

BEAM AND TARGET PARAMETERS MEASUREMENT SYSTEM ON HELIUM IONS LINEAR ACCELERATOR

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A system for measuring beam and target parameters on helium ions linear accelerator is presented. The measurement system consists of sensors set, signal converters and computer with codes for processing experimental data. The measurement system is designed for recording, visualizing, storing and processing data directly when samples are irradiated with helium ions with energies of 0.12...4 MeV. The sample temperature, the ion beam current and its shape, the sample tilt angle to the beam axis, the irradiation dose, the ionization, damage and helium range profiles are measured/calculated.

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INTRODUCTION

To maintain the operation of the power units and design new nuclear power plants, as well as thermonuclear reactors (TNR) creation, it is necessary to take into account the structural materials irradiation effects [1, 2]. Irradiation of nuclear power plants and TNR structural materials on linear accelerators makes it possible to conduct study faster than in experimental reactors [1, 3]. To study the behavior of structural materials during ion beam irradiation in NSC KIPT created irradiation complex [4, 5] on the basis of helium ions linear accelerator with an energy up to 4 MeV [6 - 9] with appropriate measurement systems. Below is given detailed description of them.

1. ACCELERATOR AND IRRADIATION PARAMETERS MEASUREMENT

The accelerator produces helium ions with energy 4 MeV, a pulsed current ~ 1 mA with frequency of pulses up to 5 Hz and pulse duration 500 μ s, injection energy 120 keV, injection current up to 20 mA. The IH accelerating structure with APF and step change of the synchronous phase along the focusing periods [10, 11] is used in the accelerator. The accelerating field in the initial part of the structure is made incremental to proceed maximum ions capture. The beam focusing and transporting system on the quadruple lenses basis makes it possible to obtain an accelerated beam current up to 0.8 mA in a spot ~ 1 cm in diameter on the target.

To study the properties of metallic, semiconductor and ceramic materials on the helium ions accelerator with energy of 0.12...4 MeV, a camera for structural materials irradiation was created (Fig. 1), as well as a system for measuring beam and target parameters. Vacuum in the chamber is provided by roughing and turbomolecular pumps.

During sample irradiation *in-situ* various physical quantities are measured and calculated. E.g., the beam current and the irradiation dose, the tilt angle between sample and beam axis, the helium range profile in the sample, etc. Below, the physical quantities that are measured directly in the experiment and which do not require a large amount of computation are called direct parameters. Those physical quantities that require significant mathematical processing, both direct parameters and data drawn from outside, e.g., the helium range pro-

file, are called indirect parameters. Direct parameters include: sample temperature, beam current and its shape, tilt angle between sample and beam axis. Indirect parameters include: irradiation dose, ionization, damage and helium range profiles.



Fig. 1. Chamber for the study structural materials properties

To increase the measurements accuracy during irradiation and to provide data transmission for a distance of ~ 50 meters, the measured parameters are digitized, filtered from interference and transmitted to computer for processing and visualization.

To measure the direct parameters, were used a transient beam current sensor [12] (beam current and beam current shape), a thermocouple (sample temperature) and scanning device (tilt angle between sample and beam axis). Data is digitized using ZET-210 DAC/ADC and transmitted to personal computer. Codes that implement various filters and algorithms for data processing are written in C # in Microsoft Visual Studio environment.

2. DIRECT PARAMETERS

Sample temperature, current and shape of the beam current, tilt angle between sample and beam axis are direct parameters.

2.1. SAMPLE HEATING AND TEMPERATURE MEASUREMENT

To irradiate various materials samples with helium ions with energy of 0.12...4 MeV produced sample holder with a heating element (Fig. 2). Sample holder is attached directly to the vacuum irradiation chamber (see Fig. 1).



Fig. 2. Sample holder with inlet flange and heating element

The sample temperature rate change linearly. It depends from heater power, and regulated by voltage that is supplied to the heater. Getting to the stationary temperature, with a constant heater power, occurs in 50...100 seconds (Fig. 3), which satisfies the requirements for irradiating samples at the accelerator.

