INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2026, VOL.72, NO. 2, PP. 1-6
Manuscript received April 23, 2026; revised April 2026. doi: 10.24425/ijet.2026.157944

# A non-invasive online method for real-time determination of the Most Probable Energy (MPE) of industrial electron beams

Sylwester Bułka

***Abstract* —A non-invasive method for real-time determination of the most probable energy (MPE) of industrial electron beams is presented. The method is based on the use of beam energy dispersion in a scanning magnetic field combined with local detection of beam intensity using a thin collecting electrode. Due to the lack of synchronization between the accelerator pulse generator and the scanning magnet, the beam is sampled in an asynchronous manner, allowing reconstruction of the spatial and energy distribution through signal accumulation. Two methods for MPE determination were investigated: local parabolic approximation and a centroid-based approach. The latter was found to be more robust under noisy industrial conditions and provided superior repeatability. Application of the method to an industrial linear accelerator demonstrated that the beam energy exhibits significant temporal fluctuations. The proposed method provides a direct, real-time measure of effective beam energy and can be used as an operational parameter for accelerator tuning and process control. It complements standard dosimetric techniques by enabling continuous monitoring of beam energy under normal operating conditions.**

***Keywords*—linear accelerator; electron energy spectrum; magnetic deflection; RF matching; most probable energy; histogram reconstruction**

## I. INTRODUCTION

RADIATION sterilization processes using electron accelerators require strict control of beam parameters, which determine the dose distribution within the irradiated material. According to the requirements of quality management systems for medical devices, as specified in ISO 13485, the sterilization process must be fully monitored and conducted in a manner that ensures its reproducibility and traceability. In particular, this implies continuous control and recording of the accelerator operating parameters during the process.

In industrial practice, quantities such as the average beam current, scanning width, and product transport parameters are routinely monitored. However, the electron beam energy, which is one of the key parameters affecting penetration depth and dose distribution, is not directly measured in continuous operation.

According to [1] (ISO/ASTM 51649), beam energy is most commonly determined by indirect methods based on the analysis of the depth-dose distribution, using parameters such as $R_{50}$ and $R_P$. These methods are inherently offline and are primarily used during qualification procedures (IQ, OQ, PQ), rather than for real-time process control.

Furthermore, under actual operating conditions of industrial magnetron-driven linear accelerators, beam parameters are subject to fluctuations caused, among other factors, by temperature variations, instability of the microwave source frequency, and mismatch between the magnetron and the accelerating structure. As a result, the electron beam energy is not constant in time, which may lead to variations in dose distribution and affect both the quality and efficiency of the sterilization process.

For beams with a broad energy spectrum, typical of industrial electron accelerators, a particularly useful parameter is the most probable energy (MPE), defined as the maximum of the electron energy distribution. This parameter provides a practical measure of the “effective” beam energy and directly reflects changes in the operating conditions of the RF system.

Despite its importance for both process control and accelerator tuning, currently available diagnostic methods do not allow direct, continuous determination of MPE during operation. Measurements based on reflected power analysis (SWR) provide information about RF matching conditions but do not allow an unambiguous assessment of the efficiency of energy transfer to the electron beam.

In this work, a method is presented that enables non-invasive, continuous measurement of the most probable energy (MPE) of an electron beam in an industrial linear accelerator during normal operation. The proposed solution allows real-time monitoring of beam energy variations both as a function of time and of RF tuning parameters, thereby providing a useful diagnostic and operational tool for radiation sterilization processes.

In view of the above considerations, there is a clear need for a method that enables direct measurement of beam energy under actual operating conditions, without interfering with the irradiation process and without relying on offline procedures. In particular, a solution allowing continuous tracking of the most probable energy (MPE) as a function of time and RF tuning parameters is highly desirable.

In this work, a method fulfilling these requirements is proposed, based on the use of beam energy dispersion in a scanning magnetic field combined with local detection of beam intensity. Moreover, the method enables reconstruction of the full beam energy spectrum, which can be used for diagnostic assessment of RF system performance. The principle of operation and implementation of the proposed approach are described in the following section.

