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LETTERS

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Particle simulation of non-neutral plasma behavior

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It is demonstrated that particle-simulation techniques can explore a broad range of dynamical behavior exhibited by non-neutral plasmas. New features isolated by this approach include collective relaxation through generation of core and halo populations; self-organization without radial transport as the plasma is cooled; spontaneous generation of solitonlike structures upon axial reflection from the external confining potential.

The properties of non-neutral systems confined in traps have been elucidated in several elegant experiments[1,2] in recent years. As plasmas, these systems have the virtue of being confinable for extremely long times because conservation laws[3] place strict bounds on particle loss. Most of the detailed experiments in this area have explored the quasistatic evolution of a well-confined configuration near thermal equilibrium. The transient, nonequilibrium phase during which the plasma achieves its near-equilibrium profiles is dominated by strong nonlinear wave–particle interactions. These processes are difficult to probe experimentally and are not easily described by analytical methods. However, advances in experimental sophistication (e.g., new ion machines coming on line) and increasing interest in this field are naturally leading to the consideration of the nonlinear collective interactions supported by these systems. Consequently, it is of interest to develop computational methods that allow the investigation of the fast time-scale, nonequilibrium properties.

In this Letter, we report the results of a systematic application of particle-simulation techniques to explore the broad range of behavior exhibited by non-neutral plasmas. It is demonstrated that this computational technique (also known as the particle-in-cell method[4]) permits the detailed study of a broad range of dynamical features, including maintenance of a Vlasov equilibrium; cross-field transport by neutral collisions; relaxation by collective interactions between core and halo populations; development of self-organization as a confined plasma blob is cooled externally. It is our objective here to highlight the broad range of dynamics that can be explored and to stimulate new theoretical studies and experiments. Future publications will address, in depth, each of these topics.

The particle simulation code used in this study is a generalization of a code previously developed[5] to investigate heating of neutral plasmas by externally launched radio frequency waves. It consists of an electrostatic, bounded, magnetized two-and-one-half-dimensional system (follows two spatial coordinates and three velocities for each particle). The magnetic field is aligned with the z direction and confines particles along the x direction (the radial direction in a cylindrical experiment), with the y coordinate ignorable (x, y, and z are orthogonal Cartesian coordinates). As is usual in such studies, we normalize lengths to the initial Debye length, λ_D, and velocities to the initial thermal velocity, $\bar{v}$. Walls located at $x=\pm L_x$ make the plasma bounded in that direction. The potential may be prescribed as a function of z on those walls, and diverse experimental situations can be reproduced. We have explored two such schemes: (1) a slab equivalent of a Penning trap in which the vacuum potential is approximately of the form $\phi(x,z)\simeq\phi_0(z^2-x^2)/(L_z^2-L_x^2)$, with ϕ_0 a controllable parameter and L_x and L_z the half-lengths of the system along x and z, respectively; and (2) localized potential hills well separated along the z direction, in a manner analogous to the traps developed[1] at the University of California, San Diego. The capability of turning on and off these confining hills permits the investigation of plasma expansion and recapture with this code. Typically the numerical studies use more than 16×10^3 finite size particles, with a minimum of 64 computational grids in the x direction and 512 along z (of course, larger numbers are used when needed to resolve the dynamics of a given situation). For the results reported here, the strength of the confining magnetic field satisfies $\Omega_e/\omega_{pe}\geqslant2.5$ with Ω_e the electron gyrofrequency and ω_{pe} the electron plasma frequency. This choice provides good radial confinement (below the Brillouin limit[6]) and does not require an excessive number of computation steps (the detailed electron gyromotion is calculated with a resolution of $\Omega_e\,\Delta t\leqslant\frac{1}{6}$, which is to be contrasted with the guiding-center simulations[7] previously used to explore these systems).

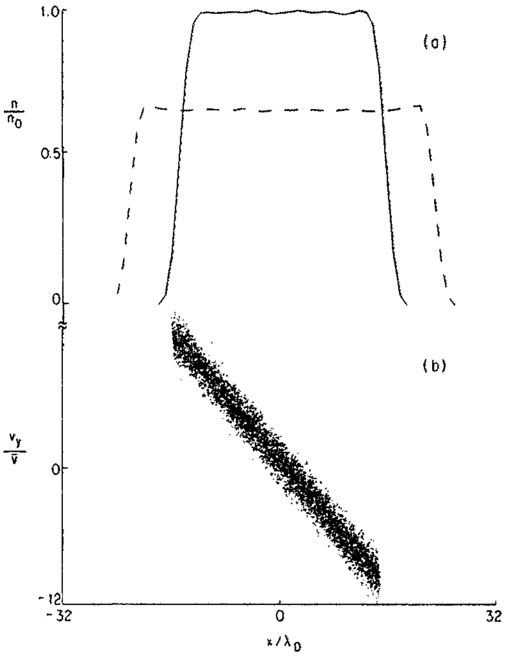

FIG. 1. Demonstration of quiet equilibrium of a simulated non-neutral plasma after a time $t=435\ \Omega_e^{-1}$. (a) Density profile across the magnetic field. The solid curve is without collisions and the dashed curve shows the effect of cross-field transport due to neutral collisions. (b) Self-consistent velocity profile demonstrating the equilibrium electric field $E_y \propto x$. Spatial scale is Debye length λ_D and the velocity scale is thermal velocity $\bar{v}$.