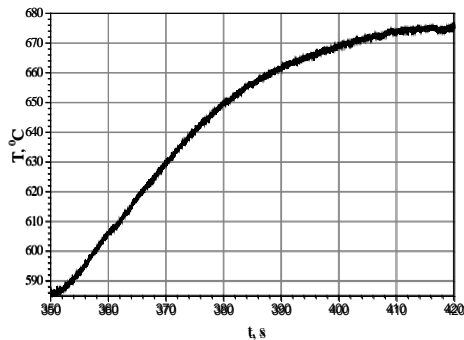


Fig. 3. Dependence of the sample temperature on the heating time (getting to stationary mode of heater)

Particular attention was paid to the influence of high-frequency field on the temperature measurement error. On personal computer, the input data is filtered using a nonlinear averaging filter with exponential transformation:

$$y_k = -\frac{1}{\alpha} \ln \left(\frac{1}{n+1} \sum_{k-n/2}^{k+n/2} \exp(\alpha x_i) \right),$$

where α – weight coefficient, x – input signal, y – output signal, n – number of input signal count, k – number of output signal count.

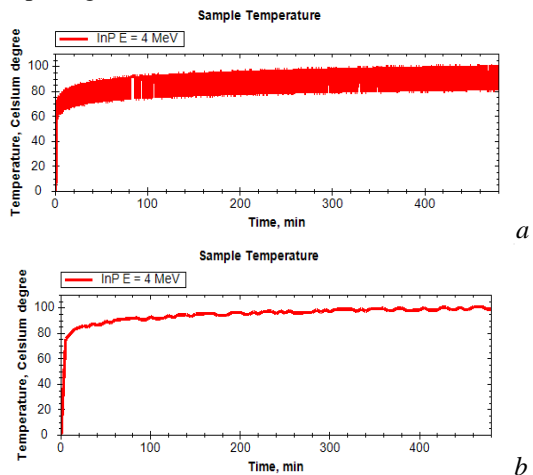


Fig. 4. Signal from the thermocouple before filtration (a). Signal after filtration (b)

Fig. 4,a,b shows the temperature dependences without filter and with filter, respectively. As can be seen from Fig. 4a,b the usage of digital filter in temperature measurement significantly improves the measurement accuracy, and substantially suppresses HF-interference.

The thermocouple is connected to the ZET-210 ADC input, which transmits the thermo-EMF digitized value to a DC voltmeter. After the voltmeter, the measured temperature value is displayed on the screen in the form of a graph, and also on the digital indicator (current at the moment) and saved as a file on the computer hard disk for subsequent work with it. Fig. 5 shows the temperature measurement scheme. Fig. 6 shows the sample temperature time dependence displayed on the computer monitor.

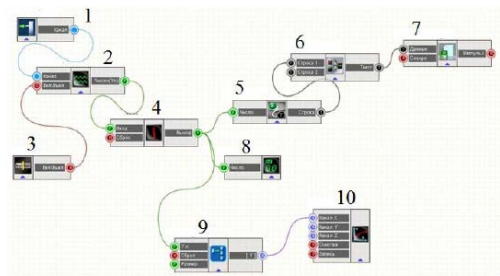


Fig. 5. Scheme of sample temperature measuring: 1 – input channel; 2 – voltmeter; 3 – power button; 4 – integrator; 5 – converter; 6 – addition of lines; 7 – write to a file; 8 – LCD; 9 – array; 10 – XYZ-plotter

