Anomalous transport reduction via feedback suppression

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A feedback control system using an ion beam as a remote suppressor has been previously shown to be very effective in suppressing plasma instabilities in the Columbia Linear Machine. Here we present experimental measurements of the effect of this feedback system on anomalous particle transport, as determined from the cross correlation of density and potential fluctuations. We show that feedback reduces transport due to a rotational **E**×**B** mode by up to a factor of 3 in this experiment. Also, we show that feedback control does not alter the scaling of particle transport with fluctuation amplitude. [S1063-651X(96)03208-4]

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The anomalously rapid loss of heat and particles from magnetically confined plasmas has been the subject of intensive research for decades, and it is now widely believed to be caused by fluctuations driven by plasma instabilities. Feedback control systems can potentially suppress some of these instabilities and may reduce transport. However, very few experiments on control of plasma instabilities have been performed. The past work on feedback studies appear in [1].

We have shown in the past how a nonperturbing, feedback-modulated ion beam can be used to suppress the plasma instabilities [2,3] in the Columbia Linear Machine (CLM) [4,5] using only a very moderate amount of feedback power. Results obtained with an ion beam can be readily applied to tokamaks using modulated neutral beam suppressors [6]. We have also shown in the past how a single sensor and suppressor can be used in a feedback system to stabilize multiple instabilities in CLM by using differentiators in the feedback loop as ''state observers'' [7] to provide the additional information needed. Although these experiments showed that a strong suppression of instabilities could be achieved, the effect of this reduction in fluctuation level on anomalous transport was not measured. In this paper, we show experimental proof that such a feedback control system reduces the anomalous particle transport in plasmas.

The CLM generates a steady-state collisionless hydrogen plasma column in a uniform magnetic field. The experimental setup is shown in Fig. 1. The plasma is produced by a gas discharge in a source chamber, which is separated from the experimental cell chamber by a differentially pumped transition region (only the experimental chamber is shown in the figure). The plasma leaves the source through a circular limiter and flows through the cell chamber for a distance $L \simeq 180$ cm, terminating on a cold conducting end plate. The collisionless plasma in the cell normally has a density N of 5×10^8 cm^{-3}, electron temperature T_e of 5 eV, and ion temperature T_i of 3 eV.

A small hydrogen ion beam source (IBS) [8] is placed behind the end plate, with a small hole in the end plate to allow the beam to be injected into the plasma column. The IBS is an **E**×**B** hot-cathode discharge source specifically designed for feedback studies in CLM. It contains two meshes in the beam aperture that can be biased independently. The inner mesh is mainly used to modulate the plasma beam, while the outer mesh is biased to contain the electrons and allow the ions to escape as a beam. In addition, by applying the appropriate bias on the inner mesh, the IBS can also be configured to produce an electron beam, without the need to bias the outer mesh. In this case, the outer mesh is connected to the end plate, and acts as an extension of the end plate. It has been found that either configuration is suitable for feedback stabilization [8]. Due to the ease of setup and diagnosis of the electron beam, it was used as the suppressor in this experiment. The radial position of the beam can be manually adjusted, and is usually placed where the maximum mode fluctuation occurs ($r \simeq 2$ cm). The feedback loop consists of a feedback sensor, which is a Langmuir probe biased to collect ion saturation current, a band-pass filter, a phase shifter, an amplifier with a dc offset to bias the modulation mesh properly, the IBS, and the plasma column. The phase shifter can be adjusted to either drive or suppress an instability.

Many different instabilities have been studied in CLM, including trapped-particle modes and the ion temperature gradient mode. The most robust instability, which we use for this study, is a centrifugal flute mode driven by the **E**×**B** rotation of the plasma [9]. Under most conditions, the dominant mode has azimuthal mode number $m=1$ and a broad radial extent, peaking near the limiter radius at 1.8 cm. The amplitude of the instability can be varied by changing the electric field in the plasma. This can be accomplished

