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Fast electron energy deposition in inertial fusion capsules

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Three-dimensional (3D) hybrid PIC simulations are presented to study fast electron transport and energy deposition in a full-scale fast ignition configuration. This study is motivated by the next generation of high power facilities to demonstrate fast ignition.[1,2] We assume that fast electrons propagate in cone-guided targets,[3,4] in which a gold cone is inserted in a spherical shell to generate fast electrons near the compressed DT blob. Our study is focused to the dense part of the imploded target, from the cone tip to the dense blob, where beam resistive filamentation can occur.[5] Since full PIC simulations are not feasible yet for the high densities found in the fast ignition scenario, we have investigated fast electron energy deposition by means of 3D hybrid PIC simulations.[6] Two-dimensional simulations of fast electron transport in pre-compressed targets have been reported recently.[7-10]

Fast electrons are injected in the simulation box by assuming a Gaussian pulse with a duration of 10 ps (FWHM), a mean power of 6 PW (FWHM) and a total energy of 60 kJ (30 kJ within FWHM) focused onto a spot diameter of 40 μm (FWHM). Beam electrons energy distribution is assumed to be 1D relativistic Maxwellian with temperatures obtained from the ponderomotive acceleration scaling. Studies of laser accelerated electron spectra in large scale plasmas, such as those expected in cone-guided fast ignition, reveal that fast electron mean energy is higher than that obtained from the ponderomotive scaling.[9] Therefore, we have multiplied the scaling formula by a variable front factor to obtain electron mean energies from 1.5 to 5.5 MeV in order to study the effect of the electron kinetic energy on energy coupling with the dense core. A fast electron initial divergence of 22.5º has been assumed in agreement with the cone-guided experiments described in reference 3.

The main parameters of the imploded target configuration considered here are shown in Fig. 1. They have been adapted from implosion simulations with the code SARA-2D. The compressed DT blob has a Gaussian distribution in density with a peak value of 400 g/cm^3 located at a distance of 150 μm from the cone tip and is surrounded by a halo with a density of 1.5 g/cm^3. For simplicity, a uniform initial DT temperature of 500 eV has been assumed, which sets an initial resistivity of 10^{-8} Ωm throughout the target.

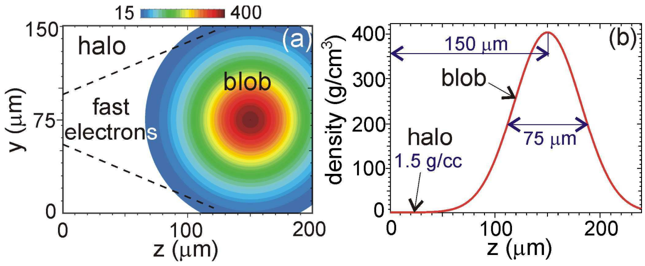

Figure 1. Configuration of the imploded target considered here. (a) density isocontours in g/cm^3 at x = 0, (b) density profile at y = 100 μm.

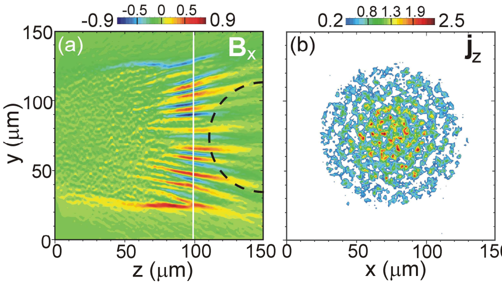

Figure 2. (a) Longitudinal cut of the magnetic field B_x in kT at x = 0, (b) perpendicular cut of the axial beam current density in units of 10^{14} A/cm^2 at z = 98 μm.

Figure 2 shows transport of 2.5 MeV electrons through the target near the peak injection time in terms of self-generated magnetic fields and beam current density. Notice beam filamentation onset at z = 70 μm. Filaments are seeded in the halo and are then amplified in the rising density profile, carrying about 10 MA beam current each in diameters of a few μm (see Fig. 2(b)). This current is almost completely compensated by plasma return current, $j_r \approx -j_f$, where j_f is the beam current density, with a net current j_f - j_r of the order of 10 kA consistent with $B_x \approx 1$ kT shown in Fig. 2(a). Figure 3 displays ion temperature at the end of the pulse. Electron temperatures in the halo are very high due to the strong ohmic heating by the return current ($\eta\, j_r^2/\rho$, where j_r is the return current density and η the resistivity), varying from 100 keV near the cone tip to 20 keV close to the blob. Much lower ion temperatures are shown in Fig. 3(a) for z < 50 μm due to the poor ion-electron energy coupling in the low-density halo.

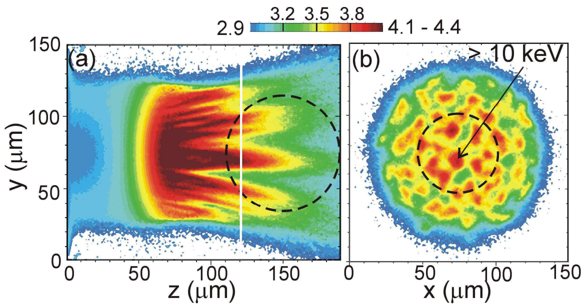

Figure 3. Ion temperature of the DT heated by 2.5 MeV electrons at the end of the pulse in units of $\log_{10} T_i$ (eV). (a) longitudinal cut at x = 0, and (b) transversal cut at z = 120 μm. Densities higher than 200 g/cm^3 are located inside the dashed circle.

