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Numerical Analysis of Forward Expansion Characteristics of Ablated Plasma by Pulsed Ion-Beam Interaction with Al Target

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Abstract: The main objective of the current study was to investigate the behavior of ablation plasma which was produced by irradiating pulsed ion-beam with a solid target of Al thin foil. The technique used here was called a forward expansion---beams irradiation and the ablation plasma expansion are in an opposite direction. A one-dimensional hydrodynamic model was used to simulate the dynamic of the target with a thickness of 9 μm and the plasma. In this model, the internal energy together with both of the latent heat of fusion phenomenon and the latent heat of vapor are also taken into account. Physical parameters are presented in terms of ablated plasma temperature, pressure and the energy deposition distribution.

Key words: Ablated plasma, numerical analysis, pulsed ion-beam

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INTRODUCTION

Ion-beams have been used for various applications, particularly in material sciences, such as evaporation, ion implementation and ion sputtering depending on voltage and current. For example, several megavolts intense pulsed ion-beam produces a high-temperature and high- density ablation plasma through fusion, vaporization and ionization by the ion energy deposition that is penetrated into the solid material[1-3]. The ion-beams are able to form ablation plasmas efficiently, because absorption and beam generation is better than that of laser. Using these characteristics, we have reported tests of a possible application by flyer acceleration using the reaction and expansion of ion beam ablation plasma[4,5]. At this university, the research has been conducting of both numerical simulation and experiment. Yatsui et al reported that a flyer velocity of 7.7 km/s was achieved by irradiating an intense pulsed ion-beam energy density of 2 kJ/cm^2 with Al foil thickness of 50 μm[1,2]. We then developed a numerical tool for the analysis of flyer acceleration which is produced by pulsed ion beam irradiating with Al thin foil[4]. In this study, the new technique of forward expansion is introduced, while the numerical procedures are still based on the ion beam-solid material interaction concept. The advantage of this new concept is that it is able to understand the ablated plasma production phenomenon clearer, because the ion-beam irradiation and the plasma expansion are in the opposite direction. The set of one-dimensional hydrodynamic equations together with the equation of state of an ideal gas are used. Internal energy and the latent heat of a fusion and the latent heat of a vapor of a target material are also taken into account.

Principle and modeling: The basic concept of the forward expansion of ablation plasma by the interaction of pulsed ion-beam and the solid target is shown in Fig. 1. When we irradiate Al target with pulsed ion-beam, which is produced by the pulse power generator, ablation plasma is formed as soon as the ion beam energy penetrates the target to the certain depth. Because the ablation plasma produces extremely high pressure at a position closest to the final depth of 9 μm, therefore, ablation plasma with high pressure or high momentum expands to the opposite direction of the ion beam irradiation. This ablation plasma acts as the exhaust momentum to drive space probes forward[5].

We use a one-dimensional fluid model in order to simulate the dynamics of the target and the ablation plasma while incident ion beams interact with the target[3,4]. Different parts of the target are in solid, liquid and gaseous and also plasma form, which is treated as a compressible fluid without any charge effects. This approximation is acceptable because the ratio of the Debye length to the electron mean free path is much less than 1 for an electron density of about 10^{23} cm^{-3} and the electron temperature is several tens of eV (10^6K).

Moreover, the ionization process can be expressed by Saha's equation because the ablation plasma is considered to be a local thermal equilibrium under the extremely high pressure[5,6]. Therefore, the basic hydrodynamic equations[3] employed are:

$$\frac{D\rho}{Dt}+\rho\frac{\partial u}{\partial x}=0 \tag{1}$$

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$$\rho\frac{Du}{Dt}=-\frac{\partial(P+q)}{\partial x} \qquad (2)$$

$$\frac{DU}{Dt}=-(P+q+U)\frac{\partial u}{\partial x}+S+H \qquad (3)$$

$$U=C_vTn_i^0+\sum_{z=1}^{n}n_i^z\varepsilon_z+(L_{f(T)}+L_{v(T)})n_i^0 \qquad (4)$$

Where ρ is the target mass density and u is the relative velocity. P is pressure, T is temperature and q is Von Neuman viscosity. C_v represents the specific heat at constant volume. S indicates energy deposition (stopping power) of the ion beam based on the ion beam-target interaction[4,5]. In addition, the term H denoting energy loss due to thermal conductions is also taken account. U is the internal energy, while L_f and L_v are the latent heat of a fusion and the latent heat of a vapor. The n_i defines an ion number density and ε is for ionization energy. The subscripts ab and z are the ablation plasma and the ionization number, respectively

According to the fact that the ablation plasma is produced instantaneously, the phase changed effects and electromagnetic effects are ignored[7,8]. All the above equations are solved by a difference method in the Lagrange scheme[3,4]. The physical parameters used in the simulation are listed in Table 1 and are based on the experimental conditions of a pulse power generator "ETIGO II" installed at the Extreme Energy-Density Research Institute, Nagaoka University of Technology, Japan[9,10].

