https://doi.org/10.46813/2022-139-023

UNIVERSAL EXPERIMENTAL FACILITY OF IHEPNP NSC KIPT FOR RESEARCH OF HIGH-ENERGY ELECTRON BEAM INTERACTION WITH THIN AMORPHOUS AND SINGLE-CRYSTAL STRUCTURES

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The description and bench test results of the developed universal experimental facility [1] are presented. It mounted at the direct beam line of IHEPNP NSC KIPT 30 MeV Linac for the fundamental and applied research of high energy electron interaction with amorphous and single-crystal structures. The universal facility consists of the following structural elements and systems: electron beam transportation system; electron beam parameters formation and measurement, secondary electron emission monitor (SEM); electron beam full absorption Faraday cups (FC), collimators, goniometrical device system and magnetic energy analyzer.

PACS: 29.20.-c, 07.07.-a, 07.07.Df

INTRODUCTION

In order to expand the possibilities of 30 MeV Electron Linac beam applications in the fundamental and applied research the universal experimental facility was developed, installed and tested. This experimental facility application allows providing the experimental studies of secondary electron emission depending on the primary electron beam energy and the thin foil materials; dependencies determination of the density effect versus ionization losses of primary electron passing through thin foils; the electron dechanneling length for single crystals for the energy range of primary electrons from 10 to 30 MeV.

The features of the relativistic electron interaction with a thin foil are that interactions with matter near the front and back foil surfaces are different. In the relativistic electron energy range, the changes in the medium properties by the passing particle field are necessary to take into account [2]. The effect of medium polarization (density effect) is absent in a thin layer of matter near the front surface and it is significant for energy losses in a thin layer of matter near the front surface when the primary electron has passed through the entire thickness of the target.

Based on the requirements of the above processes experimental studies the developed experimental facility should have the following characteristics and parameters such like:

- the ability to thin amorphous and single-crystal targets research;
- the possibility of electron beam parameters measurements and control (electron beam profiling, energy distribution of primary and secondary electron, electron beam current);
- the free oil pumping vacuum system with the residual pressure less than 10^{-4} Pa;
- electron beam position visual observation in the experimental chamber;
- remote controls of secondary electron emission monitor, Faraday cups, collimators;
- remote control of the target orientation in the goniometrical device;
- the ability to remotely change targets during the experiment;
- an automatic system application for measuring and recording experimental data.

1. GENERAL DESIGN OF THE UNIVERSAL EXPERIMENTAL FACILITY

During the research NASU project ***"Development of the experimental complex based on a linear electron accelerator IHEPNP NSC KIPT and detection systems development for fundamental and applied research"*** in 2020-2021 years a schematic diagram of the experimental facility, all elements drawings and design documentation were developed. After some constructional beam line components manufacturing the complex (vacuum and electromechanical) bench tests were done. As a final result the developed experimental facility at the end of 30 MeV Electron Linac direct beam line was installed and demonstrated experiments of the high-energy electron beam interaction with amorphous thin foil were performed [3].

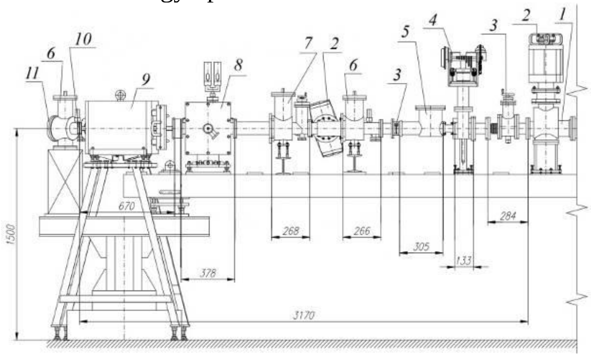
On the Fig. 1,a the general scheme of installed and tested the experimental facility at the direct beam line of 30 MeV Elecron Linac is presented.

The proposed experimental facility consists of standard systems and components developed by NSC KIPT, including custom-made within the project. These include vacuum, power supply and control systems, accelerated electron beam parameters formation and measurement and electronic measuring equipment for ensuring of physical experiment.

To ensure the appropriate vacuum conditions of experimental research in the universal experimental facility, two operation modes were introduced: the previous one – the low vacuum regime (10^{-2} Pa) (when the atmospheric gas was leaked in one of the facility parts), and the main high vacuum regime (10^{-4} Pa) – produced by two magnetic discharge pumps (2) type NMDO-01-1.

