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**FEEDBACK CONTROL AND STABILIZATION
EXPERIMENTS ON THE TEXAS
EXPERIMENTAL TOKAMAK
(TEXT)**

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CONTENTS

	Page
ABSTRACT	1
1. INTRODUCTION	1
2. FEEDBACK WAVE-LAUNCHING SYSTEM AND DIAGNOSTIC	2
3. EXPERIMENTAL OBSERVATIONS AND RESULTS	4
4. DISCUSSION	11
ACKNOWLEDGMENTS	11
REFERENCES	12

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ABSTRACT

Plasma edge feedback experiments on the Texas Experimental Tokamak (TEXT) have been successful in controlling the edge plasma potential fluctuation level. The feedback wave-launcher, consisting of electrostatic probes located in the shadow of the limiter, is driven by the local edge potential fluctuations. In general, the edge potential fluctuations are modified in a broad frequency band. Moreover, it is observed that the potential fluctuations can be reduced (≤ 100 kHz) without enhancing other modes, or excited (10 to 12 kHz), depending on the phase difference between the driver and the launcher signal, and gain of the system. This turbulence modification is achieved not only locally but also halfway around the torus and has about 2 cm of poloidal extent. Experiments on the characterization of the global plasma parameters with the edge feedback are discussed. Effects of the edge feedback on the estimated fluctuation-induced radial particle flux as well as on the local plasma parameters are presented.

1. INTRODUCTION

The edge plasma fluctuations in tokamaks play a significant role in the overall plasma confinement characteristics [1]. Experiments on the Texas Experimental Tokamak (TEXT) indicate that electrostatic fluctuations in the edge plasma are responsible for most of the energy and particle transport [2]. Although the underlying basic mechanisms that drive the edge turbulence are still the subject of ongoing research in fusion devices, in this work, a possible control and influence of the edge plasma fluctuation level are investigated on TEXT. These exploratory experiments have been performed utilizing edge plasma feedback to study its effects on edge turbulence characteristics as well as on the global plasma parameters. The local edge potential fluctuations are used to drive the feedback wave-launcher located in the shadow of the limiter. A number of earlier feedback

experiments in various plasmas, that is, mirrors, Q-machines, and stellarators [3], have been designed to stabilize and suppress low-frequency instabilities. The overall observation in those experiments was that while suppression of the dominant lowest-order mode was possible, nevertheless, new, higher-order modes appeared [3,4]. In this report, the results observed from the recent edge feedback control and stabilization experiments performed on TEXT are summarized. Moreover, experimental measurements are presented on the broadband reduction of edge plasma fluctuations on a tokamak machine without enhancing new modes. In addition, observations on the effects of the edge feedback on local plasma parameters are discussed.

2. FEEDBACK WAVE-LAUNCHING SYSTEM AND DIAGNOSTIC

The edge feedback experiments are performed with a wave-launching system consisting of two electrostatic launching probes (L1, L2) shown in Fig. 1. These active probes (APs) are operated on the electron side of the (I,V) characteristic. This operating region, which is made by introducing a positive dc bias to the probes, provides a large dynamic response to the launcher as a result of the broad linear region available there. Each probe is fed separately by independent ac power supplies capable of providing up to 1.5 kW of power in the frequency range of 9 to 250 kHz. As shown in Fig. 1, the power sources are driven by a plasma signal through an isolated voltage divider and an adjustable frequency band pass filter, typically 10 to 100 kHz, with a voltage gain (G) control, and then a unity gain variable phase shifter follows. The input sensing (driver) signal to the launcher can either be fluctuating density or plasma potential. The phase shifter provides an independent control of the ac phase difference $\Delta\phi$ between the driver and the launching signals. To expect to have significant external influence on the edge turbulence, APs are poloidally separated by $d \sim \lambda/2 = 1.8$ cm, with $\lambda = 2\pi/\bar{k}$, where $\bar{k}$ is the mean poloidal wavenumber of the electrostatic fluctuations. The AP can handle an ac probe current of up to $\tilde{I}_{ac} \sim 15$ A. An impedance matching (MATCH) (Fig. 1) network between the launcher and the power source is included for maximum power delivery to the plasma. On the launcher head, beside the APs there are two extra small sensors (S1, S2), as illustrated in Fig. 1, separated by $d/2$, to measure the local plasma floating potential ϕ . To reduce the power load on AP during the plasma discharge, the launcher head is placed on a pneumatic mechanism that provides the fast radial stroke. The fast plunging action into the plasma takes about 50 ms for a 5-cm stroke; the probe stationary time is ~ 100 ms. The main diagnostic utilized during these experiments is a poloidally aligned seven-pin (these are 1 cm poloidally separated) sensor probe (SPSP) array for measuring ϕ , located at the bottom center of the machine halfway around the torus from AP, separated by $\sim 157^\circ$ toroidally and 180° poloidally, and used as a downstream sensing probe.

