Planned for High Energy Density Physics based on All Ion Accelerator Facility

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High energy density physics (HEDP) experiments using a newly designed accelerator; an all-ion accelerator (AIA) is presented. Possible ion beam parameters of the AIA based on modified KEK proton synchrotron ring are estimated. For making high energy density (HED) state of matters irradiated by KEK AIA with and without injector, we evaluate the achievable state of aluminum target as a function of beam radius and target density using a heavy ion beam deposition profile. Results show that the beam radius should be less than 0.2 mm to make the HED state of matter irradiated by the KEK AIA without injector case. We also estimate the achievable state of matter irradiated by the KEK AIA with proton synchrotron ring. The result indicates that the irradiated matters become HED state, in which the target is not only in a hot dense state but also in a radiation dominant matter.

Keywords: High Energy Density Physics, All-Ion Accelerator, Equation of State, Transport Properties

1. Introduction

High energy density physics (HEDP) is of great significance for the implosion dynamics in inertial confinement fusion (ICF) [1], the modeling of interior of giant planets (e.g. Jupiter) [2], and the astrophysical phenomena as the supernova explosion [3–5]. To understand these behaviors and/or structures, we should have accurate information on the equation of state (EOS) and the transport properties in the high energy density (HED) state. HED state of matter, which is categorized as a warm dense matter (WDM), a hot dense matter (HDM), and a radiation dominant matter (RDM) has a potential of abundant scientific discovery including the properties of plasmas.

WDM is a complex state of matter, because of the ion-ion coupling, the partially degenerated electrons, and the phase transition accompanied by two-phase state. Predicting the mass of rock core in the Jupiter needs a highly precise EOS model in WDM state. HDM and RDM are interesting state of matter not only for astrophysical explosion phenomena but also for the target physics of ICF These hydrodynamics are considerably affected by the EOS and the optical property of condensed matter.

Recently, intense heavy ion beams (HIBs) are opening up an attractive branch for HEDP [6–11]. Accelerators producing appropriately tailored energies of intense HIBs are promising energy drivers for inertial fusion energy and are also expected to be able to provide a useful tool for creating HED matter. For the HEDP study, intense HIBs have a number of advantages; in uniformity of energy deposition, in large volume of the samples compared to diagnostic resolution, in virtue of the long stopping range, in an advantageous environment for diagnostics, in an ability to heat a variety of target materials in a condition with high repetition rate and multiple beam lines.

An accelerator, modified KEK 500 MeV booster based on induction synchrotron technology, is under development as an all-ion accelerator (AIA) [12, 13]. This accelerator is capable of generating an extremely long bunch, which stores the beam particle up to 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 accelerator system can be a useful tool to make HED experiments in a wide range of parameter regime.

For the HEDP study based on the ion beams irradiation, the target should be in equilibrium and as well-defined as possible to accurately diagnose the physical parameters. In this study, we propose a method to make a HED state of matter based on KEK AIA facility.

2. Present and future status of KEK AIA

The KEK AIA is a medium energy synchrotron capable of accelerating all ion species based on a novel technology of the induction synchrotron [12–14]. Table 1 shows the expected specification of KEK AIA with and without injector [13, 14] and the prospect of beam parameters stored by the KEK proton synchrotron (PS) provided by KEK AIA. The beam en-

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Table 1 Specification of the KEK AIA with and without injector [13, 14] and the prospect of stored ions by the KEK-PS.

Parameters	without injector	with injector	stored by PS ring
Specimens	Gold	Uranium	Gold
Intensity (W/cm^2)	3.3×10^{10}	1.8×10^{12}	7.7×10^{13} (expecting)
Beam Energy (kJ)	0.33	5.6	241
Bunch Length (nsec)	100	100	100
Particle Energy (MeV/u)	96.8	80	96.8
Providable Ions (per bunch)	4.4×10^8	2×10^{10}	2×10^{12}
Beam Radius(mm)	~ 1	~ 1	~ 1 (expecting)

ergy of the accelerator with injector is fifty times higher than that of the injection free all-ion accelerator (IF-AIA). Without injector, the transportable ion number per bunch of the IF-AIA is expected to decrease due to the space charge effect at the initial low energy phase. Kikuchi et. al. [7] have estimated the beam optics from the injector to the target chamber for WDM experiments based on half-mini beta system. The results have indicated that the minimum beam radius is less than 1 mm at the focal point in the target chamber. KEK AIA is proposed not only for the HEDP study but also low intensity ion beams for a hybrid cancer therapy using proton and carbon specimens, a material science based on ion implantation, and a selective mutation breeding for agricultural study. All but HEDP study do not need a high current beam and the accelerator should be versatile for a variety of topics in physics and engineering. Therefore, for HEDP based on KEK AIA, we have to examine a method of amplification of the beam current, independently. For making HED state and understanding the physics of space-charge-dominated beam, we proposed a method for generating high current beam based on KEK AIA with a multifunction accumulation ring, which is modified KEK proton synchrotron (KEK-PS).

