Laser and Particle Beams (2015), *33*, 163–167.

doi:10.1017/S0263034615000051

Impedance control using electron beam diode in intense pulsed-power generator

RYOTA HAYASHI,[1] TOMOAKI ITO,[2] FUMIHIRO TAMURA,[2] TAKAHIRO KUDO,[2] NAOTO TAKAKURA,[2] KENJI KASHINE,[3] KAZUMASA TAKAHASHI,[2] TORU SASAKI,[2] TAKASHI KIKUCHI,[2,4] NOB HARADA,[2] WEIHUA JIANG,[5] AND AKIRA TOKUCHI[5,6]

[1]Department of Energy and Environment Science, Nagaoka University of Technology, Nagaoka, Japan
[2]Department of Electrical Engineering, Nagaoka University of Technology, Nagaoka, Japan
[3]Department of Electrical and Electronic Engineering, National Institute of Technology, Kagoshima College, Kirishima, Japan
[4]Department of Nuclear System Safety Engineering, Nagaoka University of Technology, Nagaoka, Japan
[5]Extreme Energy-Density Research Institute, Nagaoka University of Technology, Japan
[6]Pulsed Power Japan Laboratory Ltd., Kusatsu, Japan

(Received 9 August 2014; Accepted 6 January 2015)

Abstract

To control an input energy for a load, an impedance control with a gap distance of an electron beam diode was studied using an intense pulsed-power generator. The output current of the pulsed-power generator as a function of the gap distance of electron beam diode was measured. It indicated that the behaviors of the experimentally obtained peak current and the theoretically obtained space-charge limited current were found to decrease with an increase in the gap distance. The input energy for the load was estimated from the output current, which decreased with an increase in the gap distance. It also revealed the space-charge limited current suppresses the input energy for the load with a decade.

Keywords: Electron beam diode; Inertial confinement fusion; Impedance control; Pulsed-power generator; Warm dense matter

1. INTRODUCTION

In inertial confinement fusion (ICF) driven by heavy ion beams, the fuel pellet consists of a fuel, a pusher, a tamper, and a radiator. A foamed metal such as the pusher and the radiator is considered as structural materials in the fuel pellet (Atzeni & Meyer-ter-vehn, 2004). The fuel pellet is rapidly imploded by irradiation from the energy driver. The fuel becomes dense plasma at the center of the fuel pellet, and causes thermonuclear fusion reactions. In order to obtain effective nuclear fusion reactions, it is a key issue to understand implosion dynamics of the fuel pellet.

The structural materials in the fuel pellet become dense plasma through the warm dense matter (WDM) (Dewald *et al.*, 2002; Constantin *et al.*, 2004; Hoffmann *et al.*, 2005; Ng *et al.*, 2005; Sasaki *et al.*, 2006; Drake, 2009; Redmer & Röpke, 2010) region with implosion time-scale (several-10 ns). The WDM region corresponds to densities from about 10^{21} to 10^{24} cm^{-3} and to temperatures from 10^3 to 10^5 K. To estimate on the accurate state of the fuel pellet, the effects of ion–ion correlations and degenerate electrons should be taken into account in the WDM region. However, the WDM is a complex region, because of the unclear theoretical model, and lacked experimental evaluations. Therefore, the properties in WDM should be clear to design the fuel pellet. To understand the properties of matter, we should design evaluation methods for the properties of the WDM.

In previous studies, a short pulse laser (Yoneda *et al.*, 2003; Glenzer *et al.*, 2007) and a pulsed-power discharge (DeSilva & Kunze, 1994; Saleem *et al.*, 2001; Sasaki *et al.*, 2011; Clérouin *et al.*, 2012) were used for the measurement of WDM. However, these experiments were difficult to compare due to the different time-scale and achievable parameters for the generation of WDM. To understand the relationship of these different experimental evidences, we considered the generation of WDM with an intense pulsed-power generator.

