Magnetic Cavitation and the Reemergence of Nonlocal Transport in Laser Plasmas

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We present the first fully kinetic Vlasov-Fokker-Planck simulations of nanosecond laser-plasma interactions including self-consistent magnetic fields and hydrodynamic plasma expansion. For the largest magnetic fields externally applied to long-pulse laser-gas-jet experiments (12 T) a significant degree of cavitation of the B field (>40%) will be shown to occur from the laser-heated region in under half a nanosecond. This is due to the Nernst effect and leads to the reemergence of nonlocality even if the initial value of the magnetic field strength is sufficient to localize the transport.

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Recent interest in inertial confinement fusion (ICF) with the near completion of the National Ignition Facility (NIF) [1], and in magnetic reconnection in the novel high energy-density regime [2,3], has brought long-pulse laser-solid interactions back to the forefront of plasma physics. Magnetohydrodynamics (using Braginskii's classical transport theory [4,5]) is the most commonly employed theoretical model in the simulation of such experiments. The validity of this model to many of these experiments is poorly understood. This is of particular interest to indirect drive ICF [1]. In this scheme a deuterium-tritium fusion capsule is placed in a hohlraum (hollow chamber) of high-Z material. This hohlraum generally contains an initially homogeneous under-dense gas fill. The hohlraum wall and gas fill are heated by many long-pulse lasers creating a plasma. This emits x rays which drive the compression of the capsule. Whether the heat flow in the plasma is given by Braginskii's theory directly affects the uniformity of the hohlraum conditions which, in turn, can affect the drive uniformity of the capsule and so the fusion yield. The breakdown of classical heat transport in laser plasmas has been shown to be important in experimental measurements by Hawreliak *et al.* [6] and Gregori *et al.* [7] over nanosecond time scales.

Large magnetic fields—ranging from tens of kilogauss to a megagauss—have been inferred to be important in indirect drive ICF experiments [8,9]. Thus the effect of B fields on the heat transport in long-pulse laser-plasma interactions must be better characterized. Magnetic fields can act to suppress heat flow (by reducing the mobility of the heat-carrying electrons as the Larmor radius becomes smaller than the mean free path) and redirect it. However, this Letter is concerned with the fact that B fields may suppress the breakdown of Braginskii's transport theory. This has recently been addressed in an experiment relevant to a hohlraum gas fill [10]. The evolution of the magnetic field determines in which regions classical theory is valid at a given time. Under the conditions investigated by Froula *et al.* [10] the B field may evolve by advecting by "frozen-in" flow at the plasma's bulk flow velocity or by the Nernst effect [11] (with a velocity $\mathbf{v}_N = 2\mathbf{q}_e/5n_eT_e$ which is proportional to the heat flow [12]). The Nernst effect is often not considered in the modeling of long-pulse interactions and in principle could lead to a strong coupling between magnetic field advection and nonclassical transport. This coupling could arise because nonclassicality affects the heat flow and so the speed of the Nernst advection, which in turn modifies the B field and so determines the degree of the breakdown of classicality. The advection of B fields in laser-solid interactions—generated by the thermoelectric mechanism when the density and temperature gradients are not parallel—is crucial to determining the rate of reconnection in recent experiments [2,3]. The Nernst effect may lead to an enhancement of the magnetic field dynamics and so more reconnection.

In this Letter we present the first discussion of the time evolution of the feedback between magnetic field dynamics and nonclassical transport and will show that it is important to current experiments by simulating that of Froula *et al.* [10]. Others have considered how B fields affect nonlocality or how nonlocal effects modify B-field dynamics [13–16] but have not elucidated how these phenomena evolve when coupled together. In particular, Kho and Haines described how nonlocality modifies the rate of B-field advection. This was in a regime where the Hall parameter ($\omega\tau$) was relatively low (between 0.02 and 0.2) and so the change in the B-field strength as a result of the Nernst effect was not enough to significantly change the importance of nonlocality. In the results presented here, feedback occurs between nonlocality and B-field dynamics as the Hall parameter spans a larger range ($0 < \omega\tau < 20$). We will show that an applied magnetic field—which is initially sufficient to localize transport—is eventually expelled from the laser-heated region, leading to a reemergence of nonlocal transport. The effects of frozen-in flow and Nernst advection on the magnetic field profile are separated in order to determine which is more important. This novel investigation has been made possible by the development of IMPACT [17], the first two-dimensional Vlasov-Fokker-Planck (VFP) code including magnetic fields, hydrodynamic ions, and the ability to run over nanosecond time scales. This solves the VFP equation in two Cartesian spatial dimensions and three velocity space dimensions. The distribution function was expanded in the spherical harmonics in velocity space.

