of

the electron beam influence radiation-field characteristics within the existing facility configuration.

2. Materials and Methods

The Particle and Heavy Ion Transport Code System (PHITS), developed by the Japan Atomic Energy Agency [4], was used to model the irradiation horn, chamber, conveyor region, beam stop, surrounding concrete walls, maze, operator room, and adjacent accessible areas. The electron source energy was 10 MeV with a beam current of 5 mA. The calculations used 1.0×10^5 particles per batch and 300 batches, corresponding to a total of 3.0×10^7 particle histories. The material compositions and densities used in the PHITS model are summarized in Table I. The facility geometry is shown in Fig. 1.

Four beam conditions were evaluated: normal operation and angular deviations of 1.72° , 3.44° , and 5.19° [5]. The [T-Track] tally was used to evaluate electron fluence and lateral flux profiles, while the [T-Deposit] tally was used to evaluate energy-deposition and dose distributions. The lateral profiles were compared in terms of peak value, peak position, full width at half maximum (FWHM), and integrated value. Radiation levels were also evaluated at selected accessible locations, including the entrance, exit, side walls, upper floor, and operator room.

Area dose-rate measurements obtained with a Fluke Biomedical 451B-DE-SI ion-chamber survey meter were used to provide an operational reference for the calculated radiation levels under normal beam conditions. Measurements were performed at routinely accessible locations around the irradiation facility, as shown in Fig. 2. Because the calculated values in these low-dose regions were limited by Monte Carlo statistics, the measurements were used primarily to characterize the actual radiation environment outside the shielding rather than for direct quantitative validation of the PHITS calculations.

Table I: Material data of the model [6]

Material	Composition		
	Density	Element	Weight Fraction
Air	0.001205	N	0.784429
		O	0.210750
		Ar	0.004671

Concrete	2.3	H	0.001416
		C	0.562526
		O	0.011838
		Na	0.001400
		Al	0.021345
		Si	0.204119
		K	0.005656
		Ca	0.018674
		Fe	0.004264
		C	0.003011
Titanium alloy	4.43	O	0.005650
		N	0.001614
		H	0.006727
		Fe	0.003238
		Al	0.102610
		V	0.035493
		Ti	0.841657
		C	0.000800
		Mn	0.020000
		P	0.000450
Stainless Steel	8.00	S	0.000300
		Si	0.010000
		Cr	0.190000
		Ni	0.095000
		Fe	0.683450

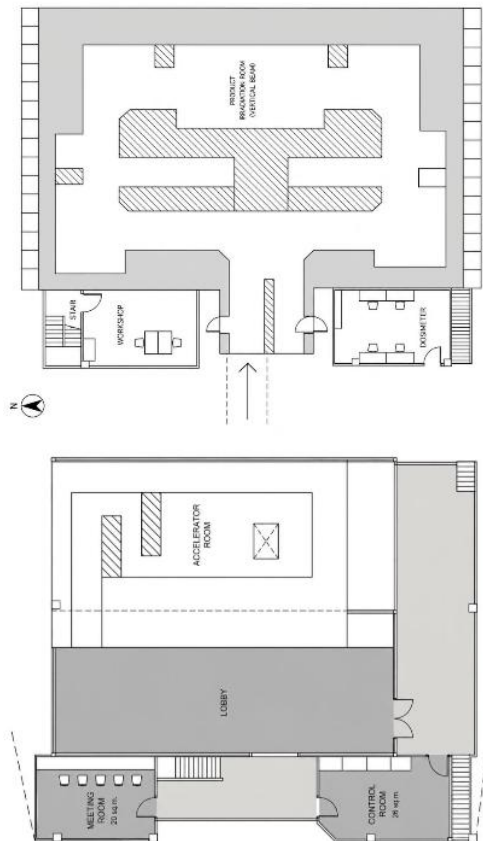


Fig. 1. Top views of the first and second floors of the electron beam irradiation facility

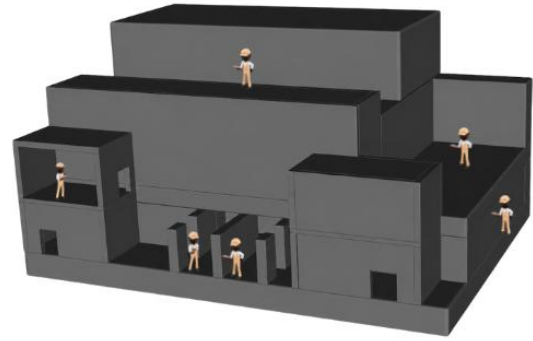


Fig. 2. Measurement locations around the electron beam irradiation facility.

3. Results and Discussion

The lateral electron distributions show similar profiles under all four beam conditions, as illustrated in Fig. 3. The quantitative characteristics summarized in Table II show that the peak flux varied by less than 1%, the peak position remained close to -5 cm, the FWHM changed by less than 0.41 cm, and the integrated electron flux differed by less than 0.55% compared with the normal condition. Fig. 4 shows the differences in lateral electron flux between the normal and misaligned beam conditions, with noticeable variations occurring mainly near the beam center. Overall, these results indicate that beam misalignment within the investigated angular range had only a limited effect on the lateral electron distribution.

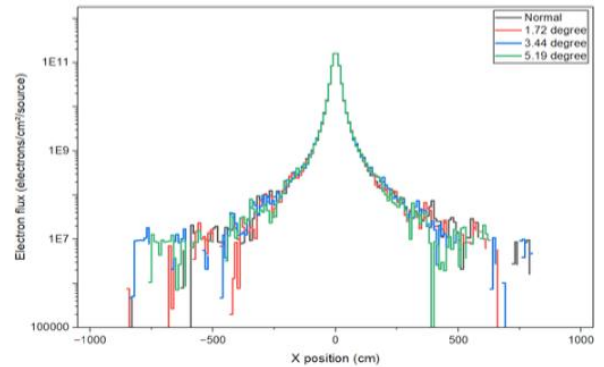


Fig. 3. Lateral electron flux profiles under normal operation and beam misalignment conditions.

