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Technical Paper

Beam Energy Determination for a 10 kW LINAC through Monte Carlo Calculation

Hoje Kwon[1,*]

[1]*Advanced Radiation Technology Institute, Korea Atomic Energy Research Institute, 29, Geumgu-gil, Jeongeup-si, Jeollabuk-do 56212, Republic of Korea*

Abstract - Beam energy is one of the most important parameters in assessing the performance of an electron accelerator. Consequently, many methods to estimate the beam energy have been developed. Among them, the measurement strategy employing the depth-dose distribution curve is widely utilized. In the meantime, even though, recently, the 10 kW electron accelerator installed in Advanced Radiation Technology Institute (ARTI) in South Korea had been experienced some repairs including the replacement of the Klystron and some components constituting the Modulator of the irradiator, there had been no trial to evaluate current performance of this accelerator. Therefore, as a part of evaluating the performance of the electron irradiator, beam energy level was estimated by exploiting the depth-dose distribution curves in accordance with International Standard ISO/ASTM 51649. From the obtained results, it was possible to realize that there is a difference by about 1 MeV between the initially designed beam energy level and current energy value.

Key words : Electron beam energy measurement, Depth-dose distribution curve, Monte Carlo calculation

INTRODUCTION

As a clean and efficient irradiation source, electron accelerator has been widely utilized in a variety of fields, such as industry, agriculture, medical industry, health, food sterilization, and national defence. Consequently, measuring and evaluating some meaningful parameters of the electron beam is valuable and urgent issues (Hu *et al*. 2014). The beam energy of an electron accelerator is one of the most important parameters, is concerned with the problems related with irradiation effect of physics and chemistry, and has an effect on the penetration depth and the dose (Hu *et al*. 2014; Askarbioki *et al*. 2019).

There are many methods to measure the electron beam energy like applying the electron activation method (Askarbioki *et al*. 2019 (T09009)), utilizing tuneable magnetic fields and measuring the beam's radius deviation (Zagorski 1983), studying depth-charge distribution (Fuochi *et al*. 2005), studying the wavelength of the scattered photon resulting from the Compton interaction (Abakumova *et al*. 2012), and considering depth-dose distribution (Lundh *et al*. 2012). The brief explanation including merit or (and) demerit for each measurement approach is given elsewhere (Askarbioki *et al*. 2019 (P03003)).

Of those methodologies, when it comes to the depth-dose distribution method which necessitates the standard and dosimetry systems to assess beam energy, it is the most widely utilized energy measurement technique employing the derived various equations to determine the energy. And these equations and energy measurement methodologies can be utilized for quality assurance and control of the electron beam energy (ISO/ASTM 51649 2015). As for the aforementioned equations (or formulas), there is one formula

* Corresponding author: Hoje Kwon, Tel. +82-63-570-3252, Fax. +82-63-570-3259, E-mail. kwonhj@kaeri.re.kr

based on Monte Carlo calculations, which exploit the Monte Carlo-derived Correlations between the incident electron energy value and the value of half-value depth R_{50}, practical range R_p or extrapolated range R_{ex} obtained from the data of Monte Carlo simulation (Vargas-Aburto and Uribe 2003; ISO/ASTM 51649 2015).

Meanwhile, there is a linear electron accelerator with the maximum power of 10 kW in the Irradiation Facility of Advanced Radiation Technology Institute (ARTI), affiliated with Korea Atomic Energy Research Institute (KAERI). In the case of this 10 kW LINAC, ever since the replacement of the Klystron and some components constituting both charging and discharging parts of the Modulator, there was no trial to assess the operating characteristic of the LINAC when this accelerator runs under general operation condition.

Therefore, as a part of estimating the operation performance of the LINAC under general operating circumstances, beam energy level was calculated by means of the approach suggested in ISO/ASTM 51649 and the obtained results are provided in this work. Specifically, the Al stack type energy measurement device was designed and manufactured, then with the obtained depth-dose distribution curve from the fabricated apparatus, the anticipated energy was estimated by using the second-order equation obtained from the Monte Carlo-derived correlation between energy and range. Besides, for the credibility of the calculated energy level, the beam energy was evaluated with the commercially available wedge type energy measurement system.

MATERIALS AND METHODS

1. Beam energy measurement device

In order to measure the electron beam energy, stack type energy measurement device was designed and fabricated with Aluminum (Al) as an absorber in accordance with International Standard ISO/ASTM 51649. This stack type device consisted of 25 pieces of single Al plate with the thickness of 1.18 mm. Besides, commercially available wedge type energy measurement device (RISØ WEDGE, GEX Corporation) was exploited to calculate the energy and compare the result.

