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COMPARISON OF X-RAY SOURCES ON THE BASIS OF BREMSSTRAHLUNG AND PARAMETRIC RADIATIONS

A.S. Gogolev, A.P. Potylitsin

Tomsk Polytechnic University
E-mail: alextpuftf@tpu.ru

The comparative analysis of the X-ray tube and source on the basis of parametric X-ray radiation has been carried out. The parametric x-ray radiation intensity of source on the basis of compact linear accelerator with beam energy of 6 MeV and current of 100 μA is compared with intensity of ordinary X-ray tube. The performance of slow change of parametric X-ray line energy in a wide range from 6 to 130 keV with line width of about 300 eV may provide the good contrast of received image and decreases the radiation dose.

Introduction

X-ray sources are widely used for fundamental and applied researches (biology, solid-state physics, microelectronics, medicine etc.). Sources developed on the basis of electron storage rings with energy ~1 GeV for generation of synchrotron radiation (SR) are rather bulky and expensive devices and require significant operating costs as well. X-ray tubes are rather cheaper but do not allow obtaining high resolution, for example, in lithography, medical diagnostics [1] and others.

Recently beams of parametric X-ray radiation (PXR) have been suggested to be used. Its spectral-angular density exceeds one of traditional X-ray sources such as synchrotron radiation and bremsstrahlung as it was shown in [2]. In this case there is no need for using beams of high energy electrons and narrow spectral line may be obtained directly at PXR generation. Dispersion relation [3] connects strictly PXR photon energy with the its outgoin angle that allows obtaining a beam of monochromatic radiation with variable wave length.

At present there are X-ray radiation sources on the basis of PXR in (Nihon University Japan) [4] and laboratories LUE (USA) [1], at electron beams with energy of 100 and 56 MeV, respectively. Average current of the linacs used ~1 mA. Average intensity of a source [4] is $\sim 10^{-1}$ photon/e$^-$/sr, source [1] $\sim 10^{-2}$ photon/e$^-$/sr.

In this paper the characteristics of X-ray radiation source on the basis of PXR from moderate relativistic electrons were compared with X-ray tube. Source on the basis of linac with particle energy of 6 MeV may generate PXR with intensity of $>10^{-5}$ photon/e$^-$/st in narrow spectral range $\Delta\omega/\omega \sim 10^{-2}$ and energy range 6...130 keV. Intensity of ordinary X-ray tube per 100 kV is about 10^{-6} photon/e$^-$/sr.

1. PXR yield

Parametric X-ray radiation refers to a class of polarization radiation the characteristics of which do not depend on initial particle mass and are determined only by its energy and charge. Within the kinematic model PXR mechanism may be considered as a diffraction of the virtual-photons field of moving charge particle on crystal planes [5].

By the moment many experiments on studying PXR properties excited by relativistic electrons have been carried out. It was shown that PXR of relativistic electrons $\gamma>50$ (γ – Lorentz-factor) gives high spectral-angular density in a narrow cone with solution $\sim\gamma^{-1}$ around the direction of mirror reflection [6]. However, in the case of moderate relativistic particles ($\gamma\leq 20$) opening angle of cone in which the main virtual-photons flux is concentrated is rather wide. As a result PXR reflections stipulated by the reflection of virtual-photon initial flux from crystallographic planes give contributions near the reflection direction from the selected (main) surface. This effect was firstly experimentally observed by the authors of the work [7] where a beam of electrons with energies 15,7 and 25,7 MeV was used; correspondingly, cone apex angle amounted to 32 and 19 millirad. The authors registered a contribution from satellite planes in the main peak at the level 1 %.

In 2005 the experiment was carried out at the extracted beam of carbon nuclei with energy of 2,2 GeV/nucleon (γ=3,36) of Nuclotron LHE JINR (Dubna). The purpose was to detect PXR in silicon crystal (001) from heavy charged particles [8]. The contribution from satellite planes in the main peak amounted to the value $\eta\sim 40$ %.