By the mechanical valves (3) and the valve of the collimator chamber (7) it is possible to replace the experimental target the stationary secondary emission monitor (5) chamber and in the goniometrical device chamber (8) without violating the high vacuum in the accelerator system.

The collimating device (4), SEM (5) and the first FC (6) actually form an independent system, which allows to perform experimental studies of the secondary electron emission yield measurements from thin amorphous foils by recording in situ emitter currents depending on the potentials on the collectors when accelerated electron beam passing through thin foils. This beam line section for a preliminary test on the direct beam channel of the electrostatic accelerator ELIAS [4] was mounted. The research of secondary electrons yields from thin aluminum, nickel and beryllium foils at primary electron beam energy up 2.5 MeV was executed.



a

b

Fig. 1. General scheme of experimental facility: 1 – connecting electron beam line section; 2 – magnetic discharge pump; 3 – mechanical valve; 4 – multi-collimating device; 5 – stationary secondary electron emission monitor (SEM); 6 – Faraday cup chamber; 7 – chamber of remote collimator; 8 – goniometrical device chamber; 9 – magnetic energy analyzer; 10 – direct electron beam output window in air; 11 – 35° deflected electron beam output window in air (a); General view of the installed universal experimental facility at 30 MeV Electron Linac direct beam line (b)

At the experimental facility a standard Faraday cup (6) of full absorption developed by NSC KIPT was used. It is widely used to measure the current of the accelerated electron beam. Electromechanical control system FC allows to implement two modes: on the beam – for measuring the electron beam current with a diameter of not more than 56 mm and with a maximum energy of 300 MeV and electron current magnitude from 0.1 nA to 100 μA, and in the raised position for electron beam transportation.

A standard FC chamber (7) with a mechanical valve was used to place an additional collimator in front of the goniometrical device (8) (the length of the aluminum or graphite cylinder is 60 mm and the centric through hole is 16 mm) for scattered electrons collimation. The measurement of the electron current by the collimator (8) allows for the accelerator operator to monitor the position of the electron beam on the accelerator axis during the experiment based on the registration of the minimum beam current that has passed through the through hole.

The goniometrical device chamber (9) provides to apply the standard goniometrical device [5] of NSC KIPT development and also in addition developed and made electromechanical target device with change of targets on 7 positions.

Magnetic analyzer (9) with vacuum chamber, which allows obtaining data about the energy spectra of primary and secondary electrons, is installed after goniometrical device chamber.

FC (6) with electron beam output window (11) installed after magnetic analyzer (9) for measuring the electron currents of direct and 35° deflected beams (after the electron beam passing through a target located in the goniometrical device chamber).

2. MULTI-COLLIMATING DEVICE

The collimating device (4) is a remote-controlled electromechanical element of the electron beam formation and transportation system. It allows collimating the electron beam diameter at the entrance of the experimental facility in a given interval from 3 to 20 mm. The general view of the multi-collimator device is presented on the Fig. 2,a. This vacuum electromechanical water cooling electron beam collimation system developed by NSC KIPT and was used as a main collimator. Its vacuum and mechanical tests are shown its application feasibility as an element of the primary electron beam formation at the experimental setup entrance.

An electric control system has been developed and installed, which allows remotely collimating the electron beam size in the range from 3 to 20 mm without violating the vacuum insulation. The control scheme of the collimator device consists of such main systems: power supply and control system (namely – installation of the collimator device at the seven positions of the required diameters: position №1 – 3 mm, position №2 – 3.5 mm, position №3 – 4 mm, position №4 – 5 mm, position №5 – 7 mm, position №6 – 15 mm and position №7 – 20 mm, respectively). Also, it has a visual alarm on the accelerator control panel of the selected collimator position on the electron beam axis. The possibility of video monitoring of the electron beam imprint on fluorescent ZnS screen on an aluminum flag is presented. The flag in the SEM chamber (5) after the stationary secondary electron emission monitor is placed. The collimator length of the copper through-holes is about 60 mm. The existing system of water cooling of structural elements in vacuum ensures their long-term use with an intense electron beam with partial or complete absorption.