Bragisnskii theory assumes that the velocity distribution of the electrons is close to Maxwellian and from this derives the classical forms of the resistivity, thermoelectric tensor, and thermal conductivity ($\underline{\alpha}_c$, $\underline{\beta}_c$, $\underline{\kappa}_c$). Nonclassicality is a result of the distribution function f deviating strongly from Maxwellian. As a result the classical heat flow equation does not apply, i.e., $\mathbf{q}_e \neq -\underline{\kappa}_c \cdot \nabla T_e - \underline{\beta}_c \cdot \mathbf{j} T_e/e$. T_e and $\mathbf{q}_e$ are the electron temperature and heat flow; $\mathbf{j}$ is the current. Thus the VFP treatment described is necessary to capture nonclassical effects as it allows the distribution to deviate strongly from a Maxwellian. Note that the VFP treatment used here naturally recovers the classical Ohm's law and heat flow equation in the limit where f is Maxwellian.

We simulate the conditions of Froula *et al.*; an initially homogeneous nitrogen gas-jet plasma, with an electron number density of 1.5×10^{19} cm^{-3} and temperature of 20 eV, was heated by a laser [through inverse bremsstrahlung (IB)] with intensity 6.3×10^{14} W cm^{-2}, a wavelength of 1.054 μm, and a pulse length which rose linearly in intensity up to the maximum in 180 ps; the focal spot had a diameter of 150 μm. The initial applied magnetic field was set as either 0 T, 2 T, 4 T, or 12 T (12 T was the maximum field used by Froula *et al.* [10]). After 440 ps an instability was seen to develop in the magnetic field, possibly caused by Nernst advection of the magnetic field—results after 440 ps were not used. A magnetically driven instability has recently been observed experimentally [18] and so the instability we see in the simulations warrants further investigation. However, the important physical phenomena discussed in this Letter have emerged by 440 ps. Periodic boundary conditions were used—the simulation domain was large enough to contain the hot electrons with 2–3 times the thermal speed—these are the electrons responsible for most of the heat flow. The plasma was fully ionized at $Z = 7$.

Figure 1 shows the radial temperature profiles after 440 ps. In the field-free case there is preheat of the plasma outside the laser-heated region. This is an indication that Braginskii's theory has broken down due to nonlocal transport [19]. This is the most important cause of nonclassicality in long-pulse laser-plasma interactions and occurs when the scale length of the temperature becomes smaller than 0.01 times the mean free path of an electron moving at the thermal speed. The preheat is caused by those electrons moving at 2–3 times the thermal speed—which are responsible for most of the heat flow—streaming almost collisionlessly out of the laser-heated region and heating the plasma ahead of the main heat front. Figure 1 shows that the amount of preheat decreases as the magnetic field is increased; nonlocal transport is suppressed. B fields can

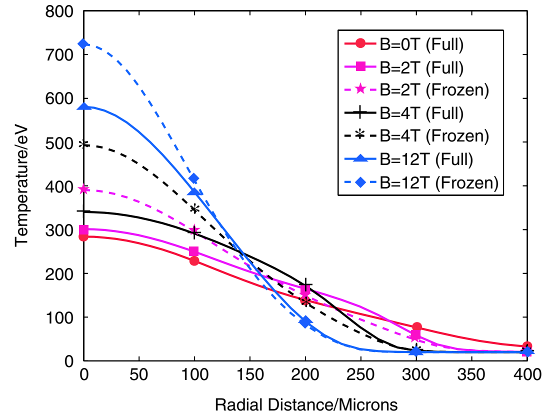

FIG. 1 (color online). Plasma temperature profiles after 440 ps with imposed B fields of 0 T, 2 T, 4 T, and 12 T. The lines labeled "full" use the full equation for $\partial \mathbf{B}/\partial t$. Those labeled "frozen" assume that the magnetic field is frozen to the plasma.

result in those electrons carrying most of the heat having gyro radii which are smaller than their collisional mean free paths. This reduces the mobility of the electrons and reduces the preheat.

