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Evaluation of Ion Flux and Ionization Degree in Free-Jet Plasma driven by Wire Explosion
細線爆発で生成される自由噴流プラズマのイオン流束と電離度の評価

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We propose a new method for evaluations of ionization degree of high energy density plasma. A dense plasma is generated by a wire explosion in a quasi-rigid container, and a part of the plasma expands freely into a vacuum through a small hole (throat). Because of the rapid expansion, we can apply a “sudden freeze” model to the freely expanding plasma in which the ionization degree freezes in a thin transition layer. Analytical solutions of the free expansion flow can estimate the relationships among the number density, the temperature, and the velocity profile of particles in the free jet as a function of the distance normalized by the throat diameter. We show that we can estimate the ionization degree of plasma at stagnation, based on an inverse analysis of the results.

1. Introduction

Every matter in an equilibrium state can be placed in a regime of a density-temperature diagram [1,2]. In the diagram, “warm dense matter (WDM)” is defined as a strongly coupled plasma having a temperature of 10^3 to 10^5 K and a number density of 10^{20} to 10^{24} cm^{-3}. When we increase the energy density of a solid, it changes to a plasma inevitably through the WDM region. Thus, when we study the evolution of matter over a wide parameter space, it is important to know the physical properties of the WDM. Recently, importance of the study on the WDM has been recognized, particularly in studies on interiors of giant planets such as Jupiter and the hydrodynamics of fuel pellet of inertial confinement fusion.

However, in the WDM regime, appropriate equations of state (EOS) have not been established in spite of a large amount of experimental and theoretical efforts in this field [3,4,5]. This is due primary to difficulties in accurately measuring the state variables. In laboratory experiments, it is impossible to confine the warm dense plasma for a long time because the WDM state is inevitably accompanied with a high pressure of order of GPa. As a result, experimental data in this parameter region have not yet been obtained so much.

In our laboratory, several experimental attempts have been performed on the WDM study. In the previous studies using wire explosion in water, we obtained electrical conductivities under well-defined condition. Namely, we can define the state by the input energies evaluated from current-voltage properties as well as the plasma densities evaluated from plasma volume [2]. Typical current and voltage waveforms, and the time evolution of a plasma produced by a wire explosion in a semi-rigid glass capillary are shown in ref. 2. Those results showed that well-defined states of warm dense matter can be produced with this experimental configuration.

In this study, we propose a new scheme for the evaluation of ionization degree of WDM based on a semi-experimental approach.

2. Experimental Setup

Figure 1 shows a schematic illustration of the experimental apparatus, with which a WDM is produced by the capillary-confined wire-explosion technique based on pulsed power discharge. A discharge current of several tens of kilo-amperes is driven by coaxially connected low-inductance capacitors which are switched by a pressurized spark gap.

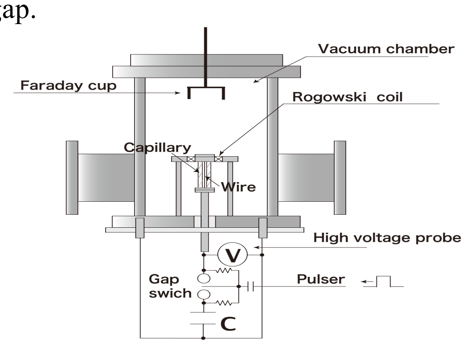

Fig.1. Schematic of experimental setup.

An aluminum wire mounted in a Pyrex glass capillary is rapidly heated by the discharge current during sub-microsecond time scales. The diameter of the wire (typically 50-100 μ m) is chosen so that the skin effect can be negligible. Therefore the input energy is expected to be uniformly distributed in the wire. The voltage across the ends of the capillary and the current through the capillary are measured with a high voltage probe and a Rogowski coil, respectively. Assuming uniform plasma, we evaluate the resistivity of WDM as a function of the input energy density.

In our new scheme, the upper electrode has a small hole (throat) of 0.2 mm in diameter, from which the wire plasma expands freely into the vacuum. A Faraday cup is placed ~10 cm downstream from the capillary, which obtains a current signal of the charged particle flow ejected from the capillary.

3. Experimental Result and Calculation

Figure 2 shows typical ion flux signals at 85 mm downstream from the throat. Several peaks of the ion flux seem to indicate that the stagnation temperature of plasma decays with time.

Figure 3 shows spatial evolutions of the number density and the temperature of free jet estimated by analytical equations, where n_0 is the number density and T_0 is the temperature at stagnation. In the figure, x-tilde shows the position normalized by the throat diameter, and t-tilde is time normalized by the throat transit time of flow.

