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MODELING AND PRELIMINARY EXPERIMENTAL RESULTS OF THIN FILM HEATING DURING THE PASSAGE OF A HIGH-ENERGY ELECTRON BEAM

M. Luhanko[1], O. Shopen[2], S. Karpus[2], T. Malykhina[2]
[1]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;
[2]Institute of High Energy Physics and Nuclear Physics, NSC KIPT, Kharkiv, Ukraine
E-mail: luhanko2021tya11@student.karazin.ua

The preliminary experimental results as well as modeling the heating of thin-foil materials during the passage of high-energy electrons with energy of 15 MeV are presented. Foils of 50 μm titanium, 50 μm aluminum and 125 μm Kapton® were chosen as the test targets. A calculation technique has been developed, which consists of automating the finite difference method applying Python programming language tools. These tools allowed solving the problem of heat distribution in the thin foil, taking into account the ionization losses of the primary electron beam and the black body radiation. The data on the surface temperature distribution of the research samples were obtained. The time for establishing thermal equilibrium was determined taking into account the distribution of the electron beam current density. It is shown that optimization of the main parameters of the high-energy electron beam beam (for example the current density) makes it possible to neglect the thermal loads on these films, which was confirmed during bench tests at 30 MeV electron accelerator of the IHEPNP NSC KIPT.

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INTRODUCTION

During the experimental research of high energy beam interaction with thin foils one of the most important aspects of such interaction are difficulties with measuring and controlling the thin foil heating stability or its temperature regime induced by deposited energy of primary particle beam irradiation. For special cases when electron beams energy losses due thin foil passing are extremely low but experimental conditions: contact and noncontact techniques of experimental target temperature measuring (in situ) application are limited. Usually, experimental targets are located in the vacuum chamber, and they have electrical contact only with low current measuring system. Extremely high radiation background conditions (neutron and gamma background irradiation) are present as well. The first fact is a limitation of the application of thermocouple measurements. The second one is a system for applying infrared temperature sensors installed near the irradiated experimental targets. Usually, for experimental targets located in a vacuum chamber, heat losses are determined by the geometric dimensions of the target as well as the target holder and their materials properties.

A particular case is a device for extracting a beam of charged particles from the vacuum volume of a particle accelerator into the air environment. Such devices are useful for the wide applications of high-energy electron beam and bremsstrahlung facilities for fundamental and applied research. In this case, the mode of stabilization of the temperature of the outer side of the window film includes additional heat losses, for example, due to the convection airflow or the power of the blower.

Traditionally, the output devices of the high-energy electron beam of the NSC KIPT electron accelerator uses thin titanium foils that have a thickness of 50 microns [1]. This use of foils ensures, first of all, the stability of their thermal and mechanical properties during long-term operation in various types of linear accelerators and modes of accelerated electron beams.

As part of the research project of the National Academy of Sciences of Ukraine, an experimental setup for the interaction of a high-energy electron beam with a substance (amorphous and single-crystal thin foils) was developed, assembled and tested [1]. A new type of foil was used in the vacuum-to-air electron beam outlet device instead of the standard titanium thin foils. Computer simulation of the passage of electron beams through thin films was carried out using our computer program based on the Geant4 toolkit. Electron energy ranges from 3 to 15 MeV as well as different thickness of thin films were investigated. The main objectives of that work [2] were to estimate the probable values of the energy absorbed in the films, as well as the characteristics of the bremsstrahlung beam for each type of thin film.

The yield of secondary electron emission from 50 μm thick Al foil was studied [3] as a function of the energy of the primary electron beam. The dependences of the yield of delta electrons [4] at constant electron energy of 15 MeV on the thickness of the aluminum target were also measured. In both cases, it is important to know the temperature of the foil. The yield of secondary electron emission, which causes heat, depends on the temperature of the emitted surface and is proportional to T^2 (well-known Richardson's law [5]).

1. EXPERIMENTAL TESTS

Taking into account the positive results of the simulation [2] and preliminary complex thermo mechanical experimental tests, it was decided to use 125 μm Kapton® [6] of two diameters, Ø56 mm and Ø36 mm, as the outlet windows of the electron beam [1]. Kapton® thin films have been successfully tested in bench tests at an electron beam accelerator. A low-current mode of electron beam extraction was chosen. The average current was ~1 μA at at pulse duration of 2 μs and repetition rate of 50 Hz. This system worked without breakdown, and also without destabilization of the vacuum system.

