Energy Monitoring Device for Electron Beam Facilities

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Abstract. An easy-to-use and robust energy monitoring device has been developed for reliable detection of day-to-day small variations in the electron beam energy, a critical parameter for quality control and quality assurance in industrial radiation processing. It has potential for using on-line, thus providing real-time information. Its working principle is based on the measurement of currents, or charges, collected by two aluminium absorbers of specific thicknesses (dependent on the beam energy), insulated from each other and positioned within a Faraday cup-style aluminium cage connected to the ground. The device has been extensively tested in the energy range of 4 - 12 MeV under standard laboratory conditions at Institute of Isotopes and CNR-ISOF using different types of electron accelerators; namely, a TESLA LPR-4 LINAC (3 to 6 MeV) and a L-band Vickers LINAC (7 to 12 MeV), respectively. This device has been also tested in high power electron beam radiation processing facilities, one equipped with a 7-MeV LUE-8 linear accelerator used for crosslinking of cables and medical device sterilization, and the other one equipped with a 10-MeV Rhodotron TT100 recirculating accelerator used for in-house sterilization of medical devices. In the present work, we have extended the application of this method to still lower energy region, i.e. from 1.5 to 2.4 MeV. Also, we show that such a device is capable of detecting deviation in the beam energy as small as 40 keV.

1. Introduction

Reliable measurement of the electron beam energy is one of the critical actions scheduled by standard procedures for quality assurance and quality control in commercial radiation processing [1, 2]. These procedures require that the beam energy be determined during the facility qualification and be monitored and controlled during routine irradiation, since it determines the size of the product box that can be processed and a variation of the energy affects the dose uniformity ratio (maximum absorbed dose over the minimum absorbed dose) in the product box, especially in the two-sided irradiation process. Amongst various possible methods for measuring the electron beam energy, the study of the dose distribution with depth in a homogeneous reference material, using a wedge or a stack geometry [1] is the widely used technique.

Another possible method, which is the subject of this work, is the study of the influence of the electron beam energy on the charge distribution with depth in homogeneous absorbers. In previous works we have reported the results obtained in laboratory facilities equipped with electron beams of the energy range 7-12 MeV [3], the extension of this method to the energy range 4-6 MeV [4] and its possible use in industrial facilities [5].

The advantage of this method is that it could be used almost on-line, providing real-time information on very small variations in the electron beam energy; thus, this device is a very useful tool for monitoring the beam energy during the process.

In the present work we describe extension of the method to a lower energy region, namely, from 1.5 to 2.4 MeV, together with tests on the sensitivity performances of the energy monitoring device.

2. Experimental

2.1. Irradiation source

Irradiations were carried out at Aérial (Strasbourg) with a Van De Graaff electron accelerator, which produces a continuous electron beam with tunable energy in the range of 0.5 - 2.4 MeV and adjustable current from 1 to 125 μA. The energy of the electron beam was varied by controlling the accelerating voltage, whose value was calibrated during the facility installation using the technique of foil activation [6]. The nominal electron current was measured with a Faraday cup integrated in the accelerator control system. Static irradiations and dynamic irradiations, using the actual conveyor system, were carried out, as described later in this paper.

2.2. Energy monitoring device

The basic module of the energy monitoring device consists of a robust Faraday cup-style aluminium cage containing two aluminium plates of appropriate thicknesses, insulated from each other (Fig. 1). The thickness of the front plate was selected according to the energy range to be monitored, since the shape of the charge distribution with depth varies with the beam energy ([3] and references therein reported). Total thickness of the two plates was sufficient to stop all the electrons at the maximum beam energy. The plate thicknesses adopted for the different energy ranges are reported in Table I. The back plate was 25 mm thick for all electron beam energies investigated. The diameter of the two plates as well as of the opening in the cage was 100 mm. Also, there was an air gap of at least 5 mm between the plates and between the plates and the sides of the cage, sufficient to avoid discharges and to assure the electrical insulation of all of the three elements. The plates were supported by ceramic pillars and connected to the measuring instruments, located in the accelerator control room, using BNC connectors and coaxial cables with characteristic impedance of 50 Ohm. The aluminium cage was grounded by a copper braided wire to the metallic frame of the accelerator facility in order to avoid the build-up of any electric potential around the plates, generated by the accumulated electrons from the beam. When the device is exposed to the electron beam, electrons are accumulated in the two plates and the currents generated are measured continuously. For specific thicknesses of the two plates, the values of these currents depend on the beam current and beam energy [3].

TABLE I: THICKNESS OF THE FRONT ABSORBER PLATE APPROPRIATE FOR THE DIFFERENT ENERGY RANGES.

