MICROTRON M-30 FOR RADIATION EXPERIMENTS: FORMATION AND CONTROL OF IRRADIATION FIELDS

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The results of the formation and study of the parameters of the electronic accelerator microtron M-30 are presented. The absorbed dose and spatial-energy distribution of the density of the beam in the area of the opinion are installed, which is important for protocols of radiation tests of various materials and devices. Several variants of the radiation formation, as well as the spatial distribution of radiation density are considered. For the homogeneity of radiation investigation, a commercial glass is used as a recording medium. The analytical dependence of radiation dose from the distance to the output node M-30, the control of the energy of accelerated electrons is carried out using an aluminum and glass absorber. Control of the accelerator parameters is carried out remotely from the control panel with the help of the developed "virtual remote" program**.**
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Microtron M-30 began work in the Uzhhorod department of Nuclear Research Institute in 1974. It is a resonant cyclic accelerator of electrons with a variable reduction of acceleration [1 - 3]. As a generator of microwave oscillations, magnetron Mi-262 with a capacity in the pulse 9 MW, the frequency of 3200 MHz generations is used. The microtron M-30's electrons beam is taken out through the titanium of 25 μm (11.3 mg/cm^2) foil with a primary energy loss of up to 30 keV. The electron beam at the exit of the accelerator M-30 has the shape of an ellipse with diagonals of 10…12 mm horizontally and 3…4 mm vertically, the expansion of the electron beam from the M-30 output window: in the vertical direction is $1.5 \cdot 10^{-3}$ radians, in the horizontal – $1.5 \cdot 10^{-2}$ radians. The operation process of the microtron is held remotely from the control panel, the monitoring of the parameters occurs with the help of the developed "Virtual Remote" program. Table 1 shows the main characteristics of the accelerator M-30.

Table 1

The main characteristics of the microtron M-30

The energy of accelerated electrons	1.5…25 MeV
Current	0.1…50 μA
Fluence intensity of electrons beam	$10^9…10^{12}$ cm^{-2}s^{-1}
The size of the radiation field with uniformity is not worse than 30%	400·700 mm^2
The efficiency of beam output	80…100%
Pulse duration	0.3 μs
Pulses frequency	1000 Hz
Duty cycle	3300
The number of orbits	29
Output window titan 25 nm foil	11.3 mg/cm^2

DESCRIPTION OF THE MICROTRON M-30

The electrons acceleration in microtron M-30 is carried out in a high-yielding volumetric resonator, which is excited by an impulse magnetron. The vacuum chamber of the accelerator is placed in a homogeneous magnetic field of ≈0.1 T. As a microwave oscillator generator, magnetron Mi-262 with power in the pulse 9 MW, the frequency of 3.2 GHz generation, the duration of the generation pulse of 0.3 μs. Thus, impulse radiation of microtron is the sequence of clots of electrons, which configure one by one with a frequency of 3.2 GHz and duration of 30 ps.

Fig. 1. General view of the M-30 accelerator

In microtron M-30, for each passage of a beam of electrons through the resonator, the energy of electrons increases by 0.51 MeV. They begin to move on the next orbit of a greater radius in the magnetic field. The maximum number of orbits in the vacuum chamber M-30 is 29. The main parameters that determine the energy of accelerated electrons in M-30 are the number of circular orbits and the magnitude of the magnetic field of the vacuum chamber. The change of electrons energy takes place smoothly in the range of 1…3 MeV by changing the magnitude of the magnetic field and steps within a range of 1.5 to 25 MeV. The latter requires a distance change from the resonator to the output node (replacing the inserts of waveguides) and requires 5…6 h. Management of microtron, control of parameters is carried out remotely from the control panel.