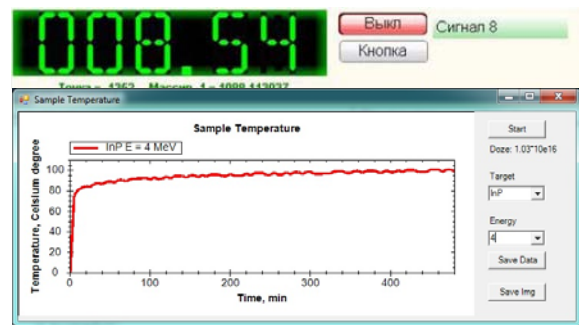


Fig. 6. Sample temperature time dependence displayed on the computer monitor

2.2. BEAM CURRENT MEASUREMENT

The most common method for measuring the beam current at the accelerator output is a non-contact method based on the electromagnetic induction phenomenon. It allows continuous measurement of the beam current, which irradiates the sample [12], with the subsequent calculation of the irradiation dose. Fig. 7 shows a manufactured and calibrated floating-drift sensor that connects to the output of linear accelerator and irradiation chamber.



Fig. 7. Induction sensor for beam current measuring in assembled state

The ZET-302 digital oscilloscope and ZET-210 DAC/ADC are used for calibration and operation with the sensor, which are connected to a computer with further data registration and processing. To amplify the signal, a pulse amplifier is used, and to filter the interference – an adaptive digital Kalman filter with an infinite impulse response [13].

Fig. 8 shows the filter scheme. The general mathematical expression of the filter is:

$$x_k = F_k x_{k-1} + B_k u_k + w_k,$$

where x_k – current signal; k – count number; F_k – process evolution matrix; B_k – control matrix; u_k – control vector for a signal x_k ; w_k – vector of a normal random process with zero mathematical expectation.

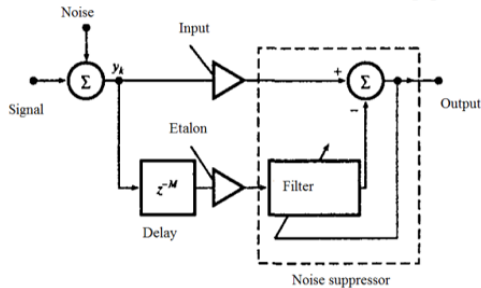


Fig. 8. The algorithm of the filter

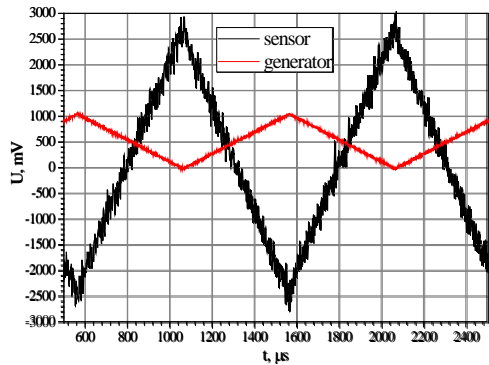


Fig. 9. Sensor calibration waveforms

Rectangular and triangular pulses from the signal generator were used in the process of the sensor calibration. Fig. 9 shows the oscillograms of the input signal (from the generator) and the output one (from the sensor) for triangular pulses.

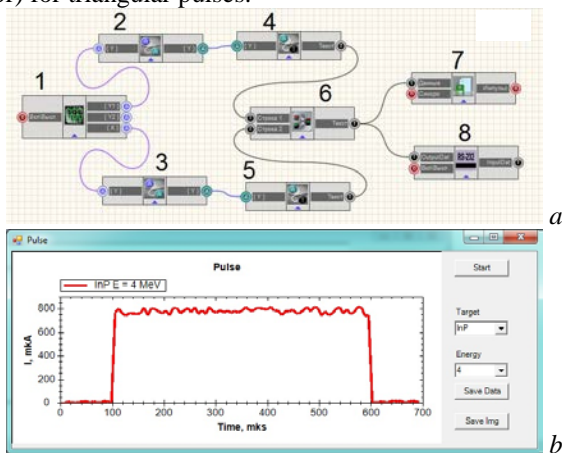


Fig. 10. Block diagram of beam current pulse shape measurement (a). 1 – high-frequency oscilloscope; 2-5 – converters; 6 – addition of lines; 7 – write to file; 8 – external interface. The beam current pulse profile on the computer monitor (b)

The induction sensor thermal noise is ~7% of the amplitude value. The Kalman filter allows to reduce this noise up to 2%. Scheme for measuring beam current pulse shape was developed and manufactured, it is shown in Fig. 10,a,b shows the beam current pulse profile displayed on the computer monitor during irradiation.

