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BREMSSTRAHLUNG GENERATION BY 7.5 MEV ELECTRONS IN CONVERTERS MADE OF DIFFERENT MATERIALS[†]

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The present paper shows that, besides the technologically complex water-cooled converters made of Ta or W, a simple and efficient converter in the form of air-cooled Mo and Al plates can be fabricated for a number of tasks. The generation of bremsstrahlung by electrons with the energy of 7.5 MeV in the converter plates made of Ta, W, Cu or Mo and in the Al filter was studied by the Monte Carlo method in the PENELOPE software package. The thicknesses range of the plates made of Ta, W, Cu or Mo was chosen on condition that the total mass thickness of the converter and filter made of Al (in g/mm^2) provided complete absorption of the primary electrons. It is shown that the photon yields from Mo at mass thicknesses above 25 g/mm^2 are higher than those from Ta and W, but the energy transferred from electrons to BS is lower. With the same mass thicknesses of Ta and W converters, practically all characteristics of bremsstrahlung and the absorbed energy in the target are the same. The conditions for cooling the converter elements with water and air are determined for the level of heat release in the converter up to 10 kW. The minimum dimensions of the electron-irradiated region of Ta and Mo converters, cooled by water, are determined. It is shown that with the really existing air compressors taken into account, the permissible heat release of air-cooled Mo converters should not exceed 4 kW.
Keywords: radiation technologies, converter, bremsstrahlung**,** electron beams.
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At present, the radiation technologies, intended mainly for sterilization by electron beams, use accelerators with energies $E_e \leq 10$ MeV and power from several kilowatts to tens of kilowatts. The same accelerators can serve as sources of bremsstrahlung (BS), with energy not exceeding $E_e = 7.5$ MeV, i.e. the maximum bremsstrahlung energy allowed for food processing. Generally, refractory materials with a large atomic number, such as Ta and W, are used for the converters [1-3]. For the manufacture of such converters, complex technologies are used: tungsten carbide (WC) is spattered on the aluminum plate, and the tantalum plate is welded to aluminum by explosion welding [2]. In this paper simple design options for bremsstrahlung converters with air and water cooling are considered. The air-cooled converter model comprises a plate, made of Ta, W, Cu or Mo, and an air-spaced aluminum filter. The water-cooled converter is a rectangular tube made of aluminum or steel filled with water, whose front wall is made of Ta, W, Cu or Mo. In addition to the commonly used Ta and W the generation of bremsstrahlung by electrons with the energy of 7.5 MeV in targets made of Cu or Mo was investigated with these designs of the converters taken into account. The calculations of the spectral-angular characteristics of the bremsstrahlung and the energy release of electrons with energy E_e=7.5 MeV in the designs of the converters, subject to the target thickness, were performed by the Monte-Carlo method. The conjugate problem of thermodynamics and hydrodynamics (gas dynamics), when the converter elements were cooled with water and air, was solved with the heat release in the converter taken into account.

CALCULATIONS OF THE BREMSSTRAHLUNG BEAM CHARACTERISTICS

In [1-3] the characteristics of bremsstrahlung radiation generated by converters were investigated subject to the thickness of Ta or W. As the characteristics of bremsstrahlung, the yield (number) of photons into the front hemisphere, or the fraction of energy transferred from electrons to bremsstrahlung photons, was used. Virtually, there are no data on the fraction of the absorbed energy of electrons in the material of the converter, as well as on the fraction of the energy carried away by the electrons reflected from the surface of the converter. Note, that at the Ta or W optimal thickness, which provides the maximum bremsstrahlung yield, some of the primary electrons pass through the converter material [2]. These electrons, falling on the surface of the irradiated object, can increase the near-surface dose in addition to the bremsstrahlung photons. The applied designs of converters for cooling, as a rule, use water flowing through pipes made of steel or aluminum, which serve as absorbers (filters) for the electrons that passed through the Ta or W plates.

