CALIBRATION OF A SYSTEM FOR ON-LINE MONITORING OF ELECTRON ENERGY AND ABSORBED DOSE AT AN INDUSTRIAL ACCELERATOR LU-10

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Particle beam energy and absorbed dose are critical parameters of product processing at industrial electron accelerators. For on-line monitoring of those parameters, a method based on measuring of distribution of the charge induced by irradiation in a wide-aperture stack-monitor, positioned behind an irradiated object, has been developed. A brief review of a control system for monitoring of the processing parameters created with the use of the EPICS package as well as the data of its operating experience at an LU-10 Linac of NSC KIPT are presented in the article. The procedure and results of calibration of the measuring channels within the electron energy range 8…10 MeV are described.

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INTRODUCTION

The irradiation efficiency depends on the measurements and the assessment of the absorbed dose in the process of radiation treatment. This is done using dosimetric systems having a known level of accuracy. Dosimetric systems used in radiation processing of materials comply with international standards ISO/ASTM (Table 1) [1]. Determination of the absorbed dose using such dosimeters is usually carried out after the irradiation process in off-line mode.

Table 1

Dosimetric systems

Dosimeter system	Method of analysis	Useful dose range [Gy]	Nominal precision limits [%]	References
Ceric-cerous sulphate	UV spectrophotometry	$10^3…10^6$	3	ISO/ASTM 51205:2017
L-alanine	EPR	$1…10^5$	0.5	ISO/ASTM 51607:2013
Perspex systems	VIS spetrophotometry	$10^3…5·10^4$	4	ISO/ASTM 51276:2019
B3 film	VIS spectrophotometry	$10^3…10^5$	3	ISO/ASTM 51275:2013
Calorimetry	Resistance/ temperature	$1.5·10^3…5·10^4$	2	ISO/ASTM 51631:2013

Tracking such critical parameters as electron energy and the absorbed dose in the irradiated object during radiation processing of the product is very important. The use of a wide-aperture stack monitor (SM) in the form of a set of ten aluminum plates located behind the irradiated object makes it possible to continuously monitor the absorbed dose in the object and track changes in the electron beam energy. This allows one to adjust the processing parameters (beam current, conveyor velocity, sweep width) in real-time.

A method based on measuring the distribution of charge induced by radiation in a stack-monitor has been developed for continuous monitoring of critical parameters [2]. The use of this method requires calibration measurements and determination of the corresponding coefficients.

This article provides a brief description of the radiation treatment parameters monitoring system based on the EPICS (Experimental Physics and Industrial Control System) [3]. The procedure and results of the calibration of the measuring channels using a plate stack-monitor in the range of electron energies of 8…10 MeV are described.

1. CONTROL SYSTEM OF RADIATION PROCESSING PARAMETERS

The control system of radiation processing parameters consists of the following elements (Fig. 1):

– PC-based processing database server (Linux OS);
– the local network;
– PC-based automated operator workstation (AWP) with an operator screen (CS-Studio);
– multifunctional module NI USB-6341;
– measuring devices connected to the local network (oscilloscopes, multimeter, generator);
– EPICS input/output controllers (IOCs) based on single-board computers (Linux OS).

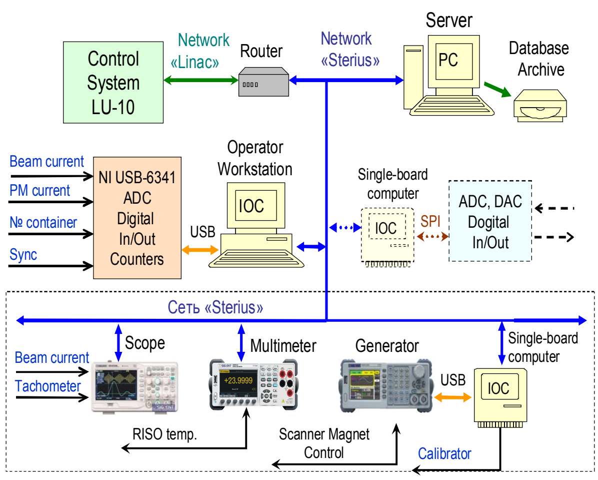

Fig. 1. The block diagram of the control system

The sweep signal for the scanner magnet is generated by the function generator SDG1010. The operation of the generator is controlled by an input/output controller (IOC) via the USB bus. The controller runs on a single-board Raspberry Pi-3 computer with Linux system.

The system EPICS [4] was selected as the software environment for the control system.

The parameters of the radiation process are displayed with graphical interfaces – "operator screens" (Fig. 2).

