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Magnetic Field Dynamics and Non-Locality in Laser-Plasma Interactions

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The applicability of classical (Braginskii) transport theory [1] to laser plasma interactions is crucial for accurate modeling of such situations. For example, the need for drive uniformity in both direct-drive and indirect-drive inertial confinement fusion requires an intimate knowledge of the heat flow. Measurements of self-generated mega-gauss fields in laser-solid target experiments necessitate the inclusion of magnetic field effects in any such discussion [2]. Although classical transport has been shown to breakdown under typical conditions in some regions of inertial confinement fusion (ICF) experiments – for example when the laser propagates through the gas fill in a hohlraum [3] – large, self-generated, B-fields may act to mitigate this effect. This is based on the fact that non-local transport is suppressed by a large enough magnetic field.

Non-local transport becomes important when the collisional mean free path for electron-ion collisions of the thermal electrons is comparable to 0.01 times the scale-length of the physical variables, such as temperature, density. The mean free path in question is given by: $\lambda_{ei} = v_t^4/YZ^2 n_i \ln\Lambda_{ei}$; where $Y = 4\pi(e^2/4\pi\varepsilon_0 m_e)^2$, n_i is the number density of ions, v_t is the electron thermal velocity and $\ln\Lambda_{ei}$ is the Coulomb logarithm. In this case the transport is no longer given by a consideration of the local gradients of these quantities [4]. The classical heat-flow equation does not apply – i.e. $\mathbf{q}_e \neq -\underline{\underline{\kappa_c}}\cdot\nabla T_e - \underline{\underline{\beta_c}}\cdot\mathbf{j}T_e/e$, $\underline{\underline{\kappa_c}}$ and $\underline{\underline{\beta_c}}$ are the classical thermal conductivity and thermoelectric tensors, T_e and $\mathbf{q}_e$ are the electron temperature and heat flow, $\mathbf{j}$ is the current. Non-local transport leads to a strong departure of the distribution function away from a maxwellian. Thus the transport coefficients are no longer those of Braginskii [1] (as corrected by Epperlein and Haines [5]) whose derivation is based on this assumption. A strong magnetic field can result in those electrons carrying most of the thermal energy – those at speeds of 2-3 times that of the thermal electrons – having gyro-radii which are smaller than their mean free path's. In this case the gyro-radius and not the collisional mean free path becomes the step-length that controls the diffusive transport. Increasing the magnetic field can reduce this step-length to a point where it is much smaller than the physical scale-lengths and so transport is localized.

The large effect that magnetic fields can have on transport means that it is important to keep track of the evolution of the B-field. The equation describing this is obtained from Faraday's law: $\partial\mathbf{B}/\partial t = -\nabla\times\mathbf{E}$. It is clear that the evolution of the magnetic field depends on our choice of Ohm's law. Classical transport theory gives: $en_e\mathbf{E} = -\nabla p_e + \mathbf{j}\times\mathbf{B} + \underline{\underline{\alpha_c}}\cdot\mathbf{j}/n_e e - n_e\underline{\underline{\beta_c}}\cdot\nabla T_e$. Where

E and **B** are the electric and magnetic fields, p_e and n_e are the electron pressure and number density and $\underline{\underline{\alpha_c}}$ is the resistivity. Contained within this Ohm's law are the well understood effects of: frozen-in flow – where the magnetic field advects with the plasma's bulk flow; resistive diffusion; thermoelectric magnetic field generation – by non-parallel density and temperature gradients. However, other effects are included and can be important.

The VFP code IMPACT [6] was used in this investigation. This solves the VFP equation (and so does not demand that the distribution is maxwellian – as in classical transport) in two cartesian spatial dimensions and three velocity space dimensions; with the magnetic field in the z-direction and all gradients in the (x,y) plane. The distribution function is expanded in the spherical harmonics to reduce the *effective* velocity dimensionality to one. Furthermore, the diffusive approximation is used (neglect terms greater than first order in the spherical harmonics) as is the Lorentz approximation (neglect the effect of electron-electron collisions on the electron's momentum). We have simulated the interaction between a laser and a nitrogen gas jet; a magnetic field was imposed parallel to the laser. The gas jet had a density of $1.5\text{x}10^{19}\text{cm}^{-3}$. The laser had an intensity of $6.3\text{x}10^{14}\text{Wcm}^{-2}$ (corresponds to 100J in 1ns), a wavelength of 1.054μm and a pulse length which rose linearly in intensity up to the maximum in 350ps; the laser heating is by inverse bremsstrahlung (IB). The focal spot had a diameter of 150μm and the applied magnetic field was set as either 0T or 12T.

