Reconstruction of a 6-MeV bremsstrahlung spectrum by multi-layer absorption based on LiF:Mg, Cu, P

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In this paper, TLD (LiF: Mg, Cu, P) is used as detector. A multi-layer absorption (MLA) model is designed. Combined with Monte-Carlo processes, a bremsstrahlung X-ray spectrum is reconstructed by an iterative method; the reconstructed results agree with the results of simulations by the MCNP process essentially, especially in middle energy region.

Keywords: bremsstrahlung spectrum, reconstruction, industrial electron accelerator

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1. Introduction

The application of radiation processing depends mainly on using a high-energy electron irradiation accelerator (HEEIA) and radioactive isotopes. Each of the two ways has its advantages such as a high dose rate and long-range respectively. As a novel method, using an electron beam shooting target to generate bremsstrahlung can combine these two advantages. In the next 10–20 years it will become the primary method to gradually replace the radioactive isotopes in radiation processing, so that the studies of the properties of radiation fields generated by HEEIA become necessary and urgent. Hence the investigation of the bremsstrahlung spectrum becomes initially important, as it determines the irradiation uniformity and efficiency of radiation processing by industrial electron accelerators.

Bremsstrahlung has been studied mostly in the last century.[1,2] Based on the Born approximation and the Coulomb correction, many theories of bremsstrahlung cross sections were raised.[3,4] The energy distribution and angular distribution of the bremsstrahlung photons can be predicted well by the formulas at different segments. Schiff's formula[1,5] is used in this paper as a comparison with experimental data. Theoretically, it is easy to estimate the bremsstrahlung spectrum directly,[4,6] but it is difficult for an industrial electron accelerator because the scattering surrounding the true fields is complicated in real cases. Besides, the high intensity of the electron beam makes it hard to be measured directly.

In this paper, the bremsstrahlung spectrum is measured by Multi-Layer Absorbtion (MLA). TLD (LiF:Mg, Cu, P) is used as the detector. Combining with the Monte-Carlo method,[7] a comparison has been made between experimental results and the results obtained by Monte-Carlo method.

2. Theory

Absorbed dose in a medium is defined as

$$D = d\varepsilon/dm, \tag{1}$$

where $d\varepsilon$ is the energy deposited in the irradiated medium, dm is the mass of the irradiated medium. In the MLA structure, the absorbed dose deposited in the medium could be described by

$$D(x_A) = \frac{\int_0^{E_{\max}} F(E)\,\mathrm{d}E\,\mathrm{e}^{-\mu_A(E)x_A}E(1-\mathrm{e}^{-\mu_\mathrm{d}(E)d})\xi(E)}{\Delta m}, \tag{2}$$

where $F(E)$ is the intensity distribution of the bremsstrahlung with energy E, x_A, and d are the thicknesses of the absorbing medium and the detector respectively, $\mu_A(E)$ and $\mu_\mathrm{d}(E)$ are the attenuation coefficients for photons with energy E in the absorber and detector respectively, the subscript A means the material of the medium, Δm means the mass in which the energy deposits, and $E_{\max}$ is the maximum energy of the spectrum. $\xi(E)$ is the relative energy response of TLD, and it is defined by[8]

$$\xi(E) = \frac{\left(\frac{\mu_\mathrm{en}}{\rho}\right)_\mathrm{d}}{\left(\frac{\mu_\mathrm{en}}{\rho}\right)_\mathrm{air}}, \tag{3}$$

which means the ratio of the absorbed energy in the detector to that in air. $D(x_A)$ is the deposited dose of the bremsstrahlung in the TLD just following the absorber layer with x_A thickness.

Obviously, $F(E)$ could be divided into many fractions of $F_1, F_2, F_3, \ldots, F_n$ with equal energy interval ΔE, and $E_1, E_2, E_3, \ldots, E_n$ are the middle values of $F_1, F_2, F_3, \ldots, F_n$ respectively. Suppose that the attenuation coefficient μ varies very slightly in each energy interval, the absorbed dose D_i under attenuation with thickness of x_i in Eq. (2) may be written

