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SUPPRESSION OF FLUCTUATIONS IN A MICROWAVE-PRODUCED PLASMA BY A FEEDBACK TECHNIQUE*

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ABSTRACT

A feedback control system has been used to reduce the level of incoherent density fluctuations in a microwave-generated plasma. This system, which controls the total input power, can reduce the low frequency noise in the plasma, eliminate line noise and transmitter noise from the system, and hold the plasma density constant for an extended period of time.

The stabilization of a number of instability modes in laboratory plasmas has recently been effected by electronic feedback systems of various types. Ion cyclotron[1] and m = 1 flute[2] modes in the OGRA II device, "drift type" modes in hot cathode reflex[3] and in hollow cathode arc[4] discharges, and collisional[5] and collisionless[6] drift modes in potassium plasmas have been suppressed in this way. We describe here a control system that we have used to reduce the level of incoherent density fluctuations over a frequency range extending from zero up to as high as 50 kHz in a cw microwave-produced plasma.

Our scheme differs from previous methods of feedback stabilization in that it is designed to suppress only that component of the fluctuations which is due to changes in the plasma as a whole; it is not directed toward a specific plasma instability mode.

The experiments were carried out using the plasma source "COMPLEX" (Cold Microwave Plasma Experiment) (Fig. 1), a detailed description of which has been given elsewhere.[7] A cylindrical vacuum vessel is situated in an axial magnetic field of the form shown and is filled with hydrogen gas to about 10^{-4} torr. The plasma is produced at one end of the device, where a "Lisitano Coil"[8] is used to couple microwave power (10 GHz, $\lesssim$ 1 kW) to a region of magnetic field where the electron-cyclotron frequency matches the input power frequency. The plasma streams along the magnetic field, forming a column of diameter $\approx$ 5 cm and of the length of the vessel, $\approx$ 150 cm. This "downstream" plasma is typically of electron density $\approx 10^{11}$ cm^{-3}, electron temperature $\approx$ 10 eV, and ion temperature $\lesssim$ 1 eV; downstream magnetic field is variable up to 10 kG. The properties of the upstream plasma near the Lisitano coil have not been measured, but the density and temperature are certainly greater than downstream. There are thus two semi-separate regions of plasma, both of which are of interest in this experiment--the hot, mirror-contained upstream plasma and the more experimentally acessible downstream plasma.

The feedback system used (Fig. 1) has as its sensor a photomultiplier arranged to view the total light emitted by the plasma at the mouth of the Lisitano coil. This provides a fast response signal

spatially integrated over the resonance region. The signal is compared with a preset reference level and the error signal so obtained is amplified, phase shifted, and fed back to a PIN diode modulator in the microwave generator. As with all feedback systems the gain and phase shifts must be designed to give negative feedback at all frequencies where the gain exceeds unity. The system employs both dc and ac loops, and covers a frequency range from 0 to 50 kHz. The low-frequency gain is several hundred and the high-frequency ($\gtrsim$ 5 kHz) gain is less than 10. Only chopper-stabilized operational amplifiers are used in the dc loop, so that the system has negligible dc drift.

This system does reduce the fluctuations in our plasma, and that improvement was observed in several ways (Fig. 1). The effect of the feedback upon the upstream plasma can be seen in the signal from the upstream photomultiplier. The downstream plasma was observed with a separate photomultiplier, and with a Langmuir probe biased to monitor ion saturation current. Feedback affects all three of these signals. This effect can be considered as consisting of two more or less separate regimes--long-term stabilization and the suppression of low-frequency ($\approx$ kHz) fluctuations. Without feedback the average signal (averaged over $\approx$ 1 sec) from the upstream photomultiplier is unsteady and may vary up to $\approx$ 10% within a few minutes. With feedback this fluctuation disappears and the signal holds constant for an hour or more to within $\approx$ 0.1%. Without feedback, 10% fluctuations are also typical of the average ($\approx$ 1 sec) current drawn by the probe in the downstream plasma. With feedback such fluctuations can be reduced to about 1%. Similar improvement is seen by the downstream phototube.