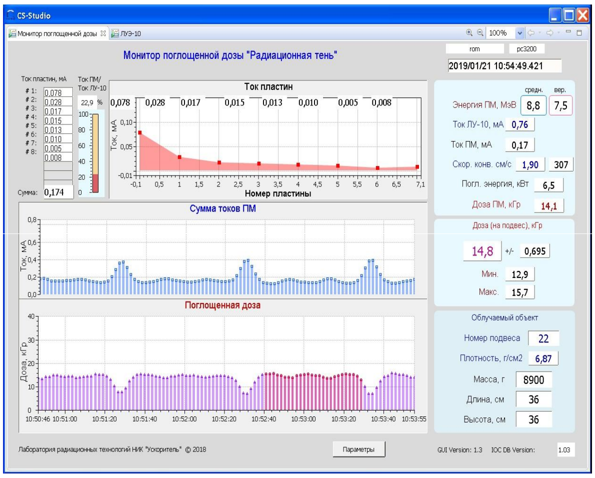

Fig. 2. The operator screen "Monitoring energy and absorbed dose"

The archiver program of data of the process [5] runs on a separate server (computer). The archiver starts as a web application and writes the PV process variables to the hard disk at certain intervals.

A web server works to monitor and display the parameters of radiation processing. It allows to viewing the main parameters in real-time using a standard Internet browser.

The control system uses more than 50 process variables, of which ~ 40 are stored at various intervals. The annual amount of data is ~ 1 GB. Data backup is carried out at certain intervals by copying the database files to external media: hard disk and flash memory (USB).

The experience in operating of control system during the year showed the stability of its work, the possibility of modification and expansion, ease of use.

2. METHOD OF MEASURING CHANNELS CALIBRATION

2.1. STACK-MONITOR CALIBRATION FOR ENERGY

The calibration procedure for the stack monitor for energy was as follows. Several measurements of energy spectra were performed with average beam energy in the range from 8 to 10 MeV. The beam energy was measured using a magnetic analyzer (MA) [6]. The plate currents and the total current of the stack monitor without an irradiated object were measured after each spectrum measurement. The measured spectra were fitted with two Gauss functions for more accurately determine the most probable and average energy (Fig. 3).

The following expression is used to determine energy with a stack monitor:

$$E = A + B \cdot \frac{\sum_k^{10} I_i}{I_{SM}}, \qquad (1)$$

where E – beam energy (MeV); A, B – coefficients derived from calibration measurements or calculations [2]; I_i – average current i-plates of stack monitor (A); I_{SM} – average total current from all plates of the stack-monitor (A).

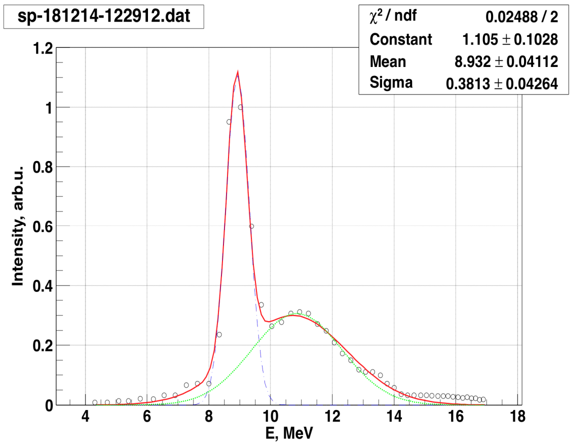

Fig. 3. Measured spectrum with the most probable energy of 8.93 MeV and fitting with two Gauss functions: circles – measurement data using MA; solid line – combined fitting function

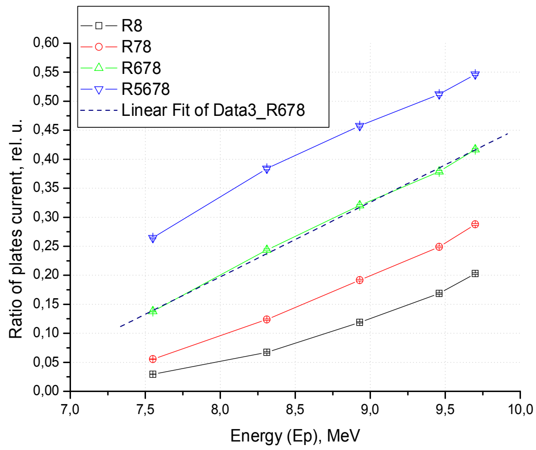

Fig. 4. The dependence of the most probable energy on the ratio of currents from k of the last plates to the total SM current: R8 – k=(8, 9, 10); R78 – k=(7, 8, 9, 10); R678 – k=(6, 7, 8, 9, 10); R5678 – k=(5, 6, 7, 8, 9, 10)

The dependence of the energy (most probable) on the ratio of currents k last plates to the total SM current is constructed based on the results of measuring the spectra and distribution of currents from the SM plates (Fig. 4).

