MEASUREMENT OF ELECTRON BEAM ENERGY CHARACTERISTICS AT AN INDUSTRIAL ACCELERATOR

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At an electron accelerator, the particle energy is one of critical parameters in the technological processes, as well as when conducting the radiation tests. The report presents the results of modernization of beam energy-spectrum analyzer on the basis of a 90˚ electromagnet of an industrial Linac LU-10 (10 MeV, 10 kW). A control system on the basis of a multifunction USB device for the analyzer data acquisition and processing has been developed. The results of measuring the energy characteristics of the accelerator beam with the analyzer, as well as using a dosimetric wedge technique are presented. A computer simulation method was used to study the features of the wedge application in case of a beam with wide spectrum. The conditions of on-line electron energy control using a wide-aperture stack monitor are investigated. A comparative analysis of results of the energy determination by the different techniques is carried out.

PACS: 29.27.Ac; 41.75.Fr; 07.81.+a

INTRODUCTION

Nowadays, above 20.000 industrial electron accelerators operate throughout the world [1]. Those installations provide a number of technological processes and diagnostic procedures – sterilization of outputs of the medical, pharmaceutical and food industry, modification of polymers and semiconductors, elemental analysis, nondestructive testing, etc. [2].

One of critical parameters of any technology using electron beam is the particle energy (see, e.g., [3]). In overwhelming majority of cases, the energy spectrum of the beam of an industrial accelerator is rather wide. The only method of its precise determination is one based on the usage of a magnet analyser. At the same time, none serial accelerator has been equipped with that device. A standardized off-line wedge-based technique is commonly used for measurement of certain characteristics of the beam spectrum (the most probable E_p and average E_{av} value of the electron energy) − [4]. A lack of information about spectrum limits the possibility of analysis and optimization of product processing regime relative to the absorbed dose, in particular, by means of computer simulation (see, e.g., [5]).

In NSC KIPT, an industrial plant with an electron Linac LU-10 operates for three decades [6]. The accelerator is supplied with a kit of diagnostic devices including a magnet analyser for measuring the beam spectrum. In the work, an updated control system of the magnet analyser, and also the results of the study of energy characteristics of the accelerator beam obtained by the different methods are described.

1. METHODS AND INSTRUMENTATION

1.1. BEAM DIAGNOSTICS DEVICES

In Fig. 1, a scheme of a control system of the LU-10 beam parameters is given. An accelerating structure AS is followed with the unit of a built-in Faraday cup FC-1 for direct measuring the average beam current. Behind it, a magnetic induction sensor (the Rogowski loop) MIS-1 for on-line monitoring the pulse beam current is situated. A chamber of the 90° magnet analyzer (MA) of beam spectrum is located downstream. The chamber has a slit collimator SC and second Faraday cup FC-2 at its exit. A current source MCS provides the feeding of MA electromagnet. Behind the MA chamber, the second sensor MIS-2 and beam scanner S have been mounted along the beam axis.

A conveyor C is situated at a distance of 920 mm from the exit window of the accelerator. Behind the conveyor with the hookup transport containers TC for placing the treated products, a wide-aperture stack-monitor SM for continuous on-line monitoring a mode of the product processing in the electron energy and absorbed dose is located [7].

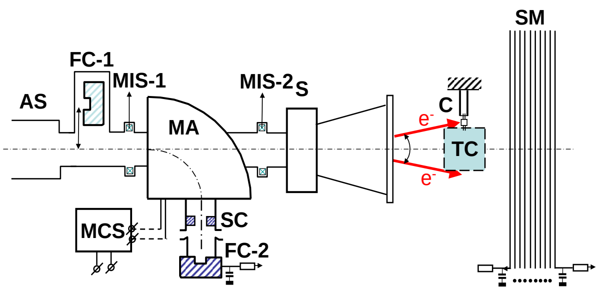


Fig. 1. Layout of beam diagnostic devices of the LU-10 Linac

1.2. MA CONTROL SYSTEM

The determination of beam energy spectrum is carried out by means of changing the current in the magnet winding within range 0…20 A with the MCS unit and simultaneous measurement of current from FC-2. To conducting that procedure in an automatic mode, a control system on the basis of a multifunctional NI-USB-6008 module (National Instruments) has been developed (Fig. 2).

