IRRADIATION TECHNIQUE OF CONSTRUCTIONAL MATERIALS ON THE HELIUM IONS LINAC

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The irradiation technique of constructional materials on a helium ions LINAC is developed. Irradiations of metal, ceramic, and also semiconductor materials are carried out. During irradiation were measured: current of a ions beam, temperature of an exemplar and a slope angle of an exemplar to a beam axis. Also during experiments were controlled: an irradiation dose, profiles of a helium ion distribution and damage on exemplar thickness. Preliminary results show the considerable change of thermo-diffusion characteristics depending on beam energy and an irradiation dose. The phenomenological description of thermo-diffusion of the irradiated exemplars was offered.

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INTRODUCTION

The nuclear power engineering development provides creation of new generation reactors on fast neutrons and thermonuclear reactors. In constructional materials of these power stations along with high extent of radiation damages of structure there is an accumulation of the significant helium amount which appears as a result of various nuclear reactions, and also can be introduced immediately from plasma in the first wall of thermonuclear reactors.

Helium has essential impact on radiation damageability of materials and often is the reason of deterioration of properties and losses of life of constructional elements of reactors. Therefore, in various materials much attention is paid to behavior of helium. It is revealed regularities [1 - 3] on influence of helium on a radiation swelling, a high-temperature and low-temperature irradiation hardening and embrittlement, the radiation-accelerated creep, surface erosion of the first wall of thermonuclear reactors, etc.

For prediction of operability of constructional materials in the accumulation conditions of the considerable helium concentration it is not enough to know regularities of development of radiation damageability – data on behavior of gases depending from various internal and external factors are necessary. Such factors are the helium distribution depth, helium concentration spatial distribution, impurities and alloying elements in metals and alloys, etc. So far, the experimental data of helium behavior in materials depends from these factors it is received insufficiently.

The purpose of this work is development of the irradiation technique of constructional materials by helium ions on a LINAC with energies from 0.12 to 4 MeV with the subsequent studying of their physical properties.

1. HELIUM ION ACCELERATOR

In KIPT was launched helium ions LINAC (He^{+}) with energy 4 MeV, which includes helium ions injector and accelerating structure [4].

In the accelerator is selected interdigitated version of the accelerating structure excited on H111-wave [5]. The advantages of this structure in this energy range lies in its small-size, high rate of acceleration and optimum electrodynamics characteristics that provide stability and efficient HF power supply mode. Interdigital accelerating structure is optimal for the use of the most simple and effective method of providing a radially-phase stability of the beam along the accelerating channel, what it is a variable-phase focusing (PFP) in the version with a step change synchronous phase [6]. The resulting calculations and settings are shown in Table 1.

Table 1

LINAC Parameters

Ion energy at the entrance, keV/nucl.	30
Energy of the accelerated ions, keV/nucl.	975
The ratio of the ion mass-to-charge	4
Operating frequency, MHz	47.2
Maximum accelerating field, kV/cm	85
Overall acceleration rate, MeV/m	1.6
Resonator length, m	2.39
Cavity diameter, cm	107.5
Pulse current of accelerated ions, mA	6
Input surge current, mA	30

For receiving a beam of ions helium with energy 30 keV/nucl., was developed, made and put into operation the injector of ions (Fig. 1) consisting of a ions source like "duoplasmatron" [7], system of extraction and formation of a beam, and also an accelerating tube [8]. The injector is mounted on the dielectric support having an adjusting plate for an injector axis adjustment with an axis of the accelerating structure.

