External Excitation and Observation of a Magnetostatic Mode in a Plasma

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A zero-frequency magnetostatic mode is excited externally in a fully ionized, magnetized plasma. Space-time–resolved measurements of magnetic fluctuations indicate that the magnetostatic mode decays with a typical time scale characterizing electron-ion collisions in agreement with theoretical predictions.

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Two modes of zero-frequency fluctuations are recognized as being particularly important for anomalous diffusion in magnetized plasmas: One is an electrostatic mode (convective cells)[1,2] which is investigated in some detail under conditions where the excitation is spontaneous[3] or controlled externally.[4] The other is a magnetostatic mode[2,5] with a linear dispersion relation

$$\omega = -i(\nu_{ei} + \mu_e k_\perp^2)/[1 + (\omega_p/k_\perp c)^2] \qquad (1)$$

where ν_{ei} is the electron ion collision frequency, μ_e the electron viscosity, c/ω_p the collisionless skin depth, while $\vec{k}_\perp$ is the wave vector for the perturbations in a direction perpendicular to the external, strong, confining magnetic field. The anomalous electron transport due to magnetostatic modes has been studied by several authors.[2,5–7]

In this Letter, we present the first observations and identifications of the magnetostatic mode which was excited externally in a controlled experiment. The measurements were carried out in the Risø *Q* machine, where a fully ionized magnetized plasma is produced by surface ionization[8] of neutral cesium on a hot (2200 K) tantalum plate of 3 cm diameter. The cylindrical plasma column (density $n_0 = 10^{10}$–10^{11} cm^{-3}, temperatures $T_e \approx T_i = 0.2$ eV, length $L = 1$ m) is confined by an axial magnetic field $B_0 = 3$ kG(see Fig. 1). In order to excite the magnetostatic mode, we introduce a time-varying external current I_{ex} on the axis $(r=0)$, which generates an azimuthal magnetic field B_θ. Evidently, the time variation of B_θ induces an axial electric field, $E_z = E_z(r)$, which in turn drives a plasma current I_p. After turnoff of I_{ex}, the plasma itself sustains the current I_p which decays on a time scale given by Eq. (1). It is worth noting that the induced electric field E_z is derived from *vector* potential in contrast to fields generated by potentials applied to, e.g., an end plate.

The excitation current I_{ex} is carried by a thin tungsten wire (0.2 mm diameter, 1 m long) which is covered by a ceramic tube of 1 mm diameter. This wire is fixed at the center of the hot plate and straightened by a spring system through a small hole in the cold end plate of 8 cm diameter. A fast–rise-time (~ 10 ns) square-wave current pulse I_{ex} of typically 200-mA peak, 1-μs duration, and 100-μs repetition period is applied to the center conductor through a matching circuit. This system constitutes a plasma-loaded coaxial transmission line short circuited at the receiving terminal point, with the outer conductor supplied by the stainless steel vacuum vessel of 15 cm diameter. The induced plasma current I_p has a loop passing through the end plate, the hot plate, and the outer conductor. Thus, this excitation scheme can be regarded as a transformer with the primary winding composed of the center conductor and the secondary winding of the plasma. The currents I_{ex} and I_p are measured by a fast-response (~ 3 ns) current probe. The azimuthal magnetic field is detected by a fast-response ($\lesssim$ 10 ns) magnetic loop with electrostatic shielding which is placed 50 cm away from the hot plate and is movable radially. The spatial resolution was increased up to $\Delta r \sim 1$ mm by elongating the loop (1 mm × 10 mm) along *B*. The loop signals, proportional to $\partial\beta_\theta/\partial t$, are sampled and averaged by a boxcar integrator. The outputs of the boxcar are digitized and processed numerically.[9]

Figure 2 shows typical examples of the magnetic signals measured near the periphery of the plasma column, together with the currents I_{ex} and I_p. The exciter current of 200 mA is turned off with a time scale (~ 20 ns) >> ω_p^{-1}(~ 0.1 ns). The plasma

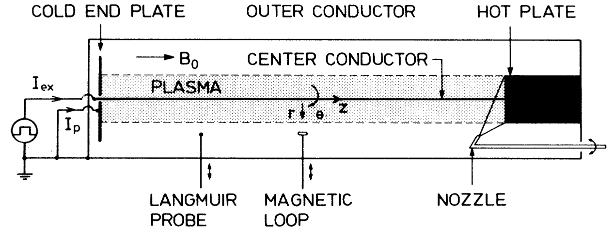

FIG. 1. Experimental setup.