Fig. 1. Schematic of edge feedback wave-launching system, the active probe (AP). Launchers (L1, L2), which are oriented poloidally, are driven by local floating potential fluctuations $\tilde{\phi}$ obtained from sensor S1. Near-field (local) feedback effects are monitored with sensor S2.

3. EXPERIMENTAL OBSERVATIONS AND RESULTS

The series of edge feedback experiments are performed in ohmically heated plasmas with a flat top of ~ 300 ms in hydrogenic discharges. The toroidal magnetic field is $B \sim 2.2$ T; the line average plasma density is $\bar{n}_e \approx 3 \times 10^{13} \text{ cm}^{-3}$. The rail limiters (top, bottom, and outside), are located at $r_p = 27$ cm; AP is at the limiter shadow, where $r_{ap} = 27.5$ cm, at the top center of the plasma column. The present feedback experiments are performed by driving the launcher system with the local floating potential fluctuations $\tilde{\phi}$, obtained from the sensor S1 (see Fig. 1). The launcher dc bias of ~ 50 V is used. Results of comparison experiments with and without the applied dc bias, which is about one-third of the local plasma potential, indicate that this dc bias is not enough to otherwise affect the results of the feedback experiments. As observed in earlier limiter biasing experiments [5] performed with ~ 50 V, there was almost no effect on the global and turbulence characteristics of the edge plasma.

Fig. 2. Feedback arrangement during plasma discharge. When AP reaches its final radial position r_{ap} , feedback is then applied (FB on) for ~ 40 ms during flat top of the discharge.

As shown in Fig. 2, when AP reaches its set final radial position, the edge feedback is then applied [feedback (FB) on] for ~ 40 ms during the flat top of the plasma discharge. The results are compared to the measurements that are taken when the feedback is off (FB off) during the same discharge. The results of the earlier wave-launching and excitation experiments [6,7], that is, injecting ~ 30 -kHz signal at the edge, have indicated that the

propagation is taking place along the magnetic field line. Therefore, these feedback experiments are performed by locating AP, the wave-launcher, and the downstream sensing probe SPSP, which acts as a far-field sensor, on the same magnetic field line. This configuration is obtained from detailed calculations of the magnetics of TEXT, which is possible with a plasma current of $I_p \sim 180$ kA at $r = 27.5$ cm.

The following experiments are carried out with a typical wave-launcher ac current of $\tilde{I}_{ac} \sim 5$ A (for the gain setting of $G = 10$) which may be viewed as the minimum value for the experiment. The observed results of the edge feedback on the spectrum of the potential fluctuations (FFT of $\tilde{\phi}$) are summarized in Figs. 3 and 4, for $\Delta\phi = 0$ and π , respectively; the no feedback case is also included for comparison. Here, Figs. 3(a) and 4(a) represent the local effects, measured with the sensing tip S2 (Fig. 1), the near-field sensor. On the other hand, Figs. 3(b) and 4(b), which are obtained from the measurements of SPSP, the far-field sensor, show the observed effects about 12 m away from where the edge feedback is introduced.

