Study on the radiation problem caused by electron beam loss in accelerator tubes*

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Abstract The beam dynamic code PARMELA was used to simulate the transportation process of accelerating electrons in S-band SW linacs with different energies of 2.5, 6 and 20 MeV. The results indicated that in the ideal condition, the percentage of electron beam loss was 50% in accelerator tubes. Also we calculated the spectrum, the location and angular distribution of the lost electrons. Calculation performed by Monte Carlo code MCNP demonstrated that the radiation distribution of lost electrons was nearly uniform along the tube axis, the angular distributions of the radiation dose rates of the three tubes were similar, and the highest leaking dose was at the angle of 160° with respect to the axis. The lower the energy of the accelerator, the higher the radiation relative leakage. For the 2.5 MeV accelerator, the maximum dose rate reached 5% of the main dose and the one on the head of the electron gun was 1%, both of which did not meet the eligible protection requirement for accelerators. We adopted different shielding designs for different accelerators. The simulated result showed that the shielded radiation leaking dose rates fulfilled the requirement.

Key words accelerator tube, beam loss, shielding design, PARMELA, MCNP

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1 Introduction

Electron linacs are widely used in facilities of radiotherapy, nondestructive inspection, container inspection system at the Customs, industrial computed tomography (ICT), etc. For a low-energy linac during its normal run, the electron beam loss takes place in the accelerator tube, in the bending magnet, in the attachment of components[1], in the electron transportation tubes[2, 3], etc. In common RF accelerators, among the total electrons emitted by the electron gun, only electrons whose phases are within a particular interval can be accelerated stably. Others are likely to be lost during the accelerating process, resulting in the capture rate of only 1/3[4]. Attention focuses on the radiation problem caused by electron beam loss and the radiation shielding system.

The particle dynamic code PARMELA[5], of which the original program written by Kenneth P. Crandall in 1980, is a flexible electron linac design code which can give information about the number, the spatial distribution, the energy and the moving direction of electrons in the transportation process in accelerator. By PARMELA, the electron beam transportation in the accelerator tubes was simulated and the lost electrons during the accelerating process as well as those through the exit windows were calculated. The results indicated that in the ideal condition, the percentage of electron beam loss was about 50% during the accelerating process, most of which happened in bunchers with low energies. The lost electrons were injected to collide with the tube wall with a small angle with respect to the beam axis. The process generated photons to originate radiation. PARMELA code and the MCNP[6] code were combined to calculate the energy and the spatial distribution. And we concluded the radiation spatial distributions rule of the electron beam loss. The following performed analysis and researches according to accelerators with different energies.

2 Electron beam loss in accelerator tubes

The S-band SW linacs with energies of 2.5, 6 and 20 MeV were made at Tsinghua University.

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PARMELA code carried out the dynamic calculation of the SW linacs respectively. The results indicated that in the ideal condition, the electron beam loss was about 50% of the incident electrons (the actual capture rate was 30%[4]). The calculations giving the locations and spectra of the three accelerators are showed respectively in Fig. 1.

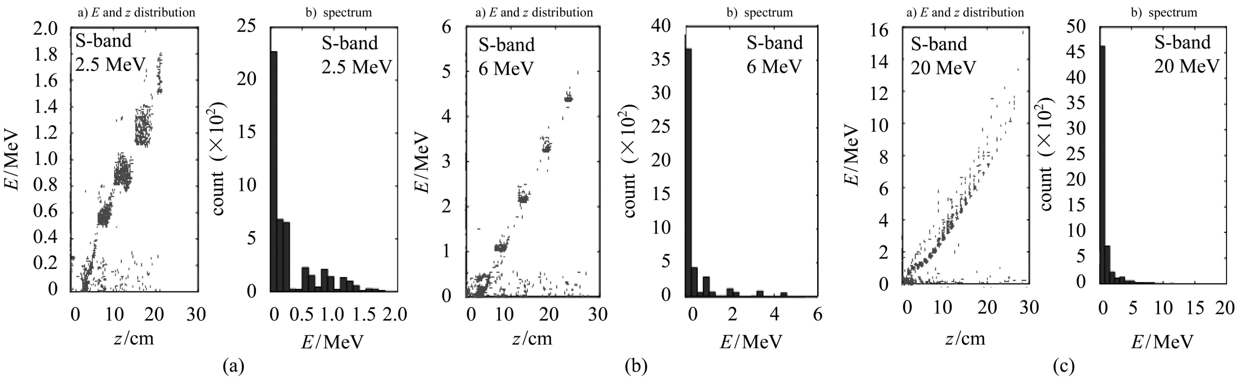

Fig. 1. Spectrum-location distributions of lost electrons in S-band SW accelerator of energies of (a) 2.5 MeV, (b) 6 MeV and (c) 20 MeV.

