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Evaluating Thermal Conductivity of Dense Tungsten Plasma toward Thermal Transport in Divertor

ダイバータの熱輸送特性評価に向けた高密度タングステンプラズマの熱伝導率解析

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Understanding properties of warm dense tungsten, we have proposed a semi-empirical evaluation method of transport coefficients as a thermal conductivity. The electrical conductivity of warm dense tungsten has been evaluated by the exploding wire discharge in water and the isochoric heating of wire in a vacuum. The results indicate that the thermal conductivity derived by the electrical conductivity is from 0.1 to 100 $WK^{-1}m^{-1}$ at temperature of 5000 K.

1. Introduction

Type of Tokamak in magnetic confinement fusion such as ITER and DEMO requires a divator. The divator is irradiated by the highly energetic particles from confined plasmas. Heating load on divator is estimated to be 10 MW/m^2 at steady state and 1000 MW/m^2 at plasma disruption condition. To prolong the lifetime, the divator is going to be made by tungsten. Ablated tungsten affects to the fusion plasmas because of high-Z elements. Therefore, we should understand the effect of fusion plasma induced by the ablated tungsten. The ablated tungsten achieves warm dense state, which affects the coupled ions and the degenerated electrons including phase-transition such as liquid-vapor, triplet points. The thermal transport and the heat capacity in ablated tungsten should be evaluated.

We proposed the evaluation of thermal transport coefficients and the heat capacity in ablated tungsten by using pulsed-power discharge and semi-empirical estimation. The pulsed-power discharge can evaluate the electrical conductivity in warm dense state, directly. Thermal transport coefficients in ablated tungsten may be recommended the ordinary relations.

2. Experimental setup

The experimental layout is previously published study using exploding wire discharge in water [3] and isochoric heating confined by sappier vessel [4]. To drive a wire explosion, we arranged low inductance capacitors cylindrically (8×0.4 μF). The capacitor bank was charged up to 10 kV to ensure vaporization of the wire.

The mass density and temperature assuming local thermodynamic equilibrium is evaluated by the ratio of radius and the black body emission. The input energy history and the electrical conductivity is evaluated by the voltage-current waveforms and the expansion radius.

3. Results and Discussions

Figure 1 shows the electrical conductivity as a function of density at constant temperature in tungsten. Theoretical electrical conductivities based on the models of Spitzer [5], Lee-More [6], and Ichimaru [7] at 5000 K are also shown in Fig. 1. Figure 1 also indicates COMPTRA04 [8,9] made by Kuhlbrodt and Redmer at 10000 K. These results cover a wide density range for a material, from a liquid metal having highly degenerated electrons to plasma that approaches to ideal plasma conditions. COMPTRA04 indicates, fairly well, the dependence of high density regime of $\log_{10}(\rho/\rho_s) > -1.5$.

From these results, we reconstruct the thermal conductivity as following equation [10],

$$\kappa = \left(\frac{\pi^2}{3}\right)\left(\frac{k_B}{e}\right)^2 T\sigma, \quad (1)$$

where, κ is the thermal conductivity, k_B is the

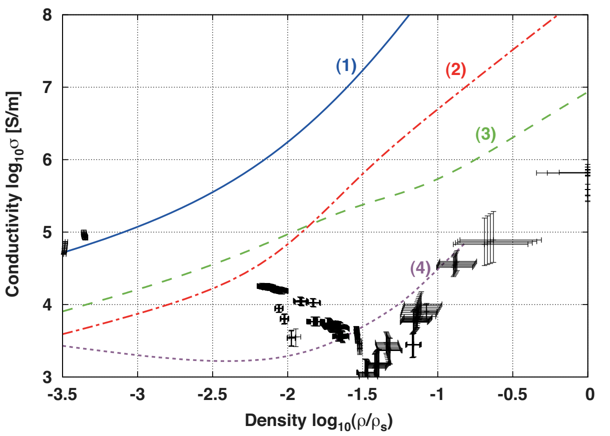

Fig. 1 Electrical conductivity of tungsten as a function of density at 5000K$\pm$10%. The solid line as (1) indicates the Spitzer conductivity model [5], the dash-dotted line as (2) reveals the Ichimaru conductivity model [6], the dashed line as (3) denotes the Lee-More conductivity model [7], and the dotted line as (4) Kuhlbrodt and Redmer model from COMPTRA04 at temperature of 10000K.