The majority of experimental data in studying PXR properties in crystals is described well by kinematic theory [3] in which photon frequency of PXR is determined by the following dispersion relation:

$$\omega = \frac{\boldsymbol{g}\cdot\boldsymbol{v}}{1-\sqrt{\varepsilon}\,\boldsymbol{n}\cdot\boldsymbol{v}/c} = \frac{2\pi c}{d}\,\frac{\beta\sin(\theta_B)}{1-\sqrt{\varepsilon}\beta\cos(\theta)}, \qquad (1)$$

where $\boldsymbol{g}$ is the reciprocal lattice vector for crystal planes with interplanar spacing $d=a/(h^2+k^2+l^2)^{1/2}$; a is the lattice constant; h, k, l are the Miller indices; $\boldsymbol{v}$ is the particle velocity vector; $\boldsymbol{n}=\boldsymbol{k}/|\boldsymbol{k}|$ is the unit vector in the direction of PXR photon; c is the speed of light; $\varepsilon(\omega)$ is the target dielectric constant; $\beta=|\boldsymbol{v}|/c$, is the Bragg angle (Fig. 1), θ is the observation angle (counted from beam direction).

Angular density of PXR photon yield from thin crystal plate neglecting absorption may be written down in general view [3]:

$$\frac{dN}{d\Omega} = \frac{Z^2\alpha L}{2\pi\hbar c}\sum_{\mathbf{g}}\frac{\omega|\chi_{\mathbf{g}}|^2}{\beta(1-\sqrt{\varepsilon}\,\boldsymbol{n}\cdot\boldsymbol{v}/c)}\times$$
$$\times\sum_i\left[\frac{(\sqrt{\varepsilon}\,\boldsymbol{v}-\boldsymbol{g}\,c/\omega)\cdot\boldsymbol{e}_{\mathbf{k}i}}{(\boldsymbol{k}_g\,c/\omega)^2-1}\right]^2, \qquad (2)$$

where Z is the charge of incident particle; α is the fine structure constant; L is the crystal thickness; $\boldsymbol{e}_{ki}$ is the unit polarization vector; $\boldsymbol{k}_g=\boldsymbol{k}+\boldsymbol{g}$, χ_g is the expansion coefficients of dielectric polarizability; $\hbar$ is the Planck constant; Ω is the solid angle.

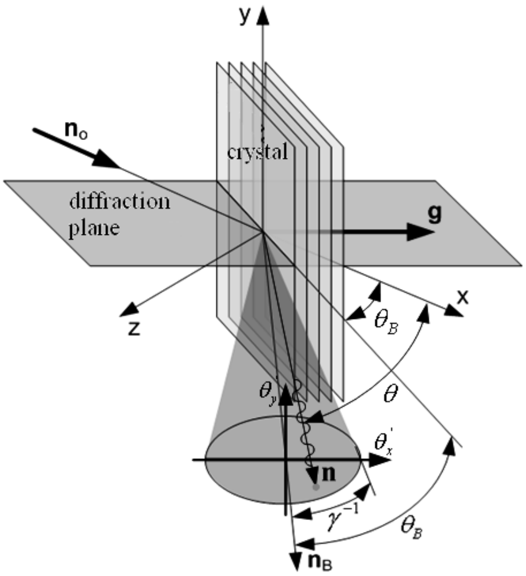

Fig. 1. *Sheme of PXR generation. Non-dash coordinate system is laboratory coordinate system, dashed is detector coordinate system*

In Fig. 1 $\mathbf{n}_B$ is the Bragg direction of PXR reflection, determined by the formula:

$$\mathbf{n}_B = \mathbf{n}_0 - \frac{2(\mathbf{g}\cdot\mathbf{n}_0)}{|\mathbf{g}|^2}\mathbf{g},$$

where is the unit vector in beam direction.

Formula (1) and (2) were used in the simulation basis of PXR generation process; crystal thickness in all cases equaled to 100 µm. Code which allows taking into account influence of such factors as radiation absorption, beam size, divergence, multiple scattering, energy losses and final aperture of detector by Monte-Carlo method was developed. In Fig. 2 the results of simulation in the ideal case for different Lorentz factors from a certain crystal family of silicon crystal planes are shown.

According to kinematic model the PXR main radiation flux in moderate relativistic case is concentrated in a rather wide cone (Fig. 2). Therefore, at a fixed observation angle a detector there may be detected some PXR lines corresponding to various reflections. It is also seen from despersion relation (1) that at fixed observation angles and beam incidence PXR quantum energy from different planes may be close in value if the condition of kinematic grouping is fulfilled:

$$\boldsymbol{g}_i\cdot\boldsymbol{v}\approx\boldsymbol{g}_j\cdot\boldsymbol{v},\ i\neq j. \tag{3}$$

To take into account correctly the contribution from different crystal planes the summation is carried out by a set of vectors $\boldsymbol{g}$ in expression (2).