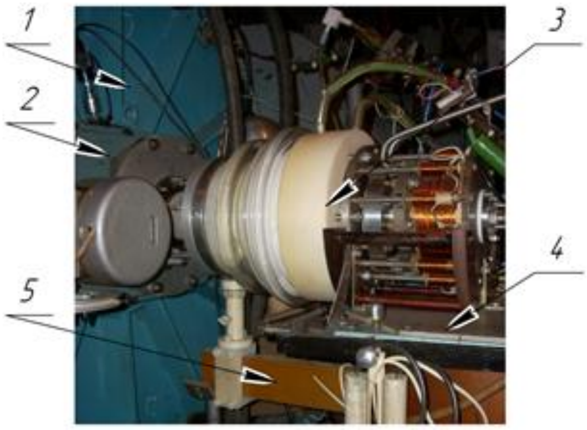

Fig. 1. General view of the helium ions injector: 1 – the accelerating section; 2 – ДУ-260 valve; 3 – injector of ions; 4 – adjusting plate; 5 – a dielectric basis with devices for fastening and adjustable movement of the ions injector

The injector allows to receive a beam He^+ with currents in some tens mill amperes. The main parameters of an injector are specified in Table 2.

Table 2

Injector parameters

The working gas	helium
Arc current, A	2…4
The beam current at the output, mA	20
The energy of the particles at the outlet of up to, keV	120
The beam diameter at the output, mm	~ 8
Sampling frequency, Hz	2…10
Pulse duration modulator arc, μs	500

Monitoring of a beam current on an input and an output of the accelerator is made by flying inductive sensors [9]. In Fig. 2 is shown the impulses current form of helium ions beam (≈ 10 mA) on the input to the accelerating structure (2), and also an arc current (≈ 3 A) of a ions source (1).

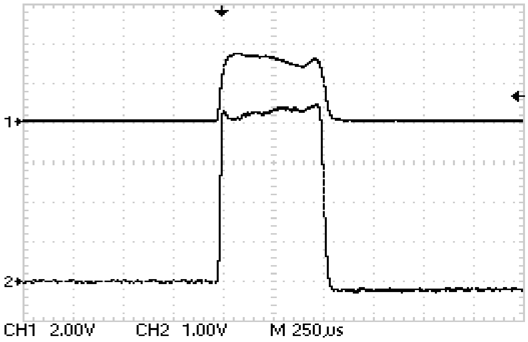

Fig. 2. Impulses of an arch current of a source (1) and a beam current of ions on an input to accelerating section (2)

After development and deployment of amplitude stabilization system of high-voltage power impulse of injector, current of accelerated helium ions beam was received ≈ 800 μA at the output of the accelerator (Fig. 3).

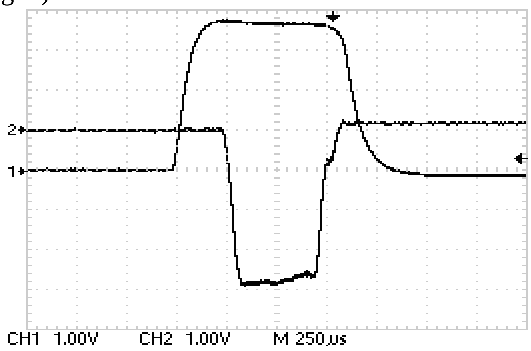

Fig. 3. Impulses HF – bending around (1) and current of the accelerated beam of ions at the output of the accelerator (2)

Tension of stabilization makes 120 kV, with possibility of fine tuning of ±12 kV. Test data showed reliability of system and resistance to high-voltage breakdowns that allows to receive high exposure doses of materials ($5 \cdot 10^{16}$ cm^{-2}) at the continuous operation of the accelerator.

2. CAMERA FOR IRRADIATION OF SAMPLES

For radiation of exemplars an installation with target knot (Fig. 4) was created. It consists of the inductive flying sensor of beam current (1) [9], a holder of an exemplar with a heating element (2), the scanner (3) and the turbo-molecular pump TMH 150/63 (4) to which the vacuum booster pump for preliminary pumping is connected.