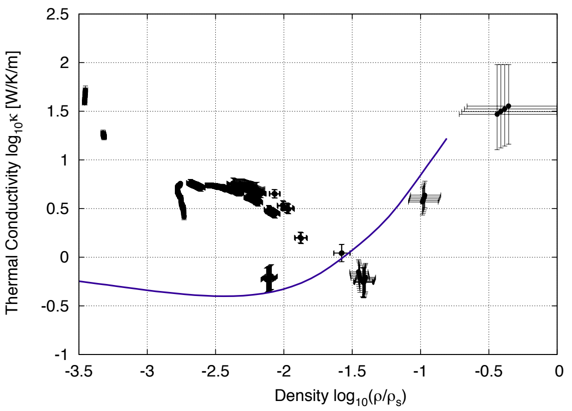

Fig. 2 Thermal conductivity of tungsten as a function of density at 10000K$\pm$10%. The solid line indicates COMPTRA04.

Boltzmann constant, e is the elementally charge, T is the temperature, and σ is the electrical conductivity.

Figure 2 shows the thermal conductivity as a function of density at constant temperature of 10000 K. Theoretical thermal conductivity based on the model of COMPTRA04. The results indicated that the thermal conductivity from empirical evaluation is almost comparative to the theoretical model of COMPTRA04 in high density regime of $\log_{10}(\rho/\rho_s)$ > -1.5. Thus, the method of empirical thermal conductivity estimation by using electrical conductivity is valid for the high density regime.

Figure 3 shows the thermal conductivity as a function of density at constant temperature of 5000 K. The predicted thermal conductivity reduces at $\log_{10}(\rho/\rho_s)$>-1.5. The minimum thermal

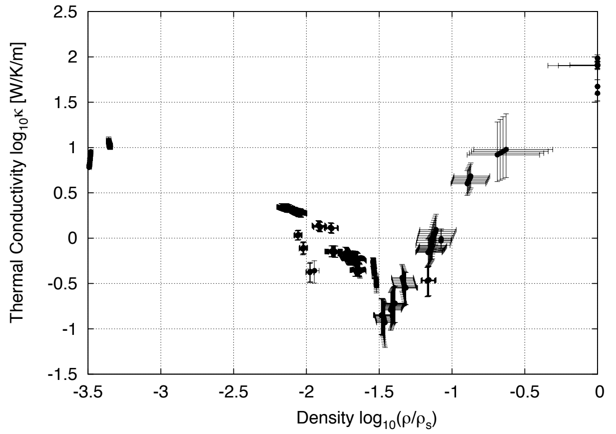

Fig. 3 Thermal conductivity of tungsten as a function of density at 5000K$\pm$10%.

conductivity is estimated to be 0.1 WK^{-1}m^{-1}.

4. Summary

We proposed semi-empirical evaluation method for thermal conductivity of dense tungsten for disrupted fusion plasma by using puled-power discharges. This method can predict the thermal conductivity from solid density to $\log_{10}(\rho/\rho_s) > -1.5$. The predicted thermal conductivity reduces at $\log_{10}(\rho/\rho_s) > -1.5$ with 5000 K of temperature. The results indicate that the thermal conductivity derived by the electrical conductivity is from 0.1 to 100 WK^{-1}m^{-1} at temperature of 5000 K. We will demonstrate the numerical simulation of thermal conductions and crosschecked evaluated thermal conductivity.

Acknowledgments

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