The peak plasma temperature in the field-free case at 440 ps is 284 eV. At this temperature the mean free path of a thermal electron is 14 μm—a significant fraction of the laser spot size—thus leading to the observed nonlocal behavior. In the 12 T case the maximum temperature is 581 eV, giving a mean free path of 78 μm; however, the Larmor radius is 13 μm in the center of the spot. The Larmor radius is less than the mean free path so the B field 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 kinks in the temperature profiles for the 2 T and 4 T cases (between 200 μm and 300 μm from the spot's center) indicate that transport barriers are formed. This is confirmed by the magnetic field profiles in Fig. 2. In the 2 T and 4 T cases the magnetic field is largely cavitated in the laser-heated region and piles up several hundred microns away from the center of the spot. This accumulated

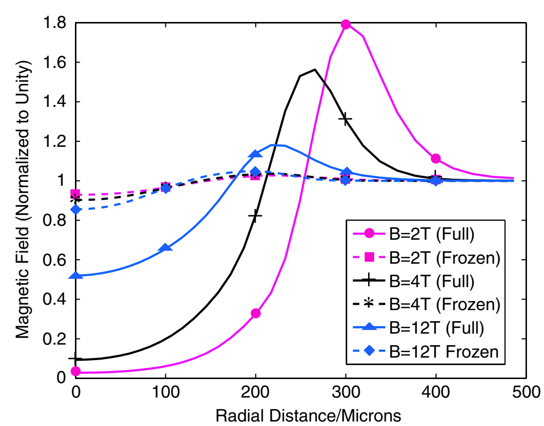

FIG. 2 (color online). Magnetic field profiles after 440 ps.

field forms the transport barrier—the consequent reduction in the thermal conductivity perpendicular to the field ($\kappa_\perp$) compared to that parallel to it ($\kappa_\parallel$), $\kappa_\perp \approx \kappa_\parallel/[1 + (\omega\tau)^2]$, slows thermal transport here.

The formation of this transport barrier can be understood by substituting the electric field from Ohm's law into Faraday's law. In the geometry considered here—cylindrically symmetric, magnetic field perpendicular to the gradients of the physical quantities—$\partial_t B + \nabla \cdot [(\mathbf{C} + \mathbf{v}_N)B] = 0$. $\mathbf{C}$ is the plasma flow velocity and $\mathbf{v}_N$ is the Nernst velocity, describing advection of the magnetic field by the Nernst effect (resistive diffusion may be neglected as the magnetic Reynolds number is between 10^4 and 10^5). The Nernst velocity is $\mathbf{v}_N = (\beta_\wedge/e\kappa_\perp B)\mathbf{q}_e$ [12,13]. Here $\beta_\wedge$ is the thermoelectric coefficient perpendicular to the B field and temperature gradient. Nonlocal transport modifies the transport coefficients and so $\partial \mathbf{B}/\partial t$—this is included in a VFP treatment. $\mathbf{v}_N$ is proportional to the heat flow. It can be expressed more simply as $\mathbf{v}_N = 2\mathbf{q}_e/5n_eT_e$, assuming that the electron-ion collisional mean free path is proportional to v^3 instead of v^4. This works well for the plasma conditions considered here [12].