The intense pulsed-power generator had some opportunities with a large volume and/or dense state of the WDM. In order to investigate the properties of the WDM in the

Address correspondence and reprint requests to: Ryota Hayashi, Nagaoka University of Technology, Nagaoka, 940-2188, Japan. E-mail: r_hayashi@stn.nagaokaut.ac.jp

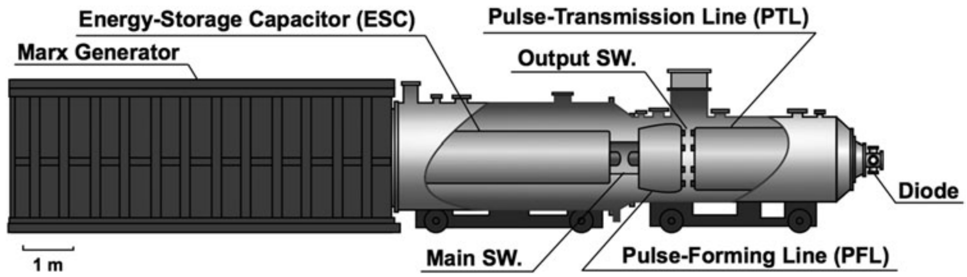

Fig. 1. Outline of intense pulsed-power generator ETIGO-II.

fuel pellet with the implosion process, the evaluation method for the WDM with isochoric heating (Amano *et al.*, 2012; Miki *et al.*, 2014; Sasaki *et al.*, 2014) using the intense pulsed-power generator ETIGO-II (~1 TW, ~50 ns) (Jiang *et al.*, 1993) has been considered. The features of the method are possible to generate WDM state with the implosion time-scale, isochoric condition, and direct spectroscopic measurement using a rigid-wall capillary having transparency, and avoiding the skin effect with a foamed metal as a sample. Despite the fact that the achievable parameters of the WDM depend on the output parameters of the intense pulsed-power generator, it was limited to change the output parameters such as voltage and current. For this reason, the impedance control using a load is required to control the energy input into the sample, because the output power of ETIGO-II is enough to generate the WDM state. A simple scheme for impedance control should be considered.

A diode has been studied for some applications in pulsed-power system (Yatsui *et al.*, 1985; Niu, 1997; Devyatkov *et al.*, 2003; Tarasenko *et al.*, 2005; Li *et al.*, 2012; Abdullin *et al.*, 2013). In this study, the use of an electron beam diode to control the impedance was investigated. A pulsed-power system with capacitive energy storage achieves its power multiplication by current amplification corresponding to the evolution of the load impedance. The electron beam diode was placed at the output terminal of ETIGO-II, and was used as adjustable impedance for the pulsed-power system. The space-charge limited current was expected to serve as the simple scheme for controlling the load impedance with changing the gap distance of the diode. The energy input into the sample was expected to be affected by the output current. Consequently, to investigate the controllability of the input energy into the sample on the variable gap distance, the output current was measured.

2. EXPERIMENTAL SETUP

The intense pulsed-power generator ETIGO-II, as shown in Figure 1, has been used to generate intense light-ion beams or to produce the dense ablation plasma (Yatsui *et al.*, 1997; Jiang *et al.*, 1998; Kashine *et al.*, 2002). To obtain the large output current, the impedance-conversion line was replaced, and its nominal output parameters of ETIGO-II were 1 MV, 590 kA, and 50 ns [full width at half maximum (FWHM)]. In the Marx generator (2 MV, 70 kJ), 20 stages capacitors were charged in parallel to a voltage of ±20 kV.

Figure 2 shows the experimental arrangement of the electron beam diode, which was placed at the output terminal of ETIGO-II. The electrodes of the electron beam diode consisted of a disk-shaped cathode (ø105 mm, 304 stainless steel) and a disk-shaped anode (ø210 mm, 304 stainless steel), in which gap distance could be adjusted. To prevent the electrical breakdown, the pressure in the chamber was controlled to be less than 0.02 Pa. The time evolution of the output current $I_K(t)$ and output voltage $V(t)$ were measured using a Rogowski coil at the cathode and a capacitive divider in the pulse-transmission line, respectively. The output current was measured for gap distances of 10, 15, and 20 mm. These measurements were performed five times for each gap distance.

