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研究課題名（和文）Study of Proton stopping power in strongly coupled plasmas for Fast Ignition researc h.

研究課題名（英文）Study of Proton stopping power in strongly coupled plasmas for Fast Ignition research.

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研究成果の概要（和文）：Ion acceleration with ultra-high intensity lasers is an active area of research with many applications, ranging from ultra-fast radiography of high energy density (HED) plasmas to isochoric heating of plasmas samples, ions sources for the Fast Ignition approach to Inertial Confinement Fusion.

研究成果の概要（英文）：Ion acceleration with ultra-high intensity lasers is an active area of research with many applications, ranging from ultra-fast radiography of high energy density (HED) plasmas to isochoric heating of plasmas samples, ions sources for cancer therapy and the Fast Ignition approach to Inertial Confinement Fusion. The purpose of the research is to study the TNSA proton beam transport and energy deposition in dense plasmas, as well as the proton beam generation by multi-beam irradiation on target, using the LFEX-GXII laser facility at the Institute of Laser Engineering, Osaka University.
Characterization of the TNSA proton beam source generated by LFEX laser by irradiating thin foils. ii) Study of the influence of multi-beam irradiation on target, with particular attention to the effects of beam interference. iii) Study of proton beam transport in cone geometry using a hemi-shell for proton generation.

研究分野： Laser Plasma Physics

キーワード： Proton accelration　Fast Ignition　Plasma modeling

１．研究開始当初の背景

Ion acceleration with ultra-high intensity lasers is an active area of research with many applications, ranging from ultra-fast radiography of high energy density (HED) plasmas to isochoric heating of plasmas samples, ions sources for cancer therapy and the Fast Ignition approach to Inertial Confinement Fusion.
In particular, the study of generation and energy deposition of proton beams in plasmas is of critical importance for the assessment of Proton assisted Fast Ignition scheme as well as for the study of HED states of matter.
In Proton Fast Ignition the heating of the compressed deuterium-tritium (DT) fuel is induced by a laser-generated proton beam, transporting the laser energy from the laser-plasma interaction region to the core and generating a lateral hot spot from which the thermonuclear burst propagates and ignites the rest of the DT fuel. However several fundamental aspects of this process are still under active investigation. In particular the transport of the proton beams from the generation foil to the compressed core and the proton stopping power in strongly coupled or even degenerate plasmas are not yet well understood. Therefore the study of these processes is of fundamental importance for the assessment of the Proton Fast Ignition scheme.
Moreveor the recent development of multi-kJ, PetaWatt-class lasers, characterized by multi-beam irradiation on target requires the study of new aspects of Physics involving the interaction of ultra-high intensity beams focused on the same focal spot. In particular the interference of the beams can influence the laser plasma interaction and consequently the proton beam acceleration.
The proton acceleration mechanism investigated in this work is the Target Normal Sheath Acceleration (TNSA). In this mechanism the proton acceleration is caused by the space-charge electric field generated by the fast electrons crossing the target vacuum interface.
In order to understand the different aspects of this physical scenario, simulations of proton acceleration and laser-plasma interaction are necessary. Therefore the development of a theoretical/modeling platform for Proton Fast Ignition has been developed for this purpose.

In summary in this work we will deepen the knowledge on these various aspects of the Proton Fast Ignition at ILE and contribute to the development of an experimental platform with the final aim of preparing a Proton Fast Ignition point design.

２．研究の目的

The purpose of the research is to study the TNSA proton beam transport and energy deposition in dense plasmas, as well as the proton beam generation by multi-beam irradiation on target, using the LFEX-GXII laser facility at the Institute of Laser Engineering, Osaka University.
In particular the research can be divided in the following sections:
i) Characterization of the TNSA proton beam source generated by LFEX laser by irradiating thin foils.
ii) Study of the influence of multi-beam irradiation on target, with particular attention to the effects of beam interference.
iii) Study of proton beam transport in cone geometry using a hemi-shell for proton generation.
iv) Study of the ion stopping power and energy deposition in dense, strongly coupled plasmas.
The results of the research will help understand the dynamics of proton beams for Proton Fast Ingnition.
In particular, the point iv) is of great interest since there is no direct measurement of proton stopping power in dense plasmas, but unfortunately due to LFEX laser technical problems, the experiment had to be interrupted and the measurement could not be taken, except for a calibration shot.

