Measurment of the energy spectrum of an electron beam extracted from an accelerator

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The electron energy spectrum is one of the most important characteristics of an electron beam that is extracted from a linear accelerator. The most direct way to determine an electron spectrum would be to use a magnetic spectrometer and this method could also give results with high precision and effectiveness. In this article we describe our design of a new multi-layer absorption method, which is based on the depth-dose curves method that can be used in most irradiation accelerators, and adds the Monte Carlo simulation and iterative algorithm in order to reconstruct the electron energy spectrum. In this article the energy spectrum was measured using these two methods, and good results were acquired. These results could be crosschecked, which made the results more reliable.

Keywords: electron accelerator, electron spectrum, magnetic spectrometer, multi-layer absorption

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1. Introduction

In recent years, non-power nuclear technology, electron accelerator (EA), has been promoted as a clean and efficient irradiation source. EAs are widely used in various fields[1–4], including industry, agriculture, medical industry, health, food sterilization, and national defense. Therefore, measuring and evaluating several important parameters of the electron beam have become important and urgent issues. The electron energy spectrum is one of the most important characteristics of the electron beam, which determines the problems related to irradiation effect of physics and chemistry. It also has an effect on the penetration depth and irradiation dose[5] of the electron beam. Thus, it is necessary to have an accurate measurement of the electron energy spectrum.

For some EAs, the measurement of electron energy spectrum can be carried out inside the accelerator vacuum tube. However, most of electron beams are extracted outside the vacuum tube. Consequently, the most commonly used measurement method is the depth-dose curves method, which uses the empirical relationships between the electron energy and the penetration depth in the medium. However, it can only give the most probable energy and cannot give the complete energy spectrum. The Monte Carlo method has also been used to get an energy spectrum,[6] but it needs to be proved by related experiments.

Blad *et al.* attempted to measure the energy spectrum of a 4-MeV linear EA using a plastic scintillator[7] and obtained a full spectrum. He reduced the electron beam intensity down to a range suitable for the scintillator detector by decreasing the filament current and adding a few pieces of scattering foil before the detector. However, this setup was difficult to operate. Therefore, the feasibility of this method was constrained.

The most direct and effective method to measure the electron energy spectrum is to use an electron magnetic spectrometer. Many experiments[8–10] have been taken to measure the energy spectrum of a hot electron with this method. In this article, a magnetic spectrometer was used to obtain the electron energy spectrum of an EA and the complete energy spectrum was recorded in a dosimetry film.

A new method, which we called "multi-layer absorption (MLA)", was designed in this article in order to crosscheck with the results from a magnetic spectrometer. Our MLA is based on depth-dose curves, and adds the Monte Carlo simulation and iterative algorithm. This method measures the depth-dose distribution of the electron beam in the absorber, and then reconstructs the spectrum using an iterative algorithm.

The electron beam extracted from the EA for irradiation has the characteristics of high energy and high beam intensity, and these characteristics make it much more difficult to measure the energy spectrum of the electron beam because the amount of high-energy electrons and high-energy bremsstrahlung are too large. In this article, appropriate shield and current-limiting were used to overcome these problems.

The energy spectrum of EA for irradiation has not previously been measured systematically and accurately. In this article, two different methods are designed to measure the energy spectrum of EA. Both of these methods can be operated conveniently and can obtain the energy spectrum quickly and efficiently. Furthermore, when the two methods were used at the same time, their results could be crosschecked, which made them more credible.

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2. Materials and methods

2.1. Magnetic spectrometer

2.1.1. Experimental arrangement

An electron magnetic spectrometer is composed of a deflecting magnet, GAFCHROMIC EBT2 dosimetry film, aluminum collimator, graphite collimator, and magnet bracket. As shown in Fig. 1(a), a magnetic field is formed between two parallel permanent magnets. The whole magnet is 28 cm long by 12 cm wide by 7 cm high. The magnetic field in the interspace of two magnets is 25 cm long by 12 cm wide by 1 cm high and the intermediate magnetic intensity is 0.209 T. From the size of magnetic field, it can be found that the maximum deflection radius is 12 cm, so that the maximum magnetic rigidity is 0.025 T·m. This is equivalent to a measurement toplimit of the magnetic spectrometer of 7 MeV. As shown in Fig. 1(b), the heterogeneity of the magnetic field is less than 2%.