The multifunction accumulation ring is under consideration as accumulating, bunching, and cooling HIBs using recirculating system [15] with AIA technology. A high current recirculator system with bunching and cooling beam using RF cavity have been discussed for TARN II ring in the RIBF at RIKEN by Kikuchi et. al. [16]. This project is similar to the modified KEK-PS. In comparison with the TARN II, the modified KEK-PS is expected to make a larger current and, low energy particles, using arbitrary beam controlling system based on the induction modules.

Large current system should consider a tune shift due to the space charge effect with betatron oscillation. The tune shift may cause instability during accumulation and cooling in the ring. The stored ion number is restricted by the maximum acceptable tune shift from Laslett tune shift $|\Delta Q_{SC}|$ as

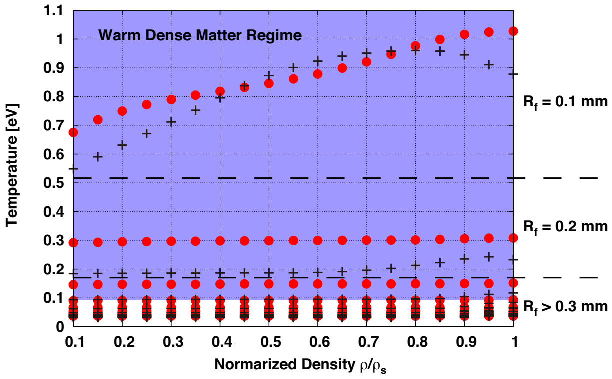
$$|\Delta Q_{SC}| = \frac{N_B r_i F_{SC}}{\pi\beta^2\gamma^3 B_f \epsilon_y \left(1 + \sqrt{\frac{\epsilon_x Q_y}{\epsilon_y Q_x}}\right)}, \qquad (1)$$

where ϵ_x and ϵ_y are unnormalized horizontal and vertical emittances, Q_x and Q_y are the horizontal and vertical tunes, F_{SC} is a form factor associated with particle distribution, B_f is a bunching factor, and $r_i(= q^2e^2/4\pi\epsilon_0 A m_p c^2)$ is the classical ion radius. The form factor F_{SC} is equal to 1 for a Gaussian transverse beam distribution, and the bunching factor B_f is assumed to be 0.01 from the ratio between the bunched beam length and a coasting beam filling of the ring. Generally, the Laslett tune shift $|\Delta Q_{SC}|$ is required to be less than 0.25 for stability over many laps. When we assumed $Q_x = Q_y$ and $\epsilon_x = \epsilon_y$, the acceptable beam particle number per bunch is estimated to be about 2×10^{12} for full stripped gold ions. Additionally, when the beam radius is 1 mm, the expected beam parameters are shown in Table 1. More detailed plan of the modified KEK-PS such as the beam optics and the achievable beam power, will be discussed in the near future.

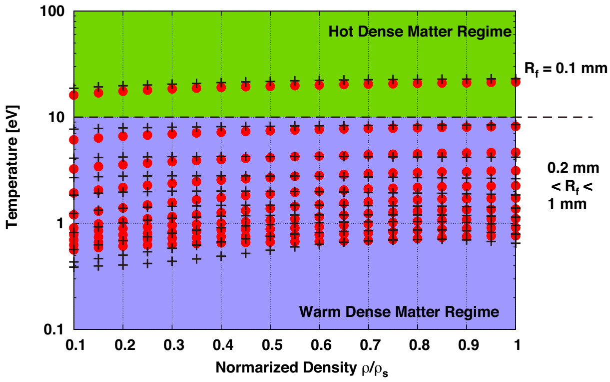
3. Achievable state of matter irradiated by KEK AIA

For making HED state of matter, we estimate the achievable state as a function of initial target density and irradiating beam radius. In order to estimate the required beam radius as a function of achievable temperature of target, we calculate the average temperature from the stopping power with EOSs based on SESAME [17] and QEOS [18]. The energy deposition of heavy ions was calculated by a stopping power using the expression described in Ref. [19]. We used a well-known expression for the effective charge of the projectile presented in Refs. [20] and [21].