2.3. SAMPLE TILT ANGLE MEASUREMENT

One of the important characteristics, during materials irradiation, is the ion path in the irradiated material and the depth of their occurrence in the sample, which is measured along its normal to the surface. As ions range in the sample is determined by the sample material, the type of ion and its energy, this length can be changed only by changing the ion type or its energy. The depth of ions occurrence in the sample can be changed by changing the angle between the beam axis and the sample. If this is done during irradiation, then it is possible to create variously shaped damage and helium range profiles. For this purpose, a scanning device and a system for measuring tilt angle between beam axis and sample was manufactured. Schematic representation of the scanning device operation and its calibration principle are shown in Fig. 11.

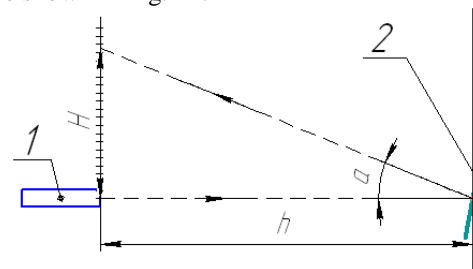


Fig. 11. Measurement of tilt angle between beam axis and sample: 1 – laser; 2 – mirror

The scanning node general view and main elements are shown in Fig. 12.

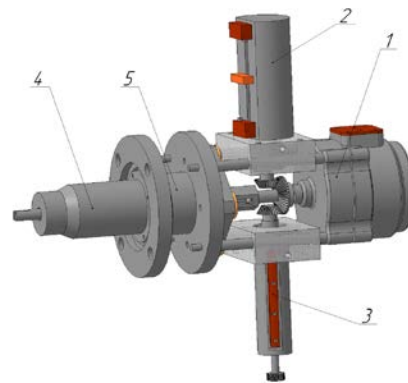


Fig. 12. The scanning unit: 1 - RD-09 engine; 2 – end caps; 3 – potentiometer PPML-I; 4 – body; 5 – vacuum bellows inlet

The unit main components are: (1) the RD-09 engine with 2.5 rpm, (2) the limit switches that limit the rod movement in the vacuum chamber and (3) the multi-turn potentiometer for measuring the sample rotation angle. To calibrate it, was used a serial connection circuit in which the resistor is connected between the generator and the voltmeter, and the data is output to a computer. The generator and voltmeter are realized on the basis of ADC/DAC ZET-210. Voltmeter readings

from potentiometer revolutions number dependence can be approximated by the expression:

$$U(n) = 340.5 + \exp(0.29n + 1.75),$$

where $U(n)$ – voltage, n – number of revolutions.

For scanning unit calibration, a laser-optical method was used in which the reflected beam determines the tilt angle. The maximum angle error is 0.5 degrees. The calibration curves are shown in Fig. 13 for three ranges of maximum tilt angle variation.

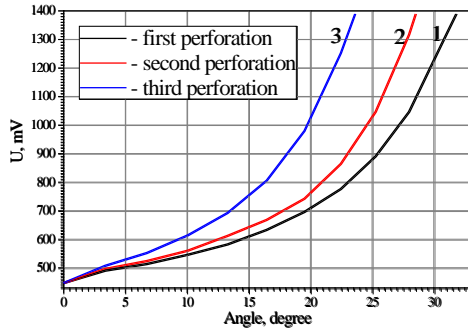


Fig. 13. Scanning device calibration curves

Voltage from the variable resistance is fed to the DAC/ADC ZET-210 (the operation scheme is shown in Fig. 14). Then the digitized signal is transmitted to the PC, where it is converted into tilt angle between sample and beam axis, displayed on the monitor and stored on the hard disk (Fig. 15). Measurements are carried out at 10 Hz frequency to determine a tilt angle more closely.