Table 1: Simulation parameters

Ion Beam Energy Density [J/cm^2]	100
Ion Beam Kinetic Energy [MeV]	0.7
Pulse Duration [ns]	60
Beam Particles	protons
Target Material	Aluminum
Target Thickness	9 μm

RESULTS AND DISCUSSIONS

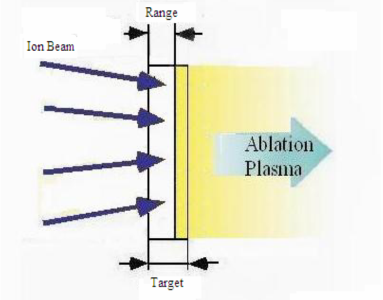

Fig. 1: Ion-beam and solid interaction concept for the forward ablation plasma expansion

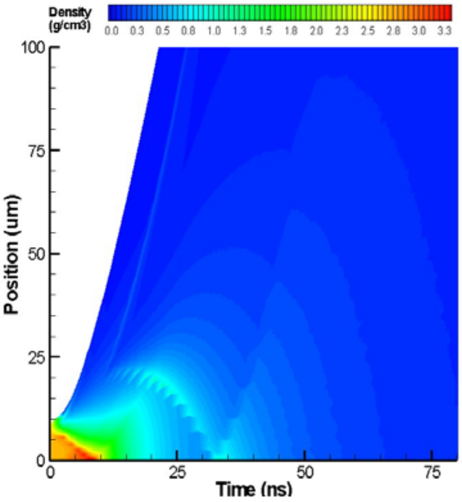

Fig. 2: Ion density

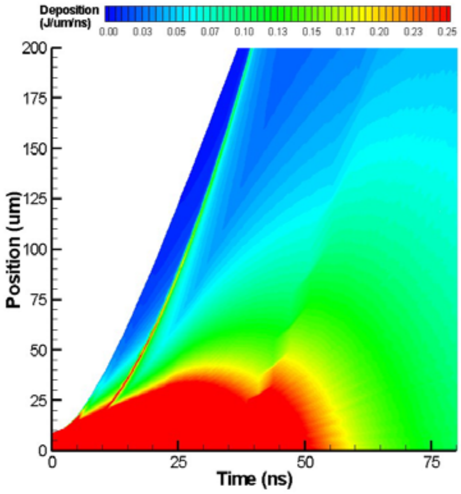

Fig. 3: Ion-beam deposition

Once a pulsed ion beam with energy density of 100 J/cm^2 at the pulse duration of 60 ns reaches Al target, the part of the target is melted, evaporated and is instantaneously ionized forming high-density, high-pressure and high-temperature ablation plasma. The 0.7 MeV of accelerating voltage was able to penetrate ion-beam energy to almost the certain depth of the Al foil of 9 μm. The ablated plasma afterward heated and expanded to the opposite direction of the irradiation. Figure 2 shows the ion density of ablation plasma after expanding to the opposite side. The point where x=0 and y=0 is the edge of Al foil. With an initial irradiating of 10 ns, ion-beam deposits its energy strongly and high density of ion is found at this stage. The ion-beam energy somehow decreases after 15 ns; because most of the energy is afterward spent for the high-temperature formation process. Ablated plasma continues its formation process, while increasing the rate of ion-beam energy penetration through the expanding phenomenon as shown in Fig. 3. Ion-beam energy terminates its penetration at 60 ns, which is as equal as its pulse duration. High-energy density ablation plasma is found at approximately 25 μm far from the edge of the target. This high-energy ablation keeps continue and transforms into the ionization process at approximately 15 ns to form high-temperature plasma as shown in Fig.

4 and 5. The more the ionization process appears, the higher ablated plasma temperature is observed and is in the range of 3 to 3.5 eV.