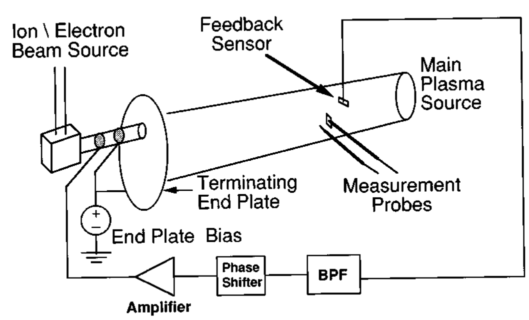

FIG. 1. Schematic of the experimental setup of the feedback experiment. The measurement probes are a Langmuir probe biased to collect ion saturation current, which measures the density fluctuation, and a capacitive probe, which measures floating potential fluctuations. BPF denotes a bandpass filter used to eliminate unwanted noise.

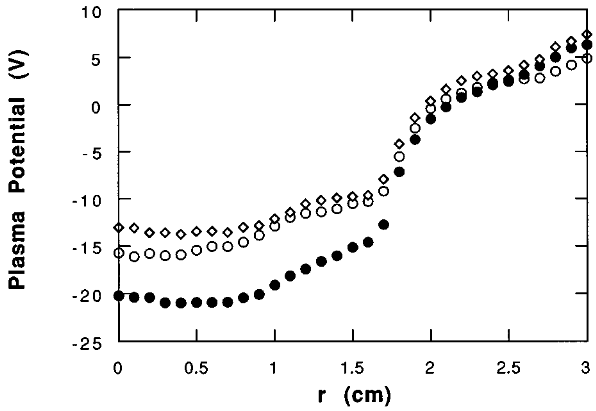

FIG. 2. Equilibrium radial plasma potential profile for different end plate biases. Solid dots: 0-V end plate bias. Open dots: 5 V. Open diamonds: 9 V.

byapplying a small bias to the terminating end plate, which directly changes the radial plasma potential profile, as seen in Fig. 2, and the corresponding transport.

The diffusion coefficients were determined by calculating the anomalous particle flux from fluctuation measurements. The anomalous particle flux is

$$\Gamma = \mathrm{Re}\{\langle \tilde{v}_r \tilde{n} \rangle\}, \tag{1}$$

where $\tilde{v}_r$ is the radial velocity fluctuation and $\tilde{n}$ is the density fluctuation, both represented in complex notation. For a flutelike mode, the plasma potential fluctuation has the form $\tilde{\phi} \sim f(r) e^{i(m\theta - \omega t)}$, where $f(r)$ is some function of radius, and m is the mode number. Hence

$$\tilde{v}_r = \frac{c\tilde{E}_\theta}{B} = -\frac{imc}{rB}\tilde{\phi},$$

where $\tilde{E}_\theta$ is the azimuthal electric field, B is the axial magnetic field, and c is the speed of light. Using this, Eq. (1) becomes

$$\Gamma = \frac{mc}{rB}\mathrm{Re}\{i\langle \tilde{\phi}\tilde{n} \rangle\}.$$

The time average of the fluctuations can be obtained through the cross correlation of the two quantities, or by integrating the cross power spectrum in the frequency domain:

$$\Gamma = \frac{mc}{rB}\int |P_{\Phi N}| \sin\Theta_{\Phi N} df, \tag{2}$$

where $P_{\Phi N}$ is the cross power spectrum of $\tilde{\phi}$ and $\tilde{n}$ and $\Theta_{\Phi N}$ is the phase of the cross power spectrum, and f denotes the frequency. We isolate the transport caused by the dominant $(m=1)$ mode by integrating only across the mode peak in the fluctuation power spectrum. The radial diffusion coefficient is then given as

