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MICROSTABILITY OF THE TMX TANDEM MIRROR EXPERIMENTS*

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ABSTRACT

In the tandem mirror device, an efficient source of warm ions, the central cell, is available for stabilization of ion loss-cone instabilities. These instabilities previously limited ion confinement in single-cell mirror experiments. In the simple tandem mirror device, TMX, the drift cyclotron loss-cone (DCLC) mode was stabilized by plasma flow from the central cell into the end cell. However, to enhance the central-cell confinement and provide MHD stability, neutral beams were injected perpendicular to the magnetic field, which resulted in the excitation in the end cell of the Alfvén ion-cyclotron (AIC) instability driven by plasma pressure and velocity distribution anisotropy. In the thermal-barrier experiment, TMX-U, the end-cell beams were injected at a 45° angle to the magnetic field to produce a sloshing-ion distribution, which is required to form the thermal barrier and the plugging potential. Ion distributions created by oblique injection were stable to the AIC mode and to the midplane (minimum magnetic field location) DCLC mode. However, an ion

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loss-cone instability remained at an axial location just outside the outboard peak of the sloshing-ion axial density profile, which is the density peak closest to the end wall. This mode can enhance the sloshing-ion loss rate, particularly at the lower levels of electron-cyclotron resonance heating (ECRH) used to form the thermal barrier. The stability to ion-cyclotron modes is critical to the performance of tandem mirrors and to designs for a mirror-based, high-fluence neutron source.

INTRODUCTION

In order to have the mirror concept scale in performance to the fusion reactor regime, it was envisioned that some enhancement of the confinement of low-energy ions was essential. This led to the invention of the tandem mirror concept that was further refined by adding thermal barriers to improve the efficiency of the various magnetic configurations in a tandem mirror. That is, a high-density plasma for fusion reactions is confined in the simple solenoidal geometry, and the complicated minimum-B configuration is driven only as necessary for stability and axial potential formation. Therefore, we needed to understand the theoretical and experimental issues concerning stability in order to accurately predict peak levels of performance. This paper emphasizes those aspects of the tandem mirror concept that relate to ion microstability.

Fig. 1 shows the measured axial profiles in the Tandem Mirror Experiment-Upgrade (TMX-U) at LLNL. In this device, the first of the thermal-barrier tandem mirrors, we used the minimum-B end cells to provide MHD stability and to create the plugging potential and thermal barrier. Highly successful experiments [1] indicated a marked reduction in the axial ion end losses derived mostly from the central cell at densities of up to 2 $\times 10^{12}$ cm^{-3}. All physics features required for a thermal-barrier tandem mirror have been shown to exist in this device. This implies we have formed the necessary ion and electron species for thermal-barrier tandem mirror confinement and have sufficiently provided for ion microstability in the end-cell regions. As in TMX (the nonthermal-barrier Tandem Mirror Experiment), the TMX-U central cell has provided a warm ion stream consistent with the requirement for stability to loss-cone modes at the end-cell midplanes. Similarly, in TMX-U, by injecting neutral beams in the end cells at an angle to the axial magnetic field, we have created a

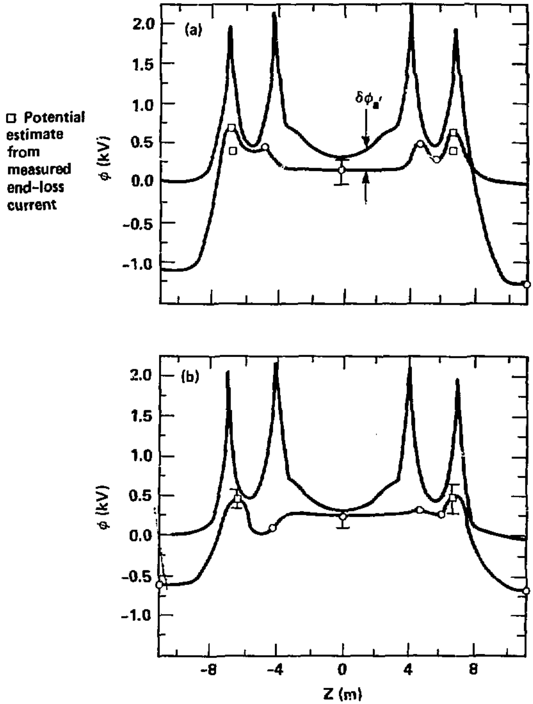

Figure 1. Typical TMX-U axial potential profiles: (a) at 30 ms, when the axial current is low, and (b) at 36 ms, after loss of plugging.

sloshing-ion distribution stable to the AIC mode. These two observations are indicative of a resounding success in the area of mirror ion microstability and the details of that successful evolution will be discussed here.

