RADIATION SHIELDING OF UPGRADED ACCELERATOR LUE-10M

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The LUE-10M accelerator operating in NSC KIPT is used for sterilization of a considerable amount of medical products in Ukraine, thereby contributing to national security and health of population. However, by the present time the accelerator component parts have become worn out and outdated. So, it is anticipated that the LUE-10M should be upgraded on the basis of new hardware components with arrangement in the same premises of a new 10 MeV radiator with average beam current up to 2 mA. The calculations performed have demonstrated that the characteristics of the actual LUE-10M shield and ventilation systems meet the requirements of the guidelines provided that the accelerator is operated at the design parameters of the beam.

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INTRODUCTION

The accelerator LUE-10M, now in operation, is used for sterilization of a considerable amount of medical products in Ukraine, thereby contributing to national security and health of population. However, by the present time the accelerator component parts have become worn out and outdated. Therefore, it is necessary that the accelerator should be upgraded with the use of new accelerating structure, a microwave power supply system, modern systems for controlling the accelerator operation and radiation treatment processes.

In view of the indicated tasks, it is supposed that the accelerator LUE-10M will be modernized with arrangement of a new advanced radiator in the same premises. The reconstruction of the LUE-10M accelerator implies the replacement of the present accelerating section and the beam injection system by the ones with some changes in their overall dimensions. The physical parameters of the installation, as well as its target functions and capabilities will also be changed. The output devices remain at the same places.

Fig. 1 shows the layout of the accelerator's vault at a mark of -3.60. The vault is 5 m in width and 2.7 m in height. The side radiation shielding is provided by concrete walls and soil. At the top, the installation is covered with reinforced concrete beams and units of total thickness up to 1.8 m, over which packed soil 2 m thick is built. The vault cross section is shown in Fig. 2.

1. ESTIMATION OF RADIATION SHIELD

Here we give the calculation of the radiation shield thickness required for the accelerator LUE-10M operation conditions with electron energy up to 10 MeV and average beam current up to 2 mA.

For calculations, we have chosen the points at mark +0.10 and at the personnel location areas with expected the highest radiation level (see Figs. 1 and 2).

O and O′ – are the points of the radiation sources (a tungsten target and a stack-monitor respectively) locations at mark 00;

