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Received: *December 7, 2017*
Revised: *April 2, 2018*
Accepted: *April 24, 2018*
Published: *May 8, 2018*

XII International Symposium on Radiation from Relativistic Electrons
in Periodic Structures — RREPS-17
18–22 September, 2017
DESY, Hamburg, Germany

2018 JINST 13 C05004

Generation of X-rays by electrons recycling through thin internal targets of cyclic accelerators

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Abstract: The use of thin ($< 10^{-3}$ radiation length) internal targets in cyclic accelerators leads to multiple passes (recycling effect) of electrons through them. The multiplicity of electron passes (M) is determined by the electron energy, accelerator parameters, the thickness, structure and material of a target and leads to an increase in the effective target thickness and the efficiency of radiation generation. The increase of M leads to the increase in the emittance of electron beams which can change the characteristics of radiation processes. The experimental results obtained using the Tomsk synchrotron and betatron showed the possibility of increasing the yield and brightness of coherent X-rays generated by the electrons passing (recycling) through thin crystals and periodic multilayers placed into the chambers of accelerators, when the recycling effect did not influence on the spectral and angular characteristics of generated X-rays.

Keywords: Beam dynamics; Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Interaction of radiation with matter; X-ray generators and sources

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https://doi.org/10.1088/1748-0221/13/05/C05004

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1 Introduction

The study conducted using the Tomsk synchrotron [1] have shown that the multiple passes (recycling) of accelerated electrons through thin internal amorphous targets increase the Bremsstrahlung (Bs) yield and the width of angular distribution of Bs due to the increase in the emittance of electron beams, which is a negative factor for some physical experiments, such as the study of effects connected with the generation of radiation in crystal and periodic radiators.

This article shows the possibility of increasing the yield and brightness of coherent X-rays generated by the electrons recycling through thin crystals and periodic multilayers placed into the chambers of the synchrotron and betatron. The recycling effect does not influence on the characteristics of generated X-rays when the multiplicity M of passes is varied from $M = 1$ (single pass) to $M \gg 1$ (recirculation).

2 Tomsk synchrotron studies

The general arrangement of the experiments using the Tomsk synchrotron is shown in figure 1.

The experiments were performed for the energy of accelerated electrons E_0 = 300–900 MeV [2, 3]. The internal targets (T) were placed in the goniometer head inside the equilibrium electron orbit at a distance of 65 mm from it. The accelerated electrons were dumped on the target by means of reducing the amplitude of accelerating voltage. When electrons pass through the target, some electrons generate Bremsstrahlung, lose a significant amount of energy and stop recycling. The other electrons which lost some energy due to ionization and subjected to the Coulomb scattering can pass through the target again. The criterion for a single pass is when the measured values of radiation losses (W) at the full solid angle and the form of the angular distribution of Bremsstrahlung are in good agreement with the calculated results [1].

The angular divergence of the electron beam was about 0.3 mrad, the energy dispersion was about 0.5%, and the pulse duration of electron dump on the internal target was 20 ms. The radiation losses W_e were recorded by a Gauss quantometer (Q) and normalized using the data of an induction sensor (I), which measured the number N_e of accelerated electrons, with an error of about 3% ($W = W_e/N_e$). A scraper (S) was a 10 mm lead plate placed on the opposite side of the synchrotron

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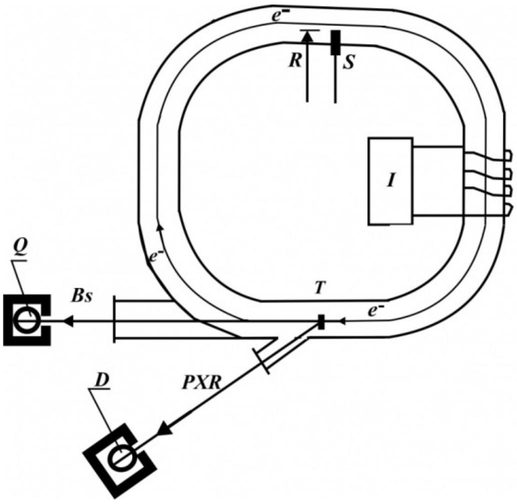

Figure 1. Experimental arrangement: T — target, Q — Gauss quantometer, D — NaI γ-spectrometer, S — scraper, I — inductive device.