4. Scheme of Evaluation

In our experimental condition, we can apply the simplified analytical model to the free expansion flow and the "Sudden freeze" model to the recombination process in the plasma [6]. Under these approximations, we can calculate the evolutions of number density, temperature and ionization degree in the freely expanding flow.

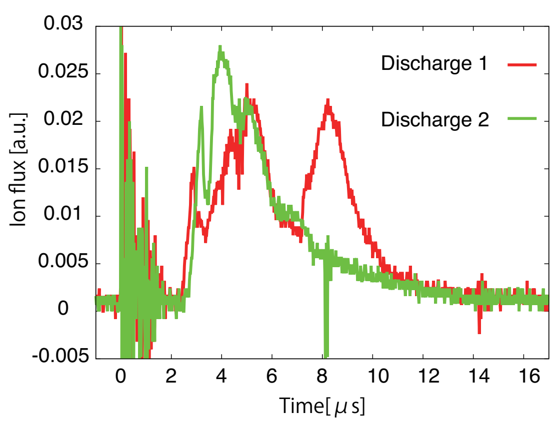

Fig.2. Typical ion-flux signals.

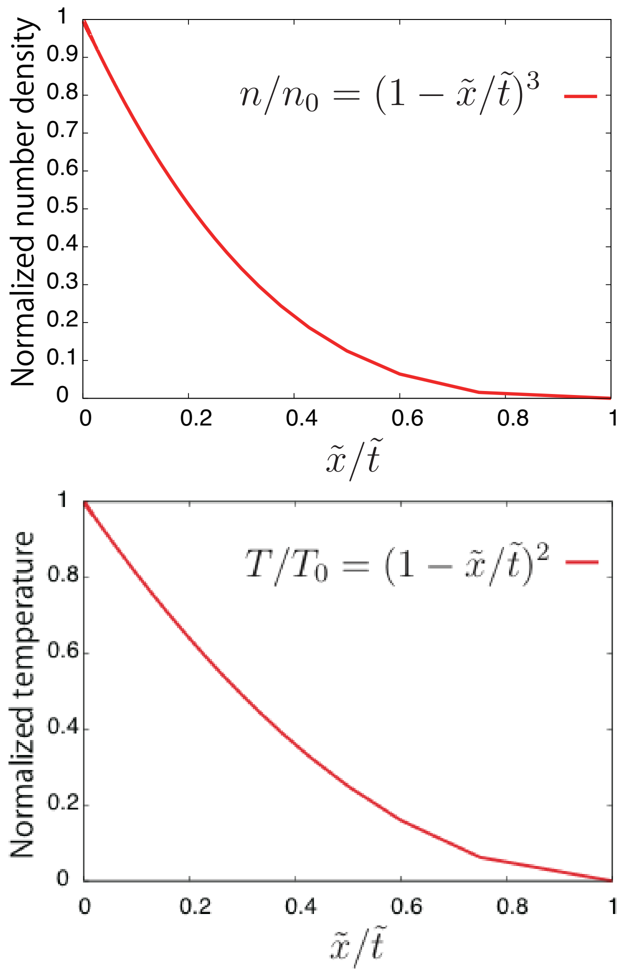

Fig.3. Analytical estimations of number density and temperature of freely expanding flow.

Also we can improve the accuracy by fitting the calculation to the measurements through trial and error iteration. As a result, we can find the initial value of ionization degree corresponding to the ion flux signal. Thus, we are expecting to estimate the ionization degree of warm dense plasma from the ion flux signal by the inverse analysis.

References

[1] K. Horioka: JPSJ. **67,** pp. 252 - 257 (2012).

[2] H. Sakai, K. Iwasaki, M. Nakajima, T. Kawamura, and K. Horioka: NIFS-Proceedings, **90**, pp.36-39 (2012).

[3] S. P. Lyon and J. Jhonson: SESAMI The Los Alamos National Laboratory Equation of State Database, Report No. LA-UR-92-3407.

[4] P. Renaudin, C. Blancard, G. Faussurier and P. Noiret: Phys. Rev. Lett. **88** (2002) 215001.

[5] A. W. DeSilva and H.-J. Kunze: Phys. Rev. E. **49** PP.4448-4454 (1994).

[6] A. A. Morozov, A. B. Evtushenko and A. V. Bulgakov: Appl. Phys. A, **110**, pp.691-696 (2013).