Return Currents in Intense Laser-Plasma Interactions: A Fokker-Planck Approach

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In high-intensity laser-plasma interactions, fast electrons are produced in a thin region near the plasma surface and travel into the plasma at relativistic speeds. As they do so, they set up a space-charge electric field which in principle acts to decelerate the fast electrons. However, the electric field also acts on the cold electrons which make up the bulk of the plasma through which the fast electrons are travelling, thus the cold electrons form a current opposing the forward current of the fast electrons. Being less energetic, these cold electrons are collisional and so may be expected to respond linearly to electric fields, as in the simple relation of Spitzer's transport theory: $j_x=\sigma(Z,T_e)E_x$, where σ is the temperature-dependent Spitzer conductivity. Spitzer conductivity (see, e.g. [1]) is strictly only valid when the perturbation on the electron distribution function due to the current is small, the unperturbed distribution function is Maxwellian and the electrons are collisional. Strong fields and Joule heating, both of which are a feature of intense laser-plasma interactions, may force the plasma into a non-Spitzer response regime. We briefly outline recent Vlasov-Fokker-Planck simulations of the propagation of fast electrons through solid Al plasma targets.

The computational model is KALOS [2], a code for solving the relativistic Vlasov-Fokker-Planck equation,

$$\frac{\partial f}{\partial t}+v_x\frac{\partial f}{\partial x}+q(\mathrm{E}+\mathrm{v}\times\mathrm{B}).\nabla_p f=\left(\frac{\partial f}{\partial t}\right)_{ei,ee},$$

self-consistently with Maxwell's equations. KALOS represents the electron distribution function (f) as an expansion in spherical harmonics:

$$f(x,\mathrm{p},t)=\sum_{n,m} f_n^m(x,p,t)Y_n^m(\theta,\varphi),$$

where θ and φ are angles in momentum-space. In the current simulations, we include 30 terms in the expansion study a 1d2p system. Electron-ion collisions and electron-electron collisions are retained for all harmonics, with only the isotropic component of f (f_0) contributing to the Rosenbluth potentials.

The system is initialised at solid Al density (around 700 times the critical density) with a temperature of 500eV (assumed fully ionised). Fast electrons are injected at the left-hand boundary with a density profile gradually falling over 5 microns (the target being 110 microns thick) and a Gaussian temporal profile with a 2ps width at half-maximum. Injected electrons have a relativistic Maxwellian distribution in momentum and a characteristic temperature taken from ponderomotive scaling [3] corresponding to a laser intensity of 10^{20}Wcm^{-2}.

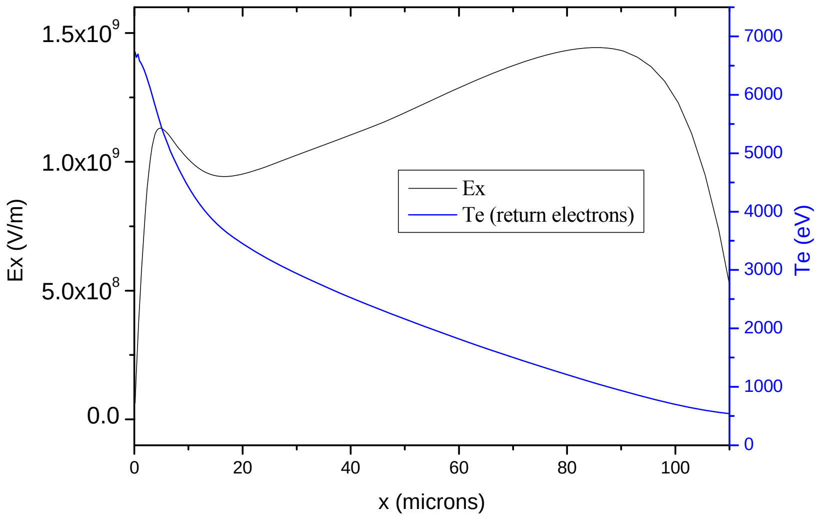

Fig. 1. Electric field and temperature of return current electrons.

In this contribution we focus on results at t=2.4ps (not long after the peak in power). Fig. 1 shows the electric field and electron temperature profiles at this time. The electric field, produced by the fast electron current, reaches strengths exceeding 10^9V/m. The electron temperature corresponds to the return current electrons only, which are at least partially collisional and therefore Joule heat to a peak temperature of around 6.5keV. As the electrons heat their mean-free-path increases and transport may therefore become non-local. Fig. 2 plots the ratio of the return current to the Spitzer current calculated for the same electric field, Z and return electron temperature. Also shown in Fig. 2 is the degree of non-locality of the return current electrons, parameterised by $k\lambda_{ei}$, where λ_{ei} is the electron-ion mean-free-path for thermal electrons at the return-current temperature and k is the spatial frequency of the electric scalar potential Φ. It is clear that deviations from Spitzer theory coincide with regions of non-local transport. The degree of deviation is quantitatively in good agreement with the non-local electron transport theory developed by Bychenkov et al. [4] (valid for any value of $k\lambda_{ei}$) which predicts a reduction in current flow by a factor of

~0.5 for $k\lambda_{ei}$ ~0.5. However a better comparison would involve reproducing scaling with the non-locality parameter and it should be noted that Bychenkov's theory is strictly linear. These results, although preliminary, will have direct implications for models of laser-plasma interactions in which high electron temperatures are reached, e.g. the fast ignitor scheme.

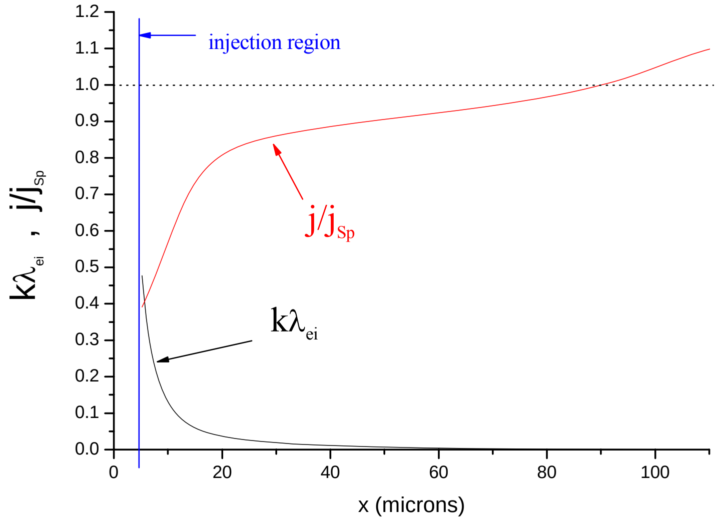

Fig. 2. Deviation from Spitzer conductivity and non-locality parameter at 2.4ps.

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[2] A.R. Bell *et al.*, Plasma Phys. Control. Fusion 48 (2006) R37.

[3] S.C. Wilks *et al.*, Phys. Rev. Lett. 69 (1992) p1383.

[4] V.Yu. Bychenkov *et al.*, Phys. Rev. Lett. 75 (1995) p4405.