# Ion Microinstability at the Outer Sloshing-Ion Turning Point of the Tandem Mirror Experiment Upgrade (TMX-U)

L. V. Berzins and T. A. Casper
*Lawrence Livermore National Laboratory, University of California, Livermore, California 94550*
(Received 26 March 1987)

Since the start of TMX-U operations we have observed weak oscillations with a frequency approximately twice the ion-cyclotron frequency at the end-cell midplane. Recent results show that this instability is driven at the sloshing-ion outer turning point. We find that the sloshing-ion lifetime scales inversely with the instability amplitude. The sensitivity of this instability to the cold-ion density shows that this is a loss-cone instability. These results have important implications for mirror fusion experiments as well as solar and space plasmas.

PACS numbers: 52.35.Qz, 52.25.Gj, 52.55.Jd

Microinstabilities are driven by the free energy associated with non-Maxwellian distribution functions. These instabilities are important in understanding of magnetic-fusion plasmas as well as solar[1,2] and space plasmas.[3,4] Ion microinstabilities occur at frequencies near the ion-cyclotron frequency and are driven by the free energy of the magnetically confined energetic-ion population. In magnetic-fusion plasmas, such as TMX-U, an energetic-ion population is created by neutral-beam injection.

Past mirror fusion experiments with neutral-beam injection perpendicular to the magnetic field have shown that confinement times were limited by ion-cyclotron instabilities at the midplane of the magnetic mirror.[5,6] The presence of these instabilities is theoretically well understood.[7,8] Theory predicts that skew injection should be more stable to both anisotropy and loss-cone modes.[9,10] Skew neutral-beam injection creates ions, called sloshing ions, with an axial-density profile that peaks away from the end-cell midplane.[11] Skew neutral-beam injection produces a more isotropic ion distribution than does perpendicular injection. This makes TMX-U more stable to anisotropy-driven instabilities. Skew neutral-beam injection also produces a potential dip at the end-cell midplane that will trap low-energy ions. The ions trapped in the potential dip, along with the low-energy central-cell ions confined by the potential peak, fill in part of the loss cone to reduce the free energy available to loss-cone–driven instabilities. Skew neutral-beam injection in the end cells of TMX-U is observed to produce ion populations that are stable to midplane ion-cyclotron fluctuations.[12,13] Theory predicts the possibility of ion microinstability near the turning points of the sloshing ions. The ion distribution has an empty loss cone outboard of the potential peak, and therefore the location most susceptible to loss-cone–driven instabilities is the outer turning point (OTP). In this paper we report measurements of fluctuations associated with an instability driven at the OTP.

Thermal-barrier tandem mirrors[13,14] rely on axial variations in the magnetic field and electrostatic potential to confine the plasma along magnetic field lines. The thermal-barrier potential profile is created by the controlling of two populations: a population of mirror-trapped, hot electrons created by electron-cyclotron heating (ECH) at the end-cell midplane (which is the location of the minimum magnetic field) and a population of energetic ions created by skew neutral-beam injection. To heat the electrons that charge neutralize the sloshing ions, ECH is used at the outer sloshing-ion density peak (also called the outer turning point, where outer indicates away from the central cell). Heating these electrons increases their loss rate, which increases the potential peak. This potential peak confines those low-energy ions from the central cell that are not magnetically confined. The experimentally measured stability of these sloshing ions is the topic of this paper.

Our initial observations[15] showed an instability with a frequency representative of the ion-cyclotron frequency at the OTP. Because this frequency is also twice the fundamental ion-cyclotron frequency at the midplane of the end cell, a unique conclusion could not be drawn about the axial location of instability. To determine where the instability was located, we added neutral beams with an injection angle of 40° with respect to the magnetic axis, in addition to those already aimed at 47°. Using an array of secondary-emission detectors (SED), each sampling a different pitch angle at the end-cell midplane, we measured the energetic charge-exchange flux from the plasma.[11] Beam-injected neutrals or background-gas neutrals penetrate the plasma and undergo charge exchange with a sloshing ion to create these energetic neutrals. From the angular SED data, we have calculated the magnetic field at the OTP of the sloshing ions, assuming that the axial position of the turning point is independent of the ambipolar potential. When we change from 47° to 40° injection the SED data imply that the OTP of the sloshing ions moves from around 8.6–9.1 kG to approximately 10 kG, a change of 0.9–1.4 kG. The large uncertainty comes from the large separa-