ISSN 1562-6016. ВАНТ. 2022. №3(139)

For electron beam dimensions determination depending on the accelerator operation regimes in the position of the collimator №6 (15 mm) slotted device was installed. This device consists of two tungsten plates with 2 mm thickness. The width of the slit is 0.5 mm. The slit device (see Fig. 2,b) application makes possible during the experiment to estimate (by scanning mode in the horizontal plane) the geometric dimensions of the electron beam. It is useful for providing the optimal beam transportation condition in the experimental setup. On the Fig. 2,c the electron beam print on the flag at the SEM chamber (5) using the collimator with Ø10 mm is shown. It was obtained during bench tests of electron beam transportation on the experimental setup. On the Fig. 2 (d) the electron beam current profile of the electron beam collimated by the collimator scanning mode is shown too. The electron beam current was measured by the Faraday cup (6) installed after the SEM (5) and electron beam current scale for collimator positions Ø3 – Ø10 and Ø20 was equal 10 μA, for slit 0.5 mm – 1 μA.

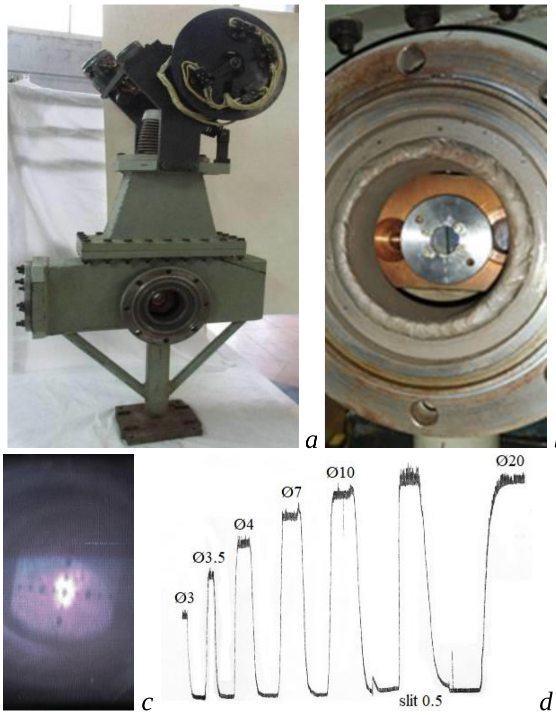


Fig. 2. General view of the multi-collimating device (a); slit device (the clearance between slits is 0.5 mm) in the collimator device (b); 16 MeV electron beam print in the SEM chamber at 30 MeV electron Linac direct beam line (the distance between the holes on the flag is 5 mm and their diameter is 2 mm) (c); electron beam current (arbitrary units) profile measured by FC for collimator scanning mode from position №1 to 7 (from Ø3 to Ø20 mm respectively) (d)

3. THE SECONDARY EMISSION MONITOR

The secondary electron emission monitor (SEM) of NSC KIPT development is a vacuum chamber that houses a remotely controlled electromechanical system. It consists of three ring insulated electrodes (directly SEM) and an electron beam position control system. Both systems have two operation positions: on the beam axis and outside the electron beam axis.

Preliminary analysis [6] of three electrodes SEM construction design (ring collector, emitter and ring collector) was showed that the design features of the electrodes do not allow providing the accurate measurement of the emission electron energy spectrum. Such systems are applicable only for monitoring the electron beam current by registering δ-electron yield produced by primary electron beam passing through thin targets. The main problem of viewed collector electrode design consists of large diameter of through holes (Ø16 mm in our case) which located in front of and after the target (emitter). The clearance between SEM electrodes is 5 mm. The main collector functions are extraction and (or) retarding secondary electron emission from the frontal and (or) back surface of thin foil under electron beam irradiation. For this geometrical construction of SEM the axial electric field distribution introduces ambiguity in determining of secondary electron energy due to the unknown value of potential differences between the collector body and center of through hole. To minimize this potential difference in the SEM system, a well-known method of grids was used, which allows reducing the value of the potential difference to 1%.

On the Fig. 3,a,b the general views of the flange-mounted SEM and flag of electron beam position control system are shown respectively. On the Fig. 3,c the SEM collector electrode view is shown. The through hole of collector electrode covered with Al grid. The clearance between wires is 1 mm and their thickness equals Ø25 μm.