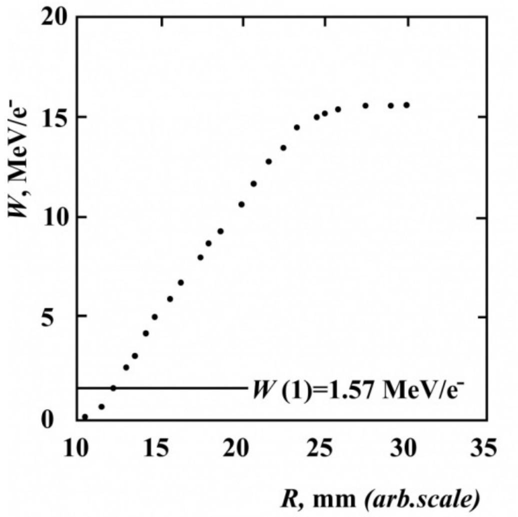

Figure 2. "Scraper curve" — the energy loss of 900-MeV electrons in a 163-µm-thick Si crystal as a function of scraper position R.

ring. When the scraper moved perpendicularly to the electron orbit with a step of 0.25 mm, some electrons passing through the internal target were separated. The "scraper curve" was determined as a function of the normalized data W, depending on the radial position (R) of the scraper. Figure 2 shows the radiative losses of 900-MeV electrons in a 163 µm silicon crystal versus the radial position of the scraper. Figure 2 demonstrates the growth of the radiation losses of electrons up to the value $W_{\max} = 16$ MeV/e. The ratio between the experimental value $W_{\max}$ and value W_1 calculated for a single pass of electron through a target determines the actual coefficient of the maximum multiplicity achieved in this case: $M = W_{\max}/W_1 \sim 10$. Using this method, the authors also determined a coefficient M for other targets. The coefficient M was equal to approximately 20 for a 48 µm Si crystal, 46 for a 12 µm Mylar film and 23 for a target consisting of ten 10 µm Mylar films separated by the intervals of 52 µm. It should be noted that the last target was designed to investigate the resonance X-ray transition radiation (RTR) [2]. To verify the assumptions that the multiple passes due to the integration of the multiple-scattering angle can lead to the degradation of spectral and angular characteristics of RTR and parametric X-rays (PXR), we conducted the comparative measurements of the RTR and PXR characteristics for the coefficients $M = 1$ and $M = M_{\max}$ [2].

The spectral and angular characteristics of PXR were measured at the energy of the accelerated electrons $E_0 = 800$ MeV and orientation of a 48 µm (110) Si crystal at the angle $\theta_0 = 9°6'$ with respect to the electron beam. The detector position was $\theta_D = 2\theta_0 = 18°12'$ (Bragg condition) with respect to the electron beam. The PXR spectra were measured using the gamma spectrometer based on the NaI(Tl) detector with a crystal 1 mm in thickness. The energy resolution was about 40% on the line of isotope Co^{60} — 14.6 keV and 20% on the line 59.6 keV. The detection threshold was about 7 keV. The statistical errors of measurements of the spectra and orientation dependences of PXR were about 1.5% and 25% for the maxima and "wings" of the peaks. The spectra of PXR generated at the angle $\theta_0 = 9°6'$ and 10–30 keV PXR yield dependences on the crystal orientation

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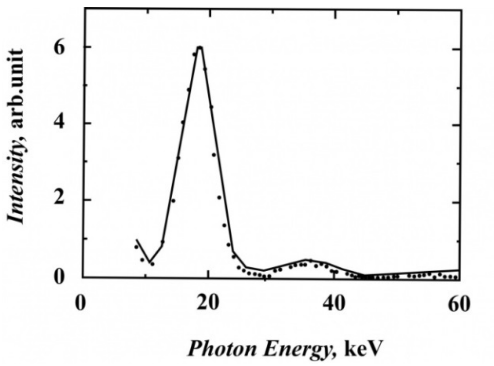

Figure 3. Normalized PXR spectra measured at the angle $\theta_0 = 9°6'$ and $M = 1$, dots, and $M = 20$, curve.