From Fig. 1, we can see, respectively, for all the three accelerators, most of the lost electrons are in the bunchers with low energies. About the 6 MeV accelerator tube, for instance, electrons whose energies were less than 0.2 MeV occupied above 60% of the total lost electrons. The calculation also did statistics of the diverging angular distribution of the lost electrons in different accelerators. Fig. 2 shows only the distribution of the 6 MeV accelerator. It can be seen that the angle between the lost electrons and the beam axis is small, which agrees with the Ref. [2].

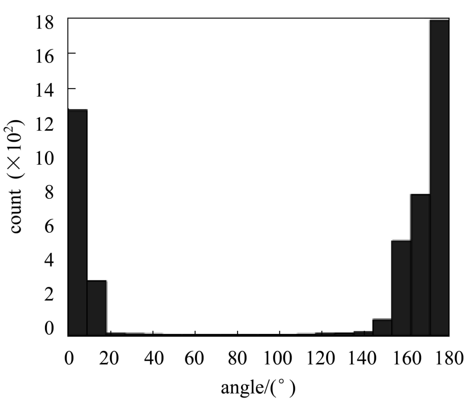

Fig. 2. Diverging angular distribution of lost electrons in 6 MeV accelerator.

3 Leaking dose caused by lost electrons

According to the calculation by PARMELA code, the statistical information about the energy, location and diverging angular distribution of the lost electrons in accelerator tubes was used as the input source file of MCNP code. The accelerator tube model of the exact parameters was built by MCNP. By recompiling the source file and the model, we could actually calculate the radiation leaking dose. Fig. 3 shows the corresponding coordinates to calculate the leaking radiation distribution: (a) is 1 m away from the accelerator tail (assuming the axis of the accelerator is direction y, and the initial buncher corresponds to y=0); (b) is 1 m away from the axis of the accelerator tube. In the calculation, the target material is tungsten; and the target thickness is equal to the average range of electrons with different energies ($t = r_0$).

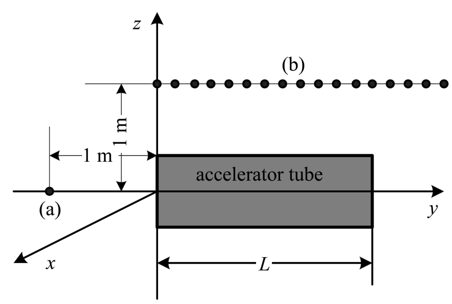

Fig. 3. Coordinate to calculate the radiation distribution of lost electrons.

Corresponding to the coordinate defined in Fig. 3, Fig. 4 performs the relative dose distributions of the lost electrons along the axis of each accelerator of different energies. The results have been normalized by the dose at the isocenter (1 m away from the target along the beam direction).

From Fig. 4 we can see that though the most lost electrons are in the bunchers in accelerator tubes, the radiation dose distribution of the beam loss is nearly equal along the axis of the accelerator. This effect is caused by the lost electrons and the generated photons scattered by the structure material of the accelerator tube. Fig. 4 also shows that the percentages of the radiation of electron beam loss of the total radiation production vary corresponding to different accelerating energies. For 2.5 MeV, the radiation of lost electrons influences the most: about 3.7% of the total photonic dose at the isocenter. It is at the electron backscattering direction, the head of the electron gun, that the highest dose of the lost electrons occurs, which is 1% of the dose at the isocenter. Commonly the accelerator shielding safety requirement is that the leaking dose of the X-ray in the non-main beam direction must be less than 0.1%[7] of that of the main beam. Thus, shielding designs are recommended for these accelerator tubes.

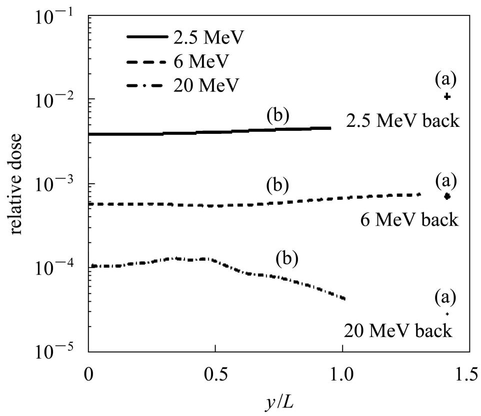

Fig. 4. Leaking dose rate along the axis of the three accelerators.

