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Simulated ablation of carbon wall by alpha particles for a laser fusion reactor

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ABSTRACT

Thermal reactions of materials heated by charged particles may lead to serious damage in a laser fusion reactor. When charged particles irradiate and heat the wall material with high intensity like at above 10^9 W/cm^2, the material can be ablated. Once the wall is ablated, expanding gas or plasma can disturb the propagation of laser light irradiating the fuel target if it stagnates long enough for next laser shot. In order to understand the ablation dynamics in detail, we have performed 1-D hydro simulation to evaluate this ablation. As a new feature, we introduce the calculation of energy deposition by charged particles focusing on the interaction between ablated material and charged particles.

1. Introduction

As one of the critical issues in developing and designing laser fusion reactors, it is of critical importance to study possible first wall ablation. The first wall of a reactor chamber is exposed to extreme heat load originating from the burning fusion targets. Extreme heat load includes X-rays and charged particles. The charged particles consist of alpha particles, carbon ions, protons, deuterons and tritons [1]. Carbon and Tungsten are often considered to be candidate materials for the dry first wall because of their high sublimation and melting temperatures [2].

In this study, we focus on the ablation of wall materials heated by charged particles. The ablated materials become gas or plasma and expand into the vacuum space. It may disturb the propagation of the laser light irradiating the fuel target if it stagnates in the optical path of laser for more than 100 ms in case of high repetition rate of 10 Hz. Therefore, the thermal reaction of a reactor wall materials heated by charged particles is an important topic for stable operation of a laser fusion reactor.

We estimate the temperature increase by irradiation of charged particles from the calculation of the particle energy deposition and thermal conduction. As a new feature, we couple the calculation of the particle energy deposition to hydrodynamics in order to describe the variation of density, velocity and temperature. The interactions between projectile ions and the ablated material can be treated in the simulation code.

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2. Energy deposition of charged particles

2.1. Stopping power of projectile ion

In order to estimate the temperature increase by charged particle irradiation, we calculated the energy deposition of charged particles in the material. The energy losses of projectile ions are due to the collisions with nuclei and electrons in the material. In case of unionized materials, the electrons are bound electrons of target atoms. Stopping power represents the energy losses per unit distance. The stopping power is given as:

$$-\frac{dE}{dx} = (S_N + S_E)n_i \tag{1}$$

where S_N and S_E are nuclear and electron stopping cross sections and n_i is the atomic density of the material.

The nuclear stopping is described in the binary collision model. For the nuclear stopping cross section, we use the equation established by Ziegler et al. [3].

2.2. Electron stopping cross section

Electron stopping represents inelastic scattering between the projectile ion and bound electrons. We used two models to calculate the electron stopping cross section. First, we used the Bethe–Bloch model [3]. The electron stopping cross section is

$$S_E = \frac{Z_1^2 e^4}{4\pi\varepsilon_0^2 m_e v^2} Z_2 \left[ln\frac{2m_e v^2}{I} + \sum_i C_i \right] \tag{2}$$

where Z_1 and Z_2 are the atomic number of projectile ion and the target material, v is the velocity of projectile, I is the average ionization potential [3], e is the electron charge, m_e is the electron mass and C_i is the correction term. The Bethe–Bloch model is valid when the velocity of a projectile ion is larger than the mean velocity of bound electrons in the material. Inclusion of a correction term C_i enables to calculate S_E more accurately.

In the case of low energy projectile ion, we used another calculation model. If the velocity of the projectile ion is slower than the mean velocity of bound electrons in the material, S_E is proportional to the projectile velocity [3]. In this region, we estimate the heavy ion S_E by Z_1 dependent scaling from proton S_E. Proton S_E is given by empirical formula based on the experimental data corresponding to each target material [4].

If temperature of the material heated by charged particles increases up to more than 10 eV, the material begins to ionize. This ionization increases the number of free plasma electrons and reduces the number of bound electrons resulting in the net increase of stopping power [5]. When the ionization degree of ablated material becomes 2.0 or higher the stopping power may increase twice or so. However the areal density of the ionized region may correspond to only 20% of the entire ion stopping range. Thus we consider that the influence of ionization does not alter the energy deposition distribution significantly.