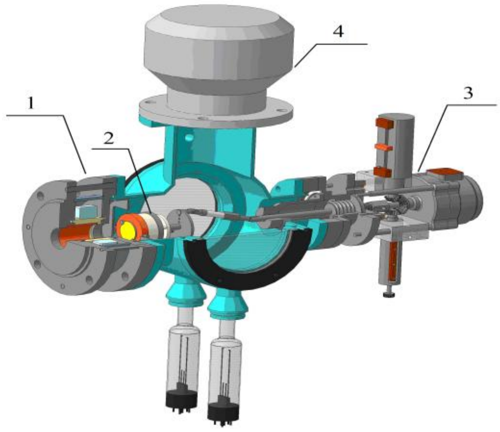

Fig. 4. Target chamber: 1 – a flying sensor of beam current; 2 – a sample holder with a heating element; 3 – a scanner; 4 – a turbo-molecular pump

The independent system of pumping allowed to get rid of a incrustation of carbon compounds on an exemplar surface. The photo of the installation is given in Fig. 5.

Fig. 5. Irradiation installation of exemplars

For heating of exemplars the heater is developed and manufactured, which allows to regulate temperature in the range of 20…900ºC during irradiation. Temperature of an exemplar is measured by the hromel-alyumel thermocouple attached to an internal surface of an exemplar in relation to incident beam. The signal from the thermocouple is given on ADC/DAC ZET-210 [10], connected to the personal computer, with further data recording on the computer, digital and graphic visualization. For a more accurate temperature measurement and filtering of high-frequency interference the integrant amplifier with an intensification coefficient 1000 has been created, which allows to measure the temperature with an error ± 0.5°C at distance of 70 meters from the thermocouple.

For ensuring the experiment parameters on irradiation of materials, the device for scanning of a sample and registration of a corner between an axis of a beam and the flatness of a sample was developed and created. This device allows get preset profile of helium distribution or damage on a sample thickness. Necessary distributions obtain at change of a tilt angle of a sample to a beam axis in the course of irradiation. For more exact definition of a tilt angle the device has three ranges of change (23, 30 and 40°). The corner is measured by means of variable resistance. At graduation of the scanner the laser interferometer was used. The maximum mistake made less than ±0.5° that completely meets requirements for carrying out experimental works. The main characteristics of the camera for irradiation of samples are provided in Table 3.

Table 3

Characteristics of chamber

Parameter	Range of values	Error
Temperature	20..900°C	< 2%
Slope angle	0…23°, 0…30°, 0…40°	0.5°
Average current of a beam	2 μA	±2%
Vacuum	10^{-6} mm Hg	5%

3. HARDWARE AND SOFTWARE SYSTEM FOR MEASUREMENT OF IRRADIATION PARAMETERS

In the course of irradiation were registered: temperature and corner of irradiation of sample, form and amplitude of impulse of beam current, and also such parameters as irradiation dose, the profiles of helium distribution and damageability, ionization profile of sample are calculated on the personal computer by means of specially developed programs. All measured parameters, during irradiation, were digitized by the analog-digital converter ZET-210 "Sigma USB" [10] connected to the personal computer. The general scheme of digitization and measurements of irradiation parameters of a sample is provided on Fig. 6.

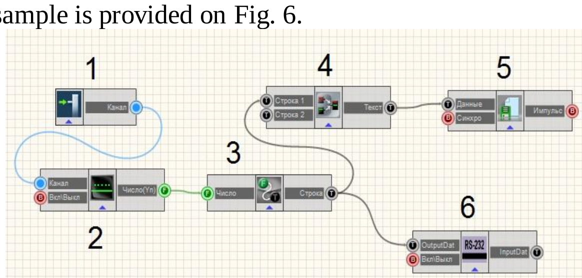

Fig. 6. The common scheme of digitization and measurement of irradiation parameters of a sample:
1 – the input channel; 2 – the measurement block (for temperature – the voltmeter of constant tension; a slope angle – the generator of constant tension + the voltmeter of constant tension; a beam pulse shape – a high-pitched oscilloscope; an impulse current of a beam – the peak voltmeter; indirect parameters – the peak voltmeter + the integrator); 3 – the converter; 4 – toting of lines; 5 – file recording; 6 – the external interface

For increase in accuracy of measurement of irradiation parameters the program adaptive digital filter, which use the algorithm of the smallest squares was developed and created [11]. This algorithm is most effective from the point of view of computing complexity and requirements to the computer memory. Program realization of the filter was created in the C# language in the environment of programming of Microsoft Visual Studio.

