Transport in the presence of inverse bremsstrahlung and magnetic fields

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Abstract

The effects of inverse bremsstrahlung (IB) heating on transport in nanosecond laser-plasma interactions are elucidated in the presence of magnetic fields. IB results in the distribution function tending towards a super-Gaussian. The theory of transport will be derived for this distribution. In the resulting theory the classical transport coefficients of Braginskii need to be modified and new ones must be introduced.

Introduction

Using the appropriate theory to describe transport in a long-pulse laser-plasma interaction is essential to achieving a predictive modelling capability for inertial confinement fusion. In such interactions large (mega-gauss strength) magnetic fields are expected to be generated around the laser spots by the thermoelectric mechanism [1]; these are caused by non-parallel electron density and temperature gradients. Kinetic effects, such as non-local transport, are also expected to be important [2,3]. Therefore the effects of both non-Maxwellian distributions and B-fields on transport must be accounted for.

Classical transport theory [4] relies on the isotropic part of the electron's distribution function being Maxwellian and is commonly employed in magnetohydrodynamic (MHD) modelling of long-pulse interactions. Kinetic effects must be considered when this is not the case. Non-local transport, particularly non-local heat flow, is very important in long-pulse interactions. The effect of magnetic fields on non-locality has been discussed previously [5]; additionally the coupling between magnetic field dynamics and non-local heat flow has recently been elucidated experimentally and theoretically [6,7].

A second, less often considered, kinetic effect can play a role in long-pulse interactions. This is the distortion of the isotropic part of the electron's distribution function by inverse bremsstrahlung (IB) laser heating. IB heating is dominant at moderate laser intensities well away from the critical surface. IB causes the isotropic part of the electron distribution function to approach a Langdon distribution $f_0 \propto e^{-v^5}$ in the limit of strong heating [8]. Electron-electron collisions tend to relax the distribution towards a Maxwellian so the more general super-Gaussian distribution (also known as the Dum-Langdon-Matte, or DLM, distribution) is more appropriate, i.e.: $f_0 \propto e^{-v^m}$ where $2 \leq m \leq 5$ in transport calculations. A theory of transport has been derived for this distribution. This has been looked at in the context of turbulence [9] but not for laser-plasmas.

Classical transport theory

The transport relations used to close the MHD equations are given by the classical transport theory originally proposed by Braginskii [4] and later corrected by Epperlein & Haines [10,11]. The classical Ohm's law and heat flow equation are given by:

$$en_e\mathbf{E} = -\nabla P_e + \mathbf{j}\times\mathbf{B} + \frac{\underline{\underline{\alpha}}\cdot\mathbf{j}}{n_e e} - n_e\underline{\underline{\beta}}\cdot\nabla T_e \tag{1}$$

$$\mathbf{q} = -\underline{\underline{\kappa}}\cdot\nabla T_e - \underline{\underline{\beta}}\cdot\mathbf{j}\frac{T_e}{e} \tag{2}$$

Here α, β and κ are the classical transport coefficients. α is the resistivity, β is the thermoelectric coefficient, and the thermal conductivity is κ. The magnetic and electric fields are **B** and **E**. The electron pressure is given by P_e, the electron temperature and number density by T_e and n_e, the current by **j** and the heat flow by **q**. Equations (1) and (2) are derived by taking moments of the Vlasov-Fokker-Planck equation (neglecting electron inertia and expanding the distribution function in Cartesian tensors). The isotropic part of the distribution function f_0 is assumed to be a Maxwellian and the anisotropic part $\mathbf{f}_1$ (responsible for flows and transport) is assumed to be small. If f_0 departs strongly from Maxwellian then classical transport theory is not valid. The transport equations are crucial to plasma modelling. The heat flow equation closes the MHD equations and in doing so determines the energy flow in the plasma. Ohm's law, in conjunction with Faraday's law, gives the rate of change of the magnetic field.

