EXPERIMENTAL COMPLEX FOR INVESTIGATION OF CONSTRUCTION MATERIALS ON THE HELIUM IONS LINEAR ACCELERATOR

R.A. Anokhin*, B.V. Zaitsev, K.V. Pavlii, V.G. Zhuravlev, V.A. Soshenko
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: anokhinra@kipt.kharkov.ua

The paper describes the experimental complex for the helium ions linear accelerator consisting of an irradiation chamber, sensors, analog signal converters (ADC) and a computer with a program for processing experimental data and then outputting it to a display. The complex is intended for carrying out experimental works on the study of the physical properties of structural materials used in nuclear power plants and nuclear fusion reactors. The complex was tested under the irradiation of titanium dioxide (TiO_2) with helium ions energies of 0.12 and 4 MeV. The experimental data of the TiO_2 electrophysical characteristics are presented, which confirm the expediency of using the complex to study the properties of materials used in high-power radiation fields.

PACS: 29.27.Ac

INTRODUCTION

Nuclear energy in Ukraine is an important part of the overall fuel and energy complex of the country. To maintain and design new nuclear power units, as well as to create fusion reactors, one of the main factors is the influence of irradiation on construction materials [1]. Carrying out irradiation on linear accelerators allows studying the construction materials faster than in experimental reactors due to a higher degree of damage [2]. To improve the accuracy of measurement during irradiation and to provide data transmission distance of 50 m ~ measured parameters are digitized immediately after measuring and digitally transmitted to the personal computer.

1. METHOD OF IRRADIATION MEASUREMENT PARAMETERS

To study the properties of metallic, semiconductor, and ceramic materials on a linear helium accelerator with energy of 0.12…4 MeV, a camera was developed for irradiating and investigating the properties of structural materials (Fig. 1) and a software and hardware complex for measuring and recording parameters irradiation and experimental data. The irradiation parameters of the samples are given in Table 1.

Fig. 1. Chamber for the study of the properties of constraction materials

Table 1

Sample irradiation parameters

Parameter	Value
Pule current	700…900 mkA
Pulse duration	500 mks
Pulse frequency	2…5 pulse/s
Avarage current	0.7…2 mkA
Current Density (s)	$0.155 \cdot 10^{13} \ldots 0.44 \cdot 10^{13}$ part/cm^2

During irradiation, both direct and indirect irradiation parameters and experimental data are measured. After that, the digitized signals filtering from noises, output and saved on a personal computer.

The direct parameters include current measurement and beam shape, sample temperature, sample tilt angle and its resistance. Indirect parameters include sample irradiation dose, deposition, damage and ionization profiles of the sample. Indirect parameters are measured by mathematical transformations of direct parameters. For direct parameters measurement used span beam current sensor [4] (the beam current and the shape of the beam current), the thermocouple (temperature of the sample), a scanning device (specimen tilt angle to the beam axis) and a bridge circuit (measuring the resistance of the sample). After measurement, these parameters are digitized using a ZET-210 DAC/ADC [5] and transmitted to a personal computer. On the personal computer, the input data are filtered using Kalman's adaptive digital filter with an infinite impulse response [6], the circuit of which is shown in Figs. 2, and 3,a,b result of his work. The program for implementing the filter was written in C # in a Microsoft Visual Studio environment [7].

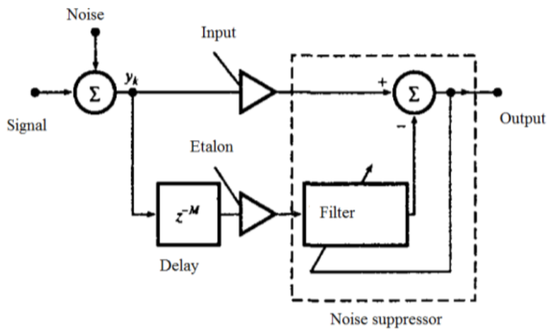

Fig. 2. Filter circuit

After filtration, direct measurement data transmitted program that can display and store them on a personal computer. Also, the data from the span beam current sensor is transmitted to programs that perform their mathematical processing to display and store indirect measurements on a personal computer.