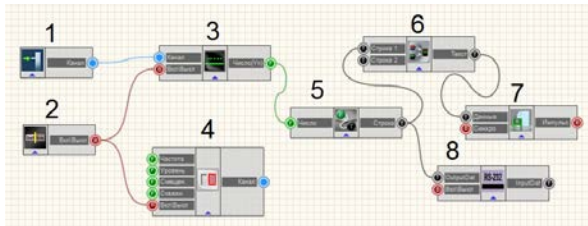


Fig. 14. Scheme of tilt angle measuring:
1 – input channel; 2 – power button; 3 – DC voltmeter;
4 – generator; 5 – converter; 6 – addition of lines;
7 – write to a file; 8 – external interface

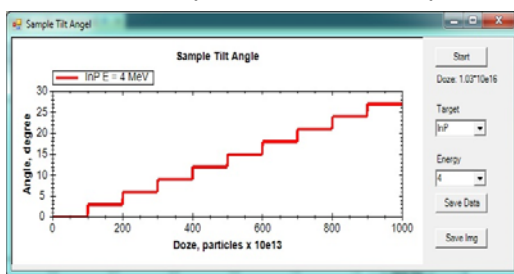


Fig. 15. The angle of the sample on the computer monitor

Table shows the ranges and errors in measuring direct parameters.

Ranges and errors in measuring direct parameters

Parameter	Range	Error
Beam current	up to 1 mA	± 2%
Pulse duration	480...510 μs	± 1.65%
Temperature	20...1100°C	± 1%
Tilt angle	0...27 degree	± 1.5%

3. INDIRECT IRRADIATION PARAMETERS

The irradiation dose, ionization, damage and helium range profiles are indirect parameters that are obtained by mathematical processing of the measuring direct parameters results and displayed on the computer monitor when samples are irradiated. A special feature of systems for measuring and displaying indirect parameters is the need for additional calculations; in other respects they are identical to systems for measuring direct parameters. To calculate the range, damage and ionization profiles are used: (1) special analytical expressions which we obtained by approximating the data of the SRIM code [14], and (2) the values of the irradiation doses which are measured during the experiment. To register these parameters in the SCADA ZETView system, codes have been developed to interface with the ZET-210 DAC/ADC. To display the results on a computer monitor were developed C# codes in Microsoft Visual Studio environment.

3.1. IRRADIATION DOSE

To determine the irradiation dose, the data of the floating-drift sensor is used (see par. 2.2). The radiation dose is measured by summing the beam current in each pulse, after what the data is programmatically converted into a dose. In the scheme for measuring the irradiation dose after the voltmeter, the value of the pulsed beam current is fed to the integrator, which sums all the previous values (see Fig. 10,a). Fig. 16 shows the process of displaying the irradiation dose on a computer monitor.

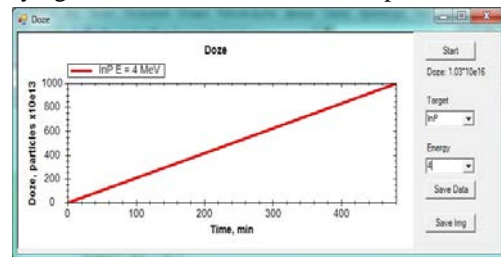


Fig. 16. The irradiation dose as a function of time on a computer monitor

3.2. HELIUM RANGE PROFILE

After calculating the helium range profile using the SRIM code, and by approximating the calculated profiles along the sample depth, analytical expressions are obtained for given beam energies and irradiated material. The range profile is described by the asymmetric Gauss function:

$$y = \begin{cases} b_1 \exp(d_1(x - x_c)^2) & x \leq x_c \\ b_2 \exp(d_2(x - x_c)^2) & x \geq x_c \end{cases},$$

where x_c – range profile maximum; b_1, b_2 – irradiation dose rate factors; d_1, d_2 – approximation coefficients. The dose-response factors are determined by the expression:

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

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

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

where Φ_0 – irradiation dose; N_A – Avogadro number; ρ – irradiated sample density; μ – irradiated sample molar mass; V – sample irradiated volume. Fig. 17 shows calculated data and approximating curve comparison for TiO_2 sample.

