RADIATION SHIELDING OF ELECTRON ACCELERATOR LIAM-2: CALCULATION AND GEOMETRY

A.V. Mazilov, B.N. Razsukovannyj, J.A. Degtyar, V.A. Vinokurov
NSC KIPT, Kharkov, Ukraine
E-mail: mazilov@kipt.kharkov.ua

In the present paper the calculation is carried out and the geometry of radiation shielding construction for a linear induction electron accelerator LIAM-2 with the energy of 2 MeV and current in a pulse $3 \cdot 10^3$ A developed at the NSC KIPT is offered. It is shown that despite high accelerated electron current in the accelerator using a ferromagnetic tape, by a virtue of practical absence of beam dispersion in a transportation path, and specificity of X-ray bremsstrahlung topography, it is possible to realize, the effective radiation shielding of the personnel of categories "A" and "B" serving the accelerator with the aid of, for instance, lead.

PACS: 06.60.Wa, 87.50.N,P

1. INTRODUCTION

Application of the radiation technologies in the industry which are based on the use of high energy electron beams (beam-ozone technologies) demands creation of electron accelerators with the energy up to 10 MeV and average beam power on the output over 200 kW [1-3]. The necessity for such electron beams is great today. It is caused, first of all, by realization of the technologies concerned with purification of Industrial drains, drains of the large pharmacological and medical plants, cattle-breeding farms with yield up to several thousand cubic meter of water per day. To obtain such high-strength electron beams, the multimodule accelerating systems consisting of a set of resonant (as a rule) accelerators are used at present. Novelty of such technologies is caused also by the circumstance that until recently there were no ways of manufacturing of windows for lead-out of beam from the high power accelerator.

The way of manufacture of the accelerator output window based on the coal-coal material impregnated with silicium [4] is offered at the NSC KIPT. This allowed making an experimental linear inductive accelerator with electron energy 2 MeV and current in a pulse $3 \cdot 10^3$ A.

The accelerator consists of four cylindrical half-sections connected in series and having the length 78 cm each one. The inductive system around the half-section axis, being the axis of a beam, consists of an iron layer with the thickness of 17 cm and a copper layer winding that has thickness of 22 cm with factor of packaging 0.9. The transitive chamber of the length of 35 cm with the copper winding thickness equal to 10 cm is located between the second and the third half-section.

The accelerator is located in the room №316 of building A of NSC KIPT. The layout of the accelerator arrangement relative to the room №316 and adjacent rooms is represented in Fig.1. Permanent workplaces of the *A*-category personnel are located in adjacent rooms №314 and №318, while the workplaces of the B-category personnel are in the room №230 that is situated one floor below the room №316. The B-category personnel is also allowed being present in a corridor and outside the building №A at a distance not less than 30 m from the accelerator beam output. In the given paper we will show that despite high accelerated electron current in the accelerator using a ferromagnetic tape, by a virtue of

practical absence of beam dispersion in transportation path, and specificity of X-ray bremsstrahlung topography, it is possible to realize, without special difficulties, the effective radiation shielding of the personnel serving the accelerator with the aid of lead, for instance. We will specify the most dangerous areas of ionizing radiations in a path of the accelerator.

2. PARAMETERS OF THE ACCELERATOR

An electron beam from injector that is located in the first half-section is accelerated up to the energy of E_1=1 MeV in the accelerating gap between the first and the second half-section. Then, the electron beam passes the second half-section, the transitive chamber, and the third half-section. After this it is accelerated in the accelerating gap between the third and the fourth half-section up to the energy of E_2 =2 MeV, passes the fourth half-section and "breaks in" a target (the point *A* in Fig.1). The current in a pulse at the all stages of acceleration makes I_{pulse}=$3 \cdot 10^3$ A, duration of a pulse τ=$0.125 \cdot 10^{-6}$ s, frequency of pulses f=$5.6 \cdot 10^{-3}$ s^{-1} (1 pulse per 3 minutes). In emergency mode the electron beam breaks into a wall of a beam pipe in the beginning of the second half-section (the point *B* in Fig.1).

Since radiation losses of electrons in the target material grow as atomic number grows, the aluminum having the greatest effective atomic number has been chosen from three probable materials (carbon, water and aluminum) as a target for carrying out the calculations. Iron was chosen as a material of the target for the case of emergency mode (stainless steel of the beam pipe).