The control voltage at the exit of MCS (0…3V) is formed with a D To A converter of the NI-USB-6008 module. The value and rate of the voltage change are command-driven from PC. An interface of the program for the MSC module control and measurement of energy spectrum is given in Fig. 3.

1.3. MEASUREMENT OF ELECTRON ENERGY

A benchmark study of MA characteristics was conducted by measuring the magnetic field strength along the trajectory of the bent beam in the magnet chamber (a magnet track) using a Hall probe.

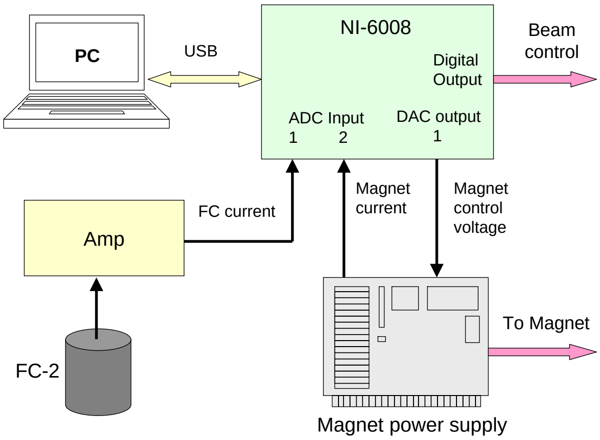


Fig. 2. Control system diagram of LU-10 magnet analyzer

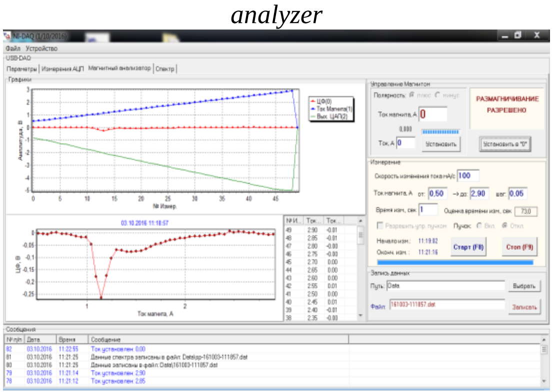


Fig. 3. Graphical interface of the MA control system

At the same time, the additional calibration is necessary after mounting the MA unit at an accelerator. Such study was carried out using a dosimetry wedge method [4]. The independent analysis of conditions of the measurement of beam energy characteristics with the wedge was fulfilled by means of computer simulation on the basis of a transport package GEANT 4 (Fig. 4).

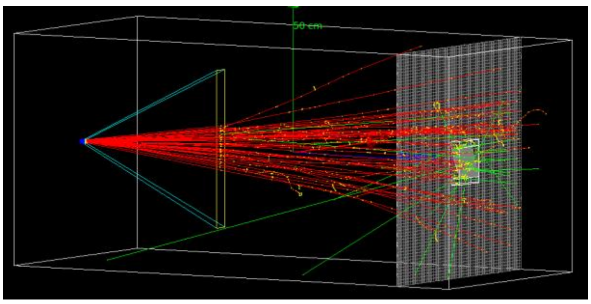


Fig. 4. Conditions of modelling the electron energy measurement by the wedge technique

The distribution of the absorbed dose along a dosimetry film (GEX Corporation, USA; the thickness 18 μm) in the wedge was reproduced with step 0.1 mm. It corresponds to the uncertainty of the wedge depth coordinate within ±0.015 mm. 5×10^7 particle trajectories were simulated for every value of the electron energy.

2. RESULTS AND DISCUSSION

2.1. BEAM SPECTRUM MEASUREMENT WITH MA

The control of beam energy characteristics at the LU-10 accelerator is carried out by changing the RF-power in the accelerating structure AS, as well as by the height of the beam current pulse. The beam spectra with various energy in its maximum E_p, measured with the use of magnet analyzer, are given in Fig. 5. Apart from the main peek, each spectrum has one more, and the height of that is decreased with the rise of E_p. When E_p=13.08 MeV, the cutoff of upper end-point energy of the spectrum is observed connected with the limit of MCS current.

