Ignition requirement for HBRPA C^{6+} beam driven fast ignition

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1. Introduction

In fast ignition, an ultra-intense short-pulse laser is irradiated to heat a pre-compressed fusion fuel up to the ignition temperature. When the laser-accelerated electron beam is used for core heating, the large beam divergence, the broad energy spectrum and the difficulty in generating fast electrons having suitable energy to the core heating inhibit the efficient core heating. One of the alternative core heating schemes is use of ion beam generated by the hole boring radiation pressure acceleration (HBRPA). The 1D theoretical and numerical predictions [1,2] showed that it is possible to accelerate ions to the energy suitable for the core heating with the small energy spread and the small angular divergence. However, the 2D PIC simulations [2,3] showed the broader energy spectrum, the larger angular divergence and the lower conversion than those in the 1D predictions. In addition, there are no ignition requirement evaluations based on the integrated simulation including the ion acceleration, the core heating and the fusion burning.

In the present study, we evaluate the ignition requirement for HBRA-Carbon-beam-driven fast ignition by the integrated simulations where the properties ion and electron beams are evaluated with 2D PIC simulations using PICLS2d [4] and the following core heating and fusion burn processes are simulated by a 2D hybrid code FIBMET [5].

2. Ignition requirement of mono-energetic C^{6+} beam

To evaluate the beam energy required for ignition, we firstly carried out 2D hybrid-simulations where beam particles are treated by a particle scheme and a bulk plasma is treated by a radiation-hydro model. For a pre-compressed DT core (ρR = 2 g/cm^2, ρ = 500 g/cm^3, T = 0.3 keV) [6], a mono-energetic C^{6+} beam with the radius of 20 μm and the duration of 1 ps is injected at Δz = 100 μm away from the core center. For the particle energy ε_i = 100, 200, 300, 400 MeV and the beam divergence $\Delta\theta_b$ = 0°, 10° and 20°, the beam energy required for ignition $E_{b,ig}(\varepsilon_i, \Delta\theta_b)$ was evaluated by changing the beam energy E_b for a given (ε_i, $\Delta\theta_b$). The obtained result is plotted in **Fig.1**. In the parallel beam case ($\Delta\theta_b$ = 0°), $E_{b,ig}$ does not depend on ε_i and the value is 8 kJ, which agrees well with the Atzeni's estimation [7]. With increasing $\Delta\theta_b$, the heating region becomes larger in the perpendicular direction and the part of the beam particles does not hit the core, which enhances $E_{b,ig}$. This increment is larger for higher ε_i since the beam particles with higher ε_i have the longer range and then the diverging effect become more significant; in the case of $\Delta\theta_b$ = 20°, $E_{b,ig}$ for each ε_i becomes 2x ~ 3x larger than that in the parallel beam case. For reducing the diverging effect, the beam injection point was move to the core edge (Δz = 60 μm). As the results, $E_{b,ig}$ can be reduced to 11 kJ, which does not depend on ε_i, which means the monochromaticity of ion energy within ε_i = 100 ~ 400 MeV region is not important for ignition. Such a close beam injection (beam generation) may be possible by using cone attached solid ball target [8].

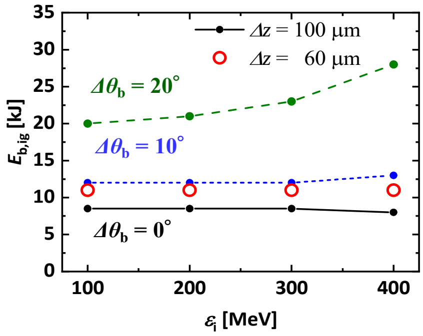

Fig.1 Beam energy required for ignition $E_{b,ig}$ as a function of particle energy ε_i for different divergence angle $\Delta\theta_b$. Closed and open circles are for Δz = 100 μm and 60 μm.

