Collective Enhancement of Radial Transport in a Nonneutral Plasma

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Experimental evidence is presented showing that collective effects may enhance the radial transport produced by an asymmetric perturbing field applied to a rotating nonneutral plasma column. The field asymmetry drives an asymmetric plasma mode and the mode field produces additional transport. Of particular interest for confinement systems is the existence of a zero-frequency plasma mode which can be driven by static field asymmetries. Applications to tandem mirrors are discussed.

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This paper deals with the radial transport of particles in a rotating plasma column confined by an axial magnetic field. Experimental evidence is presented that transport produced by field asymmetries may be enhanced by collective resonance. The experiments are performed on a nonneutral plasma column[1,2] but the enhancement mechanism is quite general and may be applicable to a variety of rotating plasma systems. For example, under certain operating conditions a collective resonance may enhance the radial transport of ions in the central cell of a tandem mirror. In this case the field asymmetries are the quadrupole magnetic fields associated with the end plug mirrors.

The theory of resonant particle transport[3] was originally developed to deal with radial ion transport in nonaxisymmetric tandem mirrors[4] but can also be applied to nonneutral plasmas.[2,5] The elementary radial step in this transport process occurs when a particle passes through the region of field asymmetry and experiences a radial drift (a grad$B$ drift for a magnetic field asymmetry and an $\vec{E}\times\vec{B}$ drift for an electric field asymmetry). The name resonant particle transport derives from the fact that the dominant contribution to the transport is made by the particles which satisfy a resonance condition between their axial bounce motion and their rotational motion; these particles can make many successive steps of the same sign. The theory includes the effect of these bounce-rotation resonances and of collisions, but not collective effects.

To understand how collective effects may enhance the transport, we first note that a plasma column normal mode of the form $\phi=\phi_1\cos(kz)\times\cos(l\theta-\omega t)$ with nonzero axial and azimuthal wave numbers (k,l) will produce a radial $\vec{E}\times\vec{B}$ drift and a resultant resonant particle transport. Of particular interest for confined plasmas is a mode with zero frequency. Such a mode propagates backwards on the rotating column so that it has zero frequency in the laboratory frame. Since it has zero frequency, the mode can be driven secularly to large amplitude by static field asymmetries[6] and the large mode field can then produce enhanced transport.

This enhancement has been considered previously for toroidal systems[7] but only recently for linear systems.[5,8] In a toroidal system, the plasma rotation frequency changes self-consistently at a rate fast compared with diffusion. The rotation frequency approaches certain stable values[9] and for these values the transport enhancement is only modest.[10] In a pure electron plasma column the radial electric field, and hence the rotation frequency, are set by the zero-order electron number density and cannot be appreciably modified by a small rearrangement of the system. In tandem experiments it may be that substantial steady-state radial electric fields are maintained by the rf heating or boundary conditions, or both. These effects are not yet understood in detail.

For maximum enhancement of the transport, it is required that ω, k, and l of the field asymmetry satisfy the dispersion relation for the mode of interest. For the case of a tandem mirror, the mode might be a drift wave with $l=2$ and $k=\pi/L$ where L is the plasma length. The azimuthal wave number is determined by the fact that the perturbing field is quadrupole and the axial wave number by the fact that the two quadrupole fields at either end of the central cell are rotated by $\pi/2$ relative to one another. By using the approximate dispersion relation $\omega-l\omega_R=l\omega_e^*$, where ω_R is the rotation frequency and ω_e^* is the diamagnetic drift frequency, we see that the condition for an $\omega=0$ model is $\omega_e^*+\omega_R=0$. Interestingly, this condition is satisfied when the electron density and the potential associated with the radial electric field satisfy the relation for electrostatic confinement of electrons, $n(r)=n_0\exp[e\phi_0(r)/T_e]$ where n_0 is a constant and T_e is the electron temperature.

