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Fusion energy in degenerate plasmas

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Abstract

In inertial confinement fusion (ICF), a high density, low temperature plasma can be obtained during the compression phase, so minimizing the energy needed for compression. If the final temperature reached is low enough, the electrons of the plasma can be degenerate. In this case, bremsstrahlung emission is strongly suppressed and ignition temperature becomes lower than in classical plasmas, which offers a new design window for ICF. Fusion ignition can then be triggered by an additional energy beam. The main difficulties to produce degenerate plasmas are the compression energy and the compression performance needed for it. Besides that, the low specific heat of degenerate electrons (as compared to classical values) is also a problem because of the rapid heating of the plasma. The main contribution of the Letter is to show that the plasma degeneracy lowers the ignition temperature for DT plasmas, but it does not increase the target energy gain. Some numerical results are given on that. In the case of proton–boron 11 plasmas, the densities have to be extremely high in order to reduce the ignition temperature, but even so the energy gains remain rather low.

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1. Introduction and scope

In inertial confinement fusion, high densities are required to obtain high gains [1,2]. In the fast ignition scheme [3,4], high density–low temperature plasmas can be obtained during the compression phase [5–9], so minimizing the energy needed for compression. If the temperature is low enough, the electrons of the plasma can be degenerate [10]. In this

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case, bremsstrahlung emission is highly suppressed [11–15], because Pauli's exclusion principle forbids many electron energy transitions after photon emission. As bremsstrahlung is the main energy loss mechanism from the fusion plasma, the temperature needed for ignition decreases.

In the fast ignition scheme, a small portion of the compressed target is suddenly heated by an external beamlet of energy, and the fusion burning wave is launched from there to the rest of precompressed plasma. The small volume heated is called the ignitor. There are different mechanisms for energy deposition in the ignitor (laser induced fast electrons, ions, plasma jets, plasma impact, etc. [16–23]). One of the most appealing mechanisms to trigger fast ignition is plasma block impact [24–27] but practical configurations for accelerating the plasma blocks are still under discussion.

To take advantage of the degenerate plasma, the electron temperature has to be below Fermi energy for enough time. This means that heating mechanisms have to deposit the energy to the ions in the plasma, not to the electrons. That is the reason why ions have been chosen in this study as heating mechanism. The energy deposited in electrons and ions depends of the stopping power in both species. In degenerate plasmas, the equation that defines the stopping power of ions is different from the one governing classical plasmas. As will be seen later in this Letter, for highly degenerate electrons, the equation of the stopping power is nearly independent on density. Since the stopping power of ions behaves as the classical expression, it mainly depends on density.

In very high densities plasmas, the energy of the incoming ions goes to the plasma ions and not to the plasma electrons, in agreement with early analysis on this subject [28]. When the ions temperature is higher than the electron temperature, energy from collisional phenomena goes from ions to electrons. If electrons are degenerate, the energy exchange term between ions and electrons is different from the classical one. For very high densities, the ignition temperature of the plasma is lower than classical predictions, but the compression energy is high. However, for moderate densities, the electrons temperature increases very fast (due to the energy deposition of the external ions), so the plasma becomes classical rapidly (very low specific heat of degenerate electrons), and the ignition temperature is similar to the classical predictions.

A potential way for the practical realization of the scheme proposed in this Letter is depicted in Fig. 1. In the left-hand side image, a typical ICF target is depicted. In this case, a solid target is considered, instead a hollow one, because of the need of suppressing strong shock-waves and strong shocks between material layers in the compression process, which must be as close to isentropic as possible. (In Ref. [29, pp. 182–183], some calculations are given about the features of this type of compression, and the results are very promising to achieve very high densities.) A close-to-

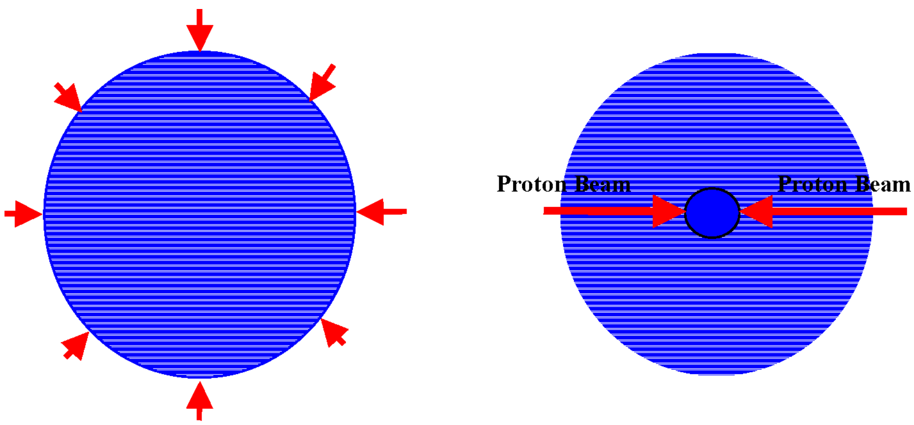

Fig. 1. Implosion scheme for obtaining a very high density at the end of the compression phase, followed by a fast ignition system based on the interaction of particle beamlets into a fraction of the compressed target. The left-hand side image shows the interaction of the ablation driver beams with the initial target. The right image shows the fast ignition onset, once the central core of the target has been compressed.