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Reducing the Size of the Bremsstrahlung Focal Spot in a Small-Size Betatron

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Abstract

Specialized sharp-focus sources of bremsstrahlung are considered to be crucial for high-energy tomography. The quality of the obtained tomograms is closely related to the size of the source, which is typically required to assess the resolution of industrial tomographs. In this paper, we have experimentally investigated the technique to reduce the focal spot size in the betatron through the decreased velocity of electron displacement onto a standard target. The results of the experiment showed that the decreased radial velocity of electron displacement onto the target significantly reduces both the horizontal and vertical dimensions of the focal spot.

Keywords: betatron, focal spot, bremsstrahlung, microfocus radiation, high-energy tomography.

INTRODUCTION

Industrial X-ray tomography is increasingly becoming the main quality control method, the means for optimization of technological solutions, reverse engineering and control of assembly operations in manufacturing sophisticated essential components [1-6]. At the same time, advanced production techniques make these components larger and more complex. For example, additive technologies (Direct Metal Printing and Selective Laser Melting) [7] enable manufacturing components of 500x500x500 mm size with a heterogeneous internal and external structure from high-strength and high-density materials in one technological process. The technology of manufacturing components using composite materials will enable production of sufficiently large components as a unit (helicopter blades, wind turbine blades, constructional load-carrying elements for aircraft, cars, etc.). In the future, these technologies will indisputably take the leading position in high-tech production, which enhances the development of methods and means for quality control of large-size complex components manufactured using advanced technologies.

Today, several dozens of firms and research centers in the USA, Germany, Great Britain, Belgium, Japan, Russia, Italy, China and India produce industrial X-ray tomographs of a wide variety of models for different applications. Most of them are focused on the control of components with surface density of up to 40 g/cm^2. In most of these tomographs, the radiation source is an X-ray tube operating at up to 450 kV with a focal spot of the micron range. To test large-size and high-density components, penetrating radiation generated by these sources is not efficient. Therefore, higher energy radiation sources are required. These sources are charged particle accelerators in the energy range of 1-10 MeV – linear accelerators, betatrons and microtrons. However, only linear accelerators and betatrons find practical application [8, 9].

Despite significant progress in the field of X-ray industrial tomography, no advances of the kind have been observed in high-energy tomography for more than 30 years. The causes of stagnation in this area are of physical nature, and these have been relevant since the development of the local tomography method [10]. The main deterrent is the absence of specialized tomographic radiation sources. As shown in [9], the main characteristics of the radiation source for industrial tomography are the energy of accelerated electrons, the size of the effective focal spot, and the power of the beam incident on the target. These three parameters can be expressed in terms of the classical parameter of radiation sources – radiation source brilliance. The brilliance of the source can be found as [11]:

$$briliance = \frac{photons}{second \cdot mrad^2 \cdot mm^2 \cdot 0{,}1\%BW}$$

and it depends on:

- the number of photons emitted from the target per time unit;

- angular distribution of photons;

- the size of the photon exit area (the size of the effective focal spot);

- the width of the radiation spectrum..

The higher the brilliance, the more photons provide valuable information, the higher the parameters of the X-ray tomograph as a whole. In this paper, we experimentally show the technique to increase the brilliance of a high-energy source based on a small betatron [12].

The main techniques to obtain brighter radiation sources based on the betatron at specified maximum energy of accelerated electrons are:

- increased average accelerated electron current;

- reduced size of the focal spot.

The first technique is implemented in high-current betatrons [13]. However, the technical solutions employed to develop these betatrons significantly increase the mass and dimensions of the accelerator that is unacceptable for small-size betatrons. In these betatrons, the average accelerated current cannot be significantly increased. It can be performed mainly through the increased acceleration pulse repetition rate per time unit. Currently, the maximum frequency of 400 Hz is limited to thermal loads in the elements of the betatron electromagnet.

A reduced size of the focal spot in a small-size betatron is of particular interest since it allows the most economical way to increase its brightness. The size of an effective focal spot in the betatron can be reduced through dumping electrons onto a target of small size. In this case, the target size is smaller than that of the accelerated electron beam, and it affects the size of the bremsstrahlung focal spot [14, 15]. It should be noted that this technique to increase the radiation source brightness can be employed only in cyclic accelerators, which implement a multi-turn (more than 1000 revolutions) mode of electron dumping onto the target. An appropriately chosen displacement mode causes electrons gradually fall onto the target. As a result, the average electron current on the small-size target is maintained.

In this paper, another technique to reduce the betatron focal spot size has been experimentally investigated. This technique implies a decreased velocity of electron displacement onto a standard target. In this case, the size of the target is larger than that of the electron beam. The description of the experiment and assessment of the effectiveness of the proposed solutions are given below.

