Simulation analysis for ion assisted fast ignition using structured targets

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Abstract. As the heating efficiency by fast electrons in the fast ignition scheme is estimated to be very low due to their large divergence angle and high energy. To mitigate this problem, low-density plastic foam, which can generate not only proton (H^+) but also carbon (C^{6+}) beams, can be introduced to currently used cone-guided targets and additional core heating by ions is expected. According to 2D PIC simulations, it is found that the ion beams also diverge by the static electric field and concave surface deformation. Thus structured targets are suggested to optimize ion beam characteristics, and their improvement and core heating enhancement by ion beams are confirmed.

1. Introduction

In the fast ignition scheme, first a fuel target is imploded by long-pulse implosion lasers, and then its compressed core is heated by a short-pulse ultrahigh-intense laser. The FIREX project has started at ILE, Osaka University to demonstrate core heating up to 5 keV with the fast ignition scheme using Au cone-guided targets. Results of both fundamental experiment campaigns and 2D PIC simulations indicate that the coupling efficiency from fast electrons to the core is quite low because the divergence angle of fast electrons is too large to efficiently hit the core and their slope temperature is too high to deposit the energy into the core even the energy conversion efficiency from the heating laser to fast electrons is generally high [1]. Thus a relatively small enhancement in neutron yield was achieved in integrated experiment campaigns.

To mitigate this critical issue, the ion assisted fast ignition scheme is suggested, where a plastic (CH) ion beam generator is introduced into the cone-guided target and additional core heating is expected by proton (H^+) and carbon (C^{6+}) beams [2,3]. To adapt the Ponderomotive force ion acceleration [4], the low-density CH foam is installed in front of the cone tip surface as the ion beam generator in order to shorten the distance between the ion generation point and the compressed core. This simple design can reduce core-arrival time lags due to different ion energies or between electrons and ions, and not only fast electrons but also energetic ions with wide energy range can be used to heat the core. In addition, this design makes it easy to introduce the ion beam generator into FIREX experiments combining with currently used Au cone-guided targets. Ion beam characteristics are

investigated by 2D PIC simulations, and found that the divergence angle of energetic ions is smaller than that of fast electrons but it is still too large to efficiently heat the core using the simple unstructured targets. Thus structured targets for the ion generator are needed to optimize the ion beam properties, and improvements for the divergence angle of energetic ions are confirmed.

2. Unstructured targets

Initial electron density profile of the unstructured target is shown in figure 1 (a). The Au cone plasma ($Z=30$, $A=197$, $20n_{cr}$, 60 degree open angle, 10 μm tip width, yellow in figure) is introduced and the low-density CH foam ($Z=6$, $A=12$, $7.37n_{cr}$ and $Z=1$, $A=1$, $1.23n_{cr}$, 8 μm thickness, light blue in figure) is placed in front of the cone tip surface. The total electron density of the foam, $8.60n_{cr}$, is selected to be the relativistic critical density to maximize the ion acceleration. The heating laser is set to $\lambda_L=1.06$ μm, $I_L=10^{20}$ W/cm^2, $\tau_{rise}=\tau_{fall}=50$ fs, $\tau_{flat}=400$ fs and $\phi_{FWHM}=10$ μm. Super-Gaussian with $\alpha=5$ laser is injected to flatly push plasmas than the Gaussian laser beam. Energetic 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.