Fig. 3. Effects of edge feedback ($G = 10$) on frequency spectrum of potential fluctuations (FFT of $\tilde{\phi}$) measured at the location of (a) AP (near-field effects from S2), and (b) SPSP (far-field effects) for the phase shift setting of $\Delta\phi = 0$ compared to no feedback case.

Fig. 4. Same measurements as in Fig. 3, but for $\Delta\phi = \pi$.

In general, as discussed in detail in ref. [7], a broadband frequency modification of the edge potential fluctuations, which are the dominant edge fluctuations in TEXT [8], is achieved. Moreover, it is observed that the edge potential fluctuations can be reduced (≤ 100 -kHz) negative feedback (stabilization), $\Delta\phi = \pi$, without enhancing other modes, or excited (~ 10 -kHz) positive feedback (destabilization), $\Delta\phi = 0$, depending on $\Delta\phi$, both the near-field and at the location of the far-field sensing probe SPSP. The $f_{\text{mhd}} \sim 9.5$ -kHz peak seen in Fig. 4, with the feedback, is identified to be the MHD activity.

Fig. 5. Effects of edge feedback on MHD signal (FFT of $\dot{b}_r$) for $\Delta\phi = \pi$.

In Fig. 5, the effects of the edge feedback observed from one of the MHD coils, which is located at the top of the machine ($r > r_p$) and oriented to sense the radial component of the fluctuating magnetic field $\dot{b}_r$, is presented for $\Delta\phi = \pi$. The $f_{\text{mhd}} \sim 9.5$ -kHz activity is somewhat enhanced by about 15%, and the rms value of $\dot{b}_r$ is $\sim 12\%$ higher with the feedback. In the case of $\Delta\phi = 0$, there is no significant change on f_{mhd} while the rms value of $\dot{b}_r$ is $\sim 15\%$ higher.

Fig. 6. Effects of edge feedback on spectrum of potential fluctuations measured at far-field sensor SPSP for $\Delta\phi = 0$ and $G = 20$ compared to no feedback case.

In the next experiment the feedback gain is increased by a factor of 2 ($G = 20$), and the resulting spectrum of $\tilde{\phi}$ in the far-field sensor is given in Fig. 6 for $\Delta\phi = 0$. In this case $\tilde{I}_{ac} \sim 10$ A is causing a significant, by about a factor of 3, destabilization (excitations) near ~ 12 kHz. At the same time $\tilde{\phi}$ level around $f_{mhd} \sim 9.5$ -kHz (Fig. 6) is also increased by about a factor of 2.

Fig. 7. Poloidal profile of feedback excitation [FFT of $\tilde{\phi}(\sim 12$ kHz)] with respect to no feedback case] obtained by 7-pin poloidally aligned sensor probe array (pins are 1 cm poloidally separated) located at $r = 27.5$ cm; it is ~ 12 m away from AP. Typical measured poloidal extent is about 2 cm (FWHM).

In addition, the poloidal extent of the feedback excitations on $\tilde{\phi}$ is investigated. The measurements with SPSP give about 2 cm (FWHM) poloidal extent (Fig. 7) for the feedback excitation of $\tilde{\phi}$. These results indicate that the edge feedback can modify the amplitude of the potential fluctuations effectively not only locally but also halfway around the torus along a magnetic field line.

Previous edge feedback experiments [6] (with $G = 10$) carried out with a fast reciprocating Langmuir probe (FRLP) array [9], located at the same port as SPSP, gave similar results, but only in low frequencies (≤ 10 kHz), on the fluctuating ion saturation current, which is mostly dominated by the local density fluctuations $\tilde{n}$. The results of those feedback experiments in terms of the phase shift $\Delta\phi_{12}$ between the probes L1 and L2 with respect to L1 on the rms values of the potential and the density fluctuations, normalized to their values without the feedback, are given in Fig. 8.