Spectra of the noise seen by the upstream photomultiplier with and without feedback (with conditions otherwise identical) were recorded (Fig. 2a) using a wave analyzer (Hewlett-Packard type 302 with motorized dial). The noise in the upstream plasma--at least as measured by this signal--is almost completely eliminated below 5 kHz (about two orders of magnitude reduction) and is much reduced everywhere below 50 kHz. Since this upper frequency limit is due to the electronics of the system, the upper limit of the method of control may be higher still. Our interest is not primarily in the plasma in this region, apart from its bearing on the downstream plasma. A number of experiments, however, are very directly concerned with hot-electron mirror-contained microwave-produced plasma,[9] and the application of a feedback system of the type described here may, in some instances, be desirable.

In Fig. 2b is shown a similar spectrum analysis of the signal from the probe in the downstream plasma. The higher-frequency noise, which does not originate in the source, is not affected by feedback. There is considerable improvement at lower frequencies, though, as is shown in more detail in Fig. 2c. There is here a white noise spectrum which is reduced by feedback. Also present when there is no feedback are two peaks of about 20 and 140 Hz. These appear to be instabilities in the resonance region. Their exact nature has not been investigated except to note that they are strongly dependent on neutral gas pressure and, as can be seen, they are eliminated by feedback. The feedback was found to be most effective when the downstream magnetic field was fixed at the resonance value (3.7 kG). This was the case when the data of

Fig. 2c were taken. Less reduction in the white noise was seen under other conditions, but such features as the two peaks are always completely eliminated by feedback. If there is transmitter noise or 60 Hz noise in the plasma (not shown in Fig. 2c), this also is eliminated by feedback.

The probe ion saturation current is a measure of ion density. The light emitted from the plasma, however, is due to only the more energetic electrons because the average electron energy ($\approx$ 10 eV) is less than that needed to excite a neutral atom.[10] Nevertheless, spectra of low-frequency noise in the signal from the downstream photomultiplier are quite similar to those from the probe, and comparable improvement due to feedback is seen. The indication is that if one can stabilize a plasma source one can thereby reduce the fluctuations in various aspects of the resulting plasma.

It should be pointed out that fluctuations in our plasma source can be reduced by carefully "tuning" the gas pressure, magnetic field strength, and microwave power. Regimes can be found where the behavior is good and where the addition of the feedback control effects little additional improvement in the downstream plasma. (The upstream plasma is always improved.) These "quasi-quiescent" regimes are, however, only a small part of the entire range of achievable parameter space. The significance of our system is that it can considerably increase the extent of the "quasi-quiescent" regimes.

In conclusion, the feedback system we have described suppresses low-frequency fluctuations in a microwave-produced plasma. The method

has its obvious limitations, but we propose that our system may well complement other feedback-stabilization schemes which are directed toward specific plasma instability modes. In addition, the long-term density stability is a feature of considerable attraction per se. Although our experiments were performed on a microwave-produced plasma, the method should be applicable to any plasma-preparation process in which there is a sufficiently rapid control over the power input to the plasma. Finally, we suggest that the method may be improved by more sophisticated optical sensing (e.g., wavelength and spatial localization), and, further, that optical sensing of plasma instability modes, when possible, may provide a convenient, nonperturbing sensor for the feedback stabilization of fusion-type plasmas.

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9. For example: R. A. Dandl, A. C. England, W. B. Ard, H. O. Eason, M. C. Becker, and G. M. Haas, Nucl. Fusion 4, 344 (1964); H. Ikegami, H. Ikezi, M. Hosokawa, S. Tanaka, and K. Takayama, Phys. Rev. Letters 19, 778 (1967).
10. Furthermore, any modulation of input source power is seen by the probe after a delay of about 30 μsec, whereas the same signal is seen by the downstream photomultiplier without any such delay.

Finally, an attempt was made to operate the control system with the downstream photomultiplier as sensor. This was successful to the extent that the control did function and fluctuations in the sensor signal were reduced, but no effect was seen on the probe, further indicating the different nature of the two signals.

FIGURE LEGENDS

Fig. 1. Diagram of the experimental device and control system and graph of the magnetic field shape.

