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INITIAL ASSESSMENT OF THE MHD
STABILITY OF TMX-U

W. E. Nexse,

August 4, 1983

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

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INITIAL ASSESSMENT OF THE MHD STABILITY OF TMX-U

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ABSTRACT

In its operation to date TMX-U has reached values of beta which, for all except the hot electron beta, are close to the proposal values and has not encountered MHD stability problems. The hot electron beta values are presently limited by gyrotron output power and pulse length as well as ion confinement time. Further exploration of stability awaits full thermal barrier operation.

Introduction

In our first Tandem Mirror Experiment (TMX) we demonstrated the existence of a scalable magnetic field geometry that maintained magnetohydrodynamic (MHD) stability at finite beta.¹ More extensive investigation of the MHD stability boundary for simple tandem operation has been done in the Phaedrus experiment.² During the initial experiments, Tandem Mirror Experiment-Upgrade (TMX-U) has confirmed the TMX results and in normal operation has not shown any sign of MHD instability.

This stability has allowed us to concentrate on our primary goal--more effective plasma confinement by production of a thermal barrier in the end cells (plugs). Once this goal is obtained, we plan to explore the unique effects of thermal barrier operation on MHD stability.

In the remainder of this report we summarize our present knowledge of the MHD stability of TMX-U.

Experimental Method

Recent developments in tandem mirror MHD theory show that the only important perturbation to consider is a rigid displacement of the plasma cross section,³ i.e., a perturbation in which the MHD displacement varies only as a function of distance along the magnetic axis. With such a perturbation, there are no finite Larmor radius (FLR) effects because both ions and electrons experience the same average force.

Consequently, in comparing our experimental results with theory we now use radially averaged values of beta instead of peak betas. Such values are more easily determined than peak values because the latter require more detailed knowledge of the plasma pressure profile. The average perpendicular plasma beta can be obtained by combining measurements of plasma diamagnetism with measurements of the plasma radius. In addition, MHD-stability calculations require the proper modeling of how the plasma pressure varies with the magnetic field in the various regions of the tandem mirror.

We used an array of 14 diamagnetic loops⁴ to measure the magnetic moments/unit length at three different field values in each end plug and five field values in the central cell. (Three of the loops are redundant.)

For our calculations we determined that if $m(z_j)$ is the diamagnetic moment/unit length obtained from a loop located at z_j , then the radially averaged value of perpendicular beta at z_j is given by

$$\overline{\beta}_{\perp}(z_j) = \frac{0.8 m(z_j)}{B r^2} \quad (1)$$

with $m(z_j)$ measured in A cm²/cm, magnetic field B in G, and radius r in cm. The plasma radius is determined by a combination of beam-attenuation measurements⁵ and flux mapping (assuming $B r^2$ is constant).

Experimental Observations

In Table 1 we list our best values of the plasma parameters to date, compared with the proposal values, emphasizing that these values were not all obtained on the same shot or under the same operating conditions. The uncertainties in the beta values reflect mainly the uncertainties in the values of radius. We show that except for the hot electron beta, we have approached the proposal values without encountering MHD stability problems; furthermore, any increase in the hot electron beta should be stabilizing because it is in the minimum B well in the end plugs. The hot electron beta values are presently limited to about 20% of these proposal values by gyrotron output power and pulse length as well as ion confinement time.

Since MHD stability calculations require the proper modeling of the plasma-pressure variation with magnetic field, the stability boundary depends on the method of containing and heating the plasma. Figure 1 shows two

Table 1. Comparison of plasma parameters of TMX-U: June 1983 vs proposal values.

	End cell		Central cell	
	Hot electrons	Sloshing ions	Warm ions	Beam-injected ions
Energy (keV)	30-70 (50)	5-10 (10)	0.1 (0.9)	5-10 (6)
Density (10^{12} cm ⁻³)	1 (4)	0.5-3 ^a (2.5)	0.3-5 (15)	2 (6)
Beta (% perpendicular, average ^b)	3-5 (15)	1 (1)	0.1 (3)	8 (12)
Radius ^b (cm)	22-17 (15)	20 (14) ^c	26 (20)	26 (20)
Length (cm)	120 (60)	210 (210)	510 (445)	400
Confinement time (ms)	20-40 (19)	3 (7)	2 (17)	5 (10)

() = Proposal value predicted.

^a Without hot electrons; sloshing-ion mode.

^b parabolic radial profile, $\beta = 2 \langle \beta \rangle$.

