Energy depth distribution of pulsed electron beam with wide electron kinetic energy spectrum for an aluminum target

A Poloskov, M Serebrennikov, A Isemberlinova and I Egorov

National Research Tomsk Polytechnic University, 30 Lenin Ave., Tomsk, 634050, Russia

E-mail: poloskovav@tpu.ru

Abstract. Knowledges of pulsed electron beam characteristics is necessary for use it for scientific and practice applications. Current work analyses the pulsed electron beam extracted from the vacuum diode through a titanium foil (60 mkm) of the diode exit window. Electron beam energy depth distribution was measured for a target made of different number of aluminum foils. A pulsed electron beam with a wide range of kinetic energies was generated by the ASTRA-M accelerator (260 kV of accelerating voltage, up to 1 kA of beam current, 150 ns of beam pulse duration at FWHM). A calorimeter of total absorption and Faraday cup were used to measure beam characteristics. Calorimeter included two collectors: first one measures a beam energy after aluminum foils, and the second one measures a total beam energy. All measurements were performed at 10^{-5} Torr background pressure after the exit window foil. As a result, the electron kinetic energy spectrum of the beam out of diode has been reconstructed.

1. Introduction

An electron beam is a widely used instrument to solve scientific and industrial problems [1–5]. For successful application of this high-tech tool it is necessary to know its characteristics such as linear energy losses in matter and cross-section energy distribution. At the moment, most of industrial and medicine electron beam sources use well – studied continuous accelerators [6–12] with monoenergetic electron beams. Continuous accelerators have large-size insulation structures and are expensive for manufacturing. At the same time, pulsed electron accelerators for the same voltage level can be built more compact and cheaper [13–14]. Pulsed accelerators based on transformer as a rule produce beams with a wide energy spectrum of electrons, thus the depth distribution of the absorbed dose for such pulsed beams is significantly different from monoenergetic beams [15]. The electron energy spectrum dependent depth energy distribution determines the scope of the electron beam. For electron beams with kinetic energy of electrons less than 500 keV a penetration depth into a substance, for example, in water, is less than 2 mm. Specific diode systems are used to increase the thickness of the irradiated layer of the object with a uniform distribution of the absorbed dose over the thickness of the layer on both sides of the object [16]. Current article describes a method for estimating energy depth distribution of pulsed electron beam with wide electron kinetic energy spectrum for an aluminum target. The method improves techniques have been described in the following papers [17–19].

2. Experimental Setup

A pulsed electron beam with a wide range of kinetic energies was generated by the ASTRA-M accelerator (260 kV of accelerating voltage, up to 1 kA of beam current, 150 ns of beam pulse duration at FWHM) [13]. The method of cut-off foils with help of improved Faraday cup and calorimeter was used to measure beam characteristics. A distribution of electron beam current, energy and dose in cross section were measured without and with number of extra aluminum foils. Aluminum targets 30 mm in diameter was used as a filter for a central area of the beam [18]. We varied a target thickness from 40 μm to 290 μm, with a mistake of less 10 μm. The calculation of electron energy spectrum was made with help of open access database of electrons ranges [6]. A distance between the aluminum target and collectors of the Faraday cup and the calorimeter was 4 mm. Diameter of all collectors were 70 mm. All studies were performed under high vacuum conditions 10^{-5}Torr.

2.1. Faraday cup

The Faraday cup load (figure 1) was made of low-inductance resistors connected in parallel, with a total resistance of 23 mΩ, (measurement error 27 μΩ). Radio sensitive film (POR) was located along the entire length of the collector to measure dose distribution in cross section [20]. This film was used only as an electron beam indicator. Faraday cup signals were collected to average values from series of 16 pulses for statistical decreasing of the mistake in electron beam parameters.

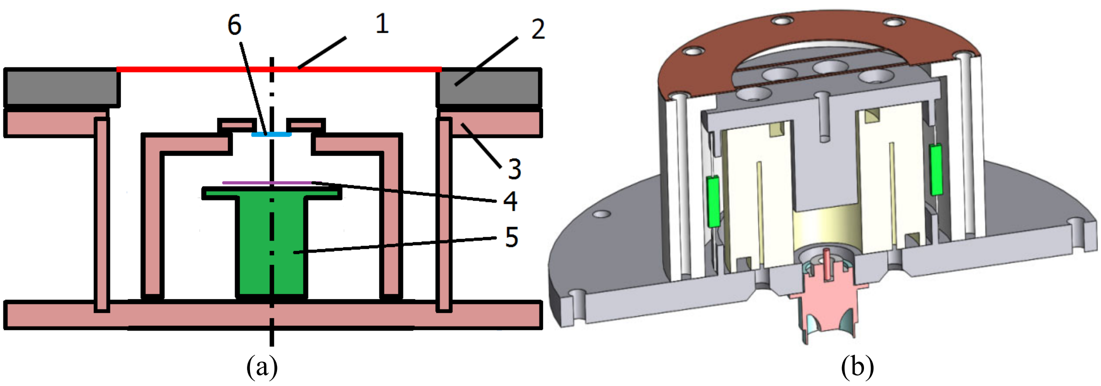

Figure 1. Experimental setup with Faraday cup (a): exit window membrane (Ti 60 μm) (1); exit window flange (2); chamber of the Faraday cup (3); radio sensitive film POR (4); Faraday cup collector (5); aluminum foils of various thickness (6). Faraday cup design (b).

2.2. Calorimeter

The calorimeter used 2 copper collectors of 300±10 mkm thickness (figure 2). The first collector (12.5±0.1 g) records the beam energy after the aluminum target. The second collector (33±0.1 g) registers the beam energy of the remaining part of the beam – to monitor stability of a beam parameters from pulse to pulse. The collectors were insulated from the vacuum chamber potential with plexiglass stands. Temperature measurement was performed using thermocouple sensors with a measurement inaccuracy of 0.1°C in the used range.

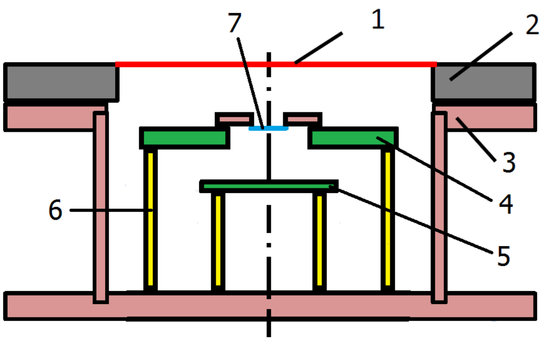

Figure 2. Experimental setup with calorimeter: exit window membrane (Ti 60 mkm) (1); exit window flange (2); chamber of the calorimeter (3); second collector of calorimeter (4); first collector of calorimeter (5); plexiglass holders (6); Aluminum foil (7).

3. Experimental results

An electron beam current extracted through the exit window was obtained (figure 3) after passing aluminum targets of various thicknesses. This study was conducted for two conditions: with and without titanium foil in the exit window. An amplitude dispersion of voltage and beam current pulses was less than 1% for a series of 16 pulses [21]. The data obtained made it possible to determine the electron spectrum in the beam.

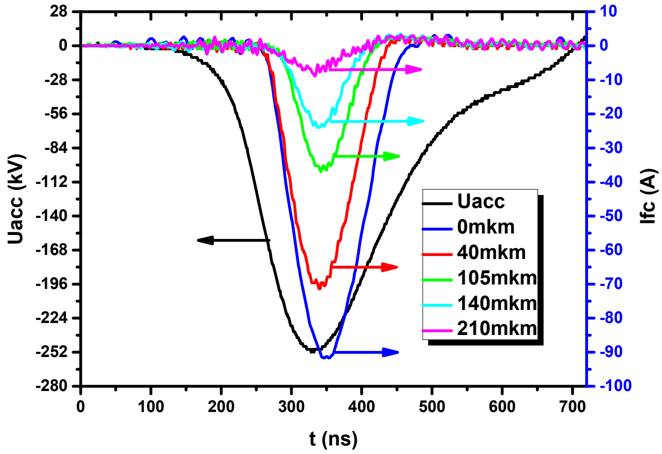

Figure 3. Typical waveforms for accelerating voltage (*Uacc*), current (*Ifc*) from Faraday cup after titanium foil (60 µm).

Analyzing of electron beam imprints showed dose distribution curves in cross section (figure 4) after 5 pulses [22]. The peaks on the dose curves plateau are the shadow of strings bearing the aluminum (figure 1b). Since the dosimetric film shows only the dose that the ionizing radiation left passing through it, and the electrons in our beam have a significant difference in energy, this makes it impossible to calculate the total energy of the beam passing through the target. That's why, in this work, a dosimetric film was used only as an indicator of the presence and dimensions of the beam on surfaces of collectors. And dose distribution in cross section on the surface of the Faraday cup ensures that the diameter of the collectors is sufficient to completely absorb the beam after the aluminum foil.