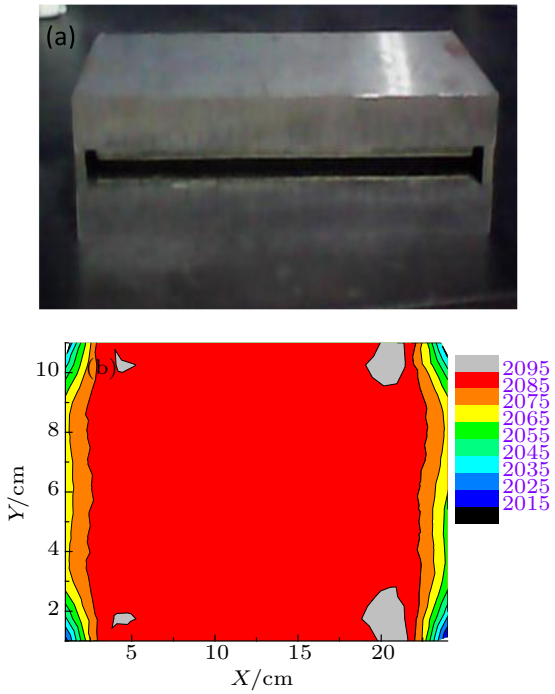


Fig. 1. (a) Appearance of the magnets. (b) Two-dimensional distribution of the magnetic field (the unit of magnetic induction is Gauss).

Figure 2(a) is the experimental arrangement for the measurement of an electron energy spectrum with a magnetic spectrometer. The electron beam was extracted from the accelerator through a titanium window. A 6-cm thick graphite plate with a 1.2-mm diameter hole was mounted directly in front of the electron beam to stop most of the incident beam. Graphite was used here to keep the bremsstrahlung production low. As shown in Fig. 2(b), in order to reduce the dose background caused by bremsstrahlung, the magnetic spectrometer was surrounded by a lead shield whose thickness was about 10 cm. This shield could reduce the intensity of bremsstrahlung to less than 1%. A hole of 0.5 cm diameter was drilled into the lead shield over the aluminum collimator so that the electron beam could be collimated and extracted into the magnetic spectrometer. After the lead collimator, the electron moved into the aluminum collimating aperture, which was 2.5 mm in diameter and 20 mm in thick. The electron beam traveled into the magnetic field vertically through the aluminum collimating aperture, it was then deflected 180 degrees in the magnetic field and was detected by the film.

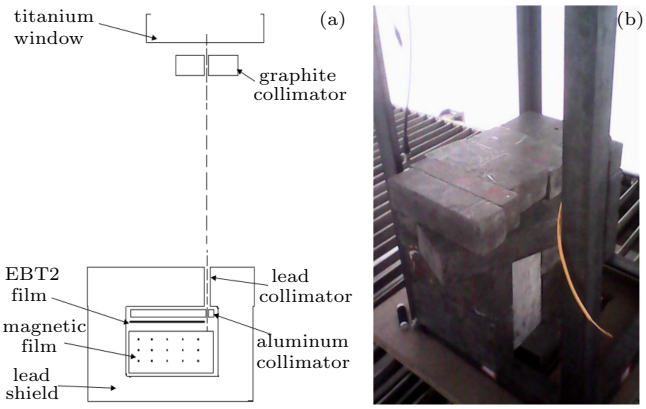


Fig. 2. (a) Experimental arrangement for the measurement of electron energy spectrum with magnetic spectrometer. (b) Appearance of lead shield.

Since the edge field of the magnetic field would cause a certain effect on the trajectory of electron motion, the EBT2 film and aluminum collimator were placed close to the magnet to minimize this effect. In this case, the electron beam would travel into the magnetic field directly after passing the collimator and it could then be received by the film directly after exiting the magnetic field. Therefore, it was hardly affected by the edge field.

