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Theoretical Justification of the Possibility of Cryocooling of a Solid Target at Irradiation with Proton Beam from Cyclotron C18

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Abstract—The thermal physics processes of solid target cooling at proton beam irradiation in C18 cyclotron were calculated. The calculations were made with the help of finite-elements method using ANSYS program for beams with nonuniform density of particle distribution in the beam profile. It was shown that the radiation efficiency and conditions of target cooling essentially depend on distributions of particles in the beam and on efficient size of beam. A principal possibility of the cryocooling of target is shown that would essentially increase the radiation efficiency and the yield of final product – the medical isotope ^{99m}Tc. The developed calculation method may be of use also for other processes of target irradiation with charged particle beams.

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1. INTRODUCTION

Last years the possibility of direct production of ^{99m}Tc (escaping the stage of intermediate ^{99}Mo) for medical purposes using nuclear reaction with charged particle beams is actively discussed world over [1, 2]. In Alikhanian National Science Laboratory a technique of ^{99m}Tc isotope preparation [3] is under development using the method of irradiation of ^{100}Mo molybdenum target embedded into a titanium-base by a proton beam of C18 cyclotron [4]. One of the restrictive factors of this technique is the removal of heat released in the target as a result of proton scattering.

In the present work a technique of cryocooling from the backside of target with liquid nitrogen was proposed. An analysis of thermal physics processes by means of finite- elements method (FEM) using ANSYS program [5] was performed.

3. TARGET MODULE

The isotope ^{99m}Tc may be produced on a cyclotron by means of bombardment of molybdenum target in reaction ^{100}Mo(p,2n)^{99m}Tc. In this process the proton beam is incident on 'Nitra Solid Compact TS06' target module [5] combining both the heat removal and the clamping of target.

The target consists of a metallic disk and of the irradiated material disposed in the central depression of the disk (Fig. 1).

The target disk has the following geometry: the diameter is 12 mm, height 2 mm, diameter of depression 6 mm, depth of depression 1 mm.

For 18 Mev proton the optimum thickness of target is determined by the cross section of reaction ^{100}Mo(p,2n)^{99m}Tc. According to preliminary calculations based on programs 'Stopping and Range of Ions

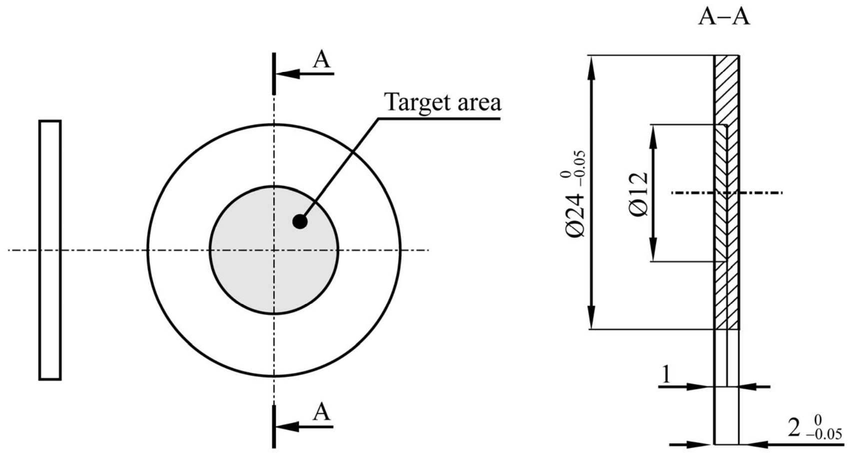

Fig. 1. Geometric parameters of the target.

in Matter' (SRIM), the thickness is 408 μm [5]. SRIM is a program package for calculation of ions range in the matter.

The material of metallic disk must have high mechanical strength, high heat conductivity for effective heat removal during irradiation and be chemical inactive. Such are, e.g., titanium and niobium.

According to the factory technology, during the irradiation the target must be cooled on both the front and the back sides. On the front side the target is cooled by purging helium. On the back side the factory technology provided for water cooling under 8 bar pressure. This method allows utilization of $W = 500$ W of thermal capacity released by the beam in the target. In case of proton energy $E_p = 18$ MeV this capacity corresponds to beam current $I_p \approx 27$ μA, while C18 cyclotron can provide the current up to 100 μA. So, by increasing in the intensity of target cooling one can appreciably increase the beam current at irradiation and the efficiency of isotope production.

To select a suitable target disk material and the cooling method, a preliminary thermal physics calculation of axially symmetric target for ^{99m}Tc production process is required.