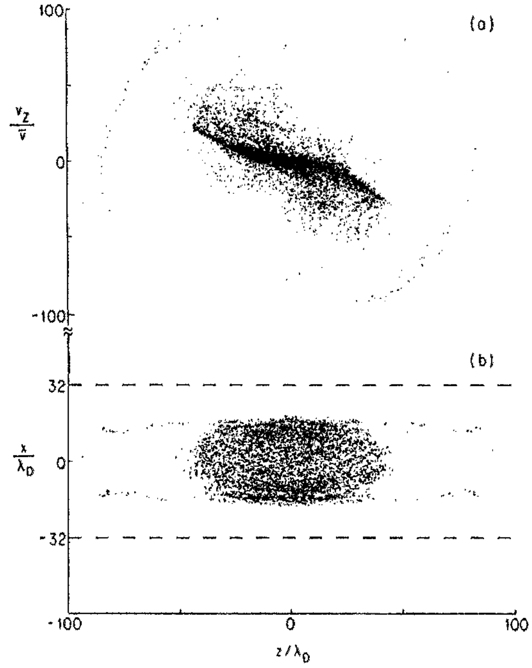

FIG. 2. Collective relaxation of a nonequilibrium initial configuration in a Penning trap. (a) Axial phase space at $t=192\ \Omega_e^{-1}$ shows a high-density "core" of slow particles interacting with an energetic "halo" population. (b) Configuration space shows the "core" population attains a football shape and the energetic "halo" forms outer rails. Dashed lines indicate location of walls.

The persistence of a quiet Vlasov equilibrium is demonstrated in Fig. 1. These results correspond to a pure electron plasma column infinitely long in the z direction (no axial potential trap is applied). The self-consistent plasma density profile achieved is shown in Fig. 1(a). As is characteristic[8] of these systems, it exhibits a nearly square profile with a sharp edge on a scale of a Debye length. The self-consistent drift profile (rotation profile in a cylinder) is shown in Fig. 1(b). It shows that $v_y \propto x$, and hence the radial electric field $E_x \propto x$, as expected from the flat region in Fig. 1(a), i.e., this is the slab analog of a rigid rotor equilibrium in a cylinder. Because the y coordinate is ignorable in the code, flute instabilities are absent here, so, in practice, we achieve a projection to lower dimensionality of a stably rotating column. These features have been observed to hold for times $t > 400\ \Omega_e^{-1}$. The ability to correctly simulate such equilibria permits the exploration of nonlinear plasma waves, cyclotron resonance,[9] and Brillouin limit.[2]

Next we highlight the collective relaxation of a nonequilibrium initial distribution suddenly placed in a Penning trap, i.e., the opposite of the quiet start shown in Fig. 1. We have identified that the dominant feature in this complex evolution is the self-consistent development of a high-density (core) population that exhibits fluidlike behavior, and surrounded by a tenuous population of energetic (halo) particles. The role of the core population is to cancel the external parabolic well of the Penning trap, so that a very small axial electric field results. However, the effectiveness of this cancellation decreases with x, hence at larger x, a larger fraction of the particles belong to the halo population [the partition and radial distribution of these populations are determined by the ratio of the length in the z direction to that in the x direction (aspect ratio)]. The axial phase space (v_z, z) at time $t=192/\Omega_e$ is shown in Fig. 2(a) for an aspect ratio of 3. The core corresponds to the high-density (darker) region of slow particles while the halo is the encircling ring. The core executes long-lived breathing oscillations on the ω_{pe} time scale. The role of these collective interactions is to generate a time-dependent balance between the internal self-repulsion and the external potential well. The configuration-space shape of the confined plasma is shown in Fig. 2(b). The core particles achieve a football-like shape bounded by a rail-like structure associated with the energetic halo particles.

To investigate the long-time behavior, we introduce an external drag force (i.e., $\nu m\mathbf{v}$). This process extracts kinetic energy (i.e., it cools) and simultaneously induces cross-field transport that results in the expansion of the plasma, as shown by the dashed profile in Fig. 1(a). The equivalent expansion process caused by collisions with neutral particles has been studied experimentally[10] in considerable detail. The isotropic drag slows down the energetic halo particles and simultaneously damps the collective oscillations of the core. In the time-asymptotic limit, the elongated edge rails in Fig. 2(b) coalesce, and the core population fully equilibrates with the external trap potential.

