Evaluation Method for Thermal Conductivity in Warm Dense Matter by using Ruby Fluorescence Probe

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Abstract. We have proposed a concept of experimentally estimating thermal conductivity in warm dense matter from the ruby fluorescence. To reduce the dimension of the system, a cylindrically arranged sample tamped by the ruby capillary has been considered. From the estimated ruby temperature, in which is simulated by the time-dependent thermal diffusion in equation, the ruby fluorescence can be obtained from 0.5 mm to 0.6 mm. The results indicated that the low density regime as $\rho/\rho_s < 0.004$ is possible to evaluate the ruby fluorescence.

1. Introduction

Magnetic confinement fusion (MCF) such as international thermonuclear experimental reactor (ITER) and DEMO is expected to use a divertor made of tungsten, which is the highest melting temperature in the material [1]. The tungsten divertor is exposed by the highly energetic particles from the core plasmas. The heat flux from the highly energetic particles on the divertor in ITER is estimated to be 10 MW/m² at steady state and over 1000 MW/m² at plasma disruption and mitigated edge localized modes (ELMs) [2, 3, 4]. Up to now, all of MCF systems cannot reach the heat flux expected during ITER ELMs. To evaluate the heat flux during ITER ELMs, the several experiments have been demonstrated by using electron[5] or plasma guns[6, 7], or intense laser aiming at reproducing relevant heat fluxes[8]. These experiments have mainly evaluated metallurgical characteristics of tungsten divertor. Predicting performances of tungsten divertor in MCF, we should analyze not only the metallurgical properties but also the thermophysical properties of ablated tungsten. The ablated tungsten is a warm dense matter and its properties should be evaluated.

The physics of warm dense matter (WDM) are interested in transport coefficients. The transport coefficients have been evaluated by quantum molecular dynamics[9, 10], statistical modeling[11, 12, 13], and ab initio simulations[14]. Recently, in order to evaluate the transport properties in WDM, the deviation of the Lorenz number have been pointed out for dense hydrogen plasma from theoretical estimations[14]. The Lorenz number $L$ is the ratio between
electrical and thermal conductivities divided by the temperature, \( L = \frac{e^2}{k_B T} \), which, \( e \) is the elementary charge, \( k_B \) is the Boltzmann constant, \( T \) is the temperature, \( \kappa \) is the thermal conductivity, and \( \sigma \) is the electrical conductivity. From the previous semi-empirical evaluation, the dense thermal conductivity evolution is similar up to the degenerate regime. Thus, the thermal conductivity for low density regime should evaluate the thermal conductivity from experimental observations.

In this paper, we propose a concept of experimentally estimating thermal conductivity in warm dense matter from the ruby fluorescence. To estimate the region of the ruby fluorescence, the temperature of the ruby by using one-dimensional numerical simulation is evaluated. To confirm the timing to generate the warm dense tungsten, we demonstrate an exploding wire discharge in vacuum.

2. Concept of experimental observation of the thermal conductivity in dense tungsten plasma as a method of ruby fluorescence probe

We consider the direct measurement method by using ruby fluorescence probe. The ruby is usually use the pressure gauge for high pressure experiments as a diamond anvil cell method. Mao [15] has been developed a formula of the fluorescence shift as a function of pressure. The lifetime of ruby fluorescence depends on the ruby temperature [16]. Thus, the ruby fluorescence is expected to use a probe for the evaluating ruby temperature.

