Observation of an Induced-Scattering Instability Driven by Static Field Asymmetries in a Pure Electron Plasma

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We show experimentally that the presence of static field asymmetries can affect the stability of a confined pure electron plasma. A new induced-scattering instability is observed whose threshold and growth rate depend on the amplitude of static field asymmetries. The presence of the instability is associated with a twelvefold enhancement of radial plasma transport. The qualitative features of this instability are found to be in agreement with recent theoretical work.

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Nonneutral plasmas have been studied for some time, both theoretically and experimentally.[1] Much of the recent work has focused on the confinement of pure electron plasmas in a particularly simple geometry.[2-10] The confinement geometry typically consists of a conducting cylinder which is immersed in a uniform axial magnetic field and is divided into at least three sections. The end sections are biased negatively to provide axial confinement for the electrons which are held in the grounded central section. If the apparatus is perfectly axisymmetric, then the confinement of such a plasma is assured by conservation of angular momentum and energy.[3] In the absence of external torques, the mean square radius of the plasma is constant. Experimental plasmas, however, are not free from external torques. Previous experimental studies[4,5] have found that collisions of electrons with neutral gas atoms produce an expected expansion of the plasma for neutral pressures $P \gtrsim 10^{-7}$ Torr. At lower neutral pressures, the confinement time is significantly shorter than expected from electron-neutral collisions. This "anomalous" transport is probably due to small electric or magnetic field asymmetries associated with fabrication imperfections.[5] These background field errors can transfer angular momentum to the plasma and cause it to expand. When care is taken to avoid construction asymmetries, the confinement improves.[6] When additional asymmetries are deliberately applied to the plasma, additional radial transport is observed.[7]

In this paper we show experimentally that field asymmetries can also affect the *stability* of a nonneutral plasma. In particular, we report on a new wave instability whose qualitative features are in agreement with the recent theoretical work of Crawford and co-workers.[8,9] These authors show that, for a rotating plasma, a static field asymmetry can act as a pump for wave instabilities. The two instabilities they consider are the decay instability and the induced-scattering instability. For the decay instability, the field asymmetry excites two unstable daughter modes. These modes (one positive energy and one negative energy) must have frequencies that satisfy a resonance condition $\omega_1 + \omega_2 \approx 0$. For the induced-scattering instability, one of these modes is in effect replaced by resonant particles. These particles have axial velocities close to the phase velocity of the beat wave formed by the remaining mode and the pump. For this process, only one unstable mode is produced and, since generally a broad range of particle velocities is present, no sharp frequency resonance condition is required. Both types of instability allow field asymmetries to transfer angular momentum to the plasma and thus are associated with enhanced radial expansion.

In this paper we report the observation of an induced-scattering instability. The experiments are performed on the device shown schematically in Fig. 1. The device is similar to ones described in detail elsewhere.[2,4] The entire apparatus is immersed in a uniform axial magnetic field which provides radial confinement. The cylindrical conducting wall of the device is divided into rings of various lengths and two of the rings (S1,S2) are divided into four 90° azimuthal sectors as well. Rings A and B are normally held at a large negative potential and the remaining rings are usually grounded. The machine operation follows an inject-hold-dump cycle. To start a cycle, ring A is switched to ground potential allowing electrons from a negatively biased spiral filament to fill the device. Ring A is then returned to a negative potential, thus producing a confined pure electron plasma. While the plasma is confined, the various rings between A and B can be used to monitor wave activity in the plasma or to apply electric fields to the plasma. After these measurements and procedures are completed, the electrons are dumped axially by grounding of ring B.

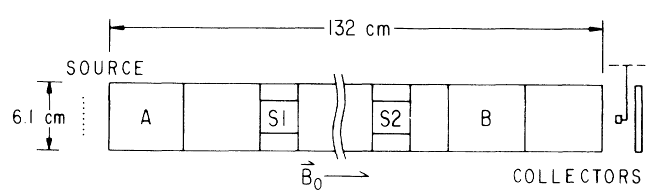

FIG. 1. Schematic of experimental device.

