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Remote Feedback Stabilization of a High-β Plasma

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A current-driven rotational instability in a magnetic arc plasma of density 10^{16} cm^{-3} is suppressed by a totally remote feedback system. Detection is achieved by transmission or reflection of a 337-μ laser beam, suppression by an oscillating transverse magnetic field.

The possibility of suppressing instabilities of magnetically confined plasmas by feedback stabilization has recently received considerable attention.[1] To date, experiments show that very little power is required to effectively eliminate single-mode low-frequency instabilities near threshold. This is an encouraging sign, but such experiments have mostly depended upon electrodes either inside the plasma or within a Debye length of the interior for detecting and suppressing the oscillations. Material electrodes, however, cannot be used in fusion plasmas. In this note we report a feedback experiment in which both detection and suppression are accomplished remotely; it is also the first successful feedback stabilization of a high-β plasma.

The plasma is produced by a high-current argon arc[2] along a magnetic field B up to 10 kG. The current channel has radius $a=0.6$ cm and length $L=15$ cm; the plasma is visible to $r=1.5$ cm. Under typical operating conditions, the current I is 200 A, the pressure p is 2 Torr, and B is 5 kG. The plasma parameters on the axis are then $n=10^{16}$ cm^{-3}, $T_e=4$ eV, $T_i\approx 1$ eV, and $\beta\equiv 8\pi nKT/B^2=8\%$. The current density $J=$ 100–250 A/cm^2 and energy density $\mathcal{E}\approx 10^{17}$ eV/cm^3 are in the range achieved in contemporary tokamaks. Our plasma is, however, collisional, with $\Omega_c\tau_i\approx 10^{-2}$ and $\omega_c\tau_e\approx 8$. Neutral collisions dominate in the halo, and Coulomb collisions dominate in the core, where the fractional ionization is estimated to be greater than 15%. Diagnostics in the halo can be done with water-cooled Langmuir probes, which can be inserted to the edge of the current channel. To probe the interior we use a dc HCN laser producing a 15-mW beam at 337 μ wavelength, corresponding to a cut-off density of 9.8×10^{15} cm^{-3}.

The plasma is normally quiescent, with $|e\tilde{\phi}/KT_e|\approx 10^{-3}$, when B and I are below and p is above their critical values. Upon exceeding the threshold in B, I, or p, an instability rotating in the electron diamagnetic drift direction appears, with frequency $f=20$–60 kHz. The dominant azimuthal mode number is $m=1$, and $k_{\|}$ is less than $2\pi/L$. We believe this to be a variant of the Kadomtsev–Nedospasov[3] helical instability previously observed in positive columns.[4] We have derived the dispersion relation with a number of simplifying assumptions. If $G_j\equiv k^2D_j+(m/r)^2D_{\perp j}$, $\omega^*=-(m/r)(KT_e/eB)d(\ln n_0)/dr$, $k=k_{\|}$, u is the longitudinal electron drift in equilibrium, and D_j and $D_{\perp j}$ are diffusion coefficients, instability occurs for

$$\theta\omega^*(ku-\theta\omega^*)>(1+\theta)G_e(G_i+\theta G_e), \tag{1}$$

where $\theta\equiv T_i/T_e$. When the variation of n_0 with p and I is taken into account, Eq. (1) predicts the threshold behavior reasonably well. The predicted frequency, however, is lower than observed, even when zero-order rotation is taken into account. We believe that the discrepancy can be removed by considering electromagnetic effects, since $\omega/k_{\|}$ is of the order of the Alfvén speed. In the absence of collisions, a kink mode can arise which is really a current-driven Alfvén wave or low-frequency whistler. The observed instability is believed to be a hybrid between this and the collisional Kadomtsev instability.

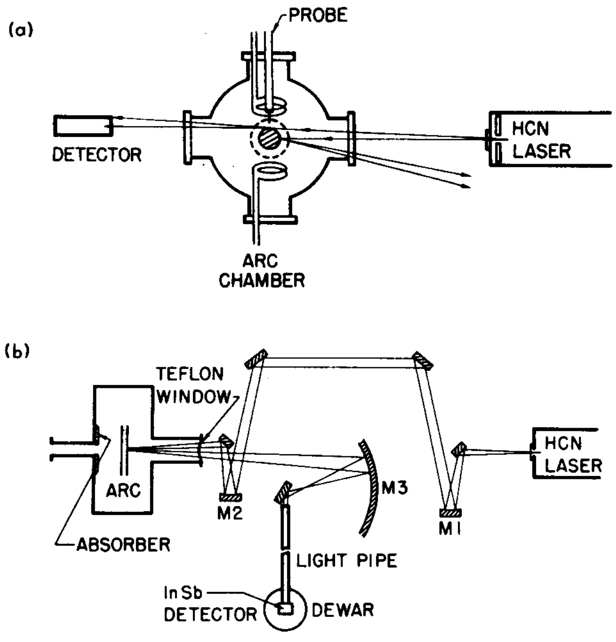

FIG. 1. (a) Schematic showing the three methods of detection. (b) Optical arrangement of the laser reflectometer.