Fig. 2. Spectra of signal received by (a) upstream photomultiplier (0 to 50 kHz), (b) Langmuir probe (0 to 25 kHz), (c) Langmuir probe (0 to 1 kHz), with and without feedback loop.

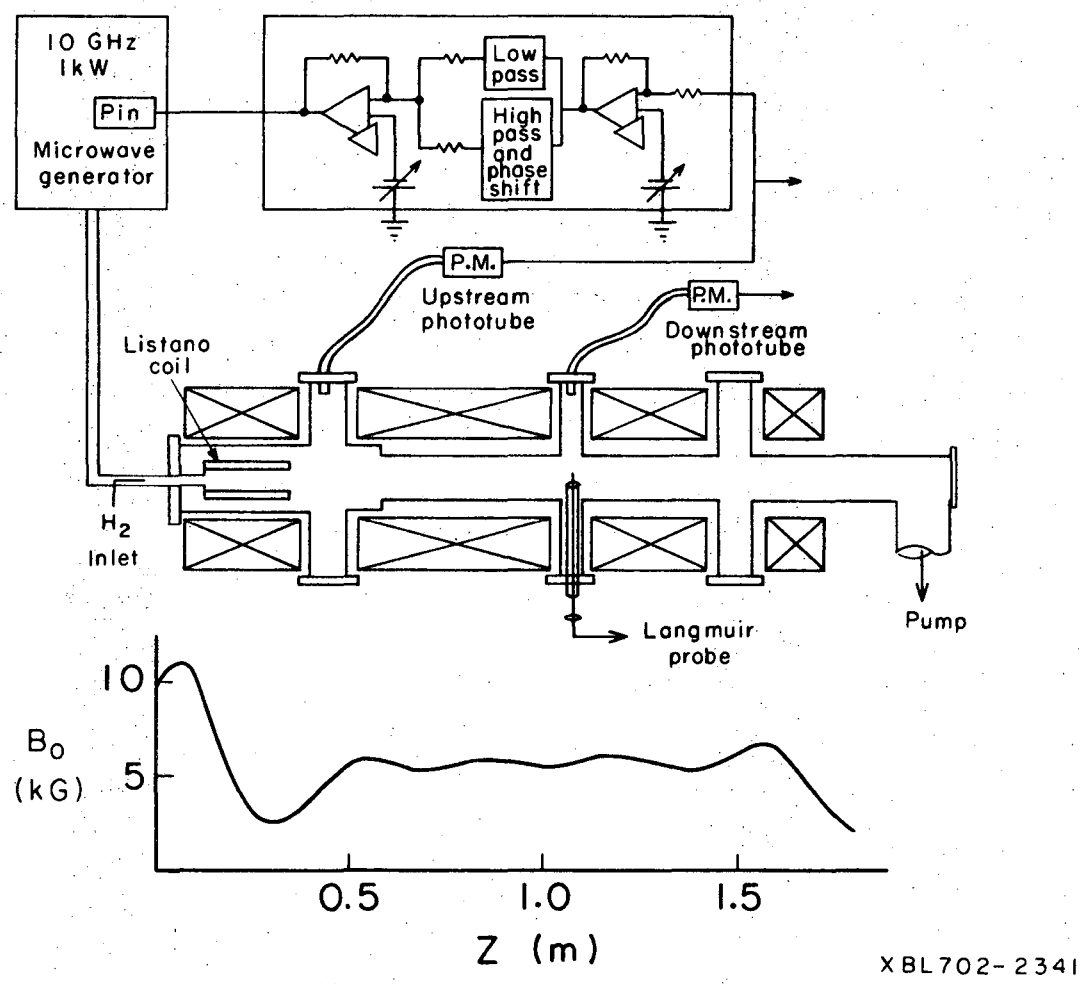
10 GHz
1kW
Pin
Microwave generator
Low pass
High pass and phase shift
P.M.
Upstream phototube
P.M.
Downstream phototube
Listano coil
H_2 Inlet
Langmuir probe
Pump
10
5
B_0 (kG)
0.5
1.0
1.5
Z (m)
XBL702-2341