Figure 3 shows the typical output waveforms for a gap distance of 10 mm. The pulse width was ~100 ns (FWHM), with peak voltage and current values of −1100 kV and −70 kA, respectively. The energy input into the sample was affected by the output current, which was depended on the impedance of the diode. In this study, the input energy was estimated without considering the sample, because the impedance of the sample was expected to be sufficiently smaller than the impedance of the diode. Therefore, the disk-shaped anode was grounded to an outer feeder of ETIGO-II and the impedance of the sample was assumed

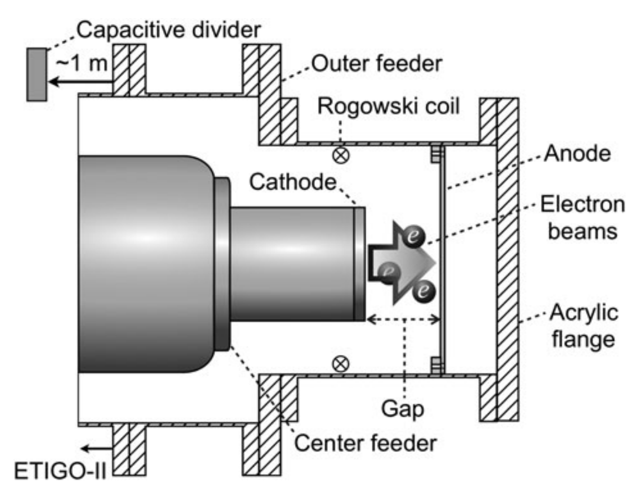

Fig. 2. Experimental setup of electron beam diode.

https://doi.org/10.1017/S0263034615000051 Published online by Cambridge University Press

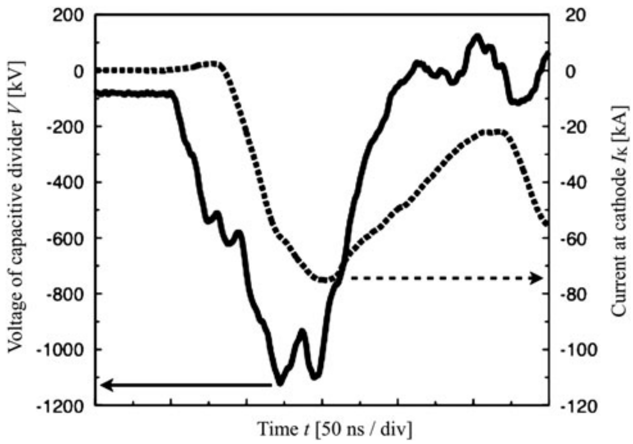

Fig. 3. Typical output waveform for 10 mm gap distance.

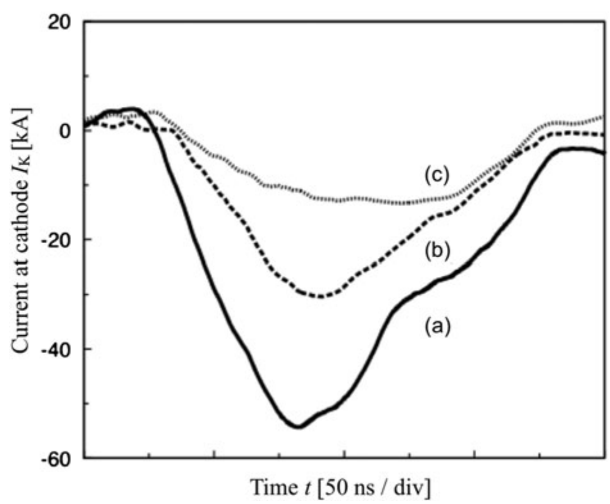

Fig. 4. Typical output current waveforms at cathode for (a) 10 mm, (b) 15 mm, and (c) 20 mm gap distances.

to be constant value for the estimation of the energy input into the sample.