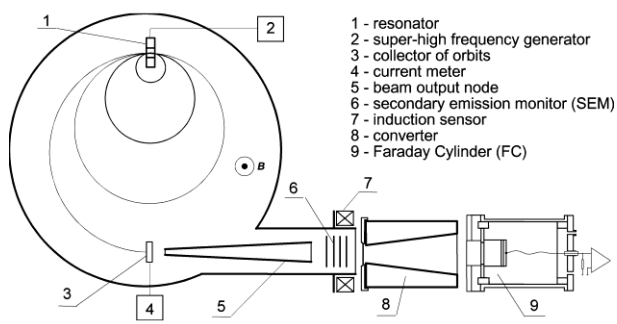The general view of Microtron M-30 is presented in Fig. 1; the layout of the M-30 devices is shown in Fig. 2.

Fig. 2. Block diagram of M-30 accelerator

1 - resonator
2 - super-high frequency generator
3 - collector of orbits
4 - current meter
5 - beam output node
6 - secondary emission monitor (SEM)
7 - induction sensor
8 - converter
9 - Faraday Cylinder (FC)

CONTROL OF SPATIAL PARAMETERS OF ELECTRONIC BEAM

One of the main characteristics of the beams is the distribution of the density of the particle stream in cross-section. As a rule, 2D scanners containing a compact Faraday Cylinder (FC) with a small aperture explore the uniformity of charged particles' flux. Metal electrodes are also used, which move by the mechanical drives of various constructors. In such configurations, the accelerator's output current is controlled by foil sensors (monitors of secondary emissions), induction sensors. Their choice is due to the convenience of use and also have economic considerations. An alternative can be planar registering environments (a variety of films and glasses) whose characteristics are changed under the action of radiation [4, 5].
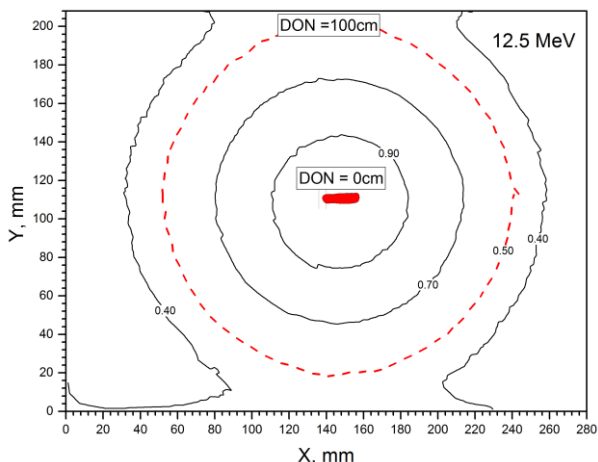

Fig. 3. Transverse distribution of the electron beam near the output node and at a distance of 100 cm, obtained by irradiation of glass.
Here, DON – Distance to the output Node

In this work, to monitor the uniformity of the radiation fields were used for sodium-silicate glass plates (commercial glass). Measuring the darkening of glass samples using the Epson Perfection 1260 scanner in 8-bit gray color. The obtained images were treated with a pre-developed utility that forms a two-dimensional matrix, whose elements contain a blackening degree of glass and are further used to build a contour picture of this degree.

Fig. 3 shows the results of processing the plates of glass. As one can see, at 100 cm distance and with the used converter, the radiation field is rather homogeneous (within 30%) and satisfies the conditions of radiation tests of large-scale objects.

When the value of the darkening is a proportional absorbed dose, the material can serve as an indicator of the absorbed dose. In our case, it is convenient to use the concept of fluence, that is, integral by time from the flow of dN particles through the dS area: dN/dS. The number of electrons falling into the FC in time t is equal to $N_e^{FC} = \frac{1}{e}\int_0^t I_{FC}(t)dt$.

