Simulation of the Focal Spot of the Accelerator Bremsstrahlung Radiation

V Sorokin[1] and V Bespalov[2]

[1]Senior Researcher, National Research Tomsk Polytechnic University, Tomsk, Russia
[2]Associate Professor, National Research Tomsk Polytechnic University, Tomsk, Russia

E-mail: sorvb@tpu.ru

Abstract. Testing of thick-walled objects by bremsstrahlung radiation (BR) is primarily performed via high-energy quanta. The testing parameters are specified by the focal spot size of the high-energy bremsstrahlung radiation. In determining the focal spot size, the high-energy BR portion cannot be experimentally separated from the low-energy BR to use high-energy quanta only. The patterns of BR focal spot formation have been investigated via statistical modeling of the radiation transfer in the target material. The distributions of BR quanta emitted by the target for different energies and emission angles under normal distribution of the accelerated electrons bombarding the target have been obtained, and the ratio of the distribution parameters has been determined.

1. Introduction

Bremsstrahlung radiation (BR) sources based on linear electron and betatron accelerators are used to test thick-walled objects [1, 2]. BR generation involves electron acceleration, focusing of the accelerated electron beam towards the target and the interaction of electrons and secondary radiation with the target [3]. When accelerating, the electrons are deflected from the equilibrium orbit straight-line in linear accelerators and circular in betatrons.

The distribution of the accelerated electron current density in the plane normal to the equilibrium orbit is assumed to be normal, which does not contradict theoretical and experimental data. A beam of accelerated electrons is formed towards the target via electromagnetic focusing in linear accelerators or via displacement of the electrons from the equilibrium orbit by the pulsed magnetic field in betatrons. The parameters of the electron current distribution in the beam change, however the distribution pattern remains unchanged. The spectrum of BR emitted by the target is continuous, which is predetermined by the electron energy, the atomic number of the target material and its thickness. As energy increases, the number of quanta in the BR spectrum rapidly decreases. The portion of high energy quanta is relatively small. The resolution of the thick-walled object testing through high-energy quanta is determined by the size of the focal spot of the high-energy portion of the BR spectrum.

The techniques to determine the size of BR focal spot similar to those developed for X-rays [1] are not selective with regard to the energy of the quanta emitted by the target. The prevalence of low-energy quanta determines the results of BR focal spot measuring, but does not provide objective information on the focal spot of the high-energy BR portion. The patterns of BR focal spots formation

can be revealed by statistical simulation (Monte Carlo method) of the radiation transfer in the target material. The method enables us to obtain quanta distributions on the target surface for different energies and angles of quanta emission and to analyze them comparing the parameters of distributions of the electrons bombarding the target.

2. Materials and Methods

Distribution of BR quanta emitted by the target is determined by the spatial and energy distribution of the electrons in the beam incident on the target, the atomic number of the target material and its thickness. Typically, the target is made of tungsten or tantalum possessing high thermal properties.

The target thickness-dependent BR emission is extreme. The optimal thickness of the betatron target is typically chosen considering the acceleration energy and by the criterion of the maximum dose. However, the use of target optimum thickness is limited since the targets in serial accelerating chambers are of a specified thickness.

Therefore, the targets of the same thickness are commonly used for different betatron acceleration energies. For example, the tantalum target with a thickness of 0.6 mm is used for an electron energy range of 4–9 MeV. However, for electron beams with high current density which are obtained in linear accelerators, the thickness of the targets is a small part of the electron path in the target material. In this respect, the simulation was performed for tantalum targets of two thicknesses: 0.05 mm and 0.6 mm, the accelerated electron energy being 6 MeV. The PCLab software was used for simulation [4].

