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Generation and acceleration of high charge state ions through the interaction between high-intense laser and high-Z matter

高強度レーザーと高Z物質の相互作用による高価数イオンの生成と加速

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The acceleration mechanism of ions in the interaction of high-intensity laser pulse with generated overdense plasmas in the Al film is identified using particle-in-cell code including ionization process. We found that the ionization wave for the laser propagation and transverse directions determines the dominant charge state: Al^{11+} which corresponds to the highest state on L-shell in the solid film. Furthermore, the ions are accelerated from rear surface, and ionized to higher charge state near the laser focusing spot so that the difference of ion energy appear due to its charge state.

1. Introduction

The development of high-intensity (I >10^{19} W/cm^2), short pulse (<1 ps) lasers have opened up an era of ion acceleration based on the laser-solid matter interaction for various applications such as ion beam radiotherapy[1] and exotic nuclei extraction[2,3]. The materials irradiated by such intensity lasers tend to become plasmas through various ionization processes. These ionization processes play essential role since they determine the initial condition of the plasma and the charge-mass ratio Q/M of the accelerated ions from the primary interaction. For applications utilizing relatively high-Z materials, atomic and relaxation processes play an important role in determining the interaction.

Many computational studies using the PIC model have been done. However, most of them made a priori assumption of ideal plasma as initial condition. In order to promote the such applications, we have developed a particle based integrated code (EPIC3D) which includes various atomic and relaxation processes. By using the code, we, then, investigate the ionization dynamics in solid matter and the ion acceleration mechanism.

2. Ionization models

Here, we carry out 2D-simulation of the interaction between Al film and short pulse laser using the EPIC3D. Simulation model assumes that the film which consists of Al atoms with multiple charge state (q =1-13), and the initial charge state is Al^{1+} with a free electron. The atom density is chosen as n_a=1.5×10^{22} cm^{-3} which is 1/4 of the solid density. The Al film is 0.8um thick along the laser propagation direction. The linearly polarized short pulse laser is irradiated from the antenna placed near the left-hand side (LHS). The laser pulse width is chosen to be τ=40 fs for laser peak time t_0=120 fs, and the maximum laser intensity is set to be I=1.0 ×10^{21} W/cm^2 based on the wave length 0.8 um assuming the high-intensity Ti:Sapphire Laser.

3. Ionization dynamics

Fig.1 illustrates the time history of Al ion abundance normalized by total ion number for each charge state. From t=37 fs, the laser field starts to ionize the Al^{1+} to Al^{3+} on the front surface of the film. Then a part of A^{3+} on M-shell is ionized to higher charge state of L-shell during the time. At t=90 fs, the Al is suddenly ionized to higher charge state including fully ionized state with high ionization rate. Afterwards, the low charge state ions are ionized to Al^{11+} which is the highest state in L-shell, and the ion abundance of each charge state on M-shell and L-shell excluding Al^{11+} decreases successively. From t=180 fs, Al^{11+} starts to decrease gradually, and then Al^{12+} and Al^{13+} keeps increasing nevertheless the laser field almost go through the simulation domain.

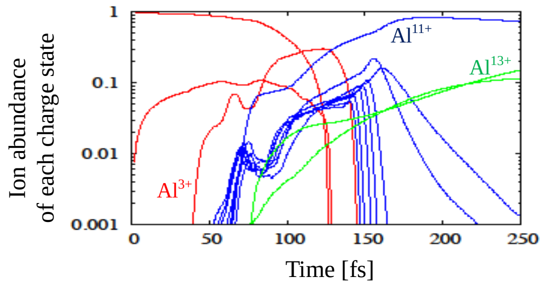

Fig.1.Time history of ion abundance. Color lines represent the abundance of each charge state. Red lines are Al^{1+}-Al^{3+} in M-shell, blue lines are Al^{4+}-Al^{11+} in L-shell, and green lines are Al^{4+}-Al^{11+} in K-shell.

