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On the expansion of high density plasmas in mirror-like magnetic topologies

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Abstract

A two-dimensional resistive MHD code in axisymmetric cylindrical geometry has been developed, which solves the conservation equations for mass, momentum and energy of plasmas coupled with the magnetic field equations. The code can handle very large magnetic fields and very steep gradients of the plasma parameters; the code is applied to study very high density plasmas in a compact fusion device with mirror-like magnetic field. A numerical study on the expansion of high density, high temperature plasma, in a compact fusion device with an external applied mirror-like magnetic configuration, and in uniform parallel to the axis in symmetric magnetic field configuration, is presented. The initial magnetic topology in this open system is given analytically, this enables modification of the initial geometrical configuration and the values of the magnetic field of the device in order to optimize the trapping time of the plasma.

Introduction

Investigations on high density and temperature plasma in compact fusion devices with external magnetic field present an increase interest due to important industrial applications. Such devices enable to be used as high flux and ultra short neutron sources for medical applications, material tests, high energy particles and high temperature plasma injectors (plasma thrusters). The study of specific magnetic configuration of the compact fusion device allows the development of advanced propulsion systems with high velocity ejecting plasma producing high thrust. Micro-pellet or neutral gases of specific clusters are potential source to refueling such devices. The interaction[1],[2],[3] of a high intensity ultra-short laser pulse with a molecular beam of neutral deuterium clusters produce the high density and temperature plasma which expands very fast in vacuum decreasing both the local density and the number of D-D ions nuclear fusion reactions[2],[3],[5]. The application of an external high magnetic field[4] enables to decreases the plasma expansion velocity, increases the trapping time of the plasma and improves the neutron production. During the laser-plasma interaction the plasma volume is described, in first approximation, by a double density layer with different plasma densities. The first layer concern the high-density and temperature plasma produced by the pulsed laser beam and the second the lower density one (at least two orders of magnitude) due to the tails of the laser beam profile. The high density plasma from the first layer expands into the second low-density plasma forming a shock wave. This expansion effect is available for both directions the radial which is perpendicular to the external applied magnetic field and the axial parallel to the magnetic field.

Here we present results from a resistive 2-D MHD code in cylindrical coordinates in an external high magnetic field with a mirror-like magnetic field topology. The novelty of our numerical simulation is based on the introduction of the shock tube model in order to describe correctly the particular initial spatial and temporal conditions of the laser plasma production, the temporal evolution of the plasma parameters and the trapping time in the external applied magnetic field. The code can handle very large magnetic fields and very steep gradients of the plasma parameters. The numerical model implements the initial plasma conditions by introducing a step function describing the double plasma density layer with different spatial occupation for the radial and the axial direction (z-direction). The laser-plasma interaction produces plasma with density up to 10^{18} cm^{-3} and accelerates D ions to high kinetic energy up to 45 - 50 keV compatible with recent laser-cluster and/or laser-micro-droplets interaction experiments[1-3]. The output from the different modules describes the temporal and spatial evolution of the physical parameters of the plasma such as density, pressure, temperature, expansion velocity, trapping time and magnetic field. One of the modules describes the topology of the external magnetic field in the mirror-like configuration. The proposed scheme combine recent laser target interaction techniques with the well know trapping method of plasmas in a ‘mirror-like’ magnetic topology.

Description of the MHD Model

The set of equations consisting of the Magnetohydrodynamic (MHD) conservation equations, Maxwell’s equations and Ohm’s generalized law is a follows:

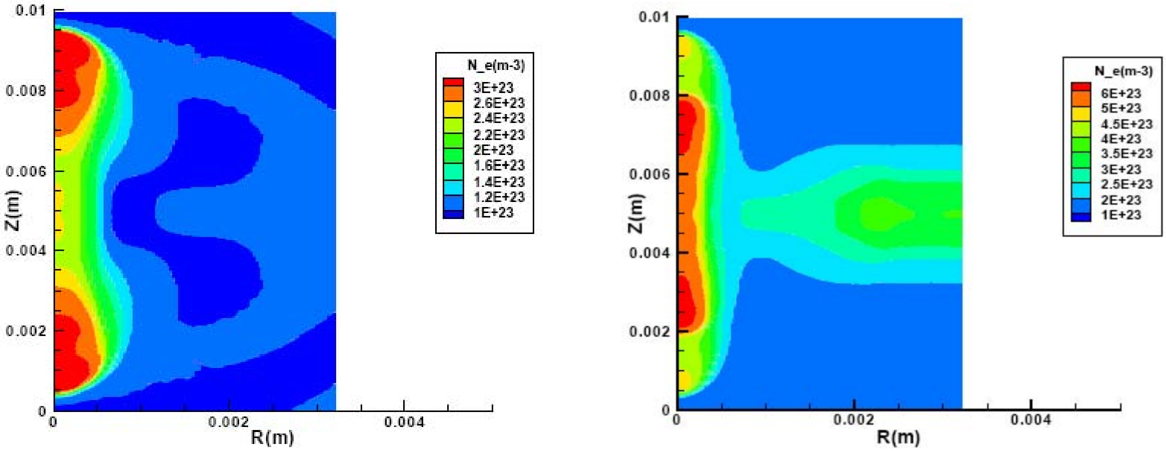
$$
\begin{aligned}
\frac{\partial \rho}{\partial t} \;+\; \nabla\cdot(\rho\mathbf{u}) &= 0\\
\frac{\partial}{\partial t}(\rho\mathbf{u}) \;+\; \nabla\cdot(\rho\mathbf{u}\mathbf{u}) \;+\; \nabla p &= \mathbf{j}\times\mathbf{B}\\
\frac{\partial \epsilon}{\partial t} \;+\; \nabla\cdot((\epsilon+p+\frac{B^2}{2\mu_0})\mathbf{u}) &= \nabla\cdot(\mathbf{B}\mathbf{B}\cdot\mathbf{u}+\mathbf{B}\times\frac{\mathbf{j}}{\sigma})\\
\frac{\partial \mathbf{B}}{\partial t} \;+\; \nabla\times\mathbf{E} &= 0\\
\nabla\times\mathbf{B} &= \mu_0\mathbf{j}\\
\frac{\mathbf{j}}{\sigma} &= (\mathbf{E} \;+\; \mathbf{u}\times\mathbf{B})\\
\nabla\cdot\mathbf{B} &= 0
\end{aligned}
$$

where $\varepsilon = \frac{1}{2} m^2 + p/(\gamma-1) + B^2/2\mu_0$ is the total energy. $\rho = m_i n$ and **u** are the plasma mass density and the macroscopic plasma velocity respectively. These equations are solved numerically, in two-dimensional axisymmetric geometry, using the finite volume[6] method. In the results presented here we assume ideal plasma, that is $\eta = 1/\sigma \approx 0$. The initial magnetic field configurations are: (i) given analytically for a mirror like topology and (ii) uniform and parallel to the axis of symmetry.

Results

Typical initial plasma conditions have been selected in order to be conforming with experimental results; for the plasma density up to 10^{18} cm^{-3} and for the temperature up to 20keV. The initial plasma density covers uniformly the high density layer corresponding to a radius of 0.5mm and a length (z-direction) of 2mm. The low density layer corresponds to a plasma density of 10^{17} cm^{-3} and initial temperature of 1 keV and fills the remaining computational domain. We investigate the influence of the external applied magnetic topology on the trapping time of the plasma, the temporal and spatial evolution of the plasma as well the plasma expansion velocity in both direction the radial and the axial.

A comparison has been performed for two different configurations concerning the initial magnetic field topology in order to establish the conditions for the plasma trapping and the plasma expansion in both directions the radial and the axial. In the first case a uniform axial magnetic field is applied with a value up to 150 Tesla and zero radial component. In the second case a mirror-like topology was calculated for the external magnetic field with radial and axial field components and a ratio of $B_{max}/B_{min} \approx 2$. These two cases allow the comparison of the sensitive physical parameters such as the velocity in the axial (z) direction and the temporal evolution of the plasma density (decreasing); very important for the neutron production. Fig.2a and fig. 2b present two dimensional plasma density distributions after 2nsec of the initial plasma expansion in two cases corresponding to a uniform magnetic field and a mirror-like magnetic field topology respectively. The plasma trapping is important in both directions the radial and the axial for the case of the mirror-like magnetic field topology.



(a) (b)

Fig. 1 Two dimensional plasma density contours corresponding to two cases for the external applied magnetic field configuration: (a) a uniform magnetic field in the axial z-direction and (b) a mirror-like magnetic field.

Conclusion

Under these conditions of initial deuterium plasma density of 10^{18} cm^{-3} and plasma trapping in a mirror-like magnetic field topology a few 10^{7} neutrons was produced with duration of 2nsec which correspond to a flux of 10^{16} n/sec per laser pulse. Improvements on the trapping conditions will allow proposing experimental set-up and experimental conditions for the development of compact laser driven fusion devices with external applied magnetic field with interesting industrial applications.

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