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Evaluation of Transport Properties in Warm Dense Matter Generated by Pulsed-power Discharge for Nuclear Fusion Systems

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Abstract

To achieve the thermonuclear fusion systems, the physical properties of warm dense matter (WDM) are key parameters. In this paper, we review the evaluation of physical properties in WDM by using pulsed-power discharges. To evaluate the thermal conductivity for a divertor wall in magnetic confinement fusion, we investigate a semi-empirical evaluation based on the experimental values for electrical resistivity. The results indicate that, in the region between the intermediate degeneracy and the non-degeneracy, the evaluated thermal conductivity has an inflection point. To evaluate the electrical resistivity for the fuel target in the inertial confinement fusion, an isochoric heating by using pulsed-power discharge in the pressure vessel has been demonstrated. The results indicate that the electrical resistivity in WDM for gold is 100 $\mu\Omega \cdot$ m at $0.1\rho_s$(ρ_s: solid density) of density and the internal energy is 1 MJ/kg.

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1. Introduction

To achieve gains from thermonuclear fusion energy, we consider confinement schemes such as magnetic confinement fusion (MCF) and inertial confinement fusion (ICF).

To realize MCF such as at the international thermonuclear experimental reactor (ITER) and DEMO, the properties of wall materials should be known to design and construct the systems. A divertor wall, which sustain buildup of fusion products and impurities in the vessel lining, is one of the key devices. However, the divertor is irradiated by highly energetic particles from fusion plasma. The heat load on the divertor for ITER is estimated to be 10 MW/m^2 at a steady state and 1000 MW/m^2 in plasma disruption and mitigated edge localized modes (ELMs) [1, 2, 3, 4]. Up to now, the heat load on the divertor in previous MCF systems has been unreached parameter. Thus, to predict properties of the divertor under these heat loads, several experiments have been performed using electron [5] or plasma guns [6, 7], or intense laser intended to

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reproduce relevant heat fluxes [8]. These experiments have mainly been employed to evaluate metallurgical characteristics of the tungsten divertor. However, to predict the performance of the tungsten divertor in MCF, we should analyze not only metallurgical properties but also thermophysical properties of ablated tungsten.

In ICF, the target structure affects ignition due to hydrodynamic compression of the fuel. Based on comparisons of the implosion dynamics by different equation-of-state (EOS) models, the maximum density, the ρR, and the time of maximum compression are influenced by the discrepancies in EOS models in the warm dense matter (WDM) region. On the other hand, a cone guide is used for the fast ignition scheme of ICF because of the efficient heating to compressed DT fuel [9]. This fast ignition scheme of ICF requires timing the irradiation of heating laser and transport of laser-generated fast electrons. The coupling efficiency of laser energy to these fast electrons and the energy deposited in the fuel should be improved by optimizing the cone material and its electrical resistivity in the ablated state. Thus, we should confirm the electrical resistivity of the ablated cone material.

To clarify these topics, we should understand the physical properties of WDM. WDM physics is applied when the density ranges from $10^{-3}\rho_s$ (ρ_s is the solid density of matter) to $10\rho_s$ and the temperature ranges from 0.1 eV to 10 eV. WDM offers the possibility for scientific exploration of the properties of plasma at high densities and moderate temperatures. In WDM, the Coulomb interaction energy between particles sometimes exceeds the thermal energy $k_B T$.

Recently, a number of theoretical approaches have been developed. They include quantum molecular dynamics (QMD) simulations [10, 11, 12, 13] to evaluate electron correlations and statistical methods [14, 15, 16] for estimating the degree of ionization and the degeneracy of plasmas. Furthormore, we have been able to produce the warm dense state in the laboratory using various experimental methods, such as ultra short pulse lasers, heavy ion beams, and pulsed-power discharges [10, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29]. We should experimentally evaluate the WDM state as a function of the thermodynamic parameters, particularly, density, temperature, internal energy, and pressure. Advantages of WDM state generated by pulsed-power discharges compared to that by the other method are ease of evaluation of resistance by direct measurements and simplified sample structure as an axial symmetrical plasma.

For this paper, we experimentally investigated transport properties of WDM for the thermonuclear fusion. To understand the thermal conductivity of the divertor in MCF, we evaluated thermal conductivity as a function of normalized parameters: a degeneracy parameter for electrons and a coupling parameter for ions and electrons. To evaluate the electrical resistivity in WDM gold, we measured the electrical resistivity as a function of internal energy.

2. Thermal conductivity evaluation of the divertor in MCF

To prolong the lifetime of the divertor, it should be composed of tungsten. Fusion plasma is sensitive to ablated tungsten because of radiative losses associated with high- Z impurities; therefore, we should understand the effects induced by the ablated tungsten. The ablation plasma evolves through a warm dense state in which coupled ions, degenerate electrons, and the liquid-vapor phase transition should affect thermal conductivity. Typically, for WDM in the case of MCF, the temperature of tungsten vapor is estimated to be approximately 6000 K because of vaporization from the divertor wall. The density of tungsten vapor depends on the expansion regime from the divertor wall to the core plasma. In this study, we focus on a region of near the divertor wall when the divertor is irradiated by highly energetic particles from the fusion plasma. To understand transport properties, thermal transport and heat capacity in ablated tungsten should be evaluated using semi-empirical approaches.

The warm dense state is characterized by the ion-electron coupling parameter Γ_{ei} and the degeneracy parameter θ for electrons. Here Γ_{ei} is a measure of Coulomb interactions and is defined as the ratio of the average Coulomb interaction energy to the average kinetic energy

$$\Gamma_{ei} = \frac{Z_{eff} e^2}{4\pi\epsilon_0 a k_B T}, \tag{1}$$