Feedback-Modulated Ion Beam Stabilization of a Plasma Instability

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A novel remote suppressor consisting of an injected ion beam has been used for the stabilization of a plasma instability. Plasma instabilities can, for the first time, be remotely suppressed by modulating the ion beam with an appropriately phased and amplified feedback signal derived from a sensor probe. A collisionless curvature-driven trapped-particle instability has been successfully suppressed down to noise levels using this scheme. The ion beam causes only a small perturbation to the plasma, on the order of 1%, so that the plasma equilibrium parameters are not significantly affected.

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Feedback techniques have been used for a long time to study plasma instabilities in laboratory plasma devices [1]. These techniques have offered a means of controlling plasma instabilities which are known to be responsible for plasma nonuniformities and anomalous transport. Most methods employed to date have required the use of material probes or electrodes [1–3] which restrict their application to plasmas of moderate temperature and density. Even in some of these instances, material probes may cause significant perturbation of the plasma. Hence alternative schemes using charged-particle beams as remote suppressors have been considered. Indeed, remote methods utilizing feedback-modulated neutral beams have been proposed for tokamaks [4–8]. Since neutral beams are converted through ionization and charge exchange into energetic ion beams after entering the plasma, the suppression of plasma instabilities would effectively be achieved via modulated ion beams.

In this Letter, we demonstrate, for the first time, that feedback-modulated ion beams can successfully suppress low-frequency plasma instabilities, thus providing a proof-of-principle experiment for the above-mentioned scheme. This novel feedback scheme was applied to the collisionless curvature-driven trapped-particle instability previously identified in the Columbia Linear Machine (CLM) [9]. An ion beam can easily serve as a remote suppressor because it can be injected along the open magnetic-field lines of CLM. In addition, a Langmuir probe served as a sensor and the feedback circuit consisted of a unity-gain phase shifter and amplifiers. Moreover, the required ion-beam density represented only a small perturbation to the plasma density, on the order of 1%, so the equilibrium parameters of the plasma were not appreciably affected.

The experimental layout is shown in Fig. 1. The CLM is a steady-state linear machine [10]. The plasma which is produced in the source region, flows through a differentially pumped transition region and into the experimental cell region. The differentially pumped transition region is necessary to maintain pressures of μtorr in the experimental region for the production of the collisionless trapped-particle instability. The plasma is terminated at the far end of the experimental region by a grounded conducting end plate. A small ion-beam source (IBS) is placed behind the terminating end plate, about 100 cm away from the 50-cm-long experimental mirror cell. The ion beam is injected axially along the magnetic-field lines at a radius of 2.2 cm from the center of the plasma column, corresponding to the radial position of the maximum amplitude of the instability. A gridded ion energy analyzer placed 45 cm downstream from the IBS is used to detect and characterize the ion beam. The mode density fluctuations are sensed with a Langmuir probe from a side port in the middle of the mirror cell at a radius of 1.4 cm. This is the "sensor" Langmuir probe for the feedback. A second Langmuir probe from the top port at the same axial location is used to scan the radial profile of the mode fluctuation amplitude.

The ion-beam source which was designed for feedback studies in CLM [11] has been improved to produce an ion beam with a narrow energy spread. This source was based on the $\mathbf{E}\times\mathbf{B}$, hot-cathode-discharge source design [12]. Two biasable meshes are used to extract the ion