For display data on a personal computer screen and their safekeeping, in the environment of Microsoft Visual Studio the software was created. Below there are examples of programs work for measurement of temperature of a sample (Fig. 7) and a profile of helium distribution in a sample (Fig. 8).

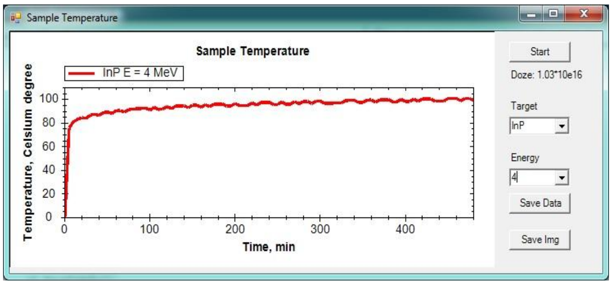

Fig. 7. The example of the program works for display of an exemplar temperature

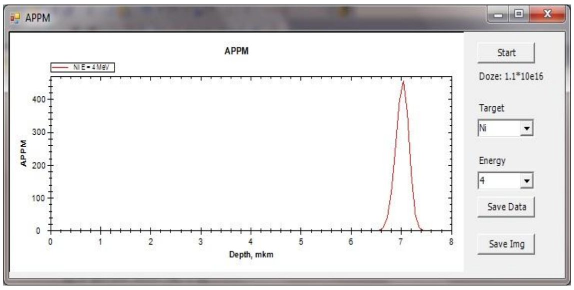

Fig. 8. The example of the program works for display of helium distribution profile

After graduation and tuning of a hardware-software complex for measurement of irradiation parameters and connection of the camera for irradiation of samples to the accelerator, methodical experiments were made. Experiments showed that use of the adaptive digital filter, optimization of program algorithms, and also use of optimum schemes of measurements of irradiation parameters, allowed reducing noise level from high-frequency fields from 20 to 2%.

4. IRRADIATION AND RESEARCH OF CHARACTERISTICS OF THE IRRADIATED EXEMPLARS

On the LINAC of helium ions there are carried out materials irradiations: constructional metal, ceramic, and also semiconductor which are used in nuclear and thermonuclear power engineering and the modern electronics engineering. Materials and conditions of irradiation are presented in Table 4.

For definition of the radiation damage influence created by helium ions on properties of constructional and ceramic materials, it is necessary to know profiles of helium distribution, damageability and ionization on thickness of the irradiated material.

Table 4

Materials and parameters of irradiation

Material	Energy, MeV	Dose
Metals		
Zr	4	$2{,}3\cdot10^{15}$, $5\cdot10^{15}$, $1\cdot10^{16}$
	2.42	$5\cdot10^{15}$, $1\cdot10^{16}$
	1.14	$1\cdot10^{16}$
	0.12	$5\cdot10^{15}$, $5\cdot10^{16}$
Nb	4	$5\cdot10^{15}$
	2.42	$5\cdot10^{15}$
Ni	4	$1\cdot10^{16}$
Mo	4	$1\cdot10^{16}$
	0.12, 2.42, 4	$1\cdot10^{16}$
Fe	4	$5\cdot10^{15}$
Steel-3	4	$1.5\cdot10^{15}$
X18H10T	4	$7.5\cdot10^{14}$
Ceramics		
TiO_2	4	$1\cdot10^{16}$
Semiconductor		
InP	4	$1\cdot10^{16}$
	2.42	$1\cdot10^{16}$

Calculations were carried out with the help of the SRIM [12] program in which for model operation of ion implantation processes the Monte-Carlo method is used, which takes into account behavior of big ensemble of particles in a solid body. In Fig. 9 are given the calculated profiles of a helium distribution and damageability for Zr from which it is visible that the maximum of a damageability profile is shifted to zero concerning a helium distribution profile maximum. Similar calculations were executed for all irradiated exemplars where this shift is also visible.