Three types of thin foils were chosen as objects for experiments. There are 50 µm titanium foil, 50 µm aluminum foil and 125 µm Kapton® foil. All studied foils were installed in massive target holders for electron-beam interaction experiments. These foils were mounted to the flange of the electron beam output window (Figs. 1, 2).

The small window in Fig. 1 (the right position) is a direct output of the electron beam into the air, the large window (the left position) is installed after the Faraday cup, at the end point of the electron beam line of the energy magnetic analyzer. The 50 µm thick titanium foil mounted to the flange of the electron beam output window is presented in Fig. 2. The energy of the electron beam operation range is 10…30 MeV. The experimental target holder as a constructional element of the secondary emission monitor system is presented in Fig. 3. The target diameter is 52 mm.

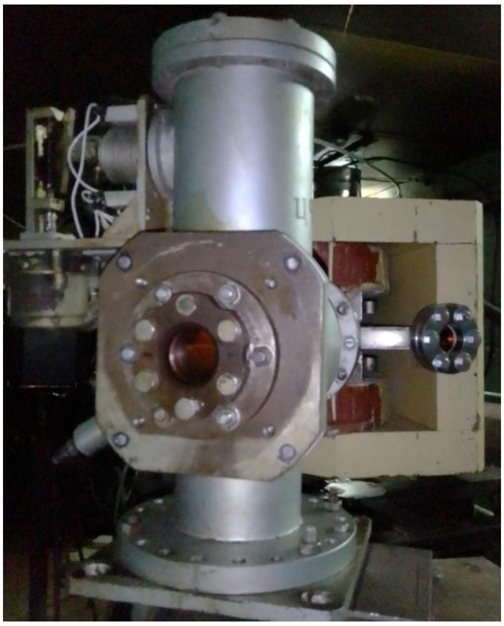

Fig. 1. The 125 µm Kapton® foil as a part of the electron beam output window

Fig. 2. The titanium foil of 50 µm thick after extreme experimental conditions (direct beam line during the operation of 30 MeV electron beam accelerator)

Fig. 3. Experimental target holder as a constructional element of the secondary emission monitor system

The sample of electron beam intensity distribution during the experimental bench test of the experimental facility [1] was printed on the laboratory glass plate with application of low time irradiation interval technique. The energy the electron beam was 15 MeV. The average beam current was 2.5 mkA on the vacuum Faraday cup. The 125 µm Kapton® film was used as a constructional element of the electron beam output window. The imprint of the inverse electron beam was reconstructed using the computational photometric manipulations. The electron beam imprint is shown in Fig. 4. The electron beam dimensions are 5×3 mm^2.

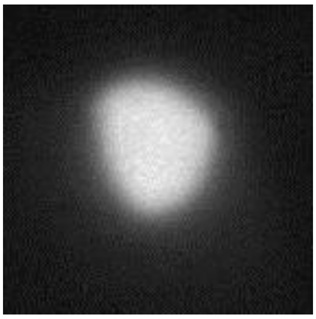

Fig. 4. Electron beam print (inverse image) on the glass plate after 15 MeV electron beam transmitted through 125 µm Kapton®

The distribution of the primary electron beam was determined by analyzing the imprints of the electron beam on a glass plate. The electron beam imprint was processed using the median filter algorithm. Applying this filter preserves the sum of all signals. Since the distribution function of the electron beam intensity, as usual, is unknown, it was decided to use the beam imprint method under optimal operating conditions of the electron accelerator and numerical methods for processing and calculating data.

Irradiation of Kapton® foils by charged particles beams is characterized not only by depletion of their components [7], but also by thermal destruction of the high-molecular structure of the foil. To determine the temperature of the secondary electron emission of a foil, knowledge of the thermal stability regime is very important, since the yield of secondary electrons is known to be proportional to the T^2 value [5]. Thus, the determination of the thermal regime of heating an irradiated object by passing beams of charged particles has a high level of fundamental and technological applications.

2. THE CALCULATION MODEL DESCRIPTION

The computer program [8] based on numerical methods [9] was developed to estimate the heat distribution for various types of thin foils under charged particle beam irradiation. The main task of this part of the study is to determine by numerical calculation the modes of heating thin foils when a high-energy electron beam is passed through them. Three types of thin foils are chosen as objects of simulation based on the performed experiments. There are 50 µm titanium foil, 50 µm aluminum foil and 125 µm Kapton® foil.

