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Warm dense matter study and pulsed-power developments for X-pinch equipment in Nagaoka University of Technology

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ABSTRACT

In order to explore high energy density physics, we have performed WDM experiment by using several pulsed-power devices. To generate well-defined warm dense state for evaluating electrical conductivity and its properties, we have proposed an isochoric heating of foamed metal by using pulsed-power discharge. The proposed technique yields the electrical conductivity of warm dense matter with a well-defined temperature. To observe the warm dense matter, a pulsed-power generator based on a pulse-forming-network (PFN) was studied toward generating an intense point-spot-like X-ray source from X-pinch technique. From comparison of the designing and the actual inductances of the X-pinch system, the actual inductance of X-pinch system is 3.5 times higher than the designing inductance. To reduce the total inductance of X-pinch system, we will modify the gap switch system such as multi spake gap.

1. Introduction

The properties of warm dense matter (WDM) are of interest for studying the prediction of implosion dynamics in inertial confinement fusion, the interiors of giant planets, and the evaluating lifetime of the divertor plates in magnetic confinement fusion [1–5]. Equation of state (EOS) and transport properties of WDM are unclear due to the complex behaviors of the ionion correlations, the degenerate electrons, and so on.

To understand the WDM physics, several experimental and theoretical approaches have been demonstrated [6–21]. To make a warm dense state, ultra-short pulse lasers, pulsed-power discharges, and intense heavy ion beams have been conventionally used. These methods are expected to provide various warm dense matters with different time scales.

On the other hand, the various theoretical evaluations such as the quantum molecular dynamics [7,8,10], *ab-initio* simulations [9,21], or statistical evaluations [3,11–13] have predicted the transport and the optical properties.

In order to evaluate the predicting thermal conductivity in WDM by using the electrical conductivity, the deviation of the Lorenz number has been pointed out for dense hydrogen plasma from theoretical estimations [21]. The Lorenz number L is the ratio between electrical and thermal conductivities divided by the temperature

$$L=\frac{e^2}{k_B T}\frac{\kappa}{\sigma}, \quad (1)$$

where, e is the elementary charge, k_B is the Boltzmann constant, T is the temperature, κ is the thermal conductivity, and σ is the electrical conductivity. The Lorenz number is almost constant in limited condition such as a solid or a plasma. Thus, to clarified the transport coefficients in WDM, the evaluation of thermal conductivity from experimental observations is possible to understand the WDM physics.

To understand the electron behaviors in WDM, the AC electrical conductivity especially in the visible and the ultraviolet regimes should be observed. The AC electrical conductivity in that regimes gives the population of electrons in WDM, in which affects to predict the transport models. The quantitatively evaluation of AC electrical conductivity requires the DC electrical conductivity. However it is difficult to evaluate both of the electrical conductivities, experimentally. Thus, we should consider the measurement methods.

Meanwhile, theoretical models of transport and optical properties exist however experimental data to support these models have heretofore not existed. To measure the above theoretical evaluations, we demonstrate the several approaches with measurement method for generated by the pulsed-power discharges and the intense ion beam. In this paper, we report on the several WDM studies in Nagaoka University of Technology. An isochoric heating of foamed material by using pulsed-power discharges could generate the well-defined density-temperature of warm dense matter [17]. To observe the interior of WDM generated by

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the intense ion beam or the pulsed-power discharge, a pulsed-power generator based on a pulse-forming-network (PFN) was studied toward generating an intense point X-ray source from X-pinch technique.

2. Isochoric heating of foamed material by using pulsed-power discharges

Sophisticated observations of electrical conductivity are required to understand its behavior in WDM. By generating and evaluating WDM for various parameters in a laboratory experiment, we aim to create a well-defined warm dense state and its measurement techniques.

Electrical conductivity measurements of the WDM state have used pulsed-power discharges in underwater [15,16,18] and isochoric heating with slow capacitor banks [6]. For underwater discharges, the WDM density has been evaluated from the expansion radius of the wire/plasma column. The internal energy and/or temperature of WDM have been estimated from the input energy history with an assumed equation of state model or from direct spectroscopic measurements. This method can evaluate electrical conductivity in an arbitrary WDM state as a function of wire/plasma explosion time. However, in dense WDM regime, both the electrical conductivity and wire/plasma density strongly depend on an accuracy wire/plasma radius. On the other hand, the isochoric heating with slow capacitor banks can produce a well-defined condition. However, the vessel should sustain for a long time the high temperatures and pressures of WDM, which are due to the highly energy input into the samples. Therefore, an accurate technique is required to measure pulsed-power discharges for generating WDM.

We have proposed a method to generate WDM that requires the well-defined density-temperature conditions of WDM [17,22]. The detail of a experimental equipment has been described in Ref. [17]. The significant feature of experimental equipment for generating WDM is easy to observe the DC electrical conductivity.