To explore the development of self-organization as the kinetic energy of the particles is reduced further, we apply

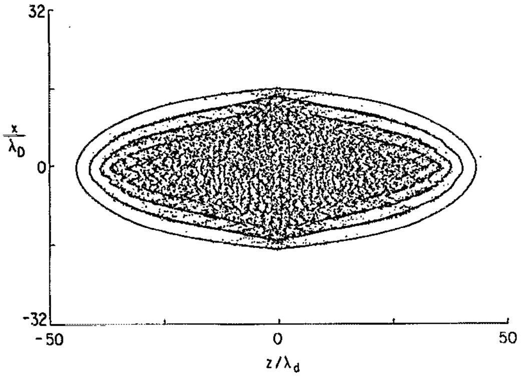

FIG. 3. Development of self-organization in configuration space, as the system shown in Fig. 2 is externally cooled by a factor of 2×10^{-7}. The ring structure develops sequentially from the outermost region inward.

a drag force only in the (x,z) plane (anisotropic friction) in order to prevent the radial expansion [documented in Fig. 1(a)], which ultimately would cause the loss of the entire plasma blob to the walls. Figure 3 illustrates the development of spatially correlated rings as the kinetic energy is lowered; they grow sequentially from the outside toward the interior and are formed without the particles ever crossing the magnetic field. Essentially, axial motion results in locally trapped particles. A detailed sampling of the particles found near the center of the blob shows that they tend to organize in parallel planes perpendicular to the magnetic field, but the outer ones form rings having the shape of a football, as required to match the external trap potential. Analogous structures have been observed in delicate laser-cooling experiments,[2,11] where they have been interpreted as liquid crystals.

Finally, we show an example of a ubiquitous feature that we have identified in several different studies, but that appears most clearly during the free expansion and subsequent recapture (in a longer cell) of a non-neutral plasma. The phenomenon takes the appearance of a solitonlike object formed when a group of particles approaches its external turning point. Spontaneously, the particles are momentarily compressed between the external potential hill and another group of slower, trailing particles, moving toward the end along the z direction. Once the structure is generated, it moves through the plasma in the form of a potential jump, which continuously accelerates slow particles that reflect from it; a behavior related to the double layers studied[12] in neutral plasmas. A characteristic pair of such objects, moving toward each other, is illustrated in Fig. 4. The instantaneous phase space is shown in Fig. 4(a), while the on-axis ($x=0$) density and self-consistent potential are shown in Fig. 4(b). Multiple encounters of the localized structures result in a steady state consisting of a relatively cold core and an energetic halo, which in this configuration is present for all x, and not just at the edge.

In summary, it has been demonstrated by key nontrivial examples that particle-simulation techniques can explore a broad range of properties displayed by non-neutral

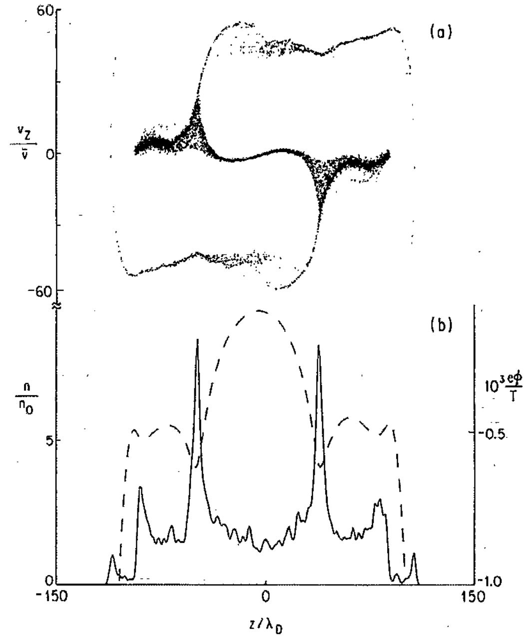

FIG. 4. Example of the spontaneous formation of solitonlike structures upon reflection from the external trap potential. (a) Instantaneous phase space showing the concentration of slow particles and the generation of reflected particles away from the external potential hill. (b) The corresponding axial density profile at $x=0$, and self-consistent axial potential. At $t=0$, the system had an extent of $100\lambda_D$ with temperature T and density n_0.

plasmas. Two interesting new features have been documented here: the development of self-organization without cross-field transport, and the spontaneous generation of solitonlike structures upon reflection from the confining potential. Detailed exploration of the properties briefly outlined here promises to yield new insight into the collective response of non-neutral plasmas.

ACKNOWLEDGMENT

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