After fitting distribution R678 with a straight line, the following expression was obtained for calculating the most probable energy (Ep) from the ratio of the currents of the last 5 plates to the total SM current (R):

$$Ep = 6.443 + 7.838 \cdot R. \qquad (2)$$

The dependence of average energy (Ea) on the ratio of currents from plates (6, 7, 8, 9, 10) to the total current SM was also obtained:

$$Ea = 7.675 + 8.767 \cdot R. \qquad (3)$$

The estimation of the uncertainty when measuring the most probable energy Ep and average energy Ea using the stack-monitor is about 2.6%.

Table 2

Results of energy measurement of the LU-10 accelerator using SM

№	MA Ep, MeV	SM Ep, MeV	ΔEp, %	MA Ea, MeV	SM Ea, MeV	ΔEa, %
1	9.46	9.41	0.53	11.05	11.0	0.45
2	8.93	8.95	0.22	10.46	10.48	0.20
3	8.31	8.35	0.48	9.75	9.81	0.61
4	7.55	7.52	0.40	8.92	8.88	0.45
5	9.52	9.71	1.96	11.02	11.33	2.74

2.2. STACK-MONITOR CALIBRATION FOR DOSE

The absorbed dose in the product depends on the average beam current, beam sweep width, conveyor speed and beam energy. Dose measurement based on these parameters is an effective calibration of the radiation facility. There is no simple relationship between dose and electron beam energy, and measurement of dose as a function of the three other parameters should therefore be made for each operating energy [7].

The following devices were used to calibrate the dose rate stack-monitor:

– dosimeters Red Perspex 4034 (RP);

– calorimeter RISO (Fig. 5);

– polystyrene phantom F-1: dimension 79×41×37 cm (length, high, depth), weight – 13 kg, surface density – 3.96 g/cm^2;

– polystyrene phantom F-2: dimension 70×38×17.5 cm, weight – 5.25 kg, surface density – 2.0 g/cm^2 (Fig. 6).

The RISO calorimeter consists of a disk made of polystyrene surrounded by heat-insulating foam (see Fig. 5). The temperature of the calorimeter is measured by a calibrated thermistor, which is located inside the disk. The dose range of measurements is 3…40 kGy, the uncertainty in the dose measurements is 3.6%.

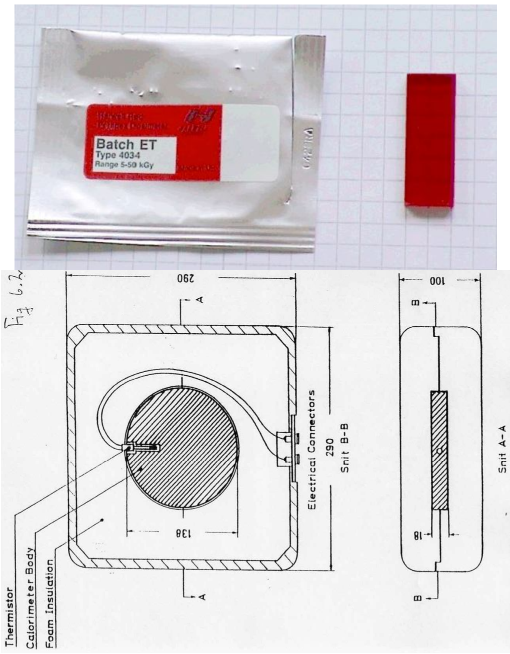

Fig. 5. Dosimeter Red Perspex (top) and calorimeter RISO (bottom)

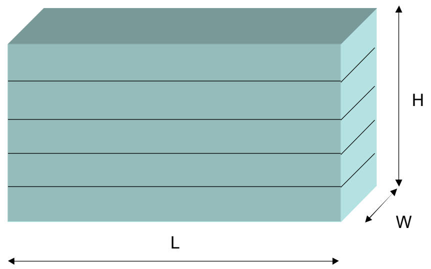

Fig. 6. Polystyrene phantom F-1 and F-2

The absorption dose in object D is determined for a given energy using the relation [2]:

$$D = \frac{[a(E,W_b,\rho)\cdot I_b - b(E,W_b,c)\cdot I_{SM}]\cdot L}{m\cdot V_C}, \quad (4)$$

where I_b – average beam current LU-10 (A); I_{SM} – total current from all plates of the stack-monitor (A); V – conveyor speed (m/s); m – object weight (kg); L – object length (m).