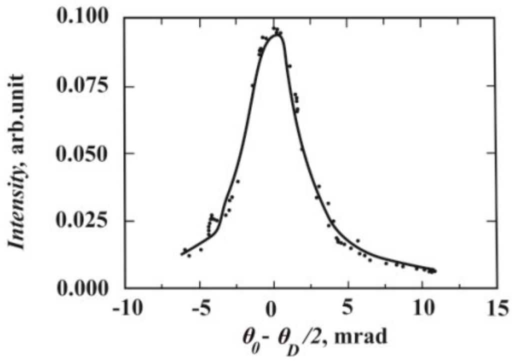

Figure 4. Normalized yields of 10–30 keV photons of PXR versus crystal orientation θ measured at $M = 1$, dots, and $M = 20$, curve.

θ relative to $\theta_0 = 9°6'$ were measured for the modes with $M = 1$ and 20. The obtained spectra and orientation dependences were normalized to their maxima. This made it possible to superimpose one spectrum or orientation dependence with another in order to compare their forms and widths. The normalized curves presented in figures 3 and 4 demonstrate that the transition from the measuring mode with $M = 1$ to the measuring mode with $M = 20$, does not change the angular and spectral properties of PXR, although the measured value M increases by 20 times. This means that the multiple passes of the electron beam through internal crystalline radiator sharply increase the PXR yield (photons/electrons) and also the PXR brightness (photons/electron/keV/sr) due to the effect of conservation of the width and form of angular distribution and spectrum of generated PXR and also due to increasing the electron current through the target because of increasing the number of electron passes to $M = 20$.

In the case of a multifoil radiator only the investigation of the influence of multipass effect on the angular distribution of RTR was carried out because the experiments at synchrotron were mainly aimed to investigation of PXR generated by multipass electrons. When measuring the characteristics of RTR, the energy of accelerated electrons was $E_0 = 900$ MeV. The target was a stack of ten 10 μm Mylar films, separated by the intervals of 52 μm. We have compared the measured angular distributions of X-ray RTR generated in the target at single and multiple passes of electrons. The images of angular distributions obtained with X-ray films demonstrated the rings of intensity with radii of about 3γ, where γ is the relativistic factor of electron. X-ray images were processed with a scanner to obtain the profiles of distributions. It was found that the observed distributions of RTR from the 10 Mylar films target did not show a marked difference between those generated at multiple passes and those generated at single pass of electrons. It means that the yield and angular density of RTR increased in about 23 times at increasing the number of electron passes to $M = 23$.

At the same time, X-rays from transition radiators placed inside an electron storage ring (Saskatchewan Accelerator Laboratory) were investigated in more detail when 118–252 MeV electrons passed through 0.18–9 μm C, Al, Cu, Ta single- and multi-layer radiators many times [4]. The electron beam lifetime in the storage ring was measured and used to determine the number of electron passes through a radiator. Multiple passes were observed between 5 and 385, which contributed to the increase in the radiator efficiency. The total output power of transition radiation

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was comparable to that of multi-layer radiators made of the same material. Thus, for this range of parameters, the number of foils and passes was constant. The work [4] notes that the results obtained in Saskatchewan are in good agreement with those obtained in Tomsk. But, PXR generation by multipass electrons was not studied.

In the case of low energy compact synchrotron the method of generation of high brilliance hard X-rays by repeated use of electron beam was proposed in [5]. Theoretical analyses showed that the brilliance of the source based on a 50 MeV electron storage ring with a thin wire target inside exceeds that of synchrotron light sources in the X-rays region. Later, a number of low-energy electron storage rings (MIRRORCLE - 20, - 6 and - 4) consisted of microtron injectors and compact storage rings were developed and a series of experimental investigations of Bs and TR generations by 20, 6 and 4 MeV electrons were done [6]. For example, the transition radiation mechanism was studied using a target of 385 nm aluminum foil placed in the chamber of the tabletop synchrotron MIRRORCLE-6X to generate soft X-rays when the mode of multiple passes of fast electrons took place when the transition radiation is generated in the target [7]. The authors expected that the power of soft X-rays increased due to introducing the target into the storage ring to apply it as a source for X-ray lithography [8]. Using the Al and Sn targets in MIRRORCLE-6X, they could observe soft X-rays with the presence of transition radiation in the form of specific angular distributions, but the changes in the width of angular distribution and the spectrum of radiation with the increased number of electron passages through the radiator were not studied. Other effective applications of radiations generated by the tabletop synchrotrons are also described in [6]. But, our investigations of PXR generation by multipass electrons in crystals and multilayers are mainly aimed to the creation of portable, tunable source of microfocus X-rays on the base of compact and non expensive betatrons.

