RADIATION PERFORMANCES OF A HIGH CURRENT DEUTERON LINAC CHANNEL

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The results of numerical simulation of spatial and time performances of the radiation field, which is produced by the induced activity in high-current deuteron linac elements, are given.

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1. INTRODUCTION

One of ion accelerator applications is production of radioisotopes used in medicine, biology, and industry. About 90% of radiological diagnostic examinations in medicine are based on the usage of technetium-99m radionuclide, which is generated as a result of decay of a parent radioisotope (generator) of molybdenum-99. The basic method of ^{99}Mo production is the irradiation of high-enriched uranium-235 targets by neutrons in a nuclear reactor, and the subsequent chemical ^{99}Mo extraction from high radioactive uranium fission products [1].

To exclude the problems with usage of nuclear reactors [1], the alternative methods for producing ^{99}Mo-^{99m}Tc have been offered, which are based on an application both electron accelerators [1,2] and ion ones [3,4]. In particular, for production of ^{99}Mo in commercial amount in a paper [4] it was offered to use a high-current deuteron linac with the output energy of W=14 MeV and average current of I=1 mA. If the accelerator operation time factor is 70%, the total ^{99}Mo production has to be about 1000 Ci/yr, when thin foils from natural molybdenum are used as targets.

The essential accelerator performance is its radioactive purity that is needed for the accelerator maintenance. As the radiation purity criterion it is considered that the equivalent dose rate at a distance of 1 m from an accelerator axis should not exceed permissible dose rate K_p in 1 hour after the accelerator switch off (radiation cooling time) and after its long-term operation (activation time) [5]. In Ukraine for the personal, in correspondence with the recommendation *ICRP* (*International Commission on Radiological Protection*), the annual dose limit is D_p=20 mZv. As the personal work time is t_p=1700 h/yr that corresponds to the permissible dose rate of K_p=11.2 μZv/h [6].

The purpose of the present work is the simulation of radiation field produced by induced activity in high-current deuteron linac elements for different activation and cooling times and finding on this basis of beam current losses dI/dz along the accelerating channel satisfying to radiation purity requirements (z is a longitudinal coordinate along the accelerator).

2. THE INDUCED ACTIVITY GENERATION

The proposed deuteron linac [4] consists of an initial section with radio frequency quadrupole focusing (*RFQ*) of length 4.7 m and output deuteron energy of W_1=2 MeV, and two *H*-cavity sections with the modified alternative phase focusing (*MAPF*), which lengths are 3.14 m and 3.8 m, and the output energies of W_2=6.4 MeV and W_3=14 MeV respectively. Between sections the magnetic quadrupole lenses are situated for matching of beam phase space characteristics with the sectional performances. The total accelerator length is 14 m. The deuteron energy W_1 of the *RFQ*-section is taken below than the threshold of activation reactions. Therefore the beam losses in the section are not limited by the purity requirements.

The accelerating channel of *MAPF1* and *MAPF2* sections represents a set of copper drift tubes with aperture radii varying from 1 cm at *MAPF1* inlet up to 2.9 cm at *MAPF2* output. The drift tubes are mounted in a copper cylindrical cavity with the diameter of 40 cm, and the wall thickness of 1 mm. Every *MAPF* section is situated in a cylindrical vacuum liner of *12X18H10T* stainless steel with 89 cm in diameter and the wall thickness of 10 mm.

The linac activation is caused by nuclear reactions, which arise when accelerated deuterons are bombarding the drift tube surfaces. Accelerator activation processes would be divided in 3 groups.

1. Deuteron activation of drift tube surfaces as a result of reactions with nuclei of natural copper isotopes of $^{63,65}Cu$. The generated radionuclides distributed in thin layer of l≤0.3 mm which is less than the path length in copper of deuterons with energy of W_3=14 MeV.
2. Activation of drift tube volume by the secondary fast neutrons, which result from $^{63,65}Cu$ (d, xn)-channels of nuclear reactions, when the deuterons are bombarding the copper drift tubes.
3. Activation of the vacuum liner by secondary fast neutrons, which were not absorbed by the copper drift tubes.

Activation of the cavity walls by fast secondary neutrons would not be taken into account owing to the small wall thickness.

For definition of nuclear reaction channels and their cross-sections for deuterons in copper drift tubes, and the secondary neutrons in drift tubes and in the liner, and also γ-rays energies, which are emitted by radionuclide decay, decay constants, and γ-ray quantum yields were used both the published data [7,9-11] and evaluated neutron data *ENDF/B-VI* and experimental nuclear data *EXFOR* libraries of Brookhaven National Laboratory of USA. The isotope abundance ratios of copper and multicomponent alloy of the liner have been determined using Ref. [8].