The coefficients a, b depend on the beam energy E, the beam sweep width W_b, and the object density ρ. Therefore, a set of coefficients is required for each energy, the sweep width and density of the object to more accurately determine the dose using SM.

The F-1 phantom and the RISO calorimeter moved at a given speed through the irradiation zone and the beam current and the SM current were recorded (Fig. 7). The measurements were carried out at several conveyor speeds: 400, 600, 200 rel.u. and for several values of average energy in the range of 8…10 MeV

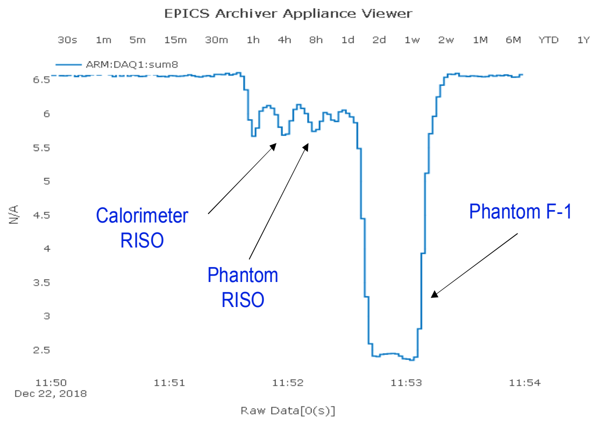

Fig. 7. The total current from the plates of the stack-monitor when irradiating the RISO calorimeter and phantom F-1

The absorbed dose was determined using a RISO calorimeter. A few calorimeter temperature measurements were taken before irradiation (*T1*) and then after irradiation (*T2*). The temperatures *T1* and *T2* were determined by the off-line method described in the standard ISO/ASTM51631:2013 [8]. The irradiation time (t_i) was also recorded. The measured temperature values before and after irradiation are approximated by two straight lines (see Fig. 7). The temperature *T1* and *T2* are determined by the value on the corresponding line at the time of irradiation t_i.

The calculation of the absorbed dose D in the RISO calorimeter was carried out using the expression:

$$D = (T_2 - T_1 - T_a) \cdot (k_1 + k_2 \cdot \frac{T_1 + T_2}{2}) \cdot k \,, \qquad (5)$$

where T_1 – calorimeter temperature before irradiation; T_2 – calorimeter temperature after irradiation; T_a – calorimeter heating from conveyor and accelerator $T_a \sim 0.05°C$; k_1, k_2, k – calibration constants (k_1=1.022; k_2=0.0108; k=1.000).

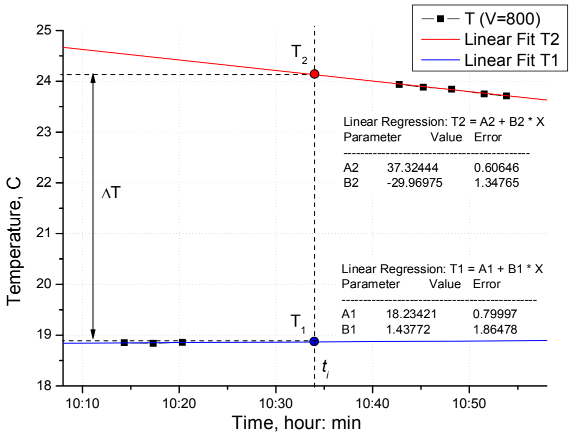

Fig. 8. Determination of the temperature difference ΔT of the RISO calorimeter

The coefficients a, b were determined from the relations presented in [7]:

Calculation of the absorbed dose in the phantom D_{ab} (Gy) was carried out using the expression:

$$D_{ab} = \frac{P_{ab,ph}}{V_{ph} \cdot \dfrac{M_{ph}}{l_{ph}}} \,, \qquad (6)$$

where V_{ph} – conveyor speed (m/s); M_{ph} – object weight (kg); l_{ph} – object length (m) along the direction of movement of the conveyor; $P_{ab,ph}$ – the absorbed power in the irradiated object (F-1 phantom) was calculated using the absorbed dose value measured using a RISO calorimeter or Red Perspex dosimeters.

The results of calculating the coefficients a, b and the absorbed dose in the F-1 phantom measured using SM at different beam energies shown in Table 3.