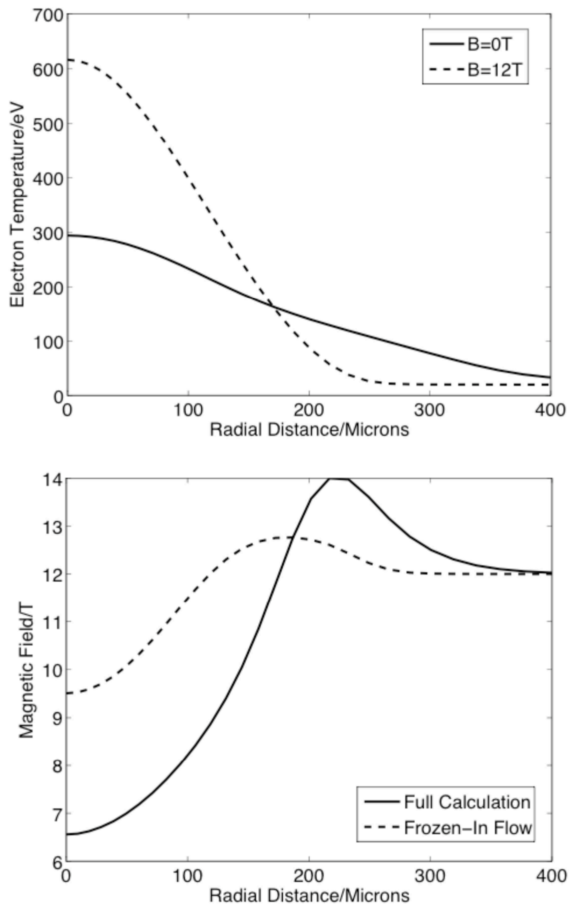

Figure 1: Plasma temperature profiles (top) and magnetic field profiles (bottom) after laser heating for 440ps

Figure 1 shows the radial temperature profiles after 440ps. In the field-free case there is non-local pre-heat of the plasma outside the laser-heated region due to the low collisionality of the hot electrons [7]. The peak plasma temperature in this case is 294eV. At this temperature the mean free path of a thermal electron is $16.8\mu m$ – a significant fraction of the laser spot size –

thus leading to the observed non-local behavior. In the 12T case the pre-heat is suppressed as observed experimentally [8]. The maximum temperature here is 616eV, giving a mean free path of $64.2\mu m$; however, the Larmor radius of electrons ranges from $11.9\mu m$ in the centre of the spot – where the plasma is hottest and the magnetic field strength least – to 1.25μm outside the laser heated region. The fact that the larmor radius is less than the mean free path means the consequent reduction in the mobility of the electrons should go some way towards localizing the heat transport; exactly how local the transport is in this and the other cases will be discussed shortly.

The magnetic field profile un the 12T case is shown by the solid line in figure 1. The magnetic field is largely cavitated in the laser heated region and piles-up several hundred microns away from the centre of the spot. The dashed line in figure 1 shows the magnetic field profile if frozen-in flow is the only advection mechanism. To account for the discrepancy between this and the field calculated in the simulation we consider the equation for the evolution of the magnetic field as derived from the classical Ohm's law: $\frac{\partial B}{\partial t} + \nabla \cdot [(\mathbf{C} + \mathbf{v}_N)B] = 0$. The Nernst velocity is given by $\mathbf{v}_N = 2\mathbf{q}_e/5n_eT_e$; $\mathbf{C}$ is the plasma flow velocity, and B is the magnetic field in the z-direction. This equation is only valid in the geometry considered here – the magnetic field is perpendicular to the gradients of the physical variables and the system is cylindrically symmetric. Thus the anomalous advection of the magnetic field is understood to be a result of the Nernst effect.

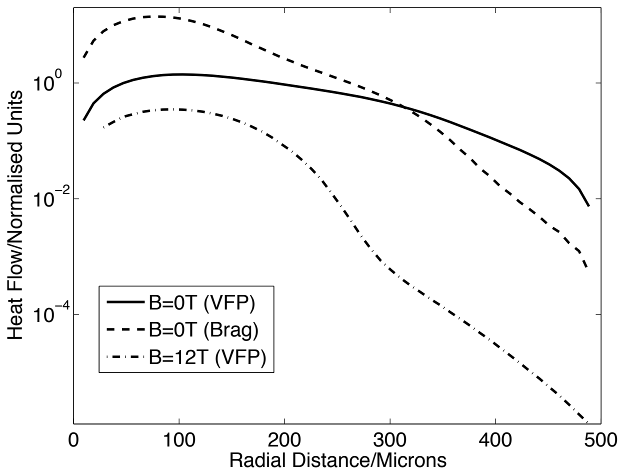

Figure 2: Magnetic Field profiles after 440ps.

Figure 2 shows the radial heat flows from the simulation and those calculated by inserting the instantaneous temperature profiles and currents at 440ps into the classical heat flow equation. The radial heat flow is classical in the 12T case, but is highly non-local in the field-free case.

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