S.Bułka is with Institute of Nuclear Chemistry and Technology, and Institute of Electronic Systems, Warsaw University of Technology, Poland (e-mail: s.bulka@ichtj.waw.pl).

## II. THE MEASUREMENT CONCEPT

Figure 1 shows a schematic of an industrial electron accelerator together with an illustration of the beam dispersion mechanism in the scanning magnetic field. The electron beam, formed in the accelerating structure, exits the accelerator through the extraction window and passes through the region between the pole pieces of the scanning electromagnet. The magnetic field, varying in time approximately in a triangular manner, deflects the beam in the transverse direction (axis X), enabling uniform irradiation of the product transported beneath the accelerator window.

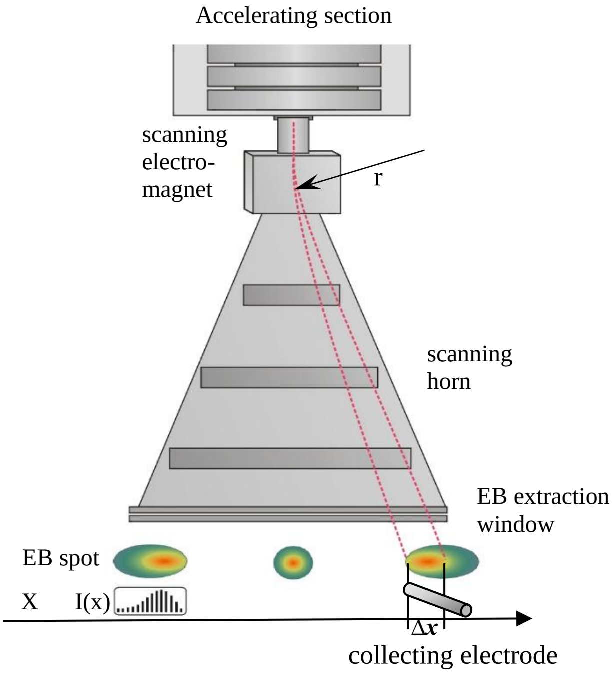

Fig. 1. Schematic of an industrial electron accelerator and illustration of the beam dispersion mechanism in the scanning magnetic field.

For a beam with a non-uniform energy distribution, typical of magnetron-driven linear accelerators, individual energy components undergo different deflections in the same magnetic field. Electrons with lower energy experience stronger bending, whereas higher-energy electrons are deflected to a lesser extent.

As a result, the energy spectrum of the beam is spatially "stretched" along the scanning direction X, which is indicated in the figure as the beam intensity distribution as a function of position Δx [2].

In the lower part of the figure, a thin collecting electrode is shown, positioned at a fixed location with respect to the scanning system. The electrode does not move mechanically; instead, the scanning function is performed by the beam itself under the action of the time-varying magnetic field. At successive moments in time, different portions of the beam, corresponding to different electron energies, pass over the electrode, generating an electrical signal proportional to the local beam intensity.

Consequently, the time-dependent signal from the electrode represents a mapping of the spatial beam distribution and, after appropriate transformation, also its energy distribution. A key role is played by the relationship between the instantaneous current in the scanning magnet coil and the beam position x, which allows each moment in time to be associated with a corresponding beam deflection and thus with a specific electron energy.

The principle illustrated in Fig.1 constitutes the basis of the proposed measurement method, enabling reconstruction of the beam energy spectrum and, in particular, determination of the most probable energy (MPE) under continuous operating conditions of the accelerator.

## III. PHYSICAL BASIS OF THE METHOD

The relationship between the electron energy and its deflection in a magnetic field may, in the first approximation, be described by the radius r of curvature of the particle trajectory in a uniform magnetic field:

(formula)

where:

p – electron momentum,

e – elementary charge,

B – magnetic flux density.

$$r = \frac{p}{eB}$$

For relativistic electrons, the momentum may be expressed as a function of the total electron energy:

$$p = \frac{1}{c} \cdot \sqrt{E^2 - (m_e c^2)^2}$$

where E denotes the total electron energy.