The accelerating section model, which was used for calculations of induced activity dose rate, is shown in Fig.1. It was supposed that the linear density of deuteron beam losses dI/dz is a constant along the accelerating channel. Since the drift tube diameters are essentially less than the distance from a channel element dz_0 to a view point $P(r,z)$, Fig.1, it is possible to consider the source of γ-rays, emitted by the i- radionuclide decay in the drift tubes as linear one with linear activity $A_{ch}(z)$. The linear activity $A_{ch}(z)$ is the function of z-coordinate, owing to monotonous deuteron energy growth along the channel.

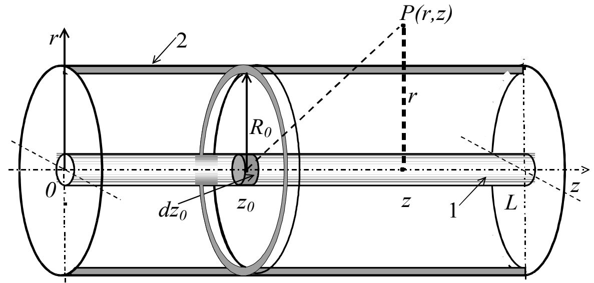


Fig.1. *Model of accelerating section for simulation of induced activity dose rate: 1- accelerating channel of drift tubes, 2- vacuum liner*

It was also supposed, that the activity uniformly distributed over the liner azimuth, and linear activity of the liner $A_{Li}(z)$ depends only on the longitudinal z-coordinate.

As γ–rays are emitted isotropically by a radionuclide of the i-kind, and if the radiation absorption is neglected in drift tubes and the liner, then the dose rate in $P(r\ z)$ point, produced by activations of drift tubes of $K_{chi}(r,z)$ and the liner of $K_{Li}(r,z)$ may be presented as [12]:

$$K_{chi}(r,z) = \Gamma_{\delta\,i}\int_0^L \frac{A_{chi}(z_0)dz_0}{(z-z_0)^2+r^2}, \qquad (1)$$

$$K_{Li}(r,z) = \Gamma_{\delta\,i}\int_0^L \frac{A_{Li}(z_0)dz_0}{\sqrt{(z-z_0)^4+2(z-z_0)^2(r^2+R_0^2)+(r^2-R_0^2)^2}}, \qquad (2)$$

where Γ_{δ_i} is the air kerma constant for the i-radionuclide [12], L is the accelerating section length. The integrand in (2) is the dose rate produced by a liner elementary ring of R_0 radius and dz_0 length, Fig.1.

The total dose rate $K(r,z)$ is the sum of partial dose rates produced by all i-radioisotopes, generated in drift tubes and the liner:

$$K\left(r,z\right) = \sum_i K_{chi}\left(r,z\right) + K_{Li}\left(r,z\right). \qquad (3)$$

The linear activity $A^{(d)}_{chi}(z)$, generated by the drift tube deuteron bombarding, is given by the expression:

$$A_{chi}^{(d)}(z) = (B_i(W)/\lambda_i)(dI/dz)[1-\exp(-\lambda_i t_a)]\exp(-\lambda_i t_c), \quad (4)$$

where $B_i(W)$ is the i-radionuclide yield due to deuteron reactions with copper [10], $W=W(z)$ is the deuteron energy, λ_i is the i-radionuclide decay constant [9], t_a is the activation time, t_c is the radiation cooling time.

To define the activation of drift tubes $A_{chi}^{(n)}(z)$ and the liner $A_{Li}^{(n)}(z)$ by the secondary neutrons it is necessary to know the distribution of neutron source strength $S_n(z)$ (n/s m) along the accelerator. If one considers that the neutron source is linear one and is located along the system axis, then the source strength $S_n(z)$ is:

$$S_n(z) = (dI/dz)\sum_i p_i B_i(W)/\lambda_i, \qquad (5)$$

where the summing is made over all $B_i(W)$ yields for reactions of ${}^{63,65}Cu(d,n)$ and ${}^{63,65}Cu(d,2n)$; p_i=1 or 2 accordingly for (d,n) or $(d,2n)$ reactions. Then the drift tubes linear activity $A_{chi}^{(n)}(z)$ will be given as:

$$A_{chi}^{(n)}(z) = \frac{N_0}{A}\frac{S_n(z)\sigma_i\rho\,\eta_i d_{sc}}{\lambda_i}[1-\exp(-\lambda_i t_a)]\exp(-\lambda_i t_c), \quad (6)$$

where N_0 is the Avogadro number, A is the copper mass number, ρ is the copper density, η_i is the abundance ratio of the i-kind isotope in copper, σ_i is the activation cross-section of this isotope by neutrons, d_{sc} is the mean neutron scattering length in copper.