To demonstrate experimentally the enhancement of radial transport due to collective effects, we have used a pure electron plasma device.[1] The extremely long confinement times[2] of these devices make them especially suitable for controlled studies of induced radial transport since the background transport is small. Radial confinement is provided by a solenoidal magnetic field while the axial confinement is provided by electrostatic potentials at the solenoid ends. Typical parameters are $n_e = 10^7$ cm^{-3}, $T_e \simeq 1$ eV, $B_0 = 250$ G, and a plasma lifetime exceeding 10^5 axial bounce times.

Our basic experimental sequence is a modification of techniques described in detail elsewhere.[1,2] The conducting wall of the experimental device, shown schematically in Fig. 1(a), is divided into rings of various lengths and some of the rings ($S1$,$S2$) are divided azimuthally as well. Rings A and B are normally held at a large negative potential and the remaining rings are grounded. To start a cycle, ring A is gated to ground potential allowing electrons from the negatively biased spiral filament to fill the device. Ring A is then returned to negative potential thus producing a confined plasma sample. A nonaxisymmetric perturbation is then applied by placing a signal of frequency ω on two 180° azimuthal sectors of ring $S1$ in a push-pull fashion. The reasons for employing this type of perturbation are discussed below. After a variable time, the perturbation is turned off and the electrons are dumped by grounding ring B. Electrons are collected by a radially moveable probe and the line-integrated density is obtained. Since the shot-to-shot variation of the plasma density is less than 1%, radial density profiles can be constructed by changing the probe position between shots [Fig. 1(c)]. If the perturbation is applied only on alternate shots, the collected signal may be analyzed with a lock-in amplifier and the density change $\delta n(r)$ due to the perturbation obtained [Fig. 1(b)].

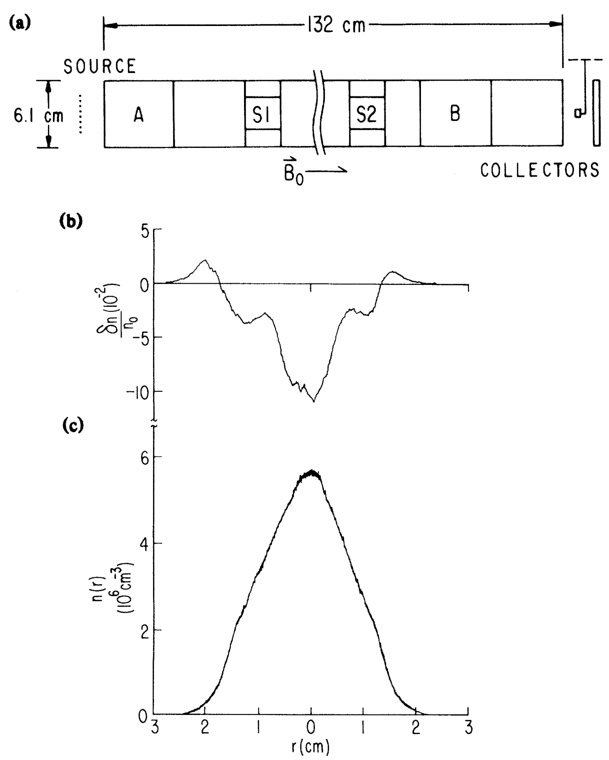

FIG. 1. (a) Simplified schematic of experimental device. (b) Normalized change in density vs r due to application of an electrostatic field asymmetry. Here $n_0 = n(r=0)$. (c) Typical density profile constructed from many shots.

For the purposes of this demonstration we have used electrostatic rather than magnetostatic field asymmetries.[11] Several experimental advantages are realized through this choice. As a result of the difference in characteristic time constants, one can switch an electrostatic perturbation on and off much faster than a magnetic perturbation. This characteristic also allows us to apply the electrostatic perturbation at a nonzero frequency ω. This is important since for a pure electron plasma $\omega = 0$ will not always be a normal mode frequency of the plasma. While it is possible in principle to adjust the plasma parameters so that $\omega = 0$ is a normal mode frequency, changing ω allows one to compare the on-mode and off-mode cases without changing the plasma sample. Finally, use of a nonzero ω allows one to monitor the time evolution of the normal mode amplitude at ring $S2$ with standard receiver techniques not available for $\omega = 0$. This information is needed if detailed comparisons between theory and experiment are to be made.