It was assumed that the electron beam with the energy of 7.5 MeV fell perpendicular to the converter surface, while the transverse dimensions of the converter were larger than the electron beam diameter. To calculate the bremsstrahlung characteristics we used the PENELOPE software package [4,5], which made it possible to calculate the

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transport of electrons, positrons, and photons through layered structures made of different materials. For Ta layers of different thicknesses, the characteristics both of bremsstrahlung and the number of primary transmitted and reflected electrons were calculated. Figure 1 shows the bremsstrahlung yields (N_γ^{tot}/N_e) both into the front hemisphere and in the range of angles 0-48° (N_γ^{48}/N_e), which is actually used, when objects are irradiated. The bremsstrahlung yields and the number of primary transmitted (N_e^{tr}/N_e) and reflected (N_e^{back}/N_e) electrons are normalized to 1 initial electron.

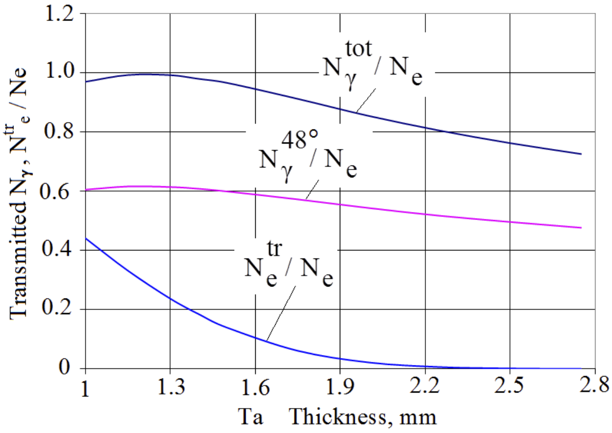

Figure 1. Yields of bremsstrahlung and primary transmitted and reflected electrons.

From the data given in Fig. 1, it follows that at the maximum bremsstrahlung yield with the layer thickness of ~ 1.2 mm, the number of primary electrons, transmitted through Ta, is ~ 30%. To reduce the amount of transmitted primary electrons to ~ 2%, a Ta layer of ~ 2 mm is required. The number of reflected primary electrons does not change in dependence of the thickness of the Ta layer and makes ~ 15%.

In [6] it was shown, that at E_e = 10 MeV, starting with a certain thickness of the converters, the bremsstrahlung forward yield is greater for converters with a lower atomic number (Mo or Cu). In this work, the characteristics of bremsstrahlung, produced by converters of Ta, W, Cu or Mo with different thicknesses upon absorption of the electrons transmitted through the material of the converter by Al filters, are studied.

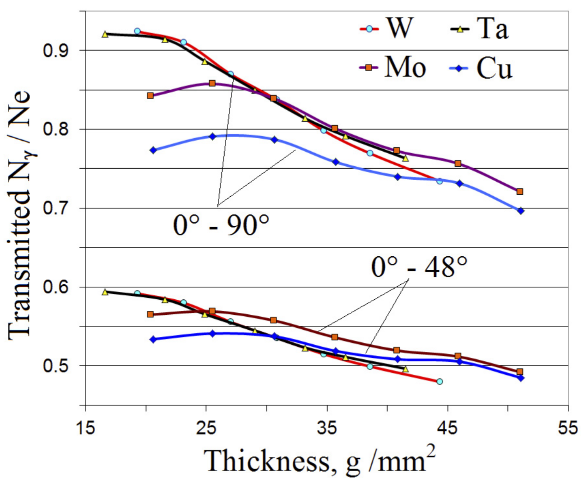

Figure 2. Bremsstrahlung yields versus mass thickness Ta, W, Cu, Mo.