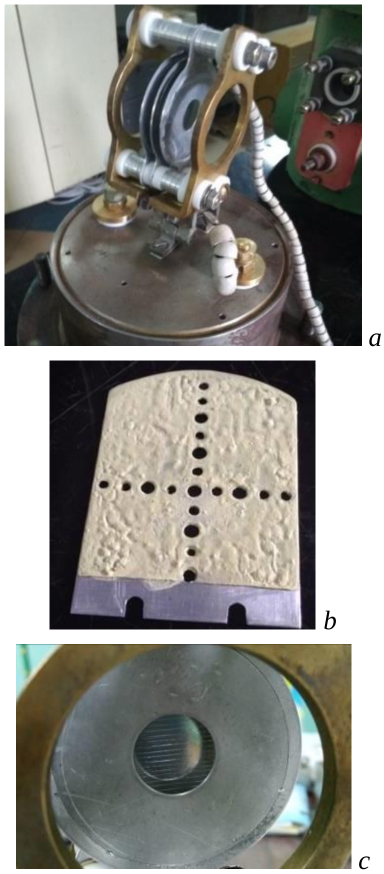


Fig. 3. General view of the SEM on the flange (a); an aluminum flag coated with ZnS (b); SEM collector electrode with grid (Ø25 μm Al wire, step – 1 mm) (c)

This approach of the SEM electrode system upgrading makes it possible to obtain experimental data on the electron emission coefficients, determine their spectrum in a given energy range up to 100 eV, and measure the correct value of secondary electron emission currents versus collector potentials from both the front and back surface of the foil relatively to the primary electron beam movement direction.

The flag (see Fig. 3,b) uses for size up the accelerated electron beam dimensions and its position determination in the SEM chamber relative to the horizontal axis. The intersection central hole (Ø2.5 mm) on the flag corresponds to the central electron beam axis of the experimental facility. It was used in the previous symmetrical placement of all elements of the facility relatively to its axis applying laser level device with reference to the accelerator axis.

4. GONIOMETRICAL DEVICE CHAMBER

This chamber was developed as multifunctional device. It allows installing two independent systems of measurements: goniometrical device and device of variable targets. The detail descriptions of goniometrical device and all developed electronic equipments were presented in the [7]. The system of variable targets was developed and manufactured to expand the experimental capabilities of research on the processes of electron secondary emission yield. The drawing, general view and goniometrical chamber installation are shown on the Fig. 4,a,b,c respectively. The production material of the chamber is non-magnetic stainless steel. It's important for residual magnetization effect reducing in the low electron emission measurement experiments. In comparison to the standard SEM, where it is functionally possible to use only one target, the device of variable targets allows to place in the goniometrical chamber up to 7 experimental targets with the capacity of positioning them relative to the electron beam. Such approach is useful for example for measuring δ-electron yield and low energy secondary electron yield versus of target thickness or material.

On the Fig. 5 The experimental δ-electron yield dependence versus Al target thickness measured during the one experiment session are present as demonstration of developed device experimental possibilities.

5. MAGNETIC ENERGY ANALYZER

According to the developed deployment scheme of experimental equipment of electron beam transportation system with energy up to 30 MeV of universal experimental facility (see Fig. 1,a) behind the goniometrical chamber (8) a magnetic energy analyzer (9) was installed. The general view of which is shown on the Fig. 6,a. Presented magnetic energy analyzer is a system that forms a uniform distribution of magnetic induction folded magnetic circuit. It is a sector magnet with a 35° deflection angle (turning radius is 860 mm, the length of the pole pieces is 440 mm, width 140 mm, the distance between the pole pieces 36 mm). The magnetic analyzer vacuum chamber and the support system on four supports with a possibility of system adjustment as a whole are developed and made. The vacuum chamber of magnetic energy analyzer has two electron beam transportation channels. The direct channel is for bremsstrahlung beam production from the target which located in the goniometrical device chamber and 35° electron beam channel. The last one houses a standard Faraday cup (6, 11) with a system of visual electron beam observation. This system consists of coated with ZnS flag located in air outside the output electron beam window (see positions 10 and 11 of the Fig. 1,a).