Consequently, the beam deflection in the scanning plane, denoted as x, is a function of the electron energy and the magnetic field value:

$$x = f(E, B)$$

For a fixed geometry of the scanning system and for an operating range sufficiently far from magnetic saturation of the scanning magnet pole pieces, it may be assumed that:

$$B \sim I_s$$

where $I_s$ is the current in the scanning electromagnet coil, measured directly (for example, by means of a Hall sensor). The relationship may then be written in the form:

$$x = f(E, I_s)$$

or conversely:

$$E = f(x, I_s)$$

which makes it possible to assign electron energy values to a given beam position.

The signal recorded by the collecting electrode is pulsed in nature and is a function of time:

$$u(t) \sim I\big(x(t)\big)$$

where I(x) denote the spatial distribution of beam intensity along the scanning direction. Since the beam position is uniquely related to the instantaneous value of the scanning current $I_s(t)$, the time-domain signal may be transformed into a form dependent on the variable x:

$$I(x) \leftrightarrow u(t)$$

As a result of accumulation of the signals from many beam pulses, together with their appropriate registration as a function of $I_s(t)$, a histogram is obtained.

## IV. SIGNAL ACCUMULATION FOR SPECTRUM RECONSTRUCTION

Figure 2 presents a representative waveform of the signal from the collecting electrode recorded during a single beam scanning period. The observed pulses correspond to successive passages of the beam over the electrode, with their amplitudes modulated as a function of the beam position and, consequently, as a function of electron energy.

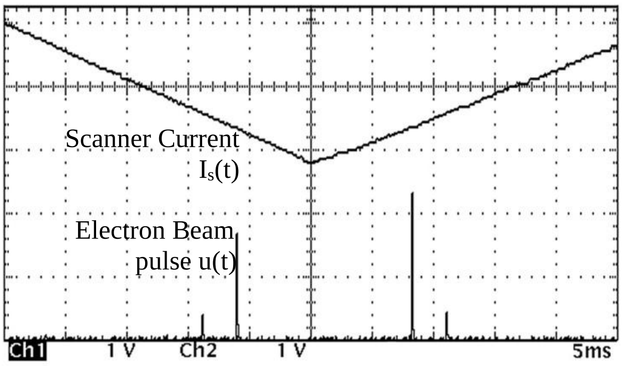

Fig. 2. Real-time waveform of the $I_s$ and signal from the collecting electrode

It should be emphasized that, in the presented system, the lack of synchronization between the accelerator pulse generator (Master Generator) and the scanning magnet current generator is intentional. As a result, successive beam pulses occur at different phases of the scanning current waveform Is(t). Consequently, the electrode signal observed in the time domain appears irregular, and the information about the beam energy distribution cannot be directly extracted from a single waveform.

At the same time, such asynchronous operation is advantageous, as it ensures uniform (equiprobable) sampling of the entire scanning range. In successive pulses, different portions of the beam, corresponding to different electron energies, are incident on the collecting electrode. As a result, given a sufficiently long observation time, it becomes possible to reconstruct the full spatial distribution of the beam and, consequently, its energy spectrum.

To reconstruct this distribution, a signal accumulation procedure is applied as a function of the instantaneous scanning current $I_s$. For each recorded beam pulse, the amplitude of the electrode signal is determined together with the corresponding value of $I_s$, allowing the signal to be assigned to the appropriate histogram bin.

As a result of accumulating signals from a large number of pulses (typically several thousand), a stable histogram $H(I_s)$ is obtained, representing an approximation of the beam intensity distribution as a function of position.

Thus, Fig.2 illustrates not only the structure of the measurement signal but, more importantly, provides a clear justification for the use of signal accumulation as a fundamental element of the method for reconstructing the beam energy spectrum under asynchronous operating conditions.

