Simultaneous Measurements of the Plasma Current Profile and Instabilities in a Tokamak

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(Received 12 June 1975)

In a small-scale tokamak, magnetohydrodynamic instabilities of small wave numbers, including the $m=1$ mode with positive voltage spikes, were observed. They were identified as kink modes and resistive tearing modes, by a direct measurement of the plasma current profile. Relations between the fluctuations and the current profile show a qualitative agreement with the theory of kink and resistive tearing modes.

The disruptive instability is one of the main concerns of the tokamak discharge in the next generation, and at least two factors are experimentally reported[1-4] to be responsible for this instability; one is the presence of helical magnetohydrodynamic (MHD) instabilities (representing kink and resistive tearing modes), and the other is the current-density excess near the center of the plasma. In either case the macroscopic properties of tokamak plasma depend strongly on the radial profile of the plasma current, information on which in turn has been very poor.

The objective of the present paper is to describe experimentally obtained relations between the plasma current profile and $m=1$, 2, and 3 helical MHD instabilites, and to report some behavior of the toroidal plasma when g_0 (safety factor on the magnetic axis) reaches unity. The results are compared with the theory of kink modes[5,6] and resistive tearing modes.[7,8]

Low-frequency oscillations ($f \lesssim 100$ kHz) of the poloidal magnetic field, similar to those in other tokamaks,[1,2] have been observed in a small-scale tokamak (MINIMAK). This device, which admits the insertion of various probes, has major radius $R=22.8$ cm, minor radius (radius of the conducting shell) $b=8.3$ cm, and limiter radius $a=6.0$ cm. Operational conditions of the present experiments are summarized in Table I, together with the typical plasma parameters. Further details about the apparatus will be reported elsewhere.[9]

The observed magnetic oscillations are interpreted as MHD modes. By means of the usual phase-correlation method,[1,2] using six magnetic probes placed outside the plasma, modes with $m=1$, 2, and 3 (all with $n=1$) have been identified. Here the mode structure is assumed to be $\exp[i(m\theta+n\varphi+\omega t)]$, which characterizes a helical perturbation. The major and the minor azimuths are denoted by φ and θ, respectively.

Each mode is found to rotate in the direction of the ion diamagnetic drift. This is reasonable, because the plasma space potential $V_s = 16 \pm 2$ V (measured by a Langmuir probe) will give the $\vec{E}\times\vec{B}$ rotation of the plasma column in this direction. Oscillation frequencies of the $m=1$, 2, and 3 modes all fit well in a single relation $f/m = 2.9\times 10^4/B_t$ (f in Hz and B_t in kG) for all values of the toroidal field.

Figure 1(a) provides the most general mode diagram, called the "t-q_a plot," which shows the unstable region of each helical MHD mode (specified by m) in MINIMAK. Here t represents time after the plasma initiation, and $q_a = aB_t/RB_a$ ($B_a = \mu_0 I_p/2\pi a$) is the safety factor at the limiter. The discharge follows a certain trajectory on the t-q_a plane, as drawn in Fig. 1(a) by various curves, as the total plasma current changes in time. Each of the trajectories is presented as a statistical average over 20 shots or more under a fixed condition, and black rectangles represent the statistical errors. These data have well-determined experimental mode boundaries, which are shown in Fig. 1(a) by thick solid curves.

Detection of the $m=1$ mode is noteworthy; it appears around $q_a = 1.5$ with a large amplitude. The total plasma current stops increasing as soon as it starts, and positive spikes ($\simeq 20$ V)

TABLE I. Experimental conditions. Plasma parameters (n_e to α) measured at a particular discharge.