Electrons are collected either by a radially movable probe (giving the line-integrated density at a particular radius) or by a plate (giving the total number of electrons in the device). Typical parameters are $n_e \simeq 7\times10^6$ cm^{-3}, $T_e \simeq 1$ eV, $B_z = 350$ G, vacuum pressure $= 10^{-10}$ Torr, and plasma lifetime $\simeq 500$ ms.

Several features of the instability which we observe identify it as due to induced scattering: (1) Only one growing mode is observed.[11] The mode is a standing electron plasma wave with azimuthal and axial wave numbers $l_m = 0$, $k_m = \pi/L$, where L is the length of the plasma column. The wave becomes unstable when a threshold condition is exceeded and eventually saturates after growing 40–50 dB. (2) The threshold and growth rate of the instability depend on the amplitude of static field asymmetries. The growth rate scales with the asymmetry amplitude in a manner consistent with theory. (3) The field asymmetry is observed to *stabilize* the mode if the asymmetry azimuthal mode number is restricted to $l_a = 1$. This behavior is predicted by theory. (4) The presence of the instability is associated with an enhanced level of radial transport. This is significant since an azimuthally symmetric wave ($l_m = 0$) does not by itself produce a radial drift of particles. (5) The instability does not require any particular tuning of conditions, but occurs over a broad range of plasma parameters [$n_e \simeq (0.8-8)\times10^6$ cm^{-3}, $B_z = 85$–675 G]. This would not be the case for the decay instability because the mode frequencies entering the resonance condition generally depend on the plasma parameters in a complex manner.

According to theory,[9] the time evolution of the observed mode is governed by the equation

$$dA_m/dt = [-|\gamma_m| + \Gamma |A_w|^2] A_m, \tag{1}$$

where γ_m is the mode damping rate in the absence of field asymmetries, A_m is the mode amplitude, A_w is the field-asymmetry amplitude at the wall of the device, and Γ is the total beat-resonant coupling coefficient. When the bracketed term is positive, the mode is unstable and grows exponentially. Assume for now that $\Gamma > 0$. Since any real plasma device will have small asymmetries due to construction imperfections, A_w is always nonzero. In our experiments these small asymmetries are sometimes large enough to exceed the threshold condition and then the instability appears as soon as the plasma is captured. Such a case is shown by curve *a* in Fig. 2. The wave starts to grow immediately after the injection gate is closed ($t = 0$). We may prevent the mode growth, in accordance with Eq. (1), by increasing the value of $|\gamma_m|$. One way to do this is by placing a resistive load between a ring within the containment volume and ground. Wall currents induced by the wave flow through this load and dissipate wave energy. This creates additional mode damping beyond that produced by wave-particle effects. The stabilizing effect of such an addition is shown by curves *b* and *c* in Fig. 2. Curve *b* shows that the plasma remains stable until the resistive load is removed at the time indicated by the lower arrow, after which time the wave begins to grow. For curve *c*, the instability is quenched by the addition of the resistive load at the time indicated by the upper arrow.

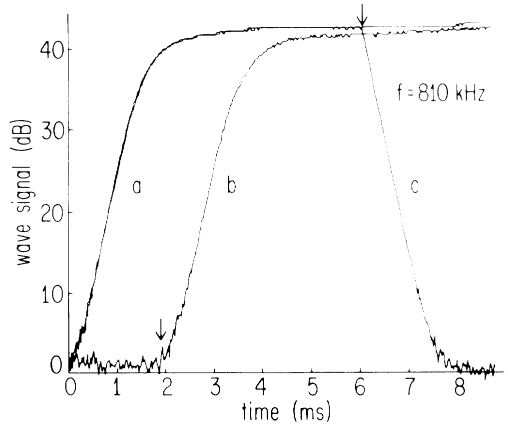

FIG. 2. Time evolution of unstable mode driven by background field asymmetries. (Curve *a*) Mode grows immediately upon creation of plasma. (Curve *b*) Mode remains stable until damping is decreased and threshold is exceeded. (Curve *c*) Unstable mode is stabilized by the increasing the mode damping. Each curve is from a single plasma shot.

