

Input energy measurement toward warm dense matter generation using intense pulsed power generator

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Abstract. In order to investigate properties of warm dense matter (WDM) in inertial confinement fusion (ICF), evaluation method for the WDM with isochoric heating on the implosion time-scale using an intense pulsed power generator ETIGO-II (~ 1 TW, ~ 50 ns) has been considered. In this study, the history of input energy into the sample is measured from the voltage and the current waveforms. To achieve isochoric heating, a foamed aluminum with pore sizes $600\text{ }\mu\text{m}$ and with 90% porosity was packed into a hollow glass capillary ($\phi 5\text{ mm} \times 10\text{ mm}$). The temperature of the sample is calculated from the numerical calculation using the measured input power. According to the above measurements, the input energy into a sample and the achievable temperature are estimated to be 300 J and 6000 K. It indicates that the WDM state is generated using the proposed method with ICF implosion time-scale.

1. Introduction

In inertial confinement fusion (ICF), understanding implosion dynamics of fuel pellet is a key issue to obtain effective nuclear fusion reactions. To suppress the implosion non-uniformity, a foamed metal such as a pusher and a radiator is considered as structural materials in the fuel pellet [1]. Implosion of the fuel shell is driven by beam energy deposition with an energy driver, and the target material becomes dense plasma through warm dense matter (WDM) region with the implosion time-scale (several-10 ns). The WDM region pertains to densities from 10^{21} to 10^{24} cm^{-3} and for temperature varying from 10^3 to 10^5 K. However, the WDM is complex regime, because of unclear theoretical model and lacked experimental evaluations.

To understand the implosion dynamics, numerical simulations are crucial approach. However, the implosion dynamics from the numerical simulation result depends on EOS model in WDM [2]. There is no accurate and useable EOS model for the numerical simulation. The achievable parameters such as the confinement parameter and the moment of stagnation are affected by the properties of WDM in early stage of implosion. Therefore, to predict the implosion dynamics, the properties in WDM such as equation of state should be cleared.



In previous studies, a short pulse laser and a pulsed power discharge were used for the measurement for properties of WDM [3, 4]. In the case of that foamed metal with a cellular structure is heated with several-10 ns, which is similar to the time-scale of hydrodynamic behavior of material, the relationship between heating time-scale and properties of matter is not well known. In order to estimate the more accurate temperature of the fuel pellet during implosion, the specific heat evaluation method for the WDM with isochoric heating [5] on the implosion time-scale using an intense pulsed power generator ETIGO-II (~ 1 TW, ~ 50 ns) [6] has been considered [7]. To measure the specific heat, the evaluation method for history of the internal energy and the temperature of the sample should be established. The internal energy need to be measured with the input energy and the sample mass. The temperature need to be measured with an optical system using spectroscopic measurement. In this study, the input energy into a sample is measured from the voltage and current waveforms. As a result of establishing the measurement method of input energy, the internal energy for the specific heat is obtained.

2. Measurement for input energy into sample

To investigate the properties of WDM as a function of temperature, the current control into the sample with an electron beam diode as an impedance controller has been proposed [8]. In this study, the input energy measurement is performed with short circuit condition without the electron beam diode.

Figure 1 shows the experimental setup for history of input energy into the sample. To achieve isochoric heating, the sample, which is a foamed aluminum with pore sizes ~ 600 μm and with $\sim 90\%$ porosity, was packed into a hollow glass capillary (ϕ 5 mm $\times$ 10 mm). The average mass and the average density of the sample in the capillary are ~ 60 mg and $\sim 0.1\rho_s$ (ρ_s is solid density of aluminum: 2699 kg/m³), respectively. history of the current $I(t)$ needs to be measured with a Rogowski coil. The voltages need to be measured with using resistive dividers before and behind the sample. The resistive divider consists of two-stage non-inductive resistors of $R_1 = 1.5$ k Ω and $R_2 = 5$ Ω . When a transmission line is terminated in its characteristic impedance $Z_0 = 50$ Ω , the resistive voltage divider's ratio was designed 615 times. history of the voltage $V(t)$ is measured to be $V(t) = V_1(t) - V_2(t) - LdI(t)/dt$, where $V_1(t)$ is the voltage at the ground, $V_2(t)$ is the voltage between the sample and ground, the stray inductance is estimated as $L = 98$ nH. The input power $P(t)$ and the input energy $E(t)$ into the sample is measured to be $P(t) = V(t)I(t)$, $E(t) = \int P(t)dt$.

Figure 2 shows the current and voltage waveforms and input power and energy into the sample with a short circuit condition. Figure 2, to compare with the heating time-scale and the implosion time-scale, t_o and t_f are defined as the rise time of the input power and the time 50 ns from t_o . The pulse width was 100 ns (FWHM), with peak voltage and current values of 80

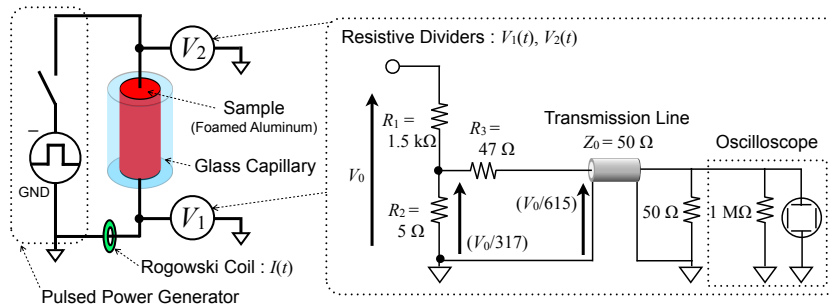


Figure 1. Experimental setup for history of input energy into sample.

kV and 140 kA, respectively. Peak input power and the input energy into the sample achieved 10 GW and 400 J at t_f .