Before the experiment, we ensured that the electron beam passed through aluminum collimator, lead collimator, and graphite collimator, and was stayed at the middle of the film.

2.1.2. Calibration of the spectrometer

The spectrometer needed to be calibrated before it was used to measure the electron spectrum of the EA. The ^{90}Sr–^{90}Y β-particle source, which had two β rays with energies of 0.61 MeV and 2.28 MeV, was used to test and calibrate the magnetic spectrometer. Since the intensity of the particle source ^{90}Sr–^{90}Y is not high enough, it is difficult to fit the measurement sensitivity of the EBT2 film. Consequently, an imaging plate (IP) that could respond to a low intensity electron beam was chosen for use in the calibration. The results are shown in Fig. 3(a).

Experiments were done in a vacuum chamber, whose atmosphere was 10^{-4} Pa. A 5-mm thick lead plate was placed in front of the magnetic spectrometer to stop most of the beta particles and a 3-mm diameter hole was drilled to permit a fraction of the β particles going into the spectrometer. Figure 3(b) shows the sensitivity of the IP to electrons of different

energy.[11] ^{90}Sr–^{90}Y beta spectrum could be obtained, together with raw data measured by the IP and the sensitivity curve of the IP.

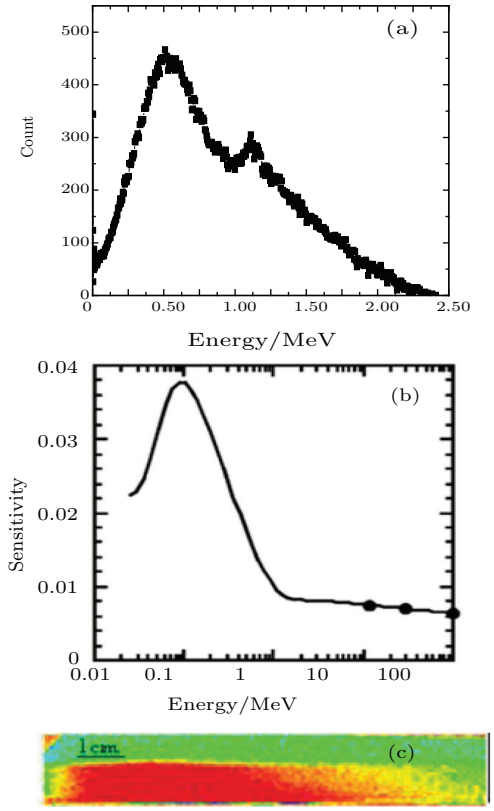


Fig. 3. (a) ^{90}Sr–^{90}Y β-ray spectrum measured by IP. (b) Sensitivity curve of IP.[11] (c) Raw data of the electron spectrum on IP.

The ^{90}Sr–^{90}Y spectrum is a mix of the ^{90}Sr spectrum and the ^{90}Y spectrum. The radioactive half-life of ^{90}Sr is much longer than ^{90}Y, which makes the ^{90}Sr occupy a dominant position in the spectrum. As shown in Fig. 3(a), the peak of the ^{90}Sr–^{90}Y spectrum is located at about 0.5 MeV. The spectrum is very similar to Deasy *et al.*'s measurement of ^{90}Sr–^{90}Y.[12] The maximum energy of the spectrum is about 2.3 MeV, which corresponds to the 2.28 MeV given by the document. The only dissimilarity is the small peak around 1 MeV. The cause of this may be the mutation of the sensitivity of IP to 1 MeV electron, as shown Fig. 3(b). It might also be caused by a relative lower count in the experiment.

In conclusion, the magnetic spectrometer in this article could be used to measure an accurate electron spectrum. A good foundation is laid for measurement of the energy spectrum from an accelerator, it also provides a reference basis.

2.2. MLA

The dose in the medium is defined as

$$D = \frac{\mathrm{d}E}{\mathrm{d}m}, \tag{1}$$

where $\mathrm{d}E$ is the energy deposited in the medium, and $\mathrm{d}m$ is the mass of the medium.