3 Betatron B-35 studies

The experimental arrangement developed for experiments [9–12] on the basis of the B-35 betatron (1) is shown in figure 5. The electrons accelerated in a special experimental chamber (2) to the desired energy are dumped onto an internal radiator (3) by an additional magnetic field of 30 µs duration, which increases the radius of the equilibrium orbit of the electrons so that the

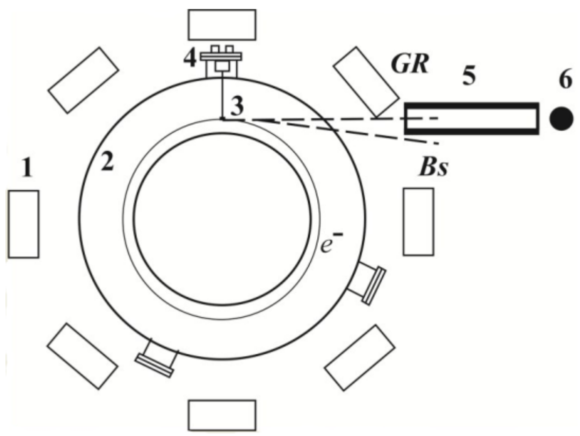

Figure 5. Scheme of the experimental setup.

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electrons reach of the radiator mounted in the goniometer (4) inside the chamber with the control of the radiator orientation from the outside. If the radiator is thin enough the electrons can pass through the radiator many times, resulting in both increased emission and increased electron-beam emittance. The repetition frequency of acceleration cycles is 50 Hz, the divergence of the electron beam moving to the radiator is about 0.3 mrad, and the energy distribution is about 0.5%. Radiation generated (GR) in the radiator passes through the 50 μm Mylar windows of B-35 chamber and of the vacuum channel (5) and is supplied to the Si detector (6) located at a distance of 150 cm from the radiator. The detector aperture is 13 mm^2, the resolution in the line Am (13.95 keV) is 250 eV.

The angle θ_D between the vacuum channel and the direction of the electron beam moving to the radiator (or the direction of the cone axis of Bs) is changed in the range of 0–20°; the azimuthal position of the radiator is changed in the chamber of the betatron using a goniometer. To measure the spectrum in different parts of the radiation cone, the Si detector can be smoothly moved perpendicular to the axis of the radiation cone using a special device. The statistical errors of measurements of the spectra of PXR were about 5% for the maxima of spectral peaks.

The experiments [9, 10] conducted to generate Bremsstrahlung (Bs) by the 33 MeV internal beam of the betatron B-35 in thin foils from Mylar, beryllium, copper and tungsten confirmed that electrons can pass hundreds of times through foils with a micron thickness, table 1, so the angular density of hard Bs becomes close to the radiation density of Bs from thick tungsten radiator used in ordinary betatrons B-35. The numbers M of 33 MeV electron passes were estimated using three methods. We compared the experimental angular distributions and maximum densities of Bs generated in thin internal targets and theoretical ones calculated for a number of thick targets. For example, better agreement was between the experimental distribution of Bs generated by 33 MeV multipass electrons in a 20 μm Be target and theoretical one obtained for a 4 mm Be target at single pass. The FWHM of the theoretical distribution is 2.24°, while the measured FWHM is about 2.3°. If we assume that the total target thickness passed by the electrons, either on many passes through the thin target or on one pass through the thick target, is equal, then the mean number of electron passes is approximately 200 for the 20 μm Be target. Similar approach of estimation of the number of electron passes was used also in the case of comparison of experimental and theoretical angular densities of radiation generated in thin and thick targets by multi- and one-pass electrons, respectively. At last, the number of electron passes through a 3 μm Mylar target was sufficient to partially melt. The estimated electron-beam current necessary to melt this target is about 5–10 μA. Therefore, one can roughly estimate that the mean number of electron passes through the target was about 250–500 because the number of electrons accelerated per second was about $1.25 \cdot 10^{11}$.