3. CONDITIONS OF RADIATION SAFETY

The value primary regulated under workers irradiation is the limit of a doze that is equal to 20 mSv/year for the *A*-category personnel and 2 mSv/year for the *B*-category personnel. Distribution of the irradiation doze within calendar year is not regulated by that [5]. At the stage of designing of the protection against ionizing radiation, the safety factor is used for designed rate of equivalent doze at the personnel workplaces and is equal to 2. Thus, taking into consideration the pulse character of the radiation it is necessary, for maintenance of standard conditions, to ensure that the average value of the equivalent doze rate P from the external side of protection does not exceed the amount of P_{lim}:

$$P \leq P_{lim} = D_{lim}/T, \qquad (1)$$

where D_{lim} is the limit of the doze designed. D_{lim}= 10 mZv for the A-category personnel and 1 mZv for the B-category personnel; T is the irradiation duration and is equal to 1700 h.

For the A-category personnel $P_{lim}(A)$=5.9·10^{-6} Sv/h.

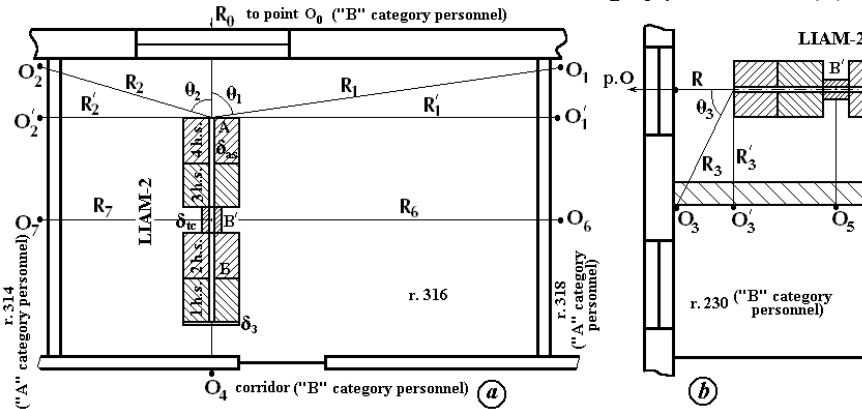For the B-category personnel $P_{lim}(B)$=5,9·10^{-7} Sv/h.

Fig.1. The scheme of an arrangement of accelerator LIAM-2: a) top view; b) side view

4. IONIZING RADIATION CHARACTERISTIC

Under interaction of electrons having an energy 1 MeV$\leq E \leq$2 MeV with a target, the radiation losses reveal itself as bremsstrahlung and process of electron-positron pairs production. As the cross-section of the pair production is small for this energy range, the main kind of radiation is bremsstrahlung with some effective energy E_{eff}=2/3 E at $E_{eff} \leq$1.7 MeV, E_{eff}=1/2 E at 1.7$<E_{eff} \leq$10 MeV with strongly pronounced anisotropy dependent both on the energy of electrons and on the target atomic number [6]. The experimental data submitted to [6] on the angular distribution of bremsstrahlung for various electron and target energies are obviously underestimated at the angles Θ lying in the vicinity of 90° (Θ is the angle between the direction of the electron beam and normal to the target plane). This is obviously related with the sharp increase in effective thickness of the target in that direction. In calculations the values for the doze rate have been used at angles of Θ=90°. These values were received by interpolation of experimental data at the angles of Θ<90° (Θ>90°), which are 2 (1.2) times higher than experimental data for the energy of electrons E=1 MeV (iron) and E=2 MeV (aluminum). For the other angles the experimental data were used. The angular distribution of the average rate of the equivalent doze at a distance of 1 m from the target in the angle range that is necessary for the given calculation at the average current $I=I_{pulse} \cdot \tau \cdot f$=2.1·10^{-6} A is resulted in Table (Sv·m^2/h).

Angular distribution of the equivalent doze rate at the distance of 1 m from target

Θ	0	50	60	70	80	90	180
Point A (aluminum target, E=2 MeV, E_{eff}=1 MeV)	0.323	0.074	0.042	0.024	0.021	0.017	0.0091
Point B (iron target, E=1 MeV, E_{eff}=0.671 MeV)	0.073	-	-	-	-	0.011	0.0077