The 2XIIB experiment, a single minimum-B mirror cell, was operated at high density ($\sim 1 \times 10^{14}$ cm^{-3}) with beta values exceeding 0.5 [2]. In this experiment, the dominant ion instability was the DCLC mode, which was stabilized by cold plasma injected from an external plasma gun. Although this method provided the necessary stability, an additional important effect may have been electron conduction to the end walls, which depressed the electron temperature and assisted stability because of the smaller hole in the velocity space distribution. Nevertheless, in terms of MHD stability and achievable beta, the performance of 2XIIB was impressive. Results from 2XIIB, along with the recent experimental advances in ion microstability, are critical to current ideas concerning a mirror-based approach to a high-fluence neutron source.

ION-CYCLOTRON STABILITY IN TMX-U

In terms of ion microstability, the greatest success in TMX-U relative to the earlier experiments is the total absence of the AIC instability. In the earlier TMX, we found that the central-cell plasma losses did provide the cold plasma stream necessary to stabilize loss-cone-driven instabilities. However, a residual loss-cone mode in TMX-U is driven unstable at an axial location outside (toward the end wall) the peak of the sloshing-ion profile. At this location, the formation of a potential maximum provides the enhanced central-cell confinement that thus limits the amount of stabilizing stream outside the peak of the sloshing-ion density--a successful tandem mirror. These results are consistent with theory developed over the past several years [3].

Stability to the AIC mode was predicted using a theoretical code developed at LLNL [4,5], which indicated that AIC stability is improved by injecting neutral beams at an oblique angle with respect to the magnetic field. The angular injection provides a "sloshing character" to the spatial distribution of the mirror-confined ions in the end cell, which is advantageous to potential formation as well as stability. For TMX-U, neutral beams were injected at 47° and 40° angles with respect to the magnetic field. Fig. 2 shows the result of numerical integration of the AIC dispersion relation [4,5], which indicates that stability is improved by varying the injection angle from 90°. Fig. 2 also shows the real frequency expected for the AIC mode, which is less than the midplane ion-cyclotron frequency. In the operation of TMX-U, we did not observe end-cell fluctuations at frequencies below the midplane ion-cyclotron frequency.

When finite perpendicular wavelengths [6] are added to the AIC theory used above, instability can occur at higher harmonics of the ion-cyclotron

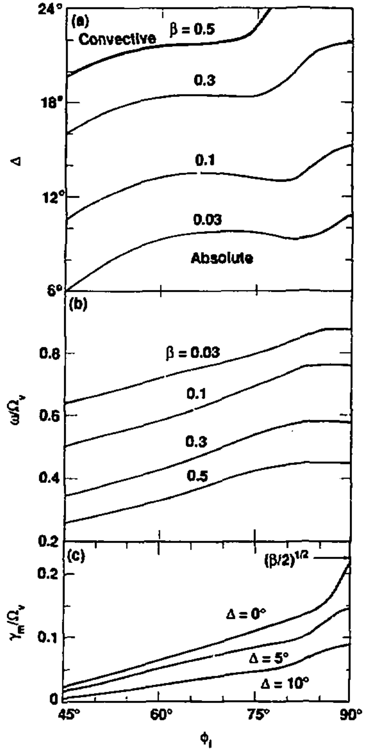

Figure 2. Summary of stability characteristics for the AIC mode as a function of the angle of injection for a model sloshing-ion distribution [4] with angular spread: (a) convective-absolute stability boundaries for different β values; (b) wave frequency; and (c) growth rate normalized to the midplane ion-cyclotron frequency Ω_v.

frequency. These higher harmonics appear as stability boundaries rather than the absolute-convective boundaries associated with instability at the fundamental ion-cyclotron frequency. Although AIC instability at a higher harmonic might be a candidate for mode identification, the wave characteristics observed in TMX-U do not support an AIC interpretation for these fluctuations. Rather, they represent a loss-cone mode driven unstable outside the peak of the sloshing-ion distribution where there is only a minimal density of the stabilizing stream plasma because of the tandem mirror confining potential.