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in the form

$$D_i = \frac{\sum_{j=1}^{n} F_j \Delta E_j \, \mathrm{e}^{-\mu_A(E_j)x_i} E_j (1 - \mathrm{e}^{-\mu_d(E_j)d}) \xi(E_j)}{\Delta m}, \quad (4)$$

equation (4) could be rewritten as

$$D_i = \sum_{j=1}^{n} M_{ij} F_j, \quad (5)$$

where

$$M_{ij} = \frac{\mathrm{e}^{-\mu_A(E_j)x_i} E_j (1 - \mathrm{e}^{-\mu_d(E_j)d}) \xi(E_j) \Delta E_j}{\Delta m}, \quad (6)$$

the term $E_j(1 - \mathrm{e}^{-\mu_d(E_j)d})$ means the deposited energy in TLD which is contributed to by the bremsstrahlung of E_j, because $\mu(E_j)d \ll 1$, so it can approximate to $E_j\mu_d(E_j)d$, the attenuation coefficient $\mu_d(E)$ and the energy absorption coefficient $\mu_e(E)$ in Pb are shown in Fig. 1. The values of $\xi(E)$ are almost the same values from 0.1 MeV to 6 MeV[8] as shown in Fig. 2, therefore it can be treated as a constant.

As a necessary parameter to describe the energy deposited in TLD, the $\xi(E)$ appears in Eqs. (2)–(6), but it is not really used in the following work. The doses used in the following discussion are characterized by the delivery dose in the water equivalent phantom measured by TLD.

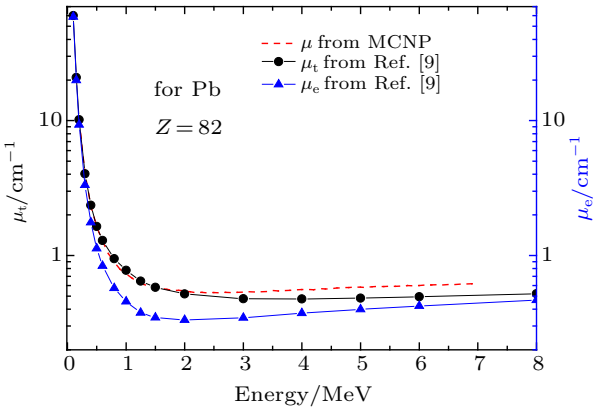


Fig. 1. (color online) The attenuation coefficient data for Pb obtained from MCNP and ANL5800.[9]

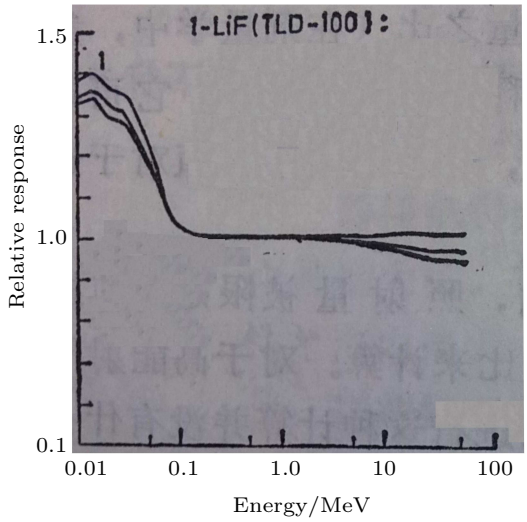


Fig. 2. Relative energy response $\xi(E)$ of TLD.[8]

M_{ij} means the absorbed dose in the TLD detector when the unit fraction of bremsstrahlung with energy E_j between energy interval $(E_j - \frac{1}{2}\Delta E_j, E_j + \frac{1}{2}\Delta E_j)$ transmitted through a medium with a thickness of x_i. The determination of M_{ij} by using the Monte-Carlo method in this article is calculated by MCNP-4C.

D_i is the deposited dose in the i-th TLD, and it could be obtained by experiment, we could reconstruct the initial bremsstrahlung spectrum F using iteration. The iteration processes of the spectrum reconstruction have been reported,[10–12] the processes we used here could refer to Huang's results.[10]

3. Monte-Carlo model

In the Monte-Carlo simulation of our experiment, it is considered that deposited doses in the TLDs could be calculated by replacing TLD by an aquatic layer of 50-μm thickness.