Table 1. The numbers M of 33 MeV electron passes estimated using three methods.

Foils (mm^2)	t, μm	Number M of 33 MeV electron passes estimated		
		Using the FWHM of Bs cone	Using the ratio of angular densities of Bs	Using thermal effects
Be (10 × 20)	20, 60, 200	200, 51 and 18		
Cu (6 × 8)	1		590 (377 at 20 MeV)	
Cu (8 × 38)	5 and 15	> 90 and 30	171	
Mylar (10 × 38)	3		460	250–500
W (8 × 20)	2		123	

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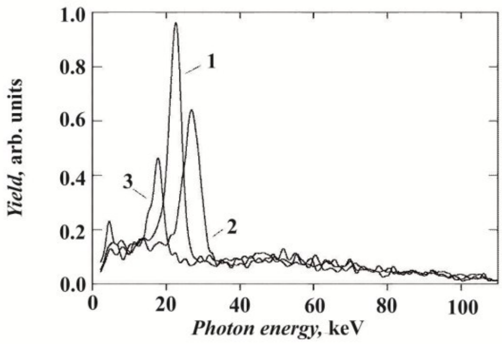

Figure 6. Spectra of PXR generated by 33 MeV electrons in pyrolytic graphite were measured at θ_0 = 4.5°, 3.6°, 5.4°, curves 1–3, respectively.

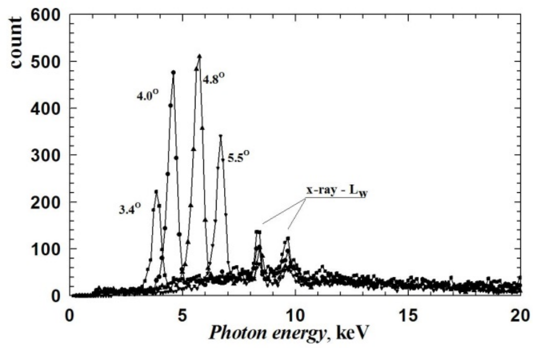

Figure 7. Spectra of PXR generated by 33 MeV electrons in X-ray mirror were measured at θ_0 = 3.4°, 4.0°, 4.8° and 5.5°.

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The used methods of determination of the number M are approximate and can be used only for estimating the M value. But, the M estimations have shown that the value M can be very large.

In the experiments [11] conducted to generate PXR, the silicon and pyrolytic graphite crystals were used in the internal electron beam of the B-35 betatron. These experiments showed that electrons recycling through thin crystals located in the chamber of the betatron could generate intensive and narrow-band PXR emitted in a narrow cone at the Bragg angle in the direction of the electron motion. Figure 6, for example, shows the spectra of PXR measured for the electron energy of 33 MeV, the location angle of the detector θ_D = 9° and the angles of atomic planes (220) in pyrolytic graphite crystal θ_0 = 4.5°, 3.6°, 5.4° with respect to the electron beam, curves 1–3, respectively. The spectra show the expressed peaks which change the position and the intensity, when the deflection angle θ of the radiator is varied. Recirculation of electrons through a crystal insignificantly changes the spectral radiation characteristics.

Figure 7 shows the spectra of PXR generated by the 33 MeV electrons in the X-ray mirror consisted of four hundreds of tungsten and boron carbide layers with the location periods of d = 14.86 Å on the 40 µm Si substrate [12]. The spectra were measured for the detector location angle of θ_D = 9° and the mirror surface angles of θ_0 = 3.4°, 4.0°, 4.8° and 5.5° with respect to the electron beam direction. The spectra show the expressed peaks which change the position (rightward) and the intensity, when increasing the deflection angle θ of the radiator relative to the electron beam. The width of the maximum spectral PXR peak is 0.7 keV at half of the height and the peak contrast (ratio of the peak height to the Bs level) is about 15.

At present, to study the generation of radiation by a recirculating electron beam in periodic structures, the 18, 6, and 4 MeV betatrons are used, since lower electron-beam energies can lead to a more competitive X-ray source. The background conditions, the quality of created structures and the efficiency of beam dump on internal target, the size of which is smaller than the electron beam diameter, are investigated.