3. Numerical calculation for temperature of sample

To estimate the achievable temperature, the history of the temperature of sample $T(t)$ is estimated from numerical calculation using measured input power $P(t)$.

The history of the temperature of sample $T(t)$ is estimated to be

$$T(t) = \int \frac{P(t)dt}{r^2\pi \cdot l \cdot \rho_{\text{foam}} \cdot c(\rho, T)}, \quad (1)$$

where the input power $P(t)$ is given by the corresponding experimental data as shown in Fig. 2, l is the length of the sample with 10 mm, r is the radius of the sample having 2.5 mm, the density of foamed aluminum sample is $\rho_{\text{foam}} = 0.1 \rho_s$ and $c(\rho, T)$ is the specific heat that the data of aluminum in solid, liquid, and gas phases are given by Refs. [9, 10]. The initial temperature is set at 300 K.

Figure 3 shows the calculation result of the temperature as a function of the time. The temperature of the sample achieved 7000 K at t_f . Figure 4 shows the peak current as a function of gap distance of electron beam diode. In short circuit condition (gap distance: 0 mm), the peak current increased that is compared with the case of adjustment of gap distance in electron beam diode [8]. Figure 5 shows the temperature as a function of input energy at the t_f . In short circuit condition, the averaged input energy and temperature were 300 J and 6000 K, respectively.

4. Conclusion

In order to investigate the properties of WDM in ICF, input energy measurement toward WDM generation using intense pulsed power generator was performed.

The input power and the input energy were estimated with experimentally obtained current and voltage waveforms. Peak input power and the input energy into the sample achieved 10 GW and 400 J at the time t_f . The achievable temperature of the sample was estimated from calculation using the input power. The temperature for the sample of foamed aluminum ($0.1\rho_s$)

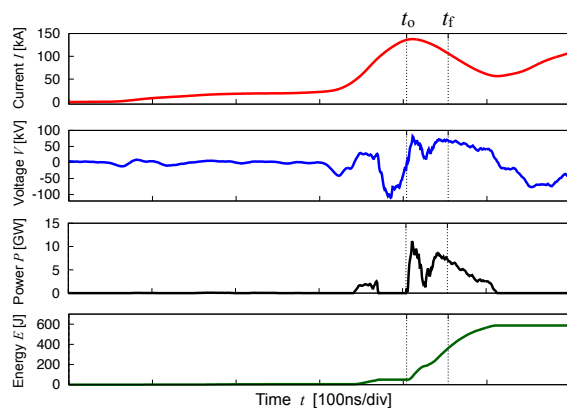


Figure 2. Current and voltage waveforms and input power and energy into the sample with short circuit condition.

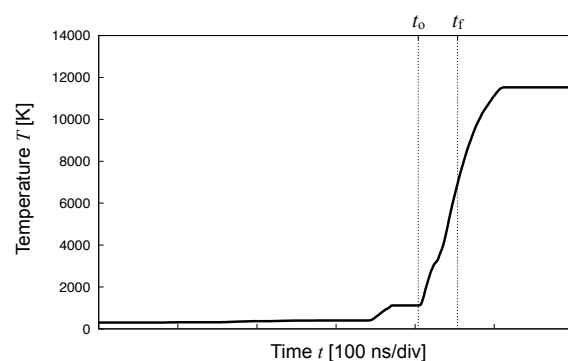


Figure 3. history of sample temperature. (t_0 and t_f are defined as the rise time of the input power and the time 50 ns from t_0 .)

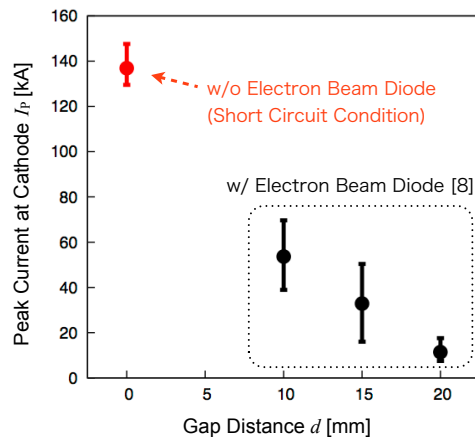


Figure 4. Peak current as a function of gap distance of electron beam diode. The error bars indicate maximum and minimum values.

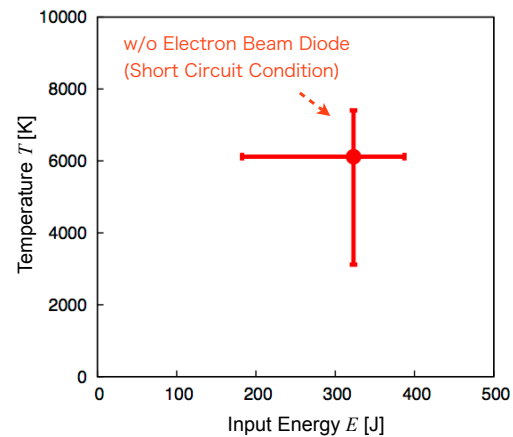


Figure 5. Temperature at t_f as a function of input energy. The error bars indicate maximum and minimum values.

was several-1000 K at the time t_f . In short circuit condition, the peak current increased that is compared with the case of adjustment of gap distance in electron beam diode.

According to above results, the measurement method of input energy with the current and voltage waveforms for the estimation of internal energy was established.

Acknowledgments

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