3. Beam generation by RPHBA

For ignition, a C^{6+} beam with a dozen kJ of beam energy should be generated at the region close to the core. In the present study, we considered RPHBA as the beam generation scheme. From a 1D momentum flux balance [2], the accelerated ion energy ε_i at the laboratory frame and energy conversion efficiency from laser to C^{6+} beam η_b can be described as

$$\varepsilon_i = m_i c^2[2\,\beta_f^{\,2} / (1-\beta_f^{\,2})] \;\propto\; I_L/n_i \text{ and } \eta_b = (1+f_R)(1-\beta_f)\,\beta_f / (1+\beta_f)) \;\propto (I_L/n_i)^{1/2},$$

$$\text{with } \beta_f = B/(1+B),\; B = [\,I_L/(n_i m_i c^2)\times(1+f_R)/2]^{1/2},$$

where m_i and n_i are the rest mass and the number density of C^{6+}, c is the speed of light and I_L and f_R are the laser intensity and the reflection ratio of incident laser power. The relations mean that the higher the particle energy becomes, the higher conversion we obtain. By the preliminary 1D PIC simulations, we checked the validity of the above relations. However, in 2D cases, both ε_i and η_b are smaller than those predicted by the above relations.

To evaluate the properties of C^{6+} beam and electron (e^-) beam generated by RPHBA, we carried out 2D PIC simulations, where fully-ionized carbon targets with the density close to the solid ones (ρ = 1.8, 2.0 2.2 g/cm^3) were assumed for beam generation targets. For the target, a circularly-polarized laser (the wavelength of λ_L = 1.053 μm) is normally irradiated with the spot width of ϕ_L = 20μm (Super Gaussian). Based on the theoretical prediction, we assumed the laser intensity of 0.9, 1.0, 1.1 × 10^{23} W/cm^2 for ρ = 1.8, 2.0 2.2 g/cm^3, respectively, to obtain ε_i ~ 325 MeV and η_b = 0.18. Using η_b = 0.18, the pulse durations τ_L should be longer than 0.21, 0.19, 0.18 ps for ρ = 1.8, 2.0 2.2 g/cm^3, respectively, for $E_b \geqq$ 11 kJ. In the simulation, after a short rising time (20 fs), the constant intensity is assumed.

In **Fig.2**, (a) the conversion efficiencies η_b and (b) time integrated beam energies E_b of C^{6+}

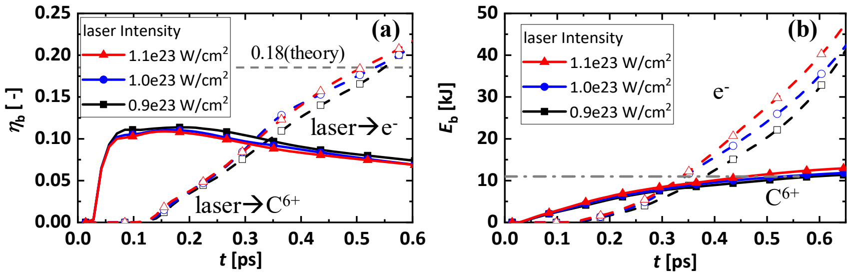

Fig.2 (a) Energy conversion efficiency η_b and (b) beam energy E_b as a function of time t.

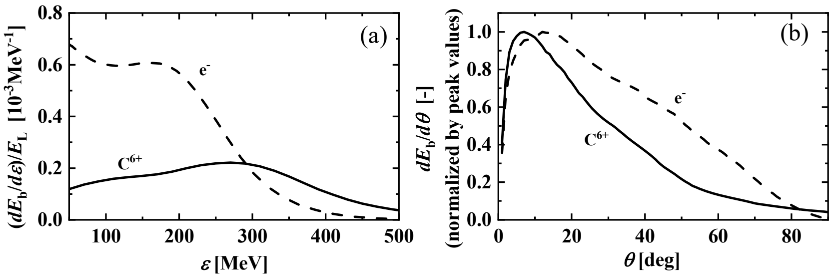

Fig.3 (a) energy spectra and (b) angular spread. These are evaluated from the particles properties passing through the observation line located at 20 μm inside of the target up to $t = 0.5$ ps.