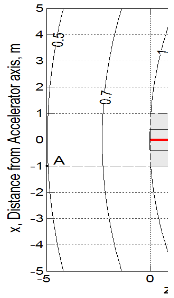
Since the neutron source strength $S_n(z)$ is known, it is possible to calculate the liner linear activity of $A_{Li}^{(n)}(z)$, produced by the secondary neutron irradiation. For that the total neutron flux through the liner elementary ring, Fig.1, irradiated by the linear neutron source $S_n(z)$ of L length, was calculated.

The neutron activation cross-sections $\sigma_i(E_n)$ are functions of neutron energy E_n. In the present work the energy distribution of the fast neutrons, generated in $Cu(d,xn)$ reactions, was not examined. For linac activation calculations the maximal σ_i values for the neutron energy range of $0,1 \le E_n \le 20$ *МэВ* have been used (upper estimation). The integrals (1) and (2) had been taken numerically.

3. RESULTS OF SIMULATION

The dose rate map of the radiation field, produced by induced activity of the linac in t_c=1 h after its switch off, and for the activation time t_a=1 yr, is shown in Fig. 2. The equivalent dose rate isolines $K(r,\ z)=const$ are normalized (%) to the dose rate K_c in the critical point P_c(1 m; 13,65 m), located 1 m apart from the accelerator axis (z=0 corresponds to the *RFQ*-section input). In this point the dose rate K_c is maximal one. As it follows from Fig.2, for the constant beam losses dI/dz along the channel, the maximal dose rate area is at the end of the accelerator. It is caused by the growth of radionuclide yields $B_i(W)$ with increasing of deuteron energy $W(z)$ and opening additional channels of radioisotope generation.

The spatial distribution of reduced dose rate $K(r,z)/K_c$, Fig.2, does not depend on the beam linear losses dI/dz, and is the important radiation characteris-



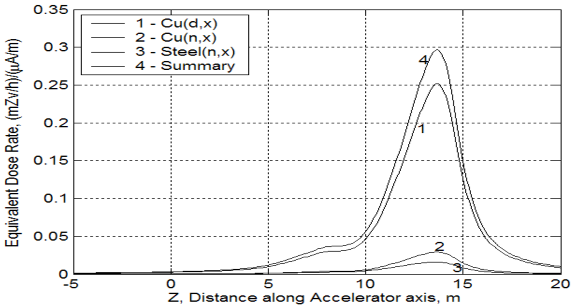


***Fig. 2.** Dose rate map of activated deuteron linac for t_a=1 year and t_c=1 hour*

***Fig. 4.** Dose rate distributions along accelerator part 1 m from axis: 1 – drift tube deuteron activation, 2 – drift tube neutron activation, 3 - liner neutron activation, 4 – total*

tics of the accelerator. The absolute value of dose rate $K(r,z,t_a,t_c)$ depends on the times of activation t_a, and cooling t_c, and is proportional to the beam losses *dI/dz*.

In Fig.3 the dose rates K_c in the critical point P_c, reduced to the beam losses *dI/dz* are given as the function of cooling time t_c, and for different activation time t_a.

For the short activation time t_a the equilibrium concentration is achieved for short-lived radionuclides. Therefore the activity decreases quickly after the accelerator switch off (t_a=1 h), Fig.3. For long activation time the essential contributions in the total activity give the long-lived radionuclides, which activity decreases slowly with growth of cooling time t_c.