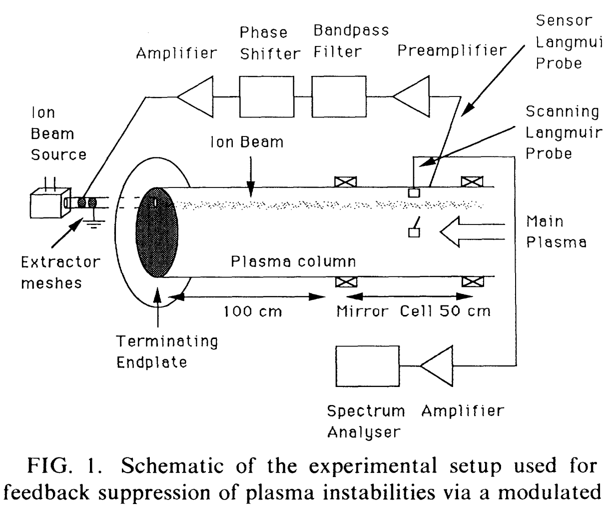

FIG. 1. Schematic of the experimental setup used for the feedback suppression of plasma instabilities via a modulated ion beam. The ion-beam source (IBS) is the remote suppressor and a Langmuir probe from a side port in the mirror cell is the sensor.

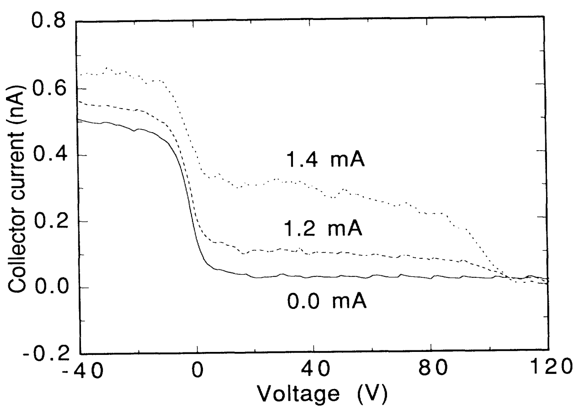

FIG. 2. Current-voltage characteristics of a gridded ion energy analyzer for three different values of discharge current. The extracted ion beam has energy of ~105 eV and energy spread of ~20 eV.

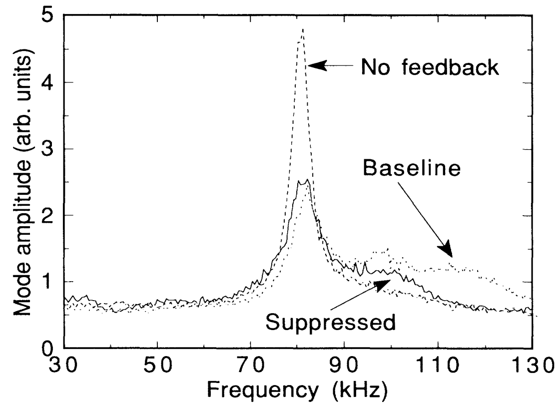

FIG. 3. Spectrum for the three cases of uncontrolled mode amplitude, suppressed mode amplitude, and the "noise" level taken with the mirror off.

beam. The inner mesh is used to modulate the plasma beam, while the outer one is used to remove the bulk of the electrons and allow all the ions to pass through. Some electrons are allowed to escape in order to neutralize space-charge effects.

The current-voltage characteristics obtained with the ion energy analyzer are shown in Fig. 2 for the three different values of discharge current of 0.0, 1.2, and 1.4 mA. When the IBS is off, the ion energy analyzer detects only the background ion population shown as the solid line. As the IBS discharge current is raised by increasing the current flowing through the filament, a small ion-beam component becomes evident and the beam increases significantly for discharge currents greater than 1.4 mA. The ions have a directed energy of ~105 eV with an energy spread of ~20 eV. The ion-beam density cannot, however, be directly compared with the background ion density from this curve, as the ion energy analyzer is directly facing the IBS, but is facing away from the main plasma flow. Also, because of the geometrical aperture of the analyzer, it would collect only a fraction of the background ions but all of the ions from the IBS. A radial scan about the IBS position with the gridded ion energy analyzer gave a beam diameter of 0.8 cm. Since the gyroradius is about 0.4 cm and the radius of the IBS aperture is 0.3 cm, the ion beam is well collimated. The beam dimensions are small compared with the plasma column diameter of 6 cm, covering less than 2% of the cross-sectional area.

