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Magnetized relativistic electron–ion plasma expansion

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ABSTRACT

The dynamics of relativistic laser-produced plasma expansion across a transverse magnetic field is investigated. Based on a one dimensional two-fluid model that includes pressure, enthalpy, and rest mass energy, the expansion is studied in the limit of λ_D (Debye length) $\leq R_L$ (Larmor radius) for magnetized electrons and ions. Numerical investigation conducted for a quasi-neutral plasma showed that the σ parameter describing the initial plasma magnetization, and the plasma β parameter, which is the ratio of kinetic to magnetic pressure are the key parameters governing the expansion dynamics. For $\sigma \ll 1$, ion's front shows oscillations associated to the break-down of quasi-neutrality. This is due to the strong constraining effect and confinement of the magnetic field, which acts as a retarding medium slowing the plasma expansion.

1. Introduction

The interaction between plasmas and time varying magnetic field is a board topic with implication to many laboratory and astrophysical configurations. Frequently, this interaction governs the dynamics and the stability of plasmas [1,2]. Different aspects of this interaction in laboratory have been investigated in numerous configurations such as theta pinches, ion diodes, plasma switches, and plasma beam transport across a magnetic field [3,4]. In astrophysical scale, the generation of magnetic field in relativistic laser-produced plasma is of central importance in reproducing conditions resembling to large-size astrophysical processes on laboratory scale such as a self-collimation of relativistic jets [5,6]. In addition, the study of the interaction of plasma winds with magnetic obstacles, was extensively investigated through magnetohydrodynamics simulation. As an example, the frozen-in transverse magnetic field, analog to IMF (Interplanetary Magnetic Field), was presented in many experiments to be achieved by launching laser-produced plasma through theta-pinch plasma in the presence of an external magnetic field [7]. The effect of the magnetic fields on laser-driven plasmas has been widely studied for applications including inertial confinement fusion, electron fast ignition, and proton beam generation [8–10]. The characteristics of an expanding laser-produced plasma are of a vital importance for the behavior of laser-target interaction processes. In fact, the presence of a magnetic field during the expansion of laser-plasma may initiate several interesting physical phenomena, including plume confinement, ion acceleration, emission enhancement, and plasma instabilities [11].

Magnetic confinement of a laser-produced plasma has been widely studied in the past decade. Recently, a relativistic pair plasma jet was effectively collimated using magnetic field from an external, pulsed Helmholtz type coil, using the magneto-inertial fusion electrical discharge system [8]. For electron–ion plasma, the basic system configuration consists of a solid planar target immersed in an externally applied magnetic field **B** parallel to the Z-axis [12], by focusing a picoseconds laser pulses of intensity $I_l > 10^{18}$ W/cm^2, hot electrons are produced of a large current with high energy, that accelerates ions [13,15]. Plasma was observed to penetrate the field by two mechanisms; The first one is due to the **ExB** drift, resulting from the growth of kinetic flute instabilities [11]. The second mechanism results from the Kelvin–Helmhotz instability actuated by the magnetic field perpendicular to the flow [16]. In a recent experiment, it has been demonstrated that, when the magnetic field lines are frozen-in the electron fluid, the magnetic forces tend to confine the plasma radially. This tendency may account for the "negative acceleration", where the magnetic energy density becomes comparable to the maximum plasma thermal one [5].

It is well known, that the production of large currents of high energy may generate an intense magnetic field through Weibel-like instabilities [5]. The importance of such generation in jet out flows and on a cosmological scale has been pointed out [17]. This electromagnetic instability occurs in plasmas with anisotropic velocity distribution [18]. Such plasmas are naturally obtained, when the thin foils are irradiated by intense laser pulses [18]. In fact, as plasma expands, the longitudinal temperature $T_\perp$ decreases and

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the anisotropy parameter $A = T_\perp/T_\parallel - 1$ increases, which eventually leads to the growth of the Weibel instability [19]. The latter gives rise to the aperiodic growth of magneto-waves with a wave vector, that is parallel to the cooling direction [17]. The hot electrons gain most of their energy through collisionless mechanisms (e.g., resonant absorption, Brunel absorption, and $\mathbf{J} \times \mathbf{B}$ heating), which heat the plasma in a colling direction. The magnetic Lorentz force bends the electron trajectories and forms current enhancing the magnetic field. Indeed, electrons give progressively apart of their momenta to the transverse direction, which results to the anisotropization suppression. Because of the strong anisotropy, the Weibel instability is triggered from the beginning of the expansion, and leads to the increase of the growth of the mean magnetic energy [18]. Then, the magnetic field drives the isotropization of the electron temperature, which eventually leads to the saturation of the instability [19]. We cited the experiment performed by Najmudin et al., in which a magnetic field exceeding $7MG$ has been measured during the interaction of circularly polarized laser pulse with an underdense helium plasma at intensities up to 10^{19} W/cm^2 [6]. Particle-in-cell simulation has shown that the Weibel instability can magnetize a planar plasma cloud that expands into vacuum, and drives radial current channels, which yield to the growth transverse magnetic (TM) field component. The latter, originates from statistical fluctuation of the current density [17]. In general, plasma with a non-zero current experiences a radial compressive force due to the self-induced magnetic field [9], which, contributes to the radial self-confinement. The external magnetic field influences the dynamics of self-confined plasma through the term $\mathbf{J} \times \mathbf{B}$. In fact, without an external magnetic field the compressive radial component of $\mathbf{J} \times \mathbf{B}$ force simplifies to $J_z B_\theta$ (in the cylindrical r, θ, z configuration), where J_z is the net axial current density and B_θ the magnetic field in azimuthal direction [9]. The compressive self-confinement force is enhanced by the term $J_\theta B_z$, once the external magnetic field is added. Motivated by experimental and theoretical works on the dynamics of large amplitude magnetic field interacting with an explosive relativistic plasma expansion, we investigated numerically the macroscopic plasma parameters such as flow speed and density within the plasma displacement in the presence of an external magnetic field. Sarri et al., studied the plasma-magnetic field having an amplitude of several tens of mega-gauss ($\sim 10^{19}$ W/cm^2) [5], and showed that, the amplitude of the magnetic fields is sufficiently large to have a constraining effect on the radial plasma sheath expansion at the target surfaces. Chen et al., studied the collimation of electron–positron–proton plasma produced by laser–solid interaction by using an externally magnetic field [8]. An exact solution of the moving boundary problem for the relativistic plasma expansion in a dipole magnetic was obtained [20]. Moreover, a self-similar solutions have been found in many analytical studies. Lyutikov and Blandford, obtained the solutions of a relativistic force-free field in two dimensions [11]. They found a self-similar solution for one dimensional expansion of relativistic strongly magnetized plasma into vacuum [14], based on a one fluid plasma approach. In the present work, we investigated the effect of an external magnetic field, oriented transversely to the flow direction into vacuum, on the dynamics of laser-produced relativistic electron–ion plasma expansion from solid foil target. The effect of the induced magnetic field and the self-confinement are not considered in this work. The behavior of the plasma species depends on their initial proper magnetization and velocities, which are generally important for electron due to their small inertia. We showed, that the self-similar approach can predict the effect of the external magnetic field which provides a cut-off of the expansion profiles at the balance point between plasma pressure and the magnetic pressure.