## V. EMI SUPPRESSION AND ELECTRODE GATING

In contrast to Fig.2, where the structure of individual pulses is clearly visible, a significant level of interference is observed as shown in Figure 3 taken in pulse accumulate mode, which obscures the useful information related to the beam distribution. These disturbances are broadband in nature and originate from the pulsed power system of the accelerator, including, among others, the PFN, thyratron, high-voltage transformer, and microwave source.

In an environment such as an industrial electron accelerator, the signal from the collecting electrode — inherently wideband — is particularly susceptible to electromagnetic interference. An additional factor contributing to noise pickup is the necessity of transmitting the measurement signal over relatively long distances between the accelerator head and the data acquisition system. As a result, even after applying signal accumulation as a function of the scanning current $I_s$ , the obtained waveform does not allow unambiguous identification of the beam energy spectrum structure.

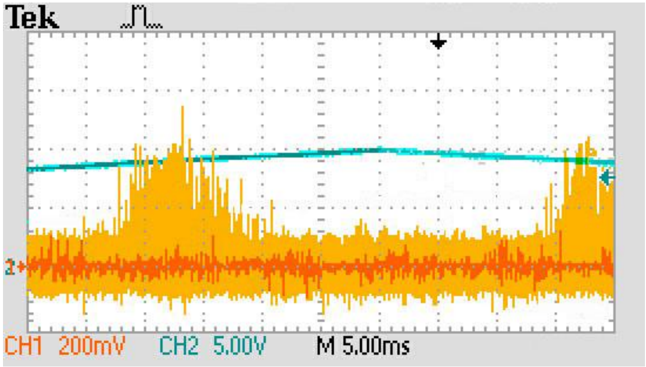

Fig. 3. Waveform oscillogram taken by oscilloscope in pulse accumulate mode.

To suppress the influence of electromagnetic interference, time-domain selection of the electrode signal was implemented, based on activating the electrode only within a short time interval corresponding to the presence of the beam pulse. Outside this interval, the electrode is short-circuited to ground (hard grounding), which significantly reduces its impedance and limits its susceptibility to electromagnetic pickup.

In practice, this means that the useful signal is sampled only within a narrow time window:

$$t \in \Delta t_{beam}$$

where $\Delta t_{beam}$ is synchronous with electron gun and lasts ~5μs

while outside this interval the electrode remains inactive. This approach simultaneously implements time gating and noise suppression, as the detector not only ignores signals outside the relevant time window but also ceases to behave as a high-impedance element capable of receiving interference.

The application of this method leads to a substantial improvement in the signal-to-noise ratio (SNR) and enables the acquisition of a stable histogram $H(I_s)$, which can subsequently be used for reconstruction of the beam energy spectrum and determination of the most probable energy (MPE).

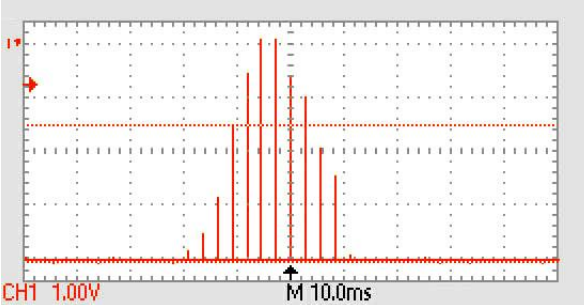

Fig. 4. Waveform oscillogram taken in pulse accumulate mode with active time-gated grounding of the electrode.

As a result of applying time-domain signal selection together with short-circuiting the electrode to ground outside the measurement window, a significant improvement in the quality of the recorded signal was achieved. Figure 4 shows the waveform obtained after applying the described procedure, in which a well-defined structure corresponding to the beam intensity distribution as a function of position is clearly visible.

In contrast to the waveform shown in Fig.3, the “cleaned” signal exhibits a high signal-to-noise ratio, enabling direct identification of the maximum corresponding to the most probable energy (MPE), as well as an assessment of the distribution width. The resulting waveform therefore constitutes a direct visualization of the beam energy spectrum under actual operating conditions of the accelerator.