The calorimetry of the pulsed electron beam is obtained (table 1) after passing of aluminum targets. For a target thickness of 210 µm, the number of pulses in the series has been increased, since they reached the minimum sensitivity threshold of the temperature sensor. Mass measurement error 0.1 mg.

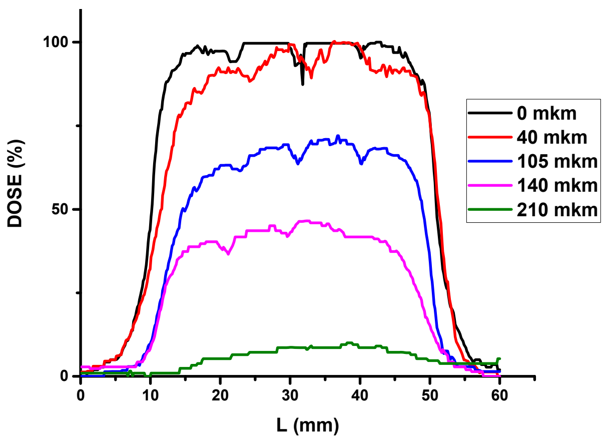

Figure 4. Dose distribution in cross section on the surface of the Faraday cup.

Table 1. Calorimetry after titanium foil.

Aluminum thickness (mkm)	Weight (mg)	Number of pulses	Δ*T*firstcol (°C)	Δ*T*secondcol (°C)	*E*firstcol (J/pulse)
0	0	4	1.5	1.35	1.82
40	76.5	4	1	1.35	1.21
105	199.2	4	0.3	1.25	0.36
140	265.6	4	0.1	1.325	0.12
210	385.8	8	0.2	2.7	0.06

4. Discussion of the results

The experimental data in figure 3 were obtained for the known total thickness of the foils. Stopped electron kinetic energy range was determined from [6]. For a comparative evaluation of the distribution within each range of the kinetic energies of the electrons, the values were expressed in relative units. The results of calculations are presented in figure 5b. The data obtained show that the spectrum of the kinetic electrons in the beam changes after the titanium foil of the exit window. Besides, about 70% of the electrons in the beam have a kinetic energy of 2 times less (130 keV) than at the maximum accelerating voltage (260 kV). In addition, electrons with maximum kinetic energy are distributed in the central region of the beam (figure 4). This situation is significantly different from the characteristics of beams with constant voltage, where the vast majority of electrons have an energy of maximum accelerating voltage [7–12].

Dependences of the beam energy and electron numbers distribution from depth aluminum target on the target thickness were reconstructed with a help of experimental data from table 1. Clearly shown, that about 70% of the electrons in the beam transmits about 80% of the energy of the entire beam to an aluminum target and all this energy is absorbed in half thickness of the electron range for the selected target material. The obtained results not contradict the results described in the literature and indicate the possibility of using an electron beam with such characteristics for surface treatment of materials [15]. There is no doubt, that the electron spectrum is important for irradiating objects and even a decrease of the electron energy sometimes leads to positive results in the processing of biological objects [2].

The described technique with cut-off foils for Faraday cup and calorimeter with two collectors can be used to quite adjust the vacuum diode pulse electron accelerator with wide electron kinetic energy spectrum for the objects processing. The second calorimeter for monitoring changes in beam parameters makes it possible to increase the accuracy of pulsed electron beam measurements.

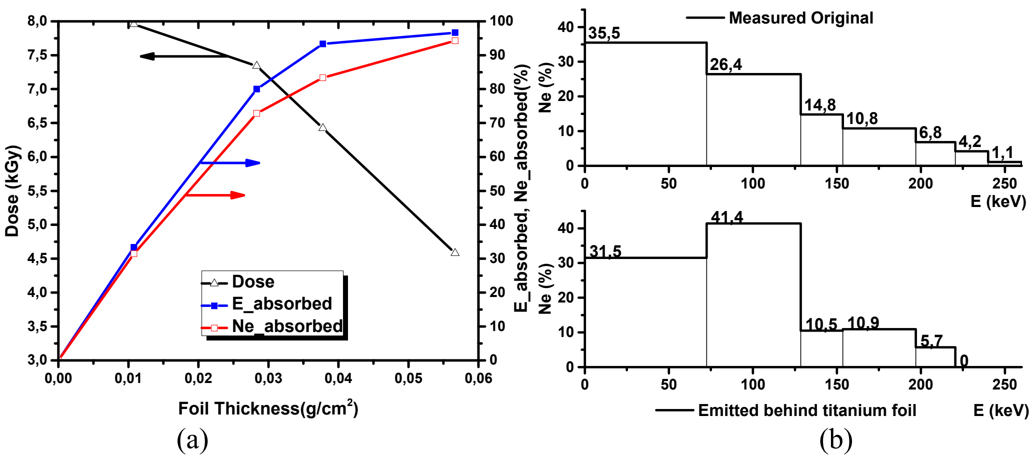

Figure 5. Depth distribution of absorbed dose, beam energy and electron numbers for aluminum target – (a), electron beam energy spectrum before and after titanium foil – (b).