Figure 2 shows the perturbation-induced density change at the center of the plasma and the power received on ring $S2$ as a function of applied frequency. We note that the presence of the three normal modes indicated by dotted lines is accompanied by an increase in $\delta n/n_0$ by as much as a factor of 3. In this case we have taken care that the modes launched remain almost linear during the experiment and that the conditions for plateau regime transport are satisfied. In cases where these constraints are lifted, we have observed up to a 25-fold increase in $\delta n/n_0$ at frequencies where normal modes were present.

The three modes indicated in Fig. 2 have been identified by comparison of the mode ω, k, and l with numerically generated theoretical dispersion

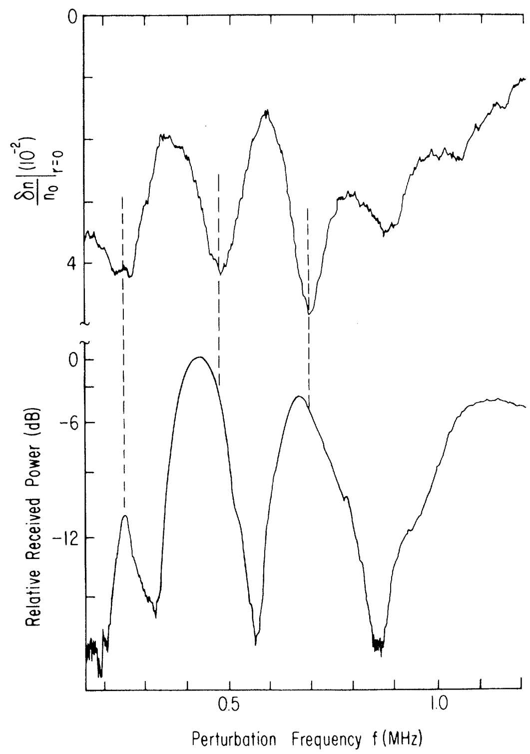

FIG. 2. The normalized density change at $r = 0$ and received wave power for a constant amplitude perturbation at varying frequencies. Dotted lines show correlation between increases in $\delta n/n_0$ and the presence of excited normal modes.

curves. Experimentally l is determined by comparing signal levels on the different sized azimuthal sectors of ring $S2$. The axial wave number k is limited to integer multiples of π/L and can be further identified by measuring the phase between the launched and received signals. In this case all three modes have azimuthal wave number $l = 1$. With the nomenclature of Prasad and O'Neil[12] they are, from left to right, $k = \pi/L$, $m = -1$ plasma mode, $k = \pi/L$ diocotron mode, and $k = 2\pi/L$, $m = -1$ plasma mode. Further modes occur at higher frequencies but in this case several modes overlap making correlation to changes in $\delta n/n_0$ difficult.

Interestingly, we have also experimentally verified the theoretical prediction that certain plasma modes produce a net inward transport of plasma. These modes rotate in the same direction as the plasma column but at a faster rate. The inward transport of particles can be simply understood by noting that these modes exert a forward azimuthal drag force F on the column and this produces a radial drift inward. Conversely, modes rotating slower than the plasma column or in the opposite direction exert a backward drag force on the column and produce an outward transport of particles.

In summary, collective effects can enhance radial transport in confined, rotating plasmas subject to field asymmetries. This enhancement was demonstrated experimentally in a pure electron plasma with applied electrostatic asymmetries. This type of enhancement may prove relevant to other rotating plasma systems including tandem mirrors.

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