Detection of the instability was done in three ways: (a) with a probe [Fig. 1(a)], (b) by a transmitted HCN-laser beam, and (c) by a reflected HCN-laser beam [Fig. 1(b)]. The suppressing signal was applied by a pair of coils consisting of several turns of copper tubing between the plasma and the vacuum wall. The coils produced an $m=1$ transverse $B_\perp$ field up to 8 G peak to peak at 30 kHz. The detector signal was passed through a low-noise preamplifier, a variable-Q tuned amplifier, and a phase shifter and applied to the coils by a low-impedance power amplifier. Optimum suppression occurred when the $\mathbf{J}\times\mathbf{B}_\perp$ force was phased to oppose the radial motion of the plasma.

As a check on the feedback system, we first used a probe as the detector in the standard fashion.[1] Results are shown in Fig. 2 by the round points. Since a feedback signal optimized for suppressing the $m=1$ mode has the proper phase for exciting the $m=3$ mode, it is necessary to limit the bandwidth of the applied signal. The suppression ratio (of amplitude squared with and without feedback) improves with the Q of the tuned amplifier up to $Q=50$. A ratio of 35 dB was the best achieved; this figure, taken at 5% above threshold B, decreases with distance from threshold. Figures 3(a) and 3(b) show the potential oscillations on a floating probe in a case when the suppression ratio was 25 dB. This was achieved with a $B_\perp$ of only 0.25 G peak to peak. The results on the effect of bandwidth are in general agreement with previous work using probes.[5]

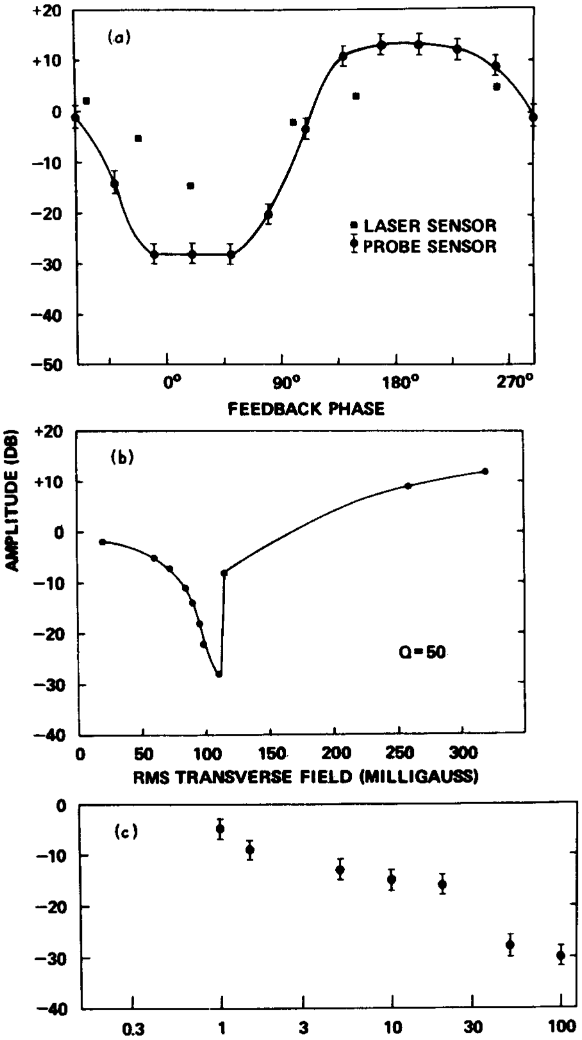

FIG. 2. Oscillation amplitude as a function of (a), phase; (b), amplitude; and (c), Q of suppressor signal.