Electron density profile at t=500 fs is shown in figure 2 (a). It is clearly seen that the low-density CH foam is pushed by the Ponderomotive force of the heating laser and ions in the center of the foam (±5 μm) are accelerated forward. On the other hand, electron density along the cone wall increases, but ion density at the same place is relatively preserved. Thus charge separation occurs and this induces static electric field in y-direction that can diverge ion beams. Time evolution of normalized angular distributions of (top) C^{6+} and (bottom) H$^+$ are shown in figure 3 (a). Angular distributions are normalized by the instantaneous maximum value at each time. At an early stage, both ions are accelerated along the laser axis with a small divergence angle. On the other hand, the surface of the low-density CH foam is concavely deformed at a later time. As ions are accelerated to the normal direction of the surface, both ion beams begin to split into two beams with 60 degree oblique angle after 800 fs for C^{6+} or 650 fs for H$^+$ due to the concave surface, and efficient core heating cannot be expected.
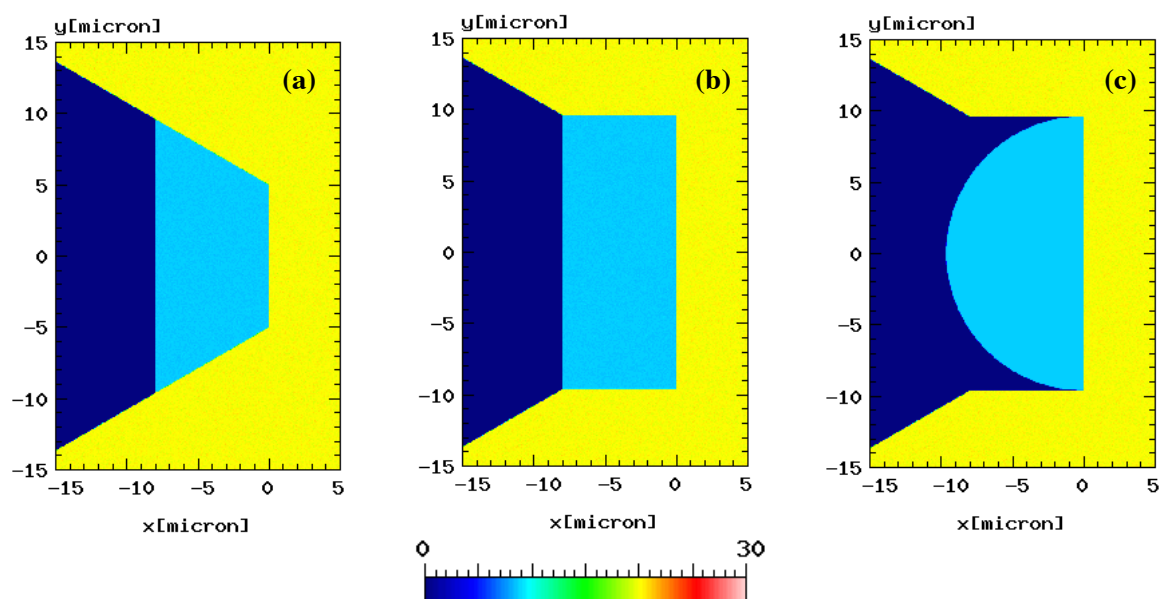

Figure 1. Initial electron density profiles of (a) unstructured, (b) non-tapered and (c) convex foam targets. Density scale is normalized by n_{cr}.

3. Structured targets

To prevent from forming the static electric field, non-tapered cone tip is introduced. Electron density profiles at t=0 fs and 500 fs are shown in figure 1 (b) and figure 2 (b), respectively. The non-tapered target can successfully suppress electron density increment along the cone wall. Time evolution of normalized angular distributions of (top) C^{6+} and (bottom) H^+ are shown in figure 3 (b). Although beam splitting for both ions are also suppressed before 1100 fs for C^{6+} or 1000 fs for H^+, the angular distributions are somewhat flat and ion beams have the large divergence angle because the foam surface is still concave shape. To compensate the concave surface deformation, convex foam target is introduced as the structured target. Electron density profiles at t=0 fs and 500 fs are shown in figure 1 (c) and figure 2 (c), respectively, it is found that the convex foam target can preserve surface flatness
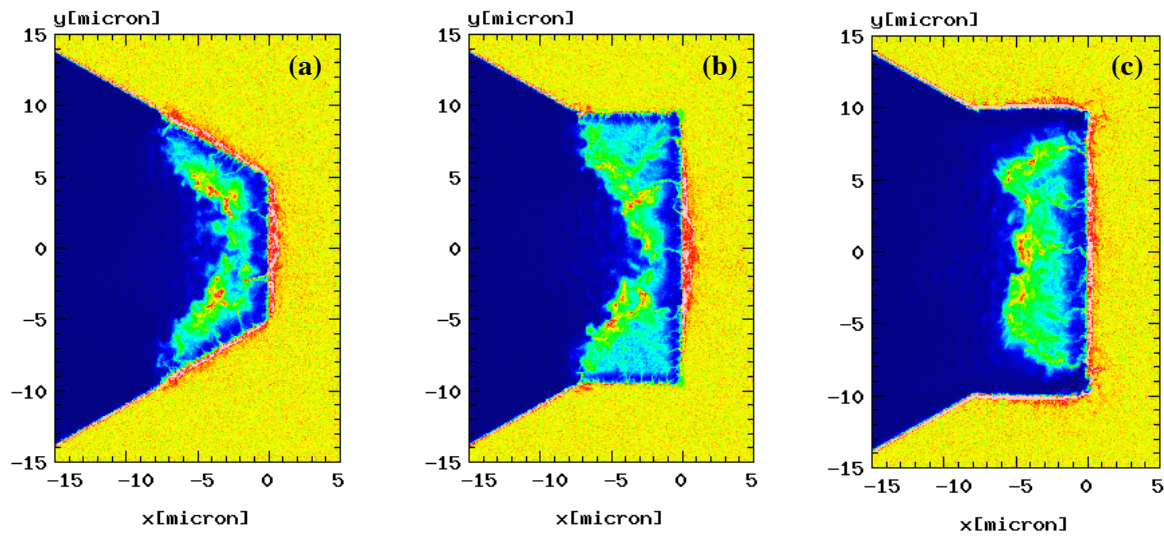

