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Design Study on Electron Energy Spread Effect on Performance of Linac Irradiation Facility with the Aid of Electron Energy Spectrum Online Analyzer

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***Abstract*—Ongoing energy measurement is one of the parameters such as: electron beam current, transporter speed, or scanning width, that must be recorded according to the conditions imposed in the accelerator validation procedure. Described measurement method based on the use of a secondary electron collecting electrode has been tested at the electron beam linear accelerator installation typically used for radiation sterilization. Data processing and presentation of the electron beam characteristics is based on the information obtained via dedicated pulse acquisition interface. The energy spectra parameters provide data for modeling and calculation of dose distribution for irradiation process optimization and also knowledge of accelerator RF alignment in case of service.**

***Keywords*—radiation sterilization; electron accelerator; electron energy; depth dose distribution; computer modelling**

INTRODUCTION

CONTINUOUS electron energy measurement is currently obligatory for accelerator installations intended for radiation sterilization. This is one of several values such as: dose rate, beam current, transporter speed, or sweep parameters, which must be recorded in accordance with the accelerator validation requirements code.

While determining the energy of electrons in electrostatic accelerators is relatively simple and results from the measurement of the accelerating voltage, in case of RF linear accelerators it can't be done in a simple and direct measurement.

Some accelerator installations have an integrated magnetic electron energy analyzer, but such a measurement procedure cannot be carried out during sterilization. Also, the use of an aluminum wedge for visualization of energy-dependant depth dose curve profile does not meet the requirements of an on-line measurement, however according to [1] it is recommended for electron beam (EB) radiation sterilization facilities as one of measurement methods used for Operational Qualification and Performance Qualification of the irradiation EB installation..

A typical solution is indirect energy estimation based on the knowledge of certain parameters, such as microwave power level and beam current, which affect electron beam energy at the output of the accelerator. The above parameters can be measured on an ongoing basis, and energy can be calculated using known relationships and calibration curves. Unfortunately, this method does not offer satisfactory accuracy of the result, mainly due to the necessary simplification of the computational accelerator model and the inability to measure many other physical parameters that this model would have to take into account.

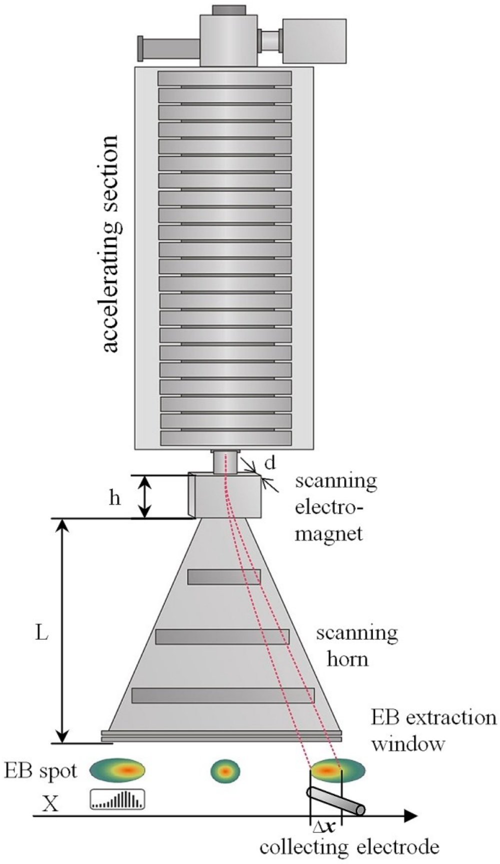

Fig.1. Linear electron accelerator and illustration of EB magnetic splitting phenomenon

One of the possible solutions [2.] is the use of a sensor electrode located directly under the window of the scanned electron beam in such a way that it does not interfere with the distribution of dose over the product irradiation area and provides data to determine the energy of electrons in the beam and the spectral distribution of this energy.

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I. THE MEASUREMENT CONCEPT

The measurement method based on the use of a secondary electron collecting electrode was tested in an electron beam scanned installation, typically used for radiation sterilization.

The electron beam formed in accelerator as in Fig.1 is passing the channel between the poles of scanning electro-magnet, that causes its deflection to draw the line in X direction over the irradiated product surface. The magnet coil current is linear time-dependant (triangle wave) providing homogeneous distribution of the radiation dose in the product moving on conveyer beneath the accelerator outlet window.

