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Integrated simulations for ion beam assisted fast ignition

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Abstract. Although the energy conversion efficiency from the heating laser to fast electrons is high, the coupling efficiency from fast electrons to the core is estimated to be very low due to large divergence angle of fast electrons in fast ignition experiments at ILE, Osaka University. To mitigate this problem, a plastic thin film or low-density foam, which can generate not only proton (H^+) but also carbon (C^{6+}) beams, is combined with currently used cone-guided targets and additional core heating by ions is expected. According to integrated simulations, it is found that these ion beams can enhance the core heating by 20~60% and it shows a possibility of ion beam assisted fast ignition.

1. Introduction

A fuel target is imploded by long-pulse implosion lasers and its compressed core is heated by a short-pulse ultrahigh-intense laser in the fast ignition scheme. Incorporated fast ignition experiments have started at ILE, Osaka University to demonstrate that the compressed core could be heated up to 5 keV using Au cone-guided targets under the FIREX project. First series of the incorporated experiments was performed in 2009, and only 30-fold enhancement in neutron yield, which was ~ 1/30 smaller than that in 2002 experiments, was achieved, and lower energy coupling from the heating laser to the imploded core was suspected.

2D PIC simulations indicate that even the coupling efficiency from the heating laser to fast electrons is generally high (>40 %) but the divergence angle of fast electrons is large (~90 degree), and it results in low coupling efficiency from fast electrons to the core [1]. The Weibel instability, which is induced by a fast electron flow and its counter stream of background electrons, generates quasi-static magnetic fields, and they grow up to more than hundred Mega gauss, large enough to scatter several MeV electrons within 1 μm. Furthermore, filamentations of the heating laser induce deformation of the plasma surface, and it could enhance the fast electron divergence. To mitigate this critical issue, advanced target designs, in which external-compressed and/or self-generated magnetic fields are expected to guide fast electrons to the core, are proposed.

On the other hand, high-energetic well-collimated proton beams were observed in many laser-thin foil experiments [2,3], and they can be used to additionally heat the core in cooperation with fast electrons. As protons are supposed to come from contaminations on the target surface, it's unclear and

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uncontrollable. Thus two types of plastic (CH) targets to generate not only proton (H^+) beam but also carbon (C^{6+}) beam are introduced. One type is a thin film target where ions are accelerated by the sheath field at the rear surface, and the other is a low-density foam target where ions are accelerated by the Ponderomotive force at the front surface [4]. Ion beam characteristics are investigated by 2D PIC simulations and core heating properties are evaluated by integrated simulations [5].

2. Target design

We put the CH as ion beam generator close to the cone tip in order to shorten the distance between the generation point and the imploded core. This design can reduce core-arrival time lags due to different ion energies, and we can accept ion beams with wide energy range. It can also reduce time lags between fast electrons and ions, and it is easy to introduce into FIREX experiments combining with currently used cone-guided targets. As the heating laser is designed to have 10 ps pulse length and the cone tip is placed 50 μm away from the implosion center, we assume that ion beams should propagate 60 μm and 5 ps time lag are accepted. So ions with the speed faster than 0.04 of the light speed can be accepted, and it means that H^+ with the energy higher than 0.7 MeV and C^{6+} higher than 9 MeV can be used to heat the core.

There are two well-known ion acceleration mechanisms. One is the sheath field acceleration on the rear surface of the target and the other is the Ponderomotive force acceleration on the front surface of the target. To adapt the sheath field acceleration, we introduce the thin film target as shown in figure 1 (a). The Au cone plasma (Z=30, A=197, 20n_{cr}, 60 degree open angle, 10 μm tip width) is introduced and the CH thin film (Z=6, A=12, 17.14n_{cr} and Z=1, A=1, 2.86n_{cr}, 3 μm thickness) is placed 5 μm away from the cone tip surface. The low-density SiO_2 foam plasma (Z=10, A=20, 0.5n_{cr}) is also placed in front of the CH thin film to enhance fast electron generation [5]. When the sheath field is induced, dense background electrons in the Au plasma are pulled into the CH thin film and it results in the sheath field being weakened. Therefore 0.5 μm gaps between the Au and the CH thin film are introduced to prevent the electron flow. For the Ponderomotive force acceleration, we introduce the low-density foam target as shown in figure 1 (b). The same Au cone plasma is also introduced and the low-density CH foam (Z=6, A=12, 8.57n_{cr} and Z=1, A=1, 1.43n_{cr}, 8 μm thickness) is placed in front of the cone tip surface.