Table II: Lateral electron-flux characteristics

Case	Peak flux ($e^-/\text{cm}^2/\text{source}$)	Peak position (cm)	FWHM (cm)
Normal	1.67953×10^{11}	-5.024	31.883
1.72°	1.68003×10^{11}	-5.026	31.705
3.44°	1.66576×10^{11}	-4.932	32.112
5.19°	1.66651×10^{11}	-5.010	31.955

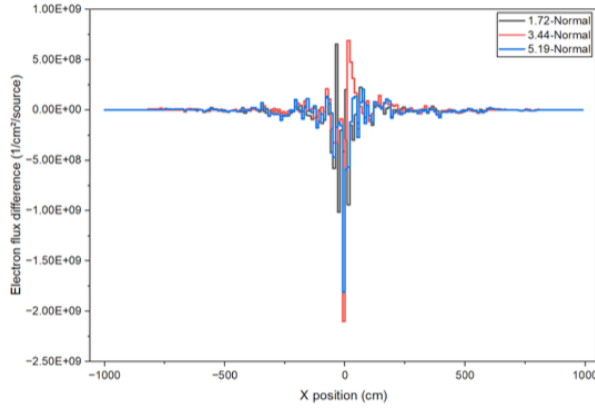


Fig. 4. Difference in lateral electron flux relative to the normal beam condition.

The main high-dose region remained concentrated around the intended irradiation path under all beam conditions. The maximum dose rate in the evaluated central profile was 7.1841×10^5 Sv/h under normal operation and decreased under all three beam-misalignment conditions. The largest decrease, 16.56%, occurred at 3.44°, while the location of the maximum remained at $x=0$ cm for all cases. No monotonic relationship was observed between the misalignment angle and the maximum dose rate, indicating that local radiation-field variations were influenced by particle interactions and secondary radiation production in the surrounding structures, as summarized in Table III.

The lateral dose profiles also remained generally stable. The peak dose differed by no more than 1.38% from the normal condition, the FWHM ranged from 31.95 to 32.73 cm, and the integrated dose differed by less than 1%. Larger relative fluctuations appeared far from the beam center, where the dose was several orders of magnitude lower. These fluctuations should therefore be interpreted with caution because of the increased Monte Carlo statistical uncertainty in low-dose regions.

Table III: Maximum dose rate in the evaluated central profile

Case	Maximum dose rate (Sv/h)	Change from normal (%)
Normal	7.1841E5	-
1.72°	6.4127E5	-10.74
3.44°	5.9946E5	-16.56
5.19°	6.8101E5	-5.21

Fig. 5 shows the calculated radiation-field distribution from electrons and photons under normal operation, with the high-dose region concentrated within the irradiation and shielding structure. No energy-deposition events were scored at the selected accessible locations in the present PHITS calculations for either normal operation

or the three beam-misalignment conditions. These results should not be interpreted as zero physical dose, but rather as radiation levels below the scoring capability achieved with the present number of particle histories in these strongly shielded regions.

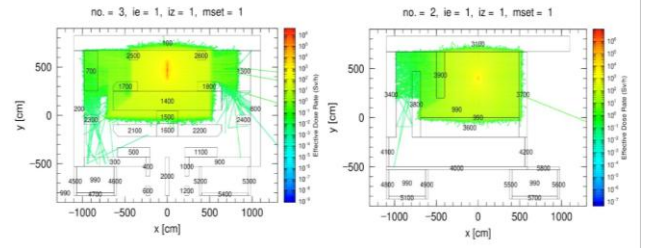


Fig. 5. Dose rate distribution from electrons and photons in normal operation.

Under normal operation, measured area dose rates were approximately 0.2 μ Sv/h at the entrance, exit, and side-wall locations and approximately 0.1 μ Sv/h at the upper-floor locations and operator room. These measurements indicate low radiation levels at the routinely accessible locations during normal facility operation. The PHITS distributions further showed no indication of a substantial shift of the main high-dose region toward accessible areas for the beam-misalignment conditions investigated in this study. However, additional particle histories or variance-reduction techniques would be required for a quantitative calculation-to-measurement comparison in these very low-dose regions.

4. Conclusions

This study evaluated the effects of small beam misalignments on radiation-field characteristics in a 10-MeV electron beam irradiation facility using PHITS. For angular deviations from 1.72° to 5.19°, the lateral electron and dose distributions remained generally stable, with only minor changes in peak position, FWHM, and integrated values. Although the maximum central dose rate varied among the misalignment cases, the main high-dose region remained near the intended irradiation path, indicating that the investigated deviations did not produce a substantial displacement of the radiation field. No energy-deposition events were scored at the selected accessible locations outside the shielding within the present simulation statistics. These results should therefore be interpreted as being below the scoring capability of the current calculations rather than as zero physical dose. Under normal operation, measured area dose rates at accessible locations were approximately 0.1~0.2 μ Sv/h, indicating low radiation levels at the measured locations. Overall, the results indicate that the investigated beam misalignments produced only limited changes in the radiation-field distribution and did not substantially redirect the main high-dose region toward routinely accessible areas. Further calculations using increased particle histories or appropriate variance-reduction techniques are recommended to quantify the

very low dose rates outside the shielding and enable a rigorous comparison with measured values.

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