Referring to Fig. 1, the signal from the sensor Langmuir probe is first passed through a preamplifier, a bandpass filter, and a phase shifter, and then passed through another amplifier. This second amplifier is used to bias the inner mesh about the ion-beam energy of 105 V and to modulate the ion beam by 25 V (rms), corresponding to 100% modulation. The phase shifter and the gain of the second amplifier can be independently varied to obtain information about the stabilization parameters. The signal from the scanning Langmuir probe was monitored on a spectrum analyzer and an oscilloscope.

The result of applying the feedback-modulated ion beam to the collisionless curvature-driven trapped-particle mode is displayed in Fig. 3, in which the mode spectrum is plotted. The collisionless curvature-driven trapped-particle instability is driven unstable by the overall bad curvature of the simple mirror configuration of the magnetic fields. An external, slotted antenna structure installed in the cell for ion cyclotron heating to improve the trapped fraction resulted in perpendicular ion temperatures of about 25 eV. The bad curvature is partly produced in CLM by a moveable, internal mirror coil, adjusted to give a mirror cell of 50 cm to maximize the bounce-averaged curvature drive. As the mirror ratio is raised from 1 to 2.2, a majority of the plasma is trapped in the mirror cell. These trapped particles experience the bad curvature and the curvature-driven trapped-particle mode becomes unstable. A strong mode ($\tilde{n}/N \sim 20\%$) is observed with a growth rate $\gamma/\omega^* \sim 0.2$, where ω^* is the electron diamagnetic drift frequency [9]. The dashed line shows the mode amplitude without the feedback on, i.e., the natural, uncontrolled mode amplitude. The "noise-level" base line, shown as the dotted line, was measured with the mirror off. The residual mode is suspected to be a low-amplitude trapped-particle mode driven unstable by a small population of electrostatically trapped particles. The solid line shows the mode amplitude at the feedback phase for maximum suppression. It is clear that the mode fluctuations are reduced down to the "noise" level via feedback.

A notable feature of this suppression scheme is that the overall fluctuation level is reduced. This was accomplished with an ion-beam density fluctuation amplitude of about 10% of the peak unstable mode fluctuations. Since the ion-beam fluctuations were so small, a synchronous

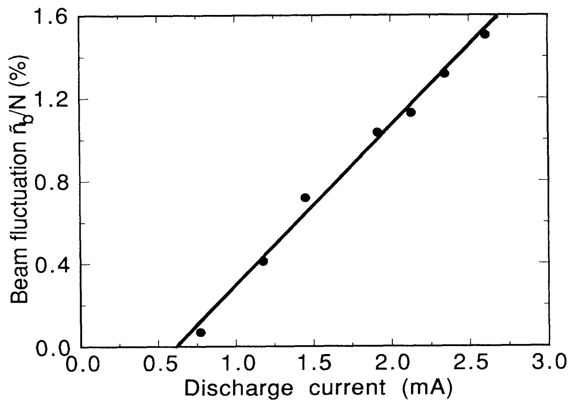

FIG. 4. Ion-beam fluctuation levels measured via a lock-in amplifier at 80 kHz for various values of the discharge current. The ion-beam density at 100% modulation is expressed as a percentage of the plasma density.

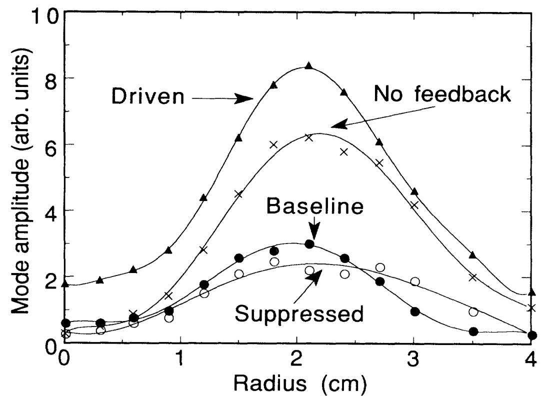

FIG. 5. A radial scan of the mode amplitudes for the four cases of maximum excitation, no feedback, maximum suppression, and "noise-level" base line, taken with the mirror off.

detection technique employing a lock-in amplifier at the mode frequency of 80 kHz was required to measure the ion-beam signal buried in the noise. The ion-beam density can be indirectly deduced in this way and is found to be typically only a few percent of the plasma density of 5×10^8 cm^{-3} as shown in Fig. 4. The beam fluctuation amplitudes have been normalized to the plasma density at the radial location of 1.4 cm.