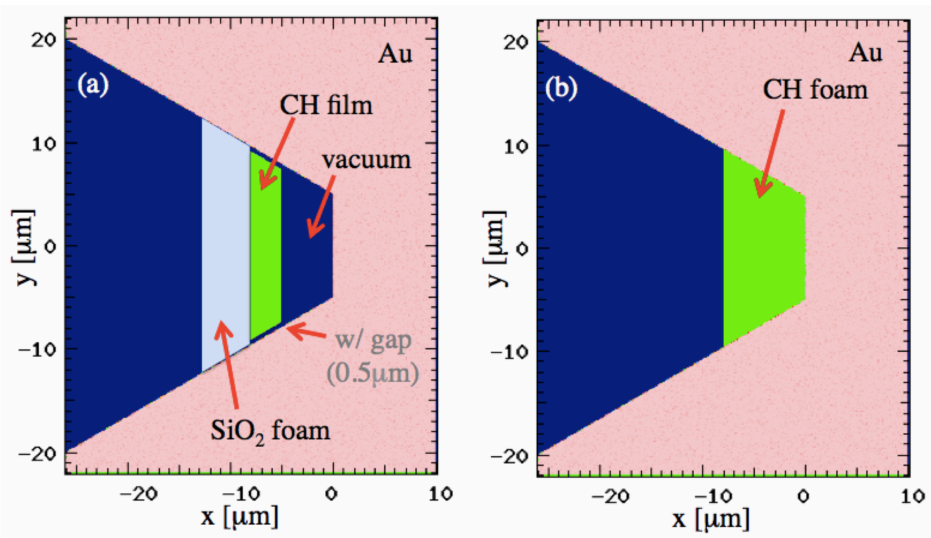

Figure 1. Targets for ion beam assisted fast ignition with (a) the sheath field acceleration and (b) the Ponderomotive force acceleration.

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3. Simulation results

The heating laser is set to λ_L=1.06 μm, I_L=10^{20} W/cm^2, τ_{rise}=τ_{fall}=50 fs, τ_{flat}=400 fs and ϕ_{FWHM}=10 μm Gaussian. In the case of the low-density foam target, super-Gaussian laser (I_L=5.333x10^{19} W/cm^2, ϕ_{FWHM}=20 μm, α=100), whose total energy is same as the Gaussian laser, is also irradiated to aim small divergence of ion beams. Fast electrons and ions are observed at 1 μm behind of the cone tip surface with 30 (±15) μm width. To ignore a circulation of fast electrons, we introduce an artificial cooling region (1 μm width), in which fast electrons are gradually cooled down to the initial temperature, behind the observation region, top and bottom regions of the Au plasma.

Time evolutions of fast ion beam intensities and time averaged fast ion energy spectra with and without the gap are shown in figure 2 (a) and (b), respectively. As sheath fields are not weakened due to existence of the gap because the thin CH film is isolated from background Au electrons, ions are much more accelerated and the ion beam intensity increase in the case with the gap.

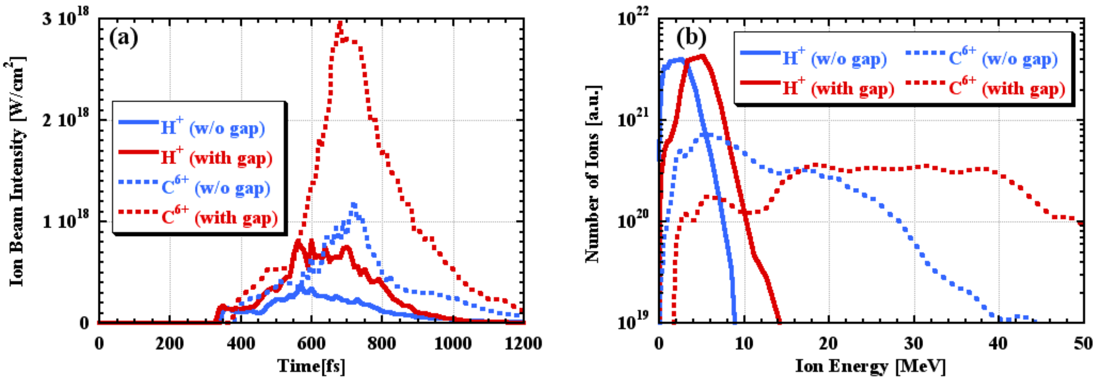

Figure 2. Fast ion (H^+:solid, C^{6+}:dash) properties. (a) time evolutions of fast ion beam intensities and (b) time averaged fast ion energy spectra with (red) and without (blue) the gap.