## VI. Determination of the Most Probale Energy (MPE)

As a result of accumulating the signal from the collecting electrode as a function of the scanning current Is , a histogram H(Is) is obtained, representing a discrete mapping of the beam intensity distribution as a function of position and, after appropriate scaling, also as a function of electron energy.

Due to the discrete nature of the measurement data and the presence of statistical fluctuations, direct determination of the most probable energy (MPE) as the position of the maximum histogram bin is associated with uncertainty related to the axis resolution and noise level.

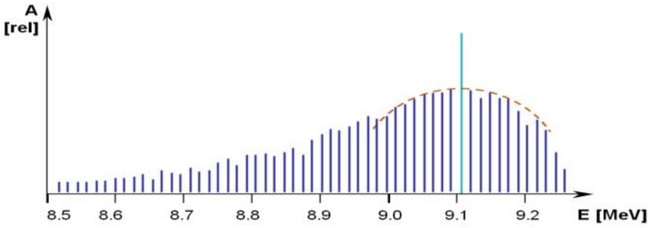

Fig. 5. A reconstructed energy spectrum with marked parabolic approximable region.

To obtain a stable and repeatable estimate of the MPE, a method based on local parabolic approximation of the histogram maximum was applied. This approach relies on the assumption that, in the immediate vicinity of the spectral peak, the intensity distribution can be well approximated by a quadratic function. In practice, the fitting is performed using a limited set of data points comprising several (typically 5–7) consecutive histogram bins around the maximum.

For the selected subset of data, a function of the form:

$$S(E) \approx \ aE^2 + bE + c$$

is fitted, where A(E) denotes the histogram amplitude corresponding to energy E. The most probable energy is then determined as the vertex of the fitted parabola:

$$E_{MPE} = -\frac{b}{2a}$$

This approach enables interpolation of the maximum position with a resolution higher than the width of a single histogram bin, which is particularly important when analyzing MPE variations as a function of RF tuning parameters.

It should be emphasized that the parabolic approximation is applied only within a narrow region around the distribution maximum. The full energy spectrum of electron beams in industrial accelerators is inherently asymmetric and cannot be accurately described by a quadratic function over a wider range. Restricting the fit to the local neighborhood of the maximum prevents systematic errors resulting from this asymmetry.

To improve the stability of the fitting procedure, simple pre-processing techniques such as moving average smoothing with a small window may be applied. However, care must be taken to avoid distortion of the peak shape. Asymmetric smoothing should be avoided, as it may lead to a shift of the maximum.

The proposed method for MPE determination is robust against statistical fluctuations and provides good repeatability, making it suitable for real-time monitoring of accelerator operation. It enables reliable tracking of beam energy variations as a function of time and RF tuning parameters, forming a basis for further analysis and optimization of the irradiation process.

## VII. Uncertainty of MPE determination

The uncertainty in determining the most probable energy (MPE) arises from several factors related both to the nature of the measurement signal and to the adopted data processing method. The main sources of uncertainty include:

- discrete representation of the energy spectrum (finite histogram bin width),
- statistical fluctuations of the signal amplitude from the collecting electrode,
- residual electromagnetic interference after filtering and gating,
- non-linearity of the E(x) mapping resulting from the magnetic field geometry,
- limited accuracy of the scanning current $I_s$ measurement.

When the MPE is determined directly as the position of the maximum histogram bin, the associated uncertainty is on the order of half the bin width. The use of local parabolic approximation significantly reduces this uncertainty by enabling sub-bin interpolation of the maximum. In practice, the accuracy of the MPE determination depends on the signal-to-noise ratio (SNR) and on the number of data points used in the fitting procedure.

For histograms obtained by accumulation of a large number of pulses (typically several thousand), and under stable operating conditions of the accelerator, statistical fluctuations are largely random and become significantly averaged out.