Figure 2. Electron density profiles at t=500 fs of (a) unstructured, (b) non-tapered and (c) convex foam targets. Density scale is as same as in figure 1.
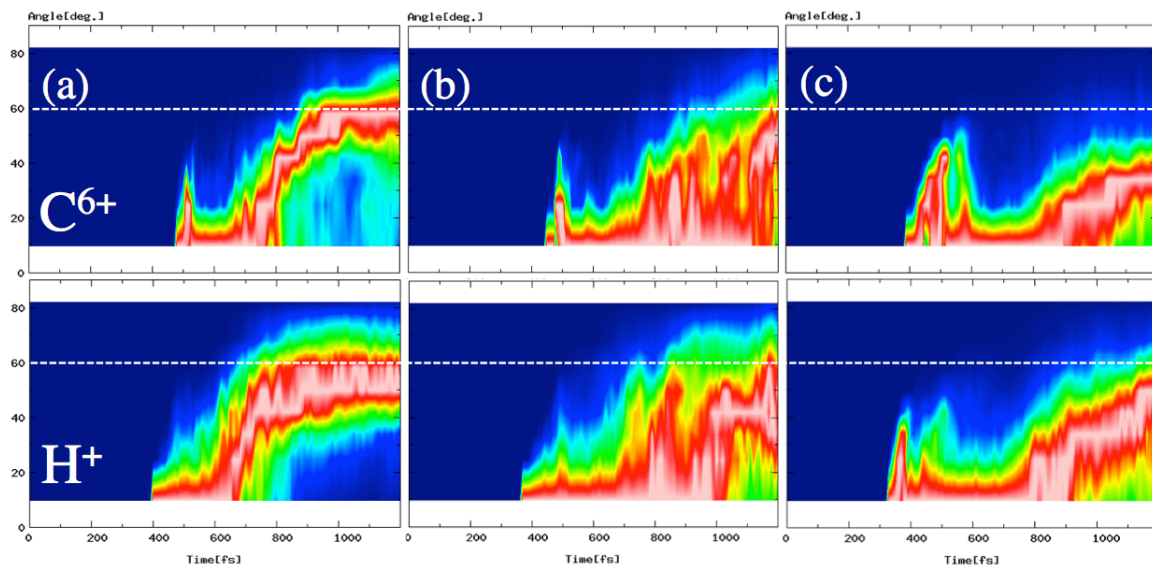

Figure 3. Time evolution of normalized angular distributions of (top) C^{6+} and (bottom) H^+ for (a) unstructured, (b) non-tapered and (c) convex foam targets. Angular distributions are normalized by the instantaneous maximum value at each time.

for a long time. Time evolution of normalized angular distributions of (top) C^{6+} and (bottom) H^+ are shown in figure 3 (c), and improvement for the divergence angle of ion beams is clearly seen.

4. Integrated simulations

Transferring 2D PIC data of fast electrons and energetic ions, which are observed in $0 < y < 3$ μm into 1D RFP-Hydro code, we carried out integrated simulations to evaluate the core heating properties [5], including 7 μm transport in the Au cone tip. Time evolutions of averaged core electron temperatures are shown in figure 4 for all 3 cases. As electrons finish to heat the core but ions do not reach the core yet due to slow speed, electrons play a dominant role in core heating before 2 ps. After that, ions finally reach and dominantly heat the core instead of electrons. In the case of the non-tapered target, enhancement to temperature increment by ions is larger than that of the unstructured target, but electron heating is somewhat reduced. On the other hand, ion heating is significantly enhanced with the convex foam target, but electron heating is seriously reduced. Fast electron generation can be enhanced by using a relativistically underdense multi-layer foam in front of the solid target [6]. So target structures should be well optimized for fast electron generation and it's left for future work. Additionally, 2D core heating simulations are needed to accurately estimate the heating efficiency in the ion assisted fast ignition as current heating simulations are performed by 1D RFP-Hydro code and divergence effects are not properly calculated.
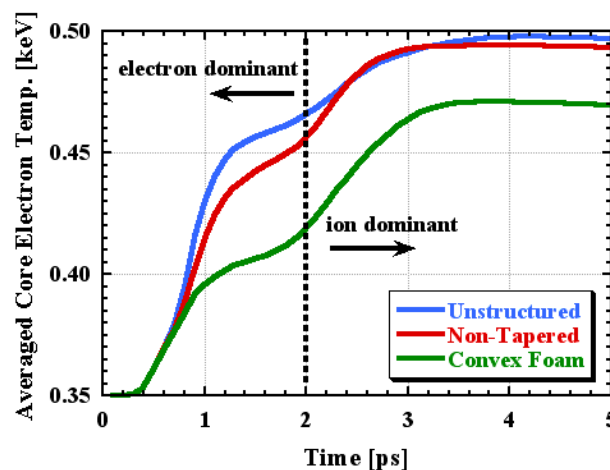

Figure 4. Time evolutions of averaged core electron temperatures for all 3 cases.

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