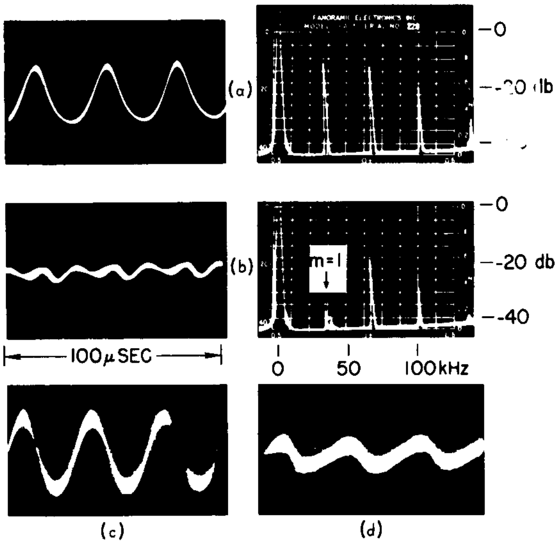

FIG. 3. Oscillograms and spectra of oscillations in a plasma with $B=5$ kG, $I=200$ A, $p=1.7$ Torr, $n_0\simeq10^{16}$ cm^{-3}: (a), floating probe signal, no feedback, 0.5 V/div; (b), same with feedback; (c), reflected laser signal, 0.1 μW/div, 10 μsec/div, incident beam on axis; (d), same off axis.

If the 337 μ laser beam is sent through an off-axis region of the plasma where the density is below cutoff, the beam will be deflected by refraction. The phase of the oscillation can be detected by changes in the angle of refraction as the density oscillates. Since a large fraction of the incident laser power is transmitted, it was possible to use a room-temperature pyroelectric detector, even though it has a poor high-frequency response. To increase the signal-to-noise ratio at 30 kHz it was necessary to use a tuned amplifier. A maximum suppression of 18 dB was achieved. This is the simplest remote detection scheme, but since the results are similar to those presented below, they will not be presented here.

To probe the interior of the plasma near the cutoff layer, it is necessary to detect the reflected laser beam. Figure 1(b) shows the optical system used. Mirrors M1 and M2 make the beam parallel and focus it onto the plasma. Mirror M3 collects the reflected radiation and sends it through a light pipe to the liquid helium cooled detector. As the plasma oscillates in an $m=1$ mode, the $\omega=\omega_p$ surface changes its position and modulates the power collected by the receiving antenna. The oscillating signal is of the order of 1 μW, or 10^{-4} of the incident power. In an auxiliary experiment in which a metal rod was substituted for the plasma, we determined that a factor of 30 can be accounted for by the solid angle of the antenna. Another factor of 30–40 is caused by collisional attenuation and severe refraction in the surrounding plasma halo. The remaining factor of 10 is due to the finite amplitude of oscillation, n_1/n_0 being perhaps 10%–25%. The 1-μW signal at 30 kHz is easily detectable with an InSb crystal at 4.2°K without magnetic field. The responsivity was 1 V/W with a bias current of 30 mA, and a coupling transformer was used. Figure 3(c) shows oscilloscope traces of the reflected signal under conditions when no instability could be seen with a probe 3 mm outside the current channel. Since no tuned amplifier was needed to see the signal, information on the shape of the instability, as well as its frequency and phase, can in principle be obtained. This is demonstrated by the nonsinusoidal signal received when the incident beam is tipped off axis [Fig. 3(d)]. If the incident beam were parallel and the plasma a perfect conductor, one would expect the reflected signal to have frequency 2ω. In fact, it has frequency ω. We believe that changes in focus and refraction with plasma position are responsible for this asymmetry.

Feedback results with the reflected-signal detector are shown by the square points on Fig. 2(a). A probe was used here to monitor the success of the feedback, but it was *not* part of the feedback loop. A suppression ratio of 15 dB was achieved, as contrasted with 25–35 dB with a probe sensor. Furthermore, although the probe signal is reduced 15 dB, the reflected-beam signal changes by less than 3 dB. When the feedback gain is increased in an attempt to improve the stabilization of the interior of the plasma, we observe that the exterior layers are overdriven and that an instability is excited there. This effect limits the usefulness of feedback systems relying on external currents for suppression. A truly local suppressor signal is needed. We are investigating the use of high-powered lasers for this purpose. The following conclusions have application to the stabilization of tokamaks and θ pinches by feedback: (1) far-infrared laser detection of instabilities is possible with existing technology, (2) an oscillating $B_\perp$ field efficiently suppresses the $m=1$ mode at the surface of a current-carrying plasma, and (3) external suppressors could not, at least in this experiment, stabilize the inner and outer regions of a dense plasma simultaneously.

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[1] References may be found in a review article by K. I. Thomassen: Nucl. Fusion **11,** 175 (1971).

[2] C. Mahn, H. Ringler, and G. Zankl, Z. Naturforsch. **23a,** 867 (1968).

[3] B. B. Kadomtsev and A. V. Nedospasov, J. Nucl. Energy **C1,** 230 (1960).

[4] G. A. Paulikas and R. V. Pyle, Phys. Fluids **5,** 348 (1962).

[5] N. E. Lindgren and C. K. Birdsall, Phys. Rev. Letters **24,** 1159 (1970).