Under such conditions, the uncertainty of MPE determination is dominated by local deviations of data points from the fitted parabola and may be estimated from the fit residuals.

An additional source of systematic uncertainty is the non-linearity of the E(x) relationship, resulting from the actual magnetic field distribution in the region between the pole pieces of the scanning electromagnet. This non-linearity primarily affects the scaling of the energy axis; however, within a limited region around the maximum, its influence on the position of the MPE is relatively small, provided that the mapping remains monotonic.

In a real scanning system, the relationship between beam deflection and electron energy is not perfectly linear due to the magnetic field geometry and the shape of the pole pieces. Since this parameter is not adjustable during accelerator operation, its effect is treated as constant and does not affect the analysis of relative changes in MPE.

In practical applications, the repeatability of the MPE determination and its ability to track changes over time and as a function of RF tuning parameters are of greater importance than absolute accuracy. In this context, the proposed method, based on signal accumulation and local peak approximation, provides high stability and sensitivity, enabling reliable detection of small variations in beam energy.

## VIII. ALTERNATIVE METHOD FOR MPE DETERMINATION

As an alternative to the parabolic approximation, a method for determining the most probable energy based on the local centroid of the histogram in the vicinity of its maximum was applied. In this approach, the value of $E_{MPE}$ is calculated as:

$$E_{MPE} = \frac{\sum E_i A_i}{\sum A_i}$$

where the summation is performed over a limited set of histogram points in the neighborhood of the maximum.

The selection of the summation range is achieved either by applying an amplitude-based criterion (e.g., $A_i > 0.8A_{max}$) or by using a fixed number of bins around the maximum. This approach limits the influence of the overall spectrum asymmetry and ensures that the calculation is restricted to the region representing the local peak of the distribution.

The method does not require fitting of an analytical function and is less sensitive to statistical fluctuations of individual data points, which is particularly important under industrial conditions characterized by the presence of electromagnetic interference. In practice, it has been observed that the local centroid method provides high repeatability of MPE determination and good long-term stability.

## IX. RESULTS AND APPLICATION

The proposed method was applied to monitor the operation of an industrial electron accelerator under normal operating conditions. In particular, variations of the most probable energy (MPE) were analyzed as a function of time and RF tuning parameters.

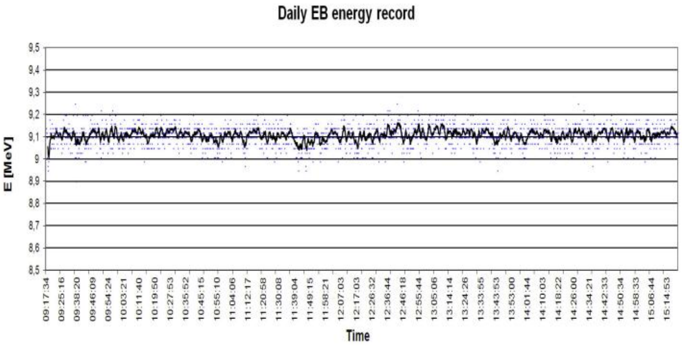

Fig. 6. Daily record of MPE at linac working in routine operational conditions.

Figure 6 presents the long-term behavior of the MPE recorded during accelerator operation. A clear variation of the beam energy over time is observed, resulting from instabilities in the operating conditions, such as magnetron frequency drift and changes in the resonant conditions of the accelerating structure.

The obtained results confirm that, under industrial conditions, the beam energy is not constant and undergoes fluctuations that may significantly affect the irradiation process.