 

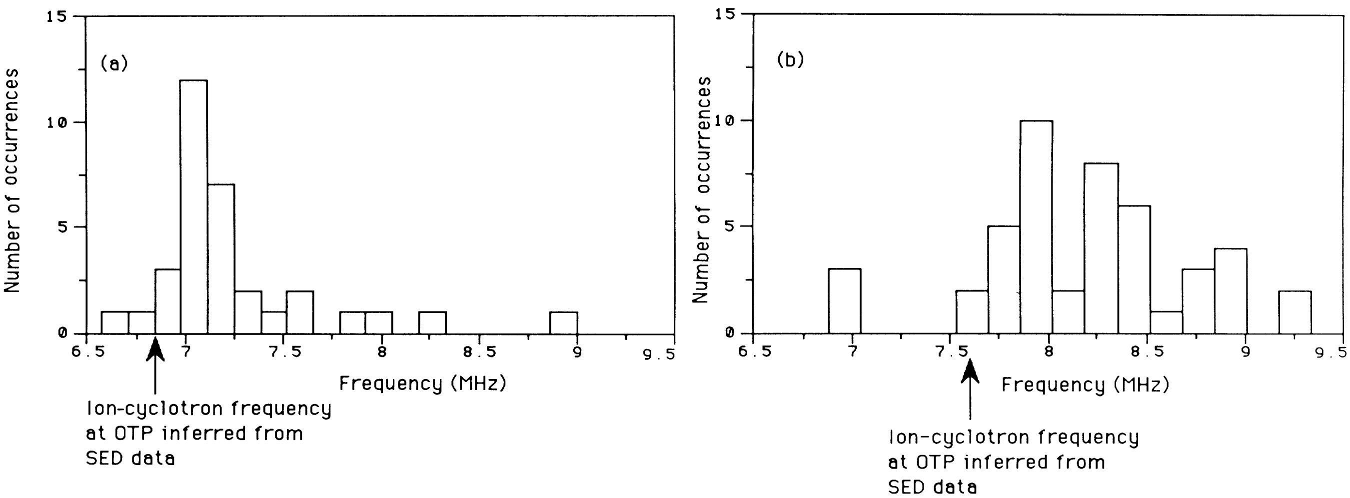


FIG. 1. Comparison of observed frequencies for shots (a) with 47° injection only and (b) with 40° injection or 40° and 47° injection.

tion of the SED's, whose angular data are inverted to obtain the magnetic field at the OTP. At the same time, the frequency observed by an rf probe (a high-impedance probe measuring local edge potential fluctuations) near the OTP has changed from 7.0 to 8.0 MHz. This change in frequency is consistent with the movement of the OTP to a magnetic field approximately 1.3 kG higher, in good agreement with the SED data. Figure 1 illustrates the change in frequency that we observe when changing from 47° to 40° injection. The exact location of the ion-cyclotron instability, and hence its frequency, depends on the plasma conditions. We have thus shown that the frequency of the instability varies with the location of the OTP, with the midplane conditions held approximately constant. This variation of frequency indicates that the instability is driven at the OTP.

At low values of ECH power, we often observe this instability, and it does have a detrimental effect on the sloshing ions. We have found that the maximum ECH power level at which the instability can be observed is dependent on the total density. At low ECH power levels, strong bursts of the instability correlate with sudden losses of sloshing ions, but the sloshing-ion density always recovers from these large dumps of sloshing ions, as observed in Fig. 2. More importantly, for this data set there is also a correlation between the amplitude of ion-cyclotron fluctuations and the sloshing-ion lifetime. As shown in Fig. 3, we observe the sloshing-ion lifetime to be inversely proportional to the fluctuation amplitude at low ECH power levels. This scaling appears to hold across many experimental operating cycles, even though the plasma parameters were different and many changes were made to the experiment.

At high ECH power levels, TMX-U generates axial-density profiles with little or no measurable density at the OTP rf probe location. This observation is from a microwave interferometer located near the OTP. Without density at the probe location, the probe does not couple to the plasma. Therefore we have no direct information on the stability of the OTP at high ECH power levels. We have observed that when the rf probe is moved closer, axially, to the end-cell midplane, the instability is present for a larger variation in plasma parameters. We did not move the rf probe close enough to the end-cell midplane to monitor stability at high ECH power levels.