Table 3

Dose calibration results

№	Current, mA	Ep, MeV	Coefficients				Dose F-1 RP, kGy	Dose F-1 SM, kGy
			a	±Δa	b	±Δb		
1	0.77	9.13	10.1	0.26	12.5	0.29	8.48	8.32
2	0.71	9.71	11.9	0.52	14.9	0.61	8.40	8.44
3	0.45	10.71	15.6	0.51	17.5	0.55	6.15	5.61
4	0.74	8.42	7.1	0.20	9.0	0.22	6.79	6.18

The estimated uncertainty in measuring the absorbed dose using the stack monitor was ~ 8%.

The dependence of the coefficients a, b on the beam energy obtained when calibrating the stack-monitor using the F-1 phantom shown in Fig. 9.

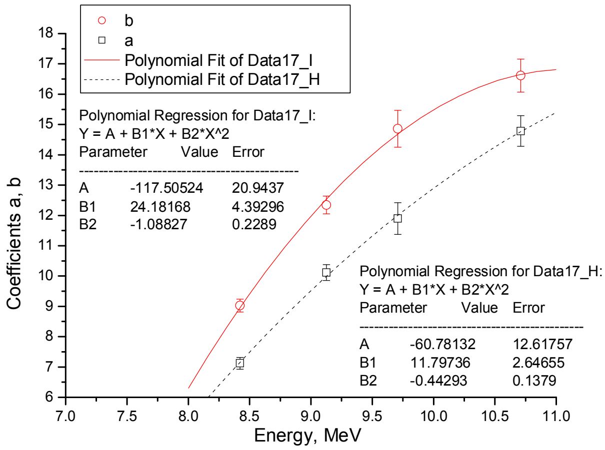

Fig. 9. The dependence of the coefficients a, b on the most probable energy of the electron beam

CONCLUSIONS

The implementation of the EPICS system unifies the control system of radiation processing parameters and increases its reliability.

A method has been developed for continuous monitoring of critical parameters using a stack-monitor. The calibration measurements have been made and coefficients and calibration curves have been obtained for determining the electron energy and absorbed dose during radiation treatment at the LU 10 accelerator in the energy range 8…10 MeV.

Continuous monitoring of the absorbed dose enables promptly carry out the necessary adjustment of accelerator parameters during processing.

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КАЛИБРОВКА СИСТЕМЫ ON-LINE МОНИТОРИНГА ЭНЕРГИИ ЭЛЕКТРОНОВ И ПОГЛОЩЕННОЙ ДОЗЫ НА ПРОМЫШЛЕННОМ УСКОРИТЕЛЕ ЛУ-10

Р.И. Помацалюк, В.Ю. Титов, Д.В. Титов, В.Л. Уваров, В.А. Шевченко

Энергия частиц пучка и поглощенная доза являются критическими параметрами при обработке продукции на промышленных ускорителях электронов. Для on-line мониторинга этих параметров разработан метод, основанный на измерении распределения наведенного облучением заряда в широкоапертурном стек-мониторе, который находится за обрабатываемым объектом. Представлены краткий обзор системы мониторинга и контроля параметров обработки, созданной с использованием пакета EPICS, а также данные об опыте ее эксплуатации на ускорителе ЛУ-10 ННЦ ХФТИ. Описаны процедура и результаты калибровки измерительных каналов в диапазоне значений энергии электронов 8…10 МэВ.

КАЛІБРУВАННЯ СИСТЕМИ ON-LINE МОНІТОРИНГУ ЕНЕРГІЇ ЕЛЕКТРОНІВ ТА ПОГЛИНУТОЇ ДОЗИ НА ПРОМИСЛОВОМУ ПРИСКОРЮВАЧІ ЛУ-10

Р.І. Помацалюк, В.Ю. Тітов, Д.В. Тітов, В.Л. Уваров, В.А. Шевченко

Енергія частинок пучка і поглинута доза є критичними параметрами при обробці продукції на промислових прискорювачах електронів. Для on-line моніторингу цих параметрів розроблено метод, що є оснований на вимірюванні розподілу наведеного опромінюванням заряду у широкоапертурному стек-моніторі, який розміщено за оброблюваним об'єктом. Надано стислий огляд системи моніторингу та контролю параметрів обробки, що створена з використанням пакету EPICS, а також дані щодо досвіду її експлуатації на прискорювачі ЛУ-10 ННЦ ХФТІ. Описані процедура та результати калібрування вимірювальних каналів у діапазоні значень енергії електронів 8…10 МеВ.