3. EXPERIMENTAL RESULTS

Figure 4 shows the typical output current waveforms at each gap distance. Figure 5 shows the absolute value of the peak current as a function of the gap distance. As shown in Figures 4 and 5, the peak current decreases with an increase in the gap distance. The peak current is compared with the space-charge limited current (solid line in Fig. 5). The space-charge limited current (Child–Langmuir current) is given by Niu (1989)

$$I = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m_e}}\frac{V^{3/2}}{d^2}S \tag{1}$$

where ε_0 is the permittivity of a vacuum, e is the electron charge, m_e is the electron mass, V is the peak voltage, d is the gap distance, and S is the cross-sectional area of the discharge.

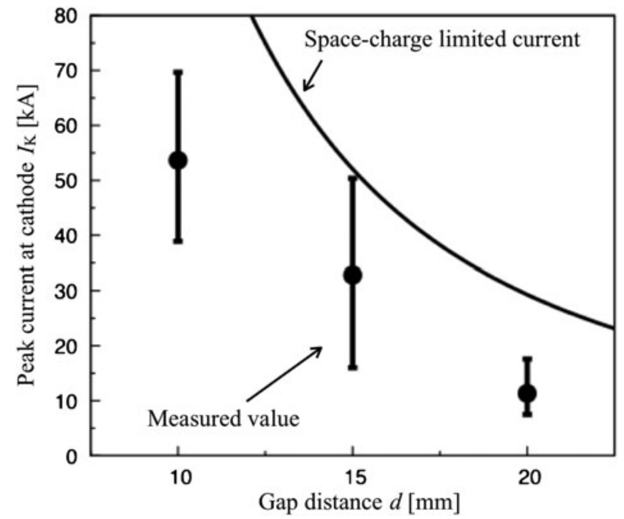

Fig. 5. Absolute value of peak current as function of gap distance for V = 1.1 MV and $S=\pi(40\times10^{-3})^2 = 5\times10^{-3}$ m^2. The error bars indicate the maximum and minimum values.

As a result, the space-charge limited current also decreased with an increase in the gap distance. Therefore, the space-charge limited current was considered to be the cause of the decrease in the output current with the change in the gap distance.

The input energy $E(t)$ can be estimated as follows:

$$E(t) = \int_{t_o}^{t_f} RI_K(t)^2 dt \tag{2}$$

where t_o is the rise time, t_f is the time after 50 ns from t_o, R is the impedance of the sample, and $I_K(t)$ is the output current at the cathode. Figure 6 shows the input energy as a function of the gap distance. The input energy was normalized by the impedance of the sample, because the sample impedance is

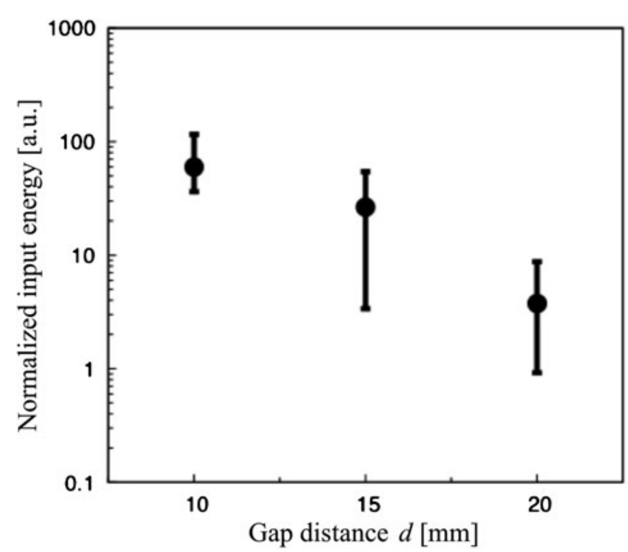

Fig. 6. Normalized input energy as function of gap distance. The error bars indicate the maximum and minimum values.

much less than the impedance of the diode. To estimate the input energy with the implosion time-scale, the input energy was estimated after 50 ns from the rise time. The beginning time to calculate the integral of the output current was defined as the response of the output current to a rise to 10% of its peak value. As a result, the normalized input energy decreased with an increase in the gap distance, because of the decrease in the output current.