Heat transfer can be estimated as a distribution only along the plane perpendicular to the electron beam direction, with a known small error [9]. Zero derivatives at a radius equal to the radius from the center to the wall are chosen as the boundary condition.

One of the conditions of the model calculation is that the target-holder has an unlimited heat capacity. The temperature of the target holder is constant and is close to the standard temperature value (300 K). The inner diameter of the holder is 58 mm. The holder is centered relative to the axial position of the passing electron beam.

Modeling calculations are performed for the energy of the 15 MeV primary electron beam for all types of thin foil, i.e., for the aluminum foil, the titanium foil and for the Kapton® film. The irradiated target surface is perpendicular to the direction of passage of the primary electron beam. The average value of the electron beam current in these computational experiments is 1 µA.

The next task of the study is to evaluate the possible values of the primary electron beam parameters, which will allow the exploitation of the Kapton® polyimide film. This is necessary to prevent extreme temperature regimes, under which the destruction of the film due to overheating is possible. First of all, it is necessary to obtain the dependences of the foils local temperature on the current density at a given value of the energy of the primary electron beam in order to solve this problem. Then, it is necessary to compare the heating dynamics of the films depending on the thin foil material (Titanium, Aluminum and Kapton®)

It has been established by calculation that the maximum temperature is reached during irradiation, until the moment of contact of the thermal wave with the wall. This can be explained by several factors:

1. The thermal wave did not have time to give energy to the walls,

2. The electron beam heats only a small part of the surface.

Due to the complexity of finding the analytical function determining the distribution of the electron beam, its graphical form was used, which makes it possible, depending on the actual distribution of the electron density in the beam, to investigate the dynamics of heating thin films by numerical methods.

Previously, using the main data on the total ionization losses of electrons when passing through thin films of 50 µm Aluminum, 50 µm Titanium, and 125 µm Kapton® were obtained [2, 10]. The calculations use the following values for the deposited energy of the 15 MeV primary electron beam: 28.81 keV for Aluminum, 51.23 keV for Titanium, and 37.36 keV for Kapton®. The input data are presented in the Table.

A simplified scheme for taking into account the heat transfer of a certain element for modeling the heating of films is presented in Fig. 5. Green arrows present losses associated with heat transfer to neighboring elements, blue arrows present radiation losses, red arrows present electron beam heating.

Tabular data of some properties [10] of thin foil materials in the simulation of electron-beam heating

	Kapton®	Aluminum	Titanium
Foil thickness, mm	$125 \cdot 10^{-3}$	$50 \cdot 10^{-3}$	$50 \cdot 10^{-3}$
Specific Heat Capacity, J/(kg·K)	1090	887	523
Density, kg/mm^3	$1420 \cdot 10^{-9}$	$2720 \cdot 10^{-9}$	$4500 \cdot 10^{-9}$
Thermal Diffusivity, mm^2/s	20	97	9
Emmisivity	0.74	0.1	0.19

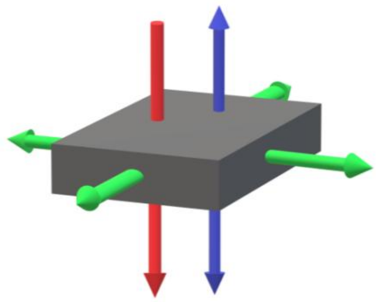

Fig. 5. A simplified scheme of the heat transfer of an element for modeling of the foil heating

To calculate non-stationary heat transfer, the method of differences was used. The minimum volume is a quadrangular prism made of Kapton®, with thickness *h*, width and length *dx*. Each element has uniform heating and uniform parameters and density. Such approximation is possible because those electrons at energy of 15 MeV have a significant stopping range, and it can be assumed that the foil is heated uniformly throughout the thickness. Accordingly, it is fair to apply the laws of thermodynamics to the system of elements, since each element receives and gives off heat and this is taken into account in the code. The next point is consideration of each of the factors that were included in the code.

The non-uniform heat flow law (1) was used to model the heat distribution [9]:

$$c\rho \frac{\partial T}{\partial t} - \nabla\left(k \nabla T\right) = \frac{dq}{dt}, \tag{1}$$

where c is the heat capacity, ρ is the density of the material, k is the thermal conductivity, q is the heat flux.