Fig. 1 shows the typical waveforms of isochoric heating of foam by using pulsed-power discharges for $0.1\rho_s$ of copper. As shown in (1), the time evolution of voltage excludes the inductive voltage estimated by the time evolution of current and the stray inductance. The voltage is observed without gap switch. It means that the voltage drop from gap switch can be neglected. The peak voltage is 1.5 kV and the peak current is 60 kA. The input energy for foam/plasma achieves 600 J at 30 μs from beginning of discharges. The internal energy density achieves 3.5 MJ/kg at 30 μs from beginning of discharges. From the observed voltage and current, the electrical conductivity is estimated to be around 10^4 S/m.

Fig. 2 shows the typical emission spectrum of $0.1\rho_s$ of copper at 9 μs from beginning of discharge. From the line spectrum, the temperature of warm dense matter is estimated by using the line-pair method, in which is selected the spectra of Cu I at 477 nm and 622 nm. The estimated temperature is 4000 K at this time. Assuming black body radiation, the radiation loss from the generated WDM is estimated to be 0.1 J. From the comparison of the total input energy and the radiation loss, we can neglect the radiation loss from the generated WDM. The observed emission spectrum is also indicated that the warm dense copper has not only neutral emission of Cu I such as 431 nm, 477 nm, and 622 nm [23] but also ionized emission of Cu II as 550 nm and 651 nm [24]. It means that the warm dense copper has two types of electron behaviors such as the electron localized at conduction band and the ionized electron.

Understanding the electron behaviors, AC electrical conductivity in WDM should be evaluated. For simultaneity evaluation of DC and AC electrical conductivities by using that equipment, we develop a spectroscopic ellipsometry based on a four-detector

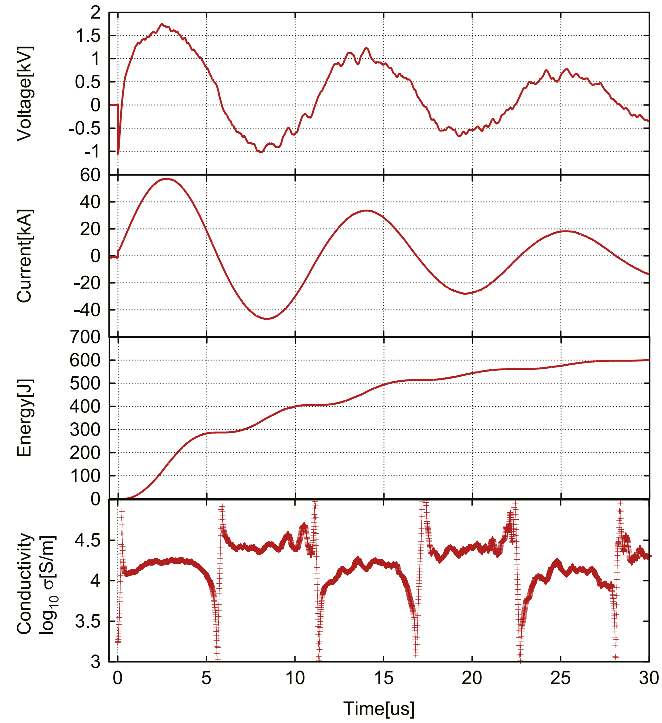

Fig. 1. Typical waveforms of isochoric heating of foam by using pulsed-power discharges.

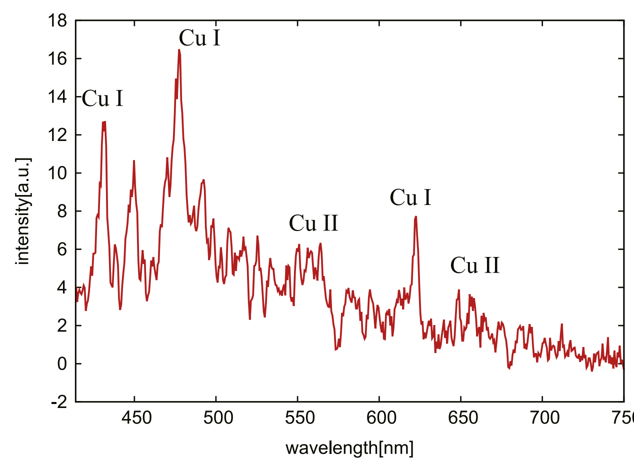

Fig. 2. Typical emission spectrum of $0.1\rho_s$ of copper at 9 μs from beginning of discharge.

photopolarimeter. From the time-evolution of input energy, the required response of detectors is estimated to be order of a few MHz. To measure the detailed spectrum, the conventional spectroscopes are too slow due to the slower reading of charge-coupled-device (CCD) signals. On the other hand, the fast spectroscopes such as the spectroscopes mounted on the steak camera or the fast flaming ICCD are expensive. Thus, we develop the spectrometer based on a data logger and a plane focusing grating.

The Lorenz number in WDM is also interesting parameter for understanding the electron behaviors. Currently, we have developed a semi-empirical estimation of the thermal conductivity from the evaluated electrical conductivity with the Wiedermann–Franz law [25]. From the comparison of the degeneracy parameter and the thermal conductivity behavior, the estimated degeneracy parameter is excess the inflection point at around