Integrated simulations of ignition scale fusion targets for the HiPER project

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Abstract. Integrated simulations of fusion targets with a re-entrant cone are presented. Fuel assembly is modeled with one- and two-dimensional (2D) radiation hydrodynamics. Fast electron acceleration in the cone is simulated with 2D planar particle-in-cell (PIC) codes. The fast electron transport and the fuel ignition are described self-consistently with a 2D cylindrical electron hybrid code coupled to hydrodynamics. It is found that at laser intensities \( \sim 10^{20} \text{W cm}^{-2} \), the front rippling at the cone tip generates strong magnetostatic fields, producing a large electron beam divergence. Fuel ignition at acceptable values of the ultra high intensity (UHI) laser energy requires a substantial reduction of the electron beam divergence.

The method of Fast Ignition (FI) of inertial confinement fusion (ICF) targets assumes a separation of compression and heating phases of the entire process \cite{1}. The use of cone targets provides a possibility to generate a relativistic electron beam near the dense core. It is supposed to carry a significant fraction of the laser energy to a small hot spot where the fusion reactions are triggered. While integrated experiments have demonstrated a high efficiency of coupling the UHI beam to the core \cite{2}, it is not clear whether these results apply to intensities and energies required for ignition-scale targets \cite{3}. In this paper, we estimate the UHI laser beam requirements, to ignite a target with a gold double cone inserted, as proposed in Ref. \cite{4}, within the context of the HiPER project \cite{5}. The entire modeling is conducted in three steps. First, we design the fuel assembly with special attention to the integrity of cone tip during the compression phase. Simulations are performed with the 1D/2D radiation hydrodynamic code SARA \cite{6}. Second, fast electron acceleration by a UHI laser pulse in a double cone is studied with 2D PIC simulations \cite{7} without collisions. The pre-plasma generated by the ASE laser pulse was neglected as we are concerned by a reference calculation in the ideal case. Third, the fast electron transport and energy deposition are studied with a hybrid code coupled to hydrodynamics \cite{8}.

The re-entrant cone can be seriously damaged during the deuterium-tritium (DT) shell implosion and compression due to i) direct irradiation by nanosecond laser beams, ii) shock wave generated at the shell-cone interface, and iii) shock wave and plasma jet produced when the shell collapses at the center \cite{9}. For simplicity, we have considered a gold cone without a plastic coating in the preliminary calculations shown here. Radiation transport has not been included in the simulations to avoid the ablation of the gold cone surface and the tip by the X rays generated in the shell, as reported in Ref. \cite{9}. In order to decrease the jet velocity and the shock pressure at stagnation, we have designed a target with an implosion velocity of
Figure 1. a) Density profile at the time of peak \(\rho R\) with asymmetric implosion velocity (highest velocity near the cone wall). The double cone has a half-angle of 15°, with an inner radius of 10 \(\mu\)m, an outer cone inner radius of 20 \(\mu\)m, and a distance between the initial shell center \((z = 0)\) and the cone tip of 75 \(\mu\)m. The thickness of the inner cone wall and the void region between inner and outer cones is 5 \(\mu\)m. b) Initial density profile normalized to \(80n_c\) used in the PIC simulation. (The cell size is \(\lambda_0/56\) in both directions, with 40 electrons and 1 ion per cell. The size of the cone and the laser beam has been scaled-down by a factor of 2.) c) Density profile normalized to \(80n_c\) (bottom) and magnetic field normalized to \(m_e\omega_0/e\) (top) near the end of simulation, \(t \sim 1.2\) ps.

