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Fast Ignition by Radiation-Pressure Accelerated Ion Beam
光圧加速イオンビームによる高速点火

Tomoyuki JOHZAKI, Yasuhiko Sentoku[1)], Atsushi Sunahara[2)],
Takamasa Morikawa and Takuma Endo
城﨑知至, 千徳靖彦[1)], 砂原淳[2)]、森川能匡, 遠藤琢磨

Graduate School of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima 739-8527, Japan
[1)] Department of Physics, University of Nevada Reno, 1664 N. Virginia Street Reno, NV 8955789557, USA
[2)] Institute for Laser Technology, 2-6 Yamadaoka, Suita 565-0871, Japan
広島大学 大学院工学研究院 〒739-8527 東広島市鏡山1-4-1
[1)] Department of Physics, University of Nevada Reno, 1664 N. Virginia Street Reno, NV 8955789557, USA
[2)]レーザー技術総合研究所 〒565－0871 吹田市山田丘2-6

On the basis of the integrated simulations, we evaluated the ignition requirement for radiation pressure accelerated C^{6+} beam driven fast ignition laser fusion. From the coupled transport and hydro simulations, it is found that the beam particle (C^{6+}) energy of 100 ~ 200 MeV minimizes the beam energy required for ignition. The 2D PIC simulations showed that the ion beam with averaged particle energy $<\varepsilon_p>$ of 210 MeV is obtained when a carbon target with the mass density of 2g/cm^3 is irradiated with the circularly-polarized laser with the intensity of 6x10^{22}W/cm^2 and wavelength of 1 μm. The energy convergence efficiency of laser to ion beam of 12 % was obtained. The core heating and burn simulations using the beam profile obtained from PIC simulations showed that the beam energy of 23 ~ 33kJ is required for ignition, which corresponds to the heating laser energy of 190 ~ 275kJ.

1. Introduction

In electron-driven fast ignition laser fusion, too high energy and too large divergence of laser produced fast electron beam inhibit the efficient core heating, which is one of the critical issues. As an alternative scheme, the fast ignition by radiation-pressure-accelerated (RPA) ion beam has been proposed [1,2], where the circular polarized intense laser is considered as the heating laser and the ions accelerated up to several tens ~ several hundreds of MeV by the radiation pressure of the heating laser heat the imploded core. In the present study, on the basis of integrated simulations, we evaluate the characteristics of RPA C^{6+} beam driven fast ignition, and estimate the generation condition of the ion beam required for ignition.

2. Requirement for Ignition

For evaluation of core heating properties and ignition condition for C^{6+} beam driven fast ignition, we have developed a particle-base transport code for fast ions, and coupled it with the fusion burn code FIBMET [3]. Using this code, we carried out the core heating and fusion burn simulations. We assumed the uniformly-compressed DT spherical core (ρ = 300g/cm^3, ρR= g/cm^2, T = 0.3keV) as an initial state of imploded fuel core. For this core, the mono-energetic no-divergence C^{6+} beam with the particle energy of ε_p = 50 ~ 400 MeV is injected with the pulse duration of τ_p = 1 or 5 ps. We evaluated the beam energy required for ignition E_{ig} by varying the beam intensity for a given ε_p. In Fig.1, the obtained E_{ig} is plotted as a function of ε_p. The ignition energy E_{ig} becomes minimum around ε_p = 50 ~ 200 MeV. For higher ε_p (such as ε_p = 400 MeV), the particle range becomes larger than the optical heating depth [4], which results in enhancing E_{ig}. As for the pulse duration, when the duration is shorter than the electron-ion

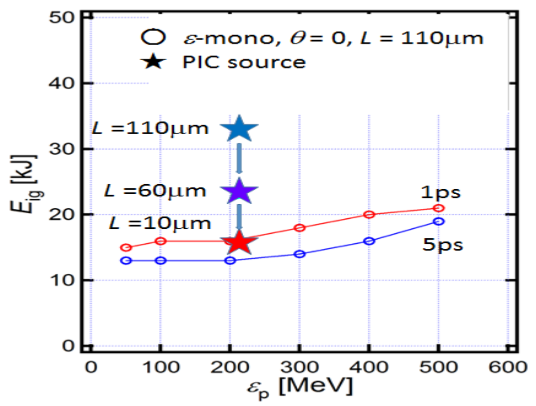

Fig.1. Minimum ignition energy E_{ig} as a function of particle energy ε_p for mono-energetic beam (lines with ○). The results for estimation using beam profiles obtained from PIC simulations also plotted by ★.

temperature relaxation time (typically a few ps), the heating region starts to expand due to the heated electron pressure before the relaxation proceeds, which enhances the energy loss from the heating region. So the pulse duration of a few ps is appropriate from the aspect of lowering E_{ig}.

