Suppression of beam merging and hosing instabilities in magnetized fast ignition fusion

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Abstract. The magnetized two-stream instability has been investigated in linear and nonlinear regimes. Using a linear analysis of the Vlasov equation in two dimensional wave number space, we studied the competition between modes with wave numbers parallel and transverse to the beam direction. In the analysis, it is found that a near transverse mode is still unstable even for large electron temperature. The nonlinear analysis is performed using a hybrid simulation code. When a sufficiently strong magnetic field is applied along the beam direction, the instabilities are well suppressed and the electron stream becomes laminar. When the magnetic field strength is not large enough, however, electron flow stagnates and the total number of beam electrons penetrating the plasma is largely reduced.

1. Introduction

The fast ignition scheme is a promising approach for the inertial confinement fusion program. In the scheme, irradiation of a sufficiently compressed target by an ultra intense laser pulse assists the fuel to burn. As a result, the requirement on the energy of a compression laser is very much reduced. In the fast ignition scheme, relativistic electrons transmit energy from the critical surface of the laser to the compressed fuel. The electrons are generated at the critical surface, and hence the density of the electron beam is of the order of the critical density given by the laser wavelength. As a result, a large electric current flows in an overdense plasma.

When such a large electron flow penetrates the plasma, a return electric current is induced in the background plasma in order to maintain current neutrality. Such a two-stream state is unstable to two kinds of perturbation. One is longitudinal, in which the wave number is parallel to the beam propagation direction. For this mode, an electrostatic field grows as well as a density modulation. The other mode is transverse, in which the wave number is perpendicular to the beam propagation direction. For this mode, known as the Weibel instability, current separation takes place and a quasi-static magnetic field grows. The magnetic field deflects the electrons broadening their spread in angles. The wide angular spread of the electron beam reduces the total number of electrons reaching the fuel region and degrades the efficiency of energy deposition.

In order to suppress the broadening of the angular spread, a group at the Institute of Laser Engineering [1] proposed the application of a strong magnetic field. In their experiments, an intense laser pulse irradiates a small capacitor and drives a large electric current through a one-turn coil connecting two capacitor plates. As a result, a large magnetic field, which is on order
of 1 kT, is generated inside the coil. When such a large magnetic field is applied along the beam propagation direction, the angular spread can be suppressed in two ways. One is by guiding the electrons along the magnetic field. The strong magnetic field restricts transverse motion, and the beam propagates along the magnetic field lines.

The other mechanism is suppression of the Weibel instability. The dispersion relation of a two-stream plasma is modified by a strong magnetic field, and unstable modes are stabilized. Due to these effects, the magnetic field increases the number of electrons reaching the fuel, and enhances the fusion burn rate. The scheme is named magnetized fast ignition (MFI) [2]. In this paper, we will describe the linear and nonlinear analysis of the magnetized two stream instability for a two dimensional configuration and discuss its advantages for the fast ignition scheme.

2. Linear dispersion relation of the two-stream instability in a strong magnetic field

In order to investigate the stability of the two-stream state in a strong magnetic field, we calculate the linear dispersion relation using Vlasov theory. In the weak instability regime, kinetic effects are an important factor of the analysis [3]. Figure 1 shows that the maximum growth rate of the Weibel instability as a function of the external magnetic field. In the figure, the results of three approaches, fluid analysis (a dashed line), Vlasov analysis (solid lines) and PIC (Particle In Cell) simulation (solid circles), are shown for different electron beam temperatures. The other parameters, such as background electron temperature (5 keV) and the density ratio of beam to background electrons (1:9) are fixed in all analyses. The drift velocity of the beam is set to be 0.9c and the ions are immobile so that only electrons engage in the instability. In the figure, the electron cyclotron frequency \( \omega_c \) and growth rate \( \gamma \) are normalized by the electron plasma frequency \( \omega_{pe} \), which is evaluated using the background plasma density. In the figure, \( T_h \) is the beam electron temperature.

As shown in the figure, the growth rate decreases with increasing applied magnetic field and no unstable modes exist above a certain value of the magnetic field, which depends on the electron temperature. The result indicates that the Weibel instability is stabilized in a sufficiently strong magnetic field. The figure also shows a difference between fluid model and the Vlasov model in comparison with the PIC results. The Vlasov results well predict the threshold magnetic field found in the PIC simulation, while the fluid analysis underestimates the threshold value. Furthermore, the fluid analysis cannot predict the existence of unstable modes for high electron temperature cases \( (T_h \geq 50\text{keV}) \).