2. Source of monochromatic radiation with tunable wave length on the basis of PXR

It is possible to show that in a case when moderate relativistic charged particle moves along the axis of type <111> and observation angle is in range θ<90(PXR reflections which give contribution >1 % relative to the strongest in the observation direction satisfy the kinematic grouping conditions (3).

Line position on energy scale in this case is determined by observation angle and does not practically depend on azimuth angle.

Enhancement in this geometry at γ=3 for silicon amounts to 40 % relative to the strongest reflection $(11\bar{1})$ with observation angle of 35° from beam axis that corresponds to angular distribution maximum. Amplification is of the same order that in Bragg geometry [8] however, satellite peaks are lost except the following diffraction orders. For tungsten the angular distribution maximum is around angle of 55° with beam axis and enhancement is 82 %. Satellite peaks are absent as well as for silicon, Fig. 4.

Increasing Lorentz factor the effect of kinematic enhancement decreases owing to narrowing the radiation cone of single reflections. For crystals with face-centered cubic lattice and diamond type lattice enhancement does not exceed 7 % at γ=12. Whereas for crystals with volume-centered cubic lattice enhancement is significant ~80 % at γ=12, Fig. 5.

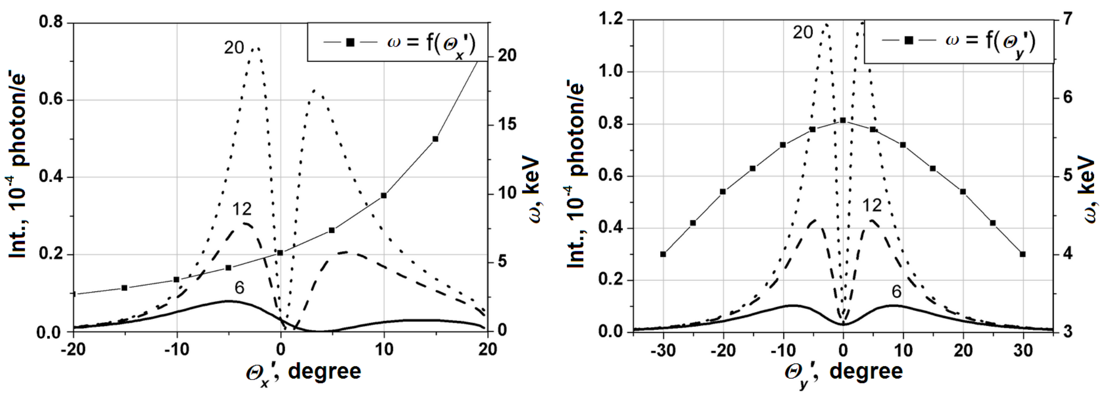

Fig. 2. *The simulation results of PXR angular distribution of reflection (111) from Si crystal (Bragg angle θ_B=20° for different Lorentz factors: —— – 6; – – – – 12; ······ – 20 (neglecting absorption). Curve –■– is the dependence of PXR photon energy on observation angle (right scale)*