The Monte-Carlo model is multi-layered — each layer consists of one Pb absorbing medium of 2-mm thickness, just as is used in the experiment, followed by one thin aquatic layer of 50-μm thickness. The values of the energy absorption coefficients μ_e for water are about 0.0165 cm^{-1} to 0.0330 cm^{-1} in the energy range from 0.1 MeV to 10 MeV.[9] Besides, the thickness of the equivalent aquatic layer is 50 μm, so the deposited energy $\Delta\varepsilon_x$ in the thin aquatic layer approximates to $E_x\mu_e(E_x)d$, where d is the thickness of the thin aquatic layer, E_x is the energy of incident photons. The mass Δm of the thin aquatic layer is $\rho S d$, where ρ is the mass density of water, S is the cross-sectional area.

For example, in calculation of M_{ij}, the calculated result $\Delta\varepsilon_{ij}$ means the absorbed dose in the thin aquatic layer when the unit fraction of the bremsstrahlung of the electrons with energy E_j between the energy interval $(E_j - \frac{1}{2}\Delta E_j, E_j + \frac{1}{2}\Delta E_j)$ transmitted through the medium Pb of thickness x_i.

The dose deposited in the thin aquatic layer is a total dose from the original incident photons, secondary photons, and secondary electrons generated during the interaction of incident photons with the medium. It is considered as the overall effective dose caused by incident photons beam.

4. Experiments and results

4.1. MLA structure

A schematic diagram of MLA is shown in Fig. 3(a), it has a multi-layered structure and each layer consists of one absorb medium following by one TLD cyclically. The axial of the MLA is parallel to the direction of the incident bremsstrahlung. Pb is chosen as the absorbing medium material, also called the attenuating layer, with thickness of 2 mm. The stability of TLDs is about 2.5% (discussed in a later section), so it is required to design the dose difference between two adjacent TLDs larger than 5% at least, the change of μ_{Pb}

with photon energy is shown in Fig. 1. It shows a small change when the energy is from 1.25 MeV to 7 MeV, and $\mu_{\rm Pb}$ is about 0.0569 $\rm cm^2{\cdot}g^{-1}$. According to the law of exponential attenuation the thickness of Pb should be larger than 1 mm for obtaining a dose difference between two adjacent TLDs larger than 5%, so the thickness of Pb medium is set to 2 mm.

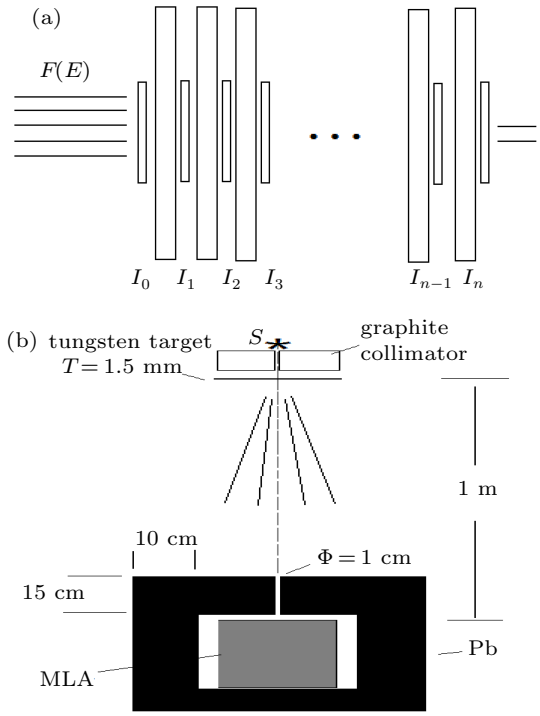


Fig. 3. (a) Schematic diagram of the structure of MLA, (b) the schematic diagram of the experimental layout.

The size of TLDs is $\phi(3\ \rm mm)\times \rm d(1\ mm)$.

The electron range in material is described by

$$R(\rm g/cm^2) = 0.5T - 0.106, \quad \text{for} \quad T > 2.5\ \rm MeV. \qquad (7)$$

where T is the kinetic energy of an electron in MLA. The electron range is 1.5 mm for a 6-MeV electron in the tungsten target, and in order to have the intensity of the outgoing bremsstrahlung beam as great as possible, the thickness of the tungsten target is set to be 1.5 mm. In this condition, the self-absorption of the tungsten to the bremsstrahlung is about 25% for photons of 0.6 MeV, and 15% for photons of 1.25 MeV.