When we operate TMX-U at high density, we observe a coherent oscillation at a frequency ranging from 7 to 8 MHz, which corresponds to the ion-cyclotron frequency at a magnetic field value close to the peak of the sloshing-ion density for the given neutral-beam injection geometry. High densities are achieved in TMX-U in two ways: (1) by fueling for operation in the sloshing-ion mode without attempting to create thermal barriers, and (2) during thermal-barrier operation but only after the strong axial plugging is lost. Potential fluctuations have been monitored using high impedance probes at the plasma edge in all regions of TMX-U. Spectra for potential fluctuations measured in the west end cell and in the central cell are shown in Fig. 3 [7] during the sloshing-ion mode of operation without thermal barriers. We note the presence of a mode at about 7 MHz in the west end cell and the nearly total absence of fluctuations in the central cell. The high frequency, azimuthal mode structure, and absence of propagation of the mode [8] into the central cell (to be discussed in the following section) indicate that these fluctuations are not the AIC mode. A more likely candidate is one driven by the hole in velocity space. Our comparison [7] of the experimental measurements with the theoretical predictions concerning the loss-cone-driven mode are summarized in Figs. 4 and 5. These figures show reasonably good agreement of the experiment and code results in terms of the wave characteristics. Particle simulation work [9] also qualitatively confirms that this mode is consistent with a loss-cone instability.

During thermal-barrier experiments, these fluctuations are generally not observed until after the strong axial plugging is lost. However, the strong plugging experiments have been limited to central-cell densities less than about 2×10^{12} cm^{-3} . A typical fluctuation spectrum measured under these conditions is shown in Fig. 6, and the phase difference measurements along the azimuthally oriented probe array are shown in

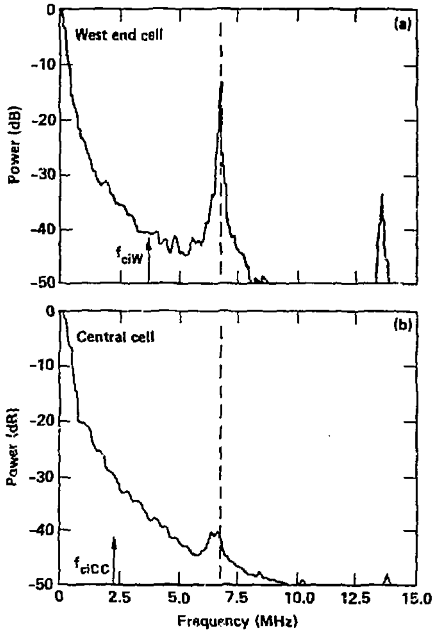

Figure 3. Potential fluctuation spectra measured in (a) the west end cell and (b) the central cell during initial TMX-U sloshing-ion experiments. The narrow peak at 7.2 MHz indicates a coherent wave in the west end cell. Power detected in the central cell is a factor of 1000 (30 dB) less than in the end cell. This figure illustrates the absence of wave propagation into the central cell in TMX-U.

Fig. 7. The mode at 7.7 MHz has an azimuthal mode number (m) of 42 (from the phase difference measurements); that is, $k_\perp \rho_i \approx 4$, where $k_\perp$ is the perpendicular wave number and ρ_i is the ion gyroradius. While this all seems quite reasonable for a loss cone mode, since 7.7 MHz is approximately twice the midplane ion-cyclotron frequency, we still lacked proof that the