5. METHOD OF PROTECTION CALCULATION

Calculation of a barrier protection thickness Δ is based on the condition, under which the maximal equivalent doze rate value in the locations of the personnel does not exceed the established value of the designed doze rate for the A- and B-category persons. Necessary thickness of protection can be determined with the help of the data given in tables, which are presented in Ref. [7]. Here it is necessary to know the multiplicity of the equivalent doze rate weakening, the protection material, and the bremsstrahlung effective energy. The necessary weakening multiplicity $K(\delta)$ is calculated according to the formula:

$$K = \frac{P_0(\Theta)}{P_{des} \cdot R^2 \cdot K(\delta)}, \qquad (2)$$

where Θ is the angle between the electron beam direction and the direction from the target to the calculation point (see Fig.1); R is the distance from the target up to the calculation point; $P_0(\Theta)$ is the doze rate at a distance of 1 m from the target at the angle Θ without protection and determined by Table; P_{des} is the designed doze rate

for the personnel; $K(\delta)$ is the weakening multiplicity due to protection via constructional materials of the accelerator and barriers with the total thickness of δ on the length R.

6. PROTECTIVE CHARACTERISTICS OF THE ACCELERATOR MATERIALS

As a material for radiation protection against photon radiation, copper is used extremely seldom despite its better protective properties in comparison with iron. Therefore, there are no data on values $\Delta(K)$ for copper in the literature. However, as one should assume, the mass weakening factors of copper and iron are practically equal because of close values of their atomic numbers ($Z = 23$ for iron and $Z = 26$ for copper) [8]:

$\overline{\mu}$ (Fe)=0.0599 cm^2/g at E=1 MeV and 0.0424 cm^2/g at E=2 MeV;

$\overline{\mu}$ (Cu)=0.0589 cm^2/g at E=1 MeV and 0.048 cm^2/g at E=2 MeV.

Because of leaky package of copper winding of the induction system its effective density makes ρ_{eff}=

$0.9\rho(Cu)=8.0$ cm^2/g. Taking into account that the density of iron is $\rho(Fe)=7.9$ cm^2/g it may be asserted that linear weakening factors of iron and copper are equal, i.e. the layer of copper winding is equivalent to the layer of iron of the same thickness. Thus, accelerating sections have radial protection thickness $\delta_{as}=39$ cm (iron); the transitive chamber has protection with the thickness of $\delta_{tc}=10$ cm. In addition, there is end cap made of iron with the thickness of $\delta_{endcap}=1$ cm placed in the face plane of the first half-section on the beam axis.

Interpolating the given thickness of the protection made of iron with regard to the weakening multiplicity and effective energy of bremsstrahlung [7], we have:

$K(\delta_{as}=39)=2.38\cdot10^6$ at $E_{eff}=1$ MeV;

$K(\delta_{as}=39)>10^7$ at $E_{eff}=0.67$ MeV;

$K(\delta_{tc}=10)=35.8$ at $E_{eff}=0.67$ MeV;

$K(\delta_{endcap}=1)=1.2$ at $E_{eff}=1$ MeV and $E_{eff}=0.67$ MeV.

The mass factors of water and wood are approximately equal [8]. Taking into account the density of wood (≈0.7) and the given weakening multiplicities for water [7], we are able to estimate the weakening multiplicity for available wooden barriers and ceiling with the thickness δ_w:

$K(\delta_w=14)=1.2$; $K(\delta_w=21)=K(\delta_w=22)=1.4$;

$K(\delta_w=40)=2.0$ at $E_{eff}=1$ MeV and at $E_{eff}=0.67$ MeV.

7. THE CHOICE OF CALCULATED POINTS

Calculation points, at which the highest possible equivalent doze rate is expected (Fig. 1) are the following:

- the point O_0 is outside the building at a distance $R_0=$ 30 m from the accelerator, $\Theta=0°$ (B-category personnel);
- the point O_1 is in the corner of the room №318 at the beam axis level (A-category personnel);
- the point O'_1 is near the wall of the room №318 at the beam axis level opposite to the point A (A-personnel);
- the point O_2 located in the corner of the room №314 at the beam axis level (A-category personnel);
- the point O'_2 located near the wall of the room №314 at the beam axis level opposite to the point O_3 that is located in a corner between the ceiling and the load-bearing wall of the room №230 below the beam axis (B-category personnel);
- the point O'_3 located near the ceiling of the room №230 beneath the point A (B-category personnel);
- the point O_4 is near the corridor wall at the beam axis level (B-category personnel);
- the point O_5 is in the corner between the ceiling and the wall of the room №230 opposite to B' (B-pers.);
- the point O_6 is near the wall of the room №318 at the level of the beam axis opposite to B' (A-personnel);
- the point O_7 is near wall of the room №314 at the level of the beam axis opposite to the point B' (A-personnel).