As it is known, linear accelerators produce electron beams with certain amount of electron energy components around the Most Probable Energy E_p . For different energies E_k, at certain scanning current I, the magnitude of the deflection x will be :

$$x(E_k, I) \approx \frac{k(I)}{\sqrt{E_k(E_k + 2E_0)}} \qquad (1)$$

where k(I) is a factor dependant from engineering and physical constants

$$k = \frac{E_0 e \mu_0}{m_0 c} \frac{h(L+h)}{d} Iz \qquad (2)$$

E_0 – resting electron energy

m_0 – resting electron mass

e – electron charge

c – light speed

μ_0 – vacuum magnetic permeability

d, h, L, z respectively – magnet poles gap, height, scanning horn height, number of coil turns

and therefore the trajectory of electron will vary. The components with various energies in the beam will be split and stretched over a certain section of Δx according to formula (3) derived from inverted (1)

$$E_k \approx \sqrt{E_0^2 + \frac{k^2}{x^2}} - E_0 \qquad (3)$$

When analyzing the intensity of the passing electron beam at subsequent points along Δx the energy spectrum of the electron beam can be obtained.

The idea of measurement is shown in Fig.1 The collecting electrode can be made of a strip of thin metal (Al) or wire. High energy electrons passing through the electrode material knock out a number of secondary electrons, some of which are able to leave the electrode. This is recorded as the flow of a small, positive current from the electrode, it is directly proportional to the intensity of the primary electron stream (Fig. 2).

The physical movement of the electrode along Δx is unnecessary, because the scanning current causes the beam to move linearly along the X axis, thus all points of the Δx section will move over the electrode at some time. As a result, the current collected by the electrode is in the form of a pulses with an amplitude modulated by the instantaneous intensity of the beam.

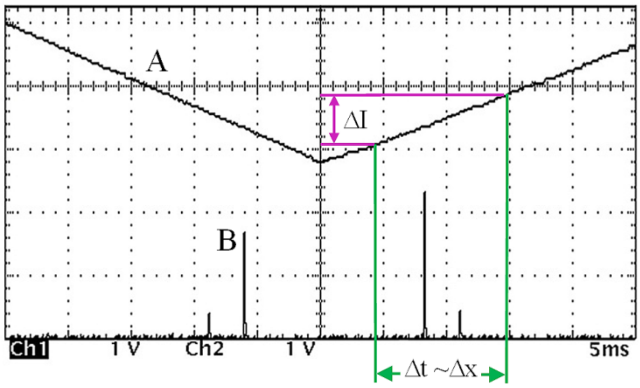

Fig.2. Waveform oscillogram taken from single EB scanning pass. A - current in scanning magnet coil, B - current from collecting electrode

II. SIGNAL PROCESSING

The collecting electrode current appears only when the coincidence of electron beam pulse (5μs over period 3ms) and appropriate scanning current value (I, ΔI) occurs within Δt interval as shows Fig. 2 which is corresponding to electron beam presence at Δx section of the scanning line. Practically it gives about 10 – 20 pulses per second. It is far insufficient to create direct visualization of EB energy spectrum at the oscilloscope screen.

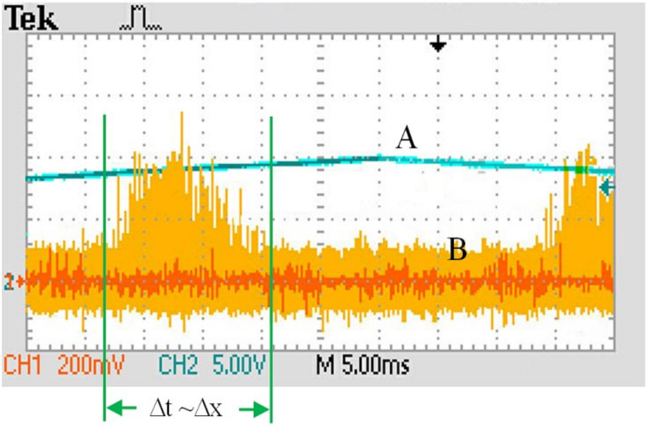

Fig.3. Waveform oscillogram taken by oscilloscope in pulse accumulate mode

Additionally oscillograms taken in pulse accumulate mode (Fig.3) show that there is high level of EMI noise collected by the electrode and connecting cable passing in the vicinity of other signal cables.