\[2 \times 10^7 \text{ cm s}^{-1},\] significantly lower than that of the HiPER reference target \((2.8 \times 10^7 \text{ cm s}^{-1})\) [10]. Our capsule has a total radius of 800 \(\mu\)m and is composed of a shell of 30 \(\mu\)m of CH and 220 \(\mu\)m of DT ice wrapping 550 \(\mu\)m of DT gas at a density of 0.04 mg cm\(^{-3}\). The 1D parameters of the capsule are as follows: \(\sim 140\text{ kJ}\) of absorbed energy at the wavelength of 0.35 \(\mu\)m, the peak \(\rho R \sim 1.6 \text{ g cm}^{-2}\), and the peak entropy parameter during implosion \(\alpha \sim 0.77\). The absorbed power pulse is designed such as all shocks are weak and arrive at the inner shell surface equally spaced in time. The maximum power is 40 TW. Due to the lack of an ALE (Arbitrary Lagrangian Eulerian) capability in the available radiation-hydrodynamics codes, we have studied the target implosion by 1D Lagrangian hydrodynamics simulations and the fuel compression including the cone by means of 2D Eulerian hydrodynamics. The 1D simulation is carried out until the peak implosion kinetic energy is attained. Then, the density, internal energy and velocity profiles are remapped onto a 2D cylindrical mesh with the gold double cone inserted and the hydrodynamic evolution continues until the peak \(\rho R\) is achieved. We use an asymmetric fuel implosion to mitigate the cone tip destruction and to optimize the mass distribution of the compressed core. This is modeled by setting a polar angle dependent implosion velocity at the remapping time (which can be obtained by a polar variation of the initial shell thickness). Assuming a \(P_1\) asymmetry of the implosion velocity, the most favourable configuration of the compressed core is obtained when the maximum velocity is 10% over the average at the cone walls. In this case, a small plasma jet preceded by a shock wave moves towards the cone tip (see figure 1(a)), while the main jet produced at the shell collapse time is directed just in the opposite direction. The thickness of the outer cone and the tip is 30 \(\mu\)m in order to avoid any plasma filling of the inner cone and the void between the cone double walls. Gold or heavier materials are the most appropriate for the cone fabrication because lighter materials would lead to a faster destruction of the cone tip due to their higher shock velocity. It is worthwhile noticing that in the compressed core configuration of figure 1(a): i) the distance between the inner surface of gold cone tip and the high density core is only \(\sim 80 \mu\)m, ii) the \(\rho R\) along the axis \((r = 0)\) has increased to \(\rho R = \int_{\text{core}} \rho dz/2 \sim 2.3 \text{ g cm}^{-2}\) due to the jet-like flow, and iii) a dense plasma jet spreads between the cone tip and the core. It will act as a wire to guide the fast electrons.

At the time of peak \(\rho R\), we assume that an UHI laser beam is launched inside the double cone generating a fast electron beam, whose characteristics have been estimated quantitatively.
Figure 2. a) Dispersion angle $\Delta \theta_0$ versus radial coordinate $y$ at time $t \sim 650$ fs for $41 \mu m < x < 43 \mu m$. b) Fast electron mean propagation angle $\theta_r$ versus radial coordinate $y$ at the same time and position. c) Beam density versus transverse coordinate $y$ at the same time. d) Hot electron temperature, in keV, depending on time for electrons with $0.25 \leq E \leq 2.5$ MeV. e) Energy density deposited. Fast electrons are injected at the left surface of the simulation box. f) Azimuthal magnetic field at the end of the pulse.

