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Analysis of magnetic Rayleigh–Taylor instability in a direct energy conversion system which converts inertial fusion plasma kinetic energy into pulsed electrical energy

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ABSTRACT

A direct energy conversion scheme to convert plasma kinetic energy into pulsed electrical energy, based on magnetic flux compression (MFC) by an inertial fusion plasma sphere, has been examined earlier. The plasma sphere, expanding across a magnetic field, is subject to the Magnetic Rayleigh–Taylor (MRT) instability. Therefore, 2D MHD simulations have been performed to analyze the MRT instability and its implications for the proposed MFC system. The simulation takes into account the effects of MFC and geometric divergence due to spherical plasma expansion. Single-mode sinusoidal perturbation evolution exhibits linear exponential growth followed by a non-linear phase towards stagnation time. We also note that near the time of stagnation, the growth in amplitude of the modes, although exponential in nature, is much lower than the growth predicted by linear theory. Furthermore, the instability amplitudes are not large enough for $\alpha_{in} \leqslant 0.1\lambda_{in}$ to severely disturb the smooth MFC during the first expansion phase. However, the growth of modes with $\alpha_{in} \geqslant \lambda_{in}$ causes plasma jetting, especially for longer λ modes, and can lead to significant reduction in MFC efficiency.

1. Introduction

We have recently examined a direct energy conversion scheme to convert plasma kinetic energy in an Inertial Fusion Energy system into pulsed electrical energy (Sijoy and Shashank, 2011, 2012). Similar work has been reported in Refs. (Haught et al., 1970; Raizer, 1963; Hyde et al., 1972; Mima et al., 1992; Shoyama et al., 1993; Nakashima et al., 1992a; Zakharov et al., 2001, 1999; Cowan et al., 1975, 1976; Wright et al., 1980). The scheme is based on magnetic flux compression (MFC) inside a solenoid by an expanding diamagnetic plasma sphere (spherical liner). The basic idea is to use a shielding electrical conductor (a solenoid in Refs. (Sijoy and Shashank, 2011, 2012)) that enclose the plasma expanding in an external magnetic field, as shown in Fig. 1. In Refs. (Sijoy and Shashank, 2011, 2012), the seed magnetic field is provided by the solenoid itself. The expanding plasma excludes the magnetic field by the diamagnetic currents produced on its surface. The inductive electromotive force induces currents in the solenoid. Thus a part of plasma kinetic energy can be converted into pulsed electrical energy. Preliminary numerical studies (Sijoy and Shashank, 2011, 2012) indicate that the proposed system, with an inductive load, is promising in terms of overall conversion efficiency.

However, such a plasma expanding across the magnetic field is subject to the Magnetic Rayleigh Taylor (MRT) instability. The MRT instability occurs when an electrically conducting fluid, e.g. plasma, is decelerated or supported by the magnetic field. The classical linear MRT growth rate (Chandrasekhar, 1961) is defined as, $\gamma_L = (kg)^{1/2}$ for $kL_n \ll 1$ and $\gamma_L = (g/L_n)^{1/2}$ for $kL_n \gg 1$; where k is the wave number, g is the deceleration, $L_n \sim (\partial \ln\,(n)/\partial x)^{-1}$ is the density scale length of the plasma and n is the plasma density. For an efficient operation of the proposed MFC system, the instability amplitude must be small so that the irregular surface caused by growth of the MRT instability does not disturb the smooth compression of the magnetic field between the plasma and solenoid. Large amplitude flute modes and plasma jetting can damage the cavity wall (Nakashima et al., 1992b).

Numerical and experimental studies on plasma expansion in an external magnetic field and the analysis of interchange instabilities can be found in Refs. (Huba et al., 1990; Winske, 1989; Ripin et al., 1993; Sgro et al., 1989; Okada et al., 1981) (also see references therein). The majority of the works reported earlier examine plasma expansion in an unconfined uniform background magnetic field where the magnetic flux compression is negligible. In the MFC system, however, the magnetic field outside the plasma increases due to magnetic flux compression. Previous work related to plasma energy conversion and including the role of MFC has been reported in

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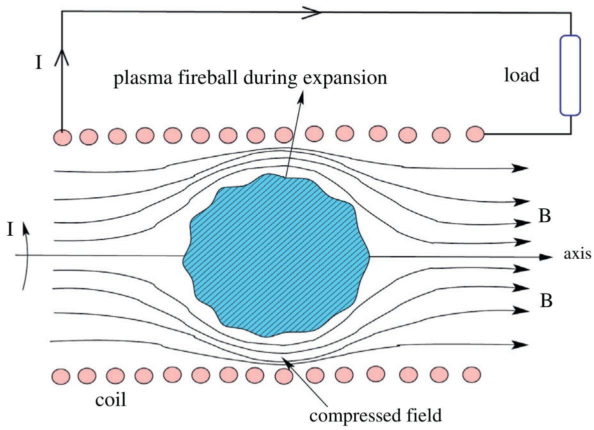

Fig. 1. Schematic showing magnetic flux compression during expansion phase (not to scale).

Ref. (Nakashima et al., 1992b) analyses a different plasma and system parameter range compared to the present work, see Refs. (Sijoy and Shashank, 2011, 2012). Apart from this, the simulation results given in Ref. (Nakashima et al., 1992b) start with an unperturbed initial plasma state, so that instabilities are seeded by numerically-produced perturbations. This was also the case in our last study (Sijoy and Shashank, 2012). In reality, perturbations with different wavelengths and amplitudes would exist on the surface of the plasma sphere even before it starts expanding. For a real-life system, therefore, it is necessary to study the growth of pre-existing perturbations with different wavelengths and amplitudes.

