Ignition of pre-compressed fusion targets by fast electrons

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Abstract. We present hybrid PIC simulations of fast electron transport and energy deposition in pre-compressed fusion targets, taking full account of collective magnetic effects. First results on actual ignition of an imploded fast ignition configuration are shown. Target ignition is studied as a function of injected electron energy, distance of cone-tip to dense core, and initial divergence of the relativistic electron beam.

1. Introduction

Fast ignition [1,2] involves transport of GA currents of laser-driven electrons through dense coronal plasma of imploded fusion targets. In the hybrid approach pursued here, the relativistic electron beam is treated by 2D/3D PIC including collisional energy loss, while the high density background plasma is modelled by resistive MHD equations to describe magnetic field suppression by plasma return currents [3]. Full scale kinetic simulation may become possible in the future [3], but presently the hybrid approach pursued here offers a unique option to investigate important transport features such as current filamentation and magnetic beam collimation simultaneously with ignition physics (fusion reactions, α-particle transport and deposition, hydrodynamics and heat conduction). One may recall that, so far, most fast ignition simulations [4] assumed ballistic straight-line beam transport, neglecting all the intricacies of high-current (GA) transport in plasma. The present hybrid-PIC approach [5] reproduces cone-target experiments [6], similar to previous simulations of same kind [7,8].

In this paper, we present first results on actual ignition of an imploded fast ignition configuration, including the high-current effects. To be explicit, a cone-guided configuration is considered, and target ignition is studied as a function of injected electron energy, distance of cone-tip to dense core, and initial divergence of the relativistic electron beam. The present study has been motivated by the HiPER project [9].

2. Imploded target configuration and electron beam parameters

The configuration of the imploded DT core used here is shown in Fig. 1. It is based on radiation-hydrodynamic calculations of cone-target implosion and consists of a super-Gaussian spherical blob with a peak density of 500 g/cm$^3$ and a diameter of 82 µm (FWHM) sited on a low density halo (1.5 g/cm$^3$). The distance $d$ from the cone tip to the blob has been taken as a parameter, varying from 75 to 150 µm.

The imploded DT core is heated by a fast electron beam injected at the left of the simulation box. Laser interaction and electron beam generation inside the cone are not treated explicitly; rather the electron beam is injected at the boundary with transverse, angular, and energy distribution controlled by a few parameters [5] chosen close to experimental values [6]. We assume that a laser
beam with Gaussian profiles in radius and time generates fast electrons with 1D relativistic Maxwellian distribution in energy and temperature given by the ponderomotive scaling formula. We have chosen electrons with a mean kinetic energy \( \langle E \rangle \approx 2 \text{ MeV} \) in order to have a high beam coupling efficiency, as discussed in [5]. It corresponds to a laser intensity of, approximately, \( 2 \times 10^{20} \text{ W/cm}^2 \) at \( 2\omega (\lambda = 0.53 \mu\text{m}) \). The focal spot radius is 20 \( \mu\text{m} \) (FWHM). Results presented below are not very sensitive to the spectrum of the injected electrons, provided that the mean energy \( \langle E \rangle \) is kept constant.

The initial beam divergence half-angle has been taken from the ponderomotive scaling multiplied by a front factor to fit the experimental value of \( \theta = 22^\circ \) (FWHM) measured in the cone-target experiments of Ref. [6]. We have also considered the cases of \( \theta = 30^\circ \) and \( 40^\circ \) to check the sensitivity of core heating to the initial beam divergence. Laser-to-fast-electron conversion efficiency is assumed to be \( \epsilon_{\text{fe}} = 0.40 \). Pulse duration has been taken from 10 to 20 ps in order to have electron beam energies from 25 to 58 kJ, depending on distance \( d \) and divergence angle \( \theta \).

3. Fast electron energy deposition

We first check the ability of the present model to simulate Coulomb energy deposition of electron beams in precompressed DT. In this case, self-generated fields are turned off and our hybrid model reduces to the relativistic Fokker-Planck equation. Coulomb energy deposition of monoenergetic 2.2 MeV electrons impinging perpendicularly on a DT slab is shown in Fig. 2(a). Notice that the beam is collimated in the first half of the range, being subject to scattering and beam blooming in the second half. It is also worthwhile noticing that the range obtained is similar to that found by other authors [10]. Figure 2(b) shows how energy deposition profiles change substantially when realistic energy and angular distributions are taken into account.