Quantity	Symbol	Value
Toroidal magnetic field	B_t	0.7–1.4 kG
Initial Ohmic loop voltage	V_0	30 and 60 V
Filling pressure	p_f	$(3-9)\times 10^{-4}$ Torr
Plasma current	I_p	4.3–5.2 kA
Discharge duration	t_d	0.8–1.5 msec
Electron density	n_e	$(5\pm 2)\times 10^{18}$ m^{-3}
Electron temperature	T_e	6 ± 1 eV
Plasma space potential	V_s	16 ± 2 V
Energy confinement time	τ_E	7 ± 2 μsec
Ionization degree	α	(30 ± 10)%

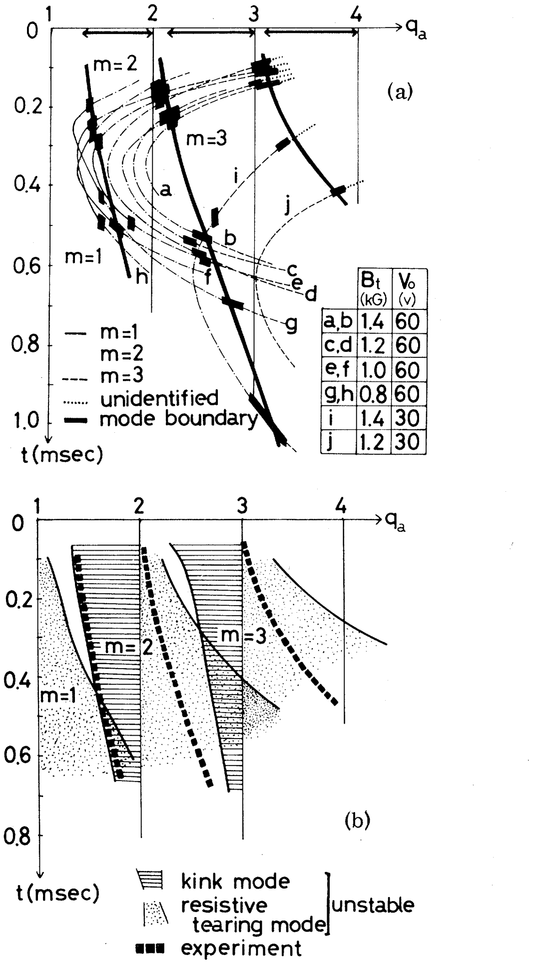

FIG. 1. Mode diagram of helical MHD instabilities in MINIMAK device. (a) Experimental results. (b) Unstable regions expected from the theory using the measured current profile.

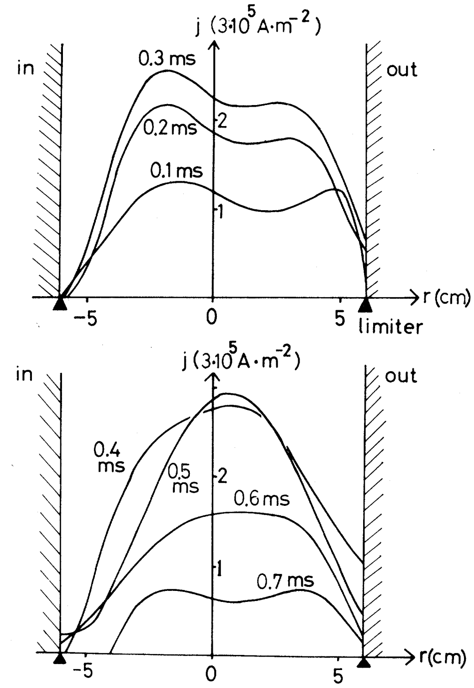

FIG. 2. Radial profile of the plasma current, with r representing the minor radius.

are observed in the Ohmic loop voltage. This mode seems to be enhanced by a larger amount of impurities, because it starts around $q_a = 1.8$ in an operation soon after the vacuum vessel opening.

In the early stage of discharge, this mode diagram shows good agreement with the Shafranov theory[5] (kink theory for a uniform plasma current), whose predictions are shown in Fig. 1(a) by horizontal arrows. However, the unstable region of each mode is seen to shift toward a grater value of q_a as the discharge goes on. This tendency is rather common to tokamaks, but in the present case it is important that discharges under rather different conditions all fit in a single diagram. Two alternative explanations are possible for this behavior: One is to assume the gradual shrinking of the current channel; the other is to invoke the gradual change in the plasma current profile, which will bring about some changes in the mode diagram.