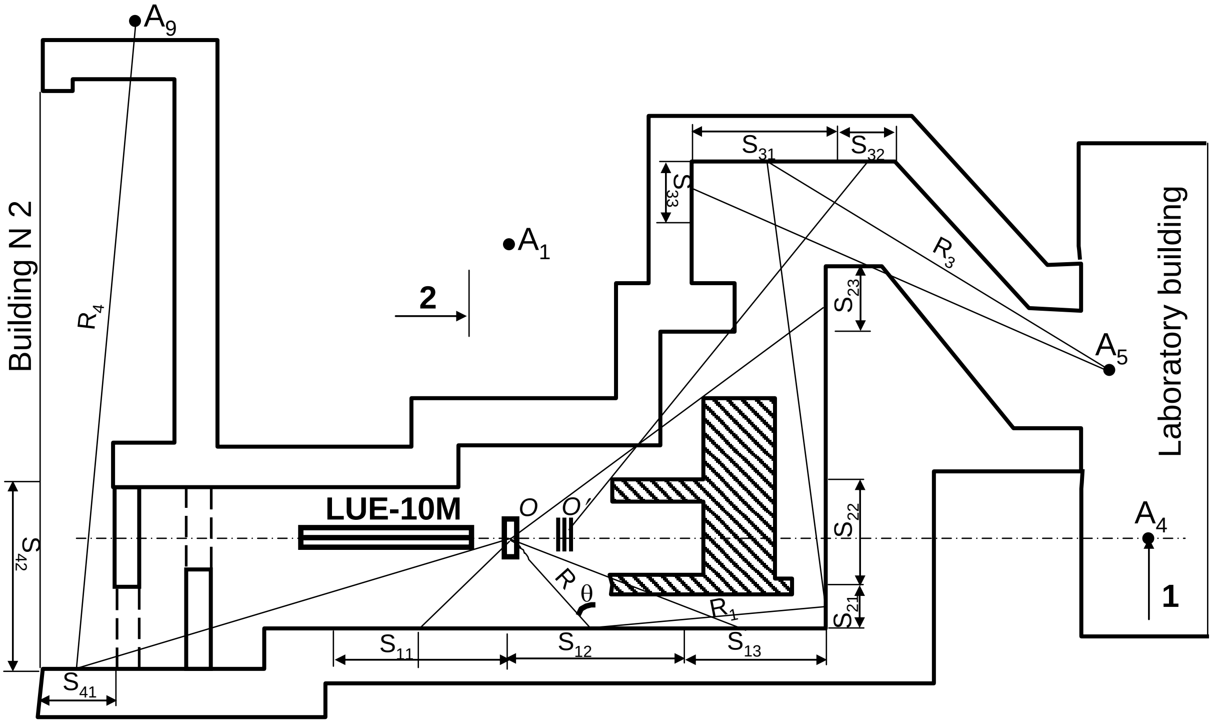

Fig. 1. Layout of LUE-10M vault

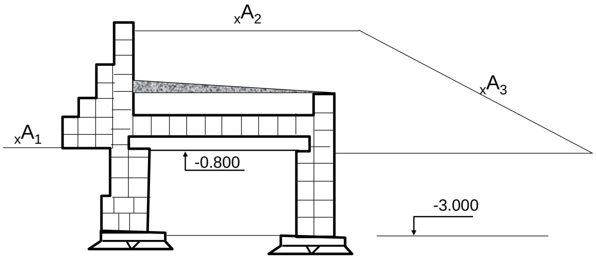

Fig. 2. Vault cross section (2-2)

A_1 is the point on the ground surface at the bottom of the side shield of the accelerator, on the left of the beam line (see Figs. 1 and 2);

A_2 is the point above point O on the roof of the accelerator vault (see Fig. 2);

A_3 is the point on the surface of the vault's side shielding, on the right of the beam line;

A_4 is the point at mark -3.00 (see Fig. 1) in the loading hall along the beam axis extension;

A_5 is the point at mark -3.00 (see Figs. 1 and 2) in the loading hall on the centerline of the conveyer;

A_6 is the point on the 2nd floor of the annex above the point 5 (see Fig. 2);

A_7 is the point before the entrance to the annex (see Fig. 2);

A_8 is the point at mark 2.6 at the exit from Building 2;

A_9 is the point at mark 00 at the entry to LUE-10M vault in Building 2 behind a protective barrier (see Fig. 1).

The calculation date of radiation characteristics for the LUE-10M accelerator are presented in Table 1.

Table 1

Calculated radiation characteristics for the LUE-10M accelerator

Maximum energy of accelerated electrons for the modes of electron (bremsstrahlung) irradiation E_0, MeV		10
Accelerated electron current I, mA		2
Beam pulse duration, µs		10
Pulse rate, Hz		600
Shielding material density, g/cm^3	concrete	2.3
	iron	7.8
Atomic number of target (tungsten)		74
Beam losses in the O target, %		100
Allowable dose rate with safety factor 2 for the "A" category of the personnel behind the shield $\dot{H}$, µSv/h		4.1

The necessary coefficient of the bremsstrahlung (X-ray) dose rate attenuation is given by the expression [2]:

$$K(X,\theta)=\frac{\dot{D}_0(\theta)\cdot T_{rad}}{T_{gh}\cdot R^2\cdot \dot{H}}, \qquad (1)$$

where X is the protective barrier thickness (cm); $\dot{H}$ is the designed equivalent irradiation dose rate with the safety factor 2 at the point of interest; R is the distance from the radiation source to the point of interest (m); $\dot{D}_0(\theta)$ is the absorbed dose rate at a distance of 1 m from the radiation source at the angle θ° relative to the electron beam axes ($0 \leq \theta \leq 180$); T_{rad} is the exposure time per shift (h); T_{sh} is the work shift time (h).

The ratio between the equivalent and absorbed radiation doses for a soft tissue is H (Sv) =1.09 D (Gy). In the calculations, we put H ≈ D.

The protective barrier thickness X is equal to

$$X=X_{\text{conc.}}+X_{\text{eq. conc.}}, \qquad (2)$$

where $X_{\text{conc.}}$ is the concrete shield thickness of the accelerator's vault in the given direction; $X_{\text{eq. conc.}}$ is the total thickness of walls, ceilings and made ground, reduced to the concrete layer thickness in the given direction.

The electron beam loss in the different LUE-10M elements was estimated at the following accelerator parameters: the beam pulse current of the accelerator gun -0.42 A; the pulse duration – 10 µs; the 4.6 MW microwave power is supplied to the accelerating structure by 328 cm in length; the pulse rate is 600 Hz; the beam is swept with a scanner within 9 degrees relative to the accelerator axis.

