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The influence of magnetised electron transport on thermal self-focusing and channelling of nanosecond laser beams

Martin Read [1,2], **Robert Kingham** [2] **and John Bissell** [3]

[1] York Plasma Institute, University of York, Heslington, York, YO10 5DQ, UK
[2] Blackett Laboratory, Imperial College London, London, SW7 2AZ, UK
[3] Department of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK

E-mail: martin.read@york.ac.uk

Abstract. The propagation of a nanosecond IR laser pulse through an under-dense $(0.01 - 0.1\,\mathrm{n_{cr}})$ magnetised laser-plasma is considered. The interplay between magnetised transport, B-field evolution and plasma hydrodynamics in the presence of a dynamically evolving beam are investigated by means of a paraxial wave solving module coupled to CTC, a 2D MHD code including Braginskii electron transport and IMPACT, a 2D implicit Vlasov-Fokker-Planck (VFP) code with magnetic fields. Magnetic fields have previously been shown to improve density channel formation for plasma waveguides however fluid simulations presented here indicate that Nernst advection can result in the rapid cavitation of magnetic field in the laser-heated region resulting in beam defocusing. Kinetic simulations indicate that strong non-local transport is present leading to the fluid code overestimating heat-flow and magnetic field advection and resulting in the recovery of beam channelling for the conditions considered.

1. Introduction

In recent years there has been an increasing use of applied magnetic fields in long-pulse (ns) laser-plasma experiments. Magnetic fields can be utilised for the purpose of easing the path to ignition in ICF (e.g., improving laser-plasma coupling in hohlraum targets [1] and increasing fusion yield in direct-drive experiments [2]), for their benefits to plasma wave-guide formation [3] and for the study of fundamental plasma physics.

Electron transport, magnetic field evolution and beam propagation are intricately linked in a magnetised plasma and under appropriate conditions, a range of magnetised transport phenomena are present. These transport effects can change the thermal and hydrodynamic evolution of the plasma and via the refractive index $\eta \propto (n_e/n_{cr})^{1/2}$, may affect laser propagation. Additionally, magnetic fields can both lead to instabilities and modify temperature scale-lengths, determining whether the local approximation is fulfilled which has ramifications on the validity of fluid codes. For these reasons, a complete model of electron transport in the presence of B-fields under such conditions is vital to the simulation and interpretation of laser-plasma experiments. This work investigates the interplay between laser propagation and plasma evolution accounting for a full range of magnetised transport phenomena.

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2. Physical Background

Electron transport in the presence of a magnetic field is governed by the Braginskii transport equations [4] for Ohms law and heat-flow $\mathbf{q}$, given in equations (1) and (2), where $\underline{\underline{\alpha}}^c$, $\underline{\underline{\beta}}^c$ and $\underline{\underline{\kappa}}^c$ are the normalised resistivity, thermoelectric and thermal conductivity tensors and τ is the electron-ion collision time. Furthermore $\mathbf{C}$ is the plasma fluid velocity and $\mathbf{j}$, n_e, T_e and P_e give the electron current density, number density, temperature and pressure respectively.

$$en_e\left(\mathbf{E}+\mathbf{C}\times\mathbf{B}\right) = -\nabla P_e + \mathbf{j}\times\mathbf{B} + \frac{m_e}{e\tau}\underline{\underline{\alpha}}^c\cdot\mathbf{j} - n_e\underline{\underline{\beta}}^c\cdot\nabla T_e \tag{1}$$

$$\mathbf{q} = -\frac{n_e T_e \tau}{m_e}\underline{\underline{\kappa}}^c\cdot\nabla T_e - \underline{\underline{\beta}}^c\cdot\mathbf{j}\frac{T_e}{e} \tag{2}$$

The electric field $\mathbf{E}$ determined by Ohm's law is combined with Faradays law yielding an induction equation describing the evolution of the magnetic field $\mathbf{B}$. Of particular interest is the $\beta_\wedge$ component of the thermoelectric term $\left(\underline{\underline{\beta}}^c\cdot\nabla T_e\right)$ perpendicular to both the magnetic field and temperature gradient which gives rise to the Nernst effect – an advection of magnetic fields along with heat-flow down temperature gradients. In previous simulations [5], Nernst field advection was shown to have a dramatic effect on magnetic field evolution, leading to changes in the density and thermal profiles and causing the re-emergence of non-local transport in systems which were previously localised. Due to the intricate coupling between magnetised electron transport, hydrodynamics and a dynamically evolving laser, a numerical approach to modelling the problem is taken.