The presence of pairs of calculation points (O_1 and O'_1), (O_2 and O'_2), and (O_3 and O'_3) is caused by competing action of the following effects. The distance increases up to the calculation point R with the angle Θ reduction. Hence, the effective thickness of the protection Δ_{eff} increases that results, on the one hand, in reduction of the equivalent doze rate and, on the other hand,

in its increase due to the radiation anisotropy, which functional dependence on Θ, generally speaking, is unknown. The greatest value will be chosen from the calculated values Δ and Δ'.

Calculation of the points O_5, O_6 and O_7 is caused by existence of supernumerary mode probability, at which the beam may "break into" the transitive chamber.

8. CALCULATION OF THE PROTECTION THICKNESS

8.1. The point O'_1: $R'_1=5.64$ m; $\Theta=90°$; $P_{OA}(90°)=$ 0.017 Sv·m^2/h; $K(\delta_w)=1.2$; $E_{eff}=1$ MeV. Substituting these parameters into Eq.(2), we obtain the desired weakening multiplicity $K=75.5$. The thickness of the protection made of lead [7] is $\Delta'_1=6.6$ cm.

The point O_1: $R_1=5.78$ m; $\Theta=77°$; $P_{OA}(77°)=$ 0.022 Sv·m^2/h; $K(\delta_w)=1.2$; $E_{eff}=1$ MeV; $K=93.0$; the effective thickness of the protection $\Delta_{1eff}=6.9$ cm, the real thickness $\Delta_1=\Delta_{1eff}\cdot\sin\Theta_1$ =6.7 cm. Thus, the protection thickness for the room №318 (A) $\Delta_A(318)=6.7$ cm.

8.2. The point O'_2: $R'_2=2.72$ m; $\Theta=90°$; $P_{OA}(90°)=$ 0.017 Sv·m^2/h; $K(\delta_w)=1.4$; $E_{eff}=1$ MeV. $K=278$; Δ'_2 =8.4 cm.

The point O_2: $R_2=3.0$ m; $\Theta=65°$; $P_{OA}(65°)=$ 0.030 Sv·m^2/h; $K(\delta_w)=1.4$; $E_{eff}=1$ MeV. $K=404$; $\Delta_{2eff}=9.0$ cm; $\Delta_2=8.1$ cm. Hence, $\Delta_A(314)=$ 8.4 cm.

8.3. The point O'_3: $R'_3=1.95$ m; $\Theta=90°$; $P_{OA}(90°)=$ 0.017 Sv·m^2/h; $K(\delta_w)=2.0$; $E_{eff}=1$ MeV; $K=3489$; Δ'_3 =12.0 cm.

The point O_3: $R_3=2.32$ m; $\Theta=57°$; $P_{OA}(57°)=$ 0.034 Sv·m^2/h; $K(\delta_w)=2.0$; $E_{eff}=1$ MeV. $K=8502$; $\Delta_{3eff}=13.1$ cm; $\Delta_3=11.0$ cm. Hence, $\Delta_A(230)=12.0$ cm.

8.4. The point O_0: $R_0=30$ m; $\Theta=0°$; $P_{OA}(0°)=$ 0.323 Sv·m^2/h; $P_{lim}(B)=5.9\cdot10^{-7}$ Sv·m^2/h; $K(\delta_w)=1.0$; $E_{eff}=1$ MeV; $K=608$; $\Delta_4=9.5$ cm; $\Delta_A(O)=9.5$ cm. In the case of supernumerary "breaking in" of the beam (supernumerary mode) at $\Theta=0°$, the doze rate is $P_{OB}(0)=0.073$ Sv·m^2/h $<P_{OA}(0)=0.323$ Sv·m^2/h. Hence, the thickness of the frontal protection $\Delta_A(O)=9.5$ cm may be considered sufficient for maintenance of standard conditions of radiation safety. The geometry of lead radiation protection we recommend on the output of the accelerator is represented in Fig.2.
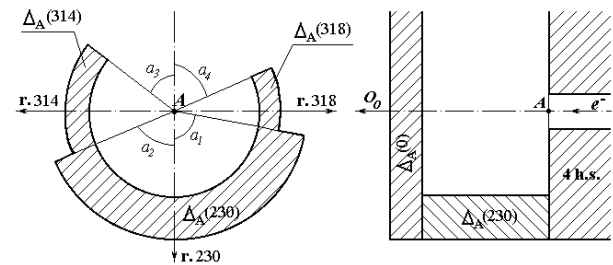