Energy range to be monitored MeV	**Thickness of the front plate mm of Al**	**Reference**
7 – 12	12	[3]
4 - 6	5	[4]
1.5 - 2.4	2	This work

The energy device was located under the beam exit window on one of the product conveyors. The conveyor system was not in operation in order to realize irradiation in static condition, because of the presence of the two coaxial cables connected to the device. As the beam was not scanned, the exact position of the device under the beam was determined by using radiation sensitive indicators. The beam spot was small compared to the plate size and the beam was completely intercepted by the plates. The accelerator was operated with several different energy and current values, as follows:

- for establishing the relation between the beam energy and the device response: nominal current was varied from 25 μA to 100 μA in 4 steps (25, 50, 75 and 100 μA), for each of the six nominal energy values: 1.50, 1.65, 1.80, 2.00, 2.20, 2.40 MeV; four measurements of the plate currents were made for each combination of beam current and energy; these measurements were done with an electrometer;
- for determining the sensitivity of the system: electron beam energy was varied in steps of 20 keV, namely at 2.16, 2.18, 2.20, 2.22, 2.24 MeV at a fixed current (50 μA); four measurements of the plate currents were made at each beam energy; these measurements were done using an electrometer as well as a multimeter.

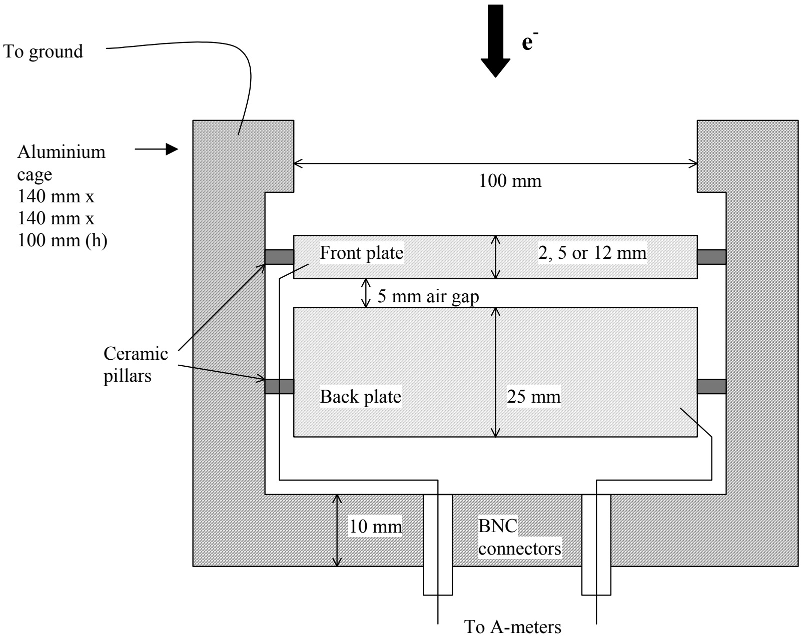

FIG. 1. Cross sectional view of the energy monitoring device: the thickness of the front plate is determined according to the range of the electron beam energy to be monitored.

2.3. Electrical measurements

The electrons accumulated in the plates give an electrical signal that can be directly measured as collected current or can be integrated over a known period of time and be measured as collected charge.

Several techniques were used for the measurement of the electrical signals. In our first work [3] two identical digital current integrators (EG&G ORTEC 439) were used, since it was possible to select the number of electron pulses incident on the device, resulting in a fixed integration time for the collected current. In our second work [4], a dedicated measuring instrument was realized using an integrated circuit, with ultra low bias and fast slew rate, selected so that its offset voltage and its temperature drift were as low as possible, hardwired in the current amplifier configuration. For the investigation at the industrial facilities [5], both the ORTEC digital current integrators used as current monitor, and the above mentioned dedicated circuit with a modified constant time in order to measure signals generated by electron pulses delivered at low frequency (5 Hz), were used.

In the present work, a sensitive electrometer (Model 610B from Keithley) capable of measuring currents down to 10^{-14} A, and a regular multimeter (ITT Metrix MX512) were used for the measurement of the currents collected by the two absorber plates. The accuracy of the electrometer had been previously checked with a Waveteck Model 9000 meter calibration system. The signals were measured sequentially, connecting one plate to the instrument and the other one to the ground, in order to avoid the build-up of any electrical field induced by the electrons accumulated in the plate not under measurement.