Figure 5 displays each leaking dose distribution in the circles centralized on the target with 100 cm as radius (The 20 MeV accelerator is longer than 100 cm. We just converted the actually calculated dose done in the circle with 200 cm radius to the 100 cm one). In Fig. 5, (a) is the spatial distribution of the leaking dose per 1 mA output current of the accelerator, which is also the angular distribution with respect to the beam axis; (b) is the results normalized by the dose at the isocenter. Fig. 5 indicates that the angular distributions of the leaking dose of the 2.5, 6 and 20 MeV accelerators are similar. The highest dose of lost electrons is at the angle of about 160° with respect to the beam axis. Among the three accelerators, the absolute leaking dose of 20 MeV accelerator is the highest while the relative one is the lowest. The highest relative dose is less than 0.1% in the 20 MeV accelerator. But for the 2.5 MeV, the highest reaches 5%.

Therefore, the shielding design was of no need for the outside of the high-energy accelerator. While additional shield should be installed outside the 2.5 MeV one. And the design should not be limited within the bunchers but to cover the whole body of the accelerator tube.

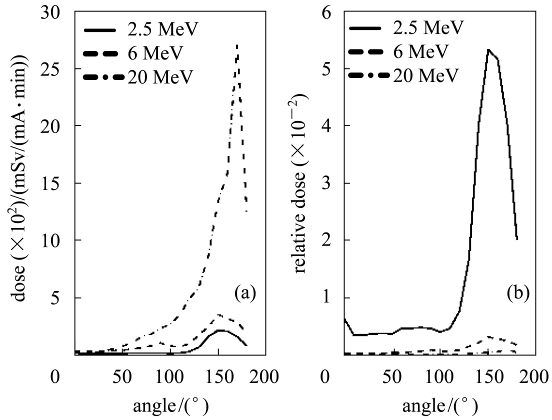

Fig. 5. Leaking dose distribution of lost electrons in the three accelerators.
(a) Angular distribution of leaking dose; (b) Leakage distribution normalized by isocenter-dose.

4 Shielding design for leaking radiation

It is commonly required that the leaking dose around the accelerator is less than 1‰ of the main dose at the isocenter. According to the above analysis of different energy accelerators, to meet the requirement, we should install a 2 cm thick lead shield around the body of the 2.5 MeV accelerator tube, a 0.5 cm thick one around the body of 6 MeV accelerator tube along with 1 cm thick one covering the outside end of the electron gun. For the 20 MeV, there is no need for such shield. And the calculated shielded dose distribution is showed in Fig. 6 with coordinate corresponding to Fig. 3.

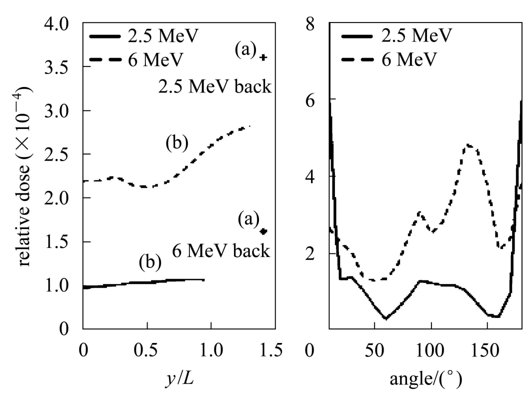

Fig. 6. Shielded leaking dose rate distribution in 2.5 and 6 MeV accelerators.
(a) Dose distribution along beam axis; (b) Dose distribution on circle (r=100 cm).

From Fig. 6 we can see that the percentages of highest leaking dose rate are less than 0.1%, in both accelerators shielded, which meet the shielding safety requirement of the accelerator radiation. Fig. 6 also illustrates that according to the requirement, we should adopt different shield designs for different accelerators.

5 Conclusion

The calculation given by PARMELA simulating the S-band SW electron linacs with different energies of 2.5, 6 and 20 MeV demonstrates that about 50% of the total electrons are lost in the bunchers with low energy. The MCNP code calculates the location distribution of radiation dose caused by the electron beam loss. The result illustrates that of all the three accelerators, the location distribution is nearly equal along the accelerator axis and the angular distributions are similar. The highest leaking dose is at the angle of 160° with respect to the beam axis.

The lower the accelerating energy, the higher the leaking relative dose rate caused by electron beam loss. The calculation indicates that the relative dose rate reaches 5% in the 2.5 MeV accelerator tube, while the one on the end of the electron gun arrives at 1%. To meet the requirement which asks for the leaking dose rate to be less than 1‰, different shielding designs should be adopted for different accelerators. A lead shield of 2 cm thick should cover the outside of the 2.5 MeV accelerator and a 0.5 cm thick one should cover the body of 6 MeV accelerator with a 1 cm thick one on the outside end of the electron gun. For the 20 MeV accelerator, the shielding effect by the accelerators tube structure, the cooling water-jacket, the focusing coil of its own can meet the "1‰ requirement". The new radiation dose rate of shielded accelerators meets the shielding safety requirement for the linear accelerator.

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