The calculation model: a plane-parallel monoenergetic beam with a normal distribution along one of the directions mutually perpendicular and normal to the beam axis (axis X) (figure 1) and uniform distribution along the other direction (axis Y) falls along the normal to the plane target surface, and the number of BR quanta is determined depending on the coordinates of their emission by the target, outgoing direction with respect to the normal to the surface and photon energy.
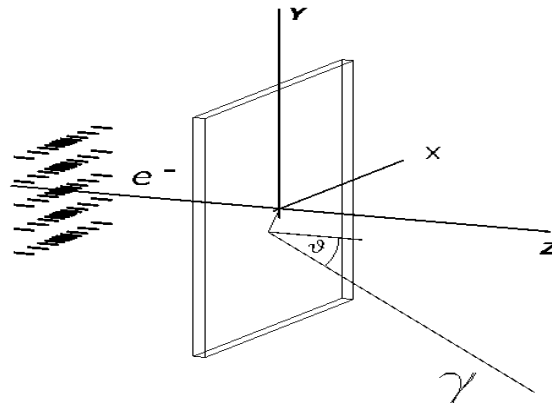

Figure 1. Simulation geometry.

Since the properties of BR by the target exposed to the electron beam with normal distribution are determined by the total contribution of the spot electron beams, the calculated angular and energy distributions of BR for these beams were calculated.

3. Results and Discussion

Increase in the target thickness results in broadening of the BR angular distribution (figure 2) followed by the reduction of the relative contribution of high-energy BR in the spectrum (figure 3). Decrease in the emission angles is followed by the increase in the contribution of high-energy BR. High-energy BR is emitted by the target at small angles to the normal, and as the target thickness reduces, the relative yield of high-energy quanta increases.

The estimated quantum distributions on the target surface are well approximated by the normal distributions for both thin and thick targets (figures 4 and 5) with the dispersion of the thin target equal

to the dispersion of the electron distribution in the beam. The coincidence of the spatial quantum distributions on the thin target surface with the normal distribution of the electrons in the beam can be observed in the entire range of the angles of the quantum emission relative to the normal and in all the energy ranges.
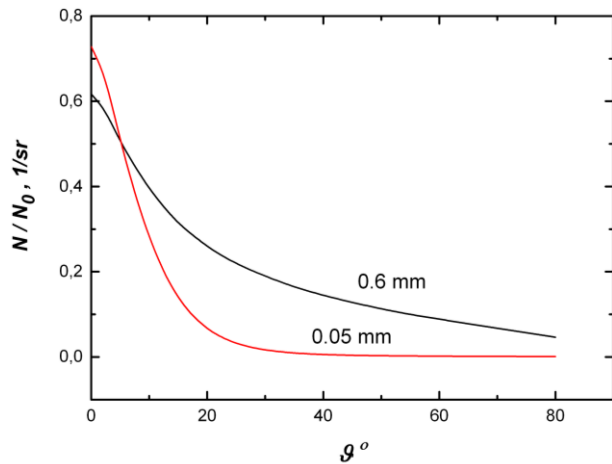

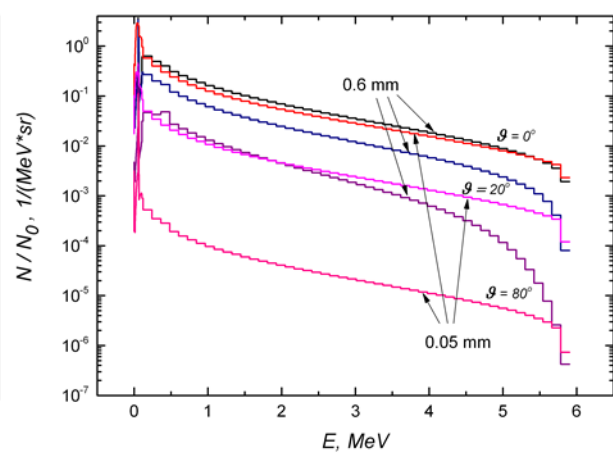**Figure 2**. Angular distributions of the BR emitted from the thick and thin targets.

Figure 3. Energy distributions of the BR emitted from the thick and thin targets at angles of 0°, 20°, 80°.