by PIC simulations. The laser maximum intensity is $I_0 = 2 \times 10^{20}$ W cm$^{-2}$, p-polarization, the wavelength is $\lambda_0 = 1 \mu m$, the pulse duration is 1 ps, and the cone density is $80 \ n_c$, where $n_c = m_e \epsilon \omega_0^2 / e^2$ is the critical density. The laser beam has a temporal and spatial Gaussian shape with a radius of $10 \mu m$ at half maximum (HWHM). A short laser pulse length and a low cone density have been chosen in order to obtain hole boring conditions comparable with the case of a realistic laser pulse length and cone density. Figure 1 (b) shows the initial plasma density profile. According to figure 1 (c), the plasma density is non-uniformly modulated by the laser pulse due to the natural front rippling enhanced by the interference fringes that appear at the cone tip inner surface. The hole boring velocity, proportional to $\sqrt{I}$, is two times higher in the fringes of maximum intensity, $I_{\text{max}} \approx 4 \ I_0$. A strong front corrugation, coupled with the transverse ponderomotive force, generates strong defocusing magnetic fields $[3]$, that increase the electron beam divergence. The local electron angular distribution $f_l(\theta, y, t)$, with $\theta = \arctan(p_y/p_x)$, can be approximated by a Gaussian function $f(\theta) \propto \exp[-(\theta - \theta_r)^2 / \Delta \theta_0^2]$, where $\theta_r(y, t)$ is the mean propagation angle and $\Delta \theta_0(y, t)$ the angular dispersion. Figures 2 (a) and (b) show $\Delta \theta_0$ and $\theta_r$ versus the radial position for electrons with energies higher than 250 keV behind the acceleration zone. The dispersion angle is maximum at the cone tip inner surface due to the strong magnetic field. However, its value is small, $\sim 15 \sim 30^\circ$ at HWHM. The high electron divergence comes from the radial velocity, given by $\theta_r$. For instance, electrons at the distance $y \sim 8 \mu m$ are ejected in the direction of $\sim 35^\circ$. Consequently, the full electron angular distribution function, $f(\theta) = \int f_l(\theta, y) dy$, presents a high dispersion angle with a HWHM of $\Delta \theta \sim 55^\circ$. Both parameters, $\Delta \theta_0$ and $\theta_r$, are constant in time. However, the fast electron beam radius increases with time, and it attains the value of the outer cone inner radius because of the double cone confinement. This effect increases the full divergence with time, since more electrons have a high radial velocity. The local fast electron energy spectrum is also estimated...
versus transverse direction and time, and it is characterized by a Gaussian function for electrons with energy between 250 keV and 2.5 MeV. The fast electron temperature does not depend on radial direction due to the electron mixing in strong magnetic fields. Moreover, as seen in figure 2(d), the electron temperature saturates below 1 MeV due to the profile steepening effect [11]. The laser-to-electron conversion efficiency is about 35% for electrons with energy $E \geq 100$ keV.

Assuming a cylindrical geometry for the initial radial velocity and the dispersion angle, the parameters of the fast electron source obtained by PIC simulations were used in the electron transport code. It is important to point out that the damaged cone tip has been artificially removed from the simulation box to avoid the scattering of fast electrons due to Coulomb collisions [12] and the magnetic defocusing caused by resistivity gradients at the Au/DT interface. Special attention has been paid to the electron initial divergence. If the initial radial current is neglected and electrons are injected symmetrically around the propagation axis, the beam is strongly collimated by the self-generated resistive magnetic field. On the contrary, if electrons are injected with the initial radial current observed in PIC simulations, the beam diverges just after injection, the magnetic field is much weaker and the beam collimation almost disappears. This is a central result of our analysis. Even with all the approximations assumed, our results show that the target of figure 1(a) can be ignited only with an unacceptably high electron beam energy ($\geq 50$ kJ) for the divergence $\Delta \theta = 55^\circ$ found in PIC simulations. A reduction of $\Delta \theta$ to $35^\circ$ lowers the electron beam ignition energy to the level of 40 kJ (delivered in 20 ps, FWHM), which could be achieved with the laser energies around 100 kJ envisioned in the HiPER project [5]. Figures 2(e) and (f) show the energy deposition and self-generated magnetic field in this case. It is worth remarking that the density jet that spreads from the compressed core to the cone tip contributes to the electron beam guiding. This can be explained the resistive magnetic field, $j_\rho \times \nabla \eta$, generated at the edges of the jet due to its lower Ohmic heating, lower temperature and higher resistivity when compared with the surrounding low density plasma.

In summary, we have performed integrated simulations relevant for FI. 2D hydrodynamic simulations show that an asymmetric shell implosion and sufficiently thick gold cone walls and tip prevent its destruction before peak compression. PIC simulations show unacceptable high electron beam divergence $\Delta \theta \sim 55^\circ$. Strong radial currents of accelerated electrons are due to the laser ponderomotive force and strong density modulations that generate defocusing magnetic fields. Fuel ignition at the electron beam energy level of 40 kJ can be achieved if the initial beam divergence can be reduced to at least $35^\circ$ by means of optimized designs of the cone and the UHI laser beam temporal and spatial profiles.

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