All programs, as well as the adaptive filtering program, were written in C # in a Microsoft Visual Studio environment.

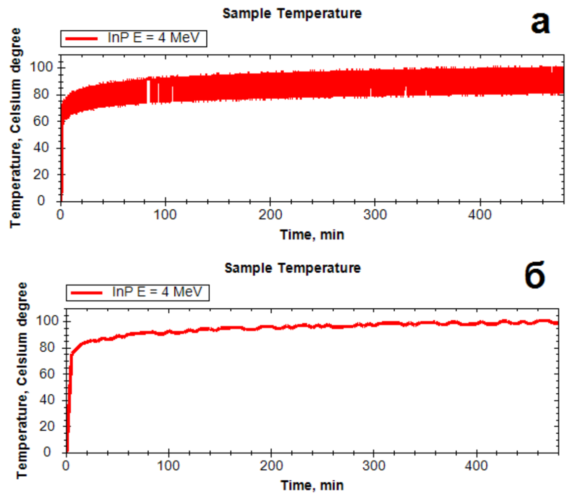

Fig. 3. Signal from the thermocouple before filtration (a) and after (b)

2. MEASUREMENT OF DIRECT AND INDIRECT PARAMETERS OF IRRADIATION

To register direct parameters in the SCAD ZETView programs were developed to connect with ZET-210 DAC/ADC. In Fig. 4,a is a block diagram of measuring the pulse of the beam current, and in Fig. 4,b program for displaying and saving it on a personal computer.

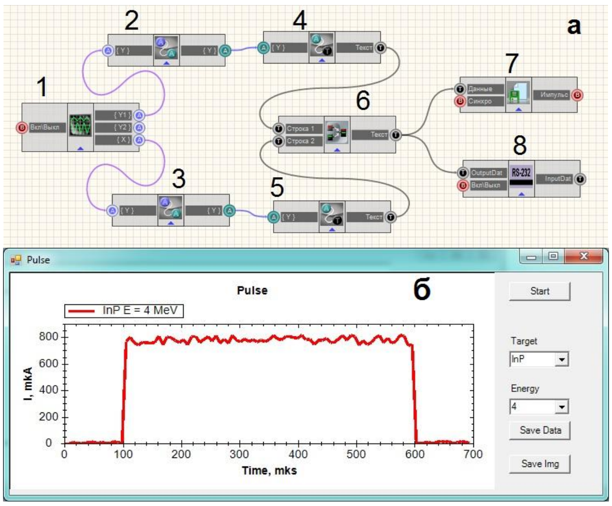

Fig. 4. Block diagram of control of beam pulse shape. 1 – the high-frequency oscilloscope; 2, 3, 4 ,5 – converter; 6 – lines adder; 7 – write to file; 8 – external interface (a). Beam pulse profile (b)

A special feature of measuring indirect parameters is the need for additional calculations; otherwise they are identical to systems for measuring direct parameters.

The radiation dose is measured by summing the beam current values in each pulse, after which the program converts the data values assuming 1 mkA = $6.2 \cdot 10^{12}$ particles. To measure the occurrence, damage and ionization profiles, special analytical expressions obtained by the approximation method based on the calculated data that was get from SRIM program [8], as well as the values of irradiation doses. For example, the occurrence profile is approximated by an asymmetric Gaussian function (1).

$$y = \begin{cases} b_1 \exp\left(d_1 (x - x_c)^2\right) & x \le x_c \\ b_2 \exp\left(d_2 (x - x_c)^2\right) & x \ge x_c , \end{cases} \qquad (1)$$

where x_c – coordinate of maximum occurrence profile; b_1, b_2 – irradiation dose rate factors; d_1, d_2 – approximation rate. Irradiation dose rate factors are determined:

$$b_1 = b_2 = appm \Big/ \int_0^{x_{max}} \bar{y}(x)\,dx ,$$

where x_{max} – the maximum depth of helium in the sample, $\bar{y}(x)$ – normalization to unity, occurrence profile of helium in the sample, and appm is determined by the expression:

$$appm = \Phi_0 \Big/ \left(N_A \frac{\rho}{\mu} V \right),$$

where Φ_0 – irradiation doze; N_A – Avagadro number; ρ – density of irradiated sample; μ – molar mass of irradiated sample; V – volume of irradiated sample.