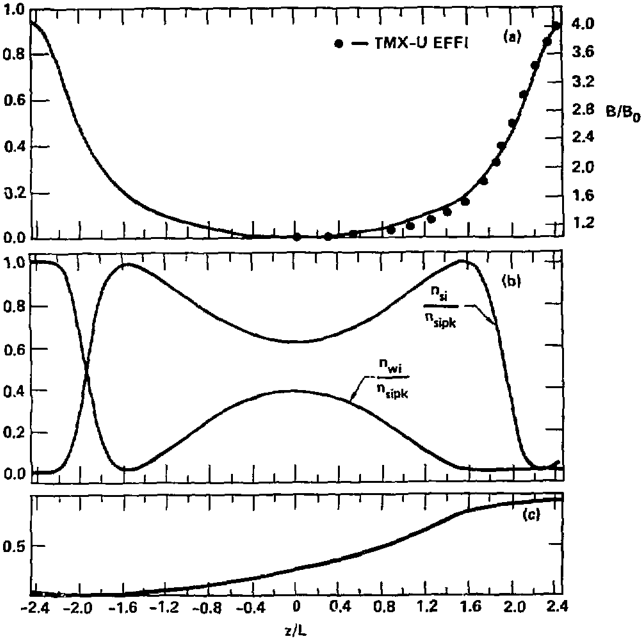

Figure 4. Stability code profiles used to simulate TMX-U conditions: (a) axial magnetic-field model compared with the TMX-U field (•); (b) sloshing ion n_{si} and warm ion n_{wi} axial-density profiles; and (c) the resulting axial eigenfunction amplitude. Profiles are plotted as a function of normalized axial length z/L, where L = magnetic-field scale length.

mode was driven unstable at the sloshing-ion peak. This confirmation [10] was made when neutral-beam injection at 40° was added to the original 47° injection. The measured fluctuation frequency systematically increased to 8 MHz, as shown in Fig. 8. We are thus convinced that the mode observed is truly a loss-cone mode driven unstable just outside the peak of the sloshing-ion density profile.

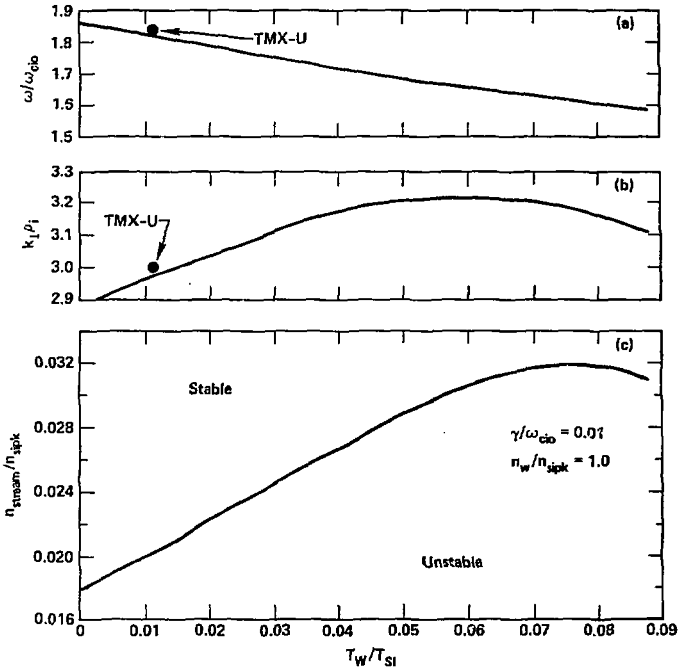

Figure 5. Stability code results as a function of the ratio of stream temperature to sloshing-ion temperature: (a) normalized wave frequency; (b) normalized perpendicular wave number; and (c) stream density at a growth rate of $\gamma/\omega_{ci} = 0.01$. Experimentally measured inputs to the code are 8 keV average ion energy, 2.8×10^{12} cm^{-3} peak sloshing-ion density at a sloshing ratio of 0.62, $R_p/\rho_i = 4.3$, warm-to-hot ion temperature ratio of 0.01, and a mirror ratio of 4.

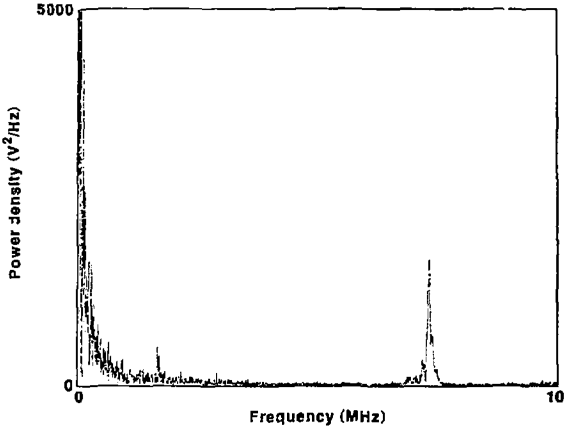

Figure 6. A typical power density spectrum for potential fluctuations measured at the west end-cell midplane. The narrow peak indicates a coherent mode exists at 7.7 MHz.