When the electron beam transmits in the medium, it would deposit energy in the medium. Assume that the i-th film dosimeter was located at the depth x_i of the medium, as shown in Fig. 4(b), hence the deposited dose of the electron beam in the i-th film dosimeter can be described as

$$D(x_i, x_i + \Delta x_i) = \int_0^{E_{\max}} f(E) D(x_i, E)\,\mathrm{d}E, \tag{2}$$

where Δx_i is the thickness of film dosimeter, which can be ignored comparing with the thickness of the medium, $f(E)$ is the energy distribution of incident electron beam, $E_{\max}$ is the maximum energy in the spectrum, and $D(x_i, E)$ refers to the deposited dose of the electron of energy E in the i-th film dosimeter.

Discretization could be used in Eq. (2). So that $f(E)$ could be divided to $f(E_1), f(E_2), f(E_3), \ldots, f(E_m)$ with $E_1, E_2, E_3, \ldots, E_m$, respectively. E_j represents the energy interval from $E_j - (E_j - E_{j-1})/2$ to $E_j + (E_{j+1} - E_j)/2$. Suppose that the doses deposited by the electron in the same energy interval are very close, equation (2) could then be written as

$$D_i = \sum_{j=1}^{m} f(E_j) D_{ij} \Delta E_j, \tag{3}$$

where D_i $(i = 1, 2, \ldots, n)$ refers to the deposited dose of the electron beam in the i-th film dosimeter, D_{ij} is the discretization form of $D(x_i, E)$. In addition, it is assumed that ΔE_j was a constant ΔE, so equation (3) could also be written as follows:

$$D_i = \sum_{j=1}^{m} M_{ij} f(E_j), \tag{4}$$

where

$$M_{ij} = D_{ij} \Delta E. \tag{5}$$

In Eq. (3), D_i is the relationship between the doses in the i-th film dosimeter and the corresponding depth of i-th absorption layer. This could be obtained by irradiation experiment with a series of layers, and each layer consists of one aluminum slice followed by one film dosimeter, as shown in Fig. 4(a). Here, M_{ij} is composed of a group of monoenergetic electron's dose distribution on the depth of absorption layer, which can be obtained by calculation using a MCNP-4C. In this case, $f(E_j)$, which represents the energy distributions of the incident electron beam, is what we needed. With D_i and M_{ij}, we could reconstruct the electron spectrum using an iterative method. The specific process of iterative method has been described in detail in Ref. [13].

For experimental measurement, as in Fig. 4(a), since the penetration depth of electron of energy 6 MeV in the aluminum was about 11 mm, the number of absorption layers was

set to be ten and the thickness of each aluminum layer was set to 1.1 mm after testing various combinations.

For MCNP simulation, various matrices could be obtained by different energy ranges and interval widths. After testing, the energy range of the matrix was set from 3 MeV to 7 MeV and was divided into ten parts averagely with an interval of 0.4 MeV. Matrix M is composed of the dose-depth distribution of the average energy of the ten parts by MCNP simulation. The electron energy is set in such a way that it represents the average value of the whole part. For example, 3.2 MeV is used to represent the part with energy between 3 MeV and 3.4 MeV. Figure 4(a) shows a comparison of the given incident spectrum and iteration result with matrix M. Obviously, the iteration result agrees well with the given spectrum, which lays the foundation for the reconstruction of the experiment spectrum and provides a reference basis.

