Modeling of the method to determine the bremsstrahlung focal spot size for the accelerator

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Abstract

The method to determine the bremsstrahlung focal spot sizes by introducing wire samples of different diameters into the bremsstrahlung field of the accelerator has been tested by statistical simulation (using the Monte Carlo simulation) in approximation of normal distributions of the bremsstrahlung quanta over the target surface.

Keywords: focal spot, bremsstrahlung.

Introduction

The accelerator bremsstrahlung is used for NDT (non-destructive testing) of the products with great mass thickness [1]. One of the main bremsstrahlung parameters is the focal spot size. The peculiarities of bremsstrahlung distribution impede implementation of direct methods to determine the focal spot sizes. The reliability of the results obtained by the modified versions of the methods used for X-ray radiation [2] is limited due to the impossibility of direct experimental testing. The data on the focal spot size of the accelerator bremsstrahlung [1,3,4] is not provided with a detailed description of the features of method implementation that impedes application of the method.

The research to improve betatrons for tomography is being conducted in the Institute of Non-Destructive Testing, Tomsk Polytechnic University. The need to test new sources of bremsstrahlung and to compare their parameters with the parameters of sources based on linear accelerators requires a reliable and simple method for determining the focal spot size.

1. Simulation of the bremsstrahlung focal spot

The sources of bremsstrahlung based on small-size and relatively inexpensive linear accelerators and betatrons operating at acceleration energy in the range of up to 4–12 MeV are used for NDT.

Bremsstrahlung generation involves electron acceleration, formation of the beam of accelerated electrons towards the target, and interaction of electrons and secondary radiation with the target.

The betatron accelerates electrons along a circular equilibrium orbit 1 (see Figure 1a) in accelerating chamber 2. At the end of acceleration cycle, electrons are deflected by the pulsed magnetic field from the equilibrium orbit along spiral paths 3 and bombard target 4 which is located on injector 5. Bremsstrahlung travels through the vacuum gap from the target to the accelerating chamber wall 2, passes through the accelerating chamber wall and electromagnet space 6 inside the betatron before the bremsstrahlung can be used.

Bremsstrahlung generation in the linear accelerator is relatively simple (see Figure 1b): an axisymmetric beam of the accelerated electrons is focused in the accelerating chamber vacuum onto the target and bremsstrahlung travels from the target immediately into the atmosphere capable of being used at any distance from the target.

When accelerating, electrons are deflected from the equilibrium orbit which is circular in betatrons and straight in linear accelerators. The distribution of the electron current density in the plane normal to the equilibrium orbit is considered to be Gaussian which is consistent with the theoretical and experimental data [5]. In the formation of electron beam towards the target, the parameters of electron distribution in the beam vary, however, the normal type of distribution remains unchanged.
The methods for determining the focal spot sizes are based on introduction of the detector and test objects between the target and the detector into the radiation field, recording of the changes in dose distribution in the detector caused by introduction of the test object, and determination of the focal spot size with regard to changes in dose distribution in the detector. The slot and cylindrical apertures and wire samples are used as test objects.

The degree of coincidence between the real size of the focal spot on the target surface and the size determined through the method implementation is a sufficient criterion of the method validity. The criterion cannot be used in the experiment since the objective of the method implementation is to determine an unknown size.

Radiative transfer simulation based on the data on normal distribution of the accelerated electrons in the beam striking the target enables application of the criterion to assess reliability of the method to determine the bremsstrahlung focal spot size.

In the initial stage of the simulation, bremsstrahlung distributions $\rho_\gamma(x)$ over the target surface under electron beam irradiation with different parameters of normal distributions $\rho_e(x)$ have been studied.

The beam current in betatrons is relatively small, and the greatest dose of bremsstrahlung is achieved by using the targets with optimum thickness corresponding to the electron energy. In practice, a serial sealed-off glass accelerating chamber with a 0.6 mm tantalum target is used within the entire range of electron energies 4–9 MeV. However, thinner targets can be applied for electron beams with high current density generated by linear accelerators.