and e^- beams are plotted as a function of time, where we assumed the axial symmetry against the laser axis for calculation of E_b. Due to the low density blow-off plasma generation on the target surface, the vending of interaction surface caused by the intensity gradient and the growth of perturbation of interaction surface, η_b for C^{6+} beam is lower than the theoretical prediction. In addition, η_b for C^{6+} beam decreases with time for $t \geqq 0.2$ ps since the e^- beam generation becomes remarkable due to the generation of low density blow-off plasma and the increase of interaction surface area with growth of perturbation. As the results, to obtain $E_b \geqq 11$ kJ, about 3 x longer duration than the theoretical prediction is needed; $\tau_L \geqq 0.60, 0.53, 0.46$ ps for $\rho = 1.8$, 2.0 2.2 g/cm^3. The energy spectra and the angular distribution for $I_L = 1.0 \times 10^{23}$ W/cm^2 are shown in **Fig.3**. Due to the same reason for the lower energy conversion, the energy and angular spreads are very large for C^{6+} beam. Also, the e^- beam has the broad energy and angular spreads. Almost the same properties are obtained for other intensity cases.

4. Core heating and fusion burning simulations using beam profiles evaluated by 2D PIC

Finally, we carried out hybrid simulations using the beam profiles evaluated by the 2D PIC simulations and by assuming the same core profile in Sec.2 to evaluate the heating laser properties required for fusion ignition. For each laser intensity ($I_L = 0.9, 1.0, 1.1 \times 10^{23}$ W/cm^2), the beam profiles observed for $\tau_L = 0.56, 0.62, 0.72$ ps are used. Also, two different beam injection conditions (both C^{6+}- and e^-- beams injection / only C^{6+}- beam injection) are assumed. Thus, the 18 simulations [3 (intensity) ×3 (pulse dureation) ×2 (with / without e^- beam)] were carried out. For all cases, $\Delta z = 60$ μm is assumed. The obtained Fusion output energy E_f are plotted as a function of (a) τ_L and (b) E_L in **Fig.4**, where E_L is calculated by assuming the axial symmetry along the laser axis. For the present simulation conditions, though the fusion ignition is not achieved with C^{6+} beam only, it takes place with C^{6+} beam and e^- beam. For the case using the PIC source, the laser energy required for ignition is $E_L \geqq$ 170 kJ, *e.g.*, for $I_L = 1.0\times 10^{23}$ W/cm^2 and $\rho = 2.0$ g/cm^3, the ignition can be occurred with $\tau_L \geqq$ 0.67 ps and then $E_L \geqq$ 170 kJ. In the ignited case, the energy conversion efficiencies from laser to C^{6+} beam and e^- beam are about 10 % and 30 ~ 40 %. The energy transport ratios from C^{6+} beam and e^- beam to the core are about 80 %, and 10 %. The core heating ratios (core heating energy/laser energy) via C^{6+} beam and e^- beam are ~8% and 3~4%, and then more than 10 % of total heating efficiency is obtained.

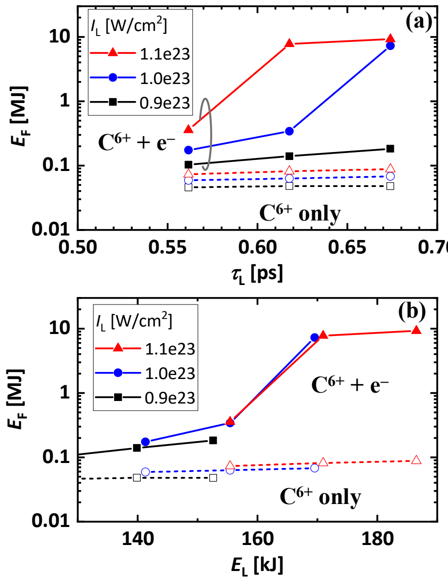

Fig.4 Fusion output energy E_F as a function of (a) pulse duration τ_L and (b) laser energy E_L.

5. Conclusion

The PIC-hybrid integrated simulations for RPHBA-C^{6+}-beam-driven fast ignition showed that the circular-polarized intense laser with $E_L \geqq 170$ kJ, $I_L \sim 10^{23}$ W/cm^2 and $r_L = 10$ μm and the carbon target for beam generation with the density of $\rho \sim 2$ g/cm^3 are required for ignition. Due to the multi-dimensional effects, e.g., vending and laser-wavelength scale perturbation of interaction surface, the C^{6+} beam qualities become poorer than the 1D prediction. Not only C^{6+} beam, but e^- beam generated at the same time plays an important role in core heating.

Acknowledgements

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