The ratio of electrons forming the central area of the image $\int\limits_{>0.9MAX}$ with darkness greater than 90% of the maximum, to those that fall into the FC with radius 25 mm, $\int\limits_{FC(\,R<25mm)}$ can be written as (Fig. 4):

$$\Phi = \frac{\int\limits_{>0.9MAX}}{\int\limits_{FC(\,R<25mm)}} = \frac{\iint\limits_{>0.9MAX} D(x,y)\,dxdy}{\iint\limits_{FC(\,R<25mm)} D(x,y)\,dxdy} . \quad (1)$$
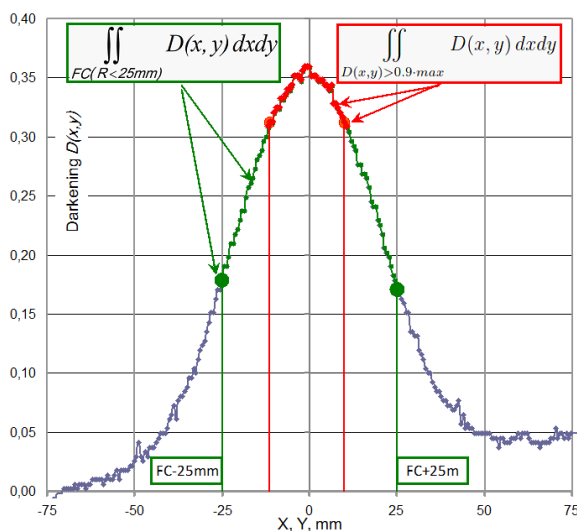

Fig. 4. Processing of a beam profile to determine the fluence

Then fluence for the central region of the beam is determined by the expression

$$\Phi = \frac{N_{0.9MAX}}{S_{0.9max}} = \frac{\frac{1}{e}\cdot\int\limits_0^t I_{FC}(t)dt \cdot \frac{\int\limits_{>0.9max}}{\int\limits_{FC(R<25mm)}}}{S_{0.9max}} . \quad (2)$$

Dosimetric characteristics of commercial glass, measured in a number of works [6 - 8], show the possibility of their use to measure high doses of radiation, considering the linearity zone of darkening vs the received dose. The results obtained in these articles indicate that the linearity range from absorbed dose is 50 Gy…20 kGy. Thermal processing (150°C for 20 min) was carried out to complete the stability since the rapid attitude of optical absorption at room temperature is observed after irradiation. Samples showed a decrease of about 10…15% per initial optical absorption, which has become much less pronounced after ten days. This research confirms the practicality of using a commercial window as a dosimeter in a certain dose range after proper calibration.
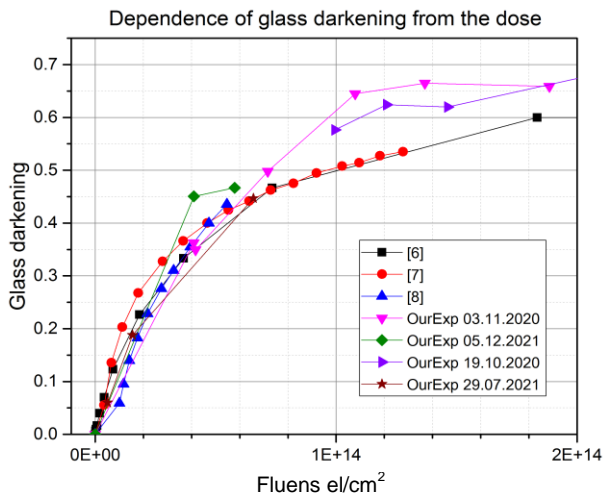
Fig. 5. The dependence of glass darkening vs electron fluence

Processing of the darkening profiles obtained on the M-30 accelerator was carried out using the formula for fluence (2). Fig. 5 shows that the linearity zones from sources [6 - 8] coincide with our data.

