BEAMLINE FOR WARM DENSE MATTER EXPERIMENT USING THE KEK DIGITAL ACCELERATOR

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Abstract

The KEK digital accelerator (DA) is an interesting device as a driver to explore a warm dense matter (WDM) state. The irradiation onto a target at a small focal spot (< a few mm) with a short pulse duration (∼ 100 nsec) is required to create an interesting WDM state. The target temperature is estimated as a function of the focal spot size and the ion number per bunch. The estimation results show that the heavy ion beam has an advantage for small number of ions required by WDM generation. Also two-dimentional hydrodynamic simulations show that the tamped target can achieve a quasi-uniform WDM.

INTRODUCTION

A research field on warm dense matter (WDM) science driven by charged-particle beam illuminations require the generation of a high-current beam [1]. A concept of an induction synchrotron was proposed for a purpose of nuclear physics study, high energy physics research, high-current beam generation, and so on. The experimental demonstrations of the induction synchrotron promise a repetition capability and a precise waveform controllability for productions of high-current charged-particle beams [2].

The KEK digital accelerator (DA), which is an injector-free induction synchrotron capable of accelerating any ions with their possible charge state, is under construction. This machine is an interesting device as a driver to explore WDM. Table 1 shows the design beam parameters produced by the KEK DA.

Table 1: Design Values for Beams Produced by KEK DA

Ion	Charge	Energy [MeV]	Range [kg/m^2]
H	1	500	1501
He^3	2	746	359
He	2	587	183
C	6	1761	62.1
Ar	18	4820	16.2
Fe	26	7156	11.9
Cu	29	7919	10.5
Au	79	19069	2.97

The irradiation onto a target at a small focal spot (< a few mm) with a short pulse duration (∼100 nsec) is required to generate an interesting WDM. We studied the beamline from the KEK DA to the target in our previous study [3]. In this study, we investigate the requirements of beam parameters to make WDM using an energy balance equation. Also hydrodynamic simulations show that the target surrounded at a tamper material achieves a quasi-uniform WDM.

ESTIMATION FOR REQUIREMENT OF BEAM IONS

At first, requirements of ion numbers to generate WDM are estimated using an energy balance equation derived as follows. The energy balance equation is described by [4]

$$E_{dep} = E_{int} + E_{kin} + E_{rad}, \quad (1)$$

where E_{dep} is the energy deposition into the target from the input beam energy, E_{int} is the internal energy of the target, E_{kin} is the kinetic energy of the fluid motion, and E_{rad} is the radiation energy in the target.

The energy deposited into the target is given by $E_{dep} = f_d P_b \tau_b$, where f_d is the energy deposition fraction, P_b is the beam power, and τ_b is the beam pulse duration. The input beam power is written by $P_b = E_k I_b$, where E_k is the kinetic energy of the beam ion, and I_b is the beam current determined by $I_b = qeN_p/\tau_b$, where q is the charge state of the beam ion, e is the elementary charge, and N_p is the number of particles per a bunch. The energy deposition is calculated by

$$E_{dep} = \int_0^{L_t} \frac{dE}{dx} dx = f_d\, P_b\, \tau_b, \quad (2)$$

where L_t is the target length and dE/dx is the stopping power along the target coordinate x. As shown in Fig. 1, when we assumed the stopping power curve (Fig. 1(a)) as the monotonic function (Fig. 1(b)), the stopping power is approximated by

$$\frac{dE}{dx} = \left(1 + \frac{x}{R_s/\rho_t}\right) \frac{dE}{dx}\Big|_{x=0}, \quad (3)$$

where R_s is the range for the stopping power and ρ_t is the target (mass) density. From the trapezoid area, the input

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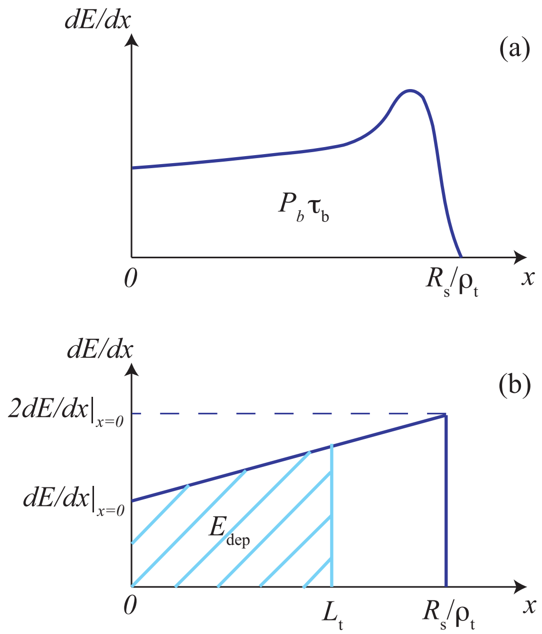

