Estimation on Achievable Parameter Regime of Warm Dense Matter Generated by Isochoric Heating Discharge using Intense Pulsed Power Generator

Ryota Hayashi¹, Kenji Kashine², Akira Tokuchi¹, Akira Tokuchi¹, Fumihiro Tamura¹, Arata Watabe¹, Takahiro Kudo¹, Kazumasa Takahashi¹, Toru Sasaki¹, Takashi Kikuchi¹, Tsukasa Aso¹, Nob. Harada¹, Weihua Jiang¹

¹ Nagaoka University of Technology, Kamitomioka 1603-1, Nagaoka, 940-2188, Japan
² Yuge National College of Maritime Technology, Simoyuge 1000, Yuge, Kamijima, 794-2593, Japan
³ Pulsed Power Japan Laboratory Ltd., Nomura 4-5-2, Kusatsu, 525-0027, Japan

E-mail: r_hayashi@stn.nagaokaut.ac.jp

Abstract. An evaluation method for warm dense matter (WDM) with similar timescale in inertial confinement fusion (ICF) by isochoric heating using intense pulsed power generator ETIGO-II is considered for evaluating target behavior. The temperature increase of the sample is estimated from the numerical calculation using the measured current. As a result, in the case that the shape of sample is φ2 mm x 10 mm and the density is 0.01 times solid density of copper, the temperature of sample increases up to 30000 K. It is expected that the WDM is generated using the proposed method with ICF implosion timescale.

1. Introduction

In inertial confinement fusion (ICF) driven by heavy ion beams, the target consists of a fuel, a pusher, a tamper and an X-ray converter. The fuel target is rapidly imploded by irradiation from the energy driver. The fuel becomes dense plasma at the centre of the target, and causes thermonuclear fusion reactions.

In the implosion process, especially, regime around solid density (10²¹~10²⁴ cm⁻³) and relatively low temperature (10³~10⁵ K) is called as warm dense matter (WDM) [1, 2]. The pusher becomes from solid to plasma through WDM regime during the implosion process. To understand the implosion dynamics in ICF, numerical simulations are crucial approach. The hydrodynamics of fuel target behaviour from the numerical simulation depends on pressure and speed of sound in WDM [3]. Therefore, the reliable physical properties of matter are required for estimation on WDM regime. However, WDM is the complex regime, because of unclear theoretical model and lack of experimental evaluations. In addition, the implosion uniformity is important to obtain the nuclear fusion reactions. To suppress the implosion non-uniformity in ICF, a foamed metal is used for the pusher or the X-ray converter [4, 5].

To understand the physical properties of matter, the evaluation method for WDM by isochoric heating [6] using intense pulsed power generator ETIGO-II (~1 TW, ~50 ns) [7] with similar timescale
of implosion has been considered. The features of the method are possible to generate WDM state with several-10 nanoseconds, isochoric condition and direct spectroscopic measurement using a rigid-wall capillary having transparency, and avoiding the skin effect with foamed metal sample.

In this study, the experimental apparatus is considered, and the achievable temperature of sample is estimated to understand the properties of WDM in wide temperature regime. The achievable temperature of the foamed metal sample is controlled by changing gap distance of an electron beam diode. Using the measured electron beam current, the achievable temperature is estimated by numerical calculations.

2. Experimental setup for measuring current
To control the current into the sample provided by ETIGO-II, an electron beam diode, which is placed at the output terminal of ETIGO-II, is used. The electron beam diode, which consists of a disk-shaped cathode ($\phi 105$ mm, SUS 304) and a disk-shaped anode ($\phi 210$ mm, SUS 304), is used as an adjustable resistance in the pulsed power system.

Figure 1 shows the experimental setup for measuring current of the electron beam diode. The provided current was measured in the gap distance for 10, 15, and 20 mm, respectively. Time evolution of the current $I(t)$ is measured with a Rogowski coil. To interfere the electrical breakdown, the interior pressure of the chamber was controlled to be less than 0.02 Pa. The electron beam current and the impedance are decided by the gap distance.

The sample is a foamed metal surrounding with a hollow rigid-wall capillary. The capillary is sapphire, which is possible to sustain up to ~GPa. The sample is placed on the anode side of the electron beam diode. However, the input power into the sample depends on the diode impedance because of relatively high impedance of the diode. Therefore, the current at cathode is measured without the sample, and the anode is grounding to the outer feeder.