The computations of loss of the particle number as well as of their average energy and current along the accelerator were carried out using the PARMELA, EGUN, SUPERFISH packages (Fig. 3). The beam loss in the elements of the accelerating structure can be divided for two groups of the electrons: some are of energy E_0= 80 keV, and some of energy E_0= 2 MeV. The bremsstrahlung power of 2 MeV electrons with average current of 0.23 mA in copper was estimated to be by a factor of ~ 80 lower than the radiation power from 10 MeV electrons with average current of 2 mA in tungsten. The X-ray power of the beam with maximum energy of 80 keV and average current of 0.27 mA will be still lower.

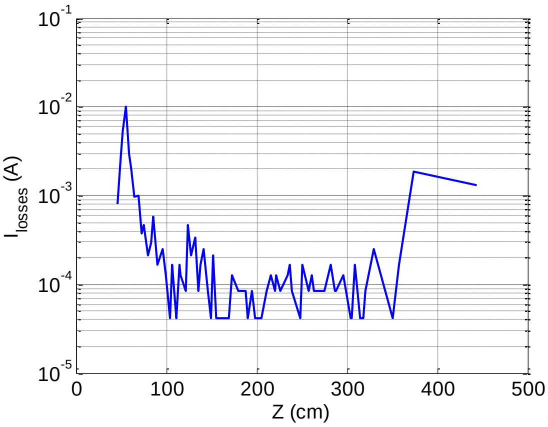

Fig. 3. Current of lost particles along accelerating structure

We have determined the angular distribution of the X-ray dose rate $\dot{D}_0(\theta)$ at a distance of 1 m from a thick tungsten target at an electron energy of 10 MeV and average beam current of 1 mA in the lines of control points using the Table 2 of the ref. [2]. The obtained data for the 2 mA current are presented in Table 2.

Table 3 lists the values of the following parameters: equivalent dose rate when a continuous operation of the accelerator with energy 10 MeV and average beam current 2 mA without shielding; the necessary dose attenuation factor; the concrete shield thickness with safety factor 2 for bremsstrahlung attenuation at the reference points A_1 to A_9; and the thickness of the actually existing shield. Here and below, the reduced dose rate attenuation coefficient for bremsstrahlung with end-point energy 10 MeV as a function of the 2.3 g/cm^3 dense concrete shield thickness was taken from ref. [4].

2. SCATTERED RADIATION ASSESSMENT

For calculating the scattered radiation effect to the equivalent dose rate at the entry to the accelerator's vault, in the premises atop the vault, and in the loading hall, we choose the reflecting surfaces that provide approximately equal contribution (see Figs. 1 and 2).

Table 2

Angular coordinates, distances from the reference points to the point O, and the absorbed dose rate at a distance of 1 m from the target in the direction of a reference point

Points	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
Angle, θº	90	90	90	3.5	3.5	3	4.4	140	135
R, m	7.7	6	9.3	17	17	18	13	9	17.5
$\dot{D}_0$,Gy·m^2/(h·2mA)	$5.6\cdot10^2$	$5.6\cdot10^2$	$5.6\cdot10^2$	$5.72\cdot10^4$	$5.72\cdot10^4$	$5.72\cdot10^4$	$4\cdot10^4$	$4.8\cdot10^2$	$5\cdot10^2$

Table 3

Equivalent dose rate without shielding, attenuation factor, calculated concrete shield thickness with safety factor 2, X (calc.), and the thickness of existing shielding, X (real.)

Points	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
$\dot{H}$, Sv/h	9.5	15.5	6.47	$2\cdot10^2$	$2\cdot10^2$	$1.76\cdot10^2$	$2.37\cdot10^2$	5.93	1.63
K(X)	$4.6\cdot10^6$	$7.6\cdot10^6$	$3.2\ 10^6$	$9.6\cdot10^7$	$9.6\cdot10^7$	$8.6\cdot10^7$	$1.2\cdot10^8$	$2.9\cdot10^6$	$8\cdot 10^5$
X(calc.),cm	260	275	255	325	325	320	330	255	240
X(real), cm	270	300	400	500	500	500	500	300	300