This indicates that the focal spots of all quanta are similar irrespective of the energy and emission angles, and the spatial distribution of BR in the focal spot of the thin target is determined by the spatial distribution of incident electrons only.
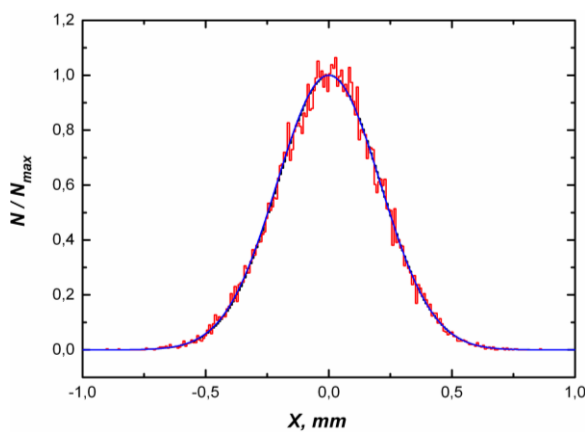

Figure 4. Quantum distribution on a thin target surface (histogram) for normal distribution of electrons in the beam (smooth curve) with a standard deviation of 0.21 mm at the angles of quantum emission by the target relative to the normal within the range of 0–10° and with the energies from 10 keV to 6 MeV.
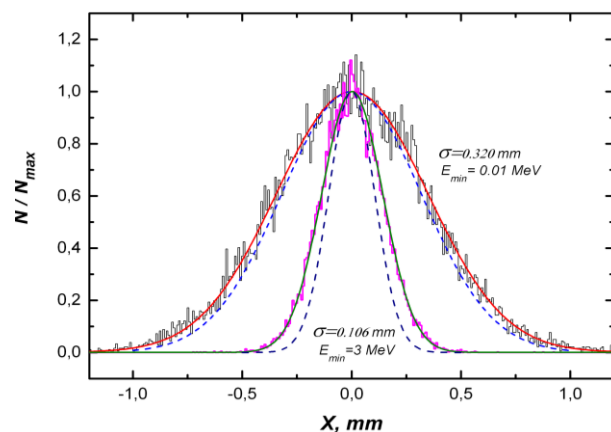
Figure 5. Distributions of quanta with the energies exceeding E_{min} on a thick target surface (histograms and solid curves) for quantum emission by the target at angles within the range of 0–20° under normal distributions of the bombarding electrons (dashed lines) with standard deviations σ.

For the thick target, the quantum distributions on the target surface are different from the electron distributions in the bombarding beam. The distributions depend (figure 5) on both the range of the quantum emission angles relative to the normal and quantum energy, but primarily on the angles of deviation from the normal with narrow distribution of the electrons in the bombarding beam (figure 6).

However, distributions of the quanta emitted by the target along the normal are mainly determined by the bombarding electron distributions. In this case, the smallest deviation of the quantum distributions from the bombarding electron distributions can be observed for the high-energy part of the BR quantum spectrum (figure 7), and the greatest deviations correspond to the narrow distributions of electrons.
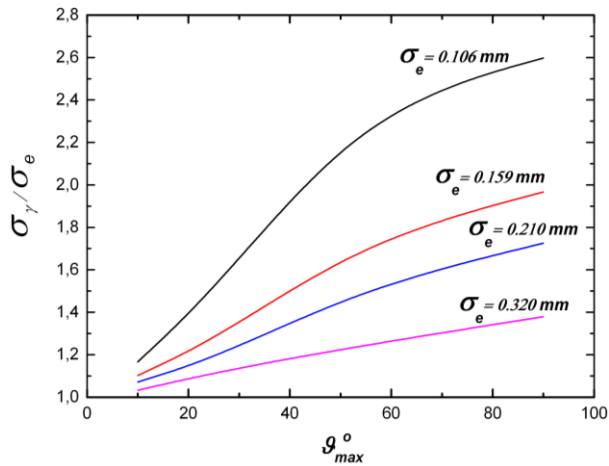