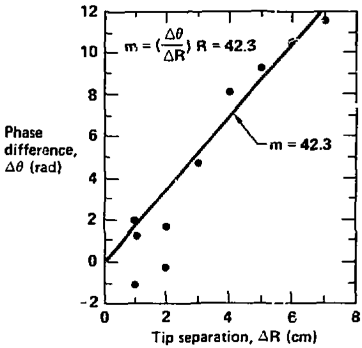

Figure 7. Plot of phase shift vs probe separation indicating the azimuthal mode number (m) is 42 for the 7.7-MHz mode.

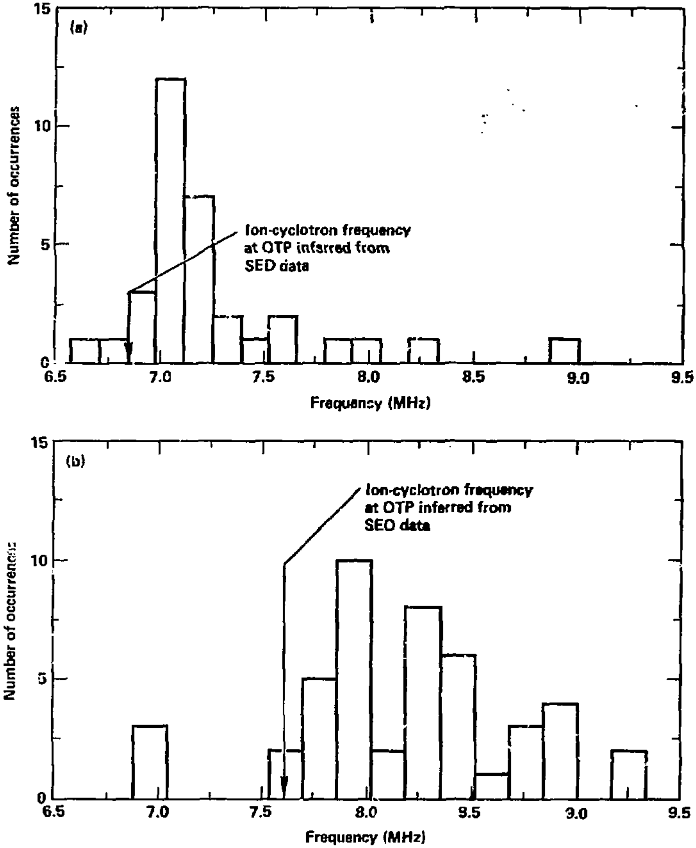

Figure 8. Histograms indicating the change in the observed frequencies for (a) shots with 47° injection only (f = 7 MHz) and (b) shots with 40° injection (f = 8 MHz).

From the beginning of our observations of this loss-cone mode, we had difficulty showing that it had any negative effects on confinement in TMX-U--good news for the tandem mirror concept. The fluctuations in potential occurred well after loss of axial plugging and were seldom observed during plugging experiments using high levels of ECRH power. However, with high ECRH power and strong thermal-barrier plugging, the axial location of the peak sloshing-ion density moved inward, leaving little density at the probe and therefore only a very low fluctuation level. After moving the probe closer to the end-cell midplane, we observed the loss-cone mode at a lower density threshold. However, we still have low density at the probe during the period of strong reduction in the axial ion end losses and generally did not observe the oscillations under these conditions.

At lower levels of ECRH power where fewer hot electrons are created, this instability causes an anomalous loss of sloshing ions in TMX-U [11]. Fig. 9 shows [10,11] the inverse scaling of sloshing-ion lifetime with the amplitude of the instability for conditions where density at the probe location is significant, i.e., at lower ECRH power levels. We do not know whether this correlation is masked during strong plugging by the movement of the sloshing-ion peak. Also, we are presently analyzing data to show how the cold ions trapped in the thermal barrier affect the stability of this loss-cone mode.

In summary, TMX-U is characterized by the total absence of the AIC mode. A loss-cone mode, probably the DCLC instability [11], is observed during the sloshing-ion mode of operation and during thermal-barrier operation at lower ECRH power levels. It does represent one loss mechanism that can explain the anomalous loss rate for sloshing ions. Since we have not detected this mode during strong plugging, perhaps because of limitations in the diagnostic, it appears not to account for the anomalous sloshing-ion loss rate during strong plugging. However, due to the nature of the temporal correlations observed, it almost certainly is not the cause for the spontaneous loss of plugging observed in TMX-U.