Integrated simulations including self-generated fields show that Ohmic heating by return currents is dominant in the halo while Coulomb energy deposition prevails in the high density core [5]. Anomalous electron stopping does not play a significant role at high densities, in agreement with the advanced PIC calculations by Sentoku [3] and the results of Kemp et al. [11]. Self-generated fields, however, are important for core heating in an indirect way via beam resistive collimation and, eventually, filamentation. Beam collimation by self-generated azimuthal magnetic field \( B_\theta \) takes place in the density ramp, where plasma resistivities are higher than in the halo and densities are not high enough to damp collective modes. Its effect on electron energy deposition and target heating is shown in Fig.3. It is worth noticing that beam collimation is also predicted by the analytical model of Bell and Kingham [12] for the beam and target parameters used in the present calculations.

Two-dimensional integrated simulations show filamentation of the \( B_\theta \)-field for distances \( d \) between the cone tip and the blob larger than 125 \( \mu\text{m} \) (see Fig. 4). Similar results were obtained in 3D simulations [5], which showed that instability is seeded in the low density halo and amplified in the density ramp. The dependence of the filamentation onset on the distance \( d \) can be explained by its long
growth time for the beam and target parameters used here. Beam filamentation leads to fragmented energy deposition in the dense core, which does not play, however, an important role for fuel ignition due to temperature smoothing by heat conduction.

4. Electron beam coupling efficiency and fuel ignition.

The electron beam coupling efficiencies (defined as the fraction of the beam energy deposited at densities higher than 250 g/cm$^3$) predicted by our integrated model are depicted in Fig. 5(a). Assuming a laser-to-fast electron conversion efficiency $\varepsilon_{fe} = 0.4$ and a minimum overall coupling efficiency of the laser beam to the dense core of $\eta_{ig} \approx 0.25$ [13], suitable fast ignition schemes have to have minimum electron beam coupling efficiencies about 0.6. We can see in Fig. 5(a) that beams with divergence half-angles lower than 30º can reach those efficiencies for the beam-target configuration chosen here. The important role played by beam collimation is also shown in Fig. 5(a). If beam-generated fields are not taken into account, coupling efficiencies higher than 0.6 are obtained only for targets with distances $d$ lower than 75 µm, which may be too short from the cone target compression hydrodynamics point of view.

The minimum ignition energies obtained with our model are plotted in Fig. 5(b). It is worth remarking their important dependence on cone – blob distance and initial beam divergence, both crucial for fast ignition. Our calculations show that the imploded target configuration of Fig. 1 heated by a rather collimated electron beam ($\theta = 22^\circ$) will ignite with minimum ignition energies between 25 and 40 kJ, depending on the distance $d$. Taking into account the laser-to-fast-electron conversion efficiency $\varepsilon_{e} = 0.4$ assumed, those energies correspond to laser pulses from 62 to 100 kJ, of the same order that those envisioned for HiPER [9]. If self-generated fields are artificially suppressed, we find that the laser beam energies necessary for ignition are higher than 100 kJ for almost all distances $d$. On the contrary, if the beam is perfectly collimated ($\theta = 0$), the minimum ignition energy is almost the same than that found for $\theta = 22^\circ$ and $d = 75$ µm. This result is consistent with the ignition energies reported by Solodov et al. [4] for perfectly collimated beams.
FIG. 5. (a) Electron beam coupling efficiency as a function of the cone-blob distance. Curves are labeled with the initial beam divergence half-angle $\theta$. The dashed line shows the e-beam coupling efficiencies when the self-generated fields are artificially suppressed. (b) Minimum ignition energies obtained with the present model. The line labeled with $\eta_{ig} = 0.25$ in (a) shows the e-beam coupling efficiency corresponding to $\eta_{ig} = 0.25$ for the assumed laser-to-fast electron conversion efficiency $\varepsilon_{fe} = 0.4$. 

5. Conclusions.

Integrated simulations show that collective behavior is suppressed in the high density core due to the large plasma-to-beam density ratio and energy deposition takes place almost exclusively by classical Coulomb deposition. However, self-generated magnetic fields play an important role for core heating in an indirect way via collimation and resistive filamentation of the fast electron beam. Both effects occur in the density ramp. Beam collimation reduces ignition thresholds substantially.

Concerning target ignition, we have chosen electron mean kinetic energies $\langle E \rangle = 2$ MeV to maximize beam coupling efficiency. Electrons with those mean energies can be generated by laser intensities about $2 \times 10^{20}$ W/cm$^2$ at 2$\omega$. We found that the minimum ignition energies of the target analyzed here depends strongly on the initial beam divergence and the cone – blob distance, both crucial for fast ignition. If plasma instabilities at densities lower than a few g/cm$^3$ are not relevant and fast electrons emerge from the cone tip with a divergence angle similar to that measured in experiments [6], our simulations show that $25 – 40$ kJ electron beams will be sufficient to ignite imploded targets. Those beams can be generated with the short-pulse laser beam parameters envisioned for the HiPER facility [9].

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