$$D = -\frac{\Gamma}{\partial n/\partial r}. \tag{3}$$

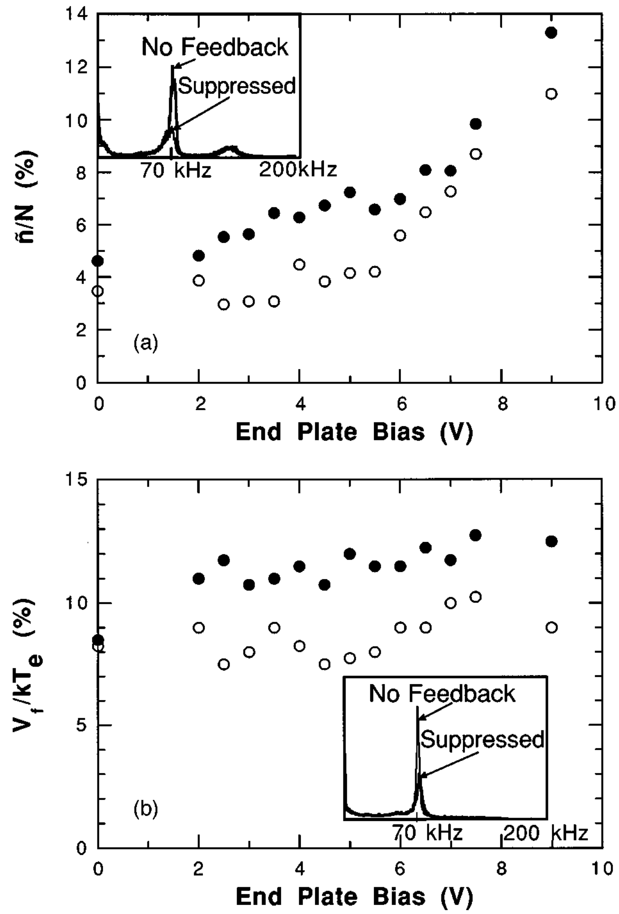

FIG. 3. Feedback reduction of fluctuations. (a) Normalized density fluctuations vs end plate bias. (b) Potential fluctuations normalized to kT_e vs end plate bias. Solid dots indicate fluctuations without feedback, hollow dots indicate fluctuations with feedback. (Insets: Typical fluctuation spectra, with and without feedback suppression. The area under the peak was integrated to obtain the points on the graph.)

Almost all the above quantities could be measured with the existing diagnostic probes in CLM, which consist of Langmuir probes, ion energy analyzers and emissive probes. To measure fluctuations in the plasma potential, we measure fluctuations in the floating potential ϕ_f of a probe. The frequency response of the standard Langmuir probes was inadequate for these measurements, leading to attenuation and (more seriously) phase shift of the $\tilde{\phi}_f$ signal. A capacitive probe [10] with a very high input impedance was used instead. In standard probe theory, $\phi = \phi_f + \alpha kT_e/e$, where e is the electronic charge and $\alpha \simeq 3$ is a constant affected by ion mass, magnetic field, and probe geometry. The result applies to fluctuations at frequencies $\omega \ll \Omega_i$, where Ω_i is the ion cyclotron frequency. When fluctuations in T_e are expected to be negligible, we assume $\tilde{\phi} = \tilde{\phi}_f$, as has been often done before. However, as there is an electron temperature gradient in the equilibrium profile, electron temperature fluctuations are expected, which we have not accounted for in the data presented. Because of the flute nature of the mode, the correlation between $\tilde{n}$ and $\tilde{\phi}$ was measured using a Langmuir probe and a capacitive probe at the same azimuthal position, separated axially by 3 cm, as shown in Fig. 1. Due to the

