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Distribution and evolution of thermal field formed by intense pulsed ion beam on thin metal target

Xiao Yu [a], Jie Shen [a], Miao Qu [b], Haowen Zhong [a], Jie Zhang [a], Yanyan Zhang [a], Sha Yan [b], Gaolong Zhang [a], Xiaofu Zhang [a], Xiaoyun Le [a,*]

[a] School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, PR China
[b] Institute of Heavy Ion Physics, Peking University, Beijing 100871, PR China

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ABSTRACT

Intense pulsed ion beam (IPIB) is characterized by short-pulsed high power density. With the strong thermal effect in the surface as the dominating feature, IPIB is an ideal technique for flash-heating surface processing of materials, especially for metals and alloys. Thus, the understanding of formation and evolution of thermal field induced by IPIB irradiation is of great significance to their application and diagnostic techniques. Due to the short pulsed duration and high energy flux of IPIB, the study in this field was so far mainly yield to numerical simulation. In this paper, with a combination of infrared image diagnostics, numerical analysis using Monte Carlo (MC) and finite element methods (FEM), the distribution and evolution of thermal field formed by IPIB produced by a magnetically insulated diode on a thin metal target was studied. The evolution of the thermal field and its effects on applications, such as the design of calorimeters was discussed reasonably.

1. Introduction

Intense pulsed ion beam (IPIB), is a technology originated from the 1960s for the purpose of inertial confinement fusion (ICF) ignition [1]. During the past three decades, as a means of flash heat source, IPIB has been extensively researched in the field of material science, especially the surface treatment of metals and alloys [2,3]. The advantage of IPIB lies in its feature that the high current density (in kA/cm^2 scale), short pulse duration (10–1000 ns) and short range of ions (typically in μm) induce a pulsed high power density in the surface region of the material. The surface region of several μm of depth can be melted, evaporated and re-solidified in the time scale from tens to hundreds of ns. Meanwhile, the induced thermal shock may affect deeper regions of the target up to 200 μm [4]. Surface layers with special properties, such as amorphous state, which is difficult to be produced using conventional methods, can be prepared with IPIB [2].

As the material response of IPIB is largely dominated by the thermal effects induced from its high power density, the research of IPIB energy deposition and thermal field evolution is of great significance to the science and engineering exploration. In previous research, the study of IPIB induced thermal field distribution and evolution was mainly carried out by numerical simulations as the direct observation of the dynamical processes on the surface is quite challenging [5]. These numerical researches, although largely deepened our understanding to the IPIB thermal response, still need further development and certification via combination with state-of-art diagnostic techniques. Also, the model scale for IPIB research also calls for expansion. In the past two decades, the numerical research mainly focused on the evolution of thermal field in the time scale of hundreds of nanoseconds and spatial scale of several μm, for the purpose of analysis of extremely high energy flux irradiation effects [5]. However, for the design of diagnostic instruments with energy deposition methods such as calorimeter and thin-plate infrared imaging diagnostics, it is of paramount importance to estimate the establishing time of thermal field in the target in order to select optimized parameters (sampling time, frequency, etc.) and for error evaluation. Moreover, in previous simulation studies there exit some modeling flaws such as using a wrong energy deposition model (e.g., using Beer's law for ion energy loss [6]); as well, there are some simulation parameters taken by subjective approximation instead of experimental diagnostics (e.g., taking some evolution and distribution behavior as Gaussian [7]). In this model, we established an IPIB energy deposition and thermal response model based on the latest results of IPIB diagnostic techniques, and then a multi-step one-dimensional temperature model with radiation power loss was built to analyze

* Corresponding author. Tel.: +86 010 82325842.
E-mail address: xyle@buaa.edu.cn (X. Le).

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the long-time scale temperature field spatial revolution and its effects on relative applications.

2. Model and method

When IPIB bombard a material, the energy of the ions is transferred to the target electrons and ions, i.e. the electron and nuclear stopping of incident ions, respectively. As the stopping process of ions (in 10^{-13} s scale) is much shorter than the duration of IPIB (in 10^{-8} s scale or more), so we can take that, the time spent on ion stopping is negligible compared with the IPIB pulsed energy deposition process in the target. In general, the modeling of temperature field evolution generated by IPIB can be divided into two problems: the first is the power density distribution and evolution in the target, i.e., mathematically, the source term of the model; the other is to depict the response of the target to the source term.