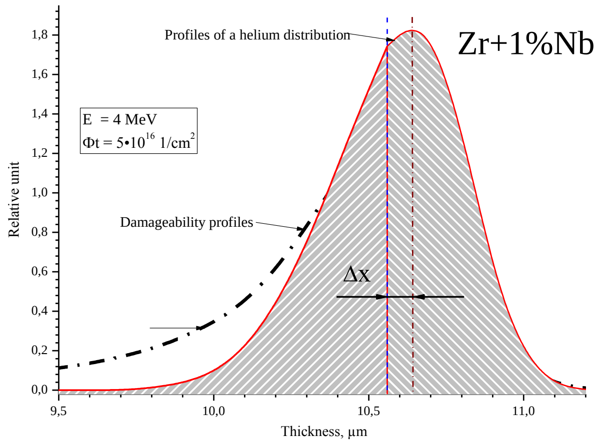

Fig. 9. Profiles of a helium distribution and damageability in Zr irradiated on a LINAC

Behavior of helium in the studied materials after irradiation by their ions of helium with energy 0.12…4 MeV studied by means of a technique of thermo-stimulated diffusion. In cases of lack of phase changes the profiles of helium output were formed by method of a thermo-stimulated desorption [4]. Data of thermo-diffusions of helium from an exemplar of the zirconium irradiated by helium ions with energy of 4 MeV and an exposure dose $5\cdot10^{16}$ are presented in Fig. 10.

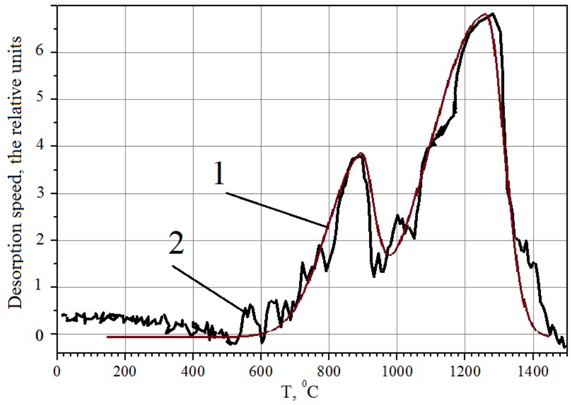

Fig. 10. The experimental (2) and calculated (1) curves of a thermo-diffusion. Zr+1% Nb, the energy of irradiation 4 MeV, the dose $5\cdot10^{16}$ 1/cm^2

For the description of a thermo-diffusion process of the irradiated exemplar of Zr+1%Nb and definition of a role of a defect formation the nonstationary diffusion equation was solved taking into account profiles of a helium distribution, damageability and phase change. The profile of helium distribution is considered in starting conditions of a diffusion equation, and temperature dependence, a profile of damageability and phase change in a diffusion coefficient. Results of calculations are shown in Fig. 10. It should be noted that at energies < 50 keV the thermo-diffusion profile has one maximum.

Calculations showed that the main contribution to formation of two maximum, brings the radiation damage which is formed during irradiation of exemplars of a zirconium alloy on the accelerator with energies more than 100 keV.

CONCLUSIONS

There are carried irradiations of materials out by energies from 0.12 to 4 MeV on a LINAC of helium ions: constructional metal, ceramic, and also semiconductor which are used in nuclear and thermonuclear power engineering, and the modern electronics engineering.

During irradiation were measured: a beam current of ions, temperature of an exemplar and a slope angle of an exemplar to a beam. Also the following parameters were calculated and controlled, during irradiation mode: an exposure dose, profiles of the helium distribution and damage on exemplar thickness, and also an ionization profile (for semiconductor materials).

Preliminary results show the considerable change of characteristics of a thermo-diffusion depending on irradiation parameters.

The phenomenological description of the thermo-diffusion process of the irradiated zirconium alloy is offered, taking into account distribution of damageability and helium. It is shown the main contribution to process of a thermo-diffusion of a profile of damageability.