The problem is reduced to finding the function $T(x,y,t)$. Accordingly, a rectangular grid was chosen for the task. Also, description of the current distribution function in the primary beam is much more difficult due to the fact that the beam cast is a two-dimensional array with and the coordinate grid is set in Cartesian coordinates.

The 2D differential grid method was used for the simulation. The main advantages of its use are as follows (Fig. 6).

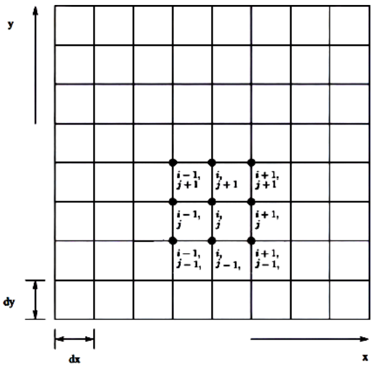

Fig. 6. Conventional designations of the division of the coordinate grid used in the calculations

Cartesian system is the method, which is usually used in such type of tasks. Parameters can be adjusted dynamically. The step can be changed at any time. But this method requires the high volume of PC RAM, since large arrays necessary to be stored and processed. Small changes in the step increase the complexity of calculations many times over. Thus the expression (2) where equals zero because the temperature is stable along the *z*-axis

$$\frac{T_{i,j}^{m+1}-T_{i,j}^{m}}{dt}=a\left(\frac{T_{i+1,j}^{m}-2T_{i,j}^{m}+T_{i-1,j}^{m}}{dx^2}+\frac{T_{i,j+1}^{m}-2T_{i,j}^{m}+T_{i,j-1}^{m}}{dy^2}\right),\quad(2)$$

where dx, dy are dimensions of domain, and dt is time step.

Three parameters dx, dy, dt have be adjusted for the best result prediction. But since the problem is a symmetrical close to axial, then dx were taken equal to dy. Having set the system, we can look at the change, and the very ones that bring in and change the temperature in the cells.

Because each domain heats up/cools down in a small interval of the others independently, then losses in a separate domain can be calculated. Thus, grid cooling can be calculated by successive application of Stefan Boltzmann's law (3), and:

$$cm\left[T_{i,j}^{m+1}-T_{i,j}^{m}\right]dt=2\left[\left(T_{i,j}^{m+1}\right)^4-\left(T_{i,j}^{0}\right)^4\right].\quad(3)$$

The upper index is responsible for the temporal component, and the lower one for the spatial one. C is the heat capacity of Kapton®, m is the mass of the domain, dt is the temperature change of the domain, t is the time during which the domain radiates.

For the first approximation, it was decided not to take convection into account. In order to find heat gain/outflow through the walls of the element, the equation of thermal conductivity (4) of the following form will be used:

$$k\frac{d^2T}{dx^2}+k\frac{d^2T}{dy^2}+e=\rho S\frac{dT}{dt},\quad(4)$$

where ρ is the density of the material, k is the thermal conductivity, S is the surface of domain which is perpendicular to the beam.

From experimental studies, it was established that the studied materials will not change their properties.

The equation (2) has 5 variables. They can be found using the exception method or iteratively. In this work, an iterative method was used due to the increased speed compared to other methods.

In order to find the distribution through t, an iterative approach with n steps is used.

The time step and the spatial step were chosen to satisfy the stability conditions described by relation (5):

$$\Delta t\left(\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}\right)<\frac{1}{2}\quad.\quad(5)$$

CALCULATION ADJUSTMENT

Heat dissipating through Kapton® also takes into account heat loss through walls. Kapton® film was fixed in an experimental stand made entirely of Iron. Due to the high heat capacity of Iron and its conductivity, it can be assumed that the area adjacent to the clamp does not heat up (Dirichlet boundary conditions). In the code [8], this is expressed by the function equating the entire temperature to *T_0* at the clamp radius.

THE ERROR DETERMINATION PROCEDURE DESCRIPTION

One step of the calculation consists of sequential application of the heat addition function and two loss functions. Schematically, the error detection algorithm is presented in Fig. 7.