Therefore, the simulation has been performed for the targets with a thickness of 0.05 mm and 0.6 mm with electron energy $E_{max}$=6 MeV. The number of bremsstrahlung quanta was calculated with respect to the coordinates of the quanta emerging from the target surface, directions of the emerging quanta relative to the normal to the surface and quantum energy with the Monte Carlo method using PCLab programme [6] (see Figure 2).

The estimated quantum distributions over the target surface for both thin and thick targets are well approximated by normal distributions regardless of the quantum energy and angles of quanta emitted by the target.

For the thin target, dispersions of quantum distributions over the target surface are equal to the dispersions of electrons bombarding the target.

The coincidence of quantum spatial distributions over the thin target surface with the normal distributions of electrons in the beam is observed in the entire range of the quantum output angles relative to the normal and in all energy intervals. This indicates that the focal spots of all the quanta regardless of the energy and angles of their emission are equal, and the bremsstrahlung distribution in the focal spot of the thin target is determined by the distribution of bombarding electrons only.

For the thick target, dispersions of quantum distributions over the target surface exceed the distribution dispersions of electrons bombarding the target.

Table 1 lists r.m.s deviations of the electron normal distributions in the beam $\sigma_{ej}$ and FWHM $b_\gamma$ of the normal quantum distributions over the target surface with the target thickness $t$=0.6 mm.

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<tr>
<td>$\sigma_{ej}$, mm</td>
<td>0.159</td>
<td>0.186</td>
<td>0.212</td>
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<tr>
<td>$b_\gamma$, mm</td>
<td>0.3946</td>
<td>0.4597</td>
<td>0.5241</td>
<td>0.6432</td>
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Distributions of bremsstrahlung quanta on the surface of the thick target are different for the quanta emitted in different angular ranges relative to the normal (see Figure 3). The quanta emitted at small angles are generated by the target mainly near the beam axis. Their distribution is insignificantly different from that of the electrons in the beam (see Figure 4). The smaller are the angles of the electron distribution, the stronger is the dependence of the quantum distribution on the emission angles.

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The smaller the angles of quantum emission by the target, the closer are the distributions of the quanta from the high-energy spectral region ($E_{\text{min}}$–$E_{\text{max}}$) to the distribution of the electrons in the beam (see Figures 5,6).
In the spectrum of the bremsstrahlung emitted by the thin target, the portion of high-energy quanta with respect to all the quanta is higher than that in the spectrum of the bremsstrahlung emitted by the thick target (see Figure 7).

The angular distribution of the bremsstrahlung quanta emitted by the thin target is narrower (see Figure 8) than that of the bremsstrahlung quanta emitted by the thick target. The narrowest distribution is observed for the quanta with the highest energy.

2. Method Model

Normal distribution of quanta in the bremsstrahlung focal spot which corresponds to the normal distribution of accelerated electrons in the incident beam makes possible to choose the FWHM of the quanta distribution over the target surface as an effective bremsstrahlung focal spot size.

The schematic of the method for determining the bremsstrahlung focal spot size based on the study of the disturbing effect of wire samples which refers to a more complex betatron pattern of bremsstrahlung generation is shown in Figure 9 (not to scale). The simulation of the radiation transfer through the structure was carried out with the program similar to that used to study the quantum distribution over the target surface.

According to the model, a parallel electron beam with energy $E_{\text{max}}=6$ MeV is directed along the normal to the surface of the tantalum target of thickness. The current density distribution in the electron beam $\rho_e(x)$ along the X axis, normal to the electron motion, is assumed to be Gaussian. The distribution in the direction normal to the X axis is uniform. $\rho_f(x)$ is the distribution of the bremsstrahlung generated by the target.
This model distribution of electrons in the beam agrees with the known estimates of the betatron bremsstrahlung focal spot shape according to which the axial focal spot size is much greater than its radial dimension [3].

During simulation, when emitted by the target, the bremsstrahlung gets free of secondary electrons, travels through a vacuum gap, a barrier made of glass with a thickness of 2 mm, and reaches a detector and a wire platinum sample with a diameter B placed in air at distance L1 from the target. A CdWO₄-based scintillator used as a detector is located at distance L2 from the sample.