3. One-dimensional hydrodynamics simulations

Thermal energy deposited by charged particles is diffused via thermal conduction in the material. In addition, the temperature profile varies by the flow of material, if the material becomes vapor. Therefore, using hydrodynamics simulation that can treat the flow of materials with thermal conduction is suitable for estimating both temperature and density profiles of the ablated material. We use the one-dimensional hydro simulation code to understand the dynamics of the ablated material. Compressible hydrodynamics consists of fundamental equations that are

$$\frac{D\rho}{Dt} = -\rho\nabla\cdot\boldsymbol{v} \tag{3}$$

$$\rho\frac{D\boldsymbol{v}}{Dt} = -\nabla p \tag{4}$$

$$\rho c_v\frac{DT}{Dt} = -p_{th}\nabla\cdot\boldsymbol{v} + \nabla\cdot(\kappa\nabla T) + S_{dep} \tag{5}$$

where

$$p_{th} = T\left(\frac{\partial p}{\partial T}\right)_{\rho} \tag{6}$$

ρ is the mass density, $\boldsymbol{v}$ is the velocity, p is the pressure, T is the temperature, c_v is the specific heat, κ is the thermal conductivity and S_{dep} is the deposition energy by charged particles [6]. In order to solve the equations, pressure derived from the equation of state is required. Specific heat and thermal conductivity can be obtained from the Network Database System for Thermophysical Property Data [7]. Until the temperature of the material reaches the sublimation point, the material is treated as a solid at rest with $\boldsymbol{v} = 0$, where the hydrodynamic motion is not considered. When the temperature of the heated material exceeds the sublimation point, the materials become fluid and expand. After that, the incoming charged particles interact with the vapor and the solid materials. Fig. 1 shows the schematic illustration of interactions between charged particles and the material.

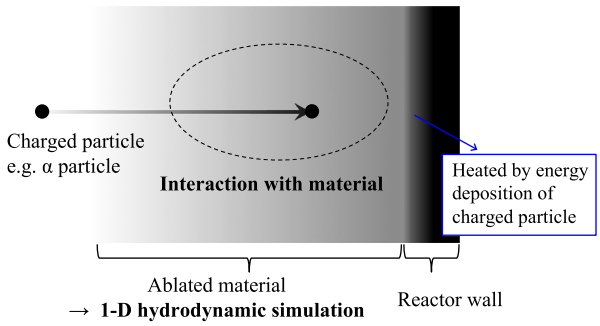

Fig. 1. Schematic illustration of the simulation.

4. Evolution of ablated material

In the present study, we have simulated the ablation of carbon heated by alpha particles. Carbon sublimates at 3915 K (sublimation point). The conditions for simulation are as follows; initial projectile energy is 100 keV and 1 MeV. Intensity of injected particles is 1.60×10^9 W/cm^2 with square pulse of 6.0 ns duration. The target is carbon of solid density with initial temperature of 300 K (0.026 eV).

Fig. 2 shows the time evolution of temperature and density of the carbon target at different times (a, d) 2.0 ns, (b, e) 4.0 ns and (c, e) 6.0 ns. Fig. 2(a)–(c) show the ablation by irradiation of 100 keV alpha particles while Fig. 2(d)–(f) show the ablation by irradiation of 1 MeV alpha particles. The horizontal axis at 0 μm indicates the original surface before injection of alpha particles. Alpha particles come from vacuum, left side of zero of horizontal axis. The simulation time has measured from the beginning of the particle irradiation. In the case of 100 keV alpha particles, temperature exceeds a sublimation point to 0.5 μm in depth at 6.0 ns. As shown in Fig. 2(c), a one-1000th point of the solid density expands to −70 μm at 6.0 ns. In the case of 1 MeV alpha particles, temperature and density profiles are totally different from the 100 keV alpha particles. Because of a large ion stopping range of the order of 3 μm, the temperature distribution shows less peak temperature in the solid carbon. However, the temperature distribution forms the Bragg peak inducing a larger pressure inside of the solid wall. As a result of this heat source, shock wave is launched toward the front of ablated carbon and forms complicated distribution of temperature and density.

5. Effect of vapor shielding

Fig. 3 shows the rate of deposition energy from 100 keV alpha particles in the vapor and solid regions. We can find a difference in mechanism that heats solid region in two phases. Solid phase is maintained until 0.5 ns in Fig. 3. In solid phase, the deposition energy from alpha particles is absorbed mainly in the solid region. The sublimation comes in quickly. The phase changes from solid to vapor at after 0.5 ns in Fig. 3. In the vapor phase, the increased vapor starts absorbing the energy instead of the solid region. After switching from the solid phase to the vapor phase completely, alpha particles deposit nearly 100% of their energy in the expanding vapor region. This states of condition represents effect of the vapor shielding [8].

Fig. 4 shows the distribution of energy deposition in carbon at 0.1 ns and 1.5 ns in two curves: one from the alpha particle (a broken line) and the other from thermal conduction (a solid line). These two curves show the distribution of energy density per a unit time and correspond to the particle heating of third term S_{dep} and thermal conduction of second term $\nabla\cdot(\kappa\nabla T)$ on the RHS of Eq. (3). In Fig. 4(a), the surface of solid material is at the zero point. In Fig. 4(b), the interface between the ablated vapor and non-ablated solid is 0.45 μm. In both Fig. 4(a) and (b), alpha particles are stopped at 0.45 μm and deposit their energy in their stopping