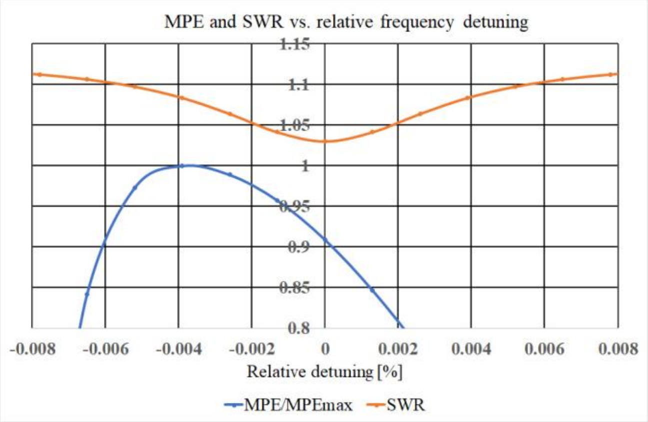

Fig. 6. Dependence of MPE and SWR on relative frequency detuning.

In the next step, the dependence of MPE on the magnetron operating frequency was analyzed. Figure 6 shows a comparison of the MPE(f) and standing wave ratio SWR(f) characteristics. This comparison demonstrates that the frequency corresponding to the maximum beam energy does not coincide with the frequency of minimum SWR. This indicates that optimal RF matching does not necessarily correspond to maximum energy transfer to the electron beam.

This result has direct practical significance, as it shows that RF parameters such as SWR or reflected power cannot be treated as sufficient criteria for optimization of accelerator operation from the perspective of the irradiation process. In contrast, the MPE provides a direct measure of the effective beam energy and can be used as a control parameter during tuning of the system [3].

From the operator’s point of view, the MPE(f) dependence provides a simple and unambiguous optimization criterion: the maximum of this function corresponds to operating conditions ensuring the most efficient acceleration of electrons. In practice, this enables real-time adjustment of the magnetron frequency to compensate for thermal drifts and maintain stable beam parameters.

## X. CONCLUSIONS

A method enabling non-invasive, continuous measurement of the most probable energy (MPE) of an electron beam in an industrial linear accelerator during normal operation has been presented. The method is based on the use of beam energy dispersion in a scanning magnetic field and local detection of beam intensity using a collecting electrode.

It has been demonstrated that, despite challenging measurement conditions associated with strong electromagnetic interference and the pulsed nature of accelerator operation, reliable information on the beam energy spectrum can be obtained by applying signal accumulation and time-domain selection, with the electrode activated only within the beam pulse window. Short-circuiting the electrode to ground outside this window significantly reduces the influence of interference and improves the signal-to-noise ratio.

Two methods for MPE determination were proposed: local parabolic approximation and a local centroid-based approach. It has been shown that, under industrial conditions, the centroid method exhibits greater robustness against signal fluctuations and provides higher repeatability, making it particularly suitable for operational applications.

The results of long-term measurements confirmed that the electron beam energy undergoes significant variations over time due to instabilities in the RF system. Furthermore, analysis of the MPE(f) dependence demonstrated that the frequency corresponding to maximum beam energy does not coincide with the frequency of minimum standing wave ratio (SWR). This indicates that conventional RF parameters do not constitute sufficient criteria for optimization of accelerator operation from the perspective of the irradiation process.

From an industrial application standpoint, a key advantage of the proposed method is its ability to directly monitor a parameter with clear operational relevance. The MPE can be used as a tuning criterion for RF systems and for real-time assessment of accelerator performance, enabling improved process stability and efficiency.

The presented approach complements standard dosimetric methods, which provide information on absorbed dose but do not allow direct, real-time assessment of beam energy. In this sense, the proposed method may be regarded as a tool bridging beam physics diagnostics with quality control requirements in radiation sterilization processes.

## REFERENCES

[1.] ISO/ASTM Standard,” Standards on Dosimetry for Radiation Processing. American Society for Testing and Material” International, West Conshohocken, PA, USA. 51649 2015(E)

[2.] Zbigniew Zimek, „Dozymetria wiązki elektronów. Pomiary elektryczne”, *Centrum Informatyki Energetyki*, Warszawa, 1989.

[3.] Lazurik, V.T., Lazurik, V.M., Popov, G.F., Rogov, Yu., Zimek, Z.”Information System and Software for Quality Control of Radiation 441 Processing”, IAEA: Warsaw, Poland 2011.