2.1. IPIB power density distribution in the target

Typically, IPIBs are generated by magnetically insulated diode (MID) with dense plasma emission on the anode surface in order to achieve high particle flux. In previous research, it was taken that the energy of the ions is defined by the working voltage of MID and the current density of the beam controls the number of ions bombarding the target. Thus, the power flux of IPIB was often calculated by taking the product of MID working voltage and beam current density [7]. However, there are drawbacks in this approximation: the MID working voltage is not equal to the accelerating voltage applied on the ions because the emission of IPIB only starts when the voltage of MID exceeds certain value. Also, there exists a time delay between the MID working voltage pulse and beam current density pulse which is difficult to determine, yet obvious changes in the power flux may be caused as it changes. Now we take another point of view: If the cross-sectional energy density distribution of the beam is known (e.g., with means such as calorimeter matrix or thermal imaging diagnostics), in order to completely characterize the power density distribution in the target, it is necessary to take the followings into account:

- The spatial distribution of energy in the target along the depth, which is defined by the ion type, energy and the characteristics of the target materials. Here we use relative distribution function of beam energy vs. the depth $d(x)$ determined by the stopping power of ions dE/dx which can be calculated by Monte Carlo method such as SRIM. The IPIB particle energy and spectrum features can be measured by Thompson parabola spectrometer and time-of-flight (TOF) method [8].
- The temporal evolution of energy deposition in the target, we take the current density evolution function $f(t)$ for description. Here we take the curve acquired by the Faraday cup which is used to detect the IPIB current density as IPIB power evolution function. Unlike usually taken as Gaussian, in most of our experimental measurements, $f(t)$ is characterized by a relatively longer falling time than rising time which is shown in Fig. 1.

Take $d(x)$ and $f(t)$ as normalized function, then the power density distribution function can be expressed as follows:

$$P(x,t) = k \cdot d(x) \cdot f(t) \tag{1}$$

where k is the cross-sectional beam energy density on the target surface with dimension energy per unit area. In one-dimensional case, k is taken as constant; in three-dimensional problem, k can be expressed as $k(x, y)$ and can be measured by infrared imaging methods [9].

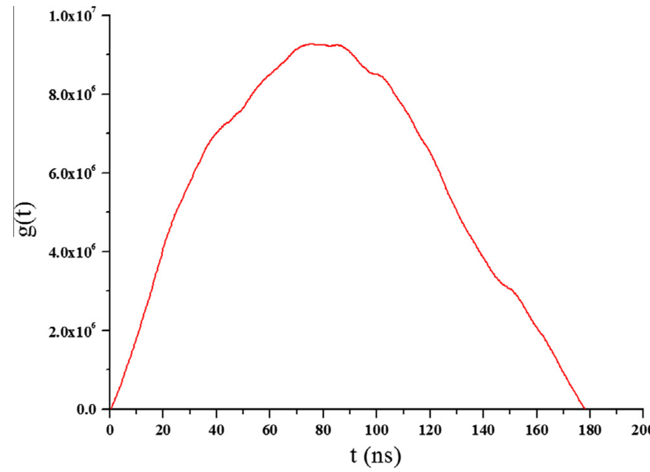

Fig. 1. Temporal evolution function of IPIB power.

2.2. Heat transfer model

In general, the heat conduction equation in the target can be described by Fourier Law and energy conservation law as:

$$\rho(T)C(T)\frac{\partial T}{\partial t} = \lambda(T)\frac{\partial^2 T}{\partial x^2} + P - E \tag{2}$$

$$E = L\delta(T(x,t) - T_m) \tag{3}$$

where $\rho(T)$ is the density of the material, $C(T)$ is the specific heat, $\lambda(T)$ is the thermal conductivity and P is the source term, i.e. the IPIB power density distribution function given above. In this work, $\rho(T)$, $C(T)$ and $\lambda(T)$ are temperature-dependent functions taken from Material Property Database (MPDB) of JAHM Software, Inc. E denotes the term of fusion latent heat. L is the latent heat of fusion, T_m is the melting temperature. The initial condition is $T(x, 0) = T_0$ ($T_0 = 298$ K). As the air pressure in the vacuum chamber is lower than 10^{-2} Pa, convective heat transfer can thus not be taken into account. In order to estimate the energy loss by surface-to-ambient radiation, Stefan–Boltzmann boundary condition was adopted:

$$j = \varepsilon\sigma(T^4 - T_0^4) \tag{4}$$

in which j is the surface-to-ambient radiation heat flux, σ is the Stefan–Boltzmann constant, ε is the emissivity. In this work, for a cleaned surface of metal we take $\varepsilon = 0.3$. The equation is solved by finite element method (FEM) program Comsol Multiphysics [10].

3. Results and discussion

The simulation was carried out with stainless steel and copper of different thickness. The normalized energy distribution function $d(x)$ is calculated from the results of Monte Carlo code SRIM. The ion type and energy spectrum of the beam are taken from Ref. [8]. The normalized power evolution function $f(t)$ is calculated from the parameters acquired with the accelerator BIPPAB-450 [11,12] with a Faraday cup with biased magnetic field in order to cut off the neutralizing electrons in the beam. The beam energy density obtained by one-dimensional simulations is 1 J/cm^2.

3.1. IPIB power deposition

As shown in Fig. 2, the energy loss function vs. depth is dominated largely by the ion energy. When taking into account the low energy ions component, the energy loss tends to have the maximum value on the target surface; this obviously differs from the