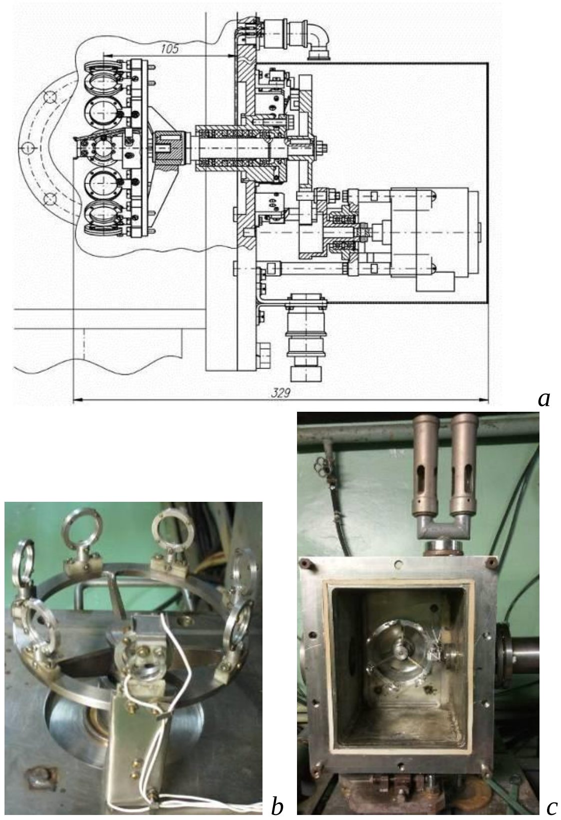


Fig. 4. Drawing (a) and general view of the variable targets device (b) installed inside the goniometrical device chamber(c)

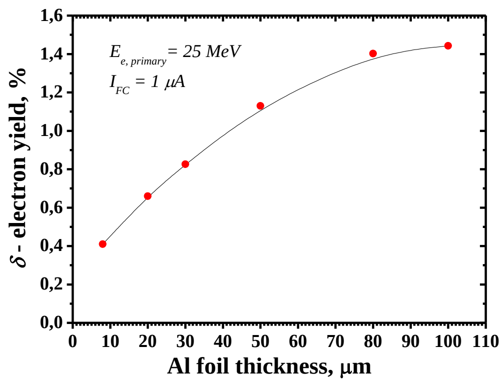
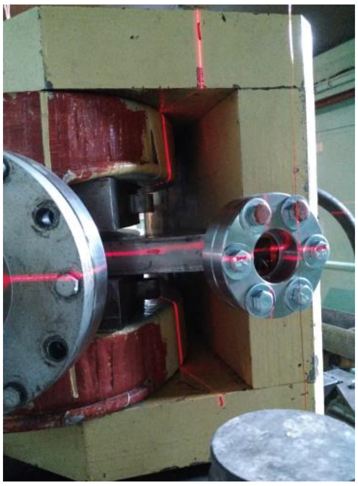


Fig. 5. δ-electron yield dependence versus Al target thickness. Primary electron beam energy is 25 MeV, electron beam current – 1 μA

Traditionally for high energy electron beam extraction from the accelerator vacuum volume to the air for NSC KIPT electron accelerators thin titanium foil (50 μm) is used. In our case after positive results of Geant4 toolkit modeling [8] and complex thermo-mechanical experimental tests the new material 125 μm Kapton was applied for two diameter output windows: Ø56 mm (position 11) and Ø36 mm (position 10) respectively. During the bench tests of universal experimental facility the Kapton® as a material of electron beam output window shown the stable operation. The electron beam output window of direct electron beam line is shown on the Fig. 6,a.

The power supply system of the magnetic analyzer was tested. The dependence of the magnetic induction flux in the interval between the pole pieces depending on the DC current in the coil windings up to 350 A was measured. The corresponding dependence is shown on Fig. 6,a.



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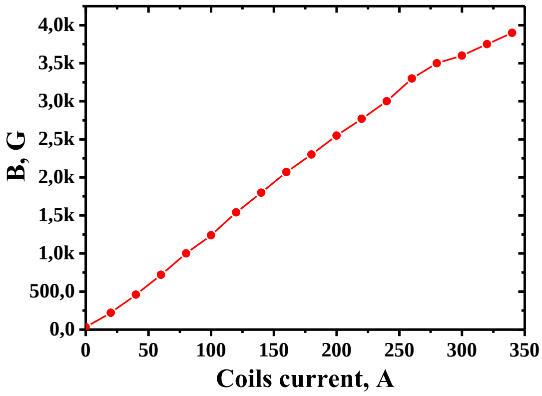

b

Fig. 6. General view of the magnetic analyzer with Ø36 mm direct electron beam output window *with Kapton® foil (a*); *dependence of magnetic induction on current in the windings of the coils of the magnetic energy analyzer (b)*

6. ELECTRONIC EQUIPMENT DEVELOPMENT

For experimental research providing on the 30 MeV Electron Linac, a software and hardware complex was developed and manufactured. It includes the following control and measuring channels:

- goniometrical device control channel, it allows orienting the target under the electron beam, consisting of a power supply system for stepper motors (SM), a power switch unit and a processor unit. The processor unit communicates with the control computer using the USB interface. The control program of the processor unit allows for the experiment operator to adapt it to control almost any type of stepper motor. The top-level program, installed on the PC, allows to orient the target in the geometrical device in X, Y coordinates and azimuth. The channel is described in more detail in the [7]. Further improvement of the channel is possible by introducing feedback on the target coordinates. To do this, it is necessary to install the target position sensors and make the corresponding electronic paths for data processing. In addition, software development will be required;