In a real configuration, it is necessary to include both longitudinal and transverse wavenumbers. We next calculate the dispersion relation including these and obtain growth rates in two-dimensional wave vector space. Figures 2 (a)-(c) show the results. In these results, the beam electron temperature is set to be 10 keV and the other parameters are the same as in Fig.1. Figures 2 (a), (b) and (c) are for different external magnetic field strengths. In these figures, \( k_x \) is the longitudinal wave number component and \( k_y \) is the transverse wave number component. As shown in the figures, the growth rate of the transverse modes depends on the strength of the external magnetic field, while the longitudinal modes are not affected as much by the field.

![Figure 1. Dependence of maximum growth rate of the Weibel instability upon external magnetic field strength](image-url)
When the external field is weak, the transverse mode grows as well as the longitudinal modes. As the strength of the field increases, the transverse modes are stabilized but the longitudinal modes are still unstable for the parameters considered.

\[
\frac{\omega}{\omega_{pe}} = (a) 0.01 \quad (b) 0.5 \quad (c) 1
\]

**Figure 2.** 2D growth rate profiles for the two-stream state for different external magnetic field strengths: \(k_x\) and \(k_y\) are the longitudinal and transverse components of the wave vector.

When the flow velocity of the electron beam approaches the speed of light, the longitudinal perturbation is suppressed because of the relativistic mass effect. As a result, the growth rate of the transverse modes becomes larger than that of the longitudinal modes. Figure 3 shows an example. In this figure, \(\omega_c/\omega_{pe}=0.5\), the flow velocity is 0.99c and the temperature of beam electrons is 150keV. Since the vertical scale of Fig.3 is much smaller than that of Figs.2, it should be noted that the growth rate of Fig.3 is much smaller than Fig.2.

Since the beam temperature is high, there is no unstable mode along the \(k_y\) axis (\(k_x=0\) line). Nevertheless, there are near transverse modes whose growth rate is much larger than the longitudinal unstable modes (at around \(k_x \approx 1.0\)).

### 3. Nonlinear hybrid simulation

In order to analyze the nonlinear evolution of the beam instability, we performed several runs of a hybrid simulation, which treats the background plasma as a fluid and the beam electrons as particles as in a PIC simulation. Typical results are shown in Figs.4(a)-(c), which are two dimensional false color images displaying the beam electron density. Figures 4 (a), (b) and (c) correspond to the cases of the normalized magnetic field \(\omega_c/\omega_{pe}=0, 0.5\) and 1, respectively. The beam velocity is 0.99c and the initial beam temperature is 150keV. The left and right boundaries are open, while the top and bottom boundaries are periodic. The beam electrons are continuously injected in the vicinity of the left boundary as their density is set to be 1/10 of the background plasma density. The length is scaled in \(\mu m\) and the background plasma density is taken to be \(10^{22} 1/cm^3\).

When there is no magnetic field (Fig.4(a)), the growth rate is large and the beam breaks up into filaments due to the transverse instability. Each filament carries net electric current as the background electrons evacuate the filaments to maintain charge neutrality. The current filaments then attract each other due to the magnetic force and they tend to collide with each other. As a result, the current filaments change direction randomly. This behavior results in the large angular spread of the electrons, and hence the number of electrons reaching to the core plasma will be small.

**Figure 3.** 2D growth rate profile for the two-stream state for the case of large flow velocity and large beam electron temperature.
Figure 4. Beam electron densities for different external magnetic field strengths at $t=310\text{fs}$. The density is normalized to the background plasma density.

On the other hand, when the magnetic field is strong enough (Fig.4(c)), the beam flows quasi-laminarly, although fine filament structures still remain. One reason for the quasi-laminar flow is the guiding effect on the filament of the strong magnetic field. As a result, a sufficiently strong magnetic field has the capability to suppress the increase of the angular spread due to both the reduction of the growth rate of the beam instability and the guiding effect on the filaments.

However, electron flow stagnates for a medium strength magnetic field. As shown in Fig.4(b) ($\omega_c/\omega_{pe}=0.5$), the electrons accumulate near $x \approx 10\mu m$ and the stagnation of the electron flow prevents the propagation of trailing beam electrons. The beam stagnation may occur because the external magnetic field is perturbed by the kink instability and reconnection of the magnetic fields lead to formation of magnetic islands. As a result, the number of electrons reaching the fuel will be largely reduced.

4. Conclusion
We have analyzed beam instability in both linear and nonlinear regimes. In the linear stage, it is found that a kinetic analysis is necessary to describe the weak instabilities. When the magnetic field is strong enough, the pure Weibel instability, which only has transverse wave vector, is suppressed, but near transverse unstable modes still exist as well as longitudinal modes.

According to the nonlinear analysis, it is found that application of sufficiently strong magnetic field is effective in suppressing the broadening of the angular spread of the beam electrons and increases the number of electrons reaching to core. However, the application of an insufficiently strong magnetic field causes stagnation of the electron flow. The cause of this stagnation remains for future study.

References
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