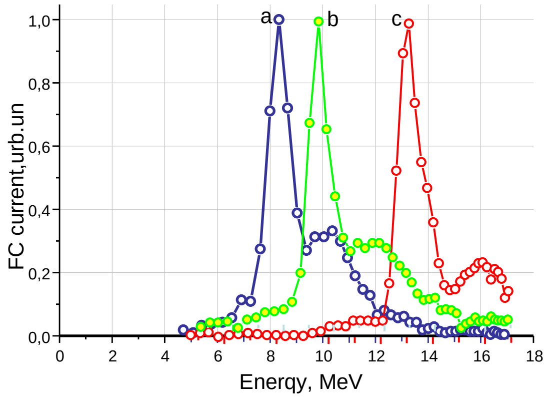


Fig. 5. Spectra of the LU-10 beam:
a – E_p=8.34 MeV; b – E_p=9.39 MeV; c – E_p=13.08 MeV

2.2. DETERMINATION OF BEAM ENERGY CHARACTERISTICS BY DOSIMETRY WEDGE TECHNIQUE

A feature of the dosimetry wedge application in the conditions of the LU-10 Linac is the wide two-maximum beam spectrum, as well as rather great distance from the accelerator exit window to the wedge, commonly positioned at a transport container TC (see Fig. 1).

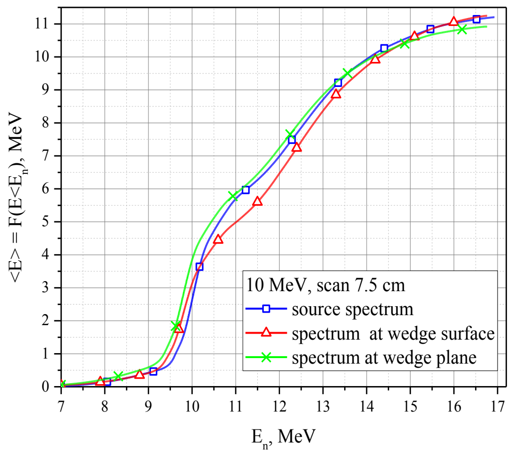


Fig. 6. Average energy over the part of the LU-10 beam spectrum, E_p=10 MeV

The simulation of measurement conditions using the GEANT 4 package has shown that the spectrum of the electron radiation incident on the wedge is differed from the initial one as a result of particle scattering in the air and beam scanning also. In particular, the tail of low-energy electrons arises, whence the probable and average energy of the spectrum of the radiation within the plane of the front surface of the wedge are decreased by a value of ~0.2 MeV. It corresponds to the beam ionization loss in the air. At the same time, the average electron energy at the wedge surface itself differs from its initial value less than by ±0.5% (Fig. 6).

That takes place because a considerable part of the electrons in the beam spectrum have energy >>E_p. Since the low-energy electrons are bent with the scanner on a grater angle, so the relative contribution of particles with energy $E>E_p$ enlarges the average electron energy on the wedge surface as compared with its value within the whole plane of the front wedge facet.

The results of the numerical experiment on the measurement of energy characteristics of the LU-10 beam using the wedge method are given in Table 1. The statistical struggling of the obtained values does not exceed ±0.1%. It was supposed in the calculations, that the beam scan amplitude at the accelerator exit window corresponds to its actual value of 7.5 cm. The determination of E'_p and E'_{av} parameters of radiation in the wedge was carried out on the basis of obtained characteristics of dose distribution along the dosimetry film and with the use of formulae given in the standard [4]. For a comparison, the cases of actual spectrum with maximum and average energy E_p and E_{av} respectively, and also of monochromatic beam with energy E_p, as well as the results of the experimental study were considered (the experimental results are denoted with the asterix). The statistical straggling of the obtained data does not exceed ±0.1%.

As it is seen from the Table 1 data, the difference between the calculated and measured E'_{av} values is no more than 1.5%. The results on E'_p for the monochromatic beam obtained in the numerical experiment are agreed with the initial data within 0.2%. At the same time, that difference reaches 12% when the LU-10 actual spectra.