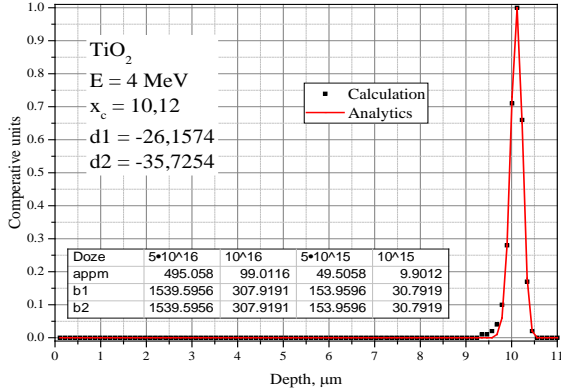


Fig. 17. Calculated data and approximating curve comparison for TiO_2 sample

Helium range profile measurement is carried out according to a scheme analogous to the beam current pulse shape measurement (Fig. 14) using the expression for the asymmetric Gaussian function that approximates helium range profile. An example of how the code works is shown in Fig. 18.

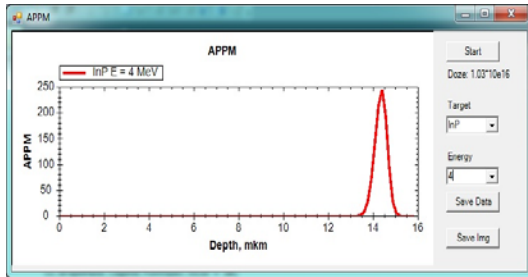


Fig. 18. Helium range profile

3.3. DAMAGE PROFILE

To approximate the damage profile, the calculation is performed using the SRIM code, a distribution is used in which profile left part is described by the Cauchy distribution, the right part by the Gaussian distribution. The expression is:

$$y = \begin{cases} \frac{b_1}{(x-x_c)^2 + d_1} & x \leq x_c \\ b_2 \exp(d_2(x-x_c)^2) & x \geq x_c \end{cases},$$

where x_c – damage profile maximum; b_1, b_2 – irradiation dose rate factors; d_1, d_2 – approximation coefficients. The dose-response factors are determined by the expression:

$$b_1 = b'_1 \cdot b_2, \quad b_2 = dpa \int_0^{x_{max}} \bar{y}(x) dx,$$

where x_{max} – the maximum depth of helium in the sample; $\bar{y}(x)$ – normalized to unity helium range profile, and dpa is determined:

$$dpa = (\Phi_0 \cdot G_{vac}) \left/ \left(N_A \cdot \frac{\rho}{\mu} \cdot V \right) \right.,$$

where G_{vac} – number of vacancies per ion; Φ_0 – irradiation dose; N_A – Avogadro number; ρ – irradiated sample density; μ – irradiated sample molar mass; V – sample irradiated volume. Fig. 19 shows calculated data and approximating curve comparison for Zr sample.

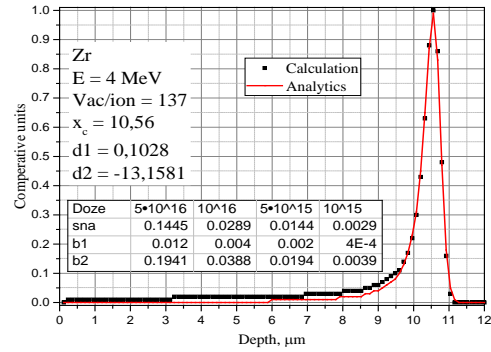


Fig. 19. Calculated data and approximating curve comparison for Zr sample

The scheme for measuring the damage profile is similar to the helium range profile measurement.

