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Sectioned calorimeter for quick diagnostic of the electron beam energy distribution

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A B S T R A C T

This article presents a description of the principle, design and results of a calorimeter intended for recording the beam parameters of a pulsed electron accelerator. The collector of the calorimeter with a diameter of 100 mm has 61 separate sections. The sections are fixed in the base made of a material with low thermal conductivity. The temperature of each section was determined by analyzing the thermal image of the collector with an IR camera. The thickness and mass of the sections are designed for beams with the kinetic energy of electrons up to 700 keV at the energy density of up to 3 J/cm^2. The calorimeter was tested on a pulsed electron accelerator "ASTRA-M" (450 kV, 1 kA, beam current duration 150 ns). When the electron beam was injected into the atmosphere, the accuracy of the measurements was reduced by 10%. The measurement for 10 s after a series of beam pulses did not lead to a significant variation in the results. The calorimeter is suitable for rapid evaluation of the beam energy distribution profiles when the beam is injected into the atmosphere without depressurizing the vacuum volume of the electron diode.

1. Introduction

Practical applications of electron beams [1,2] require information about the spatial (geometric) characteristics of the beam. One of the most important characteristics is the energy density J/cm^2 which the electron beam carries. The dose that the irradiated object receives directly depends on the energy density. The magnitude and homogeneity of the energy density over the irradiation cross section, ultimately, determine the productivity and quality of electron beam processing [3–5]. Traditionally a full-absorption calorimeter is used to measure the energy density in the cross section of an electron beam [6]. The principle of the calorimeter is to record the change in temperature of the collector which completely absorbs the energy of the beam, while the mass and heat capacity of the material of the collector are known in advance. A common method of recording the temperature of the collector in the calorimeter is to use a measuring circuit based on a thermo-resistor or thermocouple [4,7].

When it is required to measure the beam energy for different cross sections the volumetric calorimeters [3,8] and calorimeters with divided (sectioned) collectors are used. Parts of the collector in such designs have separate sensors for measuring the temperature [9]. Making a calorimeter with many parallel channels brings additional difficulties in recording and interpreting the results.

This approach becomes expensive, time-consuming and inconvenient in the diagnosis of the beams with a large cross section and a high spatial resolution, i.e., 1 cm^2 for a beam cross-sectional area of $\sim$ 100 cm^2.

To estimate the energy distribution of an ion beam over the cross section, a technique using the thermal imaging method for recording the collector temperature was developed [10]. To increase the accuracy, metal foils with relatively low thermal conductivity (for example, stainless steel) were used as a target intercepting the beam. The surface of the target facing the thermal imager was covered with a matte black paint to increase its emissivity up to 0.8–0.9. Due to the small penetration depth of ions into materials, it became possible to choose the thickness of the target which provides a poor thermal diffusivity in radial direction of the target. In this way, thermal images of ion beams with high spatial resolution were obtained [11,12].

A similar method was used in Ref. [13] to record the thermal imprint of an electron beam (kinetic energy of electrons $\sim$ 400 keV) on a tungsten target 100 μm thick. The target was placed in vacuum behind the anode made of a titanium foil (50 μm thick) with a support grid. The authors could measure the temperature field on the target in vacuum

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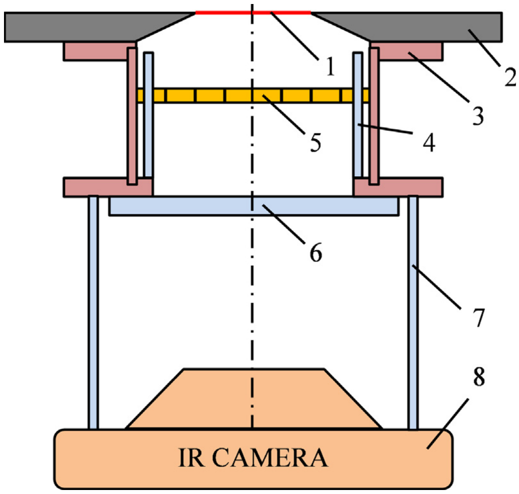

Fig. 1. General layout of the calorimeter: electron beam ejector (exit window of the accelerator) (1); exit window flange (2); sealed chamber of the calorimeter (3); adjusting screw for positioning the collector (4); sectioned collector of the calorimeter (5); sealed CaF_2 window (6); adjusting screw for positioning the IR camera (7); IR camera fixed at focus distance (8).

in less than 0.1 s after irradiation. This method required the use of an additional equipment to synchronize the injection and measurement times [13].

This paper describes a design of a calorimeter with thermal imaging of the temperature field of a sectioned collector. The calorimeter is used to estimate the electron beam energy distribution without the need for synchronization of the measuring system. A designed instrument enables to conduct measurements of the beam parameters after injection into the atmosphere at a known level of losses. This is especially important for systems in which electron beams are used at atmospheric pressure.

2. Design of the calorimeter

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) at the Laboratory of beam and plasma technologies of Tomsk Polytechnic University. From the experience of operation of such accelerators it was noted that the depressurization of the vacuum chamber of the electron diode during the installation of the calorimeter can lead to a notable change in the parameters of the electron beam during the first pulses. Therefore, special attention was paid to the design of a calorimeter capable to measure the electron beam parameters injected into the atmosphere.

2.1. General design

General layout of the calorimeter is shown in Fig. 1. The sealed casing of the calorimeter (3) contains vacuum seals for connection to the exit window of the accelerator (2) on one side and for installation of the sealing window (6) on the side of the infrared camera (8). The infrared transmitting window is made of CaF_2 glass with a known transmittance characteristic in the sensitivity range of the infrared camera [14]. The distance from the collector (5) to the outlet window of the accelerator (1) can be varied by means of the adjusting screws (4). The positioning system of the IR camera (7) ensures that the focal length remains the same in a set of experiments. The Fluke Ti10 thermal imaging camera [15] was installed only for the time of recording of the collector temperature and was not exposed to radiation and electromagnetic interference during irradiation of the collector.

The length and internal diameter of the calorimeter casing were selected based on tests at the ASTRA-M accelerator (470 keV, 0.1 J/cm^2 per pulse of 150 ns at FWHM) [16] and are l = 80 mm, D = 100 mm, respectively. The diameter of the sensitive area of the collector is made as close as possible to the diameter of the casing and reaches 94 mm. The collector has a complex sectional design to be described in details further below.

2.2. Design of the sectioned collector

In developing the design of the sectional collector the following conditions were taken into account [12]: (1) the thickness of the target should be larger than the maximum range of the beam particles, i.e. the beam should be totally stopped in the target; (2) the front and rear surfaces have achieved thermal equilibrium, i.e. the temperature field distribution along the target depth should be uniform; (3) the lateral thermal conduction is weak; (4) no obvious thermal ablation is present.

The matrix of copper sections with the dimensions of $8 \times 8 \times 1$ mm fixed in a single round shell with diameter of 100 mm has been developed as a design of sectioned collector (Fig. 2). Sections (1) were painted with black lusterless acrylic coating ($\varepsilon = 0.9$) on the rear surface to increase the infrared radiation from the material [14].

ABS-plastic was chosen as a material for the shell. This material can be 3D-printed and provide necessary conditions of low thermal conductivity. The possibility of 3D printing allows to fix the corners of the sections on tiny areas (5) of 2 mm^2 (see Fig. 2(b)) and provide a gap of 2 mm between adjacent sections (see Fig. 2(c)). Thus, the collector covers 64% of the beam cross-sectional area on the calorimeter diameter. This coefficient must be taken into account when measuring the total energy transferred by the electron beam.

Copper alloy M1 (99,9% of Cu) has been selected as material for the sections with which readings are taken. This alloy has a high thermal conductivity and a relatively low coefficient of thermal capacity. This is necessary to reduce the internal temperature gradient (temperature difference in different locations). Relatively high threshold of ablation of copper with adequate mechanical properties of the alloy M1 makes it the preferred material for the collector.

According to Refs. [7,17,18] for a complete absorption of the beam with the electron energy of 470 keV a copper foil with a thickness of at least 0.17 mm or 0.47 mm for beams with an electron energy of 1 MeV is required. From the design conditions, the thickness of the copper section was 1 mm which is sufficient to completely absorb electrons with the energy of less than 1.9 MeV. With such dimensions and energy density of 0.1 J/cm^2 per one beam pulse, the section will be heated by approximately 0.25°.

For our conditions, in order to evaluate the energy loss by infrared radiation, the Stefan–Boltzmann equation was used with the emissivity for the rear side of the target, $\varepsilon = 0.9$ and for the front side $\varepsilon = 0.3$. Radiation energy losses accounted for $4 \cdot 10^{-4}$% and 10^{-4}% for rear and front surfaces of sections, respectively. Thus, infrared radiation energy losses were not taken into account. For the same reasons, we neglected energy losses for bremsstrahlung X-rays whose conversion coefficient is ~1%–2% for the beams with kinetic energy of <1 MeV. As the air pressure in the vacuum chamber is quite low ($\sim 10^{-2}$ Pa), convective thermal transfer is also not taken into consideration for vacuum experiments.

To verify the uniformity of the temperature field distribution over the volume of the section, as in Ref. [13], a simple finite element method was performed in the Quick Field software [19]. See Fig. 3.

Analysis of simulation results showed that even after 15 ms the difference in temperature between the sides was less than 1%, which agrees with the results obtained in Ref. [13].

To perform experiments with the collector being placed in vacuum, the readings of the IR camera captured though the CaF_2 window were previously calibrated for $\varepsilon = 0.9$ according to the procedure described in Ref. [14]. Based on the readings of the IR camera, the temperatures of the sections can be obtained with an error of no more than 10%.