MATERIALS AND METHODS

The study was carried out using a small-size mass-produced betatron MIB-4 with the rated kinetic energy of accelerated electrons equal to 3.5 MeV. This betatron is equipped with a sealed acceleration chamber, which does not need additional means to maintain the working vacuum. The electrons are injected into the acceleration chamber of the betatron with initial energy of 40 keV and are accelerated to the rated energy (Fig. 1).

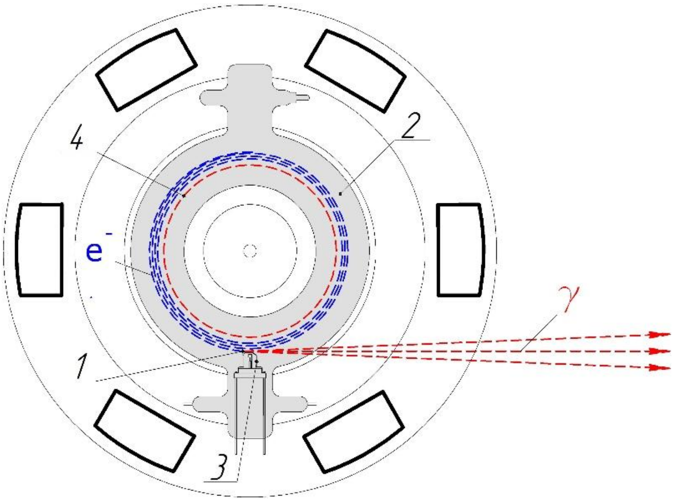

Figure 1: The scheme of the experimental setup: target (1), acceleration chamber (2), injector anode (3), equilibrium acceleration radius (4).

At the end of the acceleration cycle, the system of the orbit expansion increases the magnetic flux in the equilibrium orbit circle to make it sufficient for an increase in the electron orbit radius from the radius of the equilibrium orbit up to that of the target by means of the central winding. The rate of increment in the magnetic flux in the equilibrium orbit circle affects the radial velocity of the electron displacement onto the target. A tantalum target 12 mm high, 1.6 mm wide and 0.6 mm thick fixed on the injector anode is mounted in the acceleration chamber of the betatron. Upon reaching the target, electrons generate high-energy bremsstrahlung. The target surface area, on which the electron beam falls, determines the dimensions of the focal spot generated by bremsstrahlung. According to the form for the betatron MIB-4, the maximum vertical dimension of the focal spot is 3mm and the horizontal one is 0.3mm. The proposed characteristics show that the geometric dimensions of the target considerably exceed those of the focal spot. In this case, the vertical dimension of the focal spot is similar to that of the electron beam cross section, and the horizontal dimension depends on the radial velocity of the orbit expansion. Therefore, changes in the radial velocity of the orbit expansion can affect the horizontal dimension of the focal spot.

To verify this assumption, relative measurements of the focal spot dimensions of the betatron MIB-4 were performed at the accelerated electron energies of 1 MeV, 2 MeV, and 3.5 MeV. Two control points for each energy value were used to estimate the effect of radial velocity of the orbit expansion on the focal spot size.

The changes in the focal spot dimensions were estimated based on the lead lens (pinhole camera) principle [13]. The scheme of the experiment is shown in Fig. 2.

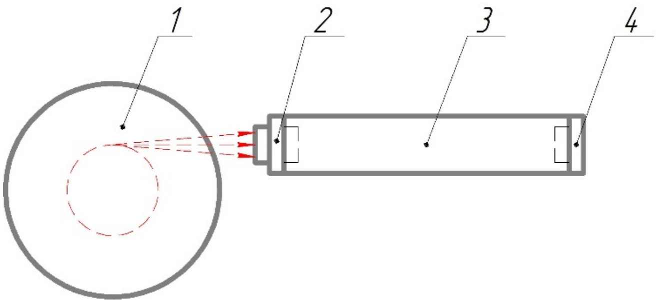

Figure 2: Scheme of the experiment: betatron (1), pinhole camera (2), lead shield (3), cassette with an X-ray film (4).

Bremsstrahlung from the betatron target was directed into the lead lens with a hole to obtain a focal spot image on the film. The lens and film were reliably protected against secondary radiation by lead shields. All the images were obtained with a single dose.