ION-CYCLOTRON STABILITY IN TMX

The predecessor to TMX-U, TMX, was significantly different in terms of stability to ion-cyclotron modes. In this conventional tandem mirror, the end cells were heated solely by neutral-beam injection perpendicular to the

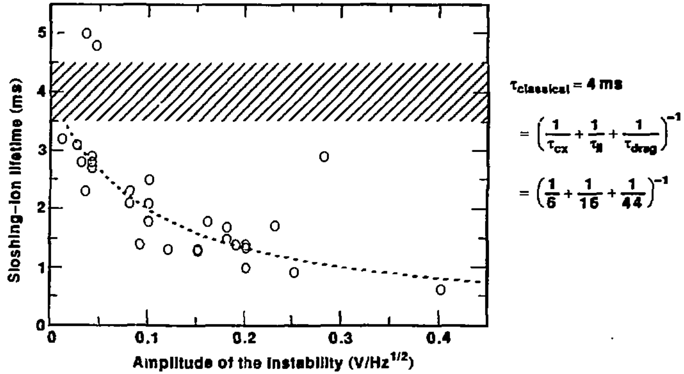

Figure 9. Inverse scaling of sloshing-ion lifetime with the amplitude of ion-cyclotron instability at the outer turning point for shots with significant density at the probe location. The curve is obtained from particle simulations [12] of ion-cyclotron turbulence using a core fluctuation amplitude 3 times the measured edge amplitude and a wave number of 1.1 cm^{-1}. The hachured region is an estimate of the classical ion lifetime for an average neutral pressure of 5×10^{-7} torr, average ion energy of 8 keV, electron temperature of 100 eV, and a total density of 1×10^{12} cm^{-3} where τ_{cx} = charge exchange time, τ_{ii} = ion-ion scattering time, and τ_{drag} = drag time of hot ions on electrons.

axial magnetic field. Perpendicular injection resulted in a much more anisotropic, nonsloshing-ion distribution with considerably higher ion beta when compared with the ion distribution in the TMX-U end cells. Therefore, TMX was more susceptible to the AIC mode than was TMX-U. Similarly, when compared with the 2XIIB experiment, the high anisotropy of the TMX end-cell plasma--even at its lower value of beta--was more favorable to the AIC mode. The parameters affecting stability for these three experiments are listed in TABLE 1.

The dominant mode observed in TMX was identified as AIC instability [13]. The instability had a very small wave number and a frequency that was less than the beta-depressed minimum ion-cyclotron frequency. Also,

TABLE 1. Comparison of mode characteristics and stability parameters.

Fluctuation characteristic	2XIIB	TMX	TMX-U
Mode	DCLC	AIC	Loss cone
Frequency (f/f_{cio})	1.1	0.85	1.9
Wavelength ($k_{\perp}\rho_{io}$)	3	0.3	3 to 7
Phase velocity direction	Ion	Usually electron	Ion
Propagation into central cell	---	Yes	No
Stability parameter			
ρ_{io}/R_p	0.37	0.13	0.25
ion β	0.33	0.07	0.02*
$A = \langle W_{\perp}\rangle/\langle W_{\parallel}\rangle$	5	14	Sloshing
βA^2	8	14	Sloshing
$\overline{E_i}$ (keV)	13	8	8
R_p (cm)	7	10	15
L_p (cm)	25	16	100
Θ injection (deg)	90	90	47 and 40

*Hot electron β = 0.3

the waves were circularly polarized, which is consistent with an Alfvén wave, and propagation was often in the direction of the electron diamagnetic drift, which is inconsistent with a DCLC mode. These end-cell-produced waves propagated over the entire length of the experiment [7] and were observed both in the central cell and in the opposite end cell, as indicated in Fig. 10. We did not determine how these modes affected end-cell confinement because our greater concern was their effect on central-cell confinement.