3.4. IONIZATION PROFILE

An important characteristic for studying the ceramic materials electro physical properties is the ionization profile, since the electrons number produced in the sample irradiated layer is $\sim 10^5 \dots 10^6$ per ion.

By approximating the ionization profiles calculated using the SRIM code, an analytical expression is obtained in which the left-hand side is described by the Cauchy distribution and the right-hand side by the Fermi distribution:

$$y = \begin{cases} a_1 + \frac{b_1}{(x-x_c)^2 + d_1} & x \leq x_c \\ \frac{1}{\exp(x \cdot b_2 + d_2) + 1} & x \geq x_c \end{cases},$$

where x_c – ionization profile maximum; a_1, b_1, b_2, d_1, d_2 – approximation coefficients. Fig. 20 shows calculated data and approximating curve comparison for the TiO_2 sample.

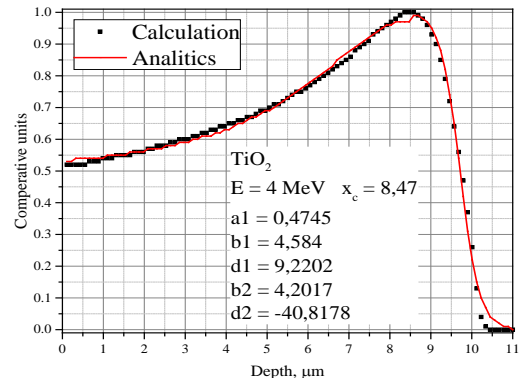


Fig. 20. Calculated data and approximating curve comparison for the TiO_2 sample

Scheme for measuring the ionization profile, similar to the helium range and damage profiles measurement.

CONCLUSIONS

On the helium ions linear accelerator basis, an experimental complex for structural materials samples

irradiation was created. Direct and indirect beam and target parameters are measured directly during irradiation. Direct parameters include: sample temperature, beam current and its shape, tilt angle between sample and beam axis. Indirect parameters include: irradiation dose, ionization, damage and helium range profiles. The experiments showed the reliability, sufficient accuracy and efficiency of the beam and target measurement system.

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СИСТЕМА ИЗМЕРЕНИЯ ПАРАМЕТРОВ ПУЧКА И МИШЕНИ НА ЛИНЕЙНОМ УСКОРИТЕЛЕ ИОНОВ ГЕЛИЯ

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Приведено описание системы измерения параметров пучка и мишени на линейном ускорителе ионов гелия. Система измерений состоит из набора датчиков, конвертеров сигналов и ЭВМ с программой обработки экспериментальных данных. Система измерений предназначена для регистрации, визуализации, сохранения и обработки данных непосредственно при облучении образцов ионами гелия с энергиями 0,12...4 МэВ. Измеряются/вычисляются: температура образца, ток и форма тока пучка ионов на образце, угол наклона образца к оси пучка, доза облучения, профили ионизации, повреждаемости и залегания гелия в образце.

СИСТЕМА ВИМІРЮВАННЯ ПАРАМЕТРІВ ПУЧКА І МИШЕНІ НА ЛІНІЙНОМУ ПРИСКОРЮВАЧІ ІОНІВ ГЕЛІЮ

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Наведено опис системи вимірювання параметрів пучка і мішені на лінійному прискорювачі іонів гелію. Система вимірювань складається з набору датчиків, конвертерів сигналів і ЕОМ з програмою обробки експериментальних даних. Система вимірювань призначена для реєстрації, візуалізації, збереження і обробки даних безпосередньо при опроміненні зразків іонами гелію з енергіями 0,12...4 МеВ. Вимірюються/обчислюються: температура зразка, струм і форма струму пучка іонів на зразку, кут нахилу зразка до осі пучка, доза опромінення, профілі іонізації, пошкоджуваності і залегання гелію в зразку.