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ASSESSMENT OF HOT-ELECTRON MICROSTABILITY
IN THE INITIAL TMX-U EXPERIMENTS

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ABSTRACT

During the initial TMX-U experiments, we investigated the sloshing-ion and hot-electron distributions. We require these components to ultimately construct a thermal barrier for improved tandem mirror confinement. The plasma parameters we achieved approach values required for thermal barrier operation but have been limited by the power available.

This report is concerned with the stability of the hot electron distribution formed. Nonthermal microwave emissions near the electron-cyclotron frequency f_{ce} of the minimum end-cell magnetic field indicate the presence of electron microinstabilities, which we have tentatively identified by their frequencies. We observed the upper-hybrid loss-cone mode ($f/f_{ce} \sim 1.1$) during high density operation with a relatively small fraction of hot electrons. We observed no evidence for enhanced end losses occurring as a result of this mode. At lower density operation with a higher hot electron fraction, we observed emissions consistent with the whistler instability. During emission bursts at 12.5 GHz ($f/f_{ce} \sim 0.9$) we observed a rapid rise in the high frequency thermal emissions, indicating a spreading of the distribution. Some of the more violent bursts are correlated with enhanced end loss currents. We have not, however, experienced any absolute limits to the hot electron density or temperature directly attributable to these instabilities. The experiments conducted to date indicate that we must suitably control the formation of the hot electron distribution to prevent instabilities or minimize their effects.

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1. INTRODUCTION

A main ingredient for improved tandem mirror confinement is the creation and maintenance of a thermal barrier.¹ This local minimum in the axial potential profile provides thermal isolation between the cold central-cell electrons n_{ec} and the warm end-cell electrons n_{ew} required to form the confining potential Φ . This isolation provides tandem-mirror operation with high central-cell densities. While a thermal barrier has not yet been established, either in the Tandem Mirror Experiment (TMX) or any other experiment, all the basic elements have been successfully created.^{2,3}

The thermal barrier is created by establishing a population of hot, mirror-confined electrons in the minimum-B mirror end cells (Fig. 1) of a tandem mirror device. In the case of TMX, required temperatures lie in the $T_{eh} = 50$ keV range, with densities $n_{eh} \approx 4 \times 10^{12} \text{ cm}^{-3}$. Using the 5-kG minimum field value, we will operate with a hot electron beta (ratio of kinetic pressure to field pressure) in the range of $\beta_{eh} \leq 32\%$. This population is created by intense electron-cyclotron resonance heating (ECRH) at the two locations in the end cell shown in Fig. 1. Heating at (a) creates the potential peak and supplies, along with the central-cell density, a feed to the hot electron population. Heating at (b), the bottom of the well, predominantly supports the thermal barrier.

Based on Fokker-Planck calculations, such an electron population can be created and supported against classical loss processes. We anticipate that the resulting velocity distribution will have a temperature anisotropy (ratio of average energies perpendicular and parallel to the magnetic field) in the range $T_{\perp h}/T_{\parallel h} = 2$ to 3. However, we must still consider the population's stability relative to loss-cone-driven and anisotropy driven modes near the electron-cyclotron frequency f_{ce} . We recognize that to succeed we must operate at steady-state hot electron densities attained by few past experiments employing a bulk electron population (as opposed to an electron ring).

The ECRH power and duration available have limited TMX hot electron experiments to date.³ Thus, we have approached the desired hot electron population but have not yet achieved it. During these experiments, we have observed nonthermal emissions in the range of f_{ce} . Using the frequency of

Fig. 1. Axial end-cell profiles for thermal barrier operation. Shown are (a) electron-cyclotron frequency and cyclotron emission detector locations, (b) ambipolar potential, and (c) electron density.

emission, the instabilities are tentatively identified as the upper-hybrid loss-cone (UHLC) mode^{4,9} and the whistler mode⁵. We have operated at lower hot electron densities and higher temperature anisotropies than proposed. At the higher total density levels, $n \approx 1 \times 10^{12}$ with $n_{eh}/n < 0.5$, we have observed bursