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Visualization and analysis of pulsed ion beam energy density profile with infrared imaging

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ABSTRACT

Infrared imaging technique was used as a surface temperature-mapping tool to characterize the energy density distribution of intense pulsed ion beams on a thin metal target. The technique enables the measuring of the total ion beam energy and the energy density distribution along the cross section and allows one to optimize the operation of an ion diode and control target irradiation mode. The diagnostics was tested on the TEMP-4M accelerator at TPU, Tomsk, Russia and on the TEMP-6 accelerator at DUT, Dalian, China. The diagnostics was applied in studies of the dynamics of the target cooling in vacuum after irradiation and in the experiments with target ablation. Errors caused by the target ablation and target cooling during measurements have been analyzed. For Fluke Ti10 and Fluke Ti400 infrared cameras, the technique can achieve surface energy density sensitivity of 0.05 J/cm^2 and spatial resolution of 1–2 mm. The thermal imaging diagnostics does not require expensive consumed materials. The measurement time does not exceed 0.1 s; therefore, this diagnostics can be used for the prompt evaluation of the energy density distribution of a pulsed ion beam and during automation of the irradiation process.

1. Introduction

The bombardment of material surface with high intensity pulsed ion beams (PIB) induces a rapid rise in temperature in the near surface layer of the target, leading to their structural and phase transformations [1–3]. As a result, the properties of materials, such as hardness, strength, and wear resistance improve. The simulation results in [4,5] show that with ion range being less than 0.3 μm in stainless steel target, the thermal field expands to 2.5 μm depth by the end of the pulse. Therefore, in materials processing the main factor that determines properties of irradiated material is the thermal effect, rather than ion implantation. To control and optimize conditions for PIB processing it is necessary to record the energy density profile of the ion beam and cross-sectional beam uniformity.

The calorimetric methods are widespread for measuring the cross-sectional energy distributions of charged particle beams. In 1976 this method was first proposed for measuring intense ion beam profiles [6]. Cross sectional beam energy distribution is usually measured by sectioned calorimeters [7]. However, a complex design of a calorimeter is required to ensure spatial resolution of 1–2 mm with a PIB of the area more 20 cm^2 and the measurement procedure becomes very time-consuming.

In 1997 Davis et al [8] proposed a new method that allowed to rapidly evaluate a large number of intense-ion-beam configurations for beam optimization and make quantitative measurements of beam energy-density profiles. The technique used infrared imaging of targets intercepting the beam. They studied PIBs with the energy density of more than 5 J/cm^2, formed by a diode with external magnetic insulation in single pulse mode. Main attention was paid to accounting for the influence of the ablation process of the target material on the results of thermal imaging measurements.

In 2013 the thermal imaging diagnostic [9] was introduced to our experimental set-up and validated for beams produced by a diode with self-magnetic insulation [10]. We analyzed different factors that may introduce an error to infrared imaging diagnostics of ion beams profiles such as contribution of electrons, generated in an ion diode and anode plasma to the target heating [11].

In several other studies [12–15] this diagnostics was successfully proofed for characterization of both pulsed electron and ion beams with various parameters.

The purpose of this work is to describe an optimized technique for visualization of ion beam energy density profiles using an infrared camera and to analyze errors caused by the target ablation and target cooling during measurements.

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2. Measurement procedure of the PIB energy density distribution

The studies were performed on the TEMP-4M accelerator [16,17] configured in the double pulse mode: the first pulse is negative (300–500 ns, 100–150 kV) and the second pulse is positive (150 ns, 250–300 kV). The beam consists of carbon ions (85%) and protons [18], the energy density on the target is 0.5–10 J/cm^2 (for various diodes), and the pulse repetition rate is 5–10 pulses/min. The diode with self-magnetic insulation and with an explosion-emission cathode, operating in the double pulse mode, is used to generate the PIB. The diode assembly with infrared imaging diagnostics is shown in Fig. 1.

The main part of the studies was performed using a 22 × 4.5 cm size flat strip diode [19,18] with an anode-cathode (A-C) gap spacing of 7–9 mm. The anode is made of graphite, the cathode is made of stainless steel with 0.4 × 2.5 cm size slits providing transparency of 70%. The design of the diode, location and calibration of the diagnostic equipment of the TEMP-4M accelerator can be found elsewhere [20].

The PIB energy density distribution on the target was measured using the Fluke TiR10 infrared camera [21] (the spectral range is 7–14 μm). The rear surface of the target was sprayed with flat-black paint to increase its emissivity and viewed with an infrared camera through a CaF_2 (or ZnSe, BaF_2 in some experiments) window located on the flange of the diode chamber (see Fig. 1). The transmission spectrum of CaF_2 window is not completely uniform in the spectral range of the IR camera, therefore readouts of the infrared camera that records the heat transmitted through the window differ from the actual temperature on the target. The description of the calibration procedure of the IR diagnostics can be found in [9].

