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Physics of the plasma-wall boundaries in inertial fusion
慣性閉じ込め核融合に於けるプラズマ-壁境界層現象の物理科学

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Interactions of intense energetic particles with matter in inertial fusion reactors are discussed. A hydrodynamics simulation code coupled to the calculations of the energy deposition from the particles has been developed to study the interactions. It has been found that the ionization processes of the ablated matter are important to determine the energy deposition of the incoming particles. Similar effects of ionization on particle interactions have been found in laboratory scale experiments of laser-ablated plasma-plasma interactions.

1. Introduction

In inertial fusion reactors, the reactor wall is exposed to high-energy particles such as fusion products, unburned fuel, and ions contained in the fuel pellet as well as high energy x-rays. The particle intensity can be above the ablation threshold of the first wall. The wall ablation is particularly crucial for solid wall reactors. It can be also important for liquid wall reactors since the ablated matter may collide each other at the central region of the reactor chamber and produce aerosols[1]. Ways to avoid the wall ablation can be increase the chamber size or reduce the fusion power, however, these solutions could reduce fusion efficiency. Another approach to minimize the effects of energetic particle irradiation to the walls uses a buffer gas[2]. The buffer gas works as an energy absorber of the energetic particles. However, the gas density is limited to avoid the optical breakdown that prevents the irradiation of the implosion laser to the fuel target.

We propose a new concept that could reduce the material ablation caused by intense, energetic particle beam irradiations. In the concept, the first part of the beam ablates the matter, and then, the ablated matter itself behaves as a shield, which is similar to the "vapor shielding" around the divertor in the magnetic confinement fusion[3]. Here, the common key of the concepts is heating of ablated matter due to the incoming energy flux.

Energy deposition efficiencies of the energetic ions in matter are determined as a stopping power. We have calculated the stopping power of matter as a function of its temperature (i.e. ionization level). For the study of the shielding phenomena in the ablated matter from energetic particle irradiations, a hydrodynamics simulation code has been developed that is coupled to the energy deposition calculation due to energetic particle injection to the matter using the temperature dependent stopping power.

We have also performed an experimental study of particle shielding using two laser-ablated plasma plumes colliding each other. In the experiments, it has been observed that the plasma particles are ionized to higher levels due to the interaction.

2. Simulation of Ablation Dynamics in High Energy Particle Irradiation to Matter

One dimensional hydrodynamics code with two-temperature model has been developed for this

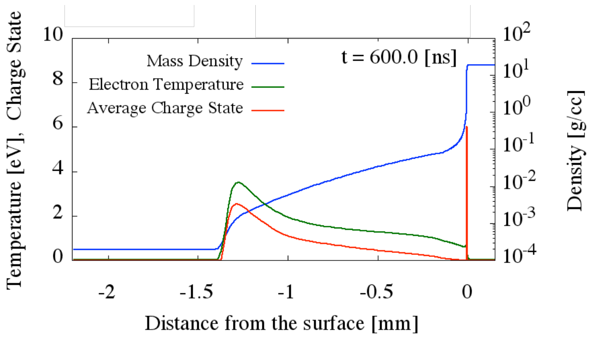

Fig. 1. Ablated tungsten profile after the irradiation of intense alpha particle beam from the left in this figure. Initially there is a tungsten slab with a solid density at x>0 with an initial temperature of 300 K.

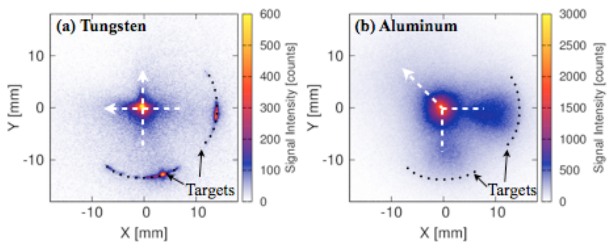

Fig. 2. Snapshots of intersecting plasma plumes produced by laser ablation of concave targets; (a) tungsten, (b) aluminum. The white allow indicates the plasma flowing direction after the interaction.

study. In the code, the stopping power of the injected ions in matter is calculated as the interactions of ions with nucleus, bound electrons, and free electrons. The total stopping power in the matter depends on its density and temperature since the ionization level of matter depends on these parameters. The stopping power originated from the bounded electrons decreases as the increase of the temperature. In the contrary, the free-electron originated stopping power increases in hotter matter. As a result, the total stopping power is higher for hotter matter. This trend indicates that when the ablated matter is heated more, it has higher stopping power i.e. absorbs more energies from the incoming particle flux resulting in becoming even hotter; a positive feedback loop to avoid further ablation of the matter. The keys of this “shielding effect” are the ionization process and the ionization level of the ablated matter. The developed code treats the phenomena self-consistently. As an example, the irradiation of intense alpha particle beam to solid tungsten is studied. The beam is assumed to have a peak intensity of $\sim 10^8$ W/cm^2 with energies up to a few MeV[4]. Figure 1 shows the hydrodynamics simulation results just after the peak of the beam injection. The ablated tungsten plasma is heated to above 1-2 eV that can have larger shielding effect than the one at the initial temperature.

3. Experiments of Colliding Plasma Plumes

The similar phenomena can be seen in low density ($n_i \sim 10^{13}$ cm^{-3}), low temperature ($T_e \sim 1$ eV) plasma particle interaction. In laboratory scale experiments, the interaction of laser ablated plasma plumes has been studied. The detail of the experimental setup can be found elsewhere[5]. It has been observed that the intersecting two plasma plumes behave differently depending on its parameters; density, temperature, ion species, and velocity. For example, the intersecting two tungsten plasma plumes just penetrate through in each other as shown in Fig. 2(a), however, the aluminum plasma collides each other (i.e. shielding) and merged after the intersection region as shown in Fig. 2(b). It has been confirmed that the rate of the scattering of the interacting plasma flow is quasi proportional to the ion-ion collision frequency that is dominantly depends on the charge state of ions and also its velocity. It has been also found in the time-resolved spectroscopy of the interacting plasmas that the plasma particles are ionized further during the intersection in the case showing high shielding effect.

4. Summary

The phenomena of energetic particle irradiation to matter and the following ablation process have been discussed from the viewpoint of the plasma-wall interactions in inertial fusion reactors. A positive feedback loop can occur spontaneously because of the ionization process of ablated matter that enhances the shielding effect of matter from the further ablation caused by the incoming particle flux. It is expected that the reactor design using the ionizing and shielding phenomena effectively can reduce the reactor wall ablation.

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