The signal processing concept includes strict filtration of pulses basing on pre-defined time gating elaborated from accelerator EB pulse synchronization and scanning current amplitude threshold window comparator.

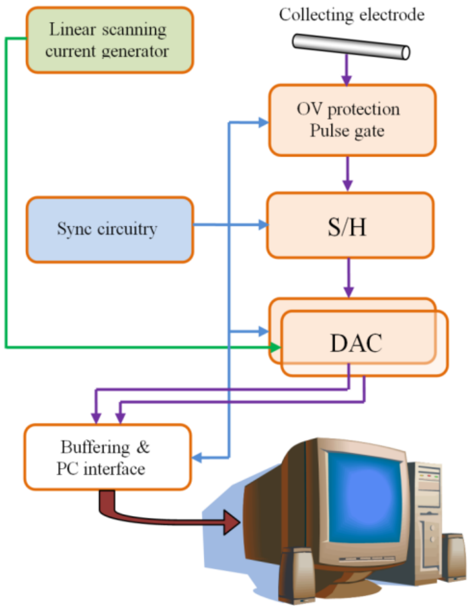

Fig.4. Configuration of data collecting hardware

This made possible to postpone conversion process to be performed in “quiet” moments of accelerator work. The analog part of converter is turned off and grounded in-between expected useful pulses and A/D conversion of voltages memorized in S/H is carried out.

III. RESULTS

The data delivered via the interface is stored in computer, after applying the error elimination procedures and averaging, it is normalized and sent for visualization as shown on Fig. 5.

The spectrum image is discrete due to pulse mode of accelerator operation To build sufficiently accurate energy spectrum shape it needs around 20 second period of data accumulation. As the fluctuations of accelerator power parameters happen in tens of minutes scale, the presented result of E_p calculation can be considered as satisfactory continuous.

As far as the accelerator has no built-in manufacturer calibrated electron energy measurement device, the only way for calibration of the spectrum analyzer is the use of certified wedge and the procedure described in [2] The most probable energy E_p is calculated as the center of gravity of the EB spectral distribution obtained from the accumulated data.

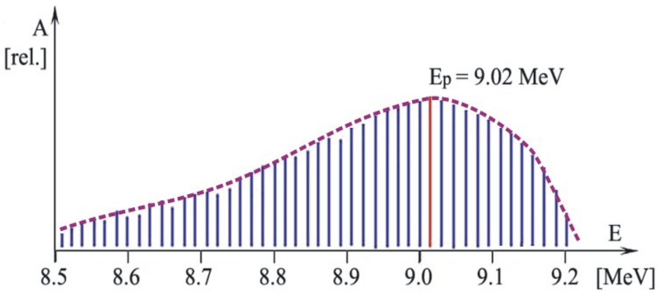

Fig. 5. Visualization of electron beam energy spectrum

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The knowledge about the electron beam energy spectrum distribution allows the operator to set up the accelerator RF devices in such a way that the machine performs the irradiation process at the optimum efficiency.

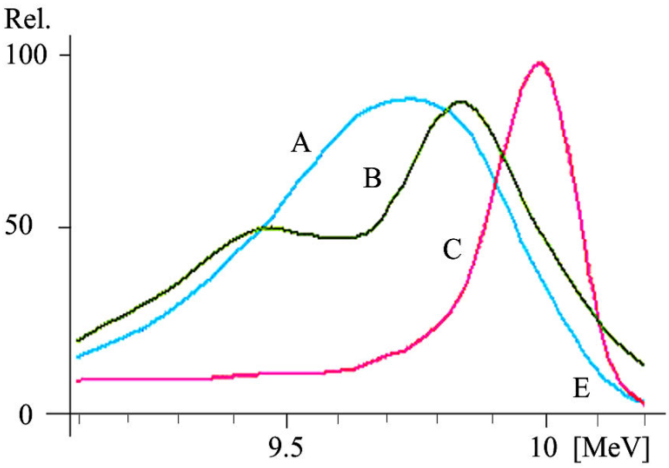

Fig.6. The example of RF magnetron HV power current influence on electron beam energy spectra. A – magnetron average current 600mA, electron gun pulse current 400mA, B – magnetron average current 550mA, electron gun pulse current 300mA, C – magnetron average current 700mA, electron gun pulse current 500mA

Magnetrons, as self-excited sources of microwave energy, are characterized by significant instability of parameters (frequency, amplitude), which translates, among others, into energy scattering and relatively large fluctuations of electron energy. (Fig. 6) During repair or maintenance works, such measurements is a very important diagnostic tool providing information on working conditions of some accelerator components, their alignment and wear level.