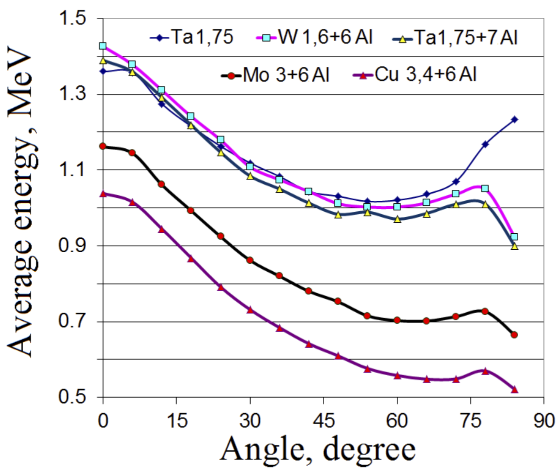

Figure 3. Dependences of the average photon energies on the emission angle for the Ta target and Ta, W, Cu, Mo with the Al filter

The characteristics of bremsstrahlung for the converters made of different materials and thickness of the converters will be compared with the same mass thickness, expressed in g/mm^2. The thickness of the Al filter is determined on condition that the number of transmitted primary electrons is less than 0.2-0.3%. The optimization of bremsstrahlung calculations showed, that this condition was fulfilled for the total mass thickness of the converter materials (Ta, W) and Al filter of 45-49 g/mm^2, and for (Cu, Mo) of 46-51 g/mm^2. Figure 2 shows the bremsstrahlung yields subject to the thickness of the converter made of different materials at the optimal thickness of Al filters. The bremsstrahlung yields for Ta, W are practically the same (atomic numbers 73 and 74, respectively), and a decrease in atomic numbers 42 for Mo and 29 for Cu at small converter thicknesses leads to a decrease in the bremsstrahlung yield for these materials. Note, that the bremsstrahlung yields for Mo in the range of 0-48° at thicknesses > 25 g/mm^2 are greater than those for Ta, W. The PENELOPE package allows calculating the spectral - angular characteristics of bremsstrahlung. One of the main characteristics of bremsstrahlung is the average photon energy. Figure 3 shows the dependences of the average photon energies on the emission angle for the Ta target and converters made of Ta, W, Cu, Mo with the Al filter. The average photon energies for the converters made of elements with a large atomic number such as Ta, W are significantly higher than those for Cu and Mo. Figure 4 shows fractions of the energy from the initial E_e = 7.5 MeV, converted into bremsstrahlung energy (E_γ), and that of the energy, carried away by reflected electrons (E_e^{back}), subject to the thickness of the converter made of different materials.

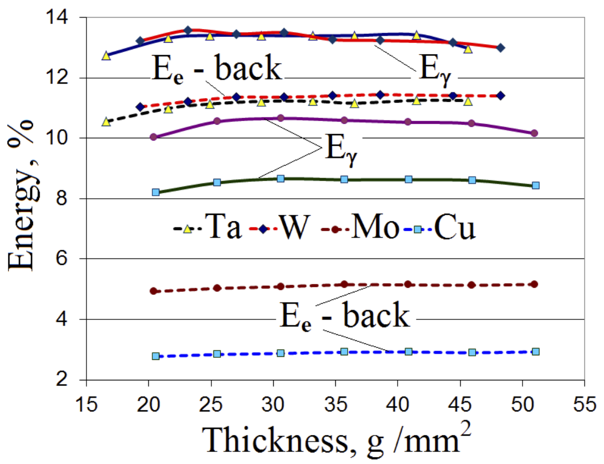

Figure 4. Fractions of bremsstrahlung energy (E_γ) and of the energy, carried bremsstrahlung away by reflected electrons (E_e^{back}), subject to the converter thickness.