Consequently, the ability to control the input energy by changing the gap distance was indicated for pulse duration of several tens of nanoseconds.

4. CONCLUSION

The use of an electron beam diode to control the impedance was proposed for applications such as the generation of WDM using a pulsed-power discharge with isochoric heating. To investigate the dependence of the input energy on the gap distance, the output current was measured for gap distances of 10, 15, and 20 mm, and was compared with the space-charge limited current. As a result, the peak current and the space-charge limited current were found to decrease with an increase in the gap distance. In addition, the input energy, which was estimated from the output current, decreased with an increase in the gap distance. It is expected that the input energy of the pulsed-power generator could be controlled using the proposed method with the implosion time-scale.

ACKNOWLEDGMENTS

This work was supported by 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

Abdullin, E.N., Ivanov, N.G., Losev, V.F. & Morozov, A.V. (2013). Generation of a large cross-section electron beam in the vacuum diode with rod current returns. *Laser Part. Beams* **31**, 697–702.

Amano, Y., Miki, Y., Takahashi, T., Sasaki, T., Kikuchi, T. & Harada, N. (2012). Isochoric heating of foamed metal using pulsed power discharge as a making technique of warm dense matter. *Rev. Sci. Instrum.* **83**, 085107.

Atzeni, S. & Meyer-Ter-vehn, J. (2004). Hohlraum targets. In *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter*, pp. 302–322. New York: Oxford University Press.

Clérouin, J., Noiret, P., Blottiau, P., Recoules, V., Siberchicot, B., Renaudin, P., Blancard, C., Faussurier, G., Holst, B. & Starrett, C.E. (2012). A database for equations of state and resistivities measurements in the warm dense matter regime. *Phys. Plasmas* **19**, 082702.

Constantin, C., Dewald, E., Niemann, C., Hoffmann, D.H.H., Udrea, S., Varentsov, D., Jacoby, V., Funk, U.N., Neuner, U. & Tauschwitz, A. (2004). Cold compression of solid matter by intense heavy-ion-beam-generated pressure waves. *Laser Part. Beams* **22**, 59–63.

Desilva, A.W. & Kunze, H.J. (1994). Experimental study of the electrical conductivity of strongly coupled copper plasmas. *Phys. Rev. E* **49**, 4448–4454.

Devyatkov, V.N., Koval, N.N., Schanin, P.M., Grigoryev, V.P. & Koval, T.V. (2003). Generation and propagation of high-current low-energy electron beams. *Laser Part. Beams* **21**, 243–248.

Dewald, E., Constantin, C., Udrea, S., Jacoby, J., Hoffmann, D.H.H., Niemann, C., Weiser, J., Tahir, N.A., Kozyreva, A., Shutov, A. & Tauschwitz, A. (2002). Studies of high energy density in matter driven by heavy ion beams in solid targets. *Laser Part. Beams* **20**, 399–403.

Drake, R.P. (2009). Perspectives on high-energy-density physics. *Phys. Plasmas* **16**, 055501.

Glenzer, S.H., Landen, O.L., Neumayer, P., Lee, R.W., Widmann, K., Pollaine, S.W., Wallace, R.J., Gregori, G., Höll, A., Bornath, T., Thiele, R., Schwarz, V., Kraeft, W.-D. & Redmer, R. (2007). Observations of plasmons in warm dense matter. *Phys. Rev. Lett*. **98**, 065002.

Hoffmann, D.H.H., Blazevic, A., Ni, P., Rosmej, O., Roth, M., Tahir, N.A., Tauschwitz, A., Udrea, S., Varentsov, D., Weyrich, K. & Maron, Y. (2005). Present and future perspectives for high energy density physics with intense heavy ion and laser beams. *Laser Part. Beams* **23**, 47–53.