The investigations of Bremsstrahlung generated in thin 50 and 8 µm silicon substrates of layered structures [13], which is background for the coherent radiation generated in a layered structure, showed a high background level when the grazing incidence angle of 18 MeV electrons was several degrees. This means that for the low electron energies, the X-ray mirrors should be used at large incidence angles of electrons on the surface of layered structures to decrease the background level. But, in this case, a softer parametric radiation will be generated.

The multilayer structures must be fabricated on the thinnest substrates because the substrates decrease the number of passes through the structures. But, the experiment in [14] showed that there was a problem connected with the quality of structures created on very thin substrates. A study of radiation generated by 5.7 MeV electrons of the extracted microtron beam in a structure consisting of 100 Cr/Sc bi-layers with a period of 2.34 nm deposited onto a 500 nm Si_3N_4 substrate showed that radiation yield was 10 times lower than that calculated theoretically. Probably, this fact can be explained by imperfection of the interfaces between layers and the surface of the thin substrate of the fabricated structure. There is a need in the improvement of the technology for manufacturing multilayer structures on the thinnest substrates.

The task concerning betatrons is to find also conditions for the effective dump of electrons on an internal target in the betatron chamber the size of which is smaller that the electron-beam diameter. The size Δs of the radiation source is an important characteristic of the source, since this size determines the brilliance of radiation. The brilliance (photons/electron/keV/sr/Δs) is proportional to the brilliance (photons/electron/keV/sr) of radiation and inversely proportional to Δs. At the grazing incidence of electron beam onto the surface of a multilayer mirror, the effective width of the multilayer target is proportional to the angle of incidence and the target length along the electron beam and can be smaller than the diameter of the electron beam. But, the work [15] showed that the use of thin silicon and tantalum targets oriented along a beam of 18 MeV electrons lead to the formation of an effective linear microfocus Bremsstrahlung source with unique characteristics. A similar source of parametric X-ray radiation is also formed using a multilayer mirror, since its effective horizontal dimension is proportional to the length of the mirror along the electron beam (a few mm) and the emission angle relative to the surface of the mirror (a few degrees). Therefore, it is also important to reduce the vertical dimension of the multilayer radiator in order to provide a spot-shaped focus of radiation. An experiment conducted using a 6 MeV betatron showed that reducing the vertical size of the target to a size in 6 times smaller than the diameter of the electron beam dropped on the target practically did not change the brightness of generated bremsstrahlung. But, this increased the brilliance of radiation by six times, since the dimension of the focal spot of radiation decreased by six times.

This approach will also be used to increase the brightness of the radiations that are generated in multilayer radiators inside the betatron chamber.

4 Conclusion

The obtained results show that the multiple passes of the electron beam of a cyclic accelerator through periodic radiators (crystals and multilayer structures) can substantially increase not only the radiation yield, but also the brightness of radiation due to the effect of conservation of the widths of angular distributions and spectra of generated radiations at increasing the number of electron passes. Multilayered structures, such as X-ray mirrors, fabricated on the thinnest substrates are most promising for the generation of parametric radiation by a recirculating electron beam because the substrates decrease dramatically the number of passes of electrons through the multilayer target installed inside the betatron chamber.

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At present, the investigation of the multipass effect using the compact 18, 6 and 4 MeV betatrons is aimed on the work out of the best condition for realization of effective source of coherent radiations on this base. The background conditions, the quality of created structures and the efficiency of beam dump on internal target, the size of which is smaller that the electron beam diameter are investigated in order to increase the brilliance of generated radiation.

To increase the brilliance of radiation the size of the target must be smaller than the electron beam cross section. During the electron dump when changing the controlling magnetic field of the betatron the radius of accelerated electron beam is changed, the electron beam is shifted to the small target position and the electrons circulating in the chamber gradually fall on the target due to betatron oscillations thus generating sharp focus radiation. To increase the efficiency of the effect of "condensation" (fallout) of electrons from circulating beam on small targets, a system of "slow dump" of accelerated electrons is created in order to have sufficiently longtime circulation of electrons in the orbit with the target location radius.

Acknowledgments

This work is supported by the Russian Science Foundation, project No. 17-19-01217.

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