During the operation of TMX, it became evident that the fluctuations were affecting the central-cell confinement. Fig. 11 shows the inverse

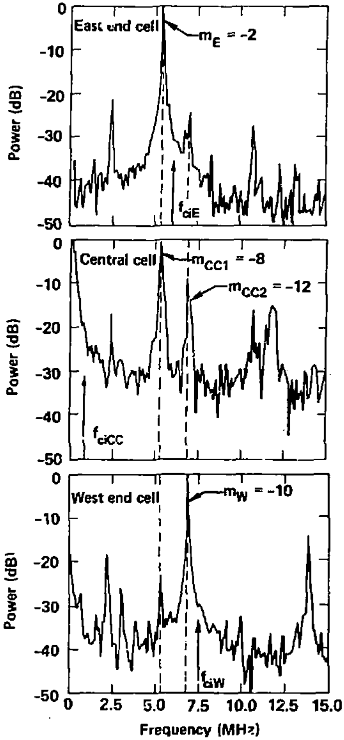

Figure 10. Fluctuation spectra from TMX indicating propagation of AIC modes excited in the end cells. The power detected in the central cell is comparable to that detected in the unstable end-cell regions. For these data, the east end cell was operated at a slightly reduced magnetic field. The mode frequencies are less than the minimum end-cell ion-cyclotron frequency (f_{ci}), m is the azimuthal mode number, and the regions are labeled as east (E), west (W), and central cell (CC).

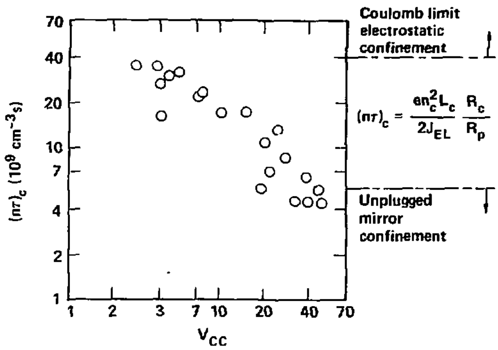

Figure 11. Central-cell confinement $(n\tau)_c$ degradation scales inversely with the level of fluctuation V_{CC}.

scaling of the central-cell confinement time with the amplitude of fluctuations measured in the central cell. Two additional observations indicated a close coupling of the central-cell confinement with the end-cell stability requirements: (1) the plug diamagnetism (AIC drive) was related to the end-loss current density over a wide variation in operating modes (Fig. 12); and (2) the end-loss ions were heated to a temperature of 1 keV from an initial central-cell ion temperature of 0.1 keV (Fig. 13), where the end-loss current was derived predominantly from the axial loss of central-cell plasma. The end-loss heating was unidirectional in that the high ion end-loss temperatures occurred only on the side being driven by neutral-beam injection and therefore was AIC unstable. These results indicated that the central-cell ions were being trapped and heated based on the end-cell AIC stability requirements. This mechanism was responsible for the reduction in central-cell confinement [14].

During this experiment, a theoretical explanation of the heating and stabilizing mechanism was lacking but work was in progress [4,5]. After the conclusion of TMX operation, the theoretical analysis of the AIC stability indicated that the growth rates for AIC could be reduced by cyclotron damping of the waves on a colder component provided the temperature of the cold species is comparable to the parallel temperature of the hot component. The parameters measured in TMX verified that

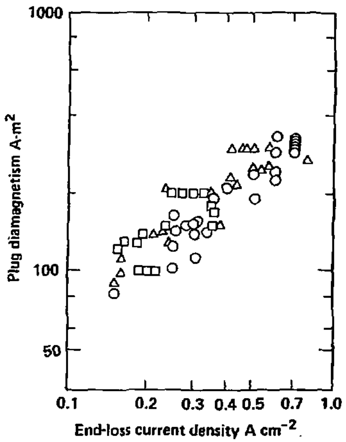

Figure 12. The variation of end-cell diamagnetism (i.e., β) with the end-loss current density for the TMX end cells where open triangle = gas fueling variation at T_e ~ 60 eV; open square = operation with varying neutral beam current at T_e ~ 60 eV; and open circle = neutral beam scan at T_e ~ 175 eV.

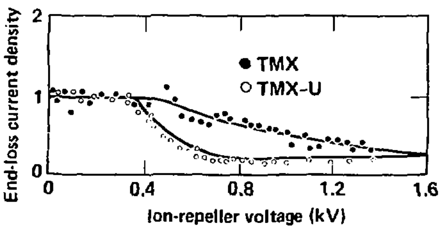

Figure 13. End-loss energy spectra at equal potentials in TMX and TMX-U showing instability heating of the end-loss in TMX from a central-cell energy of 75 eV to an end-wall energy of 810 eV. In contrast, the end-loss ion temperature in TMX-U without AIC remains at about 100 eV, the central-cell ion temperature.

trapping and heating of the end losses by the AIC mode were occurring in the experiment, as is indicated in Fig. 14. Rather than achieve stability from a spreading of the hot ion distribution in an attempt to reduce the anisotropy drive, the AIC-generated waves "diluted" the anisotropy with instability-heated central-cell ions. This process ultimately limited the central-cell confinement in TMX, which was nevertheless considerably enhanced over that of a flow-confined plasma.