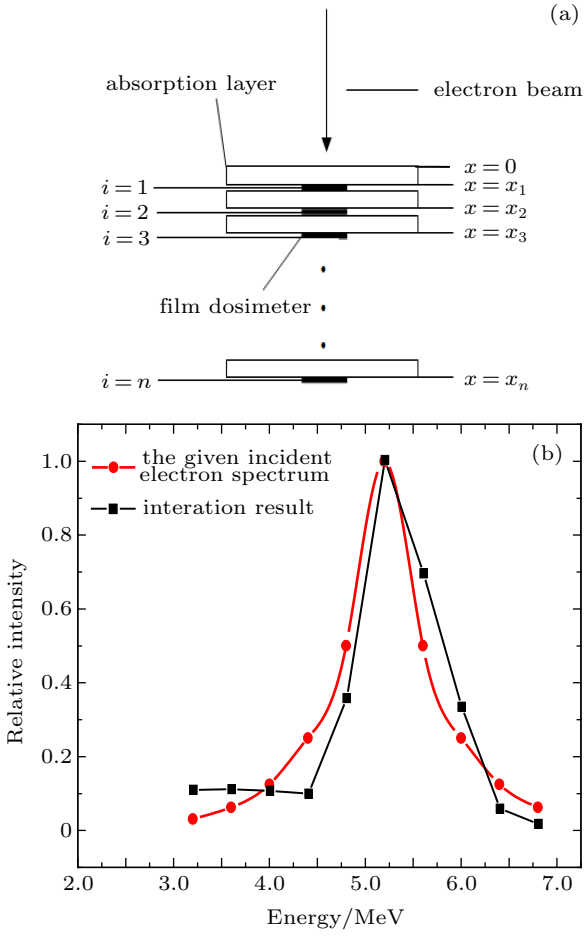


Fig. 4. (color online) (a) Schematic diagram of MLA. (b) Comparison between the given incident spectrum and iteration result.

3. Results and discussion

3.1. Calibration of EBT2 film

EBT2 film produced by GAFCHROMIC is chosen as the detector of the deflection electron in this article because of its advantages. First, the dose range of EBT2 film is from 0.01 Gy to 10 Gy, which corresponds to the experimental requirements. Second, the sensitivity of the film to the energy is very consistent. Third, the uniformity of the film is better than 1.5%. Lastly, the spatial resolution of EBT2 film is very high, which can reach 0.1 mm.

When EBT2 film was used as the detector, the absorbance value of the EBT2 film was read out by the reader. However, we must establish the relationship between absorbance and the deposited doses.

There are two important approximations in our investigation. First, it was assumed that the energy responses of the films to electron of energy 1 MeV–9 MeV were consistent. The films included the GAFCHROMIC EBT2 films which was used in the magnetic spectrometer and the FWT-60 film dosimeter were used in MLA. In fact, the values of $(-\mathrm{d}E/\mathrm{d}x)$ for the incident electrons with the energies from 1 MeV to 9 MeV were changed within 10% in the films.[14] Therefore, it is reasonable to take the first approximation. Second, it was assumed that the dose response of γ rays in the two films was in proportion to the deposited dose of the electrons. The γ rays with a strong penetrability could hardly deposit a dose in the thin medium and the dose of γ rays was usually calculated through the deposited dose of the secondary electrons from γ rays. Consequently, the response of γ rays and electrons are positively related and the relative dose of an electron could be obtained from the dose of the γ rays.

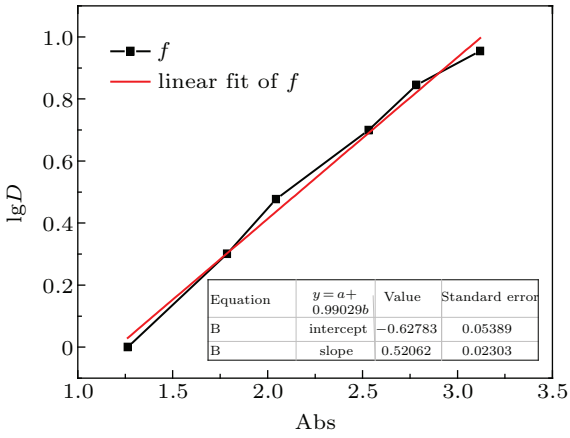


Fig. 5. (color online) Fitting curve of absorbance (Abs) and logarithm of relative dose ($\lg D$).