３．研究の方法

The research has been carried out at the Institute of Laser Engineering, Osaka University.
A fundamental requirement is characterization of the LFEX laser-generated proton sources. In particular the irradiation of simple foil targets is necessary in order to understand the proton beam characteristics in simple conditions, allowing to compare the results with those present in the literature. The irradiation of simple Al foils of different thickness was performed using LFEX laser at full energy. As diagnostic for the proton

beam, radio-chromic film (RCF) stack diagnostic as well as a Thomson Parabola (TP) spectrometer were used.
Regarding the study of multi-beam irradiation on target, the idea is to perform a single beam irradiation at full energy, followed by a 4 beam irradiation with ¼ of the initial energy in order to keep the same nominal laser intensity on target and evaluate the possible increase in intensity due to the effect of beam interference. The target was a 5 μm Al foil. Fundamental diagnostics for this work are the optical LFEX spot monitor, acquiring images of the LFEX spot on shot at 1ω (1054nm) and 2ω (527nm) wavelength, a magnetic electron spectrometer to measure the escaping electron slope temperature, and TP to measure the proton beam energy.
As for point iii) the study of proton beam transport in Hemi-cone targets has been studied by 2D collisionless particle in cell (PIC) simulations. In particular thanks the the Kakenhi grant it was possible to purchase a workstation, allowing to develop the capability to perform simulations and model future experiments.

４．研究成果

Several experimental and modeling data have been successfully obtained on almost all the research topics investigated.
Concerning the characterization of the proton beam sources in section i) a full data set was obtained.
In particular results from RCF and Thomson parabola are in great agreement, showing that the proton beam had maximum peak energy of 53 MeV for 10μm Al foils target. For thinner targets at P-polarization, the proton beam energy exceeded this value although is difficult to provide a maximum energy due to the limitation of the RCF stack thickness. The measurement also allowed to estimate the laser-to-proton energy conversion efficiency coupling the TP measured proton spectrum with the RCF data, providing the proton angular distribution. The value of the conversion efficiency has been estimated to be around 5% for Al foils and around 9% for CH plastic targets. These high conversion efficiencies are very important since confirm the possibility of sensitively heat up the compressed plasma in Fast Ignition experiments.
The LFEX laser also demonstrated high shot-to-shot stability, providing reliable and consistent proton data.
Concerning the results in section ii), a data set was successfully obtained. In particular a 5 μm Al foil was irradiated by a single beam with 258 J of energy on target, subsequently another 5 μm Al foil was irradiated by 4 beams with a total energy of 278 J on target. Experimental results show a 2 fold higher intensity and smaller focal spot from the LFEX spot monitor. This is assumed to be related to the LFEX beam interference. Electron spectrometer shows a 1.4 fold increase in the fast electron slope temperature in case of multi-beam irradiation compared to the one beam, confirming the 2 fold increase in the laser intensity on target. TP proton spectrum shows a 1.3 fold increase in the proton energy in case of 4 beam irradiation, confirming the data from LFEX focal spot monitor and electron spectrometer. 2D PIC simulations of beam interference confirm the experimental results, showing that higher electron temperature is obtained in case of 2 beam irradiation. This is due to the higher peak intensity on target resulting from the beam interference as well as for a longer expanding plasma scale length. The latter due to the preferential plasma flow in the regions of minimum intensity or destructive interference compared to the uniform irradiation of the 1 beam case. The results will soon be submitted to Physical Review Letters for publication.
Concerning the results of section iii), extensive simulation investigation using 2D Epoch PIC code have been performed. A Hemi-cone target constituted by a Hydrogen Hemi-shell connected to a Au cone, both 40 n_c, the cone is surrounded by a uniform 8nc H plasma mimicking the conditions of an implosion. The simulation results show a clear influence of the return current generated magnetic field on the proton beam dynamics inside the cone. In particular the B-field on the cone walls gets compressed by the incoming proton electron plasma, creating a charge separation between protons and electrons resulting in an electric field collimating the proton beam to the cone tip. On the other hand the B-field at the cone tip is responsible for the generation of an electric field opposed to the proton beam propagation through the cone tip. Moreover the proton beam crossing the cone tip experiences the action of the magnetic field, further amplified by the accumulation of the B-field transported by the proton beam to the cone tip. This

results in proton beam hosing and, for lower energy protons, in a large divergence as they cross the cone tip. This result is fundamental for the assessment of Proton Fast Ignition since it will influence the future point design of this approach. Experimental verification will be performed in the framework of the Firex project at the Institute of Laser Engineering, Osaka University.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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〔図書〕（計　　件）

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〔その他〕
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