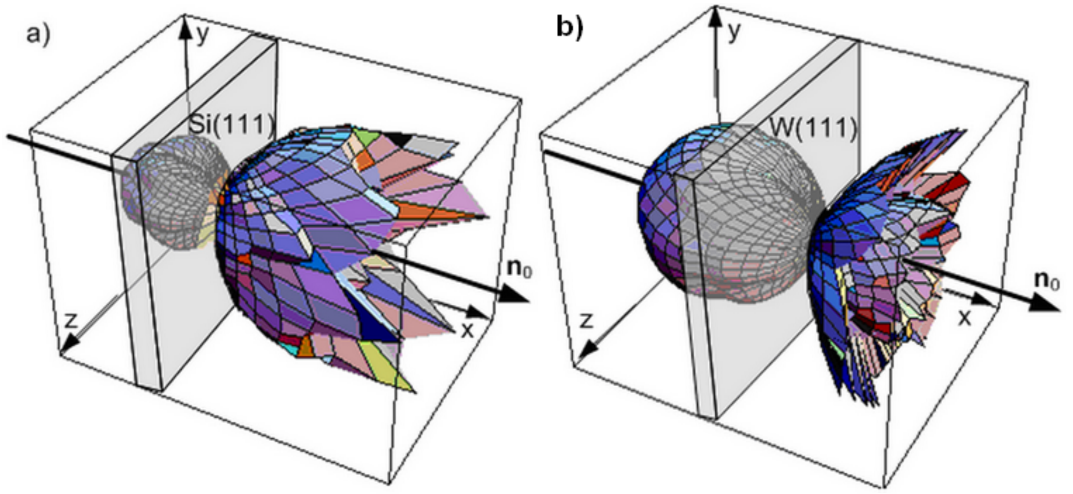

Fig. 3. *PXR angular distribution, γ=3: a) silicon (111); b) tungsten (111). Crystal is perpendicular to a beam – larger crystal face is parallel to crystal planes (111)*

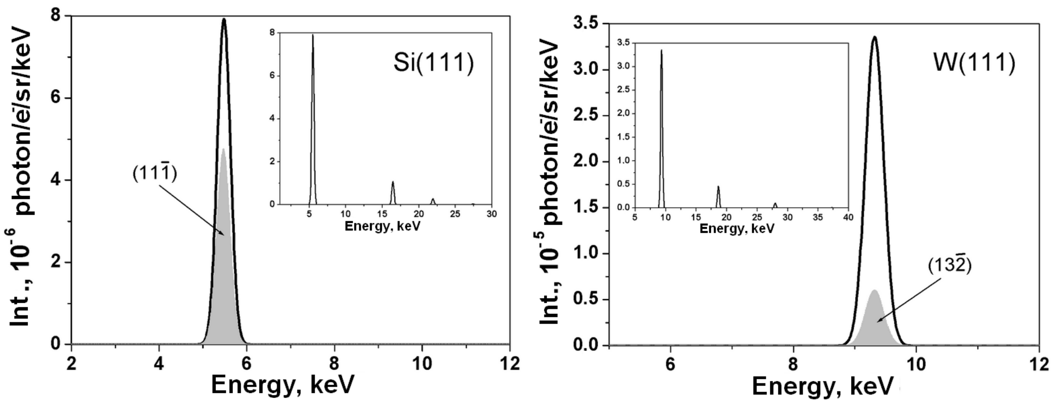

Fig. 4. *Rated PXR spectra in new geometry, γ=3*

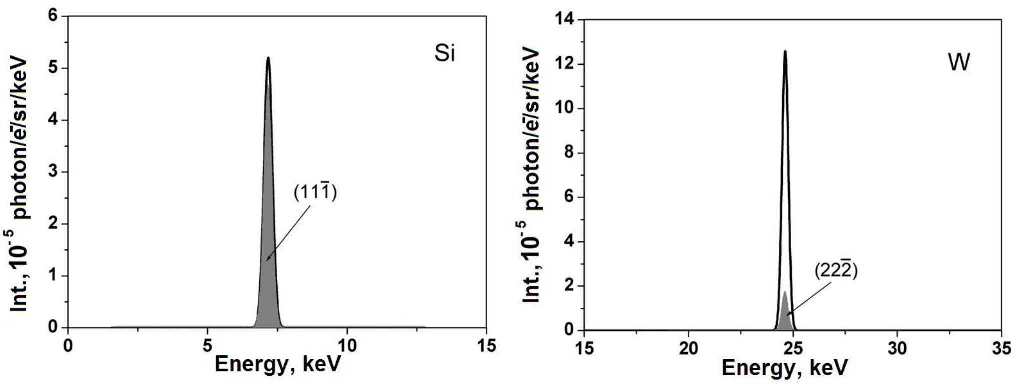

Fig. 5. *Rated spectra of PXR in new geometry, γ=12, observation angle in both cases is 35°*

Fig. 6 shows the PXR spectrum generated by electrons with energy of 5,6 MeV at the output from tungsten and silicon crystal (111) in Bragg geometry, for the comparition. According to the simulation results and the experiment [8] PXR spectrum is rather complicated. Orientation at which the angle between normal to crystal surface and beam direction is $\psi=\pi/2-\theta_B$, angle between directions <$\bar{1}$10> and axis OY equals to zero was selected for certainty. It is supposed that detector with dimension of 300 eV is placed in the reflection maximum (111) which makes angle $\theta_y' \approx \gamma^{-1}$ rad with Bragg direction.

