33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.30I, P-1.013 (2006)

# Holistic Simulations for Fast Ignition with Cone-Guided Targets

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## 1. Introduction

It was reported that the fuel core was heated up to ~ 0.8 [keV] in the fast ignition experiments with cone-guided targets at Osaka University [1,2], but efficient heating mechanisms and achievement of such high temperature have not been clarified yet. To estimate scheme performance of the fast ignition, we must consider 1) overall fluid dynamics of the implosion, 2) laser-plasma interaction and fast electron generation, and 3) energy deposition of fast electrons within the core. It is, however, impossible to simulate all phenomena with a single simulation code due to divergence of both space and time scales, and we must simulate each phenomenon with individual codes and integrate them holistically. To attack this challenging problem, we have been promoting the Fast Ignition Integrated Interconnecting code ($FI^3$) project [3,4]. Under this project, the Arbitrary Lagrangian Eulerian hydro code (PINOCO)[5], the collective Particle-in-Cell code (FISCOF1)[6], and the relativistic Fokker-Planck code (FIBMET)[7] are integrated with data exchanges.

To explore fast ignition experiments with Au cone-guided targets with holistic simulations, the heating laser is set to Gaussian pulse of $\lambda_L$ = 1.06 [μm], $\tau_{FWHM}$ = 750 [fs] and $I_L = 10^{20}$ [W/cm$^2$] to adapt the experimental laser condition. Because of the long simulation duration up to 6 [ps], ion dynamics cannot be ignored. So we introduce mobile Au ions with real mass and Z=50, which is estimated from an average ionization degree of Au calculated by PINOCO, and we model the simulation plasma profile according to PINOCO results in FISCOF1 as follows. Since the scale length of the preformed plasma affects the ion dynamics, the preformed plasma is assumed to have an exponential profile of the scale length ($L_{pr}$) 0, 0.25, 1 and 5 [μm] with density from $0.1n_c$ up to $100n_c$, where $n_c$ is the critical density. Behind the preformed plasma, the cone tip is assumed as a 10 [μm] width and $100n_c$ density plasma, following the imploded plasma of the exponential profile of the scale length 10 [μm] with density from $10n_c$ up to $100n_c$ (24 [μm] long). Thus there is the density gap between the cone tip and the imploded plasma. At the rear of the imploded plasma, the compressed core plasma of $100n_c$ is placed in 26 [μm] long. The energy of fast electrons is observed at the middle of the cone tip (Obs1), and at $20n_c$ point in the imploded plasma (Obs2).

## 2. Sloshing Electrons

To see the effect of the ion dynamics, we run FISCOF1 with immobile/mobile ions and $L_{pre}$=1 [μm]. Time evolution of electron beam intensity and time averaged electron energy spectrum are shown in Fig. 1(a) and Fig. 1(b), respectively. The electron beam intensity of mobile ions observed at Obs1 is three times as large as that of immobile ions in peak value, and gradually decreases due to the ion expansion/diffusion after laser irradiation. When the fast electron current, which flows across the gap, cannot be neutralized by the return current, a large static potential is built up at the gap [8]. This potential reflects a relatively low energy part of fast electrons and accelerates bulk electrons into the cone tip. Therefore the cone tip is filled up with sloshing electrons, which are indicated by the energy spectrum with <2 [MeV] at Obs1, comparing with that of immobile ions. It also decelerates fast electrons, which can be seen by difference between energy spectra at Obs1 and Obs2, and decreases the peak beam intensity at Obs2, comparing at Obs1. In case of immobile ions, the fast electron current is perfectly canceled by the return current, and the large potential is not induced. Thus peak beam intensities and energy spectra are same for both Obs1 and Obs2.

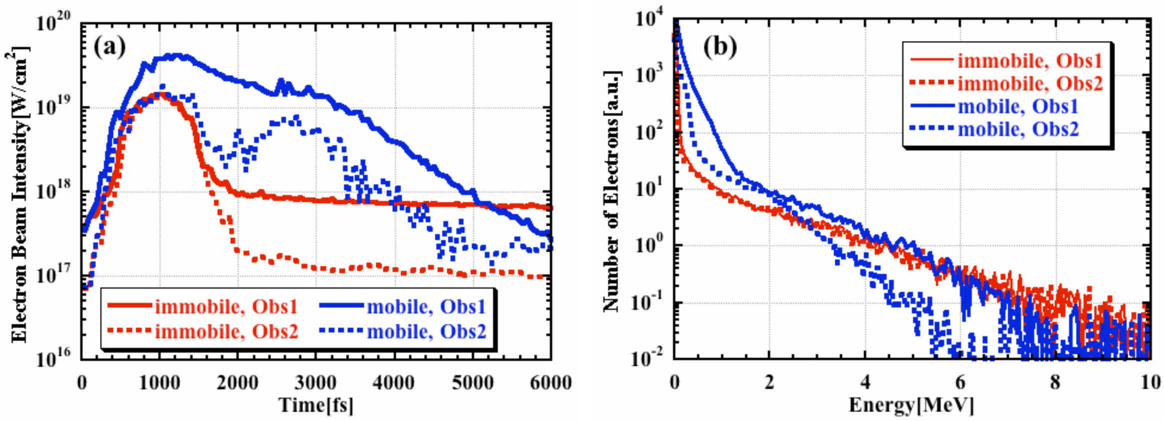


Fig.1 (a) Time evolution of electron beam intensity and (b) time averaged electron energy spectrum for immobile (red) and mobile (blue) ions. Solid lines are corresponding to Obs1, and dash lines to Obs2.