Jiang, W., Hashimoto, N., Shinkai, H., Ohtomo, K. & Yatsui, K. (1998). Characteristics of ablation plasma produced by pulsed light ion beam interaction with targets and applications to materials science. *Nucl. Instrum. Methods Phys. Res. A* **415**, 533–538.

Jiang, W., Sakagami, T., Masugata, K. & Yatsui, K. (1993). Tight focusing of intense pulsed light-ion beam by spherical "plasma focus diode". *Jpn. J. Appl. Phys*. **32**, L752–L754.

Kashine, K., Yazawa, M., Harada, N., Jiang, W. & Yatsui, K. (2002). Foil acceleration of double-layer target by intense pulsed ion beam ablation. *Jpn. J. Appl. Phys*. **41**, 4014–4018.

Li, L., Chang, L., Zhang, L., Liu, J., Chen, G. & Wen, J. (2012). Development mechanism of cathode surface plasmas of high current pulsed electron beam sources for microwave irradiation generation. *Laser Part. Beams* **30**, 541–551.

Miki, Y., Saito, H., Takahashi, T., Sasaki, T., Kikuchi, T. & Harada, N. (2014). Evaluation of transport properties of warm dense matter using isochoric pulsed-power discharges. *Nucl. Instrum. Methods Phys. Res. A* **733**, 8–11.

Ng, A., Ao, T., Perrot, F., Dharma-Wardana, M.W.C. & Foord, M.E. (2005). Idealized slab plasma approach for the study of warm dense matter. *Laser Part. Beams* **23**, 527–537.

Niu, K. (1989). Propagation of relativistic electron beams. In *Nuclear Fusion*, p. 142. New York: Cambridge University Press.

Niu, K. (1997). Simulation of propagating a proton beam in a reactor. *Laser Part. Beams* **15**, 151–165.

Redmer, R. & Röpke, G. (2010). Progress in the theory of dense strongly coupled plasmas. *Contrib. Plasma Phys*. **50**, 970–985.

Saleem, S., Haun, J. & Kunze, H.-J. (2001). Electrical conductivity measurements of strongly coupled W plasmas. *Phys. Rev. E* **64**, 056403.

Sasaki, T., Miki, Y., Tachinami, F., Saito, H., Takahashi, T., Anzai, N., Kikuchi, T., Aso, T. & Harada, N. (2014). Warm dense matter study and pulsed-power developments for X-pinch equipment in Nagaoka University of Technology. *Nucl. Instrum. Methods Phys. Res. A* **733**, 28–31.

Sasaki, T., Suzuki, T., Amano, Y., Miki, Y., Kikuchi, T., Harada, N. & Horioka, K. (2011). Evaluation of electrical conductivity in warm dense state using pulsed-power discharges. *IOP Conf. Ser.: Mater. Sci. Eng*. **21**, 012016.

Sasaki, T., Yano, Y., Nakajima, M., Kawamura, T. & Horioka, K. (2006). Warm-dense-matter studies using pulse-powered wire discharges in water. *Laser Part. Beams* **24**, 371–380.

Tarasenko, V.F., Shunailov, S.A., Shpak, V.G. & Kostyrya, I.D. (2005). Supershort electron beam from air filled diode at atmospheric pressure. *Laser Part. Beams* **23**, 545–551.

Yatsui, K., Grigoriu, C., Masugata, K., Jiang, W. & Sonegawa, T. (1997). Preparation of thin films and nanosize powders by intense, pulsed ion beam evaporation. *Jpn. J. Appl. Phys*. **36**, 4928–4934.

Yatsui, K., Tokuchi, A., Tanaka, H., Ishizuka, H., Kawai, A., Sai, E., Masugata, K., Ito, M. & Matsui, M. (1985). Geometric focusing of intense pulsed ion beams from racetrack type magnetically insulated diodes. *Laser Part. Beams* **3**, 119–155.

Yoneda, H., Morikami, H., Ueda, K. & More, R.M. (2003). Ultrashort-pulse laser ellipsometric pump-probe experiments on gold targets. *Phys. Rev. Lett*. **91**, 075004.