Solar and Stellar Plasma

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Anomalous momentum transport in astrophysical return-current beam plasmas - the two-dimensional electromagnetic case

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Abstract. Anomalous momentum transport in a typical astrophysical return-current beam plasma system is studied by means of two-dimensional PIC code simulations. A forward going hot electron beam compensated by a cold return beam is considered. A linear dispersion analysis predicts the linerarly unstable wave modes. Our simulation reveals that the nonlinerly generated waves and the consequent wave-particle interactions cause the electron heating and the relaxation of the electron drifts. Both, the developments of electrostatic and electromagnetic waves are analyzed as well as the roles they play in energy conversion. In particular it is found that the relaxation of electron drifts is stronger if the electromagnetic turbulence is taken into account.

1. Return-current in astrophysical plasma

In various astrophysical plasma environments return-current beams have to be assumed which compensated the intense electron beams generated in acceleration sites like reconnecting current sheets. Return current beam instabilities have to be taken into account also in the production of thermal X-rays by the bombardment of the neutron star surface by return-current electrons (Cheng & Zhang, 1999) and as cosmic rays streaming instabilities behind supernovae shock waves. Induced return-currents can compensate the cosmic ray currents (Amato & Blasi, 2009, Niemiec *et al.*, 2008). The spectrum of X-rays generated by energetic electrons precipitating in the solar atmosphere is likely to be influenced by return currents (Zharkova & Gordovskyy, 2006, Lee *et al.*, 2008). The localized large-amplitude electrostatic and electromagnetic structures excited by beam and return current electrons are of significant importance for astrophysical plasmas. One of the impacts of this non-linear wave-particle interaction is the anomalous transport caused by the current driven instabilities. The latter has been studied, e.g., by means of electrostatic Vlasov code simulations with open boundary conditions (Büchner & Elkina, 2006). The instability of a return-current beam system has been investigated by means of a three-dimensional electromagnetic particle-in- cell (PIC) simulation code (Karlický & Bárta, 2009). In their study the authors considered the injection of a cold electron beam into a background of electron and ions. They analyzed the parallel electric field perturbations, and found a strong background magnetic field in the electron drift direction suppresses the Weibel- (filamentation-) instability. The electrons and ions are heated preferentially in the parallel direction while the background magnetic field is weak. The anomalous transport in a return-current beam plasma was compared by means of electrostatic Vlasov-code and multifluid simulations (Lee & Büchner, 2010). It is known, however, that electromagnetic waves might accelerate and heat electrons more effectively than electrostatic waves (Tsironis & Vlahos, 2005), i.e the associated anomalous transport could be stronger. For the common case of magnetic reconnection

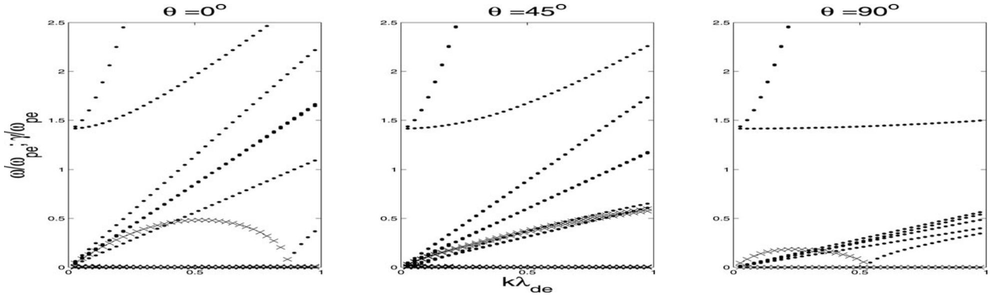

Figure 1. Wave dispersion for different propagation angles: $\theta = 0^o; \theta = 45^o; \theta = 90^o$. The dots depict the normalized real frequencies $\omega(k)$ of waves in the system while the crosses depict the corresponding growth rates $\gamma(k)$.

outflow, we consider in this paper a hot electron beam injection into the cold background plasma with the compensating the return current flow.

2. Linear dispersion analysis of warm magnetized plasma

Our multifluid linear dispersion considers thermal plasma effects, electromagnetic waves (full set of Maxwell equations), different electron drifts and oblique wave propagation as well as the real electron-to-ion mass ratio ($m_i/m_e = 1836$). We concentrate on a situation where the forward going electron beam is twice as hot as the background ions and return-current electrons as cold as the ions ($T_{e,beam} = 2T_{ion} = 2T_{e,RC}$). The densities of beam and return-current electron beams are equal $n_{e,beam} = n_{e,RC} = n_{ion}/2$ and the net current vanishes with their drift velocities ($V_{de,beam} = -V_{de,RC} = -v_{te}$).

Fig. 1 shows the dispersion relation for different prapagation angles, where θ is the angle between $\vec{k}$ and $\vec{V}_{de,beam}$. Without a background magnetic field, the instability (growth rates are depicted by crosses and the wave frequencies by the dots) is due to the interaction of two electron acoustic waves. The electron-electron acoustic wave grows fastest at an oblique propagation angle (cf. the second panel of Fig.1 for $\theta = 45^o$). Note that due to the limits of a fluid description this result is correct only for wavelength longer than the Debye length. At the nonlinear stage of the instability the inhomogeneity of the electron drift distribution results in localized currents which cause the growth of localized magnetic field structures.