REFERENCES

1. V.N. Voyevodin, I.M. Nekluydov. The current status of materials for nuclear energy – microstructural evolution and radiation resistance // *Proc. of the XVIII ICPRT.* Alushta, Crimea, 2008, p. 4-5.

2. I.M. Nekluydov, G.D. Tolstolutskaya. Helium and hydrogen in structural materials // *Problems of Atomic Science and Technology. Series "Physics of Radiation Damage and Radiation Materials".* 2003, № 3, p. 3-14.
3. A.I. Ranyuk, V.F. Rybalko. *Helium in a lattice of metals: Review.* M.: "CRIAtominform", 1986, p. 64.
4. R.A. Anokhin, V.N. Voyevodin, S.N. Dubnyuk, et al. Methods and experimental results constructions materials irradiation of helium ions at the linear accelerator // *Problems of Atomic Science and Technology. Series "Physics of Radiation Damage and Radiation Materials".* 2012, № 5, p. 123-130.
5. V.A. Bomko, A.P. Kobets, S.S. Tishkin, et al. Variant of alternating phase focusing with the stepped change of the synchronous phase // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 2004, № 2, p. 153-155.
6. S.M. Dubniuk, B.V. Zajtsev. A linac used to irradiate of construction materials // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 2014, № 3, p. 172-176.
7. R.A. Demirkhanov, Yu.V. Kursanov, V.M. Blagoveschensky. Protons source of high intensity // *Devices and technology of experiment*. 1964, № 1, p. 30-33.
8. A.T. Forrester. *Intensive ion beams*. M.: "World", 1992, p. 353.
9. A.F. Dyachenko. The high-sensitivity induction bunch current gauge of the heavy ions linac // *Bulletin of the KNU. "Nuclei, Particles, Fields"*, № 887 / Ed.1 2010/45 / p. 118-121.
10. *The module of the analog-digital and digit-analog ZET transformation – 210.* M.: "ZET", 2010.
11. B. Widrow, J.R. Glover, J.M. McCool, et al. Adaptive noise cancelling: principles and applications // *Proc. IEEE*. 1975, v. 63, p. 1692-1716.
12. J.F. Ziegler, J.P. Biersack. SRIM: The Stopping and Range of Ions in Matter // *IBM-Research,* Yorktown, 1996.

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МЕТОДИКА ОБЛУЧЕНИЯ КОНСТРУКЦИОННЫХ МАТЕРИАЛОВ НА ЛИНЕЙНОМ УСКОРИТЕЛЕ ИОНОВ ГЕЛИЯ

Р.А. Анохин, С.Н. Дубнюк, Б.В. Зайцев, К.В. Павлий

Разработана методика облучения конструкционных материалов на линейном ускорителе ионов гелия. Проведены облучения металлических, керамических, а также полупроводниковых материалов. При облучении измерялись: ток пучка ионов, температура образца и угол наклона образца к оси пучка. Также в ходе экспериментов контролировались: доза облучения, профили залегания гелия и повреждения по толщине образца. Предварительные результаты показывают значительное изменение характеристик термодиффузии в зависимости от энергии пучка и дозы облучения. Предложено феноменологическое описание термодиффузии облучённых образцов.

МЕТОДИКА ОПРОМІНЕННЯ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ НА ЛІНІЙНОМУ ПРИСКОРЮВАЧІ ІОНІВ ГЕЛІЮ

Р.О. Анохін, С.М. Дубнюк, Б.В. Зайцев, К.В. Павлій

Розроблено методику опромінення конструкційних матеріалів на лінійному прискорювачі іонів гелію. Проведено опромінення металевих, керамічних, а також напівпровідникових матеріалів. Під час опромінення вимірювалися: струм пучка іонів, температура зразка і кут нахилу зразка до осі пучка. Також підчас експериментів контролювалися: доза опромінення, профілі залягання гелію і пошкодження по товщині зразка. Попередні результати показують значну зміну характеристик термодифузії в залежності від енергії пучка і дози опромінення. Запропоновано феноменологічний опис термодифузії опромінених зразків.