A detailed measurement scheme is shown in Fig. 3. The diameter of the hole in the chamber is denoted as $d = 0{,}1\ mm$. The distance from the backside of the camera to the source plane and the image on the screen are indicated as $A = 20\ mm$ and $B = 40\ mm$, respectively. In this case, the geometric growth is found as $M = B/A = 2$. Due to the geometric construction of the ray path through the hole, the ratio between the spot size of the source and that on the image can be written as:

$$D_0 = \frac{D}{M} - \left(1 + \frac{1}{M}\right) d, \qquad (1)$$

where D_0 and D are the true size of the source spot and the resulting spot on the image, respectively. It should be noted that the dimensions indicated in equation (1) actually denote the edge boundary. In practice, the light from the source is spatially distributed, and the boundary of distribution is probably not clear. These conditions can be neglected when measuring the relative dimensions of the focal spot. The size of the focal spot can be easily calculated using the formula $D_0 = D/M$. In the experiment, the resulting spot image is projected both horizontally and vertically.

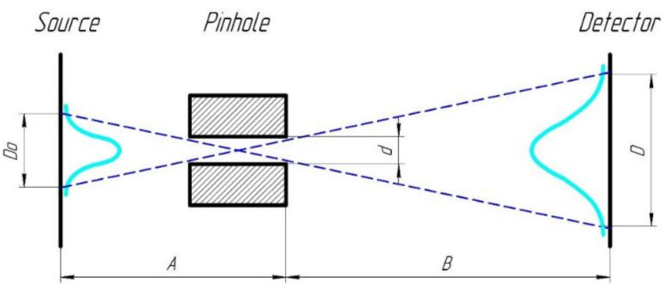

Figure 3: Measuring the spot size using the pinhole camera.

The obtained images of the focal spots were scanned at a resolution of 2400 dpi and then analyzed. Since no reliable technique for measuring the focal spot size based on the lead lens principle is available, the change in the focal spot size was estimated in relative units.

RESULTS AND DISCUSSION

The experimental results are shown in Figures 3-10. The graphs are normalized dependencies of the film blackening density on the horizontal and vertical coordinates. The coordinates with the maximum blackening density are taken as a zero spatial coordinate.

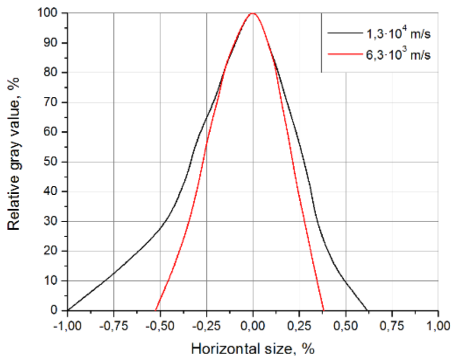

Figure 4: Energy 1 MeV.

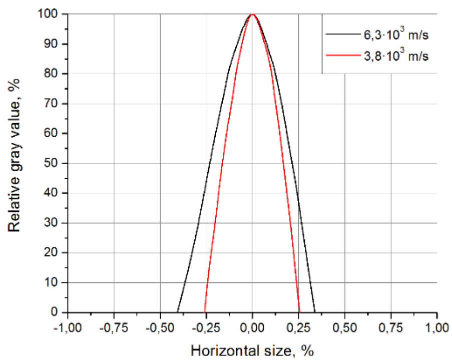

Figure 5: Energy 2 MeV.

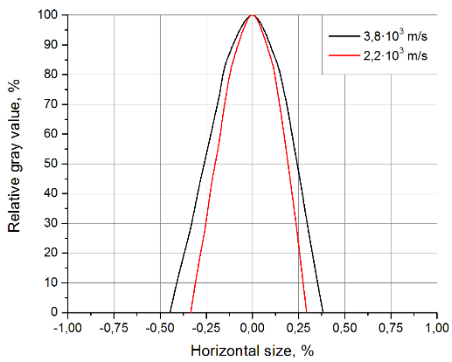

Figure 6: Energy 3.5 MeV.

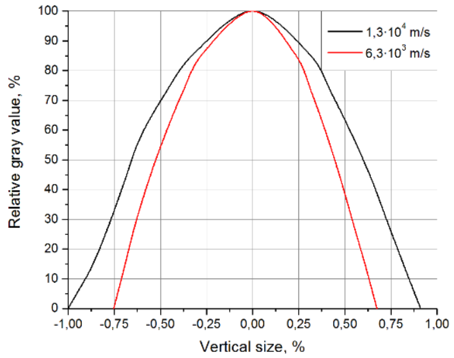

Figure 7: Energy 1 MeV.

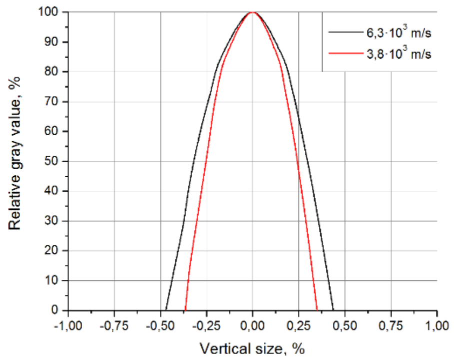

Figure 8: Energy 2 MeV.