- channel of low current integrators. It is implemented on the basis of current-voltage converters, analog-to-digital converters (ADC) and a microprocessor that performs data preprocessing and communication with an upper-level computer. The range of measured electron beam currents is within 1 nA...10 μA. To increase the accuracy of measurements, it is planned to use ADCs of a larger capacity (now 10-bit ADCs are used) and switch to gated current-voltage converters;

- channel for measuring the electron beam energy spectrum of the accelerator. It consists of a Faraday cup current integrator and magnet energy analyzer current meter. For digitization, a 10-bit ADC and a microprocessor for communication with a computer are used.

The channel is planned to be improved by increasing the bit depth of the used ADCs, using a gated integrator, and introducing the possibility of automatically controlling the current of the magnetic analyzer. This improvement will make it possible to measure the spectrum in automatic mode.

All channels use Atmega 328 microprocessors. The channels are completely independent of each other; it allows them to be upgraded without significant loss of beam time.

CONCLUSIONS

The universal experimental facility description and bench test results are presented. The developed facility provides the experimental research of high energy electron interaction with amorphous and single-crystal structures. Electron beam with energy range up 10 to 30 MeV after injection and transportation in the experimental facility was applied for thin aluminum foil secondary electron emission research. This research was performed by application stationary secondary electron emission monitor and variable targets device. The application of last one significantly expanded the experimental capabilities of the experimental facility as a whole.

The main directions of future experimental research are processes of high-energy electrons interaction with single-crystal structures with a goniometrical device application. This stage requires additional preparations related to the optimization of the electron beam transportation system in the accelerator unit. There is also a necessary to determine and optimize such parameters of the accelerated electron beam as the angular divergence and electrons energy spread. These parameters are very important for providing electron channeling technique.

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Article received 25.05.2022

УНІВЕРСАЛЬНА ЕКСПЕРИМЕНТАЛЬНА УСТАНОВКА ІФВЕЯФ ННЦ ХФТІ ДЛЯ ДОСЛІДЖЕННЯ ВЗІЄМОДІЇ ВИСОКОЕНЕРГЕТИЧНИХ ЕЛЕКТРОНІВ З ТОНКИМИ АМОРФНИМИ ТА МОНОКРИСТАЛІЧНИМИ СТРУКТУРАМИ

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Представлено опис та результати стендових випробувань розробленої універсальної експериментальної установки [1]. Установка зібрана на прямому виході лінійного прискорювача електронів з енергією 30 МеВ ІФВЕЯФ ННЦ ХФТІ для фундаментальних та прикладних досліджень щодо взаємодії електронів високих енергій з аморфними та монокристалічними структурами. Універсальна установка складається з наступних конструктивних елементів та систем: монітора вторинної емісії електронів; циліндрів Фарадея повного поглинання; коліматорів; гоніометра; магнітного аналізатора енергії електронів; системи транспортування формування та вимірювання параметрів електронного пучка.

УНИВЕРСАЛЬНАЯ ЭКСПЕРИМЕНТАЛЬНАЯ УСТАНОВКА ИФВЭЯФ ННЦ ХФТИ ДЛЯ ИССЛЕДОВАНИЯ ВЗАИМОДЕЙСТВИЯ ПУЧКА ЭЛЕКТРОНОВ ВЫСОКИХ ЭНЕРГИЙ С ТОНКИМИ АМОРФНЫМИ И МОНОКРИСТАЛЛИЧЕСКИМИ СТРУКТУРАМИ

Г.Д. Коваленко, В.И. Касилов, Ю.Г. Казаринов, С.Г. Карпусь, И.Л. Семисалов, С.С. Кочетов, А.А. Шопен, И.Н. Шляхов

Представлено описание и результаты стендовых испытаний разработанной универсальной экспериментальной установки [1]. Установка собрана на прямом выходе линейного ускорителя электронов с энергией 30 МэВ ИФВЭЯФ ННЦ ХФТИ для фундаментальных и прикладных исследований по взаимодействию электронов высоких энергий с аморфными и монокристаллическими структурами. Универсальная установка состоит из следующих конструктивных элементов и систем: монитора вторичной эмиссии электронов; цилиндров Фарадея полного поглощения; коллиматоров; гониометра; магнитного анализатора энергии электронов; систем транспортировки, формирования и измерения параметров электронного пучка.