To obtain the depth-dose distribution curve after irradiating those two apparatuses with electron beam, two types of dosimeters were utilized. One was B3 WINdose Dosimeter (B3000, Batch: CH type) manufactured from GEX Corporation (United States) which was utilized for the stack type device. The other was RisØ Energy Wedge Card Array (10 MeV) (B3110, Batch: CH type) purchased from GEX Corporation (United States) for the wedge type device.

2. Electron beam irradiation

Electron beam irradiation was carried out with the 10 kW linear electron accelerator (UELV-10-10S, NIIEFA, Russia) installed in the Irradiation Facility of Advanced Radiation Technology Institute (ARTI) affiliated with Korea Atomic Energy Research Institute (KAERI). This linear electron accelerator is operated with the operating frequency of 2,856 MHz and Klystron is employed to send the radio-frequency to the accelerating tube after amplifying it. The vacuum pressure was measured with 4 (four) ion pumps put around different parts of the beam line of the accelerator and it was read between 3.6×10^{-8} and 1.7×10^{-9} Torr when the accelerated electron was irradiated to the air through a 0.11-mm thick Titanium foil. During the irradiation, the measurement device was placed on the conveying system under the incident electron beam, where the distance between the extraction window and the energy measurement device was approximately 15 cm and the conveying system did the repetitive moving motion with the constant speed of 2 meters per min. More detailed information on the operating condition was given in Table 1.

3. Dose measurement

After irradiating the interleaved dosimeters in the beam energy measurement device and prior to dose measurement

Table 1. Specific operating parameters of the electron accelerator

Parameter	Value
Steering magnet (#1, #2)	#1: 1.09 V/3.24 A, #2: 0.62 V/1.24 A
Focusing coil	21.0
Centering coil (X, Y)	2.100, 3.503
Exciter (frequency)	2856.69 MHz
Klystron High Voltage	44.5 kV
Sync. (repetition rate)	149.5 Hz
Beam current	79~82 μA

※The unit is not given, unless otherwise stated

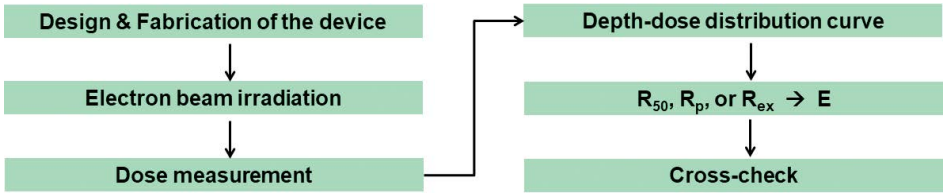

Fig. 1. Schematic procedure to measure the beam energy of the 10 kW LINAC.

for each dosimeter, both two types of dosimeters, i.e. B3000 and B3110, were annealed at 60°C for 5 minutes to prevent the variation of the absorbed dose.

Then, to draw the depth-dose distribution curve with the dose value corresponding to each height, the absorbed doses of the interlaminated dosimeters in the stack type device were measured with GENESYS 30 Visible Spectrophotometer (wavelength: 552 nm, Thermo Scientific, United States) connected to a personal computer where an application program called GEX has been installed. With regard to the dosimeters in the wedge type device, an automatic calculation program provided by GEX was exploited to obtain the depth-dose profile.

4. Beam energy calculation based on measured depth-dose distribution

In order to calculate the electron beam energy in a homogeneous material such as pure aluminum, depth-dose distribution measurement method where utilized formulas are derived based on Monte Carlo calculations was employed (ISO/ASTM 51649 2015).

According to ISO/ASTM 51649, one can exploit the depth-dose distribution method to determine the energy level of an electron accelerator by selecting proper half-value depth R_{50}, practical range R_p, or extrapolated range R_{ex} and then, subsequently, applying one of the selected parameters to the corresponding second-order equation where E is in MeV as follows.

$$E = 0.423 + 4.69 \times R_p + 0.0532 \times R_p^2$$

$$E = 0.394 + 4.77 \times R_{ex} + 0.0287 \times R_{ex}^2$$

$$E = 0.734 + 5.78 \times R_{50} + 0.0504 \times R_{50}^2$$

The described procedure to calculate beam energy with energy measurement device made with Al was depicted in Fig. 1 to help readers' understanding.