Figure 1: Simplified model for stopping power of heavy ion beams, (a) for original image, and (b) for trapezoid approximation model.

beam energy is obtained by

$$P_b \tau_b = \frac{3}{2} \frac{R_s}{\rho_t} \frac{dE}{dx}\Big|_{x=0}. \tag{4}$$

As a result, the energy deposition fraction is given as

$$f_d = \frac{2}{3}\left(1 + \frac{1}{2}\frac{L_t}{R_s/\rho_t}\right)\frac{L_t}{R_s/\rho_t}. \tag{5}$$

The internal energy of the target is calculated by [4]

$$E_{int} = \pi r_f^2 L_t \rho_t e(T), \tag{6}$$

where r_f is the focal spot radius of the beam at the target, and $e(T)$ is the specific internal energy obtained by

$$e(T) = e_0 \left(\frac{T\ [\mathrm{K}]}{1.14 \times 10^4}\right)^{\mu} \ [\mathrm{J/kg}]. \tag{7}$$

Here T is the target temperature, e_0 and μ are the coefficients for the specific internal energy determined by the target material.

From the above energy balance between the energy deposition and the internal energy of the target, if the $E_{kin} = E_{rad} << E_{int}$ can be assumed, the target temperature is

$$\frac{T\ [\mathrm{K}]}{1.14 \times 10^4} = \left(\frac{2}{3} + \frac{f_t}{3}\right)^{1/\mu}\left(\frac{qE_k}{\pi e_0 R_s}\right)^{1/\mu}\left(\frac{N_p}{r_f^2}\right)^{1/\mu}, \tag{8}$$

where

$$f_t = \frac{L_t}{R_s/\rho_t}, \tag{9}$$

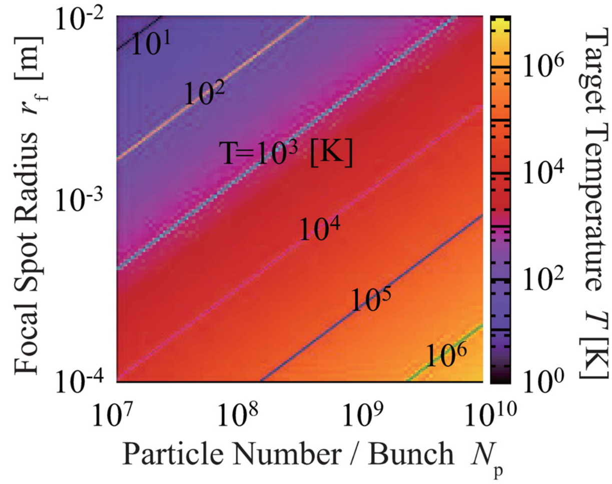

Figure 2: Temperature estimation as a function of the particle number per a bunch N_p and the focal spot radius r_f for $f_t = 0.5$ for Gold beam irradiation.

and $0 < f_t \leq 1$. Figure 2 shows the calculated temperature for $f_t = 0.5$. Here, we assumed $e_0 = 3.6 \times 10^7$ and $\mu = 1.2$ for the Al target based on an equation-of-state fitted from SESAME table data [4], $E_k = 10$ [GeV] and $q = 79$ for the beam ion species of Gold. The range of the stopping power is approximated as $R_s = 0.1$ [g/cm^2] $=$ 1 [kg/m^2] [4]. As shown in Fig. 2, the particle number per a bunch $N_p = 4 \times 10^8$ for the focal spot radius $r_f = 1$ [mm] is required for the achievement of the target temperature $T = 5000$ [K]. In the case of the focal spot radius $r_f = 2$ [mm], the particle number per a bunch $N_p = 1.8 \times 10^9$ is needed to achieve the target temperature $T = 5000$ [K]. Figure 3 shows the calculated temperature for hydrogen ion beam irradiation with the beam parameters given in Table 1. For the H ion beam irradiation, the