The energy absorbed by the target with a resultant temperature change ΔT is given by:

$$Q = c_v \cdot m \cdot \Delta T = c_v \cdot S \cdot d \cdot \rho \cdot \Delta T,$$

where c_v is the specific heat of the target material, S is the area of the target, d is the thickness of the target, ρ is the density, and ΔT is the average temperature change before and after irradiation.

Assuming a uniform temperature distribution along the depth of the target after irradiation, the PIB energy density can be written as:

$$J(x,y) = c_v \cdot d \cdot \rho \cdot [T(x,y) - T_0], \quad \text{J/cm}^2 \qquad (1)$$

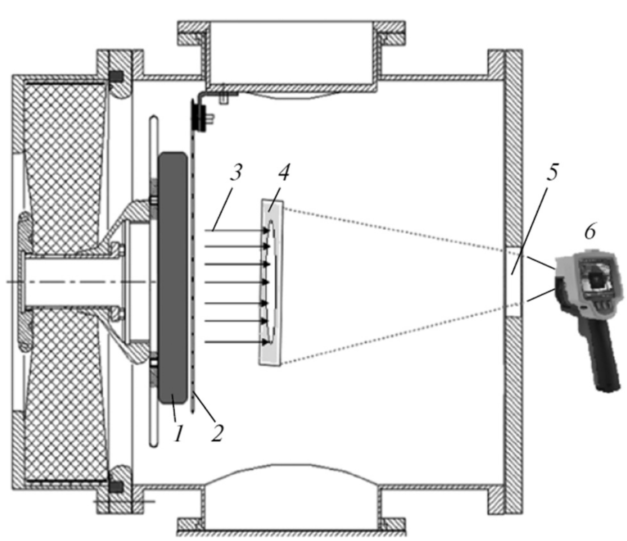

Fig. 1. Diode assembly with infrared imaging diagnostics for registration of ion beam energy density distribution: anode (1), cathode (2), ion beam (3), metal target (4), infrared-transmitting window (5) and IR camera (6).

where c_v and ρ - specific heat and density of the target material, respectively; T(x,y) – average temperature of the target after irradiation, T_0 – initial temperature of the target, d - the thickness of the target.

After the front surface of the target is heated by PIB, the temperature of the rear surface is viewed with the infrared camera (see Fig. 1). Fig. 2 shows thermal images captured by the IR camera and the energy density distribution on the target. A 100 μm thick stainless steel target was used, and the distance from the diode to the target was 12 cm. The IR images were received for one pulse.

The designed thermal imaging diagnostics was found to be very useful to control the uniformity of the PIB generation and for a quick optimization of the diode settings and irradiation regime, i.e. A-C gap spacing, diode-target distance, etc.

The time $\tau_{0.5}$, required for the rear surface of the target to reach half the maximum temperature can be calculated from the formula [22]

$$\tau_{0.5} = \frac{0.14 d^2}{a}, \quad \text{s}$$

where $t_{0.5}$ is the time for the rear surface to reach half the maximum temperature, d is the thickness of the target and a is the thermal diffusivity.

For a 100 μm thick stainless steel target (thermal diffusivity of $1.5 \cdot 10^{-5}$ m^2/s), the required time for the rear surface to reach the temperature of the front surface does not exceed 0.25 ms. For a 0.1 mm stainless steel target the time of temperature field equilibrium is less 1 ms [4]. Fluke Ti400 Infrared camera provides registration of the IR image on the target 100 ms after the PIB pulse arrival; the duration of the pulse is 120 ns. Therefore, heat transfer along the depth does not introduce a large error in the energy density measurement by IR-diagnostics.

Moreover, by analyzing the time required for temperature distribution from the front (beam irradiated side) to the rear (IR camera viewing side) surface of the target, the thermal diffusivity of irradiated samples was measured [23] using the flash method first proposed in 1961 [22].

3. Spatial resolution and limitations

When the viewing angle is 25° and the minimum focal length is 30 cm for Fluke TiR10 infrared camera, the size of a scanned object is 12.7 cm. For the 140 × 160 pixel matrix of the Fluke IR imager, the spatial resolution is 0.8–0.9 mm. However, the sensitivity of IR diagnostics is determined not only by the resolution of the IR camera. We have examined possible sources of error in the IR imaging measurements of the intense ion beams profiles, such as influence of the target ablation and spreading of the infrared image due to target cooling.

To estimate the spatial resolution of the technique we used a target with a 3 mm hole in the center (Fig. 3).

The experiments showed that the diagnostics correctly record the drop in temperature in the area of the hole with a diameter of 3 mm. Thus, we assume that the resolution threshold is 1–1.5 mm. The energy density in the region of the hole does not decrease to zero, since behind the target is a diode whose temperature is higher than the initial temperature of the target.

4. Influence of target ablation

Infrared imaging diagnostics measures the energy of the beam that is absorbed by the target. However, when the beam energy density exceeds the ablation threshold of the target, the energy absorbed by the target is less than the incident energy, because some energy is carried away in the ablated material. This leads