2.4. Beam energy determination

The most probable electron beam energy E_p was determined from the depth-dose distribution, obtained using the stack technique [1]. The stack consisted of several Polystyrene (PS) plates (each having dimensions of 4 cm by 4 cm and 1 mm in thickness) with B3 radiochromic dosimeter films [7] in between them, which was then irradiated at different beam energies. The irradiated dosimeters were then read with AerODE (Aérial Optical Dosimetry Equipment) and the changes in the optical density were related to the absorbed dose to water according to the calibration curve, which was obtained earlier by irradiating B3 dosimeters together with alanine pellet dosimeters [8] in suitable calibration phantoms. The irradiations of the stacks for the E_p measurements were carried out placing them on one of the conveyors and following the normal operating procedure: the electron beam was scanned over the entire conveyor width and the conveyors were moving below the electron exit window. For all of the irradiations, the speed of the conveyor and the electron beam current were selected in order to deliver a target dose of about 10 kGy in water.

3. Results and discussion

The nominal beam energy values selected by the control of the accelerator and the measured E_p values were quite similar as shown by the data reported in Table II. This confirmed the validity of the calibration of the control system carried out during the facility installation. Based on this, the value of the accelerating voltage (i.e. the nominal electron beam energy) was used as the reference value for the evaluation of the response of the energy monitoring device.

TABLE II: MOST PROBABLE ELECTRON BEAM ENERGY DETERMINATION FROM THE DEPTH-DOSE DISTRIBUTIONS IN POLYSTYRENE (PS).

Nominal electron beam energy MeV	**Practical electron beam range in cm, measured in PS ($\rho = 1.06$ g·cm^{-3})**	**Practical electron beam range in cm, scaled to water ($\rho = 1$ g·cm^{-3})**	**Calculated most probable energy E_p MeV**
1.5	0.62	0.64	1.5
2.0	0.86	0.88	2.0
2.4	1.08	1.11	2.4

The formulas used are reported in [1] and the continuous slowing down approximation ranges in [9].

The currents, measured from the two absorber plates, were used to define a quantity, called "energy ratio" (E.R.):

$$\text{E.R.} = \frac{I_1}{I_1 + I_2};$$

where, I_1 is the current from the front plate and I_2 is the current from the back plate.

Figure 2. shows the relationship of the values of E.R. with the values of the electron beam energy.

Figure 3. shows the data obtained from the measurements carried out by varying the beam energy in steps of 20 keV. The figure reports both the measurements, those obtained using the multimeter as well as the electrometer.

Figure 2. clearly shows that a properly calibrated energy monitoring device, with a 2 mm front absorber plate, is able to verify beam energy as well as to monitor energy variations in the range of 1.5 - 2.4 MeV with a good reproducibility and a good sensitivity; as demonstrated by Fig. 3., energy variations of 40 keV are well discriminated.

Figure 3. also shows that the value of E.R. is different when obtained using the multimeter, because of the presence of a voltage drop, caused by the current flowing through the shunt resistance and through the fuse of the multimeter itself. As electron beam energy increases, I_1 decreases; this results in loss of sensitivity for the multimeter at higher energies. Thus, E.R. measured with a multimeter is not sensitive to the energy variations at energies higher than 2.2 MeV.

A specifically designed energy monitoring device, equipped with a dedicated instrument with two input lines for the simultaneous measurement of the currents from both the plates, is planned to be installed in the Aérial irradiation facility for on-line verification of the electron beam energy.

4. Conclusion

The energy monitoring device with a 2 mm front absorber plate is able to monitor variations in the electron beam energy as well to verify its value in the range of 1.5 - 2.4 MeV with a sensitivity of at least 40 keV.

The robustness of the device and its immediate response suggest that it could easily be integrated in the control system of an electron beam irradiation facility; the range of possible beam energy can be easily accommodated by properly selecting the thickness of the two absorber plates.

It is demonstrated that a variety of techniques can be adopted to measure the currents generated by accumulated electrons in the absorber plate. However, for accurate measurements, either an electrometer or a dedicated circuit is needed, since they use the current amplifier configuration (thus avoiding voltage drops that could influence the measurement). A simple multimeter, which measures the voltage drop across a known shunt resistance, is not adequate for measuring low currents.