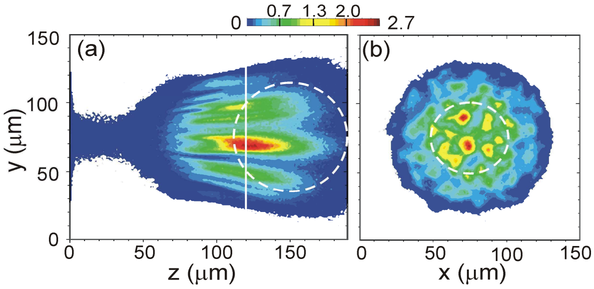

Figure 4. Pressure in Tbar of the DT heated by 2.5 MeV electrons (a) longitudinal cut at x = 0 and (b) transverse cut at z = 120 μm. Densities higher than 200 g/cm^3 are located inside the dashed circle.

The beam filamentation seeded in the halo imprints a multi-hot-spot ignition region into the high density fuel with maximum temperatures beyond 10 keV. This filamented heating can help ignition due to the non-linear scaling of fusion reactivities with temperature.

Using the generalized ignition condition described in reference 11, i.e., $p_h R_h > 45(\rho_h/\rho_c)^{1/2}$ Tbar μm, where index h refers to hot fuel and index c to surrounding cold fuel, one finds that the case shown in Figs. 3 and 4 is close to ignition.

It is worthwhile emphasizing that core heating is almost exclusively by Coulomb deposition of beam electrons. Anomalous stopping found in PIC simulations for lower plasma densities[12] plays no significant role in energy deposition in dense core. Ohmic heating by return currents dominates in the halo, but plays only a minor role for the overall energy balance. Self-generated fields turns out to be, however, very important for the core heating indirectly, mediated by filamentation and collimation effects shown in Fig. 3.

Fractions of the injected beam energy deposited in different parts of the target are shown in Fig. 5. The energy not deposited is carried by high energy electrons that pass through the target. This is a problem for increasing beam energies. For instance, 5.5 MeV electrons deposit 40% of their energy in the target and only 17% in the dense core. Notice that most of the beam energy is deposited in zones with densities lower than 200 g/cm^3 and that the energy deposited at higher densities is less sensitive to the electron kinetic energy. Beam collimation is important for energy deposition in the dense core, as can be seen by comparing the solid and dashed lines in Fig. 5. The coupling efficiency of the target configuration analyzed here, defined as the fraction of the pulse energy deposited at densities higher than 200 g/cm^3, is close to 30% for electrons with energies lower than 2.5 MeV. Assuming a laser to fast electron conversion efficiency of 50%, the laser pulse energy necessary to ignite the target exceeds 100 kJ. There may be possibilities to reduce this energy by shortening the distance between the cone tip and the blob or by careful design of the cone to reduce beam divergence. It is worth the large sensitivity of the coupling efficiency to the initial divergence angle. For instance, the energies deposited in the dense core shown in Fig. 5 are reduced to less than a half when raising this angle from 22.5° to 30°.

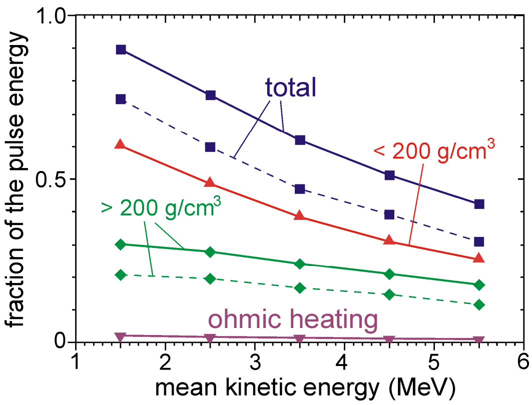

Figure 5. Fraction of the pulse energy deposited in the target (total), in zones with densities lower and higher than 200 g/cm^3, respectively. Solid lines correspond to full simulations with self-generated fields and Coulomb energy deposition. Dashed lines correspond to simulations with artificially suppressed self-generated fields.

In conclusion, a giga-ampere, multi-PW current can be transported through halo plasma and steep gradients toward the high-density fuel core. Central questions could be answered: collective magnetic effects play a major role for core heating, but in an indirect way. Resistive beam filamentation grows in the low-density halo and seeds the 3D multi-prong beam, which then penetrates the dense core. Collective behavior is suppressed in the high density core due the large plasma-to-beam density ratio, and energy deposition takes place almost exclusively by classical Coulomb deposition. As a result, we find a fragmented hot spot configuration which actually may help fuel ignition.

Concerning anomalous collective beam deposition, we find within the physical model used here that indeed beam filamentation enhances ohmic heating because it depends quadratically on the return current density. But this anomalous deposition contributes little to the overall energy balance in the present simulation of fast ignition. On the other hand, the self-generated B-fields tend to collimate the relativistic beam and significantly improve the coupling efficiency.

Acknowledgments

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