We selected six pieces of the EBT2 film from the same batch and irradiated them at different locations in the standard ^{60}Co radiation field. For the uniform irradiation and stable dose rate, the irradiation time was set to be 10 min. Since the dose range of the EBT2 film is from 0.01 Gy to 10 Gy and the dose range required in the experiment is Gy scale, the total irradiation doses of the six films were set to be 1 Gy, 2 Gy, 3 Gy, 5 Gy, 7 Gy, 9 Gy, respectively. We then measured the absorbance values of the six films, and obtained the relationship between the absorbance and relative dose of an electron.

Figure 5 shows a linear relationship between the absorbance values and the logarithm of a relative dose. The linear correlation R^2 is up to 0.99. The fitting function is

$$\lg D = 0.52062 \times \text{Abs} - 0.62783. \quad (6)$$

3.2. Spectrum results

Electron spectrum measurements were carried out at EA DZ-12/4 of China Institute of Atomic Energy (CIAE). The parameters of the EA are listed as follows: electron energy up to 6 MeV, pulse frequency of 5–400 Hz, average beam current up to 400 μA, and pulse width of 1–5 μs. The titanium window used to keep the vacuum away from the air has a thickness of 20 μm. The experimental electron beam does not scan and the spot size of electron beam out of the titanium window is about from 10 mm to 20 mm. In addition, the EA was built for irradiation and the energy of the electron beam was not monoenergetic at 6 MeV. Consequently, the experimental objective was to measure the energy spectrum of the EA.

3.2.1. Results of magnetic spectrometer

In order to crosscheck the results, we measured two EBT2 films, which were named film 1 and film 2. In addition, at the end of the experiment, the magnetic field was reversed to measure the background.

For the cases of film 1 and film 2, the experimental parameters of the accelerator were set as follows: electron energy of 6 MeV, the pulse width of 5 μs, beam intensity of 80 mA, and pulse repetition frequency of 10 Hz.

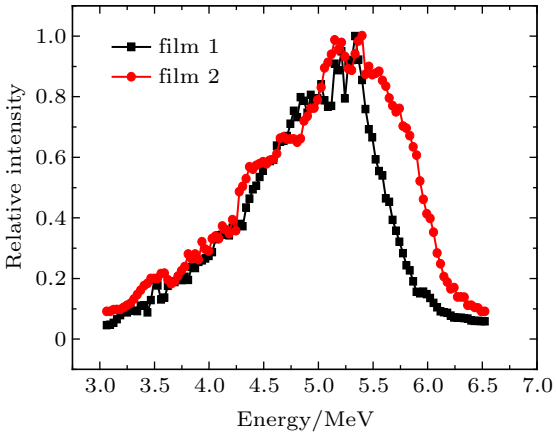


Fig. 6. (color online) Spectrum measured by film 1 and film 2.

The absorbance values of the films were measured and converted to the relative doses using Eq. (6). The electron energy spectrum shown in Fig. 6 was obtained. Figure 6 shows that electron spectrums measured by film 1 and film 2 are almost the same. The peaks of the film 1 and the film 2 are located at 5.3 MeV and 5.4 MeV, respectively, which are very close.

From Table 1, we can find that there are some differences between the mean energy and the most probable energy. Because the energy spectrum extends to the low-energy region, almost to 3 MeV, the mean energy of whole spectrum is lower than the most probable energy. Overall, the repeatability of the measurement is fairly good.

Table 1. Full width half maximum (FWHM), mean energy, and the most probable energy of energy spectrums from film 1 and film 2.

Results	Film 1	Film 2
FWHM/MeV	1.2	1.3
Mean energy/MeV	4.5	4.9
The most probable energy/MeV	5.3	5.4

We compared this electron energy with that measured inside the vacuum tube. Before electrons arrived at the EBT2 film through magnetic deflection, they passed through the titanium window, which was 20 μm thick, and air, over a distance of 131.4 cm (for 6 MeV electron energy). The average energy loss can be written as

$$\begin{aligned}\Delta E &= \int_0^{x_1} S_1\rho_1\,\mathrm{d}x + \int_0^{x_2} S_2\rho_2\,\mathrm{d}x \\ &= 325\ \text{keV}, \end{aligned} \quad (7)$$

where S_1, ρ_1, x_1 are the total stopping power, density, and the distance that the 6-MeV electrons passed through in the air, respectively. The S_2, ρ_2, x_2 have the same meaning but for titanium.