3. Code Development and Setup

The interaction of a laser with an under-dense magnetised plasma is modelled using two codes: CTC (Classical Transport Code) [6], a 2D MHD code which utilises Braginskii electron transport coupled to equations for continuity, momentum and energy, and IMPACT [7], an implicit 2D Vlasov-Fokker-Planck (VFP) code with magnetic fields which inherently incorporates transport. The codes share the same geometry – 2D slab Cartesian (x-y) with a perpendicular B-field component (B_z). CTC, benefits from a fast execution time and the means to enable/disable terms in the transport equations. IMPACT is computationally expensive but it is well known that the kinetic treatment, which accounts for non-local effects and non-Maxwellian distributions, is often required to correctly account for heat-flux in problems related to plasma ablation and ICF conditions. The laser is included in both codes using a newly developed module based on the paraxial wave treatment given by Sentis [8, 9]. The laser is coupled to the plasma codes via inverse Bremsstrahlung heating and the plasma refractive index. The addition of the paraxial module allows for the modelling of laser-pulse dynamics within an evolving plasma.

For the results presented here, beam propagation over $\sim 1\,\mathrm{ns}$ was modelled through a $\sim 1\,\mathrm{mm}^2$ domain. The initial plasma temperature and density were given by $T_{e0} = 20\,\mathrm{eV}$ and $n_{e0} = 1.5\times10^{19}\,\mathrm{cm}^{-3}$ and applied fields ranged from $0-6\,\mathrm{T}$. The input laser had intensity $I_L = 3.9\times10^{14}\,\mathrm{Wcm}^{-2}$, wavelength $\lambda_L = 1054\,\mathrm{nm}$ and spot-size $\phi_{fwhm} = 10\,\mu m$. Simulations were performed primarily using CTC to explore parameter space and the changes caused by the Nernst effect. IMPACT was used to look for non-local and kinetic effects. Parameter space exploration was limited by the computational power required to simulate macroscopic volumes of plasma over nanosecond timescales using a kinetic code and by the magnetothermal [6] instability – an instability resulting from the interplay between Nernst advection and Righi-Leduc heat-flow – which leads to unstable temperature and field profiles.

4. Results and Discussion

The CTC simulations showed significant changes in laser focusing dynamics over a 2 mm distance when Nernst advection was enabled/disabled as shown in figure 1 where the initial magnetic field

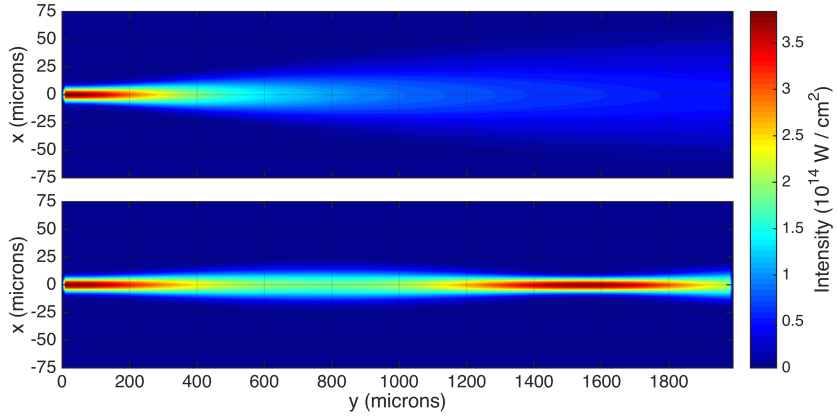

Figure 1. Changes to the intensity profile after ~ 350 ps. When the Nernst effect is enabled (upper), the laser defocuses whereas when it is disabled (lower), the beam demonstrates self-focusing due to plasma channel formation.

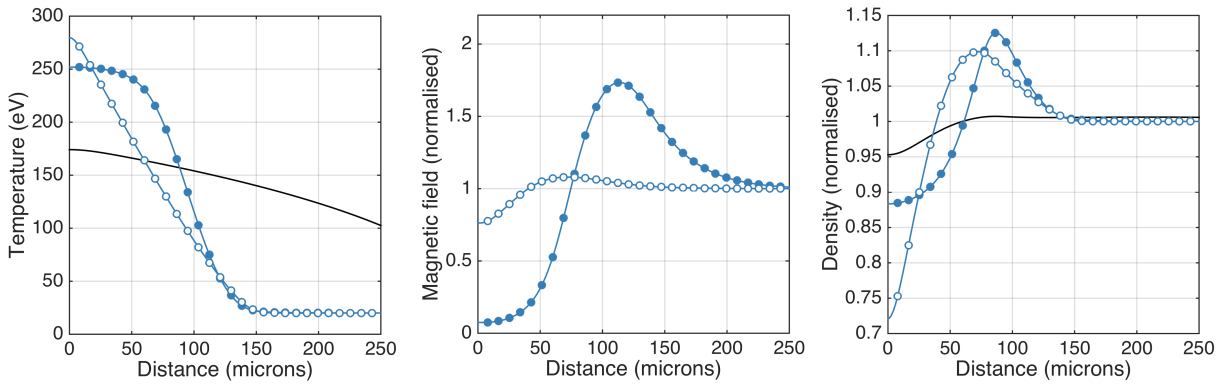

Figure 2. Temperature, density and B-field lineouts 1 mm into the domain with (closed circles) and without (open circles) Nernst advection. Unmagnetised case (solid line) shown for reference.