Fig.2. Geometry of the radiation protection made of lead on an output of the accelerator: $\Delta_A(318)=6.7$ cm, $\Delta_A(314)=8.4$ cm, $\Delta_A(230)=12.0$ cm, $\Delta_A(O)=9.5$ cm; $\alpha_1=81°$, $\alpha_2=73°$, $\alpha_3=58°$, $\alpha_4=73°$

The size of the angle α_1 should provide the B-category personnel safety in the room №230 and the adjacent premises due to an increase in the distance R_α from the point A that compensates the difference of the weakening multiplicities $K_A(318)$ and $K_A(230)$. It is obvious that

the angle α_1 is determined via the condition $\ж{R_ц}{З}{RҖш}^2_ц \doteq \dfrac{K_A(214)}{A(318)}$ 37.5; it follows that $\alpha_1 \geq 81°$. Similarly, $\alpha_2 = 73°$. Other angles are determined from the geometry of the accelerator arrangement in the room №316.

8.5. The side protection $\delta_{as} = 39$ cm provides the weakening multiplicity $K(\delta_{as}) \geq 2.38 \cdot 10^6$ under radiation from the point A in the direction of angles $180° > \Theta \geq 90°$, and $K(\delta_{as}) \geq 7 \cdot 10^7$ at the supernumerary "breaking in" of the beam in the second half-section within the angle range $180° < \Theta < 0°$. It follows from the comparison of these values with the values for K obtained under the item 8.3 that the side surface of the accelerating half-sections does not require any additional protection.

8.6. The point O_4. a) $R_{4A} = AO_4 = 4.95$ m; $\Theta_4 < 180°$; $P_{OA}(180°) = 0.0091$ Sv·m^2/h; $K(\delta_3) = 1.2$; $K(\delta_w) = 1.4$; $E_{eff} = 1$ MeV; $K = 375$; $\Delta_{2eff} = 13.1$ cm; $\Delta_{4A}(180°) = 8.9$ cm.
b) $R_{4B} = BO_4 = 2.25$ m; $\Theta_4 = 180°$; $P_{OB}(180°) = 0.0077$ Sv·m^2/h; $K(\delta_3) = 1.2$; $K(\delta_w) = 1.4$; $E_{eff} = 0.67$ MeV; $K = 1534$; $\Delta_{4B}(180°) = 6.9$ cm. Hence, $\Delta_4(180°) = 8.9$ cm.

8.7. The point O_5: $R_5 = R_3' = 1.95$ m; $\Theta_5 = 90°$; $P_{OB}(90°) = 0.011$ Sv·m^2/h; $K(\delta_{tc}) = 35.8$; $K(\delta_w) = 2.0$; $E_{eff} = 0.67$ MeV; $K = 68.5$; $\Delta_{4B}(180°) = 6.9$ cm. Hence, $\Delta_B(230) = 4.0$ cm.

8.8. The point O_6: $R_6 = R_1' = 5.64$ m; $\Theta_6 = 90°$; $P_{O6}(90°) = 0.011$ Sv·m^2/h; $K(\delta_{tc}) = 35.8$; $K(\delta_w) = 1.2$; $E_{eff} = 0.67$ MeV; $K = 1.36$. Hence, $\Delta_B(318) = 0.3$ cm.

8.9. The point O_7: $R_7 = R_2'$; $\Theta_7 = 90°$; $P_{O7}(90°) = P_{O6}(90°)$; $K(\delta_{tc}) = 35.8$; $K(\delta_w) = 1.4$; $K = 5.0$. Hence, $\Delta_B(314) = 1.7$ cm.

The geometry of the transitive chamber protection that we recommend is represented in Fig.3. The values of the angles $\alpha_1 \geq 74°$ and $\alpha_2 = 82°$ are determined similarly to the item 8.4.

9. CONCLUSIONS

The conditions of the personnel irradiation considered in this paper assume a total metamorphosis of a beam power into a radiation. The thicknesses of the accelerator protection calculated provide radiation safety of the personnel with a safety factor that is above the safety factor stipulated by the requirement of protection designing against external radiations. The given circumstance is the result of that the requirements for initial conditions such as the radiation angular distribution, radiation parameters of nonconventional protection materials (copper, wood), the duration of irradiation of the personnel were overestimated during calculations.