The mode can also be strongly excited with a 180° phase shift from the optimal suppressed feedback phase. A radial scan of the mode amplitude taken with the second Langmuir probe for the four cases of no feedback, maximum suppression, maximum excitation, and base line is shown in Fig. 5. The noise-level base line was measured with the mirror off. The "no feedback" curve shows the radial profile of the uncontrolled mode amplitude. The ion beam was injected around the location of the maximum mode amplitude to improve the coupling between the ion beam and the mode. This mode is a $m=1$ radially broad, flutelike mode and one can see that the mode is suppressed over the entire radius. Similar scans taken at other azimuthal and axial locations showed that the mode was also suppressed to the same levels. Therefore this instability was globally suppressed by feedback suppression.

Because electrons are allowed to escape with the ion beam, a question arises as to whether the electrons, indirectly modulated by the ions, are responsible for the suppression. However, we show conclusively that, if the ion beam is directly modulated about the beam energy, the ions, not the electrons, are responsible for the suppression. This is illustrated in Fig. 6. The normalized mode amplitude versus phase-shifter setting is plotted for two different ion-beam energies of 120 and 80 eV. There is a phase delay in the feedback response, indicated by the shift of the whole curve to the right, as the ion energy is decreased from 120 to 80 eV. This phase delay is associated with the propagation time of the ion beam in reaching the mirror cell where the mode is localized. The 120-eV beam ions take ~8 μsec to travel 125 cm. The phase delay expected for a fractional change in the beam energy from 120 to 80 eV, for a mode frequency of 80 kHz, is ~50°, agreeing with the experimentally observed phase delay of ~50°. Electrons, on the other hand, travel much faster than the ions and would not have exhibited any measurable phase delay.

This feedback-suppression method has two main advantages over previous methods. Because the ion beam acts as a remote suppressor, it simultaneously provides a nonperturbative access to plasmas where material probes may not survive or may cause significant perturbations of the plasma. For example, this may find potential application in tokamaks. Neutral beams have the capability of accessing the hot, dense plasmas found in most machines including the present and future fusion experimental de-

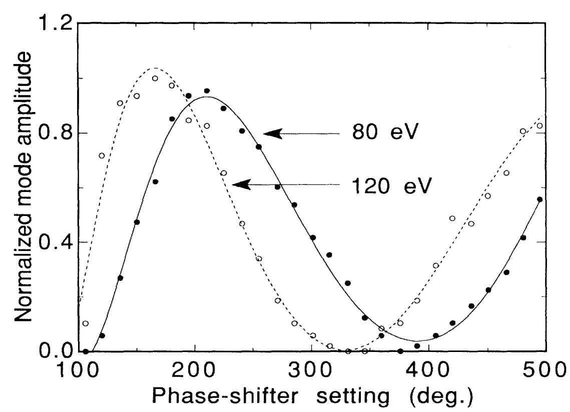

FIG. 6. Normalized mode amplitude vs the phase-shifter setting for two different values of ion-beam energy.

vices. As neutral beams are now commonly used in tokamaks for auxiliary heating, modulated ion beams derived from these neutral beams may be attractive for use as remote suppressors.

To summarize, we have successfully demonstrated that a feedback-modulated ion beam is capable of suppressing low-frequency plasma instabilities. This method is very effective, suppressing the instability to noise levels over the entire spatial extent of the mode. For effective suppression, the ion beam should have the appropriate density and should be injected around the location of peak mode amplitude. The ion-beam requirements are modest. The ion beam represents only a small perturbation to the mode and to the plasma, of the order of only a few percent.

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