Tamped Target for Warm Dense Matter Experiments using Intense Heavy Ion Beam

Toru Sasaki¹, Takashi Kikuchi², Mitsuo Nakajima¹, Tohru Kawamura¹, and Kazuhiro Horioka¹

¹Department of Energy Sciences, Tokyo Institute of Technology, Nagatsuta 4259, Midori-ku, Yokohama, Japan
²Department of Electrical and Electronic Engineering, Utsunomiya University, Yohtoh 7-1-2, Utsunomiya, Japan
E-mail: sasaki@es.titech.ac.jp

Abstract. A new approach for warm dense matter (WDM) experiments using intense heavy ion beams is presented. To improve uniformity of the ion beam driven targets, we compared behaviors of a mono-layer and a tamped cylinder target. For the estimation of target behaviors, a two-dimensional cylindrical hydrodynamics code including ion beam deposition profile was developed. Results show that both targets can reach a warm dense state. In particular, the tamped target can achieve a well defined warm dense state with long time scale.

1. Introduction

Physics of warm dense matter (WDM) is of significance for the hydrodynamics in inertial confinement fusion[1], and the modeling of interior of giant planets (e.g. Jupiter) [2]. To understand these behavior and/or structure, we should have exact information on the equation of state and the transport property about the warm dense state. The WDM is in a complex state, because of the ion-ion coupling, the partially degenerate electrons, and the phase transition accompanied by two-phase state. To make a warm dense state, we might use ultra-short pulse laser [3, 4], pulsed-power discharges [5], and heavy ion beams [6, 7, 8, 9, 10]. These methods are expected to provide different test samples with different time scales [11].

The use of ion beams to heat a matter to WDM conditions has advantageous points, such as precise control and uniform energy deposition, large sample sizes compared to diagnostic resolution volumes, and ability to heat a wide variety of target materials. However, to diagnose the physical parameters, the target should be in equilibrium and as uniform as possible.

An accelerator, modified KEK 500 MeV booster using induction synchrotron technology, is under consideration as an all-ion accelerator (AIA) [12]. This accelerator is capable of generating an extremely long bunch, which stores the beam particle under the limits of the ring size and the space-charge force in transverse direction, using a controllable, fast switching power supply and induction cells. The modified booster is expected to be able to provide about $10^{10}$ uranium ions having an energy of a 80 MeV/u. The provided ion beams are expected to be less than 1 mm in radius using a half mini-beta system[13] at the final stage with a pulse duration about 100 nsec.
In this study, we propose a method to make a quasi-uniform and large sample target using highly energetic heavy ion beams. For measuring physical parameter of WDM, the target structure should be as simple as possible. For evaluating the uniformity of large scale target, the behavior of WDM target should be investigated by using two dimensional hydrodynamics simulation including beam deposition process. Figure 1 shows a comparison of the deposition profile in gold with solid density and 10% aluminum foam, of uranium ion projectile with 80 MeV/u. As shown, the 10% aluminum foam target is expected to be able to make a large scale and quasi-uniform state in combination with gold solid target. To evaluate the tamping effect, uniformity and the scale length, we calculated the hydrodynamic behaviors of a mono-layer target and a tamped target.

2. Simulation Model
We calculate the hydrodynamics of target with two dimensional cylindrical geometry [14]. The Quotidian equation of state (QEOS) [15] has been used in this calculation. However, the thermal and radiation transport are neglected in the present study. The transports and EOS are the unclarified part for warm dense state, and a sophisticated modeling will be made through a semi-empirical fitting of the hydrodynamics. The energy deposition of heavy ions was calculated by a stopping power using the expression described in Ref. [16]. We used a well-known expression for the effective charge of the projectile presented in Refs.[17] and [18].

In this calculation, the beam radius is set to be 0.5 mm with a Gaussian distribution. The beam duration is 100 ns, and the beam particle number is $10^{10}$ uranium ions with monotone particle energy (80 MeV/u). From the estimation described in Ref. [13], the expected maximum beam shift at radial direction is estimated to be about 35 $\mu$m using 5 mm target length. The target radius is assumed to be 250 $\mu$m, which is larger than the shifts in radial direction. Therefore, the transverse beam shift can be neglected. The energy spread should also shift the peak deposition point. We estimated that if the 80 MeV/u uranium beam has a 10% energy spread, the peak deposition point extends 50 $\mu$m in length in the aluminum 10% foam target. The shift of the deposition profile is neglected in this calculation.