The experimental layout is shown in Fig. 3(b). Electron beam S is collimated by a graphite collimator with $\phi(2\ \rm mm)\times \rm L(55\ mm)$, followed by a tungsten target 1.5 mm in thickness. The MLA is located in a Pb-shell with a front thickness of 15 cm and a side thickness of 10 cm, the axis of MLA is coincided with the incident direction of the electron beam. The Pb-shell is used to screen the effects from the surrounds, in which a hole with $\phi(1\ \rm cm)$ is set in front of the shell to make the bremsstrahlung pass through, and it results in an angle to the targeting point which is ± 5 mrad (about 0.25°). It is so small that we may treat the incident beam on the MLA as a parallel beam.

4.2. Properties of TLDs

Because the inaccuracy of TLDs is about 5% when bought, the TLDs should be selected with serious consideration when they are used as detectors. The selection of the TLDs was carried out at National Institute of Metrology, China (NIM).

The calibration of the absorbed doses of the TLDs had been carried out as follows: For ^{137}Cs and ^{60}Co, the air kerma rate and absorbed dose rate in water equivalent phantoms are detected accurately at NIM. Besides, the readings of TLDs are caused by the energy deposition in TLDs, the calibration of the relationship between the dose-readings of TLDs and the absorbed doses in the water equivalent phantom was carried out under the same irradiation, so the doses of TLDs measured by the experiment can transfer to the absorbed doses in the water equivalent phantom.

The air kerma rate of ^{137}Cs at NIM was 35.843 mGy/h (1 Ry=13.6056923(12) eV), measured on 8-18-2012; the air kerma rate of ^{60}Co was 3.322 mGy/h, measured on 2-16-2014. The current air kerma rate is calculated by the law of exponential decay.

4.2.1. Selection of TLD

The selection process was carried out by irradiation of ^{137}Cs in 100 mGy, and 160 pieces of TLDs were picked out from 1000 pieces.

The stability and accuracy of the selected TLDs were tested as follows: The TLDs were irradiated under ^{137}Cs in 100 mGy, and after standing for 8 hours or more, the measurements of the TLDs were made in two processes: first, by randomly picking 50 pieces out from the 1000 pieces of TLDs, the average value $\bar{N}$ of the 50 pieces is obtained as the average value of all the 1000 pieces of TLDs; second, by reading out the values of the rest of the TLDs. When the value N of the TLD meets the condition of $|N/\bar{N}-1| \le 2.5\%$, the TLD is picked out. Then, the stability of the TLD picked out was tested twice by irradiation of 100 mGy under ^{137}Cs. The results are shown in Fig. 4, the statistics of the selected TLDs is approximately a normal distribution, the following twice repeat tests are shown in Fig. 4, and the statistical error is 2.65% and 2.50% respectively.

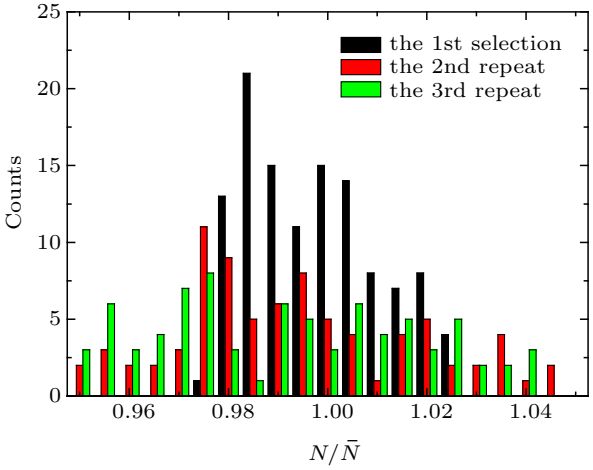


Fig. 4. (color online) The statistical distribution of $N/\bar{N}$ of TLDs picked out by irradiation under ^{137}Cs in 100 mGy.

4.2.2. Calibration of TLD

The calibration was carried out under ^{137}Cs and ^{60}Co at NIM.