In addition to controlling the transverse uniformity of the irradiation fields, knowledge of dosimetric characteristics on different distances from the accelerator output node is required. Such measurements were carried out with the use of FC installed on a metrological bench. Isotropic radiation from the point source is distributed in a vacuum following the law of inverse squares. However, the accelerators' electron beams are not isotropic themselves because it is distorted by the effects of focusing and scattering on the element of the output node. Therefore, its distribution at a distance from the output node is described by a monotonically decreasing but more complex dependence.
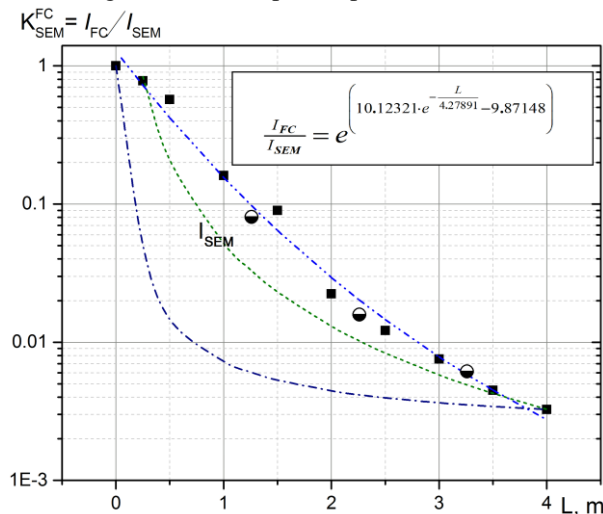

Fig. 6. Dependence the ratio of FC and SEM currents on the "M-30 – FC" distance:
($\blacksquare\ominus$) – experimental data;
($-\cdot\cdot-$) – fitting curves; ($-\cdot-$) – same data for the M-30 electron beam with the expansion in the vertical direc tion is $1.5\cdot10^{-3}$, in the horizontal – $1.5\cdot10^{-2}$ radian; (- - -) – for the part of electrons beam which only falls on the FC.
(S=19.625 cm^2)

In Fig. 6 shows a measuring attitude of currents $K_{SEM}^{CF} = \frac{I_{CF}}{I_{SEM}}$ on an area of irradiation for different distances of FC from the output node. Knowing $K_{SEM}^{CF}(L)$ and the current accelerator $I_{SEM}(t)$, we find a charge that has fallen on an object during irradiation time t: $Q_{FC}(t) = K_{SEM}^{FC}(L)\cdot\int I_{SEM}(t)dt$, and then fluence by formula (2). Thus, these are necessary for planning research of objects in different dimensions and providing controlled conditions for their irradiation.

ELECTRON BEAM ENERGY CONTROL

Currently, several methods of recognizing the energy of charged particles have been developed [9]. For electrons, a method for determining practical energy range (extrapolated range) is well known. A simple device using only two aluminum plates is described in [10]. Description of the device using a set of the copper diaphragms as an absorber, given in [11].

We have developed and manufactured the device using an absorber from a set of aluminum diaphragms isolated from each other by a teflon films (Fig. 7).
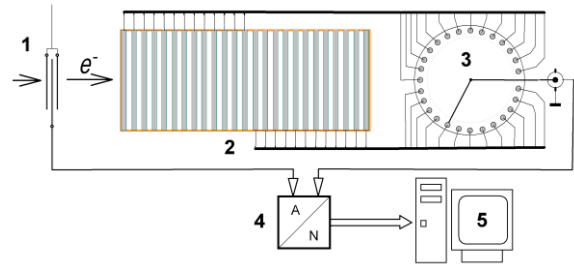

Fig. 7. Scheme of the device for controlling the energy of accelerating electrons:
1 – SEM (Secondary Electron Monitor;
2 – absorber containing the aluminum foils;
3 – commutator; 4 – Analog Digital Convertor;
5 – computer