Fig. 5 shows a comparison of the calculated data and approximating the curve for the sample InP.

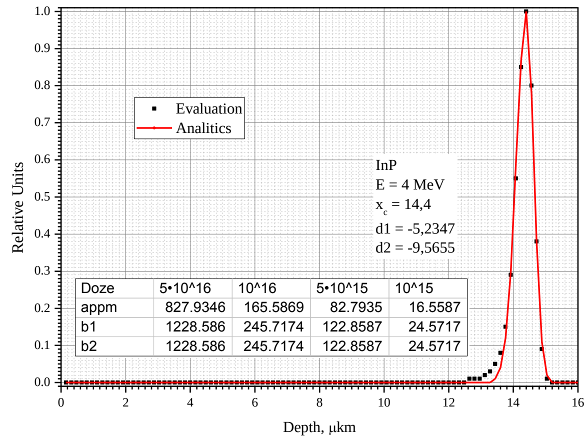

Fig. 5. Comparison of the calculated data and approximating the curve for the sample InP

To approximate damage profile were used Cauchy distribution for left part and Gaussian distribution for the right. For ionization profile were used Cauchy distribution for left part and Fermi for the right.

Fig. 6 shows example of program for measuring of occurrence profile.

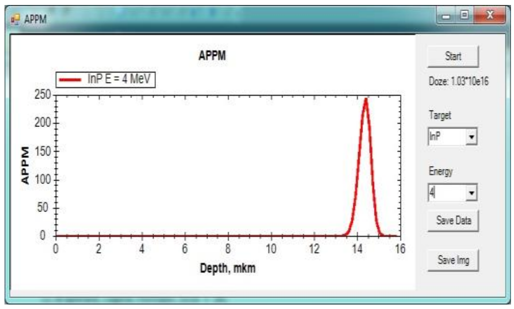

Fig. 6. Helium occurrence profile in sample

Table 2 shows the ranges and errors in measuring of direct parameters.

Table 2

Ranges and errors in measuring of direct parameters

Parameter	Range	Error
Beam current	780…810 mA	± 2%
Pulse duration	480…510 mks	± 1.65%
Temperature	20…1100°C	± 1%
Tilt angle	0…27 degree	± 1.5%

3. EXPERIMENTAL RESULTS OF ELECTROPHYSICAL PROPERTIES TiO_2

In nuclear power plants, ceramics are used as thermal insulation (Al_2O_3, SiO_2), nuclear fuel (UO_2, PuO_2), materials of regulating nodes (B_4C, Sm_2O_3), slowing and reflecting materials (BeO, ZrO_2, Be_2C), materials of neutron protection (B_4C, HfO_3, Sm_2O_3), electrical insulation in the core (Al_2O_3, MgO), shells of fuel elements (SiC, Si_3N_4) and other. In thermonuclear power engineering ceramics are planned to be used for thermal and electrical insulation of the first wall of the plasma chamber (SiC, Si_3N_4), plasma limitations (SiC, Al_2O_3, B_4C), for neutron protection (blankets from $LiAlO_2$, Li_2SiO_3, Li_2O), as a material for windows of different-frequency plasma heating (Al_2O_3, BeO) and other. Therefore, the purpose of this section is to develop a methodology for measuring the electrical properties of ceramic materials. The work was carried out using samples from TiO_2.

Titanium dioxide is widely used in chemical engineering, instrumentation and medicine. Having the properties of a semiconductor with *n*- conductivity and resistance ~10^{13} Ω·cm, titanium dioxide is a promising material for its use in nuclear and thermonuclear energy. In addition, having close radiation characteristics with UO_2, PuO_2, at the first stage, it can be used as a prototype for irradiation with helium ions with an energy of 4 MeV. For ionization TiO_2 goes 94…99.6% energy as a function of the energy of the ion beam, which corresponds to the processes in the fission UO_2, PuO_2.