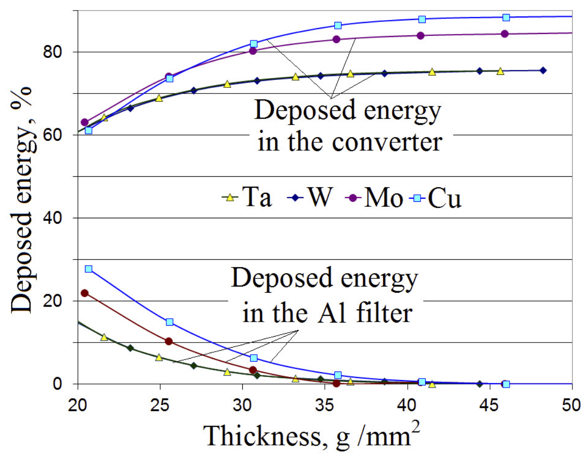

Figure 5. Fractions of the absorbed energy in the converter made of different materials, subject to its thickness, and in the Al filter.

The fractions of bremsstrahlung energy for Ta, W are practically the same, and the energies of the reflected electrons are also the same. Despite the fact that the bremsstrahlung yields (N_γ/N_e) for Mo (see Fig. 2) are the same or even higher than those for Ta and W, the fraction of the initial electrons energy, converted to bremsstrahlung, is lower. This is due to the fact that the average energies of the bremsstrahlung formed on Cu, Mo materials are lower than those on Ta, W, (Fig. 3). Figure 5 shows the fraction of the absorbed energy in the converter, made of different materials, subject to its thickness and in the Al filter. The total mass thickness of the converter materials (Ta, W) and of the Al filter is 45-49 g/mm^2, and for the converter made of Cu or Mo it is 46-51 g/mm^2. The absorbed energies determine the thermal loads on the converter material and on the converter design that ensures its cooling.

CALCULATION OF THERMAL MODES OF THE CONVERTERS WITH WATER AND AIR COOLING

In this section, simple designs of bremsstrahlung converters with different types of cooling are investigated, and the main parameters such as dimensions of the converter target and the material, as well as permissible thermal loads (electron beam power) are determined.

The calculation of thermohydraulic parameters and cooling conditions for the converters is carried out by solving the conjugate problem of thermodynamics and hydrodynamics. In 3D geometry, the most precise solution can be obtained by using Computational fluid dynamics (CFD) and finite volume technique. Simulation was carried out using the SolidWorks Flow Simulation software package [7, 8]. SolidWorks is a versatile tool for analyzing fluid dynamics and heat transfer processes. We use volumetric anisotropic heat sources. In the SolidWorks Flow Simulation software package, the heat transfer is simulated using the Navier-Stokes equations, which describe the laws of conservation of mass, momentum and energy in a non-stationary setting. In addition, the equation of state of the flowing medium components, as well as the empirical dependences of the viscosity and thermal conductivity of these components of the medium on the temperature, are used The transition between laminar and turbulent flows is determined by the critical value of the Reynolds number. Since the used differential and integral equations do not have an analytical solution, they are reduced to a discrete form and solved on a certain computational grid (discretization in space or in time is possible). After generating the computational domain and grids, volumetric heat sources are determined for computation. To take into account the anisotropy of heat distribution in the converter, its area was uniformly divided into cells. For each of these cells, the corresponding heat source was determined [9], which was averaged over the cell volume, taking into account the results of the energy release calculation by the Monte Carlo method.

To determine the acceptable operating characteristics of the converters, we carried out studies of both standard water cooling and air cooling. In the case of water cooling, a three-dimensional solid model of the converter structure was built in the SolidWorks system. The model consists of a rectangular aluminum tube, inside of which water flows and a target, made of tantalum or other metal, is built into one of its walls. Within the framework of the model, we can vary the length and width of the converter, the volumetric flow rate of water, as well as the material of the converter and the volumetric heat release in it. For this model, thermohydraulic calculations of the tantalum converter cooling were carried out in the SolidWorks Flow Simulation package.