Figure 6. The ratio for standard deviations of quantum distributions σ_γ and bombarding electrons σe depending on the range limit of the emission angles from the target at different σe.
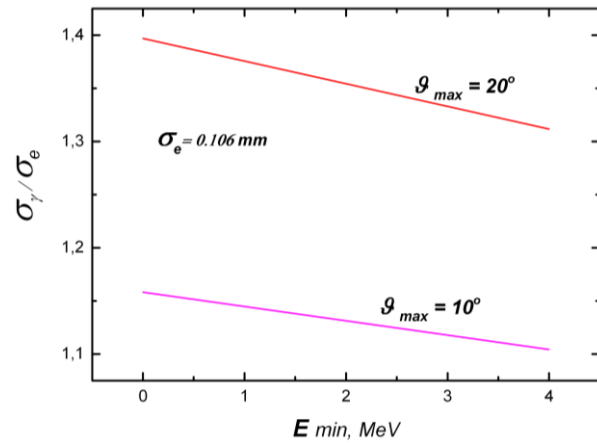
Figure 7. The ratio for standard deviations of distributions of quanta σ_γ emitted by the target at angles ranging from 0 to 10° and from 0 to 20° and bombarding electrons σ_e depending on the range limit value E_{min} of the quantum energy interval (6 –E_{min}) MeV.

The properties of the radiation from the target within small deviations from the beam axis are particularly important for practical application. Figures 8–11 show the examples of the characteristics of BR emitted by thin and thick targets within angles of 0–10° under irradiation of the target by electron beam with standard deviation of the normal distribution σe=0.218. The BR spectra (Figure 8) are normalized to the values at energy of 3 MeV. The relative yield of high-energy quanta from the thin target is greater than that from the thick one.

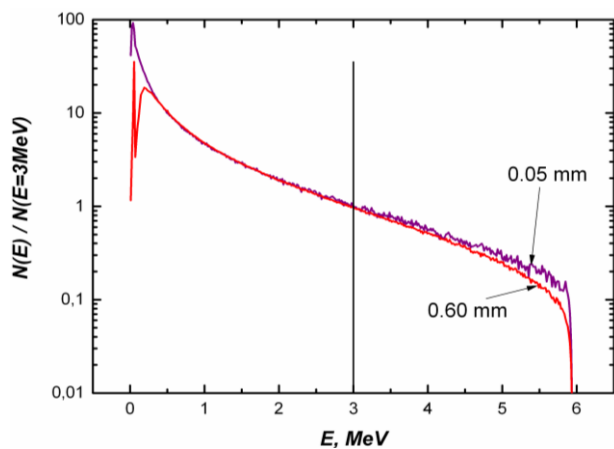Figure 9 shows the spectra of the BR secondary electrons.

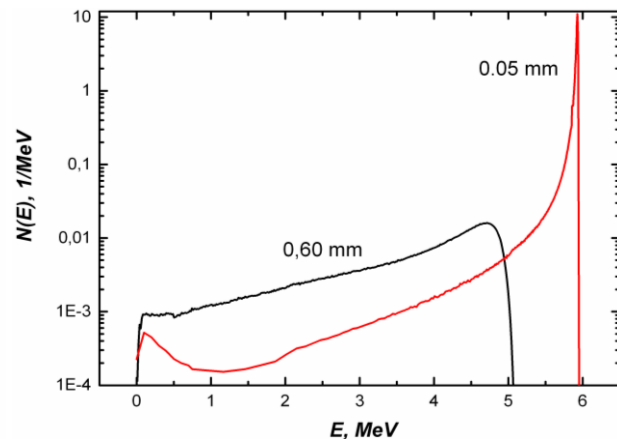**Figure 8**. BR spectra emitted by the targets with a thickness of 0.05 mm and 0.6 mm within 0–10°.