The transport coefficients are usually expressed in dimensionless form in the following way:

$$\underline{\underline{\alpha}}^c = \underline{\underline{\alpha}}\frac{\tau_B}{m_e n_e} \qquad \underline{\underline{\beta}}^c = \underline{\underline{\beta}} \qquad \underline{\underline{\kappa}}^c = \underline{\underline{\kappa}}\frac{m_e}{n_e k_b T_e \tau_B} \tag{3}$$

The collision time τ_B is that for angular scattering between ions and electrons moving at the mean averaged speed for the Maxwellian at a given point. In a magnetised plasma the B-field provides a unique axis whereby transport is different parallel to this axis as compared to perpendicular to it. Thus the components of the transport coefficients are described with reference to the magnetic field and the driving force behind the transport (s).

$$\underline{\underline{\eta}}\cdot\mathbf{s} = \eta_{\parallel}\mathbf{b}(\mathbf{b}\cdot\mathbf{s}) + \eta_{\perp}\mathbf{b}\times(\mathbf{s}\times\mathbf{b}) \pm \eta_{\wedge}\mathbf{b}\times\mathbf{s} \tag{4}$$

This defines the components of the general transport coefficient (η) with reference to **b** the unit vector in the direction of the B-field. In the case of the resistivity α the sign of the last term is negative and **s**=**j**. For the thermoelectric tensor β and thermal conductivity κ the sign is positive and **s**=∇T_e.

Transport theory for a super-Gaussian

The corresponding equations to (1) and (2) when f_0 is a super-Gaussian are[12]:

$$en_e\mathbf{E} = -\underline{\underline{\gamma}}\cdot\nabla P_e + \mathbf{j}\times\mathbf{B} + \frac{\underline{\underline{\alpha}}\cdot\mathbf{j}}{n_e e} - n_e\underline{\underline{\beta}}\cdot\nabla T_e \qquad (5)$$

$$\mathbf{q} = -\underline{\underline{\kappa}}\cdot\nabla T_e - \underline{\underline{\beta}}\cdot\mathbf{j}\frac{T_e}{e} - \underline{\underline{\phi}}\cdot\nabla P_e \qquad (6)$$

If the distribution function is non-Maxwellian then Onsager symmetry breaks down[13]. In this case the transport coefficient appearing in the term proportional to the temperature gradient is different in equations (5) and (6). In classical transport theory – when the distribution is Maxwellian – it is the same and equal to the thermoelectric tensor. There is also the need to introduce two completely new transport coefficients γ and ϕ. These result in the heat flow being dependent on the pressure