Calculations of intensity for ideal conditions are given in Fig. 7. In real situation a part of a beam is reflected from target surface layer owing to beam oblique incidence in the sheme of Bragg and Laue. For incidence angle equal to 45° at electron energy of 5,6 MeV estimates of reflected particles fractions from tungsten gives

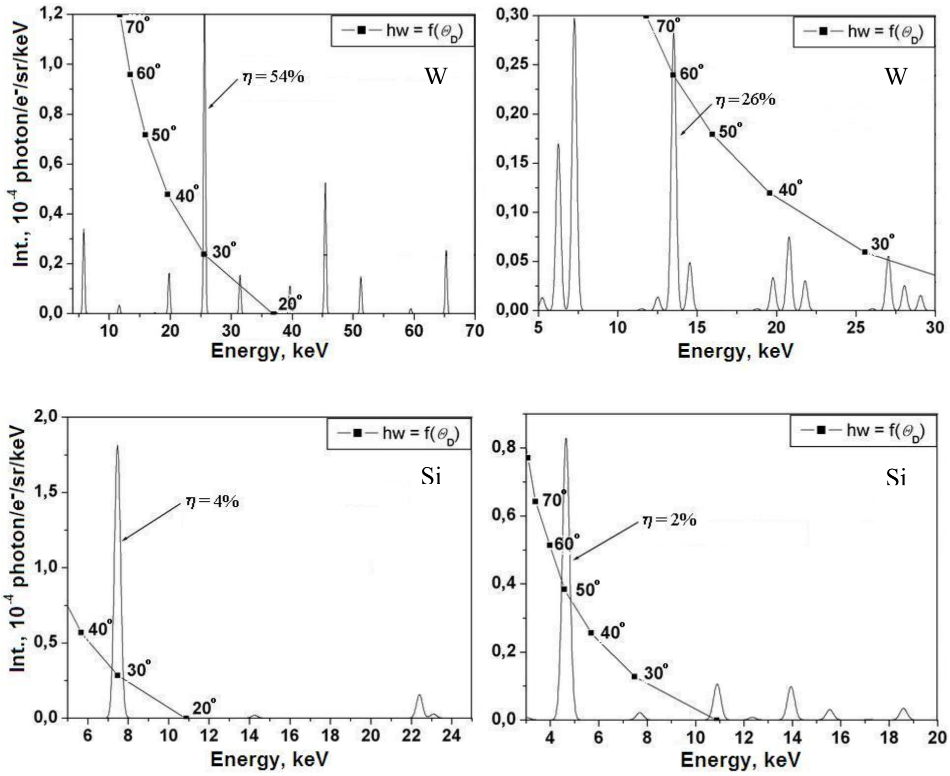

Fig. 6. PXR spectra from electrons with energy of 5,6 MeV at the output from crystal W and Si (111) for Bragg case. Angle $\theta_D=2\theta_B$ is the angle between beam direction and Bragg direction ($\theta_D \approx \theta$)

the value 22 % maximum falls on a layer of 57 μm [9]. So, decreasing Bragg angle a part of reflected beam increases. Thus, PXR yield is significantly suppressed in a spectral hard part in Bragg sheme; in Laue sheme suppression due to reflection is in soft part. In new shema the reflection effect may be minimized using crystal cut along planes (111).

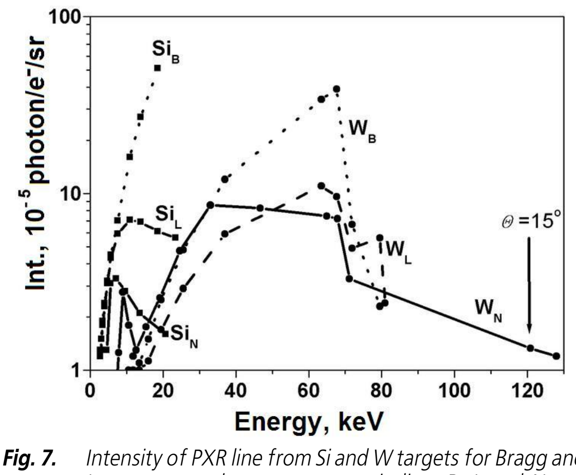

Fig. 7. Intensity of PXR line from Si and W targets for Bragg and Laue cases and new geometry, indices B, L and N, respectively. Electron energy is 5,6 MeV

Thus, if PXR line intensity exceeds 10^{-5} photon/e$^-$/sr (Fig. 7) then X-ray source intensity on the basis of linear accelerator with average current 100 μA and collimator solid angle equal to 10^{-6} sr exceeds $6{,}25\cdot10^3$ photon/s.