Given that the FWHM of the quantum distribution ρ(γ) is taken as an effective focal spot size, and that B << L₁, B << L₂ and B < 1 mm, the geometric size M of the field of the sample perturbing effect on the bremsstrahlung dose recorded by the detector is

\[ M = \frac{M_1 + 2M_2}{L_1}, \quad M_1 = B \frac{L_1 + L_2}{L_1}, \quad M_2 = b \frac{L_2}{2L_1}. \]

### 3. Testing of the method

To test the method for determining the focal spot size, we determined the coincidence between the parameters of the normal bremsstrahlung distribution ρ(γ) over the target surface under irradiation by electron beams with different parameters of normal distributions ρ₁(γ) obtained in the study of the bremsstrahlung quantum distribution over the target surface and the parameters of the bremsstrahlung quantum distribution obtained from changes in dose distributions in the detector when placing the wire samples in the bremsstrahlung field in simulation of the radiation transfer through the model schematic of the method (see Figure 9).

A typical change of dose distribution in the detector when a wire sample of diameter B placed in the bremsstrahlung field is shown in Figure 10.

The width of the change in the dose distribution in the detector d(B, σ₂) at N=17% when introducing the sample of B diameter under the distribution of the electrons in the beam with the r.m.s deviation σ₂ is the required parameter for method testing.

Figure 10 shows the relationship between the geometric size M of the field of the sample perturbing effect on the bremsstrahlung dose recorded by the detector versus the wire sample diameter B, assuming that b=B, M_*=K*(K-1)*B, K=(L_1+L_2)/L_1 and L_1=L_2=310 mm.

It also shows the dependence of the width of the changes in the dose distribution in the detector d(B, σ₂) at N=17% on the sample diameter B for the target thickness t=0.6 mm under the distribution of electrons in the beam with r.m.s. deviations σ₂ provided in Table 1.

Table 2 shows the abscissa b of the common points of the dependencies M*(B) and d(B, σ₂) and the values of FWHM of the quantum distribution on the target surface summarized in Table 1.

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<td>σ₂, mm</td>
<td>0.159</td>
<td>0.186</td>
<td>0.212</td>
<td>0.265</td>
</tr>
<tr>
<td>b, mm</td>
<td>0.394</td>
<td>0.459</td>
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Figure 11. Illustration of implementation of the method for determining the FWHM of bremsstrahlung distribution in the focal spot.
Relative difference between the widths of the bremsstrahlung distributions over the target surface $b_{\gamma j}$ and the widths of distributions $b_j$ determined through simulation $(b_j - b_{\gamma j}) / b_{\gamma j}$ (see Table 2) in the investigated range $b_{\gamma j}$ does not exceed several percent. That is, the model method for determining the bremsstrahlung focal spot size meets the validation criterion.

## Conclusion

A natural assumption about the normal distribution of the electrons during acceleration and focusing of the electron beam towards the target, and the assumed normal type of quantum distributions in the focal spot on the target surface confirmed by statistical simulation of the radiation transfer in the target material enabled modeling of the method for determining the effective bremsstrahlung focal spot size as the width of quantum distribution over the target surface at half maximum of the distribution.

Testing of statistical simulation of the radiation transfer showed the potential of this method for determining the effective bremsstrahlung focal spot size.

Since the direct experimental verification is not available, the statistical simulation of the radiation transfer is the only technique to test methods for determining the focal spot size and to assess their compliance with the validation criterion.

## References


<table>
<thead>
<tr>
<th>$b_j$, mm</th>
<th>0.418</th>
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<tr>
<td>$(b_j - b_{\gamma j}) / b_{\gamma j}$, %</td>
<td>+2.3</td>
<td>+4.2</td>
<td>+0.36</td>
<td>-0.3</td>
</tr>
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Table 2. Parameters of normal distributions of the bombarding electrons ($\Omega_{\Omega j}$) and bremsstrahlung over the surface of the target with a thickness of 0.6 mm, $(b_{\gamma j})$ and those determined through method modeling $b_j$. 