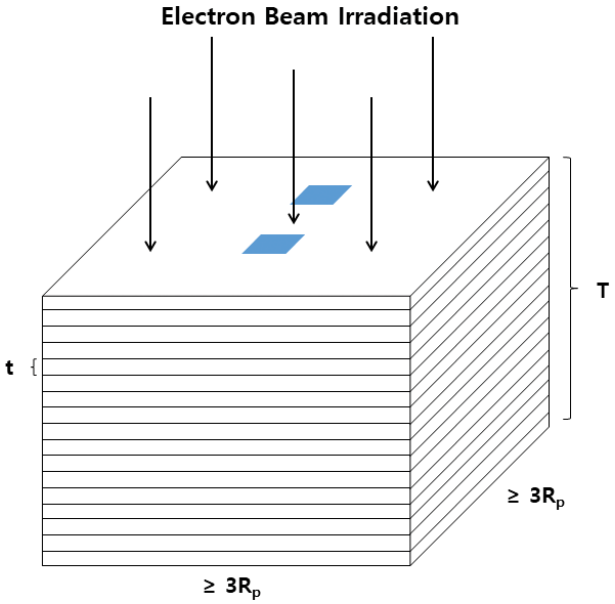

Fig. 2. Stack energy measurement device.

RESULTS AND DISCUSSION

1. Design and fabrication of stack type energy measurement device

According to ISO/ASTM 51649, stack type energy measurement device (Fig. 2) was designed and fabricated with Al to obtain the depth-dose distribution curve after irradiating the apparatus and then measuring the interleaved dosimeters in the apparatus. Since the design spec. of the accelerator is 10 MeV, practical range R_p was chosen as 1.9947 so that the thickness of single Al plate and total dimension of the device could be decided. When constructing the stack energy measurement device, we should consider that the nominal thickness of single Al plate should be one-twelfth of the anticipated R_p or less (i.e. single plate thickness $t \leq R_p/12$) to ensure an adequate number of data points for building the depth-dose distribution, the lateral dimensions of the stack should be at least $3R_p$ by $3R_p$ to avoid the influence of edge effects on the

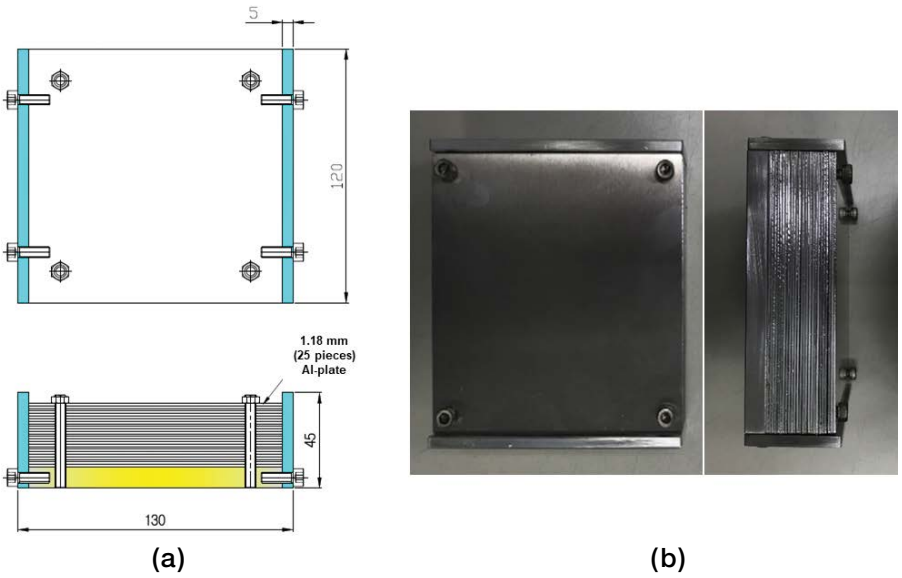

Fig. 3. (a) Design and (b) fabrication of stack energy measurement device suitable for the electron accelerator with the anticipated energy of 10 MeV in accordance with ISO/ASTM 51649.