Fig. 1A shows an option of the water cooled converter design with the flow rate of 0.5 liters per second, the dimensions of the irradiated volume of tantalum (L = 500) × 20 × 1.6 mm, and the power released in this volume is 10 kW. The figure also presents the temperature distribution both in tantalum and in the outflowing water. It is shown, that at the water flow rate of 0.5 l/s the maximum temperature on the tantalum outer surface does not exceed 123°C. The water temperature in the cooling channel does not exceed 35°C. The possibility of reducing the length of the converter L, while maintaining the power allocated in this volume of 10 kW, was investigated. Fig. 6B and Fig. 6C present the results of heat release calculations for converters made of Ta (L=200)×20×1.6 mm, and (L=50)×20×1.6 mm, respectively. From Fig. 6C it follows, that with the converter length of 5 cm, the maximum temperature of the converter outer surface is about 857°C.

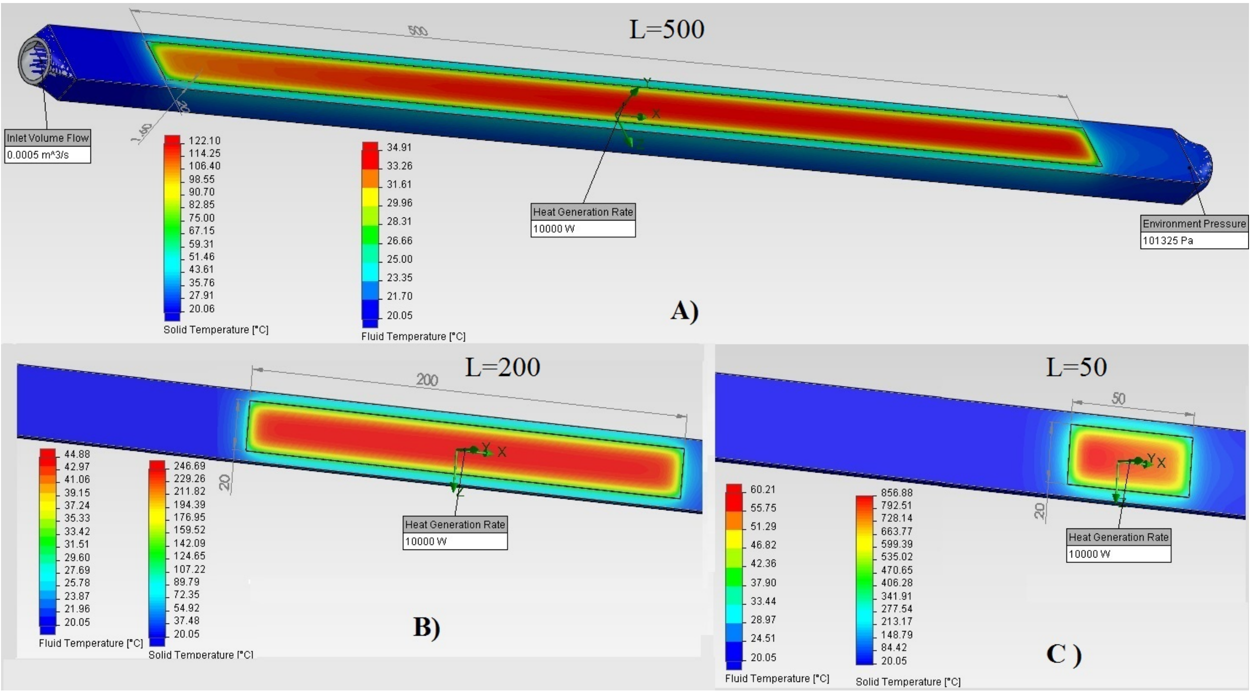

Figure 6. Options of the water cooled converter design with the flow rate of 0.5 l/s with the dimensions of the irradiated tantalum (L=500, 200, 50) × 20 × 1.6 mm

And although the maximum water temperature in the cooling channel is slightly lower than 60°C, a further reduction in the converter size in this case is not advisable, since the surface temperature at the interface between the converter and the aluminum system is about 500°C, and further decrease in the converter length can lead to the pipe melting (melting point of Al is ~ 660°C). However, this problem can be easily solved by changing the material of the cooling pipe, for example by steel. The calculations have shown, that in this case the temperature at the converter-cooling pipe interface is also about 500°C, what will not cause melting (steel melting temperature is ~ 1400°C). Structurally, it is possible to reduce the length of the converter to L = 30, then the temperature at the interface will be ~ 650°C.