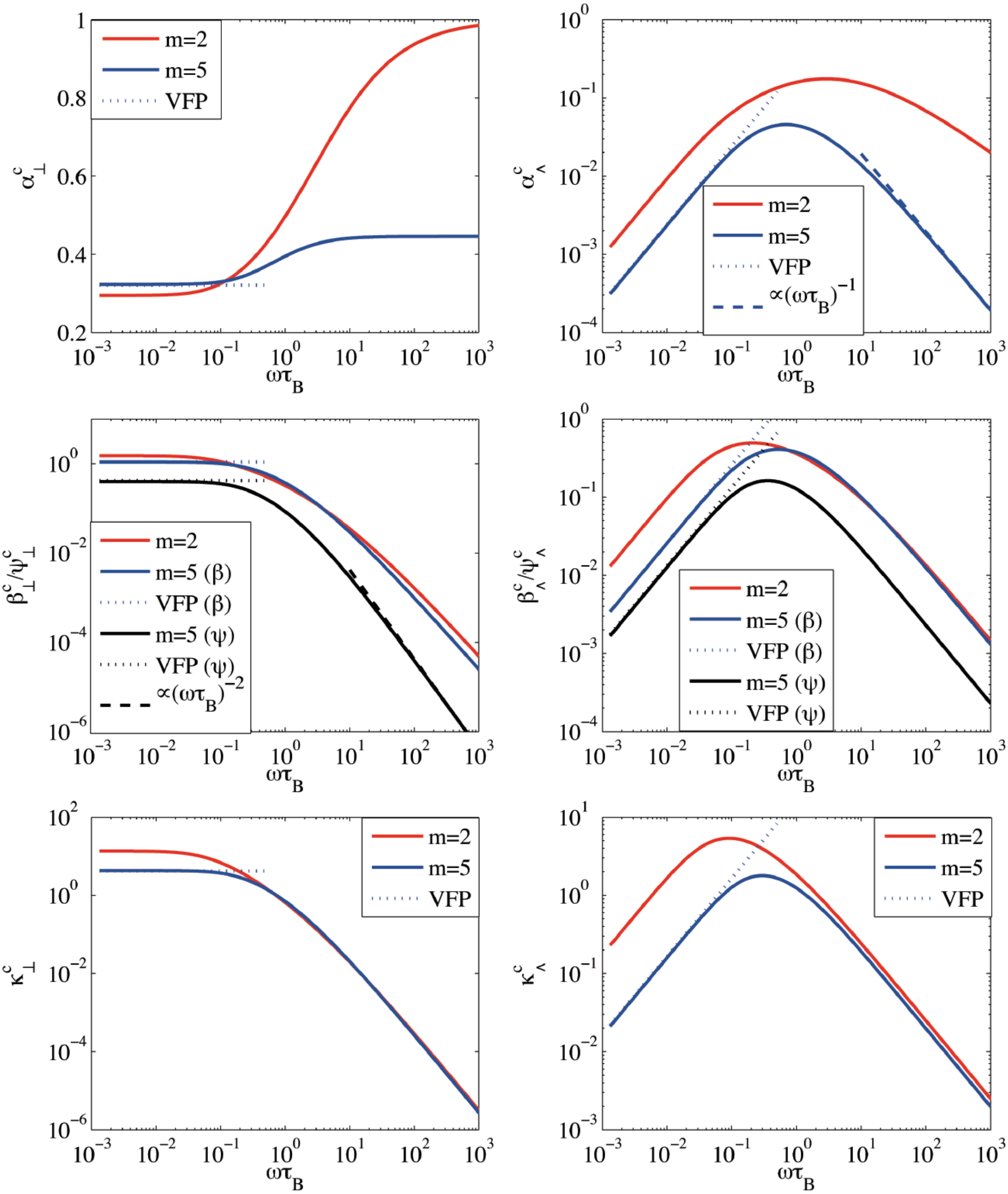

Figure 1. Transport coefficients α, β, and κ for a super-Gaussian (m=5) and a Maxwellian (m=2).