If frozen-in flow is the only advection mechanism Fig. 2 shows that there is much less cavitation of the magnetic field from the laser-heated region in all cases. This variation of the importance of the Nernst effect and frozen-in flow is described by introducing the Nernst number:

$$R_N = \frac{v_N}{C} = \frac{1900}{Z \ln\Lambda_{ei}} \frac{T_e(\mathrm{keV})^{3/2}}{n_e(n_c)} \frac{\partial T_e(\mathrm{keV})}{\partial r(\mu\mathrm{m})} \frac{\beta_\wedge}{\omega\tau}. \quad (1)$$

Temperatures are measured in keV, distances in microns, and the electron number density in terms of the critical density for 1.054 μm light ($n_c = 10^{27}$ cm^{-3}). $\beta_\wedge$) is a function of $\omega\tau$ only and is described approximately as rising linearly from 0.05 at $\omega\tau = 0.01$, to 0.5 at $\omega\tau = 1$, before falling as $(\omega\tau)^{-1}$ to 0.01 at $\omega\tau = 100$. Equation (1) shows that frozen-in flow should become dominant as the magnetic field increases. This is due to the suppression of the heat flow by the B field. For 2 T, 4 T, and 12 T the values for R_N (at the point where the heat flow is largest at $t = 440$ ps) are 8, 5, and 0.3, respectively. The dominance of the Nernst effect under these conditions could be experimentally verified by a measurement of the transport barrier; it does not develop if only frozen-in flow is included. The Nernst number may be estimated for the gas fill of an ICF hohlraum. Taking typical values of: the density to be 0.025 times the critical density for 0.33 μm light, the temperature to be 5 keV and to change by 1 keV over 500 μm, and the magnetic field to be 1 T, then R_N is of order one. Hence, the Nernst effect should be included in modeling the advection of magnetic fields generated at the hohlraum wall (by the thermoelectric mechanism [9]).

The degree of nonlocality and the magnitude of the Nernst effect are coupled to one another. The cavitation of the magnetic field, caused by the Nernst effect, will increase the importance of nonlocal transport. Additionally, nonlocality has been shown to significantly affect the magnitude of Nernst advection [13,14]. Comparison of the curl of the electric field as predicted using Braginskii theory with that produced by the VFP code reveals that the VFP code predicts a reduction in the rate of advection of the magnetic field at 250 ps—when the 2 T and 4 T fields have cavitated by about 50% from the central region. In the 2 T case it is found that the VFP result is 5 times smaller than the classical prediction; for a 4 T imposed field the VFP result is 1.3 times reduced.

Figure 3 shows the radial heat flow for each magnetic field and those calculated by inserting the instantaneous temperature profiles and currents at 440 ps into the classical heat flow equation. The radial heat flow is classical in the 12 T case—the agreement with Braginskii's transport theory gets progressively worse as the imposed magnetic field strength decreases. Nonlocality tends to cause the heat flow in the laser-heated region to be less than that predicted by classical theory as the hot electrons have flowed collisionlessly away from this region; heat flow is increased far from the laser where these electrons preheat the plasma. Figure 4 shows the more marked discrepancy between the azimuthal (Righi-Leduc) heat flows from the simulations compared to those expected classically [13,14]. Again, as the magnetic field strength decreases the agreement with Braginskii theory deteriorates. Even in the 12 T case there is a discrepancy from the Braginskii theory.

Figure 5 shows the time evolution of the deviation of the radial heat flow away from Braginskii theory for each imposed magnetic field; the deviation is defined as $\Delta q_r = (q_r - q_r^B)/q_r^B$, where q_r is the peak instantaneous radial heat flow from the VFP code and q_r^B is the instantaneous peak as predicted classically. The discrepancy decreases as the imposed magnetic field is increased; this is as expected. More surprisingly, the general trend is for the agreement to be poor initially, improve, and then deteriorate with time. Up to 20 ps, classical transport does not work well for any

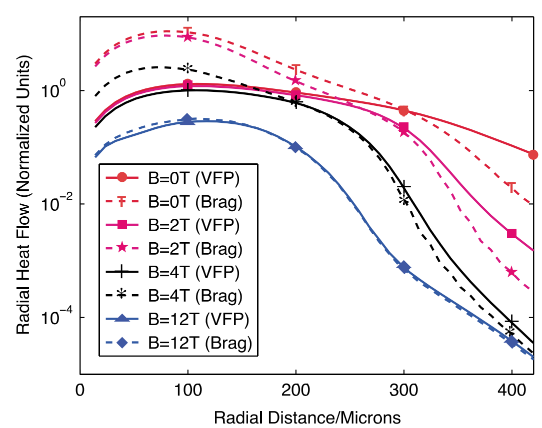

FIG. 3 (color online). The radial heat flows after 440 ps (normalized to the free-streaming limit for the background 20 eV plasma). "VFP" refers to those calculated by the VFP code, "Brag" to those predicted by classical transport theory.

