Monitoring the Energy of Electrons in Industrial Linacs

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Abstract

Recently, technological linear electron accelerators with the energy up to 10 and 25 MeV and pulsed current up to 1A have been developed and put into operation in the Scientific Research Complex (SRC) "Accelerator" of the National Science Center, Kharkov Institute of Physics and Technology (KIPT). These linacs are equipped with control systems which allow for the control of the electron energy at the exit of the linacs.

1 The output beam scanning and forming

The zone of the technological object irradiation by the accelerated electrons is created by the magnetic scanning system [2]. This system represents an electromagnet with the spatially homogeneous magnetic field and the normal boundaries on the beam input and output. The magnet is excited by the generator of a two-polar sawtooth current [6]. The scanning system provides the required value and uniformity of the scanning as well as measurement and operative control of the electron beam energy characteristics [4].

The basic characteristics of the accelerator beam and the irradiation zone, which determine the type and construction of the scanner, are presented in the following table:

Parameter	Value
The electron energy	Å=8-25 MeV
The beam diameter at the inlet of the scanning device	$\varnothing \approx$ 1cm ($r_0 = z_0 = \pm 0.5$ cm)
The input beam angular divergence	$r'_0 = z'_0 \approx 5 \cdot 10^{-3}$radn
Energy dispersion	$\Delta E / E \approx \pm 5 \cdot 10^{-2}$
The maximum angle of the beam scanning	$j = \pm 20^{o}$
The effective length of the magnet field	$L_n \cong 16.3$ cm
The scanning frequency (controlled)	$f = 1 \ldots 3$ Hz

Structurally the magnet system of the scanning device represents an electromagnet with spatially homogeneous magnetic field and normal boundaries on the beam input and output. Fig. 1 shows schematically the scanning zone from the accelerating section outlet to the output window with real boundaries of the edge field on the inlet and outlet of the scanner magnet clearance.

The magnet core and the working clearance poles are assembled from punched isolated steel plates with 2mm thickness. Such a construction appeared to be quite acceptable for the assumed scanning frequency and the manufacturing technology. The excitation winding consists of two coils with 60 turns each which are located symmetrically with respect to the working clearance and winded with copper wire of 2.36x5.00 cross section. The cooling is natural.

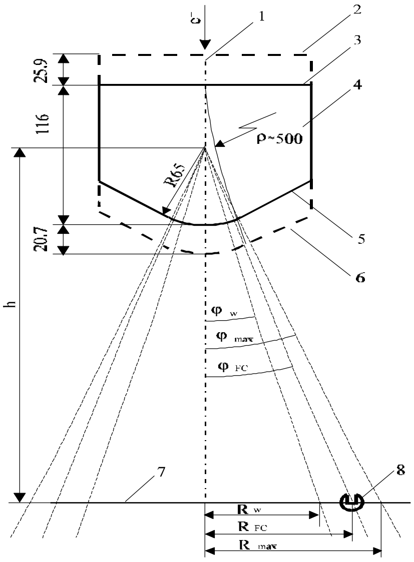

Fig. 1 The zone of beam scanning and output: 1- the accelerator axis; 2 and 6- the effective field boundaries on the inlet and outlet of the scanning magnet; 3 and 5 -the magnet boundaries (by iron); 7- the energy control plane; 8- the slot hole Faraday cylinder (FC).

2 The operative control of the electron energy

In addition to the main task the electromagnet of the output device can be used for the operative control of the electron energy. The technique is based on the relationship between the total energy of the charged particle E_n and "rigidity" of the magnetic field H (with the account of relativism) [3]:

$$H r = \frac{1}{ec}\sqrt{E_n^2 - E_0^2}, \tag{1}$$

where *c*- is the light speed, *e* and E_0 - are the electron charge and energy, respectively, r - is the radius of the particle trajectory in the magnetic field with intensity H. The following expression for the kinetic energy of the electron can be obtained by a simple transformation of (1) taking into account dimensions and units of measurement:

$$E_k = \sqrt{E_0^2 + (3 \cdot 10^{-4} H \rho)^2} - E_0, \qquad (2)$$

where E_k - MeV, H - Oe, ρ - cm. One can see that to measure E_k it is necessary to determine two values: the intensity of the deflecting magnetic field *H* and the radius of the electron curvature in this field ρ. However, while working with an accelerated beam the direct measurement of the specified characteristics, especially ρ, is connected with almost insuperable difficulties. That is why the technique is based on the measurement of the linear and angular parameters - the effective length of the deflecting magnetic field L_n (taking into account the scattered fields on the inlet and outlet of the magnet) and the geometry of the scanning zone (Fig. 1). These parameters are measured in advance and do not change their values during the experiment. The excitation current force of the scanning electromagnet is obtained from the curve of magnetization $H = f(I)$. Such a characteristic for one of the magnets is depicted on Fig. 2. Noticing that for the small angles of the beam deflection ($\varphi \le 20^o$) the following relationship is valid

$$\rho = \frac{L_n}{\sin\varphi}, \qquad (3)$$

Finally we arrive at the practical formula for E_k:

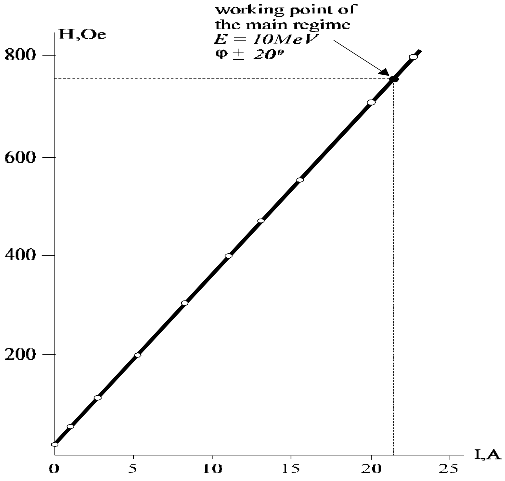

Fig. 2 The magnetization characteristic

$$E_k = \sqrt{E_0{}^2 + \frac{k^2 I^2}{\sin^2\varphi}} - E_{0,} \qquad (4)$$

where k is the constant accounting for the relationship between H, I and L_n for a specific magnet and is determined by stand investigations. From Fig. 1 one can see that if the value of the electron beam deflection from the axis (R) on the plane located at distance h from the magnet is found by using any appropriate method and the value of I is known, the value of E_k.can be obtained. In this case

$$\varphi = arctg(R/h) \qquad (5)$$

For the technological accelerators at SRC "Accelerator" two techniques are mainly used for the operative control of the most probable average electron energy.

3 The method of photometry

A piece of glass is located on the energy control plane (Fig.1). During several scanning periods this glass is illuminated by the electron beam with a fixed value of I. As a result, a blackened print of the beam trace is formed. Then the distance R is measured and the most probable average beam energy is determined by using the dependences $E(R, I)$ calculated beforehand on the basis of (3,4). The error of such a measurement is 5-10%. In this case the control time and, correspondingly, the lost beam time of the accelerator is about half an hour.

4 Express method

The paper of Ref. [4] describes the technique of energy control by using the special slot-hole Faraday cylinder(FC) and automatic control system [5]. Taking into account the maximum power of the scanning magnet feeder for each controlled energy range the distance R_{FC} (Fig. 1) is chosen so that with the working value of the amplitude of a sawtooth feeding voltage of a magnet (U) at the extreme working location of the beam center (R_w) electrons will not hit a Faraday cylinder; at the extreme control location (R_{max}) the beam center will go behind the FC. Then by using the relationship $E = f(U, R)$ the value of E is found. This process of control does not require the beam switching-off and takes a few seconds.

The operation experience showed that this technique did not allow to control the electron energy over a wide energy range, as with the sawtooth voltage (U) the current in the magnet has a sinusoidal form and, correspondingly, characteristic $E = f(U, R)$ is nonlinear. And only for a narrow energy range, within the limits of ±1 MeV, for each energy range the estimations of E can be obtained with an error less than 5%. Besides the inhomogeneity on the edges of irradiated objects reached 15%. To eliminate these flaws some work on improvement of the scanner feeder has been done [6]. As a result the strictly sawtooth form of the excitation current of a magnet has been obtained. It allows to consider that the movement of a beam center for each accelerator pulse satisfies the following condition: $\Delta\varphi = const$.

At the accelerator operator's command the control system increases the amplitude of a halfscope of a sawtooth feeding current of the magnet (I) from a working value to the maximum one. The beam deflection angle is increased up to φ_{max}. The measuring system registers (Fig. 3) values $I(t)$, pulse beam current I_{AC} and a (FC) pulse current I_{FC} and determines the scanning frequency (F_{SCAN}) and the frequency of the accelerator work (F_{AC}). Then the program of filtration and image recognition processes the graphics of $I\,(t)$, I_{AC} and I_{FC}. If the beam center crossed the FC than numbers of pulses *n1*, *n2* (Fig. 3) are calculated as well as a number of beam pulses Δn, with trajectories between J_{FC} and J_{max} .

$$\Delta n = n2 - n1\,. \qquad (6)$$

The total quantity of accelerator pulses during the quarter of a scanning period is given by the following expression:

$$n = \frac{1}{4} F_{AC} \;/ F_{SCAN} \qquad (7)$$

$$J_{max} = J_{FC} + \Delta j \cdot \Delta n / 2\,. \qquad (8)$$

By simple substitutions taking into account the relationships (5,6,7, and 8) expression (9) valid under the condition $J_w < J_{FC} < J_{max}$ is obtained from the formula (4).

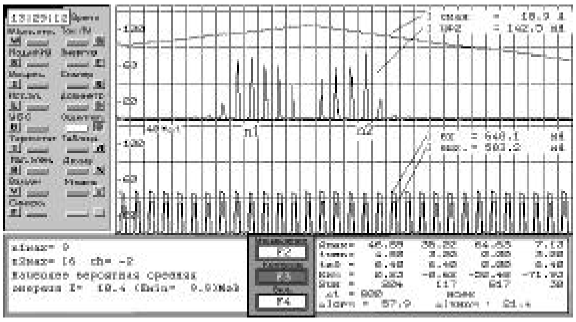

Fig. 3 The videogramme of the accelerator energy control.

$$E_k = \sqrt{E_0{}^2 + \frac{k^2 I^2}{\sin^2(arctg(R_{\mathrm{FC}} / h)(\dfrac{2n}{2n - \Delta n}))}} - E_{0,} \qquad (9)$$

Currently this expression is used to obtain the most probable average value of the electron energy. In the future it is supposed to use the proposed technique to estimate the beam energy spectrum.

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