5. Summary

The method of estimating of energy depth distribution for pulsed electron beam with wide electron kinetic energy spectrum is shown in the work. The electron beam (73%) extracted out of the exit window consists of electrons with kinetic energy (130 keV) 2 times less than at the maximum accelerating voltage (260 kV). In addition, this part of the beam transmits about 80% of the energy of the entire beam to an aluminum target. Besides, electrons with maximum kinetic energy are distributed in the central region of the beam. Described results must be taken into account in the scientific and practical applications of the pulsed electron beam with wide electron kinetic energy spectrum.

Acknowledgments

Preparation of the experiments and analysis of the data were supported by RFBR (grant No. 18-32-00184_mol_a). Electron beam irradiation carried out at Tomsk Polytechnic University within the framework of Tomsk Polytechnic University Competitiveness Enhancement Program grant.

References

[1] Kholodnaya G, Sazonov R, Ponomarev D and Guzeeva T 2017 *Radiation Physics and Chemistry* **130** 273
[2] Isemberlinova A, Poloskov A, Egorov I, Kurilova A, Nuzhnyh S and Remnev G 2018 *Key Engineering Materials* **769** KEM 172
[3] Chmielewski A and Haji-Saeid M 2004 *Radiat. Phys. Chem.* **71** 17
[4] Chen Y 2015 *Microelectronic Engineering* **135** 57
[5] Mostovshchikov A V, Ilyin A P and Egorov I S 2018 *Radiation Physics and Chemistry* **153** 156
[6] Berger M, Coursey J, Zucker M and Chang J 2017 *NIST Standard Reference Database* 124
[7] Koivunoro H, Siiskonen T, Kotiluoto P, Auterinen I, Hippeläinen E and Savolainen S 2012 *Medical Physics* **39** 1335
[8] Horita R, Yamamoto S, Yogo K, Hirano Y, Okudaira K, Kawabata F, Nakaya T, Komori M and Oguchi H 2019 *Radiation Measurements* **124** 103
[9] Visbal J, Costa A 2019 *Radiation Physics and Chemistry* **162** 31
[10] Tuan N, Van Tao C, Rangacharyulu C 2019 *Radiation Physics and Chemistry* **163** 22
[11] Kuksanov N *et al* 2012 *Problems of Atomic Science and Technology* **3** 15
[12] Kuksanov N *et al* 2014 *24th Russian Particle Accelerator Conference (RuPAC)* 137
[13] Egorov I, Esipov V, Remnev G, Kaikanov M, Lukonin E and Poloskov A 2012 *IEEE International Power Modulator and High Voltage Conference (IPMHVC)* 716
[14] Sokovnin S and Balezin M 2018 *Radiat. Phys. Chem.* **144** 265
[15] Sokovnin S, Balezin M, Vazirov R, Timoshenkova O, Krivonogova A, Isaeva A and Donnik I 2019 *Radiation Physics and Chemistry* **165** 108398
[16] Kotov Yu, Sokovnin S and Balezin M 2003 *Instruments and Experimental Techniques* **46** 379
[17] Knyazev B, Melnikov P, Nikiforov A and Chikunov V 1993 *Journal of Technical Physics* **63** 179
[18] Egorov I, Serebrennikov M, Poloskov A and Isemberlinova A 2018 *Proc.20th Int. Symp. on High-Current Electronics (ISHCE)* 27
[19] Mesyats G, Yalandin M, Reutova A, Sharypov K, Shpak V and Shunailov S 2012 *Plasma Physics Reports* **38** 29
[20] Poloskov A, Kurilova A, Egorov I and Isemberlinova A 2017 *Proc. 6th International Scientific and Technical Conference. High technology in modern science and technology* 156
[21] Egorov I, Poloskov A, Esipov V and Lukonin E 2015 *Instruments Exp. Tech.* **58** 1
[22] Ezhov V, Goncharov D, Pushkarev A, Remnev G and Mikicha J 2005 *9th Russian-Korean International Symposium on Science and Technology (KORUS)* 139