For this purpose, a direct measurement[10] of the current profile in MINIMAK has been conducted by inserting a thin magnetic probe into the plasma. This probe can move in the radial direction ($-8.0 \leq r \leq 8.0$ cm), and the time variation of the poloidal field was measured at thirty different radial positions (different positions corresponding to different shots, but the condition is the same and the reproducibility is very good). In Fig. 1(a) trajectory e corresponds to this experiment. Assuming the toroidal MHD equilibrium, the plasma current profile has been derived from the observed poloidal field structure. The result is shown in Fig. 2 for several stages of discharge. An almost flat distribution is realized in the early stage of discharge, which explains the agreement of the diagram in this stage with the kink theory for a uniform current. Also it is seen that the current concentration actually takes place gradually in time, but that the shrinking does not, except for the very end ($t \gtrsim 0.7$ msec) of the discharge. Therefore, the shift in the mode diagram is attributed mainly to the

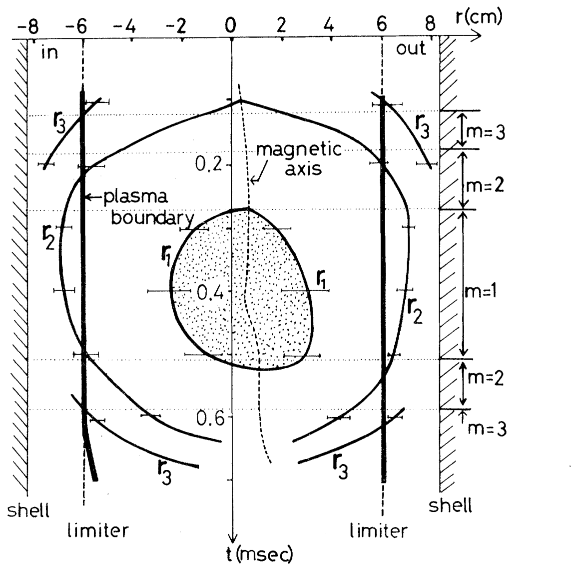

FIG. 3. Relation between observed mode number and positions of the singular surfaces.

time evolution of the plasma current distribution.

From the observed poloidal field structure, the positions of the singular surfaces corresponding to $q=1$, 2, and 3 have been derived as functions of time. These are shown in Fig. 3 by solid curves r_1, r_2, and r_3, respectively. The mode number of the fluctuation, simultaneously determined, is shown on the right-hand side. Clearly each mode is detectable as a magnetic oscillation outside the plasma, not only when the relevant singular surface falls on the vacuum region, but also when it is well within the plasma. This is the crucial evidence for the presence of a resistive tearing mode as a weak extension of the pure kink mode. This is reasonably expected in MINIMAK, because the growth rates of the kink and resistive tearing modes are expected[8] to be $\gamma_{\rm kink} \simeq 10^6\ {\rm sec}^{-1}$ and $\gamma_{\rm r.t.} \simeq 0.3\gamma_{\rm kink}$, respectively.

This situation is clearest in Fig. 3 for the $m=1$ mode: It starts as soon as q_0 reaches unity, and lasts almost until the $q=1$ singular surface disappears. This result is consistent with the prediction of Ref. 7. The safety factor near the central portion of the plasma (dotted line in Fig. 3) everywhere remains unity during the presence of the $m=1$ mode, but was never found to drop smaller. Therefore, a flute-type instability[11] and/or the $m=1$ internal kink mode[4,12] may be coexistent, localized within this area, which will enhance the outward plasma transport.

Assuming that the time evolution of the current profile does not depend on B_t critically, and consequently employing Fig. 2 as representative of all discharges in MINIMAK, the time variation of the stability diagram of helical MHD modes can be predicted theoretically. First, it is known[5,6] that the more peaked current profile gives the narrower kink-unstable regions in tokamak. Practically, the numerical calculation of Ref. 6 was applied to the observed evolution of the current profile (Fig. 2), and the kink-unstable region in MINIMAK was predicted as shown in Fig. 1(b), again a t-q_a plot, for $m=1$, 2, and 3, by hatched areas. Second, for the same current evolution, the unstable region of resistive tearing mode is readily determined if it is assumed that the tearing mode always becomes unstable during the presence of the relevant singular surface within the plasma. The result is represented in Fig. 1(b) by dotted areas. These analyses are essentially based upon the assumption of a sharp plasma boundary. However, within the error of the current profile measurement, it cannot be concluded whether or not a small fraction of plasma current flows through the limiter up to the chamber wall. If this is the case, the analysis of Ref. 7 should be employed instead, which has proved to give almost the same result. Mode boundaries in Fig. 1(a) are here reproduced for comparison.