Therefore, the energy of the electron beam measured by the magnetic spectrometer was about 325 keV lower than that in the vacuum tube. Therefore, the most probable electron energy of the results was equal to the energy 5.7 MeV in the vacuum tube, which agrees well with the nominal 6 MeV.

3.2.2. Results of MLA

As shown in Fig. 4(b), dose-depth distribution of 6 MeV electrons in the aluminum was measured by multi-layer aluminum absorptions. The energy spectrum could then be obtained by the matrix M and iteration method. The results are shown in Fig. 8 and the electron beam parameters in the experiment are as follows: electron energy of 6 MeV, beam intensity of 100 mA, a pulse width of 4 μs, and a pulse repetition frequency of 10 Hz for experiment 1 and electron energy of 6 MeV, beam intensity of 80 mA, a pulse width of 3.5 μs, and a pulse repetition frequency of 10 Hz for experiment 2.

Figure 7 shows that the results of MLA are consistent and the peaks are both located at 5.6 MeV. The overall shapes of the two spectrums are very similar, and MLA was located 35 cm away from the titanium window, so the energy loss of the electrons while passing through the air was about 96.4 keV, derived from Eq. (7). Therefore, the most probable energy measured by MLA is equal to the energy 5.7 MeV in a vacuum tube, which agrees well with the nominal 6 MeV. Consequently, the results are believable.

It can be easily obtained from Table 2 that the most probable energy and mean energy are very close. This means that

the spectrums obtained by MLA are good in symmetry. However, the FWHMs of the results are different. The difference might be caused by the changes in the parameters of the EA when operated in different experiments.

Table 2. FWHM, mean energy, and the most probable energy of the energy spectrums from MLA.

Results	Experiment 1	Experiment 2
FWHM/MeV	0.8	1.4
Mean energy/MeV	5.5	5.8
The most probable energy/MeV	5.6	5.6

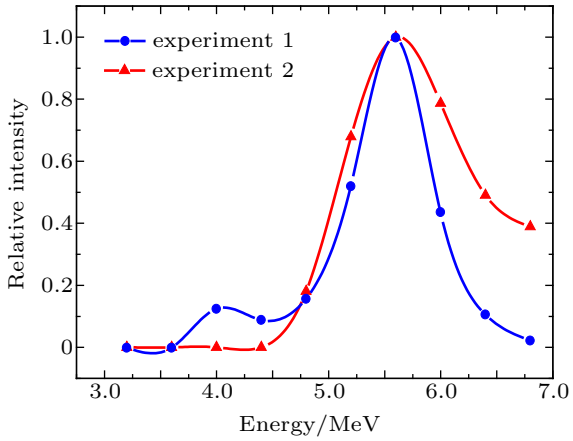


Fig. 7. (color online) Spectrums reconstructed by MLA.

3.3. Result comparison

As shown in Figs. 6 and 7, the peaks of the energy distribution obtained from MLA are about 5.6 MeV. However, the peaks of the magnetic spectrometer are about 5.4 MeV. The factors causing the difference between these two methods might be due to the different distances that the electrons traveled in the air between MLA and the magnetic spectrometer. The distance of the magnetic spectrometer was 96.4 cm longer than that of the MLA. Therefore, the energy difference was 229 keV derived from Eq. (7). Thus, it is fairly reasonable that the peak energy of MLA is 0.2 MeV larger than that of the magnetic spectrometer. The spectrum measured by film 2 is moved 229 keV to the right and is compared with the spectrum of the MLA in a one coordinate system. As shown in Fig. 8, the two spectrums have been normalized and are in good agreement with each other in the high-energy region above 5 MeV. There are some differences in the low-energy region below 5 MeV. This happens because multilevel collimators (including aluminum, lead, and graphite) were used when the energy spectrum was measured with the magnetic spectrometer and the energy of a part of electrons decreased because of the scatterings in the collimators. Thus, the spectrum of film 2 extends to the low-energy region until 3 MeV.

