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Device for estimation of current and energy density distribution in the cross section of a pulsed submicrosecond electron beam

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Abstract. Development stages of sectioned calorimeter system combined with a detector of total electron beam current by Faraday cup for estimating charge and energy distribution of pulsed electron beam are presented. The device design was determined taking into account its use for estimating the parameters of electron beams generated by submicrosecond pulsed accelerators (up to 700 keV, 0.2–10 kA, up to 60 ns at FWHM, 0.05–10 J/cm^2).
Keywords: Electron beam, energy density, beam charge, calorimeter, Faraday cup, electron kinetic energy.

1. Introduction

Electron beams are widely used for surfaces and volumes treatment [1, 2]. A proper application of electron beams requires the high accuracy in beam parameters determination. The key parameters are the energy and current density distribution in the beam cross-section as well as absorbed dose depth distribution in the irradiated object, which depends on the kinetic energy of beam electrons. For one of the quick types of beam energetic properties measurement, full-absorption calorimeters are used. They are based on measuring the calorimeter's working medium (collector) temperature before and after its irradiation with the beam, and calculation of released energy. At the moment, there are several designs of such calorimeters with solid, liquid, and membrane collectors [3–5].

Current shunts and Faraday cups are used to rapidly assess the beam current and charge [6].

Absorbed dose depth distribution is widely studied for monoenergetic beams [7], and there should not be any issues in measuring the depth distribution of absorbed dose at known values of the current and beam energy. However, when studying the composite-spectrum beams that are generated with compact electron accelerators based on pulsed transformer [8], it is crucial to apply such complex equipment and operose methods as the cut-off foil method, spectrometry [9], and others. Nevertheless, the problem could be simply and cheaply managed if the absorbed dose is estimated by the average electron kinetic energy value that can be measured by ratio from calorimeter data – that is a beam energy – and Faraday cups data – that is an amount of electrons.

Current paper is devoted to review papers on developing and modifying a device for measuring the charge and energy distribution in electron beam cross-section and based on a sectioned calorimeter with current detector. An estimation of the average kinetic energy of electrons may be performed by indirect calculations. Sectioned design of the device collector decreases the measurement error while estimating the distribution of energy by electron beam cross-section due to decreasing heat spreading on the device's collector by means of heat conduction.

2. Device development

The calorimeter was developed to measure the parameters of beams generated by a pulsed accelerator (up to 700 keV, 0.2–10 kA, 50–100 cm^2, 0.05–10 J/cm^2). Moreover, special attention has been given to the device's capability to operate under different pressures in measurement chamber. The common requirements to device collector: 1) a target thickness shall be higher than the maximum range of electrons in the target; (2) registration of data shall be performed after the thermal equilibrium has sustained at the both sides of the target; (3) convective heat transfer shall be low; (4) there shall not be thermal ablation.

2.1 Sectioned calorimeter with current detector for studying the properties of electron beams of circular cross section

Paper describe design of a calorimeter with infrared registration of temperature field in sectioned collector, the design is tested with an accelerator described in paper [8]. The modified device design is based on construction from [10]. The device setup is depicted on Fig.1.

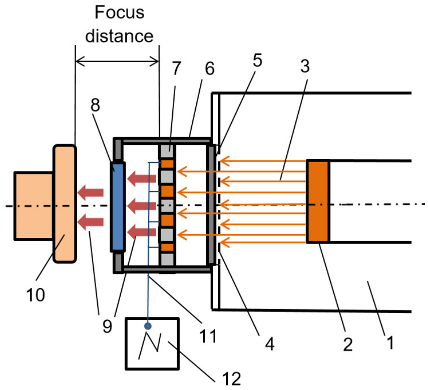

Fig.1. An operation scheme of the device with infrared registration of temperature: *1* – diode chamber; *2* – cathode; *3* – electron beam; *4* – anode grid; *5* – output window; *6* – calorimeter chamber; *7* – developed device; *8* – removable glass window; *9* – thermal radiation; *10* – infrared camera; *11* – conductors; *12* – oscilloscope.

A principle of infrared diagnostics for energy distribution of pulse electron beam by means of sectioned calorimeter is following: an electron beam emitted by the cathode – after the application of accelerating voltage pulse at it – accelerates in anode *4* direction and passes through the output window *5* on the sectioned calorimeter *7*. While subjected to the beam, sections of collector are heated up, then temperature variation is recorded with an infrared (IR) camera [11], and right after that the absorbed energy is calculated. At the same time calorimeter collector has electrical connection *11* to the oscilloscope *12*, thus current and charge can be measured.

Registration with the IR camera is performed after around 2–3 s from the end of irradiation, since it is impossible for the IR camera to operate in strong electromagnetic noise conditions that are created by an accelerator during its operation. Depending on measurement conditions, the calorimeter chamber *6* may provide adjustable pressure. Registration of the calorimeter temperature field by means of IR camera is performed with use of the removable glass window *8* that has high thermal radiation transmission coefficient (e.g., CaF_2 glass). Therefore, a preliminary calibration of IR camera readings is required. A position of calorimeter in chamber can be selected along height.

A layout of device is illustrated in the Fig.2.

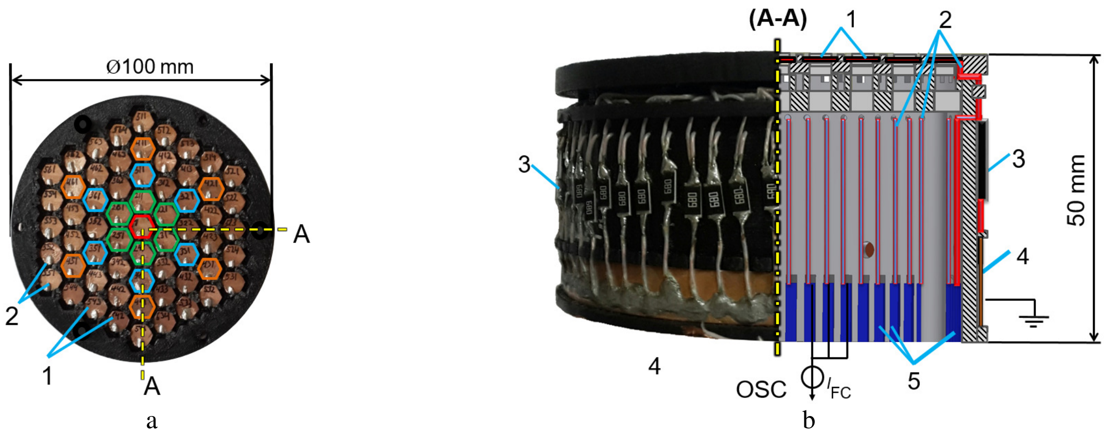

Fig.2. View of the device collector from above (a) and side view with a cut (b): *1* – sections; *2* – insulated wires; *3* – resistors; *4* – ground bus; *5* – pin connectors.

A calorimeter collector is a matrix of 61 heat-insulated hexagonal metal sections *1* with side size of 5 mm that are built in an ABS-plastic frame [12]. The material is easy-to-treat (e.g. 3D-printing) and possesses such properties as low thermal conductivity. The area of collector filled by section is 70%. In view of the thermal conductivity, heat capacity, and ablation threshold, a chosen cell material is a copper alloy M1. The section thickness of 1 mm provides full absorption of electrons with energies up to 1.9 MeV [7], that is more than enough under the device operation conditions on TPU accelerators. The temperature field inside the sections was simulated with Quick Field software and it was found that after 15 ms, temperature difference between the sides was less than 1% as a result of one irradiation pulse.

The electrical 0.12-mm^2 insulated wire connection *2* of each section *1* through SMD2512 68 Ohm resistors *3* with a common ground bus *4* and the output of a separate pin-connector *5* of each section *1* for connection to the oscilloscope (as shown in Fig.2b) provides beam current and charge registration. By the voltage on the resistor when the beam electrons fall on the collector section *2*, it is possible to evaluate what current and charge each section received. Thus, the collector of the sectioned calorimeter is at the same time the collector of the sectioned Faraday cup (FC).

Fig.3 shows examples of the calorimeter collector thermogram (a) and a calculation of the main beam parameters (b) for a limited number of characteristic sections (color-coded in Fig.2a and Fig.3a). The logic of the characteristic sections choice is explained by the assumption of the beam geometric size and the energy distribution profile in the beam cross section based on the results of previous studies, as well as the use of one oscilloscope, which allows taking an analog signal from a maximum of 4 sections. For this reason, to cover the entire circumference of the beam profile, 6 experiments were made, in each 4 sections were connected. To reduce the influence of random fluctuations of the beam parameters in each experiment, the readings were averaged over 16 measurements.

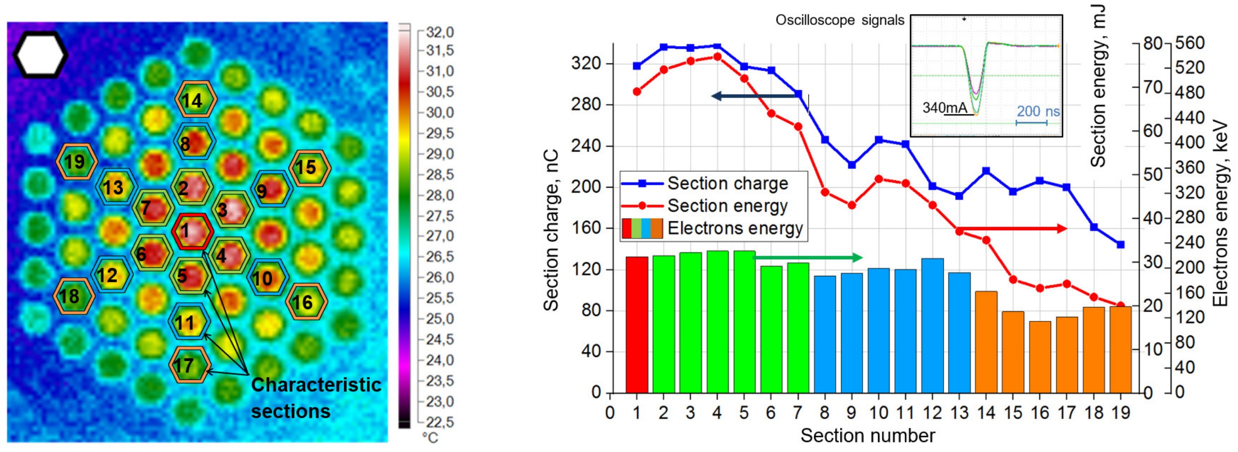

Fig.3. A typical thermogram of the calorimeter collector after beam irradiation (a) and an example of the calculated beam parameters per pulse: section charge, section absorbed energy and average kinetic energy of electrons on each section (b). In addition, a typical signal from an oscilloscope for 4 sections is shown. The color designation on the electron average kinetic energy histogram corresponds to the designation of the characteristic sections.

According to the measured values of the charge $q = \int I \cdot dt$ (ie the number of electrons) and the energy released in the sections, it is possible to estimate the average kinetic energy of electrons (185 keV here). Thus, this device makes it possible to quickly estimate the main parameters of the beam. In a particular example, the decrease in the value of the energy and charge of the beam from the center to the periphery of the beam is clearly seen. The spread of instrument readings was within 10%.

For working temperature range of 20–40 °C, the calculation of energy losses by infrared radiation was conducted with Stefan-Boltzmann equation and it is around 10^{-4} %. Energy losses on beam energy conversion into bremsstrahlung is around 1–2% for beams with kinetic energy less than 1 MeV [13]. Convective heat transfer was not taken into account for experiments under vacuum, because the air pressure in vacuum chamber is rather low (around 10^{-2} Pa). For experiments under atmosphere, it is shown that an estimation of beam energy distribution may be performed with an accuracy around 10% in interval up to 10 s since the calorimeter irradiation end [10].

The developed sectioned calorimeter with current detector has demonstrated such advantages as simple and understandable design, low manufacturing cost, affordable precision of atmospheric measurements, accessibility of measurements with 10% accuracy. System makes it possible to evaluate the energy and charge distribution for round profile beams in interval during the 10 s right after irradiation. However, the use of an infrared camera and an oscilloscope in this technique still limits the convenience and speed of data processing.

2.2 A calorimetric system for charge and kinetic energy characterizations of pulsed electron beams

In order to increase the accuracy of the device, as well as the convenience of its use, an original design was developed and created in [14], shown in Fig.5.

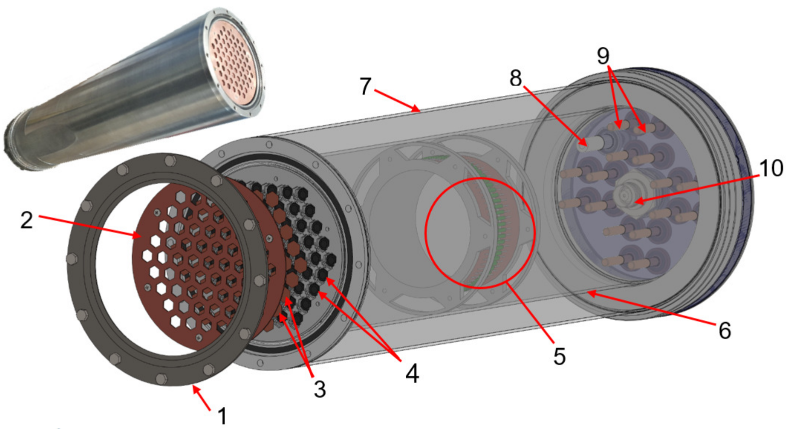

Fig.4. Appearance and model of the device without electrical connections: *1* – mounting flange; *2* – protective shield; *3* – sections; *4* – pyrometers; *5* – low-resistance shunt; *6* – internal case; *7* – external case; *8* – pump connector; *9* – pyrometer connector; *10* – shunt connector.

The collector of the device is based on the design of the previous version of the device: 61 hexagonal copper sections *3* 0.5 mm thick are fixed in the plastic shell. Each section has a separate insulated electrical connection with a common 23 mΩ shunt *5*, which is used to measure the total beam charge using an oscilloscope. FC shunt *5* is made of parallel low-inductance graphite resistors in ceramic cases. A 61 calibrated non-contact pyrometers MXL90614ESF-DCI *4* [15] are used to measure the temperature of each section *3*. Each pyrometer is installed in a plastic shell at a focal distance from the section. The pyrometer *4* matrix is controlled from a PC through 4 ATmega328 controllers using the I2C protocol. Temperature measurement can be carried out in real time with a polling rate of 40 Hz. A protective shield *2* is installed to protect the pyrometers *4* and the plastic shell from the electron beam impact. The entire assembly is placed in a cylindrical metal case *6* with a diameter of 129 mm. The second case with a diameter of 168 mm is used for vacuum pumping and electromagnetic noise protection: a thin cut-off membrane can be installed in front of the protective screen *2*, previously fixed by a flange *1*. The design makes it possible to measure the beam parameters during irradiation of various gas mixtures without these mixtures entering/influencing the calorimeter components

An example of measurements by the device is shown in Fig.5.

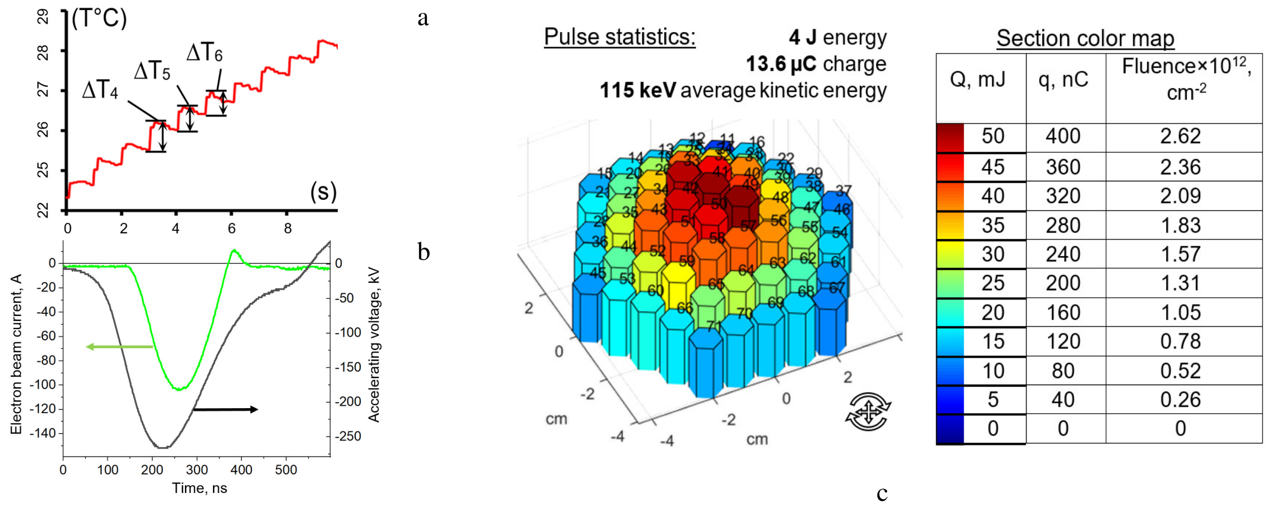

Fig.5. Recorded temperature-time chart for central section (a) in a sequence of pulses with a repetition rate of 1 pps, beam accelerating voltage and current signal from sectioned collector (b), distribution of beam energy *Q*, charge *q*, and fluence across the calorimeter's collector (c). The numbering of sections from 11 to 71 is explained by the specificity of hardware and software [15].

Control from a computer is carried out using the developed Matlab script. The developed software makes it possible to build a three-dimensional histogram to visualize the distribution of the received energy over the collector (Fig.5). Using the measured value of the total beam energy equal to 4 J/pulse and the transferred charge of 13.6 μC/pulse, it is possible to estimate the average value of the electron kinetic energy equal to 115 keV. The charge distribution over the beam cross section can be evaluated as a proportion to energy distribution under the assumption of the monoenergetic beam spectrum (Fig.5c). The described study illustrates a general technique of rapid estimation of the average beam electrons kinetic energy using the presented device concept. The average kinetic energy of electrons in the beam makes it possible to estimate the dose distribution over depth for an irradiated object with a known density and dose absorbed in the treated area. Such indicators are significant for applications of electron beams for the influence on the irradiation results.

The standard deviation of parameters values measured by the device was within 10%.

Automation of the process of calculating the energy absorbed by the sections greatly simplifies the data processing process. This configuration allows estimating the energy and charge density. The design of the device enables the estimation of the average electrons kinetic energy of pulsed electron beam up to 700 keV, energy density up to 3.6 J/cm^2, total beam energy up to 50 J per pulse, and a beam diameter of up to 10 cm in one measuring procedure. The fundamental limitation should be considered the measurement of high energy density beams that can cause ablation of the collector material.

3. Conclusion

The developed sectioned calorimetric system provides automatic measurement, data storage and signal processing for monitoring and recording the energy density, calculation of the electron beam charge in one measurement iteration. The set of recorded characteristics makes it possible to estimate the average kinetic energy of electrons. The design of the calorimeter and the measurement procedure can be reproduced in a wide range of geometric and energetic characteristics of the electron beam.

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