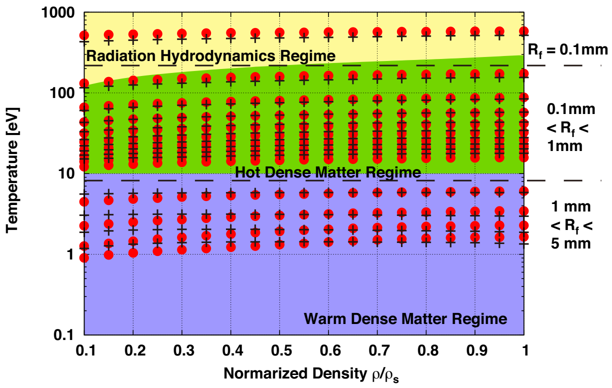
Figure 1 shows the achievable average temperature of aluminum irradiated by AIAs with irradiation of beam parameters shown in Table 1. The Bragg peak profile has no sharp edge compared to the light ion beam. Therefore, the Bragg peak was included in the deposition profile.



(a) KEK AIA without injector



(b) KEK AIA with injector



(c) Modified KEK-PS with AIA

Fig. 1 Achievable average temperature of aluminum irradiated by (a) KEK AIA without injector (IF-AIA), (b) KEK AIA with injector, and (c) modified KEK-PS with KEK AIA, as a function of normalized target density ρ/ρ_s and beam radius R_f at the target. Circles indicate the predictions based on QEOS, and crosses denote the predictions of SESAME.

As shown in Fig. 1 (a), results indicated that the beam radius should be less than 0.2 mm for making WDM state regardless of EOS models, and the average temperature also rely on the EOS models at small focusing radius. The difference of achievable average temperature also indicates that the liquid-gas two phase region of aluminum EOS models is the cause of discrepancy. These estimations indicate that the achievable average temperature is rather low for the WDM study irradiated by IF-AIA.

In the case of KEK AIA with injector, as shown in Fig. 1 (b), the matter reaches WDM regime. By controlling the focus radius R_f, KEK AIA with injector can cover a wide region of WDM state for aluminum target. Furthermore, in the case of modified KEK-PS with KEK AIA, the matter approaches HDM state by irradiation of beam with 0.2 mm to 1 mm in radius as denoted in Fig 1 (c). Note that the stopping range is from 1 mm in length at solid density to 5 mm in length at 10 % solid density. It indicates that the KEK AIA can generate a large sample of HED matter. This means highly energetic HIBs are promising tools for the physics of HED state of matter.

3.1 Warm dense matter study based on KEK AIA

Warm dense matter (WDM) in a region of HEDP is interested to explore the properties of condensed liquid/plasma state. Because of the ion-ion coupling, the partially degenerate electrons, and the phase transition accompanied by two-phase state, the atoms are no longer described by their isolated atomic behavior. For making the WDM, we conventionally used ultra-short pulse laser [22, 23] and pulsed-power discharges [24]. These methods are expected to provide various test samples with different time scales [25]. The KEK AIA can be also a useful tool to make WDM experiments in wider range of parameter regime.

We calculate the hydrodynamics of target using the beam parameters shown in Table 1, with two dimensional cylindrical geometry [6]. In this calculation, the beam radius is set to be 0.5 mm with a Gaussian distribution using AIA with injector. Figure 2 shows the target structures and the density profiles of aluminum foam irradiated by KEK AIA at beam irradiation times of 75 ns and 100 ns. The mono layer target radius and length are determined considering the beam radius and the stopping power range to preclude the Bragg peak. For the WDM study, the matter should be in equilibrium and as uniform as possible to diagnose the physical parameters. When we compare Fig. 2(a) and Fig. 2(b), we can see that the target become a homogeneous state by the tamper effect. This means the tamped target enables us to observe uniform and long scale test samples for study on WDM.