2. Modeling

The two-fluid plasma model has often been used for parametric survey of small amplitude wave properties. It has also been used to derive the dispersion relation in a hot relativistic plasma embedded in a uniform magnetic field [21]. For that, we employ two fluid model for relativistic electron–ion plasma. The set of differential equations governing relativistic magnetohydrodynamics expansion is:

$$\frac{\partial \gamma_j n_j}{\partial t} + \nabla(\gamma_j n_j v_j) = 0 \tag{1}$$

$$n_j \gamma_j [\frac{\partial}{\partial t} + v_j \nabla](h_j \gamma_j v_j) = -\nabla p_j + \frac{J_j^0 E + J_j \times B}{C} \tag{2}$$

And Maxwell equations:

$$\nabla.E = \frac{4\pi}{C} J^0,\ \nabla.B = 0,\ \frac{1}{C}\frac{\partial B}{\partial t} + \nabla \times E = 0,$$
$$\frac{1}{C}\frac{\partial E}{\partial t} = \nabla \times B - (4\pi/C) J \tag{3}$$

where, j = e (electrons), i (ions), J^0/C is the charge density, J is the current density and $J^\nu = (J^0, J)$ is the four-vector current. v, E, and B stand for velocity, total electric field, and the total magnetic field, respectively. The thermodynamical parameters, h, P, and n are the enthalpy, pressure, and particle density of the plasma, respectively.

The relativistic specific enthalpy is written as:

$$h_j = m_j C^2 + \frac{\alpha}{\alpha - 1}\frac{p_j}{n_j} \tag{4}$$

where α is the usual polytropic index, which is equal to 4/3 for the ultra-relativistic limit and to 5/3 in the non-relativistic fluid [22]. In our case, the plasma is considered as a non-dissipative and heat-conductive fluid with infinite conductivity. The magnetic field is "frozen-in" into the plasma and the motion of the fluids will advect $\mathbf{B}$ and vice versa. At this limit, the co-moving electric field $\acute{\mathbf{E}}$ is zero. This condition transformed to the rest frame gives:

$$\acute{\mathbf{E}} = \gamma[\mathbf{E} + \frac{\mathbf{vxB}}{C}] + \frac{\mathbf{v}}{C^2}(\mathbf{v}.\mathbf{E})(1 - \gamma) = 0. \tag{5}$$

However, no electric field can exist initially in the plasma which is at rest, and no component parallel to the flow direction can develop during the expansion [23]. So, the condition (5) becomes simply:

$$\mathbf{E} = -\frac{\mathbf{v} \times \mathbf{B}}{C} \tag{6}$$

We focus our study on the initial value problem of one dimensional relativistic adiabatic expansion into vacuum of a laser-produced plasma in the presence of an external transverse magnetic field. This expansion is assumed to take place in the x-direction. So $n_j = n_j(x,t)$, $\mathbf{v_j} = (\mathbf{v}_x, 0, 0)$ and $\mathbf{B} = (0, 0, \mathbf{B}(x,t))$ directed in the Z-axis. The electric field $E = B.v/C$ is entirely in the y direction. With these restrictions, equations (1) and (2) become:

$$\frac{\partial \gamma_j n_j}{\partial t} + \frac{\partial \gamma_j n_j v_j}{\partial x} = 0 \tag{7}$$

$$(\frac{\partial \gamma_j h_j v_j}{\partial t} + v_j \frac{\partial \gamma_j h_j v_j}{\partial x}) + \frac{1}{\gamma_j n_j}\frac{\partial p_j}{\partial x} = \pm \frac{B}{4\pi \gamma_j n_j}\frac{\partial B}{\partial x} \tag{8}$$

We write also the Faraday equation:

$$\frac{\partial B}{\partial t} + \frac{\partial v_j B}{\partial x} = 0 \tag{9}$$