3. Characteristics of X-ray radiation sources on the basis of X-ray tube and compact electron accelerator

In comparison with bremsstrahlung which possesses continuous spectrum PXR is monochromatic that in its turn gives the possibility to increase contrast at considerably decreased radiation dose. Normalized spectra of PXR generated by electrons with energy of 6 MeV in tungsten crystal and X-ray tube radiation per 100 kV with tungsten anode is given in Fig. 8 [10]. PXR lines for various observation angles are given in the Figure. In calculation it was supposed that detector resolution is 300 eV and aperture is 10^{-6} sr. In the given geometry PXR spectrum does not posses satellite lines as in the cases of Bragg and Laue.

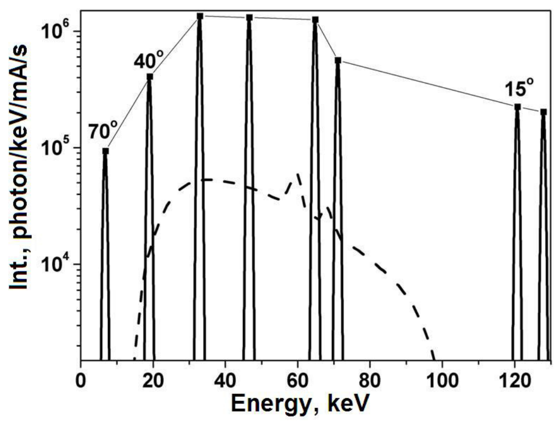

Fig. 8. Normalized spectra of PXR (solid lines) excited by electrons with energy of 5,6 MeV in tungsten crystal and bremsstrahlung (dash line) of tungsten from electrons with energy 100 keV

It is seen from comparison that source intensity on the basis of PXR from electron beam with energy of 5,6 MeV and current of 100 μA of the same order that in standard X-ray tube per 100 kV with tungsten anode current of which is of mA order. Radiation dose is integral under spectrum is rather higher from X-ray tube

$$\frac{Y^{BR}}{Y^{PXR}_{\max}} = \frac{2,37\cdot 10^{6}}{1,34\cdot 10^{5}} = 17,7.$$

In the work [11] the source of monochromatic X-ray radiation on the basis of X-ray tube using two crystals monochromator was suggested. It is clear that monochromator use results in partial radiation loss. It is necessary to increase current in compensation. The authors of the work [11] need a beam power of X-ray tube beam up to 2...4 kW to overlap energy range from 3 to 40 keV to obtain intensity of 10^4 photon/s. The design beam power of the monochromatic X-ray radiation source on the basis of PXR of the same intensity equals to 0,6 kW and overlapped range is 6...130 keV.

Estimate of PXR line width from tungsten crystal with thickness of 100 μm accounting multiple scattering amounts to the value FWHM=280 eV from electron beam with energy of 5,6 MeV and aperture of forming collimator equal to 10^{-6} sr with area of input window 1 cm^2.

Conclusion

The monochromatic X-ray source on the basis of compact electron accelerator with energy of 5,6 MeV and beam current of the order 100 μA using parametric X-ray radiation in comparison with X-ray tube was examined. Such source intensity with tungsten crystal is about 10^4 photon/s in energy range from 6 to 130 keV with line width of 280 eV.

It is seen from source characteristics comparison that the source on the basis of parametric X-ray radiation possesses a number of advantages: firstly, monochromaticity and capacity of tunning of a PXR peak energy allows increasing the resolution of studied object; secondly, radiation dose to the object decreases by an order of magnitude; thirdly, radiation intensity of the same order that the X-ray tube possesses at rather decreased power input. For example, to obtain X-ray radiation in the range from 6 to 130 keV for applying in medicine by X-ray tube the beam power up to13 kW is required while beam power of the source on the basis of parametric X-ray radiation is about 1 kW.

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