A program-controlled switch connects the diaphragms to an analog-to-digital converter, data from which is processed by the ENERSCAN program. The resulting data array $I(n)$ is formalized in an array of $T(d)$ by algorithm, the graphical representation of which is shown in Fig. 8.
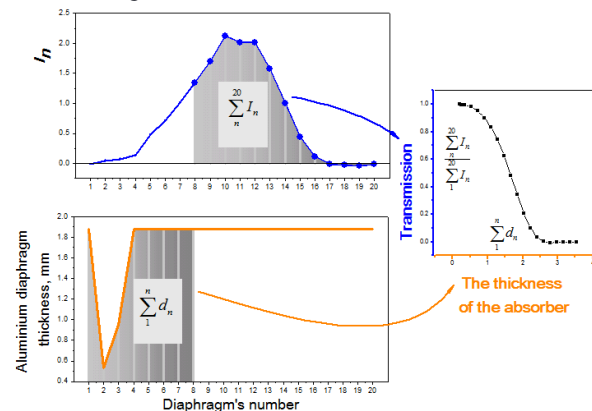

Fig. 8. On the left – the initial graphs of the absorbed current and the absorber thickness on the Al diaphragms number; on the right – the same data in the coordinates: "electrons beam transmission T on the thickness d of Al absorber"

The next stage of the search for an extrapolated range R_P is to determine the minimum coefficient of pair correlation in linear regression (Fig. 9,a). A program was created that allows optimizing the choice of R_P by analyzing the absorption curve of $T(d)$ using the linear regression function and the χ^2 method. Fig. 9,a demonstrates the dependence of χ^2 on the number of cycles containing arbitrarily selected points on the $T(d)$ dependence; Fig. 9,b – the same data are listed to find the parameter R_p, important in finding the probable energy the electron beam, Table 2. When you reach this minimum, the R_P search is completed (see Fig. 9,b).
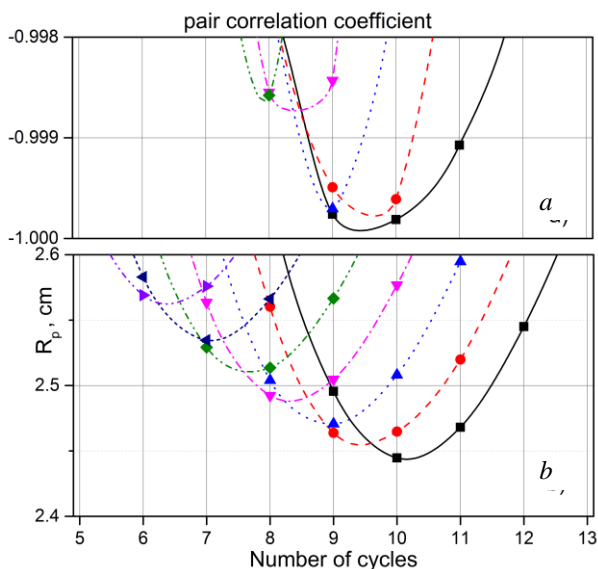

Fig. 9. Finding a minimum of pair correlation coefficient (a); calculating practical range R_P using linear regression (b)

After finding R_P it remains to choose formula $E(R_P)$. For our applications, accuracy is sufficiently accurate in 5…10%, provided as a standard of ISO/ASTM 51649 [12], and an empirical formula from [13]. From Table 2, see that formulas give values close to the estimated energy from the physical parameters of the M-30 microtron [1].

Table 2
Electron energy for practical range R_p=2.54 cm

	Energy formulae		MeV
Glass	E=(R_p+0.106)/0.53	[13]	12.5
Water	E=0.22+1.98·R_p+0.0025·R_p^2	[12]	13.9
Aluminum	E=0.423+4.69·R_p+0.0532·R_p^2	[12]	12.1
M30	E_n=f·(n+1)·0.20549·10^{-3}·0.511	[1]	12.4

Other formulas for energy and evaluating the accuracy of the value of the electron energy characteristics are given in [14].

The result of determining the extrapolated range R_P and electrons energy using the above-described device is shown in Fig. 10. Here is used an expression for aluminum with a standard [12].