TLDs were located at the stationary positions, at which the dose rates had been measured accurately, and then they were irradiated for different times with mean doses $1, 2, 5, 10, 20, 50,$ 100 mGy. After the irradiations, they were stood for 8 hours or more, then they were measured by a TL reader model: RGD-3B, with a range of 0.1 mGy to 200 mGy. The relationship between dose-reading values and the irradiated doses are shown in Fig. 5(a) and Fig. 5(b), which can be expressed in Eq. (8) for ^{60}Co and Eq. (9) for ^{137}Cs for the dose's range from 0.5 mGy to 100 mGy.

$$D_1(\text{mGy}) = 0.9847 \times d + 0.0377, \tag{8}$$

$$D_2(\text{mGy}) = 0.9788 \times d + 0.1724 \tag{9}$$

with R^2 being 0.99982 and 0.99973 respectively, where D_1 and D_2 mean the absorbed dose for ^{60}Co and ^{137}Cs respectively, and d means the instrument's reading. It shows that the dose responses of TLDs are almost the same for an energy of 0.661 MeV and for the energies of 1.17 MeV and 1.33 MeV.

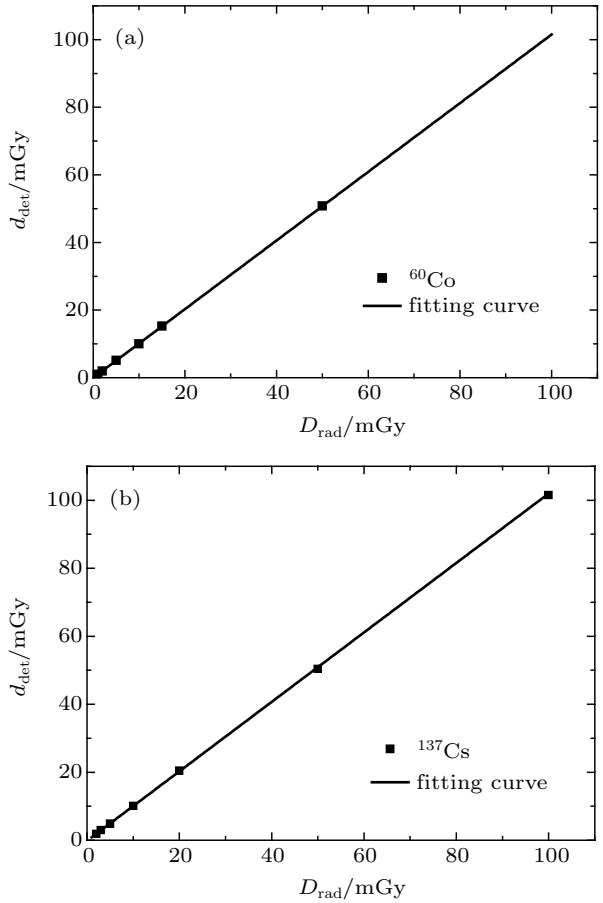


Fig. 5. Calibration of TLD for dose response under irradiation by (a) ^{60}Co and (b) ^{137}Cs.

4.3. Absorbed doses in TLDs of MLA

The experiments were carried out on a multi-energy electron accelerator (EA), Model: DZ–12/4, at China Institute of Atomic Energy (CIAE). The EA's parameters are: energy of 6/8 MeV, pulse current of 100 mA, pulse width of 1 μs, repetition rate of 5 Hz, the target is tungsten (W) with a thickness of 1.5 mm. The experimental arrangements are shown in Fig. 3(b), TLDs are located at 1 m in front of the target. The irradiation time is set to 150 s.

The deposited doses obtained from experiments and from MCNP are shown in Fig. 6.

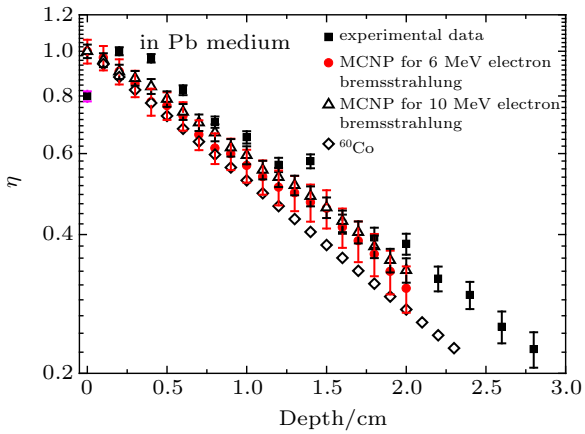


Fig. 6. (color online) The absorbed doses in TLDs of MLA.