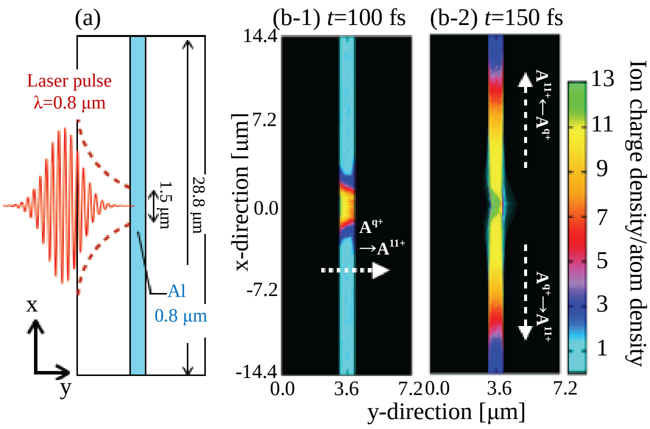

Fig.2. (a) 2D-simulation domain and (b) Ion charge density normalized by atom density.

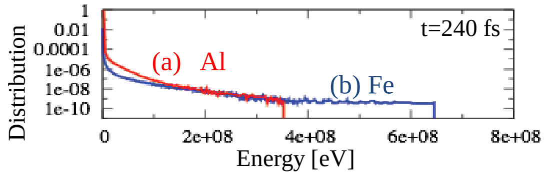

Fig.3. Ion energy distribution

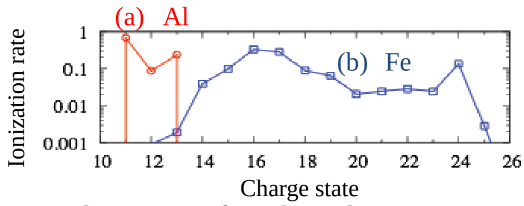

Fig.4. Charge state of accelerated ions in vacuum area

The spatial ionization process is separated into two parts for laser propagation(y-) and transverse(x-) directions as shown in Fig.2. The laser field is cut off from the film surface, so that the ionization occurs in the laser spot area which scale is illustrated in Fig.2(a). However, the ionization to Al^{11+} suddenly starts to propagate into the film along the y-direction with high velocity (=0.6c) as shown in Fig.2(b-1). This ionization is driven by the relativistic electrons, so that a part of electrons are accelerated to relativistic region through the interaction between the laser and the solid surface, which can be described as J×B heating[4]. Then, these can propagate into the film without collision due to the long mean free path and excite the electrostatic field in the y-direction like the sheath field which ionizes to the high charge state. After these fast electrons reach to the rear side of the film, a part of them pass into the vacuum area and continuously create the sheath field at the rear surface. The other electrons are reflected by the sheath field with scattering angle, and then the ionization process turn to the transverse direction as shown in Fig.2(b-2). Its ionization wave propagates gradually to Al^{11+}. And it reaches the boundary of the domain, so that all ions ionize to Al^{11+}.

4. Ion acceleration with each charge state

The Al ion acceleration from the rear surface along the y-direction by the sheath field due to the fast electron and the ions can be described as based on TNSA mechanism[5-6]. Its energy reaches to 350 MeV(=13.4 MeV/u) which corresponds to the experimental level observed in JAEA. The sheath field amplitude reaches to E=4.0×10^{13} V/m which is over the ionization threshold of Al^{13+}, so that the accelerated ions are ionized from Al^{11+} of the solid charge state to Al^{13+} , and its ionization rate increases near the laser spot area. Then, each charge state of the accelerated ions has two peaks Al^{11+} on L-shell and Al^{13+} on K-shell in Fig.4(a).

We add the Fe thin film, which has more multiple charge state (q=1-26), with 0.1 μm thick at the rear surface behind the Al film. The accelerated Fe ions get the peak energy to 640 MeV(=12.3 MeV/u which is less than the Al ion's) as shown in Fig.3(b). Its dominant charge states are Fe^{16+} and Fe^{24+}. The each state is the highest state in M-shell and L-shell as shown in Fig.4(b), This result shows that the charge state of the Fe film is almost Fe^{16+} and the sheath field ionizes it to Fe^{24+} which is same as the Al ion acceleration mechanism. However the Fe is not ionized to fully ionized state Fe^{26+}, so that the Fe ion energy per nucleon is less than the Al ion's with the fully ionized state Al^{13+}, due to the difference of the charge-mass ratio Q/M. This problem for the ion acceleration will become remarkable in high-Z matter.

Conclusion

We identify the ionization dynamics and ion acceleration mechanism with each charge state based on Al film using EPIC3D. The ionization dynamics rely on the fast electron propagation for each shell. Furthermore, the ions are ionized and accelerated by the sheath field. Its charge state determines the ion energy due to the charge-mass ratio Q/M.

Acknowledgments

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