Note, it is not considered in this paper the protection against weaker radiation concerned with the partial loss of the beam power on the parts of non-uniform magnetic field, accelerating gaps, collimator, etc is not considered in this paper. Under real conditions, the intensity of such radiation is not amenable to exact calculation and should be determined experimentally in course of starting-up and adjustment works.
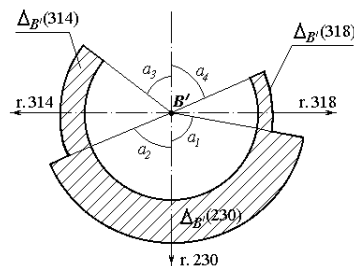

Fig.3. Geometry of the radiation protection made of lead around of the transitive chamber:
$\Delta_{B'}(318) = 0.3$ cm, $\Delta_{B'}(314) = 1.7$ cm, $\Delta_{B'}(230) = 4.0$ cm, $\alpha_1 = 82°$, $\alpha_2 = 74°$, $\alpha_3 = 58°$, $\alpha_4 = 73°$

REFERENCES

1. R.J. Adler. *Comparison of DC and Pulsed Beams for Commercial Applications*. Proc. of BEAMS–94, San Diego, v.VI, p.29.
2. P. Gehringer. *Groundwater Remediation by Ozone/Electron Beam Irradiation Treatment*. Proc. of the 1st Int. Conf. On Advanced Oxidation Technologies for Water and Air Remidiation. London, Ontario, Canada. 1994, p.30.
3. N. Getoff. *Electron Beam Remediation of Water*. Proc. of the 1st Int. Conf. On Advanced Oxidation Technologies for Water and Air Remediation, London Ontario Canada. 1994, p.128.
4. O.F. Kovpik, E.A. Kornilov, V.V. Kolosenko et al. Carbon-carbon windows for lead-out of electron and proton beams from accelerators into atmosphere // *Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations* 2004, №1(42), p.77-79.
5. *Radiation standards of Ukraine (NRSU-97). State hygienic regulations*. Kiev, 1998.
6. *Sanitary regulations of arrangement and operation of electron accelerators up to 100 MeV*. M., 1981.
7. V.D. Kozlov. *Reference book on radiation safety*. M.: "Atomizdat", 1977.
8. L.R. Kimmel, V.P. Mashkovich. *Ionizing radiation protection*. M.: "Atomizdat", 1966.

РАДИАЦИОННАЯ ЗАЩИТА УСКОРИТЕЛЯ ЭЛЕКТРОНОВ ЛИУМ-2: РАСЧЕТ И ГЕОМЕТРИЯ

А.В. Мазилов, Б.Н. Разсукованный, Ю.А. Дегтярь, В.А. Винокуров

Выполнен расчет и предложена геометрия построения радиационной защиты разработанного в ННЦ ХФТИ линейного индукционного ускорителя электронов ЛИУМ-2 с энергией 2 МэВ и током в импульсе $3 \cdot 10^3$ А. Показано, что, несмотря на большой ускоряемый ток электронов в ускорителе, использующем ферромагнитную ленту, в силу практического отсутствия рассеяния пучка в тракте транспортировки, специфики топографии тормозного рентгеновского излучения, можно осуществить эффективную радиационную защиту обслуживающего ускоритель персонала категорий «А» и «Б», используя, например, свинец.

РАДІАЦІЙНИЙ ЗАХИСТ ПРИСКОРЮВАЧА ЕЛЕКТРОНІВ ЛІПМ-2: РОЗРАХУНОК І ГЕОМЕТРІЯ

О.В. Мазілов, Б.М. Разсукований, Ю.А. Дегтярь, В.О. Винокуров

185

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2006. № 3.
Series: Nuclear Physics Investigations (47), p.182-185.

Виконано розрахунок та запропонована геометрія побудови радіаційного захисту розробленого в ННЦ ХФТІ лінійного індукційного прискорювача електронів ЛІПМ-2 з енергією 2 МеВ і струмом в імпульсі $3 \cdot 10^3$ А. Показано, що, незважаючи на великий струм електронів у прискорювачі, який використовує феромагнітну стрічку, в силу практичної відсутності розсіювання пучка в тракті транспортування, специфіки топографії гальмового рентгенівського випромінювання, можна здійснити ефективний радіаційний захист персоналу категорій "А" і "Б", що обслуговує прискорювач, використовуючи, наприклад, свинець.