4.4. Spectrum reconstruction

The reconstructed spectrum obtained by iteration on absorbed doses at different depths by MCNP processes, is shown as solid diamonds in Fig. 7. The initial spectrum used in MCNP is also shown by open triangles. The reconstructed spectrum basically agrees with the initial spectrum, except for the results in the high-energy limit, which might be caused by the relative statistical error in MCNP.

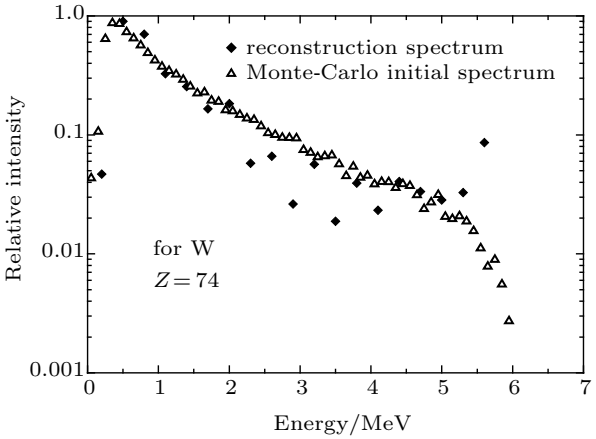


Fig. 7. Spectrum obtained by Monte-Carlo method 100 cm in front of a tungsten target of 1.5 mm.

An energy distribution[13] of the electron beam of the EA at CIAE is measured as shown in Fig. 8(a), which is with a nominal energy of 6 MeV. The absorbed doses of the TLDs, which are irradiated under the bremsstrahlung generated by

electrons with this energy distribution incident on tungsten of 1.5 mm, are shown as solid boxes in Fig. 6. The reconstructed spectrum using the absorbed doses obtained in experiments is shown as open diamonds in Fig. 8(b), in the iteration the maximum energy E_{max} is set to be 5.9 MeV. The bremsstrahlung spectrum by MCNP is shown as solids boxes in Fig. 8(b). It is obvious that there are fewer low-energy photons in the reconstructed bremsstrahlung spectrum than in that of MCNP, and the reconstructed spectrum is basically in agreement with MCNP's spectrum.

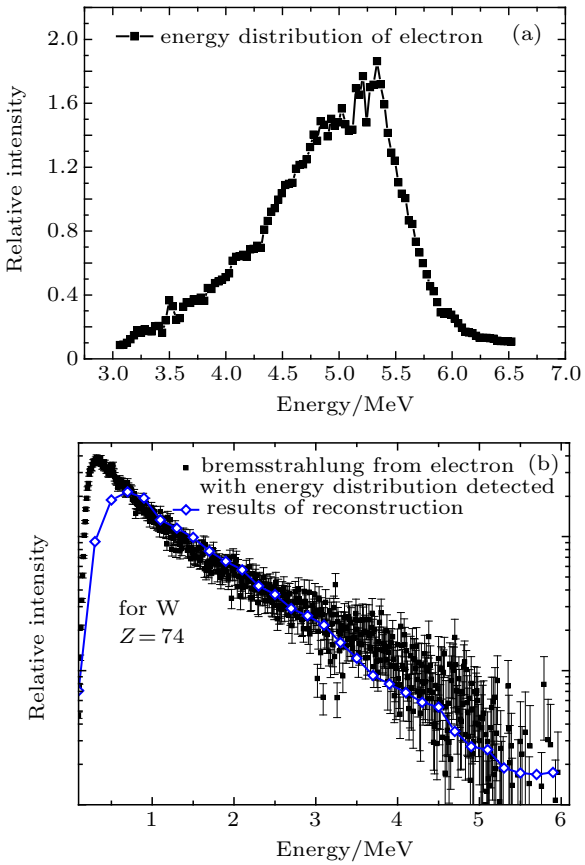


Fig. 8. (color online) (a) Energy distribution of electrons detected at CIAE. (b) The reconstruction spectrum from the detected doses and the bremsstrahlung spectrum by MCNP.

5. Conclusions

In this article, the TLD (LiF:Mg, Cu, P) is introduced to the measurement of bremsstrahlung spectra. The responses of TLD for absorbed doses were studied at NIM and a structure of MLA was constructed for the bremsstrahlung spectrum measurement.

Based on the above discussion, a spectrum has been reconstructed by iteration on the absorbed doses obtained from a 6-MeV electron targeting W at CIAE. The results essentially agree with the Monte-Carlo spectrum.

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