Another method for determining the energy described in [13] is to find an extrapolated range of electrons in a glass that corresponds to the depth of the darkening layer caused by irradiation by electrons. We used a package of glass plates, each with a thickness of

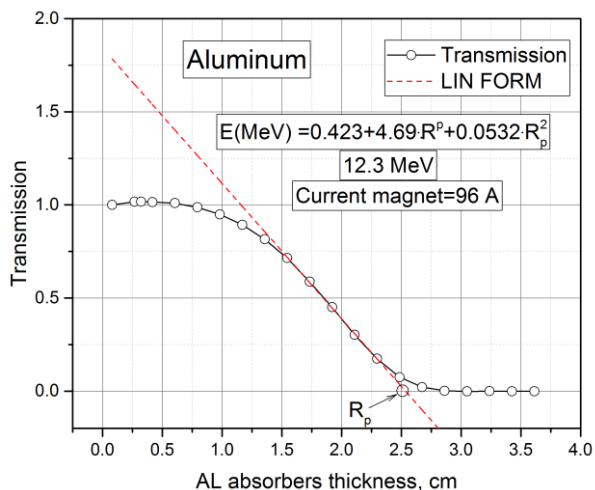3 mm, and the electrons beam from M-30 was directed on its butts (Fig. 11).

Fig. 10. Determination of extrapolated range and electrons' energy

We find an extrapolated range R_P from the dependence of optical density (darkening) along the beam's central axis. For the monoenergetic beam of electrons, energy is expressed through an extrapolated range in aluminum with an empirical formula:

$$E = \frac{R_p + 0.106}{0.53}, \qquad (3)$$

where R_P = ρ·x_0 is expressed in g/cm^2; ρ – density in g/cm^3; x_0 – range in cm; E – energy in MeV.

The density of sodium-calcium-silicate glass (commercial window glass) varies within 2.5…2.6 g/cm^3. From the guide, the usual window has a density of 2.56 g/cm^3. Using this value, we obtain the energy given in Table 2.
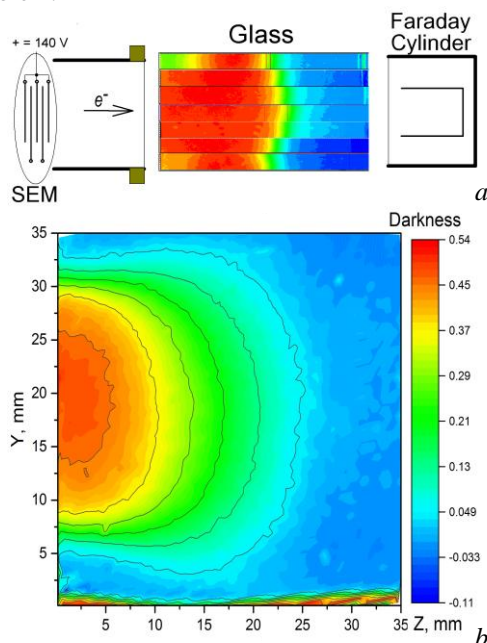

Fig. 11. Distribution of the darkening of the glass along the axis of the beam for the whole package (a) and the central plate (b)

The result of determining the extrapolated range R_P for glass is shown in Fig. 12,a. For the correct energy determination for darkening glass, it is necessary to en-

