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Sausage and Kink EMHD Instabilities and Fast Electron transport

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Abstract

In the fast ignition concept of laser fusion it is desirable that the hot electron beam generated at the critical layer by the ignitor laser pulse propagates an adequate distance and deposits its energy to the compressed target core in a sufficiently localized region for the creation of hot spot. The mechanisms responsible for energy deposition can be due to (i) the classical coulomb collision cross section and (ii) collective interaction of the beam plasma system. The present work demonstrates a possible electromagnetic turbulence aided collective mechanism of stopping of the energetic electron flow in plasma.

The transport of energetic electrons through plasma has an important significance in fast ignition (FI) concept of laser fusion [1]. The FI is a simple variant of the inertial confinement fusion (ICF) scheme, wherein the heating of the fusion target core for ignition is carried out by a separate fast laser pulse after compressing the target to fusion densities. The ignitor laser pulse by itself is unable to penetrate the precompressed overdense target. One relies instead on energetic electrons generated at the surface of the target by this pulse to propagate through the compressed plasma and deposit significant energy in a sufficiently localized region within the target for the creation of hot spot. It is thus clear that the success of FI scheme depends crucially on the transport property of energetic electrons through a dense plasma medium.

Some recent experiments have already demonstrated the superiority of the FI scheme over the conventional ICF method by showing enhanced neutron yields [2]. The underlying physical mechanism of the creation of hot spot for ignition, however, remains unclear. While some authors [3] feel that the classical collisional friction (with necessary modifications for dense plasmas) could be adequate for the heat deposition others have a viewpoint that the presence of anomalous friction is desirable and may even be necessary [4, 5]. The PIC simulations carried out in this context have shown development of electromagnetic turbulence, but the origin of turbulence and its participation in producing anomalous friction to the energetic electrons flow have not been clearly identified. Our recent work on fluid two dimensional simulations has shown that the shear driven Electron Magnetohydrodynamic (EMHD) instabilities [6, 7] are capable of producing anomalous friction [8]. However, those simulations were very restrictive due to their two dimensional nature. We present here results of three dimensional EMHD simulations for the sheared electron configuration.

The choice of EMHD model is governed by the relevant time scales in the problem. The typical time scales in which the energetic electrons traverse the target is very small (of the order of a few picoseconds). In such a short time, plasma ions are unable to respond dynamically. Thus the combined system of the energetic electron beam and the response of the background plasma can be suitably treated by single fluid Electron Magnetohydrodynamic (EMHD) description. The EMHD model has been described in detail by several authors [9]. The sheared electron flow configuration arises as a result of Weibel separation of forward energetic electron flow and the return shielding current in the FI problem. The simulations show the development of various unstable excitations in agreement with the predictions of the linearized analytical calculations [7]. Simulations also show that nonlinear interaction amongst the unstable modes produces electromagnetic turbulence and tries to quench the instability by reducing the shear in the forward and reverse electron flows. This turbulence induced nonlinear flattening of the shear profile leads to faster stopping of the current flow.

For the purpose of numerical simulation we have employed the following EMHD evolution equation for the magnetic field.

$$\frac{\partial}{\partial t}(\nabla^2\vec{B}-\vec{B}) = \vec{\nabla}\times\{\vec{v}_e\times(\nabla^2\vec{B}-\vec{B})\}. \tag{1}$$

As the total current in EMHD is due to electron motion, hence the electron velocity and the magnetic field in this case are related by the constitutive relation $\vec{v}_e = -\nabla\times\vec{B}$. Equation (1) is basically the curl of electron momentum equation. Here, the magnetic field has been normalized by some typical value B_{00}, time by the inverse of corresponding electron cyclotron frequency and the length by skin depth c/ω_p. For convenience, simulations have been carried out for a slab geometry. The radial direction of the current channel has been taken as $\hat{x}$, the poloidal as $\hat{y}$ and the current flow direction is along $\hat{z}$.

Our objective here is to provide a proof of principle of the existence of collective anomalous stopping mechanism of the beam, and the demonstration that the three dimensional characteristics of the excitations are better suited to achieve this. Hence we ignore features such as curvature of the filament, the relativistic nature of the electron beam and the plasma density gradient along the beam path, which would be necessary for investigating the issue in quantitative details.

The electron flow velocity in equilibrium is chosen to be directed along the $\hat{z}$ with the following choice of the sheared profile $v_0(x)\hat{z} = V_0 tanh(x/\varepsilon)$. The oppositely directed flows $v_0(x)$ at $\pm x$ mocks up the forward and return shielding currents after their Weibel separation, as discussed above. Here, ε represents the width of the velocity shear layer. Such a current flow produces an equilibrium magnetic field along $\hat{y}$ given by $B_{y0} = (-V_0\varepsilon)log[cosh(x/\varepsilon)]$. Equation (1) is simulated numerically with an initial choice of magnetic field profile as $\vec{B} = B_{y0}\hat{y} + \vec{\tilde{B}}_1$. Here, $\vec{\tilde{B}}_1$ represents a small initial perturbation. The simulations clearly show the development of instability. The energy in the perturbed fields show an initial exponential rise (see Fig.1), indicating the presence of unstable modes in the system. The numerically obtained estimate of the growth rate γ from Fig.1 is $= 2.68$, which agrees well with the analytical value of the growth rate for fastest growing mode as shown by the dotted straight line alongside.