^c $r_p = (B_0/B_p)^{1/2} r_c$.

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Figure 1. The MHD stability boundary for two possible central-cell pressure distributions in TMX-U. Note that $\bar{\beta}_A$ is the radially averaged value of perpendicular beta in the center plane of the end plug, and $\bar{\beta}_{c_{\perp}}$ is the same in the center plane of the central cell. The solid curve is for a constant pressure to the peak of the inner mirror, whereas the dashed curve is for an experimental mirror-trapped beam-injected central-cell plasma. The point refers to the data of Fig. 2.

examples of stability boundaries in TMX-U; the solid line represents an isotropic central cell plasma with constant pressure to the peak of the inner mirror, whereas the dashed line is obtained by using the experimental central-cell pressure profile for a mirror-trapped beam-injected central-cell plasma. The much higher stability of the mirror-trapped plasma is due to the lower pressure weighting of bad curvature regions near the peak of the central cell mirrors.

Figure 2 shows the time behavior of the diamagnetic moment/unit length at three positions along the plasma (near the east-plug center plane, the central-cell center plane, and the west-plug center plane) for one of our best cases of high beta operation resulting from hot ions (neutral beam injection). Central cell beam-attenuation measurements fitted to a parabolic radial distribution yield a parabolic radius of about 26 cm for the plasma. Equation (1) yields a maximum value of $\bar{\beta}_1 \approx 8\%$ in the central cell.

Assuming flux mapping of the plasma through the plug, we find

$$\frac{\bar{\beta}_A}{\bar{\beta}_C} \approx \frac{m_{\text{east}} + m_{\text{west}}}{2 m_{\text{cc}}} \approx 0.175 \quad (2)$$

This point is shown on Fig. 1. We see that we lie close to the boundary for a mirror-contained central-cell plasma, although our diagnostics do not indicate any sign of low frequency fluctuation. It is well within the region of predicted instability for an isotropic central-cell plasma, thus experimentally demonstrating the role of the plasma distribution on stability.

We have tried to cross the stability boundary by halting neutral beam injection of the plugs after the plasma is built up. In these attempts the central cell plasma could not maintain a steady state after beam turnoff; however, it decayed more slowly than the plug plasma, and in the process the ratio of $\bar{\beta}_A/\bar{\beta}_C$ was steadily reduced. Such a run is shown in Fig. 3. Although it appears possible that in this case we may have crossed the stability boundary, we detected no sign of instability.

In more recent operation we have produced a central-cell stand-alone mode (similar to that observed on Phaedrus⁶) with injection into the central cell only. The addition of about 40 kW of electron-cyclotron resonant heating (ECRH) at resonance ω_{ce} in the west plug resulted in a steady-state plasma as long as the ECRH was on. No plasma beta was detectable in either plug; we

Figure 2. Plasma diamagnetic moment/unit length versus time from the diamagnetic loops located near the central planes of (a) the east plug, (b) the central cell, and (c) the west plug. This data represents Shot #18 on Jan. 20, 1983.

Figure 3. Test of TMX-U stability. The neutral beams in the end plugs are turned off while the remainder continue in the central cell. As a result, the end plugs decayed more rapidly than the central cell, causing a sweeping of $\bar{\beta}_A/\bar{\beta}_C$ towards lower values. Also shown are the stability boundaries for an isotropic central cell plasma distribution and a beam-injected mirror-trapped distribution. (The term c.c. stands for central cell.) These measurements were made on July 28, 1982 on Shot #45.

estimate from our noise level that $\bar{\beta}_A/\bar{\beta}_C < 0.05$. The central cell $\bar{\beta}_{C1} \approx 1.5\%$. Again no sign of instability was observed. Under these conditions of very low β_A/β_C and flow confinement, it appears likely that other stabilizing mechanisms such as line-tying must be important or even dominant.

Under some conditions of abnormal magnetic field operation or high beam injection, low frequency fluctuations were observed that may be MHD-related. Nevertheless, major plasma losses have not occurred.

Summary

Except for the hot electron beta values, we have approached the proposal beta values without encountering MHD stability problems. Under some conditions of abnormal operation, low frequency fluctuations have been observed that apparently do not cause major plasma losses. It is probable that under the present conditions of flow confinement, some of the MHD stability may be due to line-tying. Production of a thermal barrier (leading to improved plasma confinement) should result in a test of MHD stability at higher beta and with a greatly reduced line-tying contribution.

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