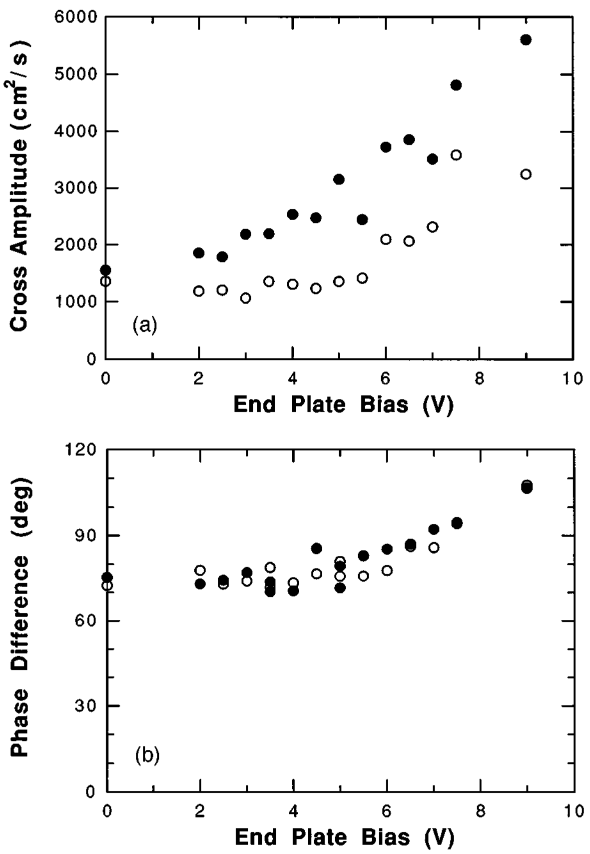

FIG. 4. Feedback reduction of particle transport. (a) Effect of feedback on cross amplitude $|P_{\Phi N}|$ vs end plate bias. (b) Effect of feedback on phase difference between density and potential fluctuations vs end plate bias. Solid dots represent amplitude and phase difference without feedback, hollow dots represent amplitude and phase difference with feedback.

nature of the flute mode, this axial separation should cause negligible phase shifts between the probes.

The effect of the feedback on the density fluctuations is shown in Fig. 3(a). Similarly, Fig. 3(b) shows the effect of feedback on the potential fluctuations. Both these graphs show that feedback consistently suppresses both the density

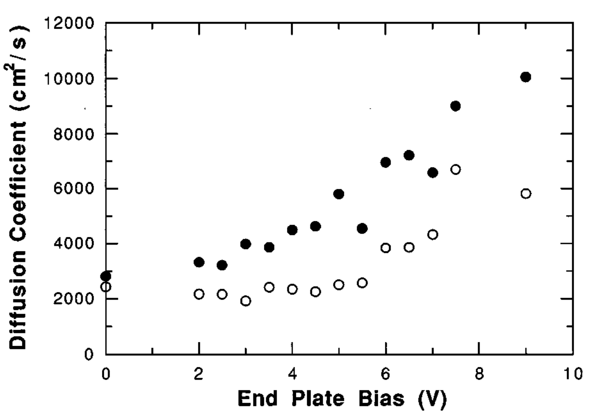

FIG. 5. Diffusion coefficient vs end plate bias. Solid dots represent the diffusion coefficient without feedback, whereas hollow dots represent the diffusion coefficient with feedback.

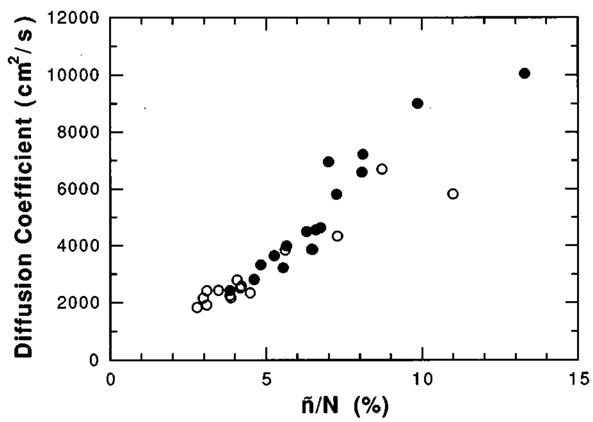

FIG. 6. Diffusion coefficient vs normalized density fluctuation level. Solid dots are cases without feedback, hollow dots are cases with feedback.

and potential fluctuations. Furthermore, the fluctuation levels scale nearly linearly with the end plate bias voltage in this case. The flux is obtained from averaging 100 cross power spectrum samples, from which the diffusion coefficients were then calculated. The magnitude of the cross correlation after averaging is shown in Fig. 4(a), which indicates feedback reduction consistent with the data of Fig. 3. The phase difference is shown in Fig. 4(b). Even though the measurement circuit was estimated to have an uncertainty of 10–15° in the measured phase difference, the error in $\sin(\Theta_{\Phi N})$ is small, since $\Theta_{\Phi N}\sim 90°$ in all cases. Due to noise in the phase measurement, especially when the amplitudes were reduced by feedback suppression, the results do not show a uniform reduction or increase in the phase. Again, this turned out to have little effect on the diffusion coefficient for the same reason mentioned above.