Fig. 1

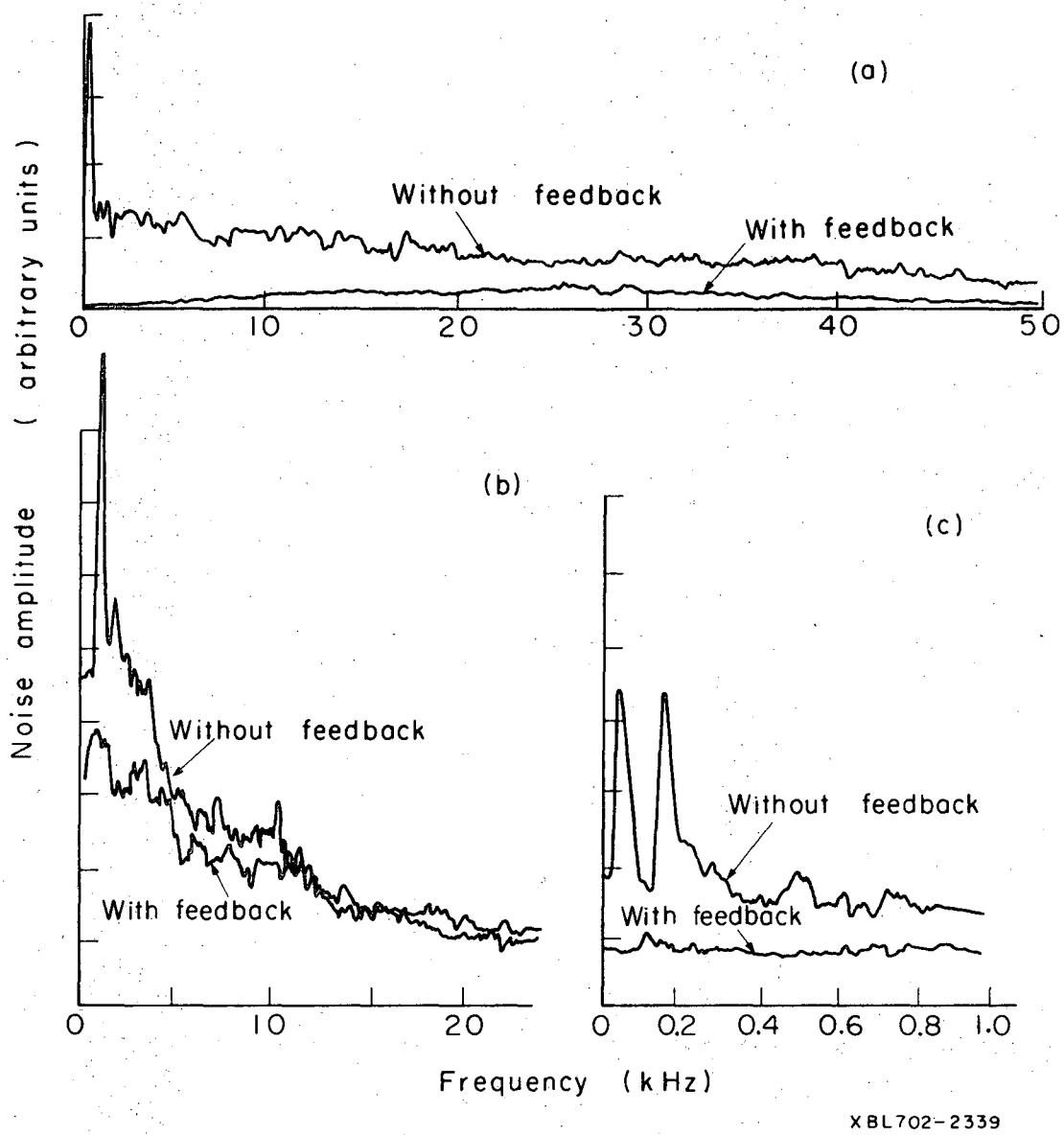
(a)
Without feedback
With feedback
0
10
20
30
40
50
Noise amplitude (arbitrary units)
(b)
Without feedback
With feedback
0
10
20
(c)
Without feedback
With feedback
0
0.2
0.4
0.6
0.8
1.0
Frequency (kHz)
XBL702-2339

Fig. 2

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