Analysis of the properties of titanium dioxide and methods of its synthesis [9, 10] indicates the possibility of changing the conductivity by introducing into the composition TiO_2 various materials that have a higher conductivity. The same effect, as shown below, is achieved after irradiation TiO_2 ions of helium. This section describes the experimental results of studying the electrophysical properties of TiO_2 irradiated helium ions at a linear accelerator with energies of 0.12 and 4 MeV.

A measuring cell for irradiating ceramic materials with an attached sample is shown in Fig. 7, which is fixed in the irradiation chamber [11]. The sample temperature can be adjusted to 1100°C, For this purpose, a nichrome heater is provided (see Fig. 7), to which a sample with measuring electrodes is mounted. The initial and irradiated samples are shown in Fig. 8.

Prior to irradiation in the SRIM program, calculations were made of the spectra of helium deposition and the damage in the thickness of the sample. Particular attention was paid to calculations of the ionization spectra TiO_2, since the accumulation of a charge when it is irradiated and the runoff of charges is of paramount importance for the change in the electrophysical properties.

Fig. 7. A cell for measuring the electrophysical properties of materials under a beam He^+ with attached sample

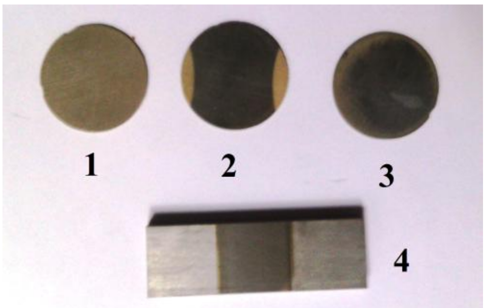

Fig. 8. Samples TiO_2. 1 – initial; 2 – irradiated dose 10^{15}; 3 – irradiated 10^{15}; 4 – a sample for measuring the electrical resistivity under a beam

In Fig. 9 shows the ionization and damage profiles at 0.12 and 4 MeV, applied to a single dose, taking into account the beam energy.

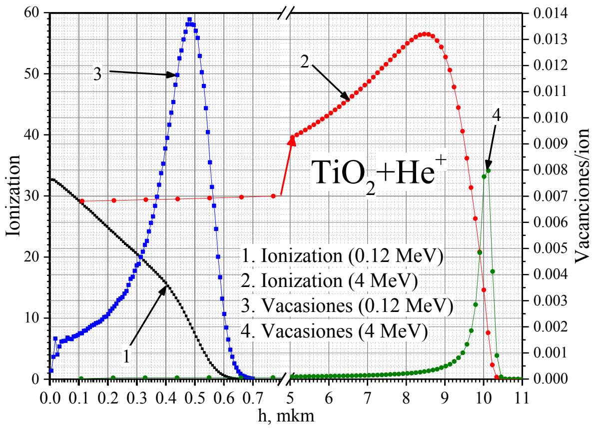

Fig. 9. The profiles of ionization and damageability at 0.12 and 4 MeV, reduced to a single dose, taking into account the beam energy

One of the most accurate methods of measuring electrical resistances at constant current is the bridge method, which has a high accuracy of measurements and reaches thousandths and ten thousandths of a percent. The range of resistance measurements by the bridge method lies in the range from fractions of the micro-ohm to 10^{14} Ω. To measure the currents from the samples, the Rogowski belt was used, with subsequent amplification and digitization of the obtained data. In Fig. 10 shows the results of measurements during the experiment. As can be seen from Fig. 10, that the current from the sample flows 100 mks longer than the incident current to the sample. And after that an inverse current is formed, although the applied potential to the sample was equal to zero.