All initial basic data, required for calculations, are given below. The equivalent dose rate of triply-scattered radiation H_S by the surfaces S_1, S_2, S_3 is determined by the formula [3]

$$\dot{H}_S = \frac{\dot{D}_0}{R^2}\cdot\left[\frac{\alpha_1(\theta_1\cdot E_0)\cdot S_1\cdot\cos\theta_1}{R_1^2}\right]\times$$
$$\times\left[\frac{\alpha_2(\theta_2\cdot E_0)\cdot S_2\cdot\cos\theta_2}{R_2^2}\right]\times \tag{3}$$
$$\times\left[\frac{\alpha_3(\theta_3\cdot E_0)\cdot S_3\cdot\cos\theta_3}{R_3^2}\right],$$

where $\alpha_1(\theta_1.E_0)$ is the differential dose albedo for the bremsstrahlung radiation with end-point energy E_0, incident on the scattering surface S_1 at the angle θ_1 relative to the surface normal; θ_{rad} is the radiation angle; R is the distance from the radiation source to the scattering surface S_1 (m); R_1 is the S_1 to S_2 distance; $\alpha_2(\theta_2.E_0)$ is the differential dose albedo for the gammas with energy E = 0.5 MeV, incident on the scattering surface S_2 at the angle θ_2 relative to the surface S_2 normal. R_2 is the distance from the scattering surface S_2 to the scattering surface S_3. $\alpha_3(\theta_3.E)$ is the differential dose albedo for the gammas with energy E = 0.25 MeV, incident on the scattering surface S_3 at the angle θ_3 relative to the surface S_3 normal; R_3 is the distance from the scattering surface S_3 (m) to the reference point A_5, found in the loading hall of the laboratory building.

In the calculations the bremsstrahlung radiation was assumed to be produced at point O during electron beam interaction with the tungsten target, and at point O′ during beam interaction with the stack-monitor (see Fig. 1). For the maze shield calculations, the scattering surfaces S_1, S_2, S_3, and S_4 were chosen as principal. The first surface S_1 is divided into three parts: S_{11}, S_{12}, S_{13}. The scattered radiation from them causes the dose rate $\dot{H}(S_{21}) = \dot{H}(S_{11}) + \dot{H}(S_{12}) + \dot{H}(S_{13}) = 0.21$ Sv/h on the subsurface S_2. Similarly to S_1, the surface S_2 is divided into three parts. The scattered radiation from the subsurfaces S_{21}, S_{22} and S_{23} produces the dose rate $\dot{H}(S_{31}) = \dot{H}(S_{21}) + \dot{H}(S_{22}) + \dot{H}(2_{13}) = 0.0001$ Sv/h on the surface S_{31}.

The subsurface S_{32} is exposed to the direct bremsstrahlung from the points O and O′. Having the radiation power attenuation factor K(x), the radiation creates the dose rate $\dot{H}(S_{32}) = 0.29$ Sv/h. At point A_5, the subsurfaces S_{31} and S_{32} contribute to the scattered radiation dose rate 1.41 μSv/h. The calculation shows that the contribution to the dose rate at point A_5 from the surface S_{33} amounts to ~10^{-9} Sv/h, and thus, it can be neglected. The surfaces S_{41} and S_{42} give their contribution to the scattered radiation dose rate at point A_9, estimated to be

$$\dot{H}(A_9) = \Sigma\dot{H}_{(S41)} + \Sigma\dot{H}_{(S42)} = 5.81\cdot10^{-6}\ \text{Sv/h}.$$

Under the accelerator operation, the personnel may stay at this point for a short time.

3. CALCULATION OF OZONE CONCENTRATION AND FORBIDDEN PERIOD

At the steady-state operating conditions, the ozone concentration in the air of the accelerator chamber will be equal to [2]

$$\tilde{N}_{ch}^{oz} = \frac{Q_{oz}}{V_{ch}\cdot\hat{E}_{ch}} = \frac{4.2\cdot10^7\cdot I_{av}\cdot d\cdot K_{zon}}{(\lambda+\hat{E}_{zon})\cdot V_{ch}\cdot\hat{E}_{ch}}\times \tag{4}$$
$$\times[1-\exp\{-(\lambda+\hat{E}_{zon})\cdot t_{zon}\}]\ mq/m^3\ ,$$

where Q_{oz} is the quantity of ozone in air, produced per hour. The LUE-10M parameters for calculation of ozone concentration are presented in Table 4.