As the perturbations acquire significant amplitude, the development of turbulent flow patterns can be seen. In Fig.2 we plot the color contours for v_z (the $\hat{z}$ component of the electron velocity) on various 2d planes in the three dimensional space. A few streamlines showing the electron fluid flow direction has also been illustrated by thick lines on the figure. The streamlines clearly demonstrate the presence of poloidal $\hat{y}$ component of electron flow velocity.

In fig.3 we plot the evolution of z and y independent $\hat{z}$ directed electron flow velocity profile defined by $< V_z >= 1/(4L_zL_y)\int_{-L_z}^{L_z}\int_{-L_y}^{L_y} v_{ez}dzdy$ as a function of x. The figure shows that the shear of the initial tangent profile tends to flatten up in the central region. The shear width, of the profile, however, grows with time. The turbulent excitations start in the central region of finite shear and expand outwards engulfing regions which otherwise were linearly stable for the chosen tangent hyperbolic profile.

It is interesting to contrast the 3 dim results with those obtained for two dimensional simulations for similarly chosen equilibrium [8]. In 2d the instability was quenched easily (the conditions for growth being very stringent) [8] without any significant development of turbulence. Moreover, in 2d the inverse cascade of power (due to the existence of two square invariants) also acted as a great impediment to the development of turbulence. It finally led to the accumulation of power towards long scale patterns. A comparison for the evolution of the inward moving current (obtained by integrating $< V_z >$ over half x space as $J = (1/L_x)\int < V_z > dx$) for the 2 and 3 dim cases, (Fig.4) illustrates a much faster drop in current in the three dimensional case. This clearly indicates that the collective stopping of the current is more rampant in the realistic three dimensional case.

In summary we have shown that the 3d EMHD instabilities driven by velocity shear can produce significant turbulence (unlike 2d simulations in similar scenario). We also find that the enhanced turbulence aids in stopping of electron flow, thereby producing anomalous friction.

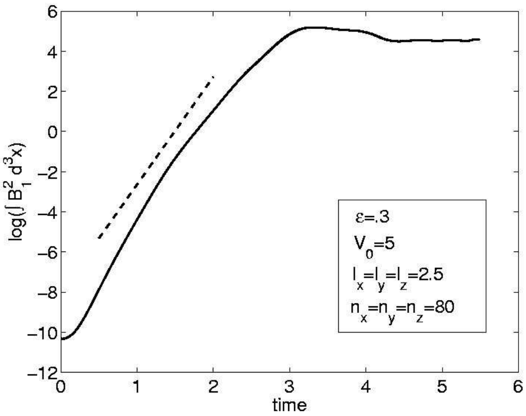

Figure 1: Growth of total energy.

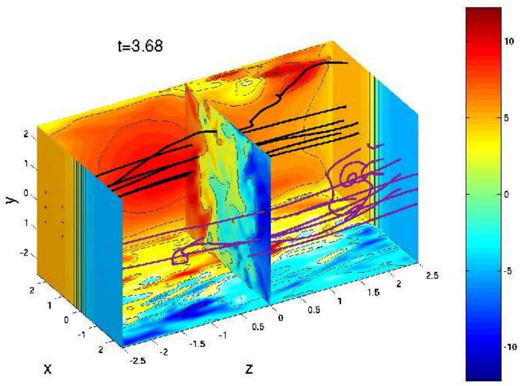

Figure 2: V_z contours and flow lines.

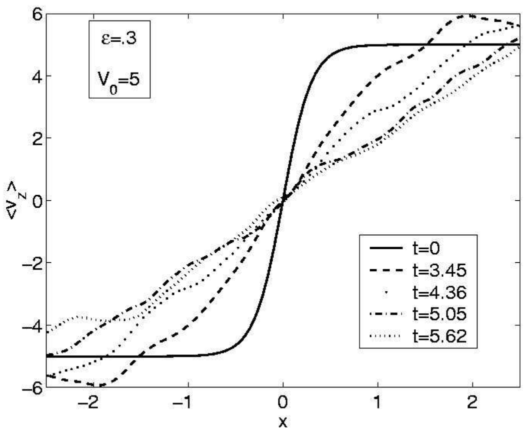

Figure 3: Evolution of $< V_z >$.

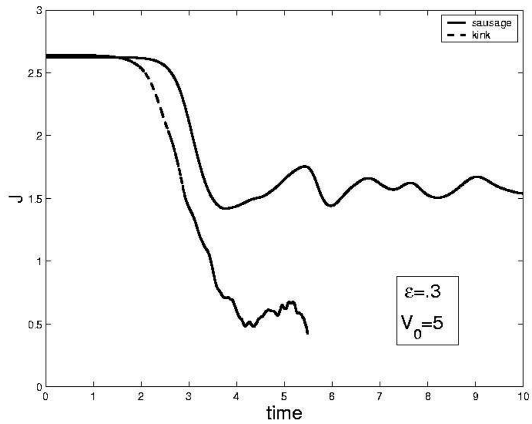

Figure 4: Evolution of J.

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