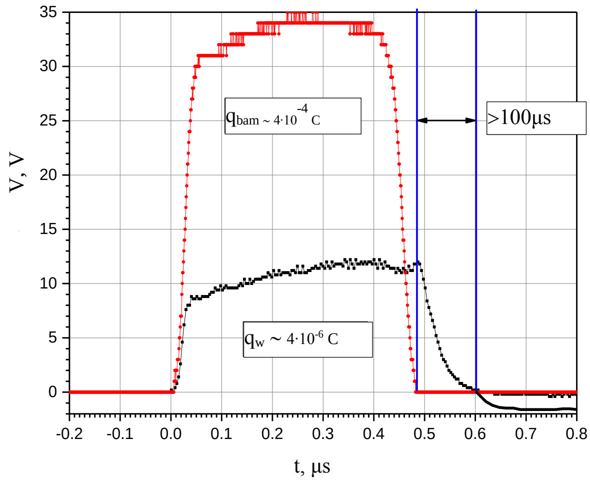

Fig. 10. Results of current measurements on the sample during the experiment (red color shows the beam current, black current from the sample)

In Fig. 11 shows the dynamics of resistance changes *TiO_2* during irradiation *He^+* with an energy of 0.12 MeV and after irradiation. As can be seen from the graph, the greatest drop in resistance occurs in the first hour of irradiation. In the absence of a beam, the resistance is partially restored.

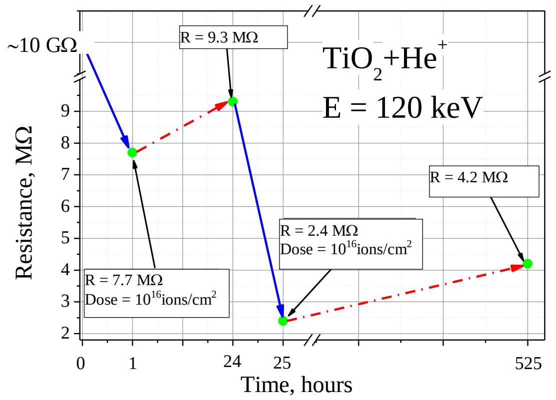

Fig. 11. Dynamics of resistance change TiO_2 during irradiation (blue solid lines) and after irradiation (red dot-dashed lines)

From the obtained preliminary data on the study of the electro-physical properties of ceramic materials, the following conclusions can be drawn, which must be taken into account in the further planning of experimental work:

1. As can be seen from Fig. 8 ionization on the surface of the sample upon irradiation with an energy of 0.12 MeV is greater than at 4 MeV. Consequently, the degree of ionization of the near-surface layer at 0.12 MeV is greater than at 4 MeV.

2. The damage profile at an energy of 0.12 MeV is completely superimposed on the ionization profile, and at an energy of 4 MeV the overlap is practically absent. And also the damage profile at an energy of 0.12 MeV is approximately twice as high as at 4 MeV. This fact should be taken into account when interpreting the experimental results.

3. It is necessary to take into account the appearance of free electrons in the course of stripping *He^+* to an alpha particle in the surface layer to 0.7 µm.

4. Binding energy TiO_2 is within 10 eV, therefore, the formation of free oxygen atoms and titanium, which also contribute significantly to the change in electrophysical properties.

Therefore, at low energies of the helium ion beam, in addition to the ionization profiles, it is necessary to take into account the damage profile of the sample, structural radiation changes, and at energies above 1.5 MeV, the damage profile probably does not contribute significantly to the change in the electrophysical characteristics TiO_2.

CONCLUSIONS

On the basis of linear accelerator of helium ions, an experimental complex for irradiation of samples of structural materials and measuring and recording of parameters of irradiation in real time is created. Methodical experiments were carried out, which confirm the working capacity of the complex. Experimental preliminary data on changes in electrophysical properties were obtained TiO_2, from which the electrical resistivity should be reduced by 5-6 orders of magnitude when irradiated with the sample He^+ dose 10^{16} particles on cm^2 and the appearance of a reverse current in the sample during pulsed irradiation. This indicates not only the effect of the ionization profile, but also the effect of radiation damage on the electrophysical properties of the sample.

This technique for studying the electrophysical properties makes it possible to study a wide range of ceramic materials that are used and planned to be used in nuclear and thermonuclear power, when irradiated with linear accelerators over a wide range of temperatures and irradiation doses.