The quasi-statically tamped target is expected to be applicable for planetary science. In order to make a critical parameter for exploring the structure of Jupiter, we have to make a warm dense hydrogen (6000 K, 200 GPa). The critical parameter region of hydrogen in Jovian interior is estimated to be about 10 times solid density from SESAME and QEOS. A scheme with multiple shock compression may be use-

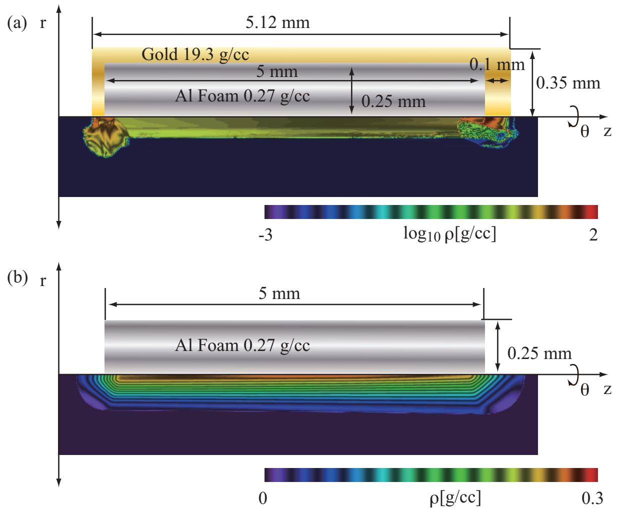


Fig. 2 Target structure and density profiles in (a) tamped 10 % aluminum foam target irradiated by KEK AIA with injector at beam irradiation time of 75 ns, (b) 10 % aluminum foam target irradiated by KEK AIA with injector at beam irradiation time of 100 ns.

ful for formation of the WDM state. However, the shock relation intrinsically includes the EOS, that is, the adiabatic index is not constant. Then the estimated condition formed by the multiple shock compression should become quite unclear. In contrast, HIBs has a great potential for shock free and volumetric heating. It enables us to make highly compressed hydrogen with low entropy state. We will start to construct the beam irradiation facility to generate the warm dense hydrogen corresponding to the critical parameter for exploring the interior of the giant planet as the Jupiter.

3.2 Radiation hydrodynamics based on KEK AIA

The hydrodynamics dominated by radiative energy flux and pressure plays a crucial role in not only for exploring astrophysical phenomena but also for evaluating the efficiency of hohlraum target for ICF driven by HIBs or lasers [3, 26]. Especially, the explosion process in supernova is strongly affected by the radiation transfer in a wide range of parameters from optical thick to thin condition. Then, we cannot determine directly the origin of radiation from the astronomical observation due to the unclarified radiative effects. In order to study such processes, we should evaluate the energy transfer in dense high temperature matter.

In a region from HDM to RDM, we should consider both the material energy flux F_m and the radiation flux F_{rad}. The ratio R of the radiation flux F_{rad} to the material energy flux F_m is defined by

$$R = \frac{F_{rad}}{F_m} = \frac{\sigma T^4}{\rho \epsilon C_s}, \tag{2}$$

where σ is the Stefan-Boltzmann constant, T is the temperature, ρ is the mass density, ϵ is the internal energy of matter, and C_s is the sound velocity. Yellow covered in Fig. 1 (c) indicates the region of the radiation flux exceeding the material energy flux using SESAME. If the focusing beam radius is 0.1 mm irradiated by modified KEK-PS with KEK AIA, we can make RDM condition and evaluate the emission, the absorption, and the transfer of radiation in the state.

4. Summary

We proposed HEDP experiments based on KEK AIA. Possible ion beam parameters of the AIA with modified KEK proton synchrotron ring were estimated. For making HED state of matter irradiated by KEK AIA, we evaluated the achievable state of aluminum as a function of beam radius and target density. Results showed that the beam radius should be less than 0.2 mm to make the HED state of matter irradiated by KEK AIA without injector case. We also estimated the achievable state irradiated by KEK AIA with modified KEK proton synchrotron ring. It indicated that the irradiated matter become HED state, in which the target material is not only in a hot dense state but also in a radiation dominant matter. For sophisticated estimation of target hydrodynamics irradiated by KEK AIA with injector, two dimensional cylindrical hydrodynamic code including ion beam deposition profile was developed. The results showed that the target can reach a warm dense state by KEK AIA with injector, and the tamped target can make a quasi-uniform profile with 4 mm in length. We should concern the possibility of programmed target heating with the induction synchrotron to make well-defined conditions for the HED experiments.

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References

[1] J. Lindl, Physics of Plasma **2**, 3933 (1995).
[2] S. Ichimaru, H. Iyetomi, and S. Tanaka, Physics Reports **149**, 91 (1987).
[3] R. P. Drake, *High-Energy-Density Physics Fundamentals, Inertial Fusion, and Experimental Astrophysics* (Springer, 2005).
[4] K. Kondo, M. Nakajima, T. Kawamura, and K. Horioka, Review of Scientific Instruments **77**, 036104 (2006).