Table 4

The LUE-10M parameters for calculation of ozone concentration

Working chamber volume V_{ch}, m^3	265
Accelerator's exit window-to-stack-monitor distance d, m	2.85
Average cross-sectional area of the beam in air S_{zon}, m^2	0.07
Air change coefficient in the working chamber, K_{ch}	45
Maximum permissible concentration of ozone (MPC_{oz}), mg/m^3	0.1
Beam ionization losses in air $(dE/dx)_{ion}$ at E_0=10 MeV, MeV cm^2/g	1.98

$$\lambda = \lambda_{rad} + \lambda_{chem}.$$

MPC_{oz} is by a factor of 50 lower than that of nitrogen oxides. Therefore, the calculation was performed for ozone. The coefficient of ozone radiation instability is $\lambda_{rad}=1.6\cdot10^{-2}\cdot P^{0.6}=1.15\cdot10^{4}\,h^{-1}$, because

$$P = 3.6\cdot10^{10}\cdot(dE/dx)_{ion}\cdot I_{av}\cdot d/S_{zon} = 5.8\cdot10^{9}\,cGy/h.$$

$$K_{zon}=K_{ch}\cdot\sqrt[3]{V}_{ch} / \sqrt{S}_{zon} = 1087\ h^{-1} \text{ and } t_{zon}= 9.2\cdot10^{-4}\ h.$$

The factor $[1–\exp(-(\lambda+K_{zon})\cdot t_{zon}]$ can be taken equal to unity at steady-state conditions. Thus, the ozone concentration in the air of working chamber will be

$$\tilde{N}^{oz}_{ch} = \frac{4.2\cdot10^{7}\cdot I_{av}\cdot d\cdot K_{zon}}{(\lambda+\hat{E}_{zon})\cdot V_{ch}\cdot \hat{E}_{ch}} = 1.74\,mg\cdot m^{-3}, \quad (5)$$

The prohibited period is given by the formula from ref. [2]

$$\grave{O}^{oz}_{chm} = \frac{\ln(\frac{\tilde{N}^{oz}_{ch}}{MPC_{oz}})}{(\hat{E}_{ch}+\lambda_{ch})} = 0.062\,h \approx 4\,\text{min}, \quad (6)$$

where $\lambda_{ch.}=1.2\ h^{-1}$ is the chemical ozone instability coefficient being independent of the radiation conditions.

At the given mode of accelerator operation, no radioactive gas generation (^{15}O and ^{13}N) is expected, because the threshold of the corresponding reactions is higher than 10 MeV.

CONCLUSIONS

The radiation levels behind the shield, and hence, the necessary thickness of the latter, are mainly determined by the direct bremsstrahlung, whereas at the point A_0 – by the scattered radiation.

The bremsstrahlung power generated when the processing of medical devices, polymeric materials and semiconductor items will be by a factor of 3 lower than if using a thick tungsten target.

It follows from the present data, that with the accelerator LUE-10M operating in the mode (10 MeV; 2 mA) the existing radiation shield will be sufficient for ensuring the permissible equivalent dose rate for the accelerator staff.

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РАДИАЦИОННАЯ ЗАЩИТА РЕКОНСТРУИРУЕМОГО УСКОРИТЕЛЯ ЛУЭ-10М

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На действующем в ННЦ ХФТИ ускорителе ЛУЭ-10М производится стерилизация значительного объема изделий медицинского назначения в Украине и тем самым обеспечивается вклад в национальную безопасность. К настоящему времени комплектующие изделия ускорителя выработали свой ресурс и устарели, поэтому предполагается провести реконструкцию ЛУЭ-10М на новой элементной базе с размещением нового излучателя с энергией 10 МэВ и средним током до 2 мА в том же помещении. Проведенные расчеты показывают, что характеристики имеющейся защиты и системы вентиляции ЛУЭ-10М при работе ускорителя с проектными параметрами пучка удовлетворяют требованиям нормативных документов.

РАДІАЦІЙНИЙ ЗАХИСТ РЕКОНСТРУЙОВАНОГО ПРИСКОРЮВАЧА ЛУЕ-10М

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На діючому в ННЦ ХФТІ прискорювачі ЛУЕ-10М проводиться стерилізація значного об'єму виробів медичного призначення в Україні і тим самим забезпечується внесок у національну безпеку. До теперішнього часу комплектуючі вироби прискорювача вичерпали свій ресурс і застаріли. Тому передбачається провести реконструкцію ЛУЕ-10М на новій елементній базі з розміщенням нового випромінювача з енергією електронів 10 МеВ і середнім струмом пучка до 2 мА в тому ж приміщенні. Проведені розрахунки показують, що при роботі прискорювача з проектними параметрами пучка характеристики наявного радіаційного захисту і системи вентиляції ЛУЕ-10М задовольняють вимогам нормативних документів.