Figure 5 shows the radial diffusion coefficient, as calculated using Eq. (3) as a function of end plate bias. This figure clearly shows that feedback uniformly reduces radial transport. Also, one can see the effect of feedback leveling off at lower fluctuation levels, which in this case corresponds to lower end plate bias. At best, feedback reduces transport by a factor of 3 in this case, the effect being reduced at both higher and lower fluctuation levels. Finally, the effect of feedback on the scaling of the diffusion coefficient plotted against the density fluctuation level is shown in Fig. 6. Here, the points with feedback seem to follow the same scaling found without feedback, indicating that feedback does not change the scaling laws of the original mode. This is of great significance, since it indicates that feedback does not alter the nonlinear physics of the mode saturation and turbulent transport. This is consistent with the assumption that the linear feedback employed here affects only the eigenfrequency, mostly the growth rate, of the underlying linear drive of the instability. Overall, the same type of strong turbulence scaling with $\tilde{n}$ was also found by McWilliams, Okubo, and Wolf from the density transport of an electron cyclotron wave via laser induced fluorecence [11].

The absolute accuracy of the transport measurements is open to question due to the neglect of the temperature fluctuations, the problem of probe shadowing in collisionless plasmas, and the well-known difficulty in calibrating Langmuir probes in a magnetic field. However, there should be no doubt as to the relative measurements of the effect of feedback on these quantities. One should also note that even though the amount of reduction varied for different fluctuation levels, the ultimate effectiveness of feedback depends on the complexity of the feedback system itself. In this case, a simple straightforward feedback system consisting only of one set of amplifiers and one phase shifter was used. It can be shown theoretically that this is far from optimum [12]. Furthermore, the setting of the phase shifter was optimized for 5 V end plate bias, which would correspond to medium fluctuation levels on the previous graphs. This setting was then used on all other fluctuation levels, in order to provide a better comparison among them. One main reason for not using a more complicated feedback system is that maximum suppression is not necessarily desired for these measurements. This is because if the fluctuations are heavily suppressed, most measurements with feedback would fall close to or under the noise floor of the spectra, causing uncertainties in the measurements.

To summarize, we have shown in this paper that not only does the feedback control system reduce plasma fluctuations, but it can also reduce the local particle transport by a substantial amount. This effect persists over a broad range in parameter space, most importantly for various drive and fluctuation levels. Lastly, the feedback system does not alter the transport scaling laws, indicating that it operates only on the underlying linear dynamics of the instability and not on its nonlinear behavior.

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[1] *Feedback and Dynamic Control of Plasmas*, edited by T. K. Chu and H. W. Hendel, AIP Conf. Proc. No. 1 (AIP, New York, 1970).
[2] P. Tham, A. K. Sen, A. Sekiguchi, and G. A. Navratil, Phys. Rev. A **67**, 204 (1991).
[3] P. Tham and A. K. Sen, Phys. Fluids B **4**, 3508 (1992).
[4] G. A. Navratil, J. Slough, and A. K. Sen, Plasma Phys. **24**, 184 (1982).
[5] R. Scarmozzino, A. K. Sen, and G. A. Navratil, Phys. Rev. Lett. **57**, 1729 (1986).
[6] A. K. Sen, Phys. Plasmas **1**, 1479 (1994).
[7] P. Tham and A. K. Sen, Phys. Rev. A **46**, R4520 (1992).
[8] A. Sekiguchi, A. K. Sen, P. Tham, G. A. Navratil, and R. G. Greaves, Rev. Sci. Instrum. **63**, 4227 (1992).
[9] T. D. Rognlien, J. Appl. Phys. **44**, 3505 (1973).
[10] N. Benjamin, Rev. Sci. Instrum. **53**, 1541 (1982).
[11] R. McWilliams, M.K. Okubo, and N.S. Wolf, Phys. Fluids B **2**, 523 (1990).
[12] A. K. Sen, J. Plasma Phys. **20**, 1 (1978).