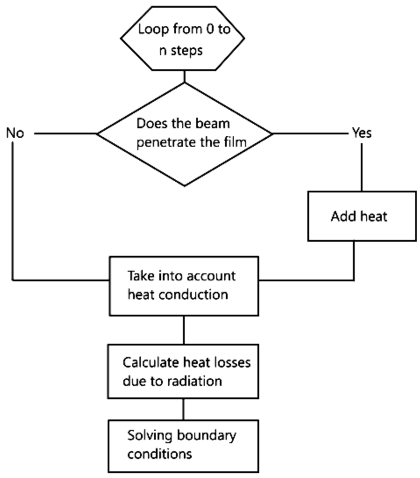

Fig. 7. Schematic representation of error determination algorithm

3. CALCULATIONS RESULTS

The distributions of heating of aluminum, titanium and Kapton® foils during the passage of beams of accelerated electrons with energy of 15 MeV through them, as well as the estimated time to reach thermal equilibrium, are obtained (Fig. 8). The feature of the considered modeling case is that all films have different thicknesses at which part of the energy of the primary beam is absorbed and different thermal-physical and heat-capacitive and emissive properties.

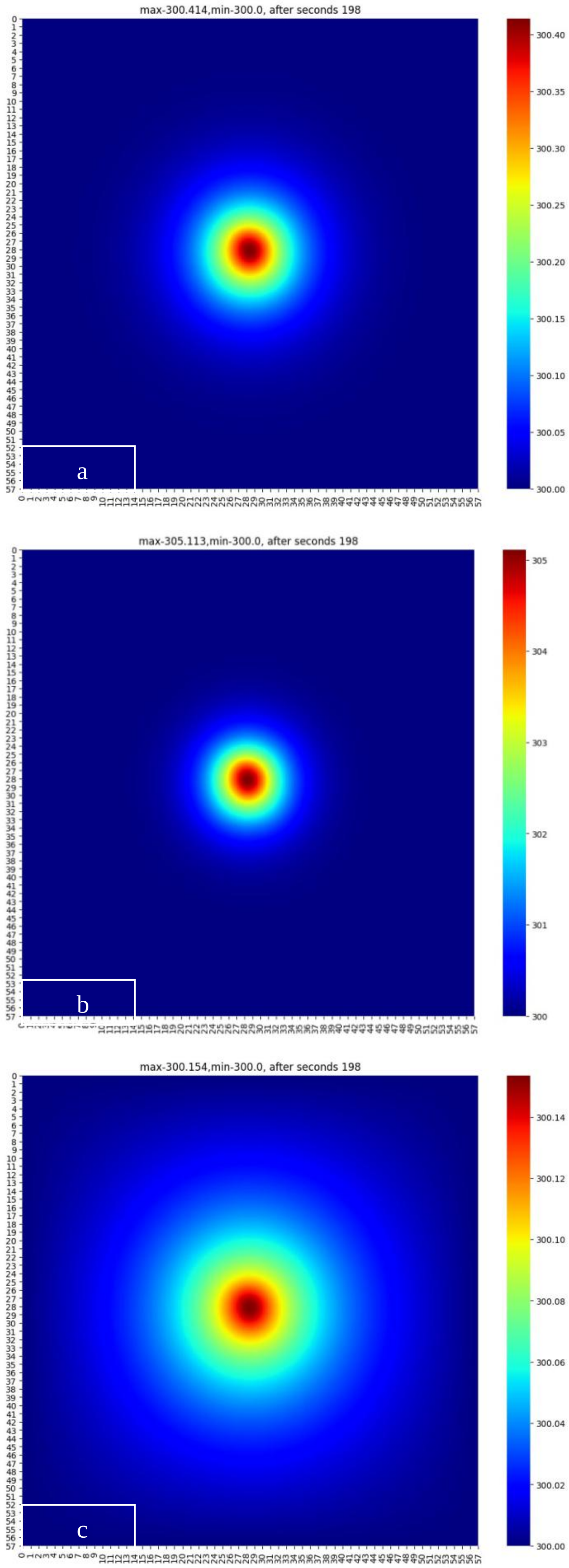

Fig. 8. Electron beam heating distribution of the thin foil: a – 125 μm Kapton®; b – 50 μm Titanium; c – 50 μm Aluminum