Time evolutions of fast ion beam intensities and time averaged fast ion energy spectra in the case of Gaussian and super-Gaussian lasers are shown in figure 3 (a) and (b), respectively. It is confirmed that C^{6+} beam divergence is improved with the super-Gaussian laser. As the total laser energy of both lasers are same, ion beam intensities and spectra are not so affected by the laser profile.

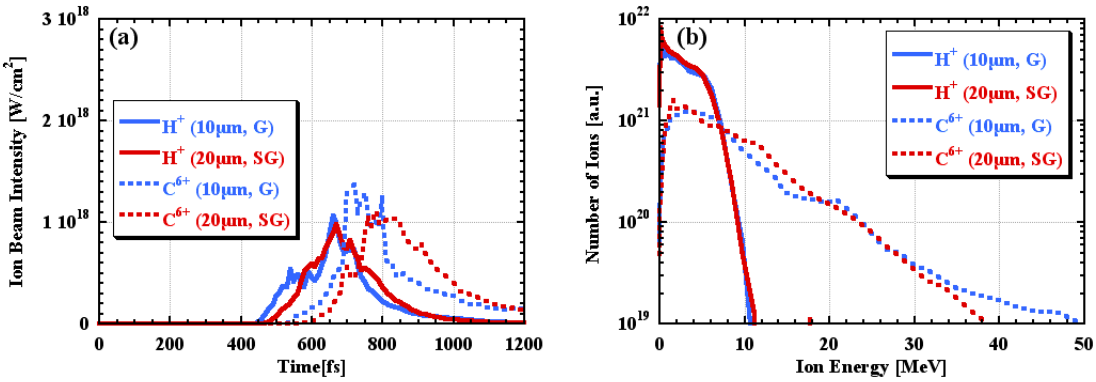

Figure 3. Fast ion (H^+:solid, C^{6+}:dash) properties. (a) time evolutions of fast ion beam intensities and (b) time averaged fast ion energy spectra in the case of Gaussian (blue) and super-Gaussian (red) lasers.

4. Integrated simulations

Using the time-dependent profiles of fast electrons and ions, which are observed in 0 < y < 3 μm in 2D PIC code, into 1D RFP-Hydro code, we carried out integrated simulations to evaluate the core heating properties [6], including 7 μm transport in the Au cone tip. Time evolutions of averaged core electron temperatures are shown in Figure 4 for all 4 cases. As electrons finish to heat the core but ions do not reach the core yet due to slow speed at 2 ps, electrons play a dominant role in core heating. After that, ions finally reach and heat the core instead of electrons. Thus temperature increment after 2 ps is dominantly caused by ions. In the case of the sheath field acceleration target with the gap, enhancement to temperature increment by ions is larger than that without the gap. On the other hand, the propagation of fast electrons is disturbed by the same sheath field and electron heating is reduced. So there is a tradeoff between ion and electron contributions, and the target without the gap results in better core heating under current conditions.

We summarize enhancement by ions for average core electron temperatures in table 1. Putting the CH thin film or low-density foam to the cone-guided target can successfully generate H^+ and C^{6+} beams and enhance the core heating by 20~60%. But structured targets are not well optimized at this moment, and it just shows potential for additional heating. Core heating simulations were performed by 1D RFP-Hydro code, and 2D Fokker-Planck simulations are needed to clarify ion beam assisted fast ignition.

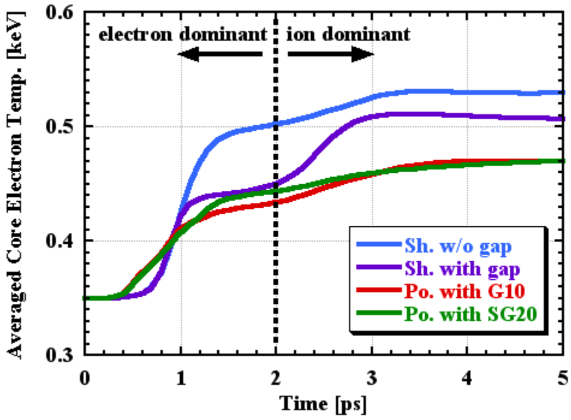

Figure 4. Time evolutions of averaged core electron temperatures for all 4 cases.

Table 1. Summary of enhancement by ions for average core electron temperatures.

		Sh. w/o gap	Sh. with gap	Po. with G10	Po. with SG20
Temperature increment keV	e only	0.15	0.10	0.08	0.09
	$e+H^++C^{6+}$	0.18	0.16	0.12	0.12
Enhancement by ions %		20	60	50	33

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