sure such a dose of irradiation in which the linear dependence of optical density (darkening) from the absorbed dose is preserved. A series of measurements of an extrapolated range with low irradiation doses showed that the R_P value is almost unchanged (see Fig. 12,b).
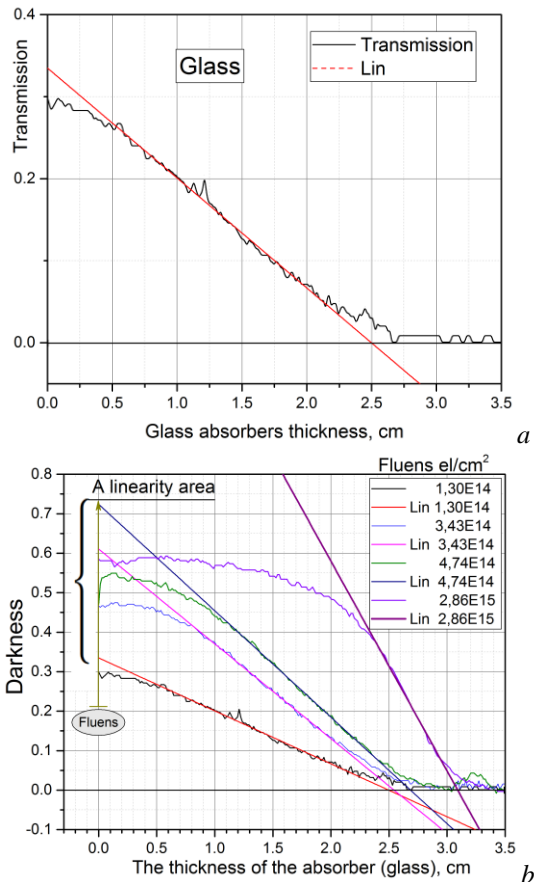

a

b

Fig. 12. Determination of extrapolated range in glass plate for a fixed dose of M-30 irradiation (a); determination of extrapolated range in glass for various doses of M-30 irradiation (b)

VIRTUAL REMOTE OF M-30 MICROTRON

Automation of the radiation and dose accumulation is an important task of the radiation experiment. The first stage is to automate the collection, accumulation, and processing of measurement data and fixing parameters of functional installation units and form a numerical and graphic information database. Solving this task for microtron M-30 has been accomplished through a graphical interface, business logic, and a circuit connection of functional blocks based on ADC modules WAD-AIK-BUS [15]; galvanically isolated input channels allow one to implement the system monitoring parameters with sufficient reliability. The program part of the control panel contains a set of virtual panels, each of which displays the value of the M-30 parameter or function for multiple parameters in real-time.

The Java programming language, technologies, and development were Swing, Java Communications API, JFreeChart, Junit, Log4j, and Spring. The number of sensors that process the software complex depends on the number of ADCs connected in one bus and is limited to 127 modules, each of which has four channels for input signals. In this project, the Model-View-

Controller template (MVC) was taken as the basis of the module pattern.

This template separates the data (model) from the User Interface (view) so that the user interface changes have minimally affected the work with data and allows one change in the data content without changing the user interface. The controller interprets the data entered and informs the (model) and the (view) of the need for an appropriate reaction. In addition to this were used as templates (adapter), (observer), (strategy), (inversion of control), (facade).

Thus, we can highlight the following modules of the remote control system, Fig. 13:

• Commons. This module contains a code that is generally for all modules.

• Communications. This module implements a portion of the MODBUS protocol that allows you to interact with the M-30 microtron through the WAD-AIK-BUS ADC modules.

• Controller. It implements business logic – rules for reading and processing values of the parameters of the microtron M-30 and their output.

• Model. The module contains data exchange classes between software part modules.

• View. This module includes a code that allows providing information to the user in the desired forms. For example, it can be graphical (in the form of a chart), sound (sound signal on the PC dynamics in the event of an exit value at least one parameter for the permissible limits), text (recording of the known one from each of the parameters in a text file).

• Runner. The system can launch the system in one of two modes: the test (when data from the ADC is not reading but is taken from the generator of random numbers) and the real one.
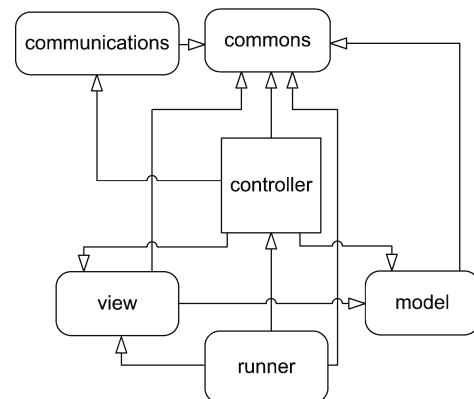

Fig. 13. Block diagram of communication between modules of the software system

Java programs are translated to the byte code performed on a virtual Java machine (JVM) – a program processing byte code and transmitting instructions to equipment as an interpreter, but with the difference that byte code, in contrast to text, is processed significantly faster.