We carried out similar calculations for the converters made of molybdenum and copper. As long as the densities of molybdenum and copper are lower than those of tantalum, the effective thicknesses for these materials will be greater. For the molybdenum converter dimensions (L=500)×20×3.0 mm the results of simulation, carried out under the same conditions of cooling and heat load, showed that the maximum temperature of molybdenum does not exceed ~ 740°C, and at the boundary with the aluminum (steel) pipe it is ~ 500°C. Note, that the water flow in the channel is laminar, what provides good conditions for cooling the converter. Since the thermal conductivity of air within the temperature range of hundreds of degrees C° is an order of magnitude less than that of water, it is obvious that the air cooling is much less effective. We have chosen the most simplified model of the air cooling system, which is a box in the form of a parallelepiped with an air cooling channel inside which there is a converter (L=500)×100×3.0 mm. For a heterogeneous distribution of the absorbed energy caused by irradiation, this converter is divided along its length into 50 zones, in each of which it is possible to vary the heat source. To determine the efficiency of the air channel at small thicknesses, the converter is displaced by 10 mm from the center of the box, thus the distance from one wall to the converter is 10 mm and from the other wall it is 17 mm. The general view of the converter model and the directions of air and electron flows are shown in Fig.7.

For the molybdenum converter, the boundary conditions are determined for the air flow at the power yield of 10 kW. It is shown that for stable cooling of this converter design, it is necessary to provide a volumetric air flow rate of at least 9 m^3/min. Figure 8 shows the temperature distribution in molybdenum and in cooling air. Similar results were obtained for the targets of the converters made of tantalum and tungsten. Note, that the air flow rate of 9 m^3/min is provided using industrial compressors with the power of about 50 kW. The calculations have shown that a decrease in heat release in the converter to 4 kW will reduce the volumetric air flow rate to ~ 300 l/min, while keeping to the permissible temperature regime. For example, the 2.2 kW Dnipro-M AC-50 VG air compressor provides the air flow of 290 l/min. The analysis of the obtained data allowed to conclude, that at the air cooling of the molybdenum converter the maximum power in the converter should not exceed 4 kW, and a further increase in the power could lead to melting of the molybdenum converter (2623°C). Thus, for heat-resistant materials such as tantalum, tungsten, or molybdenum at air cooling, based on conventional compressors for converters with plates 500×100×(t=1.6, 1.7, 3.0) mm in size, the allocated power should not exceed 4 kW.

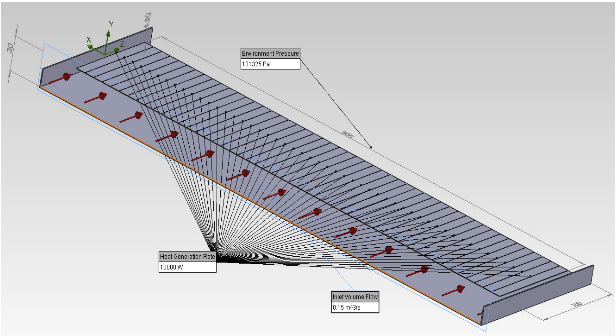

Figure 7. General view of the converter model and the directions of air and electron flows

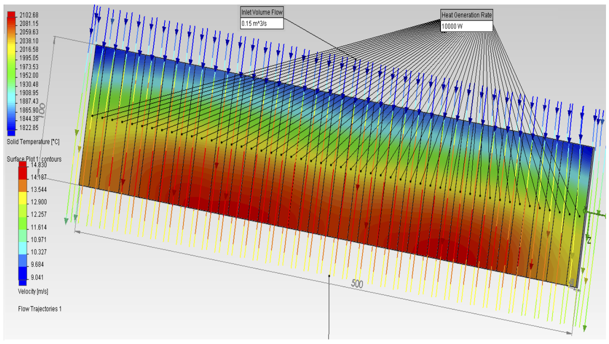

Figure 8. Temperature distribution in molybdenum and in the cooling air.