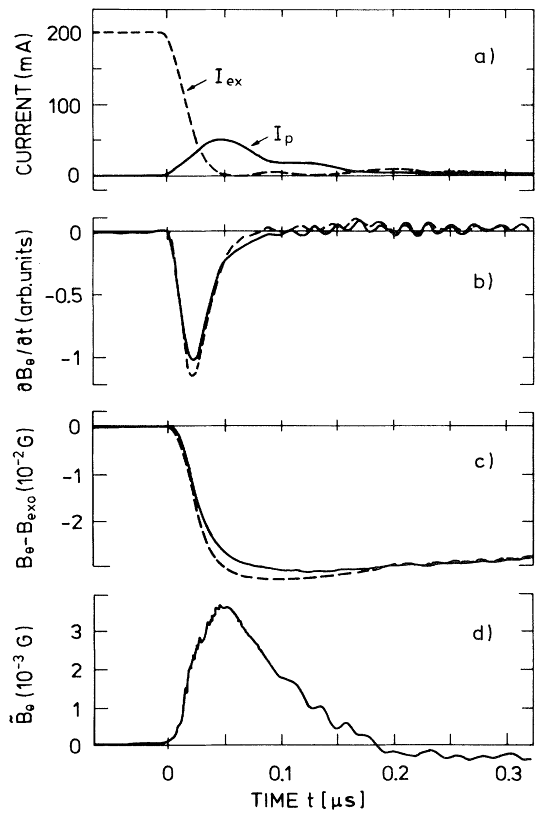

FIG. 2. Time evolutions of (a) excitation current I_{ex} and plasma current I_p, (b) magnetic loop signal, (c) azimuthal magnetic field $B_\theta - B_{ex0}$, and (d) amplitude of magnetostatic mode $\tilde{B}_\theta$. Solid and dashed lines indicate the signal with plasma and without plasma, respectively. The loop position $r = 1.2$ cm, and $n_0 = 1.5 \times 10^{11}$ cm^{-3}.

current I_p increases on the same time scale. Subsequently I_p decays slowly after the termination of I_{ex} with the oscillating (~ 50 ns period) inductive noise of the circuit superimposed.

The magnetic loop signal shown in Fig. 2(b) is integrated to give the azimuthal magnetic field B_θ shown in Fig. 2(c). The dashed lines indicate the signal in the absence of plasma where the cesium neutral beam is deflected from the hot plate by turning of the nozzle (see Fig. 1). In absence of plasma the time variation of $B_\theta = \mu_0 I_{ex}/2\pi r$ coincides with that of I_{ex}, i.e., B_θ at $t \leq 0$ in Fig. 2(c) is given by $B_{ex0} = \mu_0 I_{ex}/2\pi r$, the integration constant. This is also used for the calibration of the absolute value measurement of B_θ with the magnetic loop. The presence of plasma slows down the decay of B_θ as seen in Fig. 2(c). Here the azimuthal field is composed of two parts $B_\theta = B_{ex} + \tilde{B}_\theta$, where $\tilde{B}_\theta = (\mu_0/2\pi r)\int \tilde{j}_z \, d\rho$ with the integration of the

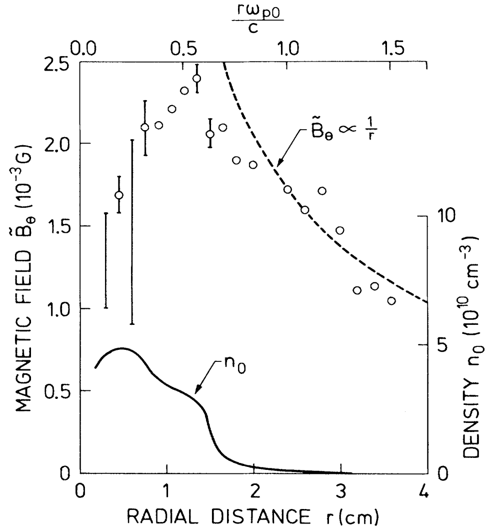

FIG. 3. Radial profile of amplitude $\tilde{B}_\theta$ of the magnetostatic mode at $t \sim 42$ ns, together with the profile of the plasma density n_0. The top scale indicates the radial position normalized by the skin-depth c/ω_{p0} where the peak plasma frequency is $\omega_{p0} = 12.5 \times 10^9$ s^{-1}.

plasma current density $\tilde{j}_z$ over $\rho \leq r$. Since I_{ex} is observed to be almost independent of the presence of plasma, subtracting B_θ *without plasma* from B_θ *with plasma* gives the plasma signal $\tilde{B}_\theta$ as demonstrated in Fig. 2(d).