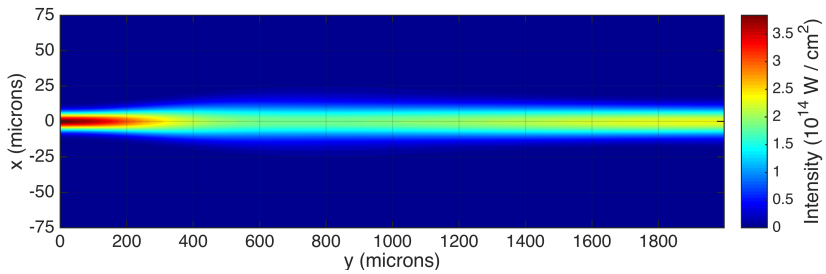

Figure 3. The intensity profiles from IMPACT (which includes Nernst advection) after $\sim$ 350 ps exhibit beam self-focusing behaviour.

was $B = 6$ T. Accounting for Nernst advection, after several hundred ps the laser defocuses as it propagates, whereas without Nernst advection, the beam continuously focuses and defocuses.

This is explained by observing the density, temperature and magnetic field profiles, transverse lineouts (1 mm into the domain) of which are shown in figure 2. Nernst advection (closed circles) leads to a rapid evacuation of 90% of the field from the central heated region after 350 ps compared with only $\sim$25% when it is not accounted for (open circles). The reduction in field leads to the central region becoming un-magnetised, giving unsuppressed heat-flow and a wide, flat temperature profile. This affects the thermal pressure, resulting in a significantly modified density profile – shallow and broad when the Nernst effect is enabled and narrow and deep when it is disabled. In the broad profile, the beam can defocus. In the narrow profile, the beam is continuously channelled.

Figure 3 shows the corresponding intensity profile from the VFP code (IMPACT) which

automatically includes Nernst advection. For these parameters, the kinetic approach results in beam channelling over the length of the domain unlike the defocusing behaviour shown in the fluid simulations including Nernst advection (Figure 1 (upper)). The change in focusing is likely due to non-local effects. Under these conditions, the transport in the heated plasma centre is non-local resulting in a decreased heat-flow in the regions of steepest temperature gradient. As shown in figure 4, CTC overestimates both the heat-flow out of the laser-heated region and the Nernst advection, resulting in a faster-than-expected cavitation of the B-field. To correctly match the non-local behaviour shown in the VFP code, CTC should make use of a flux limiter for the heat-flow and for the field advection. Choice of the correct limiter for Nernst field advection is the subject of ongoing work [10, 11].

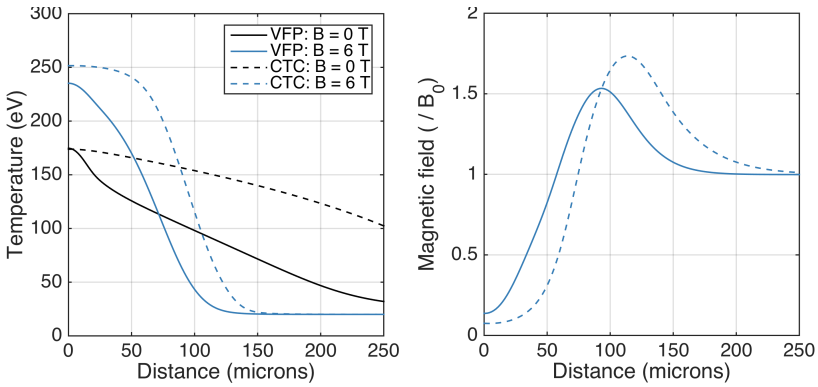

Figure 4. Temperature and B-field lineouts from CTC (dashed lines) and IMPACT (solid lines) 1 mm into the domain after ∼350 ps

5. Conclusions

Nanosecond pulse propagation through under-dense magnetised plasmas has been investigated computationally. Laser-defocusing resulting from the feedback of Nernst advected B-field onto the density profile have been observed using the fluid code CTC coupled to a paraxial wave solving module. Kinetic simulations using the VFP code IMPACT show that under these particular conditions, beam defocusing does not arise as readily and beam channelling is maintained. Previous work with VFP simulations [5] has shown significant changes to B-field and density in kinetic simulations due to the Nernst effect and therefore it is likely that non-local transport has lead to a shift in the threshold beyond which defocusing occurs at these parameters.

Acknowledgments

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