[5] K. Kondo, M. Nakajima, T. Kawamura, and K. Horioka, Journal of Physics:Conference Series **112**, 042028 (2008).

[6] T. Sasaki, T. Kikuchi, M. Nakajima, T. Kawamra, and K. Horioka, Journal of Physics: Conference Series **112**, 042027 (2008).

[7] T. Kikuchi, S. Kawata, and K. Takayama, in *Proceedings of The 2007 Particle Accelerator Conference on Accelerator Science and Technology (PAC'07)* (2007), p. 1541.

[8] J. J. Barnard, J. Armijo, R. M. More, A. Friedman, I. Kaganovich, B. G. Logan, M. Marinak, G. Penn, A. Sefkow, P. Santhanam, *et al.*, Nuclear Instruments and Methods in Physics Research A **577**, 275 (2007).

[9] F. M. Bieniosek, J. J. Barnard, M. K. Covo, A. W. Molvik, L. Grisham, M. Leitner, B. G. Logan, R. More, P. N. Ni, P. K. Roy, *et al.*, in *Proceedings of The 2007 Particle Accelerator Conference on Accelerator Science and Technology (PAC'07)* (2007), p. 141.

[10] N. A. Tahir, C. Deutsch, V. E. Fortov, V. Gryaznov, D. H. H. Hoffmann, M. Kulish, I. V. Lomonosov, V. Mintsev, P. Ni, D. Nikolaev, *et al.*, Physical Review Letters **95**, 035001 (2005).

[11] D. Varentsov, V. Y. Ternovoi, M. Kulish, D. Fernengel, A. Fertman, A. Hug, J. Menzel, P. Ni, D. Nikolaev, N. Shilkin, *et al.*, Nuclear Instruments and Methods in Physics Research Section A **577**, 262 (2007).

[12] K.Takayama, Y.Arakida, T.Dixit, T.Iwashita, T.Kono, E.Nakamura, K.Otsuka, Y.Shimosaki, K.Torikai, and M.Wake, Physical Review Letters **98**, 054801 (2007).

[13] E. Nakamura, T. Adach, Y. Arakida, T. Dixit, S. Inagaki, T. Iwashita, M. Kawai, T. Kikuchi, T. Kono, K. Okazaki, *et al.*, in *Proceedings of The 2007 Particle Accelerator Conference on Accelerator Science and Technology (PAC'07)* (2007), p. 1490.

[14] K. Takayama, *private communication* (2008).

[15] T. Kikuchi, M. Nakajima, and K. Horioka, Physics of Plasmas **9**, 3476 (2002).

[16] T. Kikuchi, S. M. Lund, T. Katayama, and S. Kawata, Nuclear Instruments and Methods in Physics Research A **544**, 393 (2005).

[17] S. P. Lyon and J. D. Johnson, *T-1 Handbook of the SESAME Equation of State Library* (LA-CP-98-100, 1998).

[18] R. M. More, K. H. Warren, D. A. Young, and G. B. Zimmerman, Physics of Fluids **31**, 3059 (1988).

[19] T. A. Mehlhorn, Journal of Applied Physics **52**, 6522 (1981).

[20] T. Peter and J. Meyer-ter-Vehn, Physical Review A **43**, 1998 (1991).

[21] T. Peter and J. Meyer-ter-Vehn, Physical Review A **43**, 2015 (1991).

[22] H. Yoneda, H. Morikami, K. Ueda, and R. M. More, Physical Review Letters **91**, 075004 (2003).

[23] S. H. Glenzer, O. L. Landen, P. Neumayer, R. W. Lee, K. Widmann, S. W. Pollaine, and R. J. Wallace, Physical Review Letters **98**, 065002 (2007).

[24] T. Sasaki, Y. Yano, M. Nakajima, T. Kawamura, and K. Horioka, Laser and Particle Beams **24**, 371 (2006).

[25] K. Horioka, T. Kawamura, M. Nakajima, T. Sasaki, K. Kondo, Y. Yano, T. Ishii, M. Ogawa, Y. Oguri, J. Hasegawa, *et al.*, Nuclear Instruments and Methods in Physics Research Section A **577**, 298 (2007).

[26] J. I. Castor, *Radiation Hydrodynamics* (Cambridge University Press, 2004).