The axisymmetric ordinary mode propagating perpendicularly to B_0 has the azimuthal magnetic field $\tilde{B}_\theta$ and an electric field $\tilde{E}_z$. In the limit of low frequencies ($\omega << \omega_p$), this mode becomes a purely damped, nonoscillatory mode, i.e., the magnetostatic mode. Actually, the observed $\tilde{B}_\theta$ shows a monotonic decay after the termination of I_{ex}, except for the oscillating (~ 50-ns period) low-level noise. In comparison with the plasma kinetic pressure, the perturbed magnetic pressure corresponds to $(\tilde{B}_\theta^2/2\mu_0)/n_0(T_e + T_i) \sim 10^{-5}$, and the ratio of the magnetic fluctuation to the steady field is $\tilde{B}_\theta/B_0 \sim 10^{-6}$. Figure 3 shows the radial distribution of $\tilde{B}_\theta$ sampled at a fixed time ($t \sim 40$ ns) when it reaches its maximum amplitude. For comparison, the radial density profile is also shown in this figure, where the density is approximated by the ion saturation current of the Langmuir probe shown in Fig. 1. The value of $\tilde{B}_\theta$ increases with r *inside,* and decreases as $1/r$ *outside* of the plasma column ($r \geq 2$ cm) as indicated by the dashed line in Fig. 3. This dashed line corresponds to the profile given by the axial current of 20 mA, which is 30% less than the measured total plasma current. The accurate measurement near the axis is extremely difficult because of $\tilde{B}_{ex} >> B_\theta$, and partly because of the limited spatial resolution of the loop.

The e-folding decay time τ of the magnetostatic mode was measured with respect to the total plasma current I_p since $\tilde{B}$ decays in the same way as I_p. Figure 4 shows the measured decay time as a function of the average plasma density n_0. The dispersion equation (1) indicates that the magnetostatic mode with a size much less than the plasma skin depth ($\omega_p^2/k_\perp^2 c^2 << 1$) decays with $\tau \simeq 1/\nu_{ei}$ since the electron viscosity is negligible. The solid line in Fig. 4 shows an example of the finite transverse dimension ($k_\perp = 0.5$ cm^{-1}). The experimental points are well explained by these plane-wave normal-mode theories.

In the present linear device, the behavior of the plasma current may be influenced by the sheaths at both ends. The sheath at the hot plate is in electron-rich conditions, so that the sheath resistivity is negligible compared with the resistivity R of the plasma column, of length L and cross section of area A; $R = (\nu_{ei}/\epsilon_0\omega_p^2)(L/A) \sim 10\ \Omega$ for $n_0 = 5 \times 10^{10}$ cm^{-3}. As long as the cold end plate is grounded, the sheath resistance is small also at the cold end plate. However, if a large negative dc bias is applied to the end plate, then the plasma current disappears. Details of the influence of the end-plate bias are under investigation. Because of the diodelike properties of our single-ended Q machine, we observe a significant dependence of the plasma current on the sign of dI_{ex}/dt, i.e., the electrons must essentially flow from the hot plate towards the cold terminating end plate.

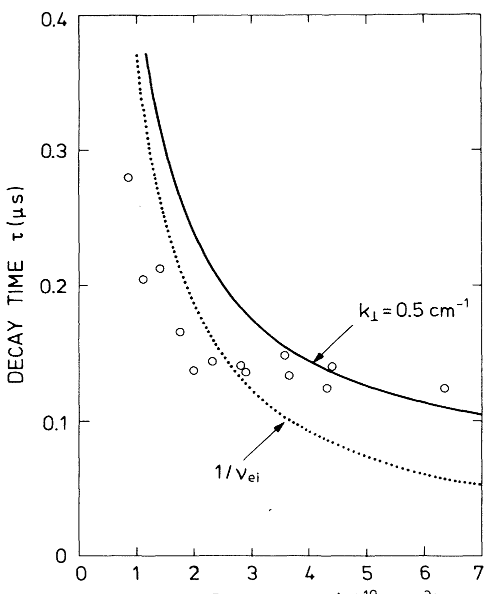

FIG. 4. Experimental points and theoretical curves of the decay time τ as a function of plasma density n_0. Solid line indicates Eq. (1) with $k_\perp = 0.5$ cm^{-1}, and dashed line indicates the electron collision mean free time.

When the excitation current amplitude is fixed, the peak plasma current is observed to increase almost linearly with the plasma density, suggesting a constant electron drift velocity. The electron flow velocity driven by $I_{ex} = 200$ mA turns out to be approximately twice the ion acoustic velocity. Under such conditions, current-driven instabilities may arise in the plasma. However, the decay time of the magnetostatic mode is much less than the ion plasma or ion cyclotron periods, and so such low-frequency instability will not be of importance. The density fluctuations were investigated by means of the Langmuir probe, and no appreciable perturbation in the plasma density was recognized due to low-frequency instabilities and not even by the magnetostatic mode itself.

To summarize, in this Letter we have presented observations of an externally excited magnetostatic mode identified by the magnetic field perturbation and a characteristic damping time which is in good agreement with theoretical predictions.[2,5]

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