

Investigation of dynamics of laser-produced plasmas during the laser-irradiation using collective Thomson scattering

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論文名 : Investigation of dynamics of laser-produced plasmas during the laser-irradiation using collective Thomson scattering (協同的トムソン散乱法を用いたレーザー照射時間帯におけるレーザー生成プラズマ挙動の研究)

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論文内容の要旨

Thesis Summary

Plasma temperature, density, and flow velocity are the critical physical properties of laser produced plasma (LPP) to reveal the ablation dynamics, energy transport, and hydrodynamic evolution. This knowledge, in turn, leads to promising improvements in LPP-based applications, such as pulsed laser deposition (PLD) and extreme ultraviolet (EUV) light source. In the time window during and just after laser irradiation, experimental investigations are very scarce so that many theoretical models remain untested. A clear evolution history of LPP expansion dynamics during and just after the laser pulse time, and in a region very close to the target (typically 0.13–0.6 mm) is investigated using collective Thomson scattering (CTS) method. The electron density (n_e), temperature (T_e), and drift velocity (V_d) in the LPPs were measured, providing a space- and time-resolved 2D profile of the LPP.

As the first step, carbon LPPs were studied to reveal the expansion dynamics of LPPs in this time window. A table-top Nd: YAG laser (at 1064 nm, intensity 6×10^9 W/cm², pulse 7 ns in FWHM) was used to generate the LPP from a planar graphite target, whose width was arranged to be smaller than the laser spot diameter to produce a one-dimensional planar expansion plasma near the target. A second Nd: YAG laser (at 532 nm, pulse 4 ns) was used as the probe laser.

The experimental observations made it possible for the expansion dynamics to be compared directly with the LPP expansion models. The results suggest that during the laser pulse, the LPP is approximately isothermal and expands predominantly one-dimensionally in the target normal direction, in which the LPP drift velocity is found to increase linearly with distance. The linear extrapolation of the velocity indicates that the LPP has a considerable velocity at the initial target surface; this velocity is approximately the speed of sound derived from the observed T_e . The experimental results were found to be in moderate agreement with the 1-D self-similar isothermal expansion model. The ratio of the internal to kinetic energy in the observed area was ~ 0.6 , as predicted by the isothermal expansion model. The experimental findings were compared with the results of the 2-D hybrid code STAR, and good agreement was obtained.

As a next step, we have expanded our diagnostic technique to laser-produced high-Z Tin (Sn) and gadolinium (Gd) LPPs. These are widely used as the light source for nanolithography in modern semiconductor industry. The density (n_e) and temperature (T_e) profiles in LPPs during the laser pulse time, and the dependence of T_e on laser intensities I_L are crucial for LPP light source applications but remain not understood, because the lack of direct measurement results.

Therefore, direct measurements on spatial and temporal profiles of electron density n_e and temperature T_e in laser produced gadolinium (Gd) plasmas was carried out, for the first time. The required relation between T_e and laser intensity are experimentally studied, over a range of laser intensities approximately $10^{10} - 10^{11}$ W / cm². It is revealed that, the measured maximum T_e in Gd LPPs increase with increasing laser intensity with a dependence $T_e \propto (I_L)^{0.37}$. Laser intensity of 1.9×10^{12} W cm⁻² is needed to achieve the optimum condition ($T_e \sim 100$ eV and ion charge states $\sim \text{Gd}^{+18}$, at $n_e \sim (2-3) \times 10^{19}$ cm⁻³) for efficient beyond EUV (BEUV) light source. In addition, two spot size (150μm and 250 μm diameter) are used to study the effect of spot size on T_e profile. Our experimental findings, supported by the simulations, exhibit that bigger spot can create uniform T_e profiles, higher maximum T_e and larger high T_e regions in LPPs. Radiation-hydrodynamic simulation using 2-D hybrid code STAR was performed under identical conditions as used in the experiment, and extended further to higher laser intensities, up to 6×10^{11} W / cm²,

and the results are found in good agreement with the experiment observations.

In conclusion, in this thesis, first direct measurements of electron density (n_e), temperature (T_e), and drift velocity (V_d) inside LPP during laser-irradiation timing have been performed using CTS. In addition, the experimental results were compared with hydro-dynamic simulations. The quantitative comparison between the experiment and simulation study firstly reveals that LPP dynamics during laser-irradiation timing were well explained by 1D self-similar solution models. In addition, this novel technique for LPP have been expanded to high-Z LPP, which were important for light-source application.