Fig. 14 contains the view of the control panel windows with the visualization of the important parameters of the microtron M-30 (currents, the ratio of the secondary emission monitor signals, and the FC, important for dosimetric accompaniment of irradiation process). The

form of setting the number and options of controlled parameters M-30 and time characteristics are provided. When monitoring the accelerator settings in a folder /LOG, a folder is created, the name of which is the date of monitoring. In this folder, subfolders are created whose names show the monitoring time in the format of hour-minute-second. The monitoring protocols are stored in files whose names point to the ADC unit number and the channel number. Thus, the name "results 23.log" means that it is a protocol of the second block measurement for the third channel. In the "results.log" file, all data measurements are saved both with time attributes and measurement channels numbers.

Fig. 14. The main window view of the M-30 microtron control panel: time dependence of the current of the SEM (a); current of the FC (b); signal of vacuumeter VIT-2 (c); the heating voltage of the cathode LaB_6 (d); the ratio (current of the FC) / (current of the SEM) (e)

CONCLUSIONS

The results of studying the parameters of the electron accelerator microtron M-30 are presented. Spatial characteristics of the radiation field are investigated using glass as a recording medium. The area of linear response to the fluence of irradiated glass samples is installed. The energy characteristics of the electron beam are controlled by the absorption method in aluminum and glass absorbers. Certified for energy 30 MeV FC has allowed obtaining analytical dependences of radiation dose from distance to the output node M-30. The aggregate of these data enables radiation testing of various objects with specified parameters.

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МІКРОТРОН М-30 ДЛЯ РАДІАЦІЙНИХ ЕКСПЕРИМЕНТІВ:
ФОРМУВАННЯ ТА КОНТРОЛЬ ПОЛІВ ОПРОМІНЕННЯ

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М.В. Гошовський, О.О. Парлаг, В.Т. Маслюк, Н.І. Сватюк

Представлені результати формування та вивчення параметрів електронного прискорювача мікротрон М-30. Встановлена поглинена доза та просторово-енергетичний розподіл щільності пучка в області опромінення, що важливо для протоколів радіаційних випробувань різноманітних матеріалів та пристроїв. Розглядаються декілька варіантів формування випромінювання, а також просторового розподілу щільності випромінювання. Для перевірки однорідності випромінювання використане комерційне скло як реєструюче середовище. Одержані аналітичні залежності дози випромінювання від відстані до вихідного вузла М-30, контроль енергії прискорених електронів здійснений з використанням алюмінієвого та скляного поглиначів. Контроль параметрів прискорювача здійснюється віддалено з панелі керування за допомогою розробленої програми «Virtual Remote».

МИКРОТРОН М-30 ДЛЯ РАДИАЦИОННЫХ ЭКСПЕРИМЕНТОВ:
ФОРМИРОВАНИЕ И КОНТРОЛЬ ПОЛЕЙ ОБЛУЧЕНИЯ

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Представлены результаты формирования и изучения параметров электронного ускорителя микротрон М-30. Установлены поглощенная доза и пространственно-энергетическое распределение плотности пучка в области облучения, что важно для протоколов радиационных испытаний различных материалов и устройств. Рассматриваются несколько вариантов формирования излучения, а также пространственного распределения плотности излучения. Для проверки однородности излучения в качестве регистрирующей среды использовалось коммерческое стекло. Получены аналитические зависимости дозы излучения от расстояния до выходного узла М-30. Контроль энергии ускоренных электронов осуществлен с использованием алюминиевого и стеклянного поглотителей. Контроль параметров ускорителя осуществляется удаленно с панели управления с помощью разработанной программы «Virtual Remote».