Table 1

Energy characteristics of the LU-10 electron beam

Specified spectrum parameters, MeV		Energy within the wedge plane, MeV		Energy within the wedge surface, MeV		Energy determined by the wedge technique, MeV	
E_p	E_{av}	E_p	E_{av}	E_p	E_{av}	E'_p	E'_{av}
8.00	mono	7.81	7.72	7.81	7.66	8.07	7.61
8.00	9.37	7.81	8.90	7.81	9.26	9.86	9.28*
9.00	mono	8.81	8.72	8.81	8.65	9.16	8.90
9.00	10.54	8.81	9.89	8.82	10.19	10.70	10.23*
10.00	mono	9.80	9.72	9.80	9.65	10.21	9.94
10.00	11.45	9.78	10.92	9.78	11.25	11.77	11.34*
11.00	mono	10.81	10.71	10.81	10.64	11.27	10.91
11.00	12.73	10.77	11.75	10.71	12.03	12.45	12.18*
12.00	mono	11.81	11.71	11.81	11.63	12.41	11.97
12.00	13.88	11.74	12.79	11.77	13.06	13.45	13.23*

2.3. ON-LINE MONITORING OF ELECTRON ENERGY

It was shown in the work [7], that the energy of the beam electrons can be determined by means of measurement of the ratio q_k of charge deposited in the k last plates of the stack-monitor SM to the total charge, absorbed in that device. In Fig. 7,a, the distributions of absorbed charge in the SM plates at various probable energy E_p of the LU-10 beam spectrum derived by computer simulation are presented.

The appropriate values of the q_k coefficient for the various sets of plates are given in Fig. 8. The data obtained in such a way was fitted with the linear dependences with the estimation of fitting quality using the coefficient of determination (COD). As it has turned out, the closest to linear dependences both for E_p and for E_{av} are occurred when k=4: COD(E_p, k=4)=0.99632, COD(E_{av}, k=4)=0.99965 (Table 2).

The measurement of currents in the plates when the monitor exposure to full-power beam has shown, that obtained distributions are considerably differed from the calculated ones (see Fig. 7,b). It can be explained by the effect of beam-induced ionization currents in the air gaps between the plates.

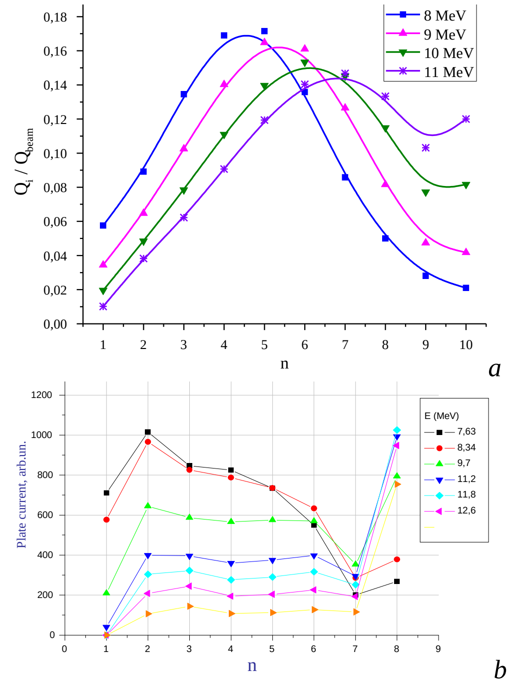


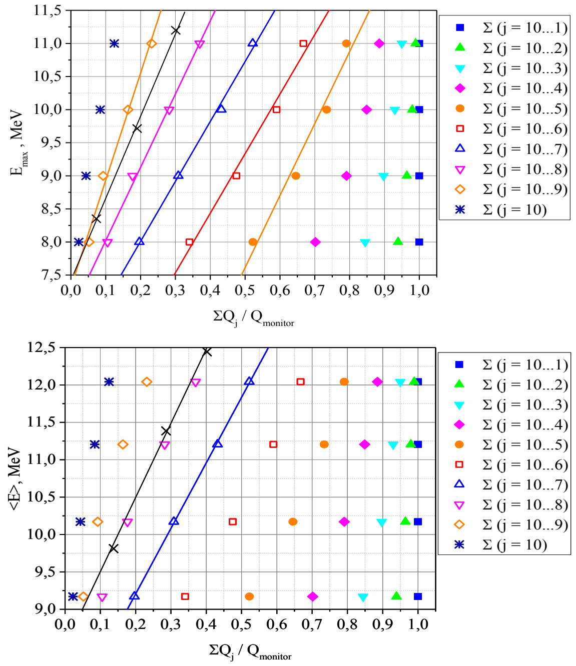
Fig. 7. Distribution of absorbed charge (current) of the LU-10 beam with various electron energy E_p over the plates of the stack-monitor: a – simulation; b – experiment