3. Numerical model for temperature increase of sample
To estimate the achievable parameter regime of WDM generated by isochoric heating, the sample impedance of the foamed copper $R$ is estimated to be

$$R = \frac{l}{\sigma \cdot S}, \quad (1)$$

where, $l$ is the length of the sample with 10 mm, $\sigma$ is the electric conductivity ($10^4$ S/m is assumed from the previous experimental results [6, 8, 9]), the cross sectional area of the sample $S$ is determined with $r^2\pi$, and $r$ is the radius of the sample (1 mm).

![Figure 1. Experimental setup for measuring current.](image_url)
The time evolution of the temperature increase of sample $\Delta T(t)$ is estimated to be

$$
\Delta T(t) = \int_{t_1}^{t_2} \frac{I(t)^2 R dt}{S \cdot l \cdot \rho_{\text{foam}} \cdot C_p(t)}, \tag{2}
$$

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

$$
T(t) = \Delta T(t) + 298, \tag{3}
$$

where, $t_1$ is the onset time of the discharge, $t_2$ is the time after 50 ns from $t_1$, the current at the cathode $I(t)$ is given by the corresponding experimental data as shown in Fig. 2, the density of foamed copper sample is $\rho_{\text{foam}} = 0.01 \rho_s$ ($\rho_s$ is the solid density of copper, 8940 kg/m³), and $C_p(t)$ is the heat capacity that the data of copper in solid, liquid, and gas phases are given by Refs. [10, 11]. The temperature increase is estimated after 50 ns from the onset time. The onset time to calculate the integral of the current was defined as the response of the current to rise to 10% of its peak value. The initial temperature is set as 298 K by a room temperature.

4. Current measurement and estimation of achievable temperature of sample

Figure 2 shows the current waveforms at the cathode, in the case of the gap distance for 10, 15 and 20 mm, respectively. The current waveforms are the average of five times for each gap distance. The peak current increases from 10 kA to 60 kA with the decrease of the gap distance. The pulse width is ~80 ns (FWHM).

Figure 3 shows the temperature of the sample as a function of the gap distance. To estimate the temperature of sample, the experimentally obtained current waveform is used by Eqs. (2) and (3). The temperature of the sample increases with the decrease of gap distance. When the sample is 0.01 times the solid density of copper with $\phi$ 2 mm x 10 mm, the temperature is estimated up to 30000 K after 50 ns from the onset time. Therefore, it is expected that the WDM state is generated by the proposed method with ICF implosion timescale.

5. Conclusion

The experiment for WDM generation with ICF implosion timescale was proposed, and the temperature increase was estimated from the numerical calculation using the experimental data. When the sample is $\phi$ 2 mm x 10 mm and 0.01 times the solid density of copper, the temperature of foamed copper sample achieved up to 30000 K. The results indicated that the WDM state is produced by isochoric heating using the intense pulsed power generator with similar timescale of implosion.

---

**Figure 2.** Averaged current waveforms (each 5 shot) measured experimentally at the cathode.

**Figure 3.** Temperature of the sample as a function of the gap distance. The density of foamed copper sample is $\rho_{\text{foam}} = 0.01 \rho_s$. The error bars indicate maximum and minimum values.
Acknowledgment
This work was supported from MEXT Grant-in-Aid for Scientific Research, and by Program for High Reliable Materials Design and Manufacturing in Nagaoka University of Technology, and by JSPS Grant-in-Aid for Challenging Exploratory Research No.25630418.

References
[1] Drake R P 2009 Physics of Plasmas 16 055501
[2] Redmer R and Röpke G 2010 Contributions to Plasma Physics 50 970
[3] Komatsu Y, Sasaki T, Kikuchi T, Harada N and Nagatomo H 2013 EPJ Web of Conferences 59 04010
[4] Atzeni S and Meyer-ter-vehn J 2004 The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter (Oxford Univ. Press, N.Y.) Chap. 9
[5] Iizuka Y, Kawata S, Kodera T, Ohoyshi A I and Kikuchi T 2009 Nuclear Instruments and Methods in Physics Research A 606 pp 165-168
[6] Amano Y, Miki Y, Takahashi T, Sasaki T, Kikuchi T and Harada N 2012 Review of Scientific Instruments 83 085107
[7] Jiang W, Sakagami T, Masugata K and Yatsu K 1993 Japanese Journal of Applied Physics 32 pp L752-L754
[8] DaSilva A W and Katsouros J D 1999 International Journal Thermophysics 20 1267
[9] Sasaki T, Nakajima M, Kawamura T and Horioka K 2010 Physics of Plasmas 17 084501
[10] NIST Standard Reference Database Number 69
[11] Chase M W 1998 Journal of Physical and Chemical Reference Data NIST-JANAF Thermochemical Tables Fourth Edition Monograph 9