Equation (1) also predicts that a stable plasma will be destabilized by an increase in the magnitude of the field asymmetry. To demonstrate this effect we adjust the injection conditions to create a stable plasma (i.e., a plasma with mode Landau damping large enough to prevent the spontaneous growth shown in Fig. 2). Shortly after injection ($t = 5$ ms) we apply a static field asymmetry to the plasma by placing equal and opposite voltages on opposing 180° sectors of both S1 and S2. We then drive the $l_m = 0$ mode by applying a short (75 μs) tone burst at the mode frequency to a ring. Figure 3 shows the mode amplitude versus time with the voltage applied to the sector probes as a parameter. When no asymmetry is applied, the mode damps away after the tone burst ends. As the asymmetry amplitude is increased, the mode becomes more lightly damped and finally becomes unstable.

Figure 4(a) shows that the change in the mode evolution rate scales like the applied asymmetry amplitude squared, in agreement with Eq. (1). The mode is driven as for Fig. 3 and the effective $\gamma = A_m^{-1} dA_m/dt$ is measured shortly after the tone burst ends. This γ is plotted versus the square of the voltage applied to the sector probes, A_s. In this case, we have made the tone burst long enough to alter γ_m, so that for $A_s = 0$, $\gamma \simeq 0$. The data points follow the theoretical scaling reasonably well up to an asymmetry drive of 5 V after which a deviation is observed. By this point the asymmetry is presumably large enough to violate the assumptions of the perturba-

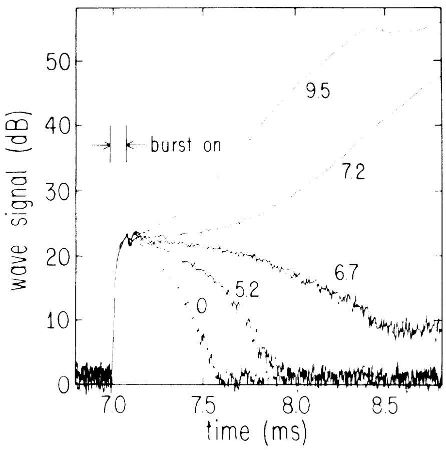

FIG. 3. Time evolution of a launched $l_m=0$ mode with asymmetric wall voltage as a parameter. The mode is destabilized as the asymmetry amplitude is increased. Each curve is averaged over eight shots.

tion theory leading to Eq. (1).

When a field asymmetry is applied with two halves of S1 with opposite polarities, many azimuthal mode numbers are present ($l_a=1,3,5,7,\ldots$), and each one contributes to the value of Γ in Eq. (1). According to theory,[9] a destabilizing (i.e., positive) contribution to Γ requires $l_a\omega_R > \omega_m$, where ω_m is the mode frequency and ω_R is the rotation frequency of the center of the plasma column. A simple physical explanation for this condition is possible. In the frame of the rotating column, $l_a\omega_R$ is the frequency of the field asymmetry (which is static in the lab frame). The mode frequency, ω_m, is the same in both frames since $l_m=0$. The inequality then expresses the requirement that the pump frequency must exceed the mode frequency in order for energy to flow from the pump to the mode. If a given l_a does not satisfy the inequality, it will make a negative contribution to Γ and thus tend to increase the mode damping.

For our experimental parameters, the above inequality reduces to $l_a \geq 3$. We know experimentally that the asymmetry produced by S1 is destabilizing, and so we deduce that the coupling coefficient for the $l_a=1$ component of the asymmetry is small. Rather than supporting this conclusion with a calculation of the coupling coefficients, we show that a stabilizing case is produced if the $l_a=1$ component of the asymmetry in the plasma is made sufficiently large. To show this, we place a signal of frequency ω_a on the two halves of S1 in a push-pull fashion.[12] The frequency is selected so as to drive the $l_a=1$, $k_a=0$ diocotron mode resonantly.[4] This procedure amplifies the $l_a=1$ component of the asymmetry in the plasma. We then drive the $l_m=0$ mode as before and measure its damping. As expected, this asymmetry increases the damping of the $l_m=0$ mode. The increase in the damping [shown in Fig. 4(b)] scales like the square of the asymmetry amplitude in agreement with

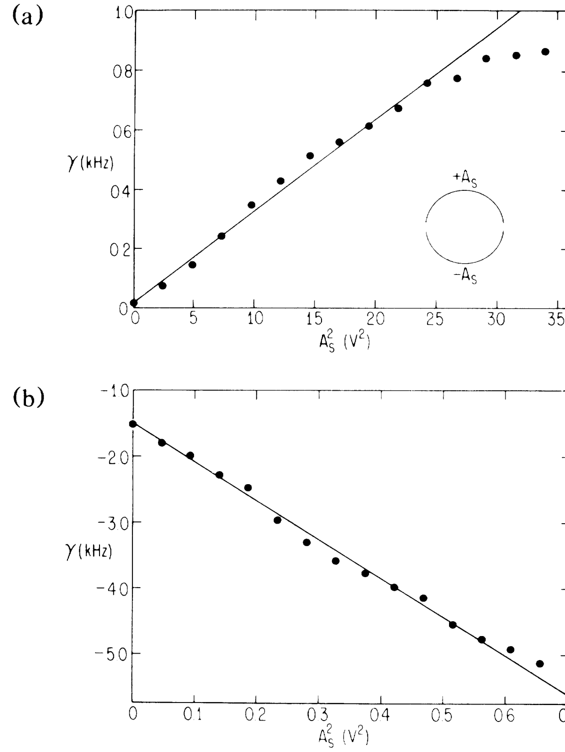

FIG. 4. Mode evolution rate $\gamma = A_m^{-1}dA_m/dt$ vs the square of the asymmetric wall voltage. (a) Static field asymmetry produced by bipolar voltage on the two halves of rings S1 and S2. (b) Asymmetry with enhanced $l_a=1$ component.

Eq. (1). If ω_a is lowered slightly so that the $l_a=1$ mode is not driven resonantly, the asymmetry becomes destabilizing and remains so as ω_a approaches zero.

The instability we have observed is of particular interest because of its ability to degrade plasma confinement. We find that the rate of loss of plasma particles due to radial transport is increased by as much as a factor of 12 when the instability is present. Since this enhanced transport is in effect produced by the beat between the unstable mode and the field asymmetry, we expect the transport to depend on both A_m and A_a. We have verified that the loss rate does increase with both amplitudes.

The induced-scattering and decay instabilities are examples of how collective processes can enhance radial transport produced by field asymmetries. They are the lowest-order nonlinear generalizations of the previously considered linear resonance between a field asymmetry and a zero frequency mode of the plasma.[7,10] Because the physical basis of these processes is quite general, they may be relevant to other rotating plasmas. Processes analogous to the linear resonance have, for example, been considered theoretically for both toroidal devices[13] and tandem mirrors.[14] To our knowledge, however, there have been no similar studies of nonlinear collective enhancement of transport in such devices.[15]

In summary, we have observed a new instability in pure electron plasmas. The instability is of the induced-scattering type and is driven by static fields which break the cylindrical symmetry of the plasma. The instability degrades the plasma confinement but can be controlled by simple techniques.

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[11]As the instability develops, up to thirteen harmonics of this mode are observed. Although these harmonics probably play a role in the saturation of the instability, they may be ignored in the context of the present studies of threshold and initial growth rate.

[12]Although we have emphasized static asymmetries in this paper, the same theory can be applied to the case of a time-varying asymmetry. In this case the instability condition is $l_a \omega_R - \omega_a > \omega_m$. For this experiment $\omega_a \ll \omega_m$, and so the instability condition remains $l_a \gtrsim 3$.

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