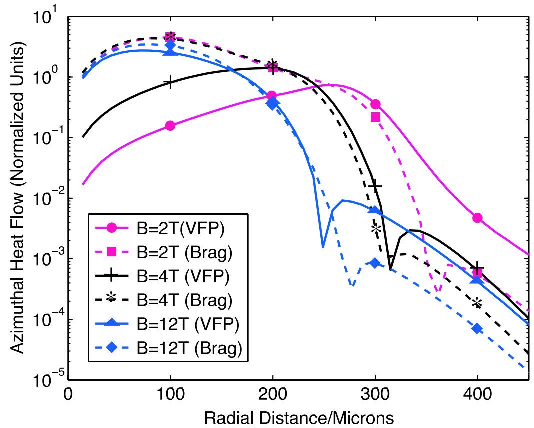

FIG. 4 (color online). The radial profile of the azimuthal heat flow (normalized as in Fig. 3).

applied B field. The transport is still relatively local (compared to later on)—the maximum mean free path here is 1.7 μm, as compared to scale lengths of 100 μm. The breakdown of the Braginskii theory early on is caused by the inverse bremstrahhlung (IB) heating causing the distribution function tend to a super Gaussian ($f \propto e^{(-v/v_T)^5}$) [20]. The IB heating rate, $\partial T_e/\partial t \propto T_e^{-3/2}$, is greatest at the start of the simulation when the plasma is coldest. The effect of IB on transport has previously been seen in unmagnetized plasmas ablating from solids [21]. Later on nonlocality becomes more important. This can be explained by considering the scalings of the mean free path, $\lambda_c \propto T_e^2/n_e$, and larmor radius, $r_g \propto T_e^{1/2}/B$. As the plasma is heated by the laser, the electron number density decreases due to plasma expansion and the magnetic field cavitates causing the mean free path and gyro radius to get longer.

Although the 12 T case is almost classical at 440 ps, with further heating, plasma expansion and cavitation of the magnetic field would eventually cause Braginskii theory to break down completely. If the magnetic field in the 12 T simulation continues to cavitate at the rate occurring at $t = 440$ ps then the B field should be completely expelled after 1 ns. This agrees qualitatively with the results of Froula *et al.* [10]. The agreement with Braginskii theory (shown in Fig. 3 in their paper) does seem to get worse beyond 1 ns under identical conditions to those investigated here, with a 12 T imposed B field. Also, the gradient of the temperature is steeper in the experiment after 1 ns than given by a simulation including only frozen-in flow; this may be an indication of the transport barrier and so the importance of the Nernst effect. Note that Froula's simulations used LASNEX which uses classical transport.

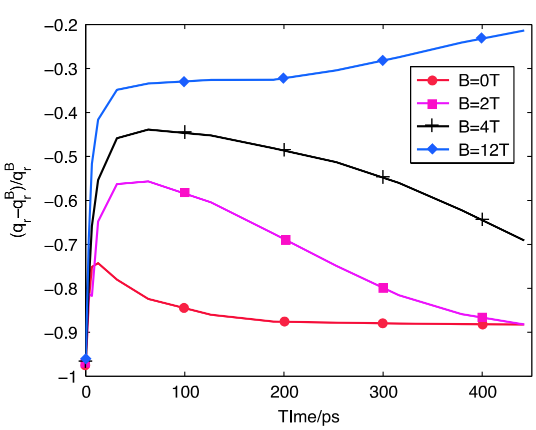

FIG. 5 (color online). Time evolution of the relative discrepancy of the radial heat flow away from the Braginskii theory.

The physical processes elucidated here may play an important role in the gas fill in a hohlraum or magnetic reconnection in solid-target experiments. It is essential for the modeling of these to include the Nernst effect and nonlocal transport. The enhanced magnetic field advection due to Nernst will act to increase the rate of reconnection over that expected from frozen-in flow based models. Finally, although a large magnetic field can localize transport, the Nernst effect can rapidly advect it, causing the unexpected reemergence of nonlocality.

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