In Fig. 1(b), a qualitatively good agreement is seen between experiment and theory. Thus, the observed fluctuations can be understood as the mixture of kink modes ($q_a < m$ region) and resistive tearing modes ($q_a > m$ region). This interpretation is furthermore supported by another observation, that the ratio $\tilde{B}_a/B_a$ ($\tilde{B}_a$ is the fluctuation amplitude of the poloidal field) of each mode always reaches its maximum in the $q_a < m$ region.

The results discussed here will apply as well to larger tokamaks, since expected features of them (higher temperature, different diffusion mechanism, and so on) have rather minor effects on the present subjects. Especially, support has been given to the conventional interpretation that the magnetic oscillations in larger tokamaks below a rather high q value ($q_a \gtrsim 4$) are of tearing type.

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Observation of Two-Dimensional Plasmons and Electron-Ripplon Scattering in a Sheet of Electrons on Liquid Helium

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(Received 12 November 1975)

The two-dimensional plasmon dispersion relation $\omega_p^2 = 2\pi Ne^2k/m$ has been verified in the classical one-component plasma formed by a sheet of electrons in image-potential–induced surface states on liquid helium. For temperatures below 0.68 K the plasmon damping indicates that the electron mobility is limited by electron-ripplon scattering.

We report an experimental study of plasmon propagation and damping in the two-dimensional (2D) classical plasma formed by a sheet of electrons in image-potential–induced surface states outside liquid helium. To our knowledge, this is the first time its peculiar dispersion relation has been verified. Furthermore, from the plasmon damping, we deduce the electron mobility and find—for the first time—strong evidence that at low temperatures the electrons are predominantly scattered by capillary waves (ripplons).

The prediction by Cole and Cohen[1] and by Shikin[2] that electrons can be bound in surface states outside certain bulk dielectrics such as He and Ne stimulated experimental searches for such states. Although the evidence for bound states in some early experiments[3,4] was questioned,[5] cyclotron resonance[6] showed that the electron motion on liquid helium is 2D and the electrons have the free-electron mass, while millimeter-wave spectroscopy[7] has firmly established that electrons are bound to a helium surface with an energy of 8 K. Consequently, at 1 K and below the electrons are predominantly in the ground state within the image-potential well and are localized within ≈ 100 Å of the helium surface, but they remain free to move parallel to the surface. Sommer and Tanner[3] found that from 0.9 to 2.0 K the electron mobility μ was limited by scattering from atoms in the He vapor, and μ had reached 2×10^6 cm^2/V sec at 0.9 K. In these experiments the surface-state electrons behaved like a highly mobile, classical, one-component, 2D plasma of variable density.

The 2D plasmon dispersion relation was first derived by Ritchie[8] and by Ferrell[9] who were treating characteristic energy loss of electrons in metal foils. Subsequently Stern[10] and Chaplik[11] have discussed plasmons in the 2D Fermi gas found in metal-oxide-semiconductor devices while Fetter[12] and Platzman and Tzoar[13] have considered the classical 2D electron gas which is of interest to us. The dispersion relation applicable to our experiment is obtained in the small-k limit ($kv/\omega_p \ll 1$) and with small damping ($\omega_p\tau \gg 1$): $\omega_p^2 = 2\pi Ne^2km_0^{-1}(1+i/\omega_p\tau)$, where v is the electron thermal velocity and τ is a phenomenological relaxation time.

We study the plasmon dispersion and damping by exciting standing-wave resonances in the surface-state electron plasma contained within a rectangle parallelepiped cell approximately $1.9\times1.2\times0.18$ cm^3 in size. The cell is assembled from metal plates electrically isolated from one another so that potentials can be applied to them. The bottom plate consists of three sections, with the center section forming a 50-Ω strip line. The strip line is connected at one end through a coaxial line to a broad-band swept-frequency spectrometer[14] and has the other end terminated in a matched load.

The experimental procedure consists of condensing enough helium in the apparatus to partially fill the cell with liquid, applying appropri-