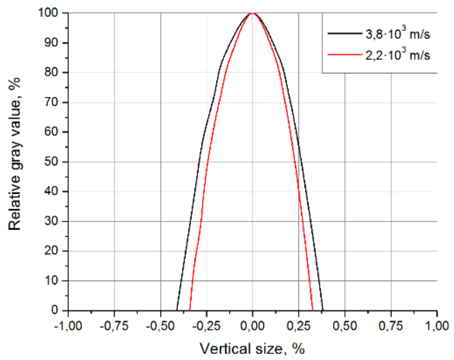

Figure 9: Energy 3.5 MeV.

Figures 4-9 clearly shows that as the radial velocity of the orbit expansion decreases, the focal spot size reduces to 0.75-0.8 of its initial size both in the horizontal and vertical dimensions. Thus, the change in the orbit expansion velocity affects not only the horizontal dimension of the focal spot, but also the vertical one. If we do not take into account the change in the angular distribution of the photons, the maximum increase in the radiation source brightness caused by reduced dimensions in both directions is $(1/0.75)\cdot(1/0.75) = 1.8$ times.

Figures 9 and 10 show the comparison of the horizontal and vertical dimensions of the focal spot at energies of 1 MeV and 2 MeV at identical radial velocity of the orbit expansion.

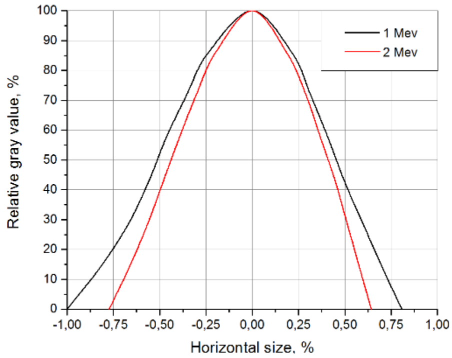

Figure 10: Orbit expansion velocity.

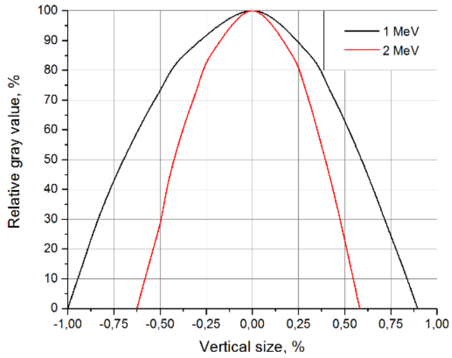

Figure 11: Orbit expansion.

$v_R = 6.3\cdot10^3$ m/s $\qquad v_R = 6.3\cdot10^3$ m/s

The transverse size of the betatron electron beam is determined by the amplitude of the betatron oscillations. The higher the focusing forces of the magnetic field, the smaller the oscillations. The increased energy of accelerated electrons results in increased focusing forces of the magnetic field. This leads to the decreased size of the focal spot. The change in the vertical dimension of the focal spot is especially significant. The horizontal dimension mostly depends on the radial velocity of the orbit expansion. In case the velocity remains unchanged, the changes in the horizontal dimension due to an increased amount of energy are insignificant. At the energy above 2 MeV, the accelerated electron beam is sufficiently compressed, and its cross section and, therefore, the vertical dimension of the focal spot, are negligibly reduced.

CONCLUSIONS

In this study, one of the possible techniques to modernize a betatron-based source has been shown experimentally. Although the betatron is significantly inferior to the linear accelerator in generation of photons per time unit (average accelerated current), it can easily compete with the accelerator in tomographic applications due to the small focal spot size. The main betatron characteristic necessary for tomographic application is the radiation source brilliance. With respect to this characteristic, betatrons are currently approaching to the sources based on linear accelerators.

Since the system of electron displacement onto the target used in the study could operate only in two modes – the regular displacement velocity and the reduced one – different changes in the focal spot size were observed at different energies. A new displacement system is required to switch operatively the modes of electron dumping onto the target. This will enable the development of the source with a programmable size of the focal spot that does not depend on the energy of accelerated electrons.

It should be noted that industrial high-energy tomography is a unique method affordable only to large companies and research centers. The attempts to develop this method and expand its application are still underway. No doubt, advances in this field are mainly due to the development of high-energy radiation sources, betatrons and linear accelerators. Physical parameters of the cyclic accelerator, betatron, enable the developers to improve its characteristics for tomographic applications.

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