Figure 9. The spectra of the BR secondary electrons emitted by the target with a thickness of 0.05 mm and 0.6 mm within 0–10°.

Angular distributions of BR within 0–10° from the thin and thick targets differ insignificantly (figure 10), and they virtually coincide nearby the beam axis, ϑ=0°. However, the yields of the secondary electrons differ by more than an order of magnitude.

The dispersions of the BR and secondary electron distributions on the surface of the target coincide only for the thin target (figure 11). The dispersion of the distribution of the secondary electrons on the surface of the thick target is much greater than the dispersion of the BR distribution.
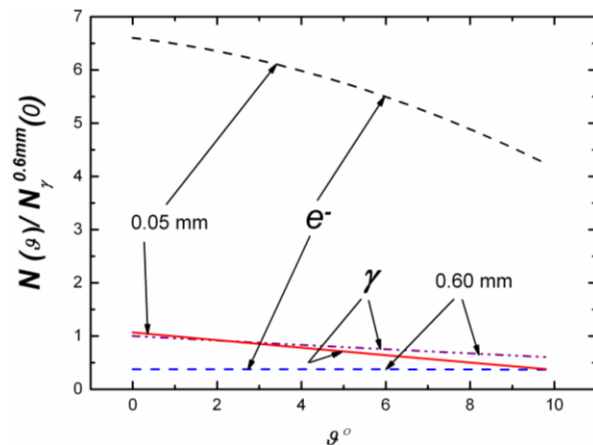

Figure 10. Angular distributions of BR quanta and secondary electrons emitted by the small and large targets within 0–10° normalized to quantum emission by the thick target at an angle of 0°.

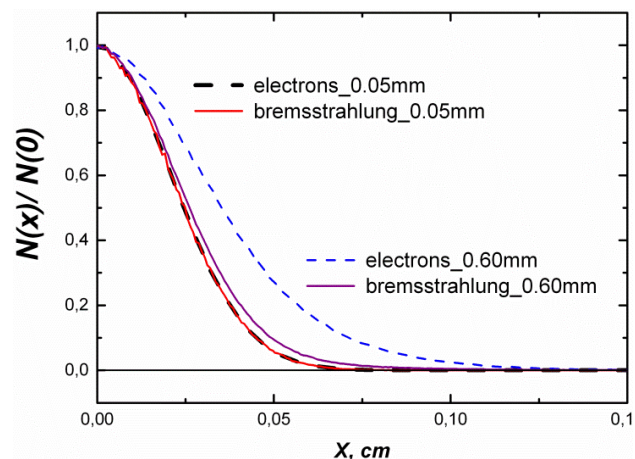**Figure 11**. Distributions of BR and secondary electrons on the surface of the thin and thick targets emitted within 0–10°.

4. Conclusion

The size of the BR focal spot is determined by the quantum distribution on the target surface. Simulation of the spatial BR distributions based of the pattern of normal distribution of electrons over the beam cross-section during acceleration, which is approved for accelerating equipment and experimentally confirmed [5], allows evaluation of the possible focal spot oversize in implementing the techniques which disregard the quantum energy.

The obtained results point out the necessity to implement the techniques for accurate focal spot specification because deviations from the optimal implementation conditions can significantly distort the results. The determination of the effective size of the accelerator BR focal spot based on normal electron distribution in the beam bombarding the target is considered to be promising for development of new techniques.

References

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[3]   Gambaccini M *et al* 2011 *Nuclear Instruments and Methods in Physics Research B*. **269** 1157–1165 DOI: 10.1016/j.nimb.2011.02.089
[4]   Bespalov   V   I   2015   *Software   "Komp'uternaya   Laboratoriya"*   URL http://portal.tpu.ru/SHARED/b/BVI/pclab
[5]   Sorokin V B 2015 *Instruments and Experimental Techniques* **58** (**3**) 395–398 DOI: 10.1134/S0020441215020256