3. Self-generated anomalous transport

The nonlinear stage of the return-current beam relaxation is studied via (2D EM PIC) simulation, for which the periodic boundary conditions are implemented. In the past mainly anomalous transport caused by electrostatic waves has been investigated, and it was concluded that the relaxation of electron drifts corresponds closely to the development of electric field structures. In the first panel of Fig. 2 the temporal evolution of total field energy in the simulation domain is shown. Indeed, at the nonlinear stage first the electric field energy strongly grows and after some time it decreases and saturates at a lower level, as shown previously by electrostatic simulations (cf. also Lee & Büchner, 2010). Howeverm as one can see further in the Figure, the total (electrostatic plus electromagnetic) field energy continues to increase even after the electrostatic waves did saturate (blue dashed line in first panel of Fig.2).

The second and third panels of Fig.2 depict the temporal evolution of electron drifts and plasma temperature. The energy conversion from the electron drift decreases at the

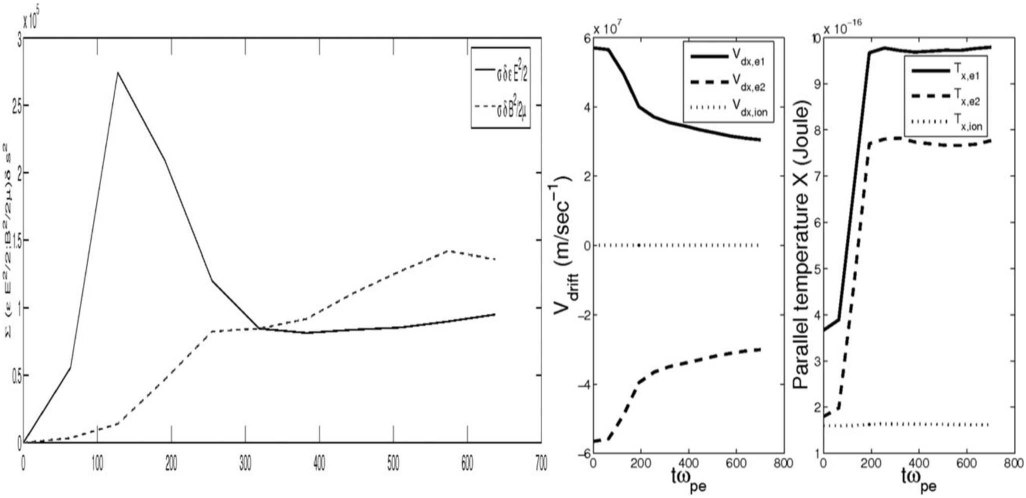

Figure 2. Temporal evolution of the electromagnetic field energy shown in the first panel. The solid line depicts the electrostatic and the dashed line the magnetic field energy. The second and third panels are the temporal evolutions of electron drifts and temperatures.

nonlinear stage of the instability evolution $T \approx 70\omega_{pe}^{-1}$. At the same time the electron temperature increases and the energy of the electric field energy rapidly decreases. At the late stage of electric field evolution $T \approx 200\omega_{pe}^{-1}$ the electron heating stops. Drift relaxation and electron heating effects correspond to those obtained in electrostatic approaches. However, the relaxation of electron drifts it is not completely stopped, as the case in electrostatic simulation. Hence, the drift relaxation continues as well as the anomalous transport. The reason is that if the excitation of electromagnetic waves are taken into account the electron drift energy is converted, in addition to electric field fluctuations, also to magnetic field fluctuations, as indicated in Fig. 2.

To conclude, the interaction of the two beams causes anomalous transport and electron heating. These processes are kinetic in nature and might be due to the interaction of the beam particles with unstably generated waves. At the nonlinear evolution stage, however, the inhomogeneity of the electron drift distribution creates local current and associated magnetic field structures. Contrary to the widely studied case of relaxation by electron interaction with the self-generated electrostatic waves, the magnetic structures do intensify the drift relaxation by extracting kinetic energy from the electron drift continuously in the late stage of evolution. We argue that electromagnetic effects play a most significant role in the anomalous transport and plasma heating at the late stage of the drift evolution.

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References

Amato, E. & Blasi, P. 2009, *Mon. Not. R. Astron. Soc.*, 392, 1591
Büchner, J., Elkina, N. 2006, *Phys. Plasmas*, 13, 082304
Cheng, K. S. & Zhang, L. 1999, *ApJ*, 515, Issue 1, 337

Karlický, Bárta, M. 2009, *Nonlin. Processes Geophys.*, 16, 525
Lee, K. W., Büchner, J., & Elkina, N. 2008, *A&A*, 478, 889
Lee, K. W. & Büchner, J. 2010, *Phys. Plasmas*, 17, 042308
Niemiec, J., Pohl, M., Stroman, T., & Nishikawa, K.-I. 2008, *ApJ*, 684, 1174
Tsironis, C. & Vlahos, L. 2005, *Plasma Phys. Control. Fusion*, 47,131
Zharkova, V. V. & Gordovskyy, M. 2006, *ApJ*, 651, 553