While this instability has occasionally been observed during plugging, there have been no correlations of its presence with the loss of plugging. The absence of end losses, otherwise known as plugging, is due to good electrostatic and magnetic confinement of the plasma. Dur-

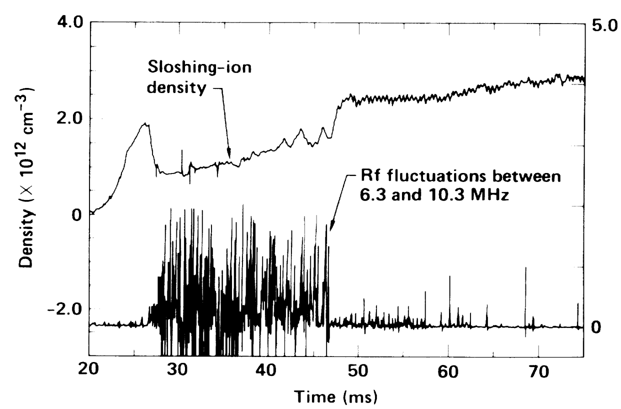


FIG. 2. The instability can cause large dumps of the sloshing ions. The sloshing-ion density is inferred from the charge-exchange flux measured by the 45° SED.

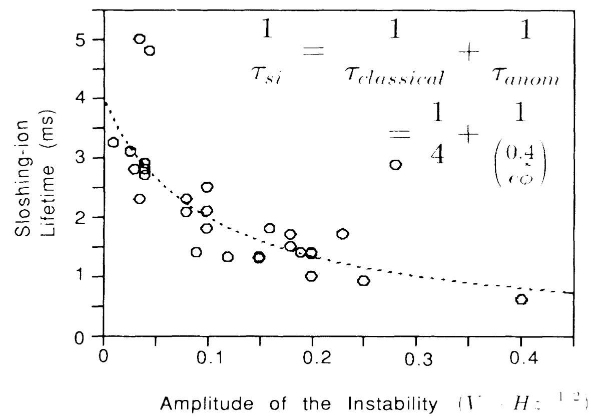


FIG. 3. The sloshing-ion lifetime depends on the amplitude of the instability. The sloshing-ion lifetime is determined from the sloshing-ion particle balance equation. For TMX-U parameters, $\tau_s = [2.1 I_{\rm beam}(1.3 n_{\rm total}/n_{\rm si} - 1)]^{-1}$. Also plotted is the theoretical prediction of the sloshing-ion lifetime when a spectrum of fluctuations is present (Ref. 16). The anomalous lifetime is defined as

$$\tau_{\rm anom} = \frac{1}{\omega} \left| \frac{\omega/k}{\Delta(\omega/k)} \right| \left| \frac{m v_{\rm beam}^2}{e\tilde{\phi}} \right|.$$

This line is for a band of frequencies with wave numbers centered around 1.1 cm$^{-1}$ as calculated at the end-cell midplane and for the fluctuations in the core being 3 times stronger than those measured on the edge.

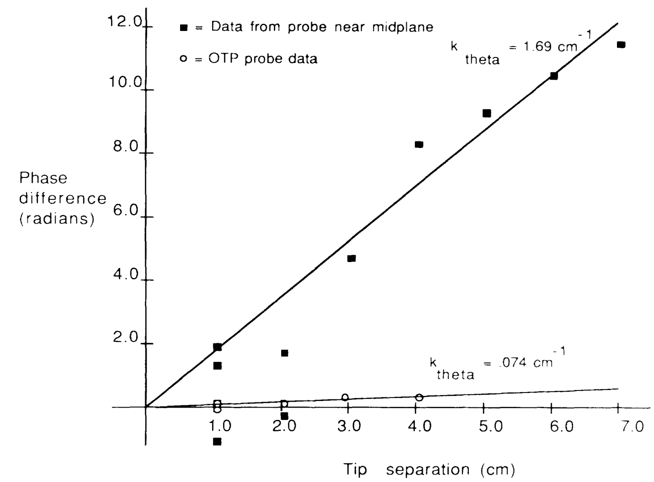


FIG. 4. Measured wavelengths near the midplane and outer turning point. These wavelengths have not been mapped back to the midplane.

ing plugging the sloshing-ion lifetime is observed to be shorter than classical predictions. Plugging requires high ECH power levels and, as we stated above, at high ECH power levels there is little or no measurable density at the OTP rf probe location. Without sufficient density at this location we are unable to monitor the stability of the sloshing ions during plugging.