Table 2. Criteria for selecting some parameters required to design the stack energy measurement device

	8 MeV	10 MeV
Plate thickness (t, cm)	$t \leq 0.132075$	$t \leq 0.166225$
Total thickness (T, cm)	$T \geq 2.37735$	$T \geq 2.99205$
$\geq 3R_p$, $\geq 3R_p$ (cm)	≥ 4.7549, ≥ 4.7549	≥ 5.9841, ≥ 5.9841

dosimeters, and the total thickness of the stack should be at least $1.5R_p$ (i.e. stack height $T \geq 1.5R_p$) (ISO/ASTM 51649 2015). Thereby, the criteria for choosing some parameters in manufacturing the stack type device are given in Table 2. As previously mentioned, since the anticipated energy level was about 10 MeV, thickness of single Al plate was determined as about 1.18 mm, total thickness was set as 3 cm, and the lateral size of the device was designed as 12 times 12 cm^2, respectively, as can be seen in Fig. 3.

2. Depth-dose distribution curve

To calculate the incident energy value of an electron accelerator having the energies between 2.5 MeV and 25 MeV, one can utilize the depth-dose distribution curve and, with this curve, by estimating half-value depth R_{50}, practical range R_p, or extrapolated range R_{ex} (ISO/ASTM 51649 2015).

For this, 26 pairs of B3000 dosimeters were interlaminated into every single Al plate and then loaded under the extraction window of the irradiator. After irradiating and subsequently measuring each dosimeter with the dosimetry system called GENESYS 30 Visible Spectrophotometer, a set of table denoting the absorbed dose for each penetration depth could be obtained and the results are given in Table 3. As can be easily seen, with the increase of the iteration number, the absorbed dose was gradually increased. As for the absorbed dose depending on the penetrating depth, it continuously increased to around the depth of 10.62 mm and then gently decreased with the increment of the penetration depth. When the depth is deeper than 21.24 mm, the dose begun to show the value that is lower than 2.5 kGy, which means the measured dose is out of range and it is unreliable.

Meanwhile, the depth-dose distribution curves for each condition were drawn in Fig. 4 based on the results in Table 3.

3. Calculation of beam energy

Extrapolated range R_{ex}, practical range R_p or half-value depth R_{50} can be exploited to estimate the incident electron beam energy from the depth-dose distribution curve. Once R_{ex}, R_p or R_{50} is determined, the energy level can be easily derived from the corresponding second-order equation. In the case of the given depth-dose distribution graph (Fig. 4), it was not easy to presume the R_p value, because the corresponding dose of the depth deeper than 22.42 mm was uncer-

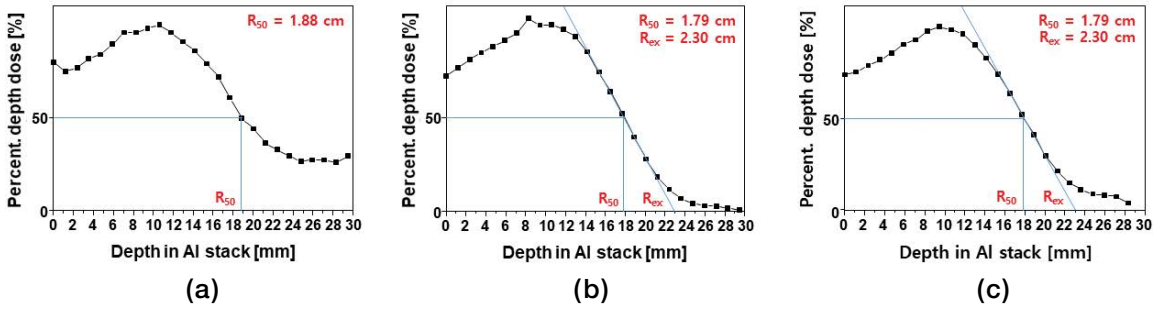

Fig. 4. Depth-dose distribution curves obtained from different conveyor iteration conditions: (a) 50, (b) 150, and (c) 350.

Table 3. Variation of the average dose corresponding to each penetration depth for different iteration numbers of the conveying system

Depth (mm)	Iteration No. of the conveyor		
	50 (kGy)	150 (kGy)	350 (kGy)
0	5.7	12	19.9
1.18	5.35	12.7	20.3
2.36	5.5	13.45	21.25
3.54	5.85	14.05	22.15
4.72	6	14.6	23.1
5.9	6.4	15.15	24.4
7.08	6.65	15.8	25.05
8.26	6.85	17.1	26.3
9.44	7	16.5	27
10.62	7.15	16.55	26.5
11.8	6.85	16.15	25.95
12.98	6.5	15.5	24.3
14.16	6.15	14.15	22.35
15.34	5.65	12.35	20
16.52	5.15	10.6	17.15
17.7	4.35	8.65	14.05
18.88	3.55	6.6	11.1
20.06	3.15	4.65	8.05
21.24	2.6	3.05	5.8
22.42	2.35	1.95	4.05
23.6	2.1	1.15	3.05
24.78	1.9	0.7	2.45
25.96	1.95	0.5	2.2
27.14	1.95	0.45	2.05
28.32	1.85	0.3	1.1
29.50	2.1	0.15	–