CONCLUSIONS

The generation of bremsstrahlung by electrons with the energy of 7.5 MeV for the converters, made of Ta, W, Cu or Mo with different thicknesses, was investigated. The thicknesses range of the convertor plates made of Ta, W, Cu or Mo is chosen on condition that the total mass thickness of the converter and the Al filter (in g/mm^2) provides complete absorption of the primary electrons. It is shown that for the same mass thicknesses of the converters made of Ta and W, practically all characteristics of BS: photon yields, average energies in the angular intervals, the energy transferred from electrons to BS, as well as the absorbed energies in the converter and the number of reflected electrons are the same. It is shown that the photon yields from Mo at mass thicknesses above 25 g/mm2 are greater than those for Ta and W, but the energy, transferred from electrons to BS, is lower due to the lower average photon energy. The absorbed energies in the Mo and Cu converter are slightly higher than those of Ta and W due to the smaller number of reflected electrons.

The conjugate problem of thermodynamics and hydrodynamics (gas dynamics) was solved for the level of heat release in the converter up to 10 kW, when the converter elements were cooled with water and air. The minimum dimensions of the electron-irradiated region of a Ta or Mo converter, cooled by water, at which water efficiently removes heat, have been determined. For the option with air cooling of a Mo converter with the heat release of 10 kW, boundary conditions for the air flow are determined. It is shown that with the really existing air compressors taken into account, the permissible heat release of air-cooled Mo converters should not exceed 4 kW.

The present paper shows that, besides the technologically complex water-cooled Ta or W converters a simple and efficient converter in the form of air-cooled Mo and Al plates can be fabricated for a number of tasks.

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ГЕНЕРАЦІЯ ГАЛЬМІВНОГО ВИПРОМІНЮВАННЯ ЕЛЕКТРОНАМИ З ЕНЕРГІЄЮ 7.5 МЕВ В КОНВЕРТЕРАХ З РІЗНИХ МАТЕРІАЛІВ

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У даній роботі показано, що крім технологічно складних конвертерів з Ta, W з водяним охолодженням, можна для ряду завдань виготовити простий і ефективний конвертер у вигляді пластин з Mo і Al з повітряним охолодженням. Досліджено генерація гальмівного випромінювання електронами з енергією 7.5 МеВ в Ta, W, Cu, Mo і фільтрі з Al методом Монте-Карло в пакеті PENELOPE. Діапазон товщини з Ta, W, Cu, Mo вибраний з умови, що сумарна масова товщина конвертера і фільтра з Al (в одиницях g / mm^2) забезпечує повне поглинання первинних електронів. Показано, що виходи фотонів з Mo більше ніж для Ta і W при масової товщині вище 25 g / mm^2, але передана енергія від електронів в гальмівне випромінювання менше. При однакової масової товщини конвертерів з Ta і W практично всі характеристики гальмівного випромінювання і поглиненої енергії в мішені однакові. Для рівня тепловиділення в конвертері до 10 кВт визначені умови охолодженні водою і повітрям елементів конвертера. Визначено мінімальні розміри області конвертера з Ta і Mo що опромінюється електронами при водяному охолодженні. Показано, що з урахуванням реально існуючих повітряних компресорів допустиме тепловиділення конвертерів з Mo з повітряним охолодженням не повинно перевищувати 4 кВт.
Ключові слова: радіаційні технології, конвертер, гальмівне випромінювання, електронні пучки.