REFERENCES

1. В.Ф. Зеленский, И.М. Неклюдов, Т.П. Черняева. *Радиационные дефекты и распухание металлов*. Киев: «Наукова думка». 1988, 296.
2. H. Ullmaier. The influence of helium on the bulk properties of fusion reactor structural materials // *Nuclear fusion*. 1984, v. 24, № 8, p. 1039-1083.
3. С.Н. Дубнюк, Б.В. Зайцев. Линейный ускоритель для облучения конструкционных материалов // *ВАНТ. Серия «Ядерно-физические исследования»*. 2014, №3(91), с. 172-176.
4. 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.
5. Модуль аналого-цифрового и цифроаналогового преобразования ZET-210. Инструкция по эксплуатации / М. *ЗЭТ*, 2010, с. 40.
6. B. Widrow, J.R. Glover, J.M. McCool, et al. Adaptive noise cancelling: principles and applications // *Proc. IEEE*. 63, p. 1692-1716.

7. Jesse Liberty, Donald Xie. Programming C# 3.0, 5th Edition // *NY, O'Reilly Media*. 2008, p. 624.
8. http://www.srim.org.
9. Б.Б. Дамаскин, О.А. Петрий, Г.А. Цирлина. *Электрохимия*. М.: "Химия", 2006, 670 с.
10. С.В. Волков, Л.Ф. Козин. *Современная энергетика и экология*. М.: "Наукова думка", 2006, 773 с.
11. С.Н. Дубнюк, Р.А. Анохин, Б.В. Зайцев и др. Методика и экспериментальные данные облучения конструкционных материалов ионами гелия на линейном ускорителе // *ВАНТ. Серия «Ядерно-физические исследования»*. 2012, №5(81).

Article received 18.10.2017

ЭКСПЕРИМЕНТАЛЬНЫЙ КОМПЛЕКС ДЛЯ ИССЛЕДОВАНИЯ КОНСТРУКЦИОННЫХ МАТЕРИАЛОВ НА ЛИНЕЙНОМ УСКОРИТЕЛЕ ИОНОВ ГЕЛИЯ

Р.А. Анохин, Б.В. Зайцев, К.В. Павлий, В.Г. Журавлев, В.А. Сошенко

Приведено описание экспериментального комплекса линейного ускорителя ионов гелия, который состоит из камеры облучения, датчиков, конвертеров сигналов (АЦП) и ЭВМ с программой обработки экспериментальных данных с последующим отображением их на дисплее. Комплекс предназначен для проведения экспериментальных работ по изучению физических свойств конструкционных материалов, применяемых на АЭС и ТЯР. Проведено тестирование комплекса при облучении двуокиси титана (TiO_2) ионами гелия с энергиями 0,12 и 4 МэВ. Приведены экспериментальные данные электрофизических характеристик TiO_2, подтверждающие целесообразность использования комплекса для изучения свойств материалов, применяемых в условиях мощных радиационных полей.

ЕКСПЕРИМЕНТАЛЬНИЙ КОМПЛЕКС ДЛЯ ДОСЛІДЖЕННЯ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ НА ЛІНІЙНОМУ ПРИСКОРЮВАЧІ ІОНІВ ГЕЛІЮ

Р.О. Анохін, Б.В. Зайцев, К.В. Павлій, В.Г. Журавльов, В.А. Сошенко

Наведено опис експериментального комплексу лінійного прискорювача іонів гелію, що складається з камери опромінення, датчиків, конвертерів сигналів (АЦП) і ЕОМ з програмою обробки експериментальних даних з подальшим відображенням їх на дисплеї. Комплекс призначений для проведення експериментальних робіт з вивчення фізичних властивостей конструкційних матеріалів, що застосовуються на АЕС і ТЯР. Проведено тестування комплексу при опроміненні двоокису титану (TiO_2) іонами гелію з енергіями 0,12 і 4 МеВ. Наведено експериментальні дані електрофізичних характеристик TiO_2, що підтверджують доцільність використання комплексу для вивчення властивостей матеріалів, що застосовуються в умовах потужних радіаційних полів.