Operation of accelerators in radiation treatment process generally requires control of basic process parameters which include:

- Nominal energy [MeV];
- Energy spread [±%];
- Energy instability [%/h];
- Energy day to day reproducibility [%/24h];

Changes in electron energy spread can have a significant impact on the technical and economic parameters of the radiation sterilization treatment process. The day to day reproducibility of electron energy (Fig. 7.) and energy spread depends on operational parameters such as cooling water temperature variations, electron gun grid voltage fluctuations, and stability of the components responsible for the electron acceleration process (e.g. magnetron).

As it results from conducted experimental works [3] information about the energy spectrum of electron beam is necessary for proper facility general description, but it is less essential for given radiation installation. What is true, when energy spread is constant during accelerator operation.

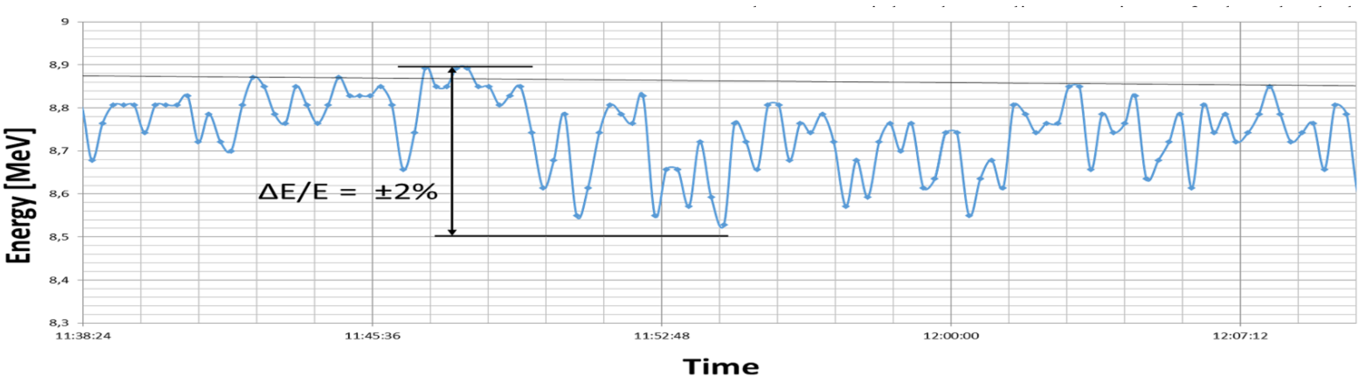

Fig. 7. Record of energy changes in a linear electron accelerator Electronics 10/10

The presence of the energy spectrum spread of electron beam can change the intensity of scanned electron beam what should be considered by suitable arrangement of beam scanning device. In practice it is hard to "improve" the depth dose distribution of the mono-energetic electron beam through utilization of additional filters.

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The depth dose distribution depends on the magnitude of the electron energy spread. Experimental results show that in the case of significant values of energy spread, the energy scatter does not allow to make a correct assessment of electron energy according to the relations described in international standards. The measurement device shown on Fig. 8A and method are described in [3] and further depth dose parametrization and calculations refer to this standard.

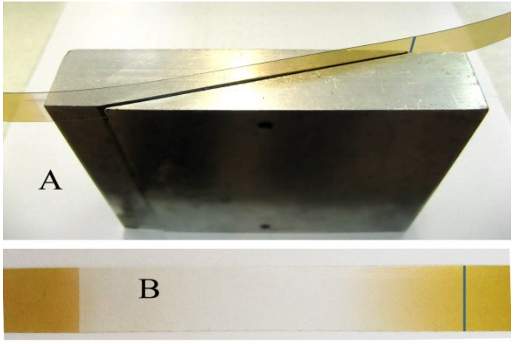

Fig.8. A - Al wedge measurement device; B – irradiated PVC dosimeter stripe

The dosimeter optical absorbance (Fig. 8B) reading in visual light gives depth dose distribution in Al to which [2] defines a parametrization as follows (Fig. 9):

D_e: Dose at entrance surface

R_{ex}: Depth in homogeneous material to the point where the tangent at the steepest point (the inflection point) on the