Electron phase space, electron density and laser field for immobile and mobile ions are shown in Fig. 2(a) and Fig. 2(b), respectively. In case of mobile ions, the preformed plasma is pushed by the Ponderomotive force and profile steepening occurs. Since the underdense plasma is cleared away due to the profile steepening, backward electrons are directly pushed back by the Ponderomotive force, and perfectly reflected at the boundary. In addition, fast electron bunches are periodically launched by the oscillating Ponderomotive force and therefore the forward current increases, building up the potential at the gap in turn, finally trapping electrons within the cone tip. After laser irradiation, no Ponderomotive force can trap electrons but a static potential is easily developed at the boundary because of the steep profile, and electrons are still circulated. As confinement of sloshing electrons is degraded due to the ion expansion/diffusion and some fractions of them are continuously released from there even after the laser pulse is dropped off, the electron beam intensity at Obs2 is much larger than that of the immobile ion case and this effect is good for core heating [9].

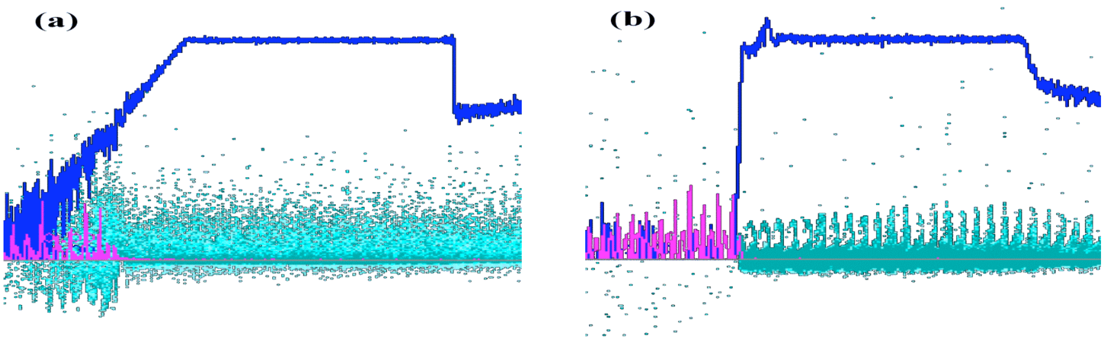


Fig.2 Electron phase space (light blue), electron density (blue) and laser field (purple) at t=1000 [fs] for (a) immobile ions and (b) mobile ions.

### 3. Scale Length of Preformed Plasma Profile

Time averaged electron energy spectra for different $L_{pre}$ at Obs1 are shown in Fig. 3(a). The preformed plasma with longer scale length has wider underdense region, where the laser-plasma interaction dominantly takes place, and higher energy electrons are generated. But such high energy electrons ( >2 [MeV] ) have long mean-free-path and do not efficiently heat the core [9]. On the other hand, shorter scale length leads to steepening the profile and to increases sloshing electrons, which are released and heat the core at a later time. When the scale length is too short, slight laser-plasma interaction causes little high energy electrons, hence little sloshing electrons. Thus there will be an optimum scale length for core heating.

Time averaged ion energy spectra for different $L_{pre}$ at Obs2 are shown in Fig. 3(b). If the scale length is long enough, a laser pressure causes an extremely large charge separation, which accelerates ions to ~500 [MeV], in the underdense plasma at early stage. These energetic ions reach at Obs2 in later time. The static potential is also built up at the gap, and ions are accelerated up to 100 [MeV]. Ion phase space for $L_{pre}$=1 [μm] is shown in Fig. 4 and two mechanisms for the ion acceleration are clearly seen.

**Acknowledgments**

This work was supported by MEXT, the grant-in Aid for Creative Scientific Research (15GS0214).

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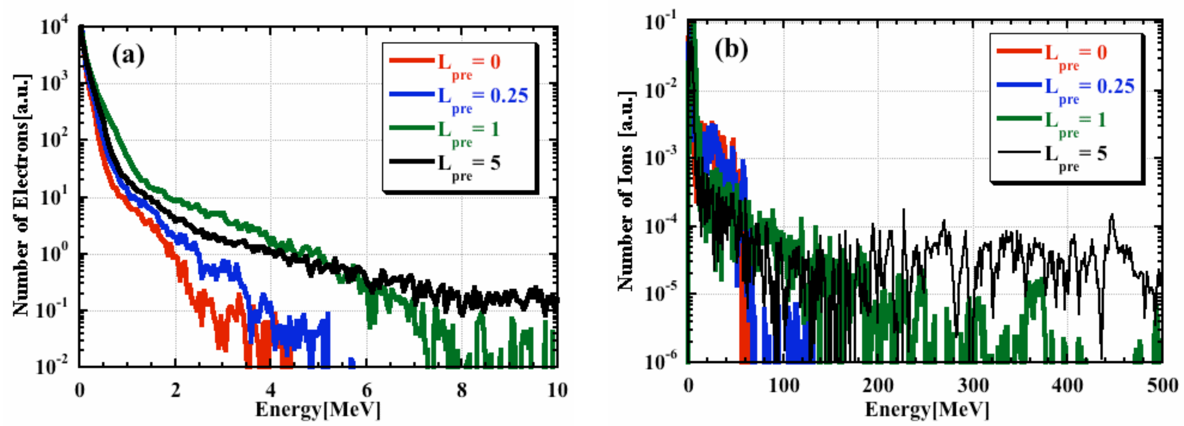


Fig. 3 (a) Time averaged electron energy spectra at Obs1, and (b) time averaged ion energy spectra at Obs2 for $L_{pre}$=0, 0.25, 1 and 5 [μm].


Fig. 4 Ion phase space for $L_{pre}$=1 [μm] at t=2000 [fs].