In addition, the film holder is quite voluminous, which absorbs all the thermal energy the film receives from the electron beam total losses. The value of 300 K was chosen as the foils initial temperature (start temperature point). The radial distributions of the foil heating by electron beams passing through them with energy of 15 MeV are calculated and presented in Fig. 8. The experimentally measured profile of the current density distribution according to the data of Fig. 4 was used for start temperature point. Total time of foil temperature stabilization (close to foil temperature equilibrium) under high-energy electron beam irradiation is 198 s. As well shown from presented temperature distribution for Cartesian coordinate system (on the surface) for all three cases electron beam irradiation doesn't change practically the maximum temperature in the central part of electron beam print. Also the dynamic maximum temperature values increasing versus time of electron beam irradiation are presented in the Fig. 9. Calculated results as our opinion are expected, because energy absorption values for all three cases (50 μm Aluminum, 50 μm Titanium, and 125 μm Kapton®) are very low: 28.81, 51.23, and 37.36 mW respectively. Modeling result of induced temperature difference values (before and after 198 seconds of partial electron beam energy absorption) is changed in the range from 0.14 to 5 K as are shown in Fig. 9 for three calculated time dependent curves.

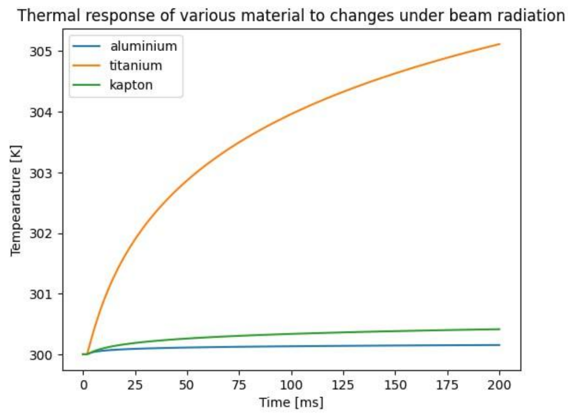

Fig. 9. Dependence of the growth of the maximum temperature versus the electron beam irradiation time (15 MeV, average beam current is 1 μA), according to Fig. 8 data

CONCLUSIONS

As the main results presented in the study, one can note the possibility of performing calculations to predict the temperature distribution in thin foils on their surface, taking into account their thickness and the actual parameters of the electron beam. These parameters are the primary energy of the electrons, the current of the electron beam, and the spatial distribution of the particle beam. The calculation results show that the three types of studied foils can be used as parts of experimental beam setups without taking into account their thermal loading at a low beam current, ~1 μA. The calculation model corresponded to the ideal conditions of the experiment. The energy distribution of the particles of the primary beam was not taken into account. It is very important to perform some calculations to determine the value of the critical heating temperature for pulsed beam modes (for example, a pulse duration of 2 μs and a repetition rate of 50 Hz) of foil irradiation and a higher range of electron beam current, up to 1 mA. It is necessary to include the option of convection temperature losses on one side of the foil in the simulation program to use a thin foil as an element of the output window of an electron beam.

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МОДЕЛЮВАННЯ ТА ПОПЕРЕДНІ ЕКСПЕРИМЕНТАЛЬНІ РЕЗУЛЬТАТИ НАГРІВУ ТОНКИХ ПЛІВОК ПРИ ПРОХОДЖЕННІ КРІЗЬ НИХ ПУЧКІВ ВИСОКОЕНЕРГЕТИЧНИХ ЕЛЕКТРОНІВ

М. Луганько, О. Шопен, С. Карпусь, Т. Малихіна

Представлено попередні експериментальні результати та результати моделювання нагріву тонких плівок з титану товщиною 50 мкм, алюмінію товщиною 50 мкм та Каптону® товщиною 125 мкм при проходженні крізь них високоенергетичних електронів з енергією 15 МеВ. Струм пучка електронів дорівнював 1 мкА. Розроблено методику розрахунків, що полягає в автоматизації методу скінченних різниць за допомогою засобів мови програмування Python, що полягає у вирішенні задачі розповсюдження тепла у плівці з урахуванням гальмівних втрат первинного пучка електронів та випромінювання абсолютно чорного тіла. Отримано дані з розподілу температури по поверхні зразків та визначено час встановлення теплової рівноваги з урахуванням розподілу густини струму пучка електронів. Показано, що оптимізація важливих параметрів пучка високоенергетичних електронів, а саме, густини струму пучка, дає змогу знехтувати тепловими навантаженнями на дослідні зразки зазначених плівок, що підтверджено під час стендових випробувань на лінійному прискорювачі електронів ІФВЕЯФ ННЦ ХФТІ з енергією до 30 МеВ.