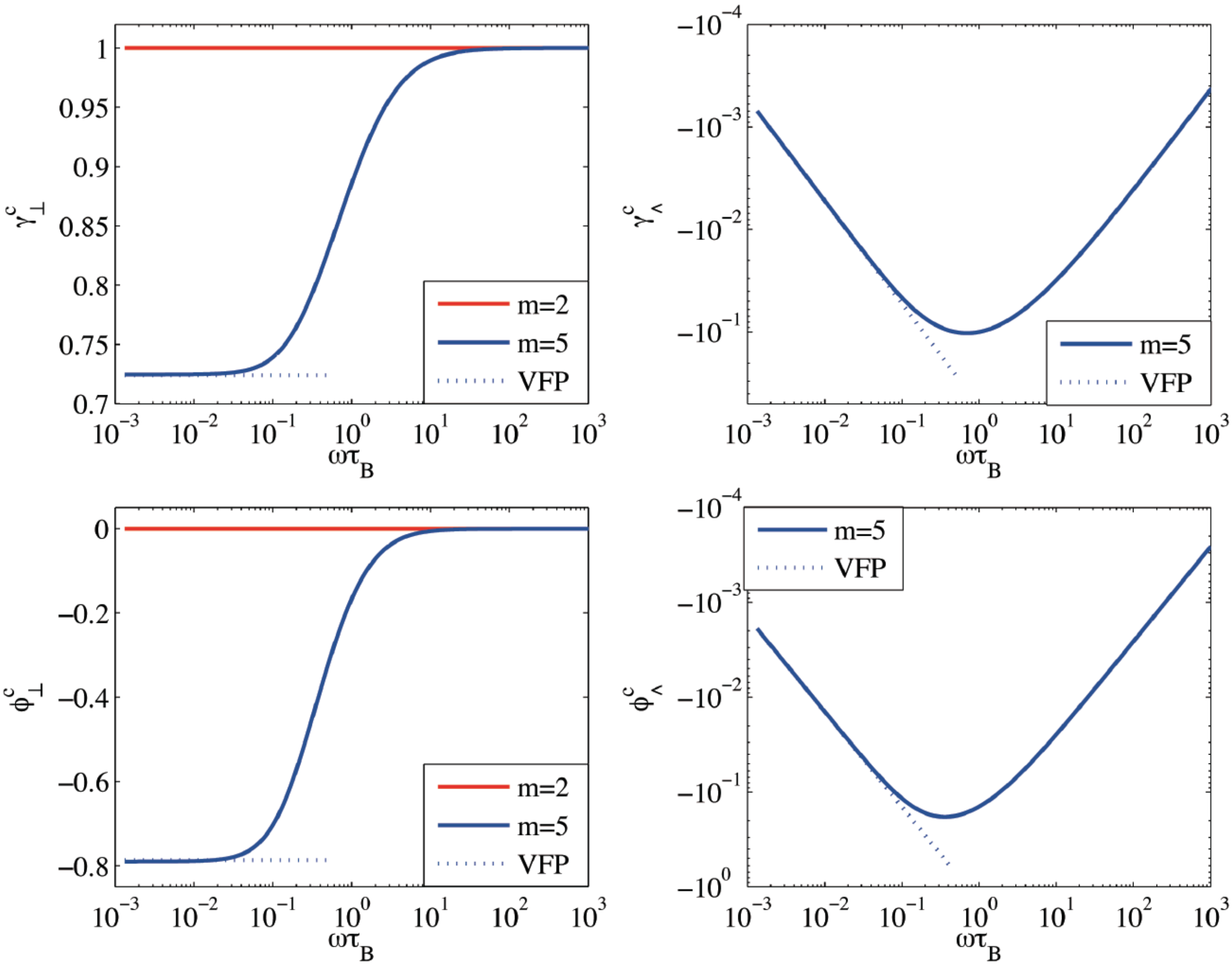

Figure 2. Transport coefficients γ and φ for a super-Gaussian (m=5) and a Maxwellian (m=2).

(and so number density) gradient and in a more complicated dependence of the electric field on the pressure gradient. The new coefficients are expressed in dimensionless form according to:

$$\underline{\underline{\gamma}}^c = \underline{\underline{\gamma}} \qquad \underline{\underline{\phi}}^c = \underline{\underline{\phi}}\,\frac{m_e}{T_e\tau_B} \tag{7}$$

The transport coefficients for a super-Gaussian are compared to those for a Maxwellian in figures 1 and 2. In general they differ from one another by up to an order of magnitude. Note that $\alpha_\wedge$ and $\beta_\perp$ approach different asymptotes to the Maxwellian case in the limit of high Hall parameter.

Conclusions

A transport theory has been derived for a super-Gaussian distribution in the presence of magnetic fields. This theory shows a significant departure from Braginskii's classical transport theory; the transport coefficients differ by up to an order of magnitude. Therefore, any effects which depend on the transport coefficients (the Nernst effect [14], the Tidman-Shanny instability [15]) may be significantly altered.

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