To obtain the thermal conductivity in dense tungsten plasma, the sense of the measurement method is following equations.

\[
Q = -\kappa \nabla T, \tag{1}
\]

\[
\frac{\partial T}{\partial t} = \frac{1}{\rho C_v} \nabla \cdot \kappa \nabla T, \tag{2}
\]

where, \( Q \) is the heat flux, \( T \) is the temperature, \( \rho \) is the density, and \( C_v \) is the specific heat. To solve the equation, we should understand the physical properties of each medium. To evaluate the specific heat of dense tungsten plasma, the pulsed-power discharge technique is compatible due to the correctly evaluation of the input energy and the temperature for dense tungsten.
plasma. From the time-resolved spectroscopic measurements of both the sample and the ruby fluorescence, we determine the temperature of dense tungsten plasma and that of ruby capillary. The time evolution of input power for the dense tungsten plasma is directly estimated by the input voltage and the current. Therefore, the specific heat of the dense tungsten plasma as a function of that temperature decide the time evolution of input power.

Figure 1 shows the typical image of a direct measurement method for the dense tungsten plasma by using ruby fluorescence probe. The dense tungsten plasma is generated by the pulsed-power discharge. The ruby capillary as a tamper can be sustain the high pressure up to 3 GPa, which is enough to conserve the dense tungsten plasma without hydrodynamic behavior.

The ruby fluorescence decreases the increasing temperature of ruby. Therefore, in order to evaluate the achieving temperature of ruby, we have estimated by a numerical simulation of the thermal diffusion equation. The hydrodynamic behavior is neglected due to the confined dense tungsten plasma by the ruby capillary. The initial condition of the numerical simulation is set to be 5000 K for the dense tungsten plasma and 300 K for the ruby capillary. The radii of the dense tungsten plasma and the ruby capillary are 0.5 mm and 2.0 mm, respectively. The thermodynamic properties and the thermal conductivity for both mediums are respected to be Refs. [17, 18, 19].

Figure 2 shows the radial temperature distribution profile at 50 μs. Evaluated ruby temperature is approximately from 800 K at the boundary between the ruby and the dense tungsten plasma to 300 K at 0.6 mm in radius. It reveals that the ruby fluorescence can be obtained from 0.5 mm to 0.6 mm. The ruby fluorescence are possible to observe the spectroscopic measurements. Figure 3 shows a maximum temperature of ruby capillary as a function of initial temperature and density of tungsten plasma. The results indicated that the low density regime as $\rho/\rho_s < 0.004$ is possible to evaluate the ruby fluorescence. Thus, the thermal conductivity in low density regime can be evaluated by this method.

3. Experimental results and discussion
To evaluate the thermal conductivity from the ruby fluorescence, we estimate a behavior of the exploding wire for tungsten in vacuum. To confirm the behavior of the exploding wire for
tungsten, we have measured a time-evolution of the exploding wire for tungsten with $\phi = 0.2$ mm in the vacuum as shown in Fig. 4. From the time-evolution of the voltage and the current, the time of vaporization is 220 ns from the beginning of discharge. The time of vaporization ensures the comparison of between the experimental observation and the numerical estimation. After the vaporization of wire, the wire/plasma radius which is observed by the streak camera expands as a function of time. The expansion velocity of the wire/plasma is estimated to be $5 \times 10^3$ m/s. Assuming 1 mm of the interior diameter of the ruby capillary, the propagation time of the tungsten plasma is estimated to be about 100 ns for filled in the capillary. The density distribution of plasma is made uniform through the propagation of rarefaction (sound) wave; in our experimental condition, the sound wave in the plasma propagates within a hundred nanoseconds. Thus, the thermal conductivity for the dense tungsten plasma is possible to evaluate after 500 ns from the beginning of discharge.

4. Conclusions
We have proposed a concept of experimentally estimating thermal conductivity in warm dense matter from the ruby fluorescence. To reduce the dimension of the system, a cylindrically arranged sample tamped by the ruby capillary has been considered. From the estimated ruby temperature, in which is simulated by the time-dependent thermal diffusion in equation, the ruby fluorescence can be obtained from 0.5 mm to 0.6 mm. From the numerical evaluation, The results indicated that the low density regime as $\rho/\rho_s < 0.004$ is possible to evaluate the ruby fluorescence. the ruby fluorescence probe are possible to evaluate the thermal conductivity in dense plasma.

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