R_{50e}: Depth at which dose has decreased to 50 % of De

R_p: Depth where extrapolated straight line of descending curve meets depth axis

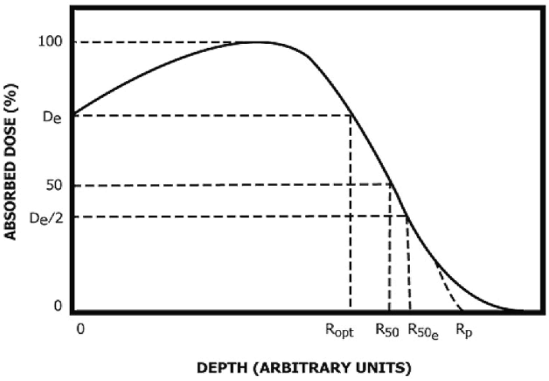

Fig. 9. A typical depth-dose distribution for an electron beam in a homogeneous material

The incident electron energy values E(MeV) can be correlated to the R_p and R_{50} range values for Al (cm) with second order equations as follows (for electron energies between 2.5 MeV and 25 MeV):

$$E = 0.423 + 4.69R_p + 0.0532R_p^2$$
$$E = 0.394 + 4.77R_{ex} + 0.0287 \cdot R_{ex}^2$$
$$E = 0.734 + 5.78R_{50} + 0.0504 \cdot R_{50}^2$$

The magnitude of the practical electron range R_p depends on the energy spread even in the case when the value of the most probable energy E_p remains unchanged. This statement follows from the analysis of the results of calculations performed during computer simulations.

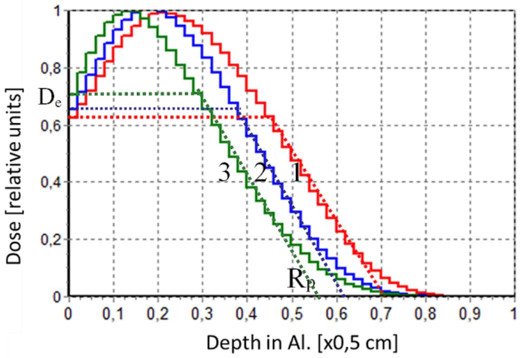

Fig. 10. Typical depth dose distribution calculations in Al, where various electron energy spread was taken.

A number of experiments followed by computer modeling [4]. have been carried out for the identification of the energy scattering effect on the profile of the depth dose distribution (Fig. 10)

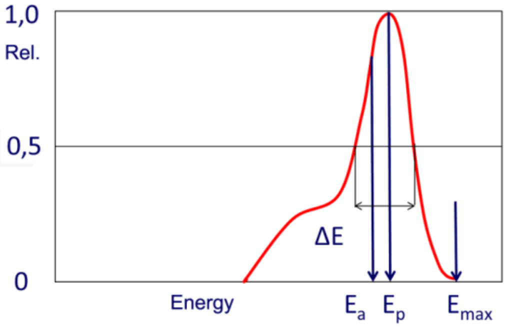

Fig. 11 Typical energy spread of electrons in a linear accelerator with: E_a - average energy; E_p- most probable energy; E_{max} - maximum energy; ΔE - electron energy spread.

For the purpose of the energy spread simplification, it is assumed, that the curve presented on Fig.11 has triangular shape with determined ΔE (Fig.12)

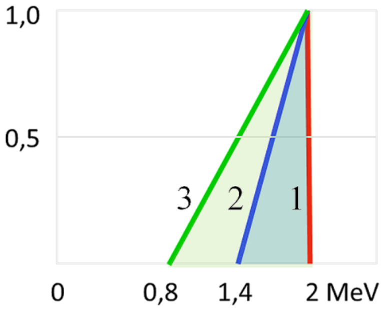

Fig. 12. The linear simplification of electron energy spread as taken for depth dose distribution calculations. (red line 1 at 2 MeV represents an ideal, monoenergetical electron beam)

Experiments based on computer calculations were conducted for an electron beam with varying energy spread, satisfying the conditions of a specific mathematical model. The depth dose distribution, initiated by an electron beam in an aluminum target, was calculated based on the Monte-Carlo method and the Mode-RTL computer program [5].

Calculations were carried out for a mono-energetic electron beam with energy of 2 MeV and for an electron beam with different energy scattering. The results are shown in Fig.10 and Table I.

