Estimation of Requirements for Warm Dense Matter Generation Driven by Intense Electron Beam

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(Received 24 March 2009 / Accepted 14 April 2009)

Beam parameter requirements are estimated for generating warm dense matter (WDM) by means of an intense electron beam. An energy balance equation between input beam and energies distributed into a target is derived. Results show that a beam of lower kinetic energy has some advantages for WDM generation from the viewpoint of radiation loss and beam current. Results also indicate that WDM (2 mm × 2 mm) at 5000 K can be generated using an electron beam with parameters kinetic energy = 1 MeV, beam current = 2.3 kA, and pulse duration = 100 ns.

Keywords: warm dense matter, intense electron beam, energy balance, stopping range, radiation yield

DOI: 10.1585/pfr.4.026

Studies on warm dense matter (WDM) are conducted worldwide using intense lasers, pulsed power devices, and intense ion beams [1]. To generate the WDM state, it is necessary to achieve a target temperature range of 0.1 to 10 eV with solid density very quickly. It is difficult to maintain the WDM state for any length of time due to the extraordinary high pressures involved.

We propose a method to achieve the WDM state by means of an intense electron beam with a pulse of short duration, generated by applying an induction accelerator on a small laboratory scale without the need of a heavy ion beam accelerator [2].

The energy balance equation is

$$E_{\mathrm{dep}} = E_{\mathrm{int}} + E_{\mathrm{kin}} + E_{\mathrm{rad}}, \tag{1}$$

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 [3]. Figure 1 shows a schematic view of electron-beam-driven WDM generation. Incident electrons are stopped inside the target at the deposition depth, which depends on the kinetic energy of the electron.

The energy deposited into the target is $E_{\mathrm{dep}} = P_{\mathrm{b}}\tau_{\mathrm{b}}$, where P_{b} is the beam power and τ_{b} is the beam pulse duration. The input beam power is $P_{\mathrm{b}} = E_{\mathrm{k}} I_{\mathrm{b}}$, where E_{k} is the kinetic energy of the beam and I_{b} is the beam current.

The internal energy of the target is $E_{\mathrm{int}} = \pi r_{\mathrm{f}}^2 L_{\mathrm{d}} \rho_{\mathrm{t}} e(T)$, where r_{f} is the focal spot radius of the beam at the target, L_{d} is the energy deposition length of electron beam in the target, ρ_{t} is the target (mass) density, and $e(T)$ is the specific internal energy obtained by [3],

$$e(T) = e_0 \left(\frac{T\,[\mathrm{K}]}{1.14 \times 10^4} \right)^{\mu} \ [\mathrm{J/kg}]. \tag{2}$$

Here T is the target temperature, and e_0 and μ are the coefficients for the specific internal energy determined by the target material. The coefficients $e_0 = 3.6 \times 10^7$ and $\mu = 1.2$ are assumed for aluminum (Al) by adjusting SESAME equation-of-state (EOS) data [3]. The length of electron beam deposition is obtained by $L_{\mathrm{d}} = R_{\mathrm{s}}/\rho_{\mathrm{t}}$, where R_{s} is the range of the stopping power and depends on the kinetic energy of the electron beam. The range is given by a continuous-slowing-down approximation [4]. As a result, the internal energy is rewritten as $E_{\mathrm{int}} = \pi r_{\mathrm{f}}^2 R_{\mathrm{s}}\, e(T)$.

The radiation loss is estimated using $E_{\mathrm{rad}} = Y_{\mathrm{r}} E_{\mathrm{dep}}$, where Y_{r} is the radiation-yield fraction of kinetic energy that is lost due to conversion into bremsstrahlung [4]. Since

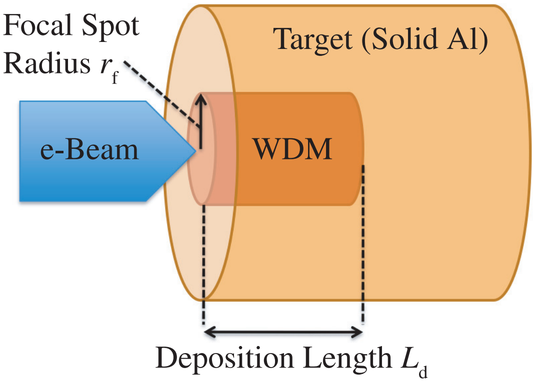

Fig. 1 Schematic view of electron beam driven WDM state.

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the target temperature is in the range 0.1 to 10 eV for the WDM state, radiation from the target illuminated by the electron beam is dominated by bremsstrahlung. The radiation-yield fraction is expected to be 7.45% at E_k = 10 MeV for Al [4]. However the fraction is estimated to be 44.5% at E_k = 100 MeV, which is clearly disadvantageous for WDM generation. Thus, the most suitable kinetic energy of the electron beam is taken to be a few megaelectron volts, and radiation loss is estimated to be < 10% for this range.

The kinetic energy E_kin of fluid dynamics in a target driven by electron beam irradiation is negligibly small when the pulse duration is short enough [5, 6].