Iteration numbers of the conveying system

tain due to the ineffective measurement range of the utilized dosimeter. Therefore, R_{ex} and R_{50} were instead employed. Since Fig. 4(a) showed a somewhat different and distorted curve from the typical plot, graphs in Fig. 4(b) and (c) were adopted to determine R_{ex} and R_{50}. In the case of R_{50}, the value

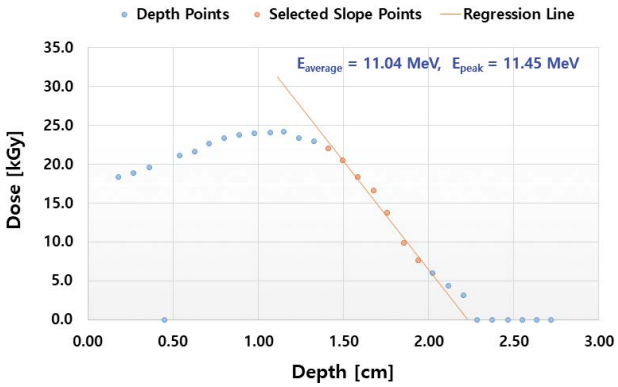

Fig. 5. Depth-dose curve and regression line obtained by using the wedge type energy measurement device and applying the automatic depth-dose curve calculation program provided by GEX, where the iteration number of the conveying system was 350.

was approximately 1.79 cm. Then, by applying $R_{50} = 1.79$ to the equation $E = 0.734 + 5.78 \times R_{50} + 0.0504 \times R_{50}^2$, the energy could be finally obtained as $E\,(MeV) = 11.24$. As for R_{ex}, it averagely exhibited $R_{ex} = 2.30$. Thereby, $E = 0.394 + 4.77 \times 2.30 + 0.0287 \times 2.30^2 = 11.52$ MeV.

Since the calculated electron beam energy ($E = 11.24 \sim 11.52$ MeV) with the fabricated stack type device was inconsistent with the initial design energy level of the accelerator, it was required to confirm the obtained results by using another methodology or device which must be officially acknowledgeable. Accordingly, the wedge type energy measurement system supplied by GEX Corporation was alternatively utilized, where GEX B3110 Energy Wedge Card Array, RisØ Aluminum Wedge and WINdose Dosimetry System were employed.

Electron beam irradiation was carried out with the wedge type device and the experimental conditions were the same as those with the stack type apparatus. After measuring the dose of each dosimeter in the GEX B3110 Energy Wedge Card Array through the calculation program supplied by GEX, the

depth-dose curve automatically appeared and the result is given in Fig. 5. As can be seen, the average energy is 11.04 MeV and the peak energy is denoted by 11.45 MeV, respectively, which are similar to that estimated with the stack type device. Therefore, one can reckon that the calculated energy is reliable.

CONCLUSION

As a part of evaluating current performance of the 10 kW LINAC installed in the Irradiation Facility of KAERI-ARTI, electron beam energy was estimated by applying Monte Carlo calculations. For this, the stack type energy measurement device was manufactured with reference to International Standard ISO/ASTM 51649. By selecting R_{50} or R_{ex} from the obtained depth-dose distribution curve and then applying the selected value to the corresponding second-order equation, the beam energy level was calculated. Besides, for the credibility of the estimated energy value, the energy measurement was performed with the commercially available apparatus called the wedge type energy measurement device, supplied by GEX. By comparing the result obtained from the stack type with that from the wedge type, it was possible to realize that there is a difference by about 1 MeV between the initially designed energy value and the current energy level. The beam energy higher than original design energy level by 1 MeV can cause a very crucial problem in terms of the lifespan of the accelerator since the constituting core components of the accelerator must have designed and installed suitable for the maximum energy of 10 MeV. Therefore, it appears that it is urgent to diagnose the reason of the abnormal beam energy and calibrate it for the stable operation of the 10 kW LINAC. Moreover, after stabilizing the beam energy to the normal condition, it is necessary to monitor the related parameters on a regular basis.

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