This instability is most commonly observed only at the OTP, but the instability occasionally extends as far as the inner turning point of the sloshing ions. This axial extent has enabled us to measure the azimuthal wavelength at two separate locations, near the midplane of the end cell and at the OTP of the sloshing ions. We will first discuss the local wavelength measured at the OTP. In Fig. 4 we show that the local azimuthal wave number at the OTP is small, or equivalently, that the instability has a long azimuthal wavelength at the probe location ($\lambda \simeq 85$ cm). At this location, the long wavelength results in measured phase shifts that are very small. The measurement made at the OTP is a local wavelength because the plasma at the OTP is highly elliptical in shape, on account of the minimum-$B$ mirror fields. The ellipticity and the axially varying magnetic fields can drastically change the wavelength. In addition, the short azimuthal coherence length of the instability ($\lambda_c \leq 3$ cm) makes wavelength measurements at the OTP difficult. The short coherence length is due in part to the presence of broad-band plasma turbulence driven by ECH and in part to strong pickup of potential fluctuations in the end cell that result from ion-cyclotron resonance heating in the central cell. These effects make it difficult to measure accurately the local wave number of the instability.

It is therefore helpful to look at the midplane wavelength and compare it to the wavelength measured at the OTP. Near the end-cell midplane we have consistently measured the azimuthal wavelength to be approximately 3 cm with propagation in the ion diamagnetic-drift direction. If we now map both wavelengths back to the midplane of the end cell using the flux tube ellipticity at the respective probe locations, we see that the OTP wavelength measurement implies a midplane wavelength of 5.7 cm, while the measurement from the probe near the midplane implies a midplane wavelength of 2.5 cm. Because of fanning of the magnetic field lines, much of the azimuthal mode structure should occur at the narrow ends of the ellipse. Since the measurement was made along the broad part of the ellipse, the measured local wavelength at the OTP should be longer than the wavelength at the midplane by the ellipticity. There are several effects that add uncertainties to the measurement that we cannot take into account. These include the effect of $\beta$ depression on the fanning of the magnetic field lines and the small phase shifts between tips, because of the long wavelength. Thus we have agreement, within the uncertainties involved, between the wavelength measured at the OTP and near the end-cell midplane.

We identify this instability as an ion loss-cone instability for several reasons. First, the instability propagates in the ion diamagnetic-drift direction. This, along with the location of the instability and the observation that the instability is present only when sloshing ions are

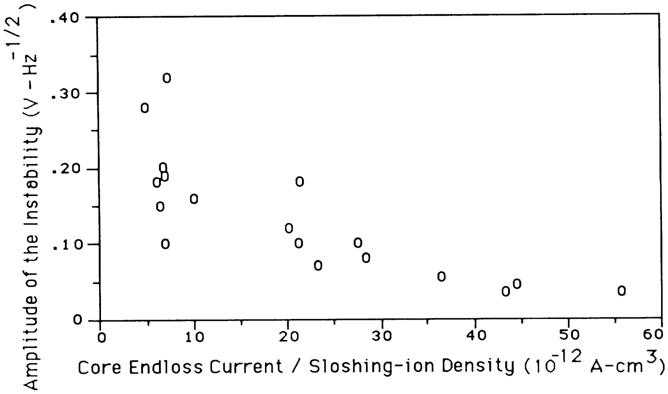


FIG. 5. The amplitude of the instability depends on the ratio of ion density in the loss cone to the sloshing-ion density. We take the core-ion end-loss current to be a measure of the density of ions in the loss cone.