Fig. 8. Effects of feedback (FB) in terms of phase shift between probes L1 and L2 on rms values of potential and density fluctuations, normalized to without feedback.

This figure shows that the present feedback scheme appears to be more effective for reducing the edge potential fluctuations than the density fluctuations, due to broadband reduction of the potential fluctuations with the edge feedback. The corresponding fluctuation-induced radial particle flux $\tilde{\Gamma}_r$ is also estimated by ignoring the temperature fluctuations [8]. Using the measurements of FRLP, the estimated $\tilde{\Gamma}_r$ is somewhat modified by the edge feedback. For example, $\tilde{\Gamma}_r$ is $\sim 20\%$ higher than without the feedback when $\Delta\phi_{12} = 0$, but it becomes $\sim 30\%$ lower when $\Delta\phi_{12} = \pi/2$.

The effects of the edge feedback on the frequency spectrum of the edge bolometer, $r \sim 27$ cm, signal P_{rad} , which is related to the impurity radiation integrated along the line-of-sight of the detector, is shown in Fig. 9 for $\Delta\phi = 0$. This signal is related to $P_{\text{rad}} \sim n_e n_z I_z(T_e)$, where n_z is the impurity density, and $I_z(T_e)$ represents the impurity radiation cooling rate for the edge electron temperature T_e .

Fig. 9. Frequency spectrum of edge bolometer signal is shown with edge feedback for $\Delta\phi = 0$.

Thus, the data of Fig. 9 indicates that the edge plasma parameters are somewhat modified by the edge feedback. For example, the rms value of the fluctuating bolometer signal is $\sim 20\%$ higher than without the feedback. The radial edge plasma density and temperature profiles are not available at this time, but their local values are observed to be affected by the feedback. The measurements from FRLP, located at $r = 27.5$ cm, show that reduced $\tilde{\phi}$ leads to somewhat lower T_e and higher n_e . For example, when $\tilde{\phi}$ is reduced as much as by about a factor of 0.7 by the feedback (Fig. 8), the measured local T_e is somewhat lower by about a factor of 0.75. On the other hand, the corresponding edge density n_e is higher by about a factor of 1.4. Overall, it appears that a reduction of the edge potential fluctuations by the feedback results in lower local electron temperatures, as is observed in earlier studies on the turbulence scaling experiments on TEXT [10], and that, in turn, may cause the increase in the local density because the plasma pressure remains constant. This result may suggest a possible application of the edge feedback for controlling the edge power loads, $T_e^{3/2}$, to the plasma facing components. Moreover, the lifetime of the edge components can also be prolonged because the sputtering yield is lower due to reduced impact energy of ions, $\sim 5T_e$ [11], as a consequence of low T_e from the edge feedback. Meanwhile the global core plasma parameters have not been affected by the present feedback experiments.

4. DISCUSSION

Plasma edge feedback experiments on TEXT have been successful in stabilizing the edge plasma potential fluctuation levels. Although the underlying physics issues have not been resolved from the present data, these experiments have demonstrated the feasibility of the edge feedback to influence, modify, and control the levels of the electrostatic edge fluctuations. Moreover, effects of the edge feedback on the local plasma parameters suggest the use of the feedback control to possibly influence the power levels on the edge components. Specifically, reduction of the electron temperature with the edge feedback lowers the erosion rate of the plasma facing components and, in turn, impurity production at the edge. On the basis of these observations, detailed experiments are planned with additional diagnostics at various feedback gain and phase shift settings for TEXT Upgrade, which has a divertor configuration. In addition, plans include measuring profiles with the optimized feedback schemes. These detailed experiments are needed for understanding the underlying mechanism of the edge feedback to design techniques for an effective control. More launchers will also be implemented to improve the poloidal flux coverage at the edge so that most impact on the global plasma characteristics can be achieved with the feedback.

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