In conclusion, a comparison between the results of the magnetic spectrometer and MLA shows that they were in reasonable agreement. The two kinds of methods both have advantages and can be competent for measurements under various conditions when matched appropriately. Furthermore, the results can be crosschecked when the two methods are used at the same time, which makes the measurement more reliable.

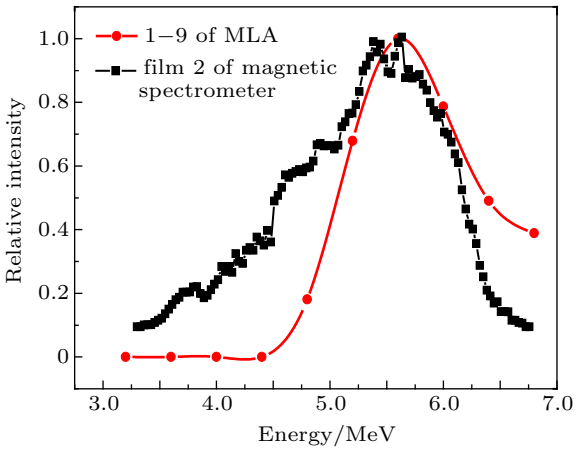


Fig. 8. (color online) Results comparison of MLA and magnetic spectrometer.

3.4. Resolution of magnetic spectrometer

The energy resolution of the magnetic spectrometer is mainly caused by the spatial resolution of detector, the size of collimating aperture, and the maximum angle of divergence after collimation. When the absorbance of the EBT2 films was measured, the measured values were obtained from each interval of 1 mm. So, the spatial resolution of the EBT2 film detector was 1 mm. The error of deflection radius caused by the size of collimating aperture, the maximum angle of divergence, and detector's spatial resolution can be written as

$$\Delta\rho = \rho\,(1-\cos\varphi) + d/2 + s/2, \tag{8}$$

where ρ is deflection radius, φ is the maximum angle of divergence after collimation, d is the diameter of collimating aperture, and s is detector's spatial resolution. Hence, the energy resolution of the spectrometer can be written in the form

$$\begin{aligned} R_E &= \frac{\Delta E}{E} \\ &= \left(\frac{eB}{m_0c}\right)^2 \rho \left\{\left[\left(\frac{eB\rho}{m_0c}\right)^2 + 1\right] - \left[\left(\frac{eB\rho}{m_0c}\right)^2 + 1\right]^{\frac{1}{2}}\right\}^{-1} \Delta\rho \\ &= \frac{A\Delta\rho}{A\rho + \frac{1}{\rho} - \sqrt{A + \frac{1}{\rho^2}}}, \end{aligned} \tag{9}$$

where A represents $(eB/(m_0c))^2$, which is a constant, B is the magnetic induction, c is the speed of light in vacuum, m_0 is the rest mass of electron, and e is the charge of electron. The energy resolution of the magnetic spectrometer could then be calculated as from 4.5% to 2.38% in the main measuring range from 3 MeV to 7 MeV, which is a fairly good accuracy.

The heterogeneity of magnetic field was ignored during the calculation of energy resolution that was made above. In addition, there could be deviation in the calibration using IP. So, combining with these factors, the energy resolution of the magnetic spectrometer was about 5%–10%.

4. Conclusion

The energy spectrum of a linear EA at CIAE was measured with two methods and ideal results were obtained. Since the high-intensity monoenergetic electron sources are hard to be found, the efficiency calibration of magnetic spectrometer and MLA have not been carried out. Thus, all of the measurements in this article are a relative measurement of the energy spectrum. The peaks of spectrums from magnetic spectrometer and MLA are located at about 5.4 MeV and 5.6 MeV, respectively. The results of the two methods agree well in allowable error and this shows that the MLA is feasible. Although its accuracy is not very high due to the limit of its absorption-layer's number, it is easily-operated and does not need complicated equipment.

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