Using the theoretical tools developed to explain the TMX data, we developed the sloshing-ion injection design of TMX-U. We believed this design would be much more stable to AIC, and as discussed previously, this enhanced stability was confirmed experimentally. In summary, TMX was stable to the loss-cone modes because of the presence of a warm plasma

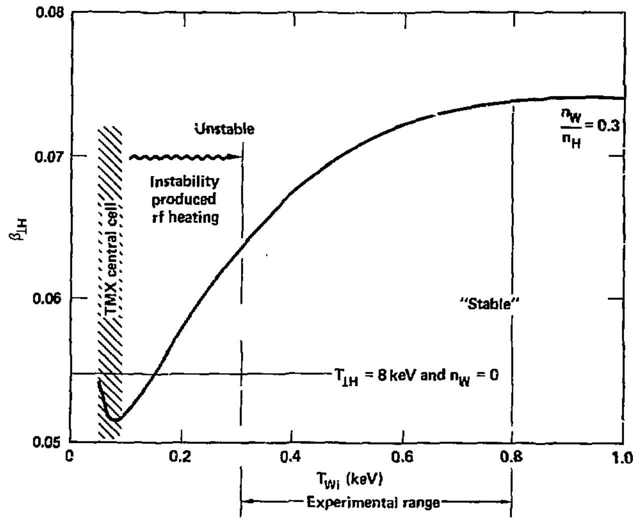

Figure 14. AIC mode convective-absolute stability boundary using a two-ion component distribution representative of TMX operation with $(T_{||}/T_{\perp})_H$ = 0.06, $(T_{||}/T_{\perp})_\omega$ = 1.0, $T_{\perp H}$ = 8 keV, and n = 8 × 10^{12} cm^{-3}.

stream well matched to the velocity space hole. However, the extreme anisotropy due to perpendicular neutral-beam injection excited the AIC mode. These instability-generated waves propagated into the central cell where they reduced the central-cell confinement time while producing a warmer plasma species via cyclotron damping, which limited the growth of fluctuations in the end cell.

APPLICATION OF MICROSTABILITY THEORY TO A MIRROR-BASED NEUTRON SOURCE

Our present concern with mirror ion microstability stems from work on a high-fluence source of neutrons for developing and testing fusion-related concepts and subsystems. Our current linear geometry designs use variations of the single-mirror cell, and there will be limitations based on the velocity-space-driven instabilities. In past experiments, these microinstabilities limited the absolute performance, i.e., density and beta, achieved, and we will consider this issue in assessing the efficiency and economics of neutron-source operation. This facility will require densities in excess of 1×10^{15} cm^{-3} with beta exceeding 0.5. In this regime, proper ion microinstability stabilization may be crucial to achieve the desired performance.

The concepts we are considering are based on a minimum-B geometry of minimal mirror ratio emersed in a high-field, high-mirror-ratio, axisymmetric mirror field. The minimum-B cell confines a hot, beam-injected ion distribution for interaction with a cold flowing plasma in a two-component-type operation. The short, minimum-B geometry provides for the MHD-stable operation of a highly localized neutron source. The cold species supplies both particle fueling of the hot ion species and a target for neutron-generating reactions. In addition, this colder species must stabilize both the loss-cone and AIC instabilities. We are applying the ideas and tools developed in TMX and TMX-U operation to assess these microstability requirements.

Our preliminary indications are that the loss-cone modes do not pose a serious problem because of the large density of relatively cold ions present; that is, the loss-cone modes will be stream stabilized as in 2XIIB, TMX, and TMX-U. Of greater concern is the stability to AIC. Unstable AIC waves will either spread the hot ion distribution (a limit to the hot-ion beta in a low-mirror-ratio device) or heat the cold background plasma. Spreading of the hot ion species will reduce the localized neutron-source fluence, which may then require additional fueling and heating. Similarly, stabilization by wave damping on the cold ion species would ultimately require additional input power to make up for this "unnecessary" heat loss. We are presently estimating the stability requirements for such a two-component neutron source.

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