3. C^{6+} beam generation

From discussion in the previous section, the particle energy of 50 ~ 200 MeV is suitable for ignition. Here, we determined ε_p = 200 MeV for the heating beam pulse, and estimated the laser and target condition for beam generation by the relativistic piston model [1]. The resultant target density and laser intensity are ρ = 2g/cm^3 (~solid carbon density) and I_L = 6x10^{22}W/cm^2. We carried out the PIC simulations [5] by assuming the above parameters and evaluated profiles of generated C^{6+} beam. Figure 2 shows the energy spectrum and pitch angle distribution of obtained C^{6+} beam. The central value of particle energy ε_0 is 210 MeV, which is close to the value obtained from the piston model. The spectrum is not monotonic but broad; the energy spread is $\Delta\varepsilon_0$ = 140 MeV. The angular spread is about 22 degree (HWHM), which is relatively large compared with the result in Ref.[1], but still small compared with the electron beam evaluated in the conventional fast ignition. In this case, the energy conversion from laser to ion beam is 12%.

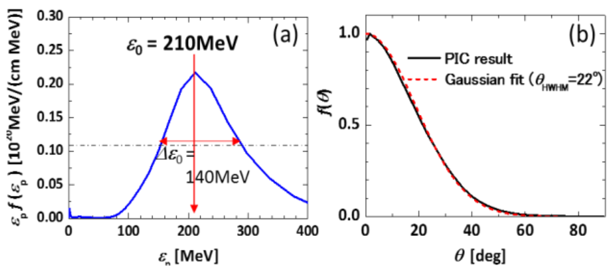

Fig.2. C^{6+} beam profiles obtained from 2D PIC simulation.

4. Integrated simulation

Using the energy and angular distribution of C^{6+} beam obtained by the PIC simulation as the heating beam pulse profile, we carried out the heating and burn simulation. The core profile is the same as that in sec.2. The heating pulse duration of τ_p = 1 ps was assumed. Then by varying the beam intensity, we evaluated the ignition energy E_{ig}. The beam injection point is 10, 60, 110 μm away from the core edge, and the beam radius is 15 μm. The obtained results are plotted in Fig.1 by ★. If only considering the energy spread and neglecting the beam divergence (i.e., no beam divergence), the ignition energy E_{ig} is the same as that for mono-energetic beam with ε_p = 200 MeV. This result shows that the energy spread slightly affects the ignition condition. In the case when the angular spread is considered in addition to the energy spread, E_{ig} becomes large with increasing the distance from the core edge to the beam injection point. This is because the beam spatially diverges with increasing the propagation distance and then the heating region is broadened in the perpendicular direction (and also part of beam particles do not hit the core). To keep the target for beam generation against the implosion, the separation of 50 ~ 100 μm from the core edge to the beam generation point is required at least. If using the energy conversion efficiency of 12% obtained from the PIC simulation, the required heating laser energy for ignition is 190 kJ (60μm injection) ~ 275kJ (110μm injection). These values are still lower than that obtained for the conventional electron-driven fast ignition [6].

5. Concluding Remarks

On the basis of integrated simulations, we evaluated the ignition condition for RPA C^{6+} beam driven fast ignition. It is found that for generation of 200MeV C^{6+} beam, which is suitable for core heating, a solid density (ρ = 2g/cm^3) carbon target and a circular polarized intense laser with intensity of 6x10^{22}W/cm^2 are required. To ignite a compressed DT fuel with ρ = 300g/cm^3, the heating laser energy of 195 ~ 275kJ is required.

Acknowledgments

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