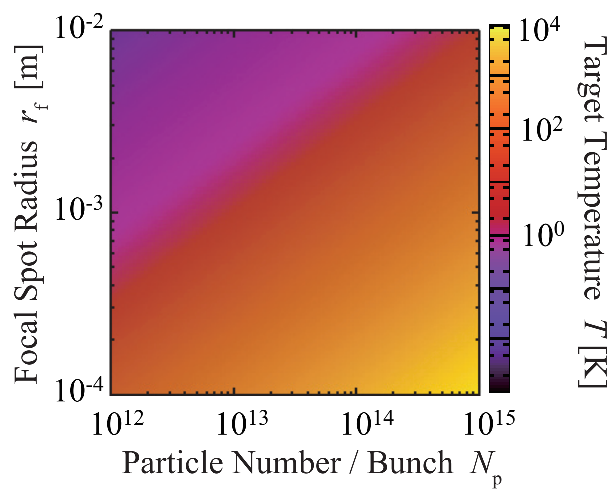

Figure 3: Temperature estimation as a function of the particle number per a bunch N_p and the focal spot radius r_f for $f_t = 0.5$ for hydrogen beam irradiation.

requirement of ion numbers per bunch is estimated to be 8.0×10^{14} for the focal spot radius of 1 [mm].

Table 2 summarizes the ion numbers per bunch for the production by KEK DA and the requirement in WDM generation estimated using above equations with the beam parameters from Table 1. The ion numbers produced by the

Table 2: Number of Ions for Requirement and Production by KEK DA

Ion	KEK DA	Requirement
H	3.5×10^{10}	8.0×10^{14}
He^3	1.8×10^{10}	6.3×10^{13}
He	1.8×10^{10}	4.1×10^{13}
C	5.8×10^{9}	1.5×10^{12}
Ar	1.9×10^{9}	5.0×10^{10}
Fe	1.3×10^{9}	1.7×10^{10}
Cu	1.2×10^{9}	1.2×10^{10}
Au	4.4×10^{8}	5.1×10^{8}

KEK DA are restricted by the space charge tune shift due to the low energy injection. Table 2 indicates that the heavy ion beams have an advantage from the viewpoint of the ion numbers per bunch. However the comparison between the KEK DA productions and the requirements to make WDM implies that the other resources for target material and the improvement of ion numbers stored in the KEK DA may be required for the WDM experiments.

COMPUTATIONAL FLUID DYNAMICS FOR TAMPED TARGET

To suppress the fluid expansion of the target, the structure of target with a tamper was proposed [5]. Figure 4 shows the computational box. The target is assumed to

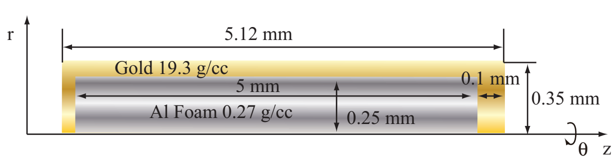

Figure 4: Numerical model for the tamped target.

be Al as a WDM surrounded with Au as a tamper. The heavy ion beam penetrates into the target, and heats the Al region. Since the Au tamper has a large inertia, the tamper can protect the fluid dynamic expansion of Al in WDM condition. Figure 5 shows the two-dimensional hydrodynamic simulation results based on the quotidian equation-of-state (QEOS) [6, 7]. Figure 5 implies that the illumination of heavy ion beam into the tamped target creates a quasi-uniform WDM. The uniformity of density, temperature, and pressure in the target is needed to be accurate measurements for WDM condition.

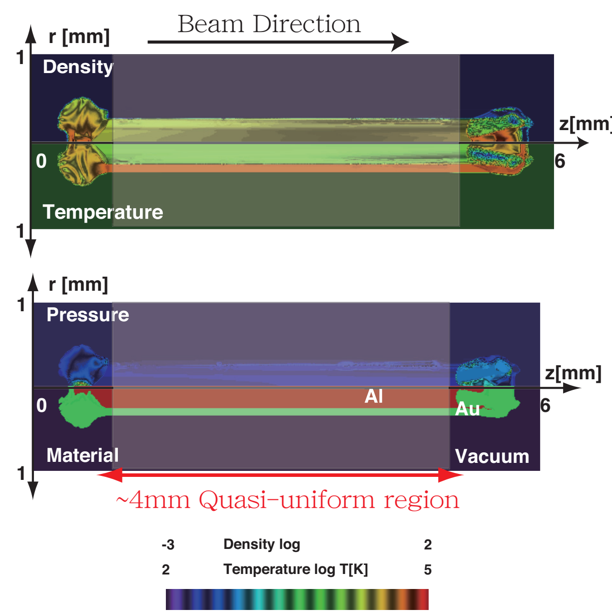

Figure 5: Target density, temperature, pressure and material function distributions after heavy ion beam illumination.

CONCLUSION

For the WDM experiment using the KEK DA, the simple model based on an energy balance equation estimated the achievable target temperature as a function of the focal radius and ion numbers per bunch. The estimation results showed that the heavy ion beam is advantageous for small number of ions required due to WDM generation. Two-dimentional hydrodynamic simulations showed that the tamped target can achieve a quasi-uniform WDM.

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