博士論文公聴会の公示（物理学専攻）

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論文題目：Ion acceleration by laser-driven collisionless shock in multi-ion species plasma

（多種イオンで構成されたプラズマ中でのレーザー駆動無衝突衝撃波によるイオン加速）

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主査：藤岡　慎介

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論文要旨：The collisionless shocks are very common in the numerous astrophysical environments such as in supernova remnants, pulsar wind nebulae, etc. These shocks are considered to be responsible for the production of high-energy cosmic rays and acceleration of particles. The astonishing growth in the development of high-power and high-intensity lasers has made it feasible to recreate the relevant conditions to examine the formation and evolution of collisionless shocks in the laboratory. The numerical and experimental findings reveal that the laser-driven electrostatic collisionless shock can be utilized as a high-energy compact particle accelerator. These accelerated particles have several desirable applications such as accelerator physics, proton radiography, and cancer therapy, etc.

In this thesis, we report on the numerical investigation of electrostatic collisionless shock formation and influence of different materials on the shock accelerated ion beams. The different target materials used are the hydrogen, carbon, oxygen, and chlorine to give a range of average charge (<Z>) to mass (<A>) ratio, i.e., <Z/A> = 0.48 - 1.

The 2D EPOCH particle-in-cell simulations are employed to investigate the laser-driven electrostatic collisionless shock ion acceleration in different materials. The density profile and laser parameters are the same for all materials. Our result indicates that the electrostatic collisionless shock is excited, and protons are reflected and accelerated by the shock-associated electrostatic field. The laser to shock-accelerated protons conversion efficiency and the number of these protons are significantly increased in the multi-ion species plasmas, such as CH and C_2H_3Cl plasmas compared to a pure H plasma.

In the upstream region of the shock, ions expand with different velocities depending on their <Z/A> under the non-oscillating component of the sheath electrostatic field. In multi-ion species plasmas, the excitation of electrostatic ion two-stream instability (EITI) between the heavier and lighter ion populations occurs. This results in the deceleration of the expanding protons and appearance of a low-velocity component. An additional EITI between the reflected and expanding protons accelerates some of the expanding protons to the higher velocity, which results in more protons being accelerated by the shock. The analytic and exact solutions for the dispersion relation of EITI indicate that the unstable modes of the instability appear in multi-ion species plasmas.

It is shown that the interaction of high intensity ($a_0 \geq 10$) laser with multi-ion species plasma leads to the formation of two shock fronts in fully ionized carbon and proton, respectively. The shock front propagates slower in C-ions compared to protons. Therefore, both C-ions and protons are accelerated by different shocks via CSA mechanism. The shock velocity and Mach number of C-ions and protons can be scaled as the power-law dependence on a_0. In case of C-ions, the Mach number is a stronger function of a_0 compared to that of protons in the multi-ion species plasma with the lowest <Z/A>, i.e., C_2H_3Cl. The flux of shock accelerated protons and C-ions is more significant in multi-ion species plasma compared to the pure H and C plasmas.

The CSA experiment is carried out by using a combination of GEKKO-XII (pre-ionization beam) and LFEX (shock-driving beam) laser facilities at the Institute of Laser Engineering, Osaka University (Japan). The rear-surface of 0.7 μm CH foil is irradiated by a pre-ionization laser beam to produce a suitable density profile for CSA. After the target expansion, a shock-driving beam is irradiated from the front side of the target to drive a collisionless shock wave. The necessary density profile is optimized by varying the time delay, $\Delta t = 0 - 1.5$ ns within the two laser beams. The passive ion diagnostics, i.e., RCF stacks and CR39 detector plates confirm that the maximum energy of the accelerated protons is in the range of 7.03 MeV - 9.03 MeV for $\Delta t = 1.2$ ns.