Thus, substituting the above energy factors into Eq. (1) if the $E_\mathrm{kin} \ll E_\mathrm{rad} + E_\mathrm{int}$ can be assumed, the required beam current is

$$I_\mathrm{b} = \frac{\pi r_\mathrm{f}^2 R_\mathrm{s}\, e(T)}{(1 - Y_\mathrm{r})\, E_\mathrm{k} \tau_\mathrm{b}}. \qquad (3)$$

Equation (3) indicates that target density does not affect WDM generation.

Figure 2 shows the electron beam current required for WDM generation as a function of pulse duration for E_k = 1 MeV at several different target temperatures. When an electron beam with parameters E_k = 1 MeV, beam current = 2.3 kA, and pulse duration = 100 ns is irradiated at a spot radius of 1 mm, a WDM target (2 mm) at 5000 K is created in Al.

Figure 3 shows the deposition energy distribution of a 1-MeV electron beam in an Al target executed by Monte Carlo simulations using the CASINO simulation program [7]. The deposition energy is normalized by the maximum value. The deposition energy profile confirms that > 50% of input beam energy is distributed to a depth of 1.5 mm.

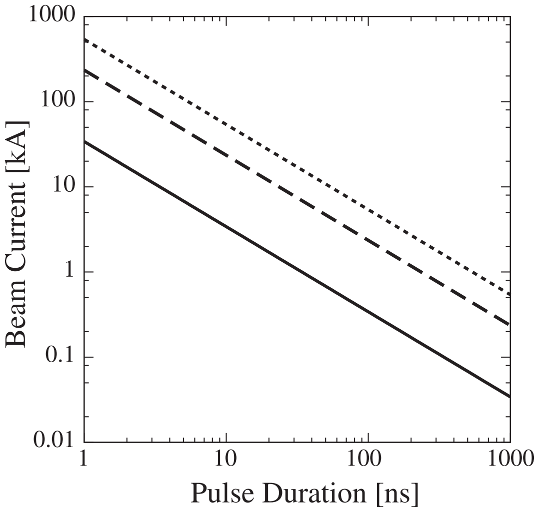

Fig. 2 Electron beam current to generate WDM state as a function of pulse duration at kinetic energy of 1 MeV at each target temperature for T = 1000 K (solid), for T = 5000 K (dashed), and for T = 10000 K (dotted).

Figure 4 shows the electron beam current required for WDM generation at 5000 K for a 100-ns pulse as a function of E_k. Since R_s increases with E_k, I_b also increases until E_k = 10 MeV. The electron beam with lower kinetic energy has an advantage for WDM generation from the viewpoint of beam current.

A high-current electron beam machine using an induction accelerator can be constructed on a much smaller scale than that using a heavy ion accelerator. For example, the parameters for an electron beam produced by the ETIGO-III inductive pulsed electron beam accelerator are E_k = 8 MeV, beam current = 5 kA, and pulse duration = 60 ns [2]. This makes the concept of WDM generation driven by an intense electron beam a reasonable scheme.

However, the results depend on the EOS model used

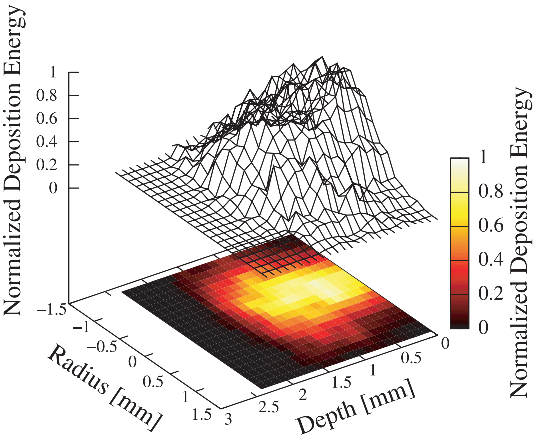

Fig. 3 Deposition energy distribution of 1 MeV electron beam in solid Al.

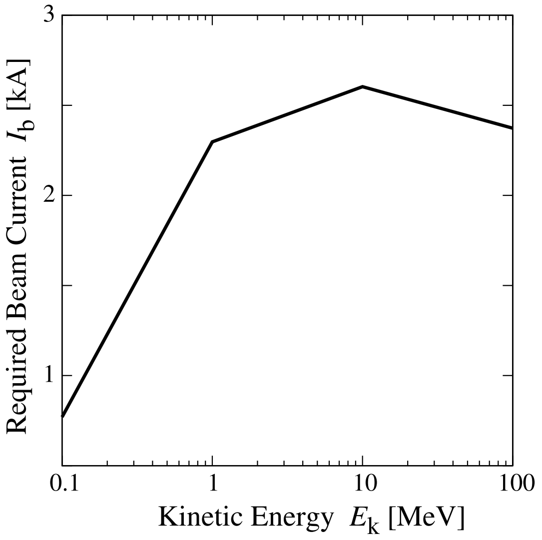

Fig. 4 Requirement of beam current to generate WDM at 5000 K for 100 ns pulse as a function of kinetic energy.

for estimation. For example, although, as shown in Fig. 2, a beam current of 2.3 kA is needed for WDM generation at 5000 K, it is predicted that a current of 3.7 kA is required for the case estimated by the ideal gas fermion EOS [8]. This difference is the motivation for WDM studies, and should be clarified by further comparative studies using numerical simulations and experiments.

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