Table 2

Linearization coefficients of the $E=F(q_{k=4})$ dependence

$E_p=A\cdot q_{k=4}+B$						$E_{av}=C\cdot q_{k=4}+D$					
A	±ΔA	ΔA/A,%	B	±ΔB	ΔB/B,%	C	±ΔC	ΔC/C,%	D	±ΔD	ΔD/D,%
0.0544	0.3890	4.3	6.1993	0.1497	2.41	8.7997	0.1159	1.32	7.4541	0.0446	0.6

Nevertheless, this time a close to linear dependence between the electron energy and the relative charge in the last 4 plates is kept as well though with the other adjustment coefficients (Fig. 8).



a

b

*Fig. 8. Dependence of the most probable (a) and average (b) electron energy in the beam on the relative charge absorbed in the last k plates of SM (**x** -experiment)*

CONCLUSIONS

The conducted up-grade of control system of the magnet analyzer of the LU-10 accelerator provided the possibility to obtain the beam energy spectra in the digital form, and hence to compute the most probable E_p and averaged over the spectrum E_{av} values of the electron energy. The measurement of the latter using the standardized dosimetry wedge technique has shown the agreement of obtained values within <1%. At the same time, when the wedge application to determination of E_p of a beam with wide spectrum (e.g., in case of LU-10 plant, E_{max}-E_{min}~E_p) the method can give the appreciably corrupted data.

One can carry out the on-line monitoring of electron energy with the use a stack-monitor (SM) of absorbed beam positioned behind the travel zone of a treated product. When the beam spectrum is known, the monitor calibration can be performed against the E_p and E_{av} parameters, and E_{av} can be determined with higher accuracy than E_p. At the same time, the application a MC simulation technique for calibration is allowable only for low-current beam, when radiation induced charge leakage in the stack is insignificant. In a case when spectrum information is absent, the SM calibration with the use of the dosimetry wedge is feasible only against E_{av} parameter.

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Article received 13.10.2017

ИЗМЕРЕНИЕ ЭНЕРГЕТИЧЕСКИХ ХАРАКТЕРИСТИК ПУЧКА ПРОМЫШЛЕННОГО УСКОРИТЕЛЯ ЭЛЕКТРОНОВ

Р.И. Помацалюк, В.А. Шевченко, И.Н. Шляхов, А.Э. Тенишев, В.Ю. Титов, Д.В. Титов, В.Л. Уваров, А.А. Захарченко

Энергия излучения является одним из критических параметров в радиационно-технологических процессах, а также при проведении радиационных испытаний на ускорителях электронов. В статье изложены результаты модернизации анализатора спектра пучка электронов на основе 90°-электромагнита промышленного ускорителя ЛУ-10 (10 МэВ, 10 кВт). Для приема и обработки данных разработана система контроля с использованием многофункционального USB-устройства. Приведены результаты измерения энергетических характеристик пучка ускорителя с помощью анализатора, а также дозиметрического клина. Методом компьютерного моделирования изучены особенности применения клина в случае пучка с широким спектром. Исследованы условия on-line мониторинга энергии электронов с использованием широкоаппертурного стек-монитора. Проведен сравнительный анализ результатов измерения энергии, полученных разными методами.

ВИМІРЮВАННЯ ЕНЕРГЕТИЧНИХ ХАРАКТЕРИСТИК ПУЧКА ПРОМИСЛОВОГО ПРИСКОРЮВАЧА ЕЛЕКТРОНІВ

Р.І. Помацалюк, В.А. Шевченко, І.М. Шляхов, А.Е. Тенишев, В.Ю. Титов, Д.В. Титов, В.Л. Уваров, О.О. Захарченко

Енергія випромінення є одним з критичних параметрів у радіаційно-технологічних процесах, а також при проведенні випробувань на прискорювачах електронів. У статті викладені результати модернізації аналізатора спектра пучка промислового прискорювача ЛУ-10 (10 МеВ, 10 кВт) на основі 90°-електромагніта. Для прийому і обробки даних розроблена система контролю з використанням багатофункціонального USB-пристрою. Приведені результати вимірювання енергетичних характеристик пучка прискорювача за допомогою аналізатора, а також дозиметричного клину. Методом комп'ютерного моделювання вивчені особливості застосування клину у тому разі, коли пучок з широким спектром. Досліджені умови on-line контролю енергії електронів з використанням широкоапертурного стек-монітора. Проведено порівняльний аналіз результатів вимірювання енергій, отриманих різними методами.