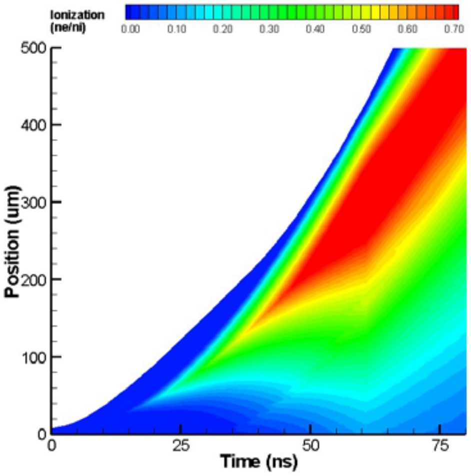

Fig. 4: Ionization

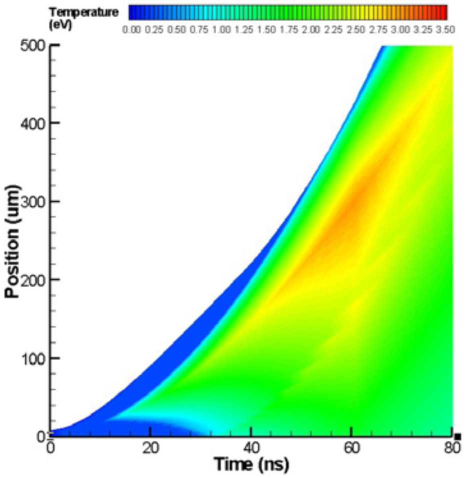

Fig. 5: Ablation plasma temperature

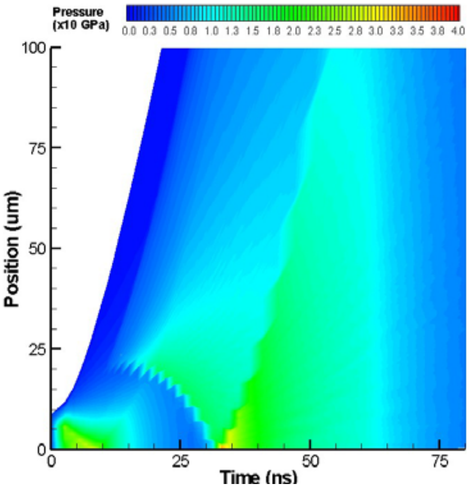

Fig. 6: Ablation plasma pressure

Figure 6 shows the ablation plasma pressure distribution after expanding to the opposite direction. One can see that the pressure trends to sharply increase and gradually fall instantaneously. At the period of about 20 ns as soon as the ablated plasma is formed, ablated plasma increases its pressure rapidly to form high-pressure ablation plasma. The pressure at this stage is in the range of 10-27 GPa. During the period of 20-30 ns, the pressure of the ablated plasma decreases as some of ion-beam energy is spent into the vaporization process. The main factor causes the decreased of ablated plasma pressure is due to the constant ion-beam current for plasma formation and expansion at the beginning of the ion-beam irradiation. The pressure of ablated plasma starts increasing once again at approximately 30 ns because of the propagation of the strong shock-wave that returns to the edge of a target. The high-pressure ablated plasma plumed consumes the area of approximately 6250 μm^2.

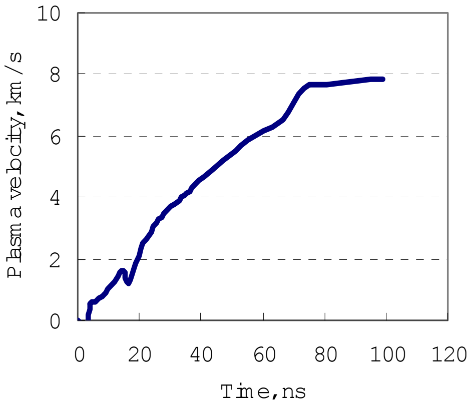

Fig. 7: Plasma velocity

Maximum pressure of approximately 35 GPa at 30 ns is observed. Not only has the ablation plasma pressure increased with time through its expansion, but also the ablated plasma velocity. The ablated plasma velocity trend is shown in Fig. 7. Plasma reaches the peak velocity of approximately 7.9 km/s at the ion-beam irradiation of 75 ns. This value of peak velocity seems to be constant afterward. We can say that this obtained velocity is the a maximum plasma velocity of Al foil with the thickness of 9 μm. The plasma velocity trend shown in Fig. 7 is also considered to be more viable and much better than that of obtained in the previous study at the same energy input of 100 J/cm^2[4,5,8]. It is too obvious that the physical characteristics of ablated plasma by the forward expansion concept show clearer understanding of the production mechanism, its expansion phenomenon and so is the plasma velocity.

CONCLUSION

This study investigated the simulation model of forward expanding ablation plasma which is produced by irradiating pulsed ion-beam with an Al foil. The set of one-dimensional hydrodynamic equations are used. The latent heat of both fusion and vaporization process, which are not included in the previous works, were also taken into account. This consideration was able to understand the ablated plasma formation and expansion clearer. Because the plasma formation process and the ion-beam irradiation were in opposite direction, the characteristics of ablation plasma understood clearer than those of obtained by the flyer acceleration concept.

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