TABLE I
RESULTS OF CALCULATION DEPTH DOSE AT 2 MEV ELECTRON ENERGY FOR DIFFERENT ENERGY SPREAD VALUES

Curve	ΔE/E	D_o	D_{max}	D_{av}	Thickness of Al for D_o=D_w [mm]
1	0	44,3	70,5	33,1	0,23
2	15%	46,5	71,0	29,5	0,19
3	30%	50,0	70,8	25,8	0,15

D_e - surface dose, D_{max} - maximum dose, D_{av} - average dose, D_w - output dose

As can be seen from the graph in Fig. 9 and Table I, a larger energy spread causes reduction in the average dose and limitation of the usable area defined by the condition D_e=D_w. The course of the curves in Fig. 9 allows us to determine the practical range R_p of electrons for normalized deep dose distribution curves.

Calculations were also carried out for a mono-energetic electron beam of 10 MeV energy and for an electron beam of different energy spread. The results and analogous conclusions are shown in Fig. 12 and Table II.

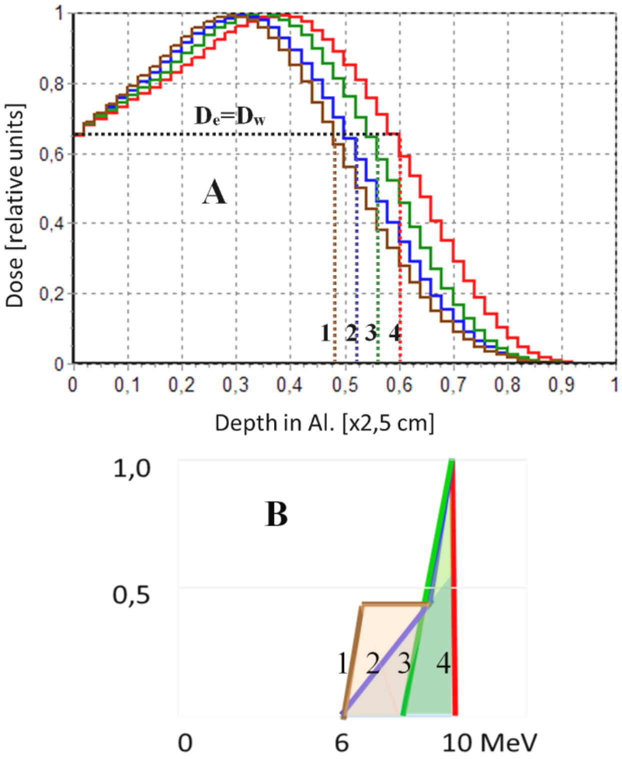

Fig. 13. Distribution of depth dose in aluminum (A) for energy of 10 MeV versus energy spread of electron beam (B)

TABLE II
RESULTS OF CALCULATION DEPTH DOSE AT 10 MEV ELECTRON ENERGY FOR DIFFERENT VALUES OF ENERGY SPREAD

Curve	D_a	Thickness Al layer
1	13,9	1,20
2	14,5	1,25
3	15,3	1,35
4	16,3	1,45

The electron energy scatter profile variations (Fig.13B) taken for calculations as the input data, show better similarity to those presented on Fig.5. obtained from the on-line analyzer working in real conditions.

I. CONCLUSIONS

The developed and tested system after calibration using other methods of energy determination described above works in continuous mode at the electron accelerator installation at the Sterilization Station. The current control of the distribution of the energy spectrum of the electron beam and automated measurements of other parameters are recorded in accordance with the applicable requirements and enable multi-parameter optimization of the irradiation process giving the accelerator operator appropriate warnings in case of machine parameters mismatch. While electron energy measurements are important for maintaining the required quality of electron beam radiation treatment, knowledge of electron beam energy spread can sometimes be used to optimize product irradiation conditions. The depth dose distribution depends on the magnitude of the electron energy spread. Experimental results show that in the case of significant values of energy spread, the energy scatter does not allow to make a correct assessment of electron energy. In practical, after long period of observations we conclude, that generally the energy scatter profile shape is most time similar to that shown on Fig.5. and fluctuations of electron energy concern mainly value of E_p, which is known as dependant from the level of magnetron RF power.

The use of computer programs for dose distribution analysis makes it possible to dispense with a significant part of dosimetry measurements and keep aware of eventual effect of energy spread factor on the quality of radiation treatment.

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