present, indicates that this mode derives free energy from the sloshing ions. Propagation in the ion diamagnetic-drift direction is characteristic of loss-cone instabilities. Second, ion loss-cone instabilities are characterized by $k_\theta \rho_i > 1$ ($k_\theta$ is the azimuthal wave number, $\rho_i$ is the ion gyroradius),[7,17] and we calculate an approximate value of $k_\theta \rho_i = 2$ for a 7-keV ion at the end-cell midplane. Last and most importantly, we show in Fig. 5 that this instability is sensitive to the ratio of the ion density in the loss cone relative to the sloshing-ion density. This sensitivity to a cold-ion population is indicative of an instability driven by the ion loss cone.[18-20] In Fig. 5 the points become more scattered at small ratios of end-loss current to sloshing-ion density because some of those shots are approaching plugging conditions and hence the density at the probe location is very low. We see in Fig. 5 that the amplitude of the instability has reached a low, steady-state level for ratios near $50 \times 10^{-12}$ A cm$^3$. When we calculate the ratio of warm ions to sloshing ions for this value, we find that a warm-ion fraction of 9% at the OTP is sufficient to reduce the amplitude of the instability to a low level. This calculation is for a core plasma area of 174 cm$^2$ at the end-cell midplane magnetic field of 5 kG, and with the sloshing-ion density at the OTP being twice the sloshing-ion density at the midplane. This ratio of warm-to-sloshing-ion density is consistent with the theoretical predictions[21] for TMX-U parameters.

In summary, we have observed an instability in TMX-U located at the sloshing-ion outer turning point. Its wave characteristics and sensitivity to cold ions are consistent with a loss-cone–driven instability. The presence of this instability was predicted by theory. We have shown that this instability can affect the lifetime of the sloshing ions. We believe that this is the first reported observation of ion microinstability activity under thermal-barrier-like conditions in a tandem-mirror experiment. In addition to magnetic-fusion applications, these results are of importance for plasmas with magnetic-mirror–confined, energetic ions, such as solar and space plasmas.

This work was performed for the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

[1] R. R. Sharma and Loukas Vlahos, Astrophys. J. **280**, 405 (1984).

[2] M. Siarkowski, Sol. Phys. **94**, 105 (1984).

[3] D. J. Simons, M. B. Pongratz, and S. P. Gary, J. Geophys. Res. **85**, 671 (1980).

[4] R. Gendrin *et al.*, J. Geophys. Res. **89**, 9119 (1984).

[5] R. P. Drake *et al.*, Nucl. Fusion **21**, 359 (1981).

[6] W. C. Turner, J. Phys. (Paris), Colloq. **38**, C6-121 (1977).

[7] B. I. Cohen, Lawrence Livermore National Laboratory Report No. UCAR 10049-80-REV1, 1980 (unpublished).

[8] H. L. Berk *et al.*, in *Proceedings of the Sixth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, West Germany, 1976* (International Atomic Energy Agency, Vienna, 1977), paper CN-35/C2.

[9] Gary R. Smith, Phys. Fluids **27**, 1499 (1984).

[10] B. I. Cohen, N. Maron, and W. M. Nevins, Phys. Fluids **27**, 642 (1984).

[11] T. J. Orzechowski *et al.*, Phys. Fluids **26**, 2335 (1983).

[12] T. C. Simonen *et al.*, Phys. Rev. Lett. **50**, 1688 (1983).

[13] D. P. Grubb *et al.*, Phys. Rev. Lett. **53**, 783 (1984).

[14] T. C. Simonen, Nucl. Fusion **25**, 1205 (1985).

[15] L. V. Berzins and T. A. Casper, Bull. Am. Phys. Soc. **29**, 1391 (1984).

[16] B. I. Cohen *et al.*, Phys. Fluids **26**, 1851 (1983).

[17] H. L. Berk, L. D. Pearlstein, and J. G. Cordey, Phys. Fluids **15**, 891 (1972).

[18] R. F. Post, in Proceedings of the international conference on plasma confinement in open-ended geometry, Gatlinburg, Tennessee, 1967, Oak Ridge National Laboratory Report No. CONF-671127, 1967 (unpublished), p. 309.

[19] M. S. Ioffe, B. I. Kanaev, V. P. Pastukhov, and E. E. Yushmanov, Zh. Eksp. Teor. Fiz. **67**, 2145 (1974) [Sov. Phys. JETP **40**, 1064 (1975)].

[20] F. H. Coensgen *et al.*, Phys. Rev. Lett. **35**, 1501 (1975).

[21] M. J. Gerver, Phys. Fluids **21**, 443 (1978).