The purpose of this study is to numerically analyze, using 2D-MHD fluid simulations, the MRT instability on the surface of the plasma liner and its implications for the proposed MFC system. The study has been done for different cases of applied initial perturbations (different wavelengths and amplitudes), taking into account the effects of magnetic field amplification (time dependent g) and the geometric divergence due to spherical plasma expansion. Approximately at stagnation or turn-around time t_s (the time at which the plasma radial expansion halts), the inductive energy across the load goes to maximum (Sijoy and Shashank, 2011, 2012). In this work, therefore, we are only interested in studying the evolution of MRT instability till the stagnation time.

2. Initial conditions and MHD model

The initial plasma parameters are taken from earlier published data for D-3He plasma. The plasma energy E_p and mass m_p used in this study are 280 MJ and 4.4 mg respectively (Mima et al., 1992; Shoyama et al., 1993; Nakashima et al., 1992a; Honda et al., 1991; Shiba et al., 1991). The value of seed magnetic field B used in the simulation is 5 T and the system parameters are taken from Refs. (Sijoy and Shashank, 2011, 2012). Immediately after the fusion the plasma is in a state of extremely high temperature (greater than few tens of keV) and density $\sim 10^6$ kg/m^3, and has a radius of 150–200 μm (Honda et al., 1991; Shiba et al., 1991). Initially, therefore, the plasma undergoes free expansion in the applied magnetic field, since the kinetic pressure, p_k is far higher than the magnetic pressure, p_B (high $\beta = p_k/p_B$ plasma). Therefore, similar to earlier works (Sijoy and Shashank, 2011, 2012; Mima et al., 1992; Shoyama et al., 1993; Nakashima et al., 1992a), we start our simulation with an initial plasma radius of about 0.2 m. Initial radial profiles for the plasma density, temperature and velocity are generated using a separate 2D simulation without considering the effect of B (free expansion up to a radius equal to 0.2 m). The initial conditions thus obtained are shown in Fig. 2 as a function of plasma radius. The perturbation is imposed by defining the outer radius as

$$R(x,y) = R_0 + \alpha_{in}\sin(2\pi r/\lambda_{in})$$

where $r = \sqrt{x^2+y^2}$ and α_{in} are the radius and perturbation amplitude respectively. We have used a mesh-size of $\sim\lambda/20 - \lambda/12$ which was sufficient to yield numerical convergence with respect to the mesh-size.

During the expansion phase, $L_n \gg r_{Li}$, c/ω_{pi} and r_D; where L_n is the characteristic scale length of the plasma, $r_{Li} \sim v_i/\Omega_i$ is the ion Larmor radius, $v_i \sim (T_i/m_i)^{1/2}$ is the ion thermal speed, Ω_i is the ion cyclotron frequency, ω_{pi} is the ion plasma frequency and r_D is the Debye radius. Similarly, the time scale (plasma radial expansion time $\sim t_s$) is longer than an ion cyclotron period. Therefore, single fluid MHD model (assuming quasi-neutrality) can be used to describe the plasma. The governing equations are solved by using an unstructured Lagrangian computational scheme (Caramana et al., 1998) with sub-zonal mass and pressure (Caramana and Shashkov, 1998) to control artificial grid distortion and hourglass type motion. Further, to stabilize the grid a node based tensor viscosity (Campell and Shashkov, 2001) and an artificial grid distortion control algorithm (Caramana and Shashkov, 1998) are used. The details of the MHD scheme and the governing equations can be found in Ref. (Sijoy and Shashank, 2011, 2012, 2010) which are omitted here for the sake of brevity.

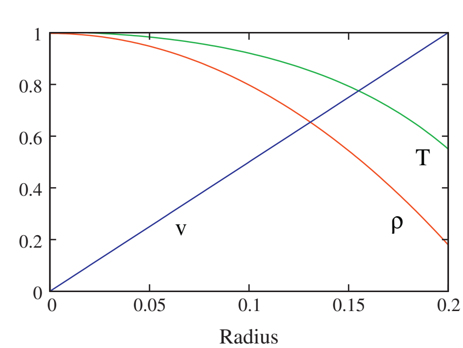

Fig. 2. Initial radial plasma profiles for density, temperature and velocity. The profiles are normalized to the peak value; $\rho_{peak} = 2.5 \times 10^{-4}$ kg/m^3, $T_{peak} = 0.275$ keV and $v_{peak} = 1.63 \times 10^7$ m/s.

3. Results and discussion

The simulation results are analyzed using a fast Fourier transform (FFT) technique. The Fourier spectrum of modes in the plasma liner at different times are obtained as follows. The simulation yields $R(\theta,t)$ on the outer surface of the plasma. We subtract the $R(\theta,t)$ from the average outer radius to yield the deviations $\Delta R(\theta,t)$ (Subhash et al., 2008). A fast Fourier transform is performed on these values to yield the Fourier spectrum.

Preliminary random mode perturbation analysis with total number of modes $n = 300$ (λ ranging from 0.1 mm to 30 cm) shows that, towards the stagnation time, the dominant modes exhibits a progressive transition to the intermediate wavelength regime ($\sim$4–8 cm) in the spectrum, see Fig. 3. Therefore, initial wavelengths used for this analysis are varied around the dominant λ regime (typically 6.9 mm–6.28 cm with $n = 5$–45) found in the preliminary random mode analysis. For each λ_{in}, four values of α_{in} are used; $\lambda_{in}/1000$, $\lambda_{in}/100$, $\lambda_{in}/50$ and $\lambda_{in}/10$. Note that for the cases with α_{in} - $\sim \lambda_{in}/10$, the mode amplitude and the wavelength are comparable. This means that α_{in} is close to the mode saturation limit (Youngs, 1984). This value, however, is included in the test cases by considering the fact that the λ of a given mode increases due to plasma