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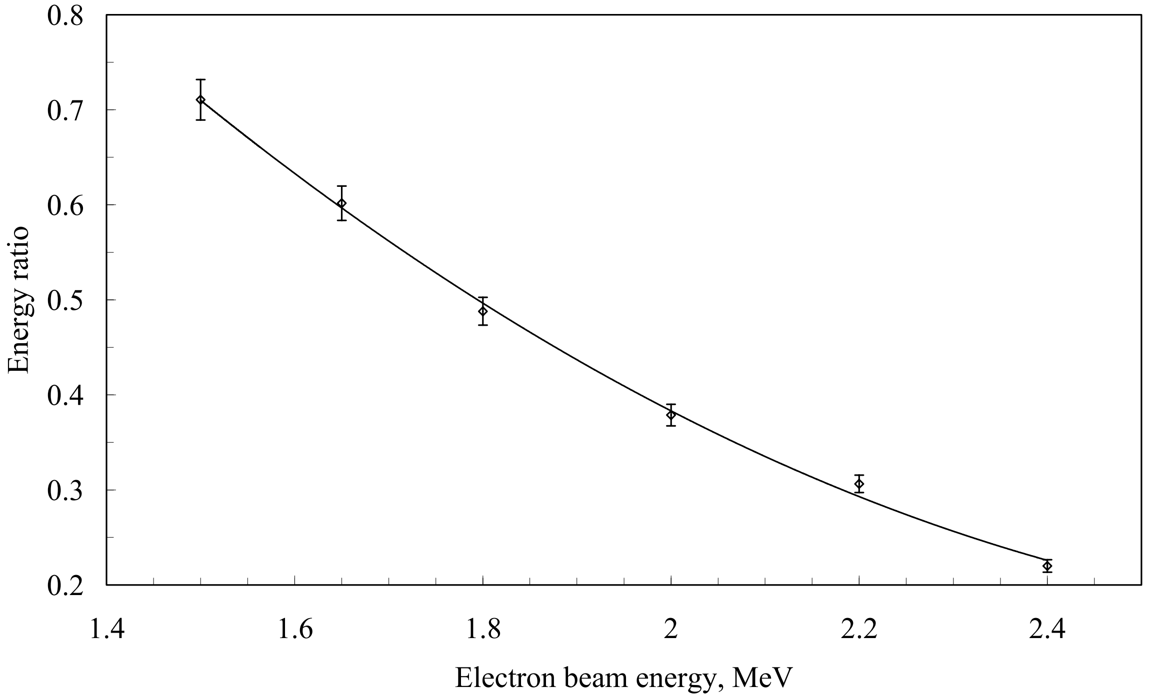

FIG. 2. Response of the energy monitoring device using the electrometer (averages and 1 standard deviation, ±3%).

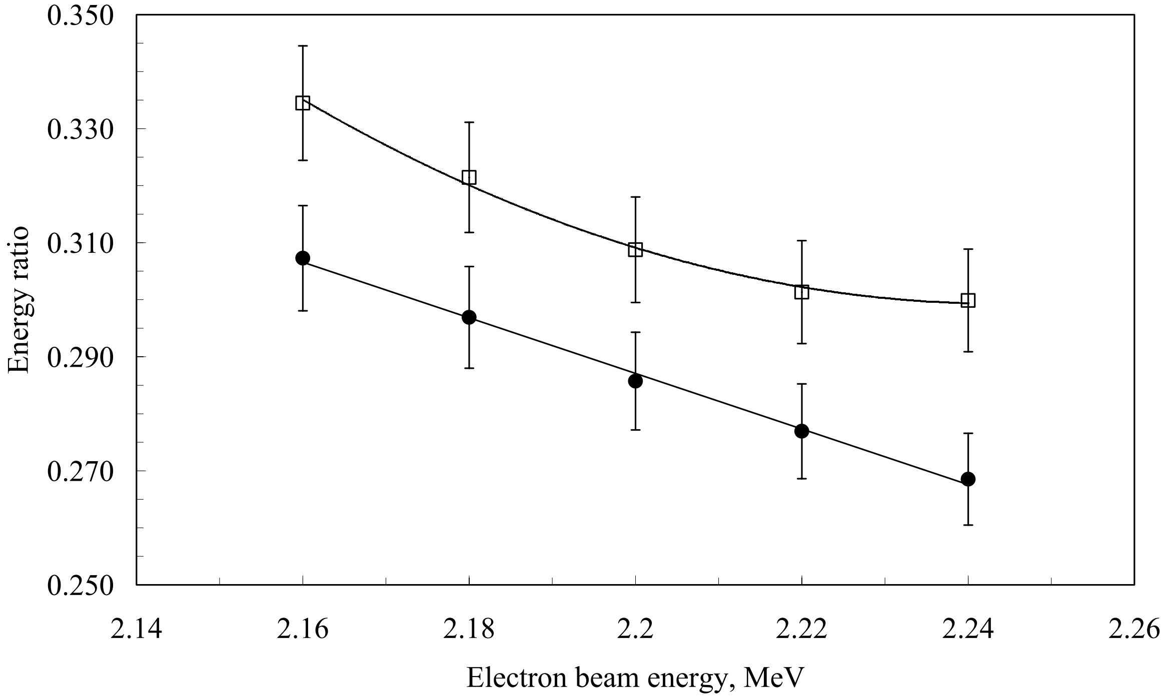

FIG. 3. Test of the sensitivity of the energy monitoring device; measurements with electrometer (•) and multimeter (□) (averages and 1 standard deviation, ±3%).

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