3. Results and Discussions
A schematic of the target structure for WDM study using heavy ion beam is shown Fig. 2. The mono-layer target (Fig. 2(a)) is initially 250 $\mu$m in radius and 5 mm in length. The target is
composed of aluminum with 10% solid density. Since the deposition profile of aluminum foam is deep and uniform as shown Fig. 1, the tamped target is expected to be able to make a large scale, quasi-uniform structure during and after the beam irradiation. The tamped target (Fig. 2(b)), in which aluminum foam with 10% solid density is coated by a gold layer with solid density, is 350 $\mu$m in radius and 5 mm in length.

The behavior of the beam irradiated mono-layer target is shown in Fig. 3. As shown in Fig. 3, the behavior of aluminum target reflects the deposition profile. Additionally, we can see a sharp temperature gradient in radial direction at the target center. Because of comparable target size with beam radius, the target temperature has non-uniformity. The average temperature and density are estimated to be 2 eV and $0.5\rho_s$, respectively, at 100 ns. It indicates that the target irradiated by the intense ion beam reaches the WDM parameter.

A preliminary result of hydrodynamic simulation for the beam driven cylindrical tamped target is shown in Fig. 4. As shown in Fig. 4, the radius of aluminum is constant until 75 ns. Because of small expansion of aluminum region, the temperature gradient depends on the radial distribution of beam. The observable region has only a slight temperature gradient compared with the mono-layer target. This means the tamped target enables us to observe long scale (\(\sim 4\) mm) and uniform samples for study on WDM.

Both the numerical estimation and the experimental evaluation are used as a complementary approach to the WDM study. For accurate hydrodynamics using intense ion beam, above all, we should know effects of liquid-vapor two-phase state on EOS[19]. Because of unclear EOS in this region, the propagating pressure wave in aluminum foam might be incorrect. Therefore, a detailed design of the target is needed to sophisticate the evaluation together with parametric experiments.

4. Summary
We proposed a quasi-statically tamped target for making a quasi-uniform warm dense state based on highly energetic ion beam irradiation. For the estimation of target hydrodynamics, two
The results show that the target can reach a warm dense state with induction synchrotron, which is expected to be modified from the KEK 500 MeV booster, and the tamped target can make a quasi-uniform profile with 4 mm in length. We are planning to evaluate the model for EOS and the energy transport from a comparative study of the hydrodynamic behaviors. For determining specific parameters, we should design an appropriate target structure. Additionally, we should make a parametric study to extend the achievable warm dense state by the beam parameters. We also concern the possibility of programmed target heating with the induction synchrotron.

**Figure 4.** Evolution of tamped target for formation of dense, uniform condition.

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**References**

[1] Lindl J 1995 *Phys. Plasmas* **2** 3933
[2] Ichimaru S, et. al. 1987 *Phys. Rep.* **149** 91
[3] Yoneda H, et. al. 2003 *Phys. Rev. Lett.* **91** 075004
[4] Glenzer S H, et. al. 2007 *Phys. Rev. Lett.* **98** 065002
[5] Sasaki T, et. al. 2006 *Laser and Particle Beams* **24** 371
[6] Dewald E, et. al. 2002 *Laser and Particle Beams* **20**
[7] Kozyreva A, et. al. 2003 *Phys. Rev. E* **68** 056406
[8] Grisham L R 2004 *Phys. Plasmas* **11** 5727–5729
[9] Tahir N A, et. al. 2001 *Phys. Rev. E* **63** 016402
[10] Tahir N A, et. al. 2005 *Phys. Rev. Lett.* **95** 035001
[11] Horioka K, et. al. 2007 *Nucl. Instr. and Meth. A* **577** 298
[12] Takayama K, et. al. 2007 *Phys. Rev. Lett.* **98** 054801
[13] Kikuchi T, et. al. 2007 *Proceedings of PAC07* p 1541
[14] Sasaki T, et. al. *Frontiers in Pulse-Power based High-Energy-Density Plasma Physics in NIFS Proceedings* in press.
[15] More R M, et. al.1988 *Phys. Fluids* **31** 3059
[16] Mehlhorn T A 1981 *J. Appl. Phys.* **52** 6522
[17] Peter T, et. al. 1991 *Phys. Rev. A* **43** 1998
[18] Peter T, et. al. 1991 *Phys. Rev. A* **43** 2015
[19] More R, et. al. 2006 *J. Quant. Spectrosc. Radial. Transfer* **99** 409–424