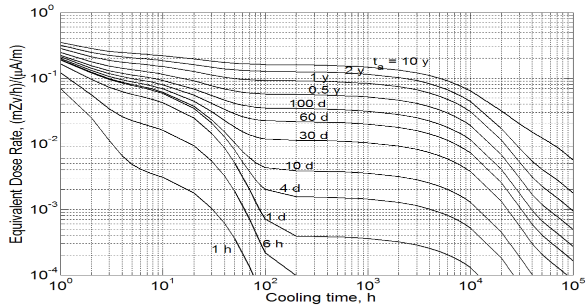


***Fig. 3.** Dependence of equivalent dose rate reduced to beam losses on cooling time t_c and for different activation time t_a in the critical point P_c*

On the base of the dependences, Figs.2 and 3, the equivalent dose rate would be calculated in any space point, and for different activation t_a and cooling t_c times, and beam losses *dI/dz.* In particular, from Figs. 2 and 3 it follows that the dose rate K_c in the critical point P_c will not exceed the permissible dose rate K_p=11.2 μZv/h through t_c=1 hour after the accelerator switch off, if the beam losses $dI/dz \leq 3.7 \cdot 10^{-8}$ A/m, and long continuous linac operation ($t_a \geq 1$ yr).

In conclusion it needs to mark, that the main contribution to the dose rate gives the copper drift tube activation by deuterons. In Fig.4 the dose rate distributions along the line, which is parallel to the accelerator axis and crosses the critical point P_c, (line *AB*, Fig.2) are shown, which are produced by: drift tube deuteron activation - 1, drift tube neutron activation - 2, liner neutron activation - 3 and the total dose rate - 4. As it follows from Fig. 4, the contribution to the total dose rate of accelerator activation by the secondary neutrons does not exceed 17 %.

REFERENCES

1. R.G. Benett, I.D. Christian, D.A. Petti et al. A System of ^{99m}Tc Production Based on Distributed Electron Accelerators and Thermal Separation // *Nuclear Technology*. 1999, v. 126, p.102–121.
2. N.P. Dikiy, A.N. Dovbnya, V.L. Uvarov. Development of New Electron Irradiation Based Technology for Technetium-99m Production*.* // *Proceedings of the Sixth European Particle Accelerator Conference.* 1998, p.2389–2391, Stockholm, Sweden.
3. P.A. Demchenko, V.A. Voronko, V.Ya. Migalenya et al. Application of Compact Linear Accelerators for Medicine // *Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations* (31,32). 1997, №4,5, p.168–170 (in Russian).
4. P.A. Demchenko, Ye.V. Gussev, M.G. Shulika. A Channel of High Current Deuteron Linac with Low Radiation Losses // *Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations* (41). 2003, №2,p.138–143.
5. *Linear Ion Accelerators*/ Ed. by B.P. Murin. v.2. M.: “Atomizdat”, 1978, p.20 (in Russian).
6. *Normy Radiotchijnoi Bezpeki Ukraine (NRBU-97).* Kiyv, 1997 (In Ukraine).
7. Catalog of Gamma Rays from Radioactive Decay // *Atomic Data and Nuclear Data Tables*. 1983, v.29, №2, p.190-406.
8. *Tables of Isotopes. 8-th Edition/* Edited by R.B. Firestone, John Willey & Sons, Inc., 1999.
9. *ICRP Publication 38. Radionuclide Transmutation, Energy and Intensity of Emissions.* New York: Pergamon Press, 1982.
10. P.P. Dmitriev. *Vyhod radionuklidov v reaktsiyah s protonami, dejtronami, al'fa-chastitsami i geliem 3. Spravochnik.* M.: Energoatomizdat, 1985, p.270 (in Russian).
11. V.M. Bychkov et al. *Sechenija porogovyh reaktsij, vyzvannyh nejtronami. Spravochnik*. M.: Energoatomizdat, 1985, p.216 (in Russian).

12. V.F. Kozlov. *Spravochnik po radiatsionnoj bezopasnosti.* M.: Energoatomizdat, 1987, p.191 (in Russian).

РАДИАЦИОННЫЕ ХАРАКТЕРИСТИКИ КАНАЛА СИЛЬНОТОЧНОГО ЛИНЕЙНОГО УСКОРИТЕЛЯ ДЕЙТРОНОВ

В.А. Воронко, Е.В. Гусев, П.А. Демченко, В.В. Сотников, Н.Г. Шулика

Приведены результаты численного моделирования пространственных и временных характеристик радиационного поля, создаваемого наведенной активностью в элементах сильноточного линейного ускорителя дейтронов.

РАДІАЦІЙНІ ХАРАКТЕРИСТИКИ КАНАЛУ СИЛЬНОСТРУМОВОГО ПРИСКОРЮВАЧА ДЕЙТРОНІВ

В.О. Воронко, Є.В. Гусєв, П.О. Демченко, В.В. Сотніков, М.Г. Шуліка

Наведено результати чисельного моделювання просторових і часових характеристик радіаційного поля, що створюється наведеною активністю елементів сильнострумового прискорювача дейтронів.