3. THERMAL PHYSICS CALCULATION OF AXIALLY SYMMETRIC TARGET

The thermal physics calculation of the target in the process of its irradiation by a proton beam is based on the solution of heat conduction equation

$$\rho c \frac{\partial T}{\partial t} = q(t,x,y,z) + \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right), \tag{1}$$

where $T(t,x,y,z)$ is the temperature as a function of time t and space coordinates x, y, z, ρ the density of material, c the thermal capacity, q the heat generation function in a unit volume in unit time, λ the heat conductivity factor (assuming the temperature dependence of λ). Function q specifies the heat production due to the scattering and absorption of proton beam in target material, i.e., the local density of the flux and cross section of proton beam absorption in this type of target material. As we are interested in the steady-state solution of this thermal physics problem, so the first term in equation (1) determining the temperature field dynamics is omitted. Besides, as the beam is usually axially symmetric, we will confine to an axially symmetric solution of the equation.

The thermal physics calculations of target is performed using the FEM. The essence of FEM lies in the fact that the range, in which the solution of differential equations is sought, is divided into a finite number of subranges (elements). The form of approximating function in each of these elements is chosen arbitrarily. It is a first-degree polynomial in the simplest case. Outside its element the approximating function is zero. The values of functions at boundaries of elements (nodes) are the solution of the problem and are unknown in advance. The coefficients of approximating functions are usually sought from the condition of equality of values of adjacent functions at the boundaries between the elements (nodes). Then these coefficients are expressed in terms of the values of functions in the nodes of elements. A system of linear algebraic equations is composed. The number of equations equal to the number of unknown values in the nodes, at which the solution of the initial system is sought, is directly proportional to the number of elements, and is limited only by computer capabilities. Since each element is associated with a limited number of neighbors, the set of linear equations has a rarefied view that greatly simplifies its solution [7].

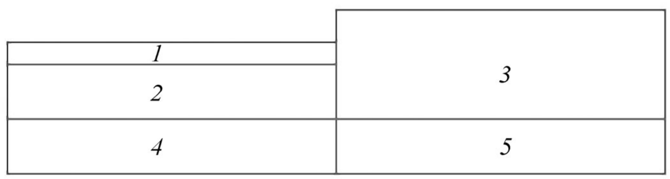

Fig. 2. Reference target areas: *1* – the target material, *2*, *3* – ranges of target disk, *4*, *5* – ranges of material adjacent to the target disk (water at water cooling and copper in case of the nitrogen cooling).

To date FEM is the main tool for complex thermal physics calculations, for which ANSYSFLOTRAN programs were used. ANSYS is a universal software system of FEM analysis that exists and is developed

Table 1. Thermal conductivity of composite materials of target and disk at various temperatures

Temperature, K	Heat conductivity, W/mm K			
	Molibdenium	Niobium	Titanium	Copper
4	0.061	0.14	0.0058	16.2
10	0.15	0.29	0.014	24
20	0.29	0.25	0.028	10.8
40	0.36	0.095	0.039	2.17
80	0.21	0.058	0.033	0.56
150	0.149	0.053	0.027	0.429
200	0.143	0.053	0.025	0.413
300	0.138	0.054	0.022	0.401
400	0.134	0.055	0.02	0.393
600	0.126	0.058	0.019	0.379
800	0.118	0.061	0.02	0.366
1000	0.112	0.064	0.021	0.352

for already 30 years, it is rather popular among professionals in the field of automated engineering calculations and solutions of linear and nonlinear, stationary and non-stationary three-dimensional problems of the mechanics of deformed solid body, the mechanics of structures, of liquid and gas, heat transfer and exchange, the electrodynamics and acoustics [5].

As the target disk is axially symmetric and the beam is also assumed to be axially symmetric with coincident of the beam and target, the problem reduces to solution of an axially symmetric model. The model of target disk and of target comprises several areas. Fig. 2 shows the section of axially symmetric model. The target axis passes along the left boundaries of the *1*, *2* and *3*rd ranges.

After setting of the parametric geometry of model, the thermal conductivity value [8] of any separate area at different temperatures is introduced in the program for each reference area (see Table 1).

With inclusion of thermal conductivities of materials, a finite-element mesh of the model, capacities generated in each range, conditions of convection heat removal from the target surface and boundary conditions at the target bottom are given. The finite-element mesh is shown in Fig. 3.

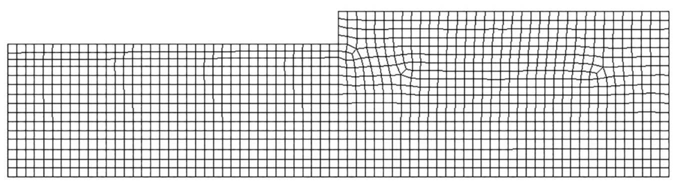

Fig. 3. The finite-element mesh of the model of target disk.

The heat removal on the front side of target is realized by purging helium, and on the back side it may be made by flushing with liquid nitrogen or water flow. According to target module specification the maximum permissible pressure of helium at the target input is 0.5 MPa, and maximum input temperature is 25°C. Under these conditions the coefficient of surface heat removal is about 550 V/m^{2}K [9] (in 3–7 m/s range of helium flow velocities). Pursuant to calculations, the variations of this coefficient lead to minor changes of the general pattern of thermal physics calculations. Different operating conditions of the target are simulated by a number of boundary conditions.

The calculations were made for different distributions of cyclotron beam, materials of target disk and

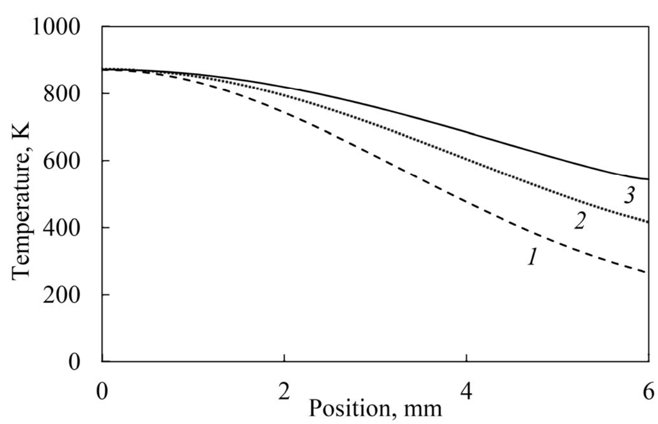

Fig. 4. Temperature distribution over target area at varied beam distributions for the Nb target disk and the liquid nitrogen cooling: (*1*) σ = 3 mm, *I* = 32.8 μA, (*2*) σ = 4 mm, *I* = 53.3 μA and (*3*) σ = 5 mm, *I* = 79.1 μA.

cooling regime of target. In each case we found the beam current, at which the maximum target temperature was within 600°C (the value, at which the molybdenum metal begins to oxidize) [10]. The results of calculations of temperature distribution on the target surface in case of the miobium target disk and of cooling regime of the back side with liquid nitrogen for different distributions of beam are seen in Figure 4.

The calculated data depending on the beam distribution, the target disk material and the cooling method are given in Table 2.

Table 2. Results of calculations versus the beam distribution, material of the target disk and the cooling method

Input parameters			Obtained parameters			
Coefficient of the beam distribution, σ, mm	Material of the target disk	Cooling method	Maximum beam current, μA	Efficiency of beam, %	Efficient current, μA	Maximum temperature in target, K
3	Ti	water	11.6	90.5	10.5	873
4	Ti	water	18	73.8	13.3	875
5	Ti	water	26	59.5	15.5	875
3	Nb	water	27	90.5	24.4	876
4	Nb	water	44.1	73.8	32.5	874
5	Nb	water	66	59.5	39.3	874
3	Ti	liquid nitrogen	16.4	90.5	14.8	873
4	Ti	liquid nitrogen	25.2	73.8	18.6	873
5	Ti	liquid nitrogen	36.2	59.5	21.5	872
3	Ni	liquid nitrogen	32.8	90.5	29.7	872
4	Ni	liquid nitrogen	53.3	73.8	39.3	874
5	Ni	liquid nitrogen	79.1	59.5	47.1	873

4. CONCLUSIONS

The thermal physics calculation of cooling processes of a solid target bombarded by a proton beam from C18 cyclotron was performed by means of finite-element method (FEM) based on ANSYS program. Calculated data on the maximum temperature of target surface at different cooling regimes, materials of the target disk and distributions of beam density on the target surface are given for the regime of cryocooling. The possibility in principle of the realization of cryocooling of the target is shown, that would permit an essential increase in the beam intensity at irradiation and, so, an increase in the efficiency of irradiation and in recovery of medical isotope. It is shown also that there is the dependence of maximum permissible beam current on the cooling method and on the distribution of beam density on the target surface, that ensure proper setting of the geometric parameters of beam for achieving optimal cooling efficiency. This also reveals a need for measurement of the profile of beam cross section on the target surface. To ensure high measurement accuracy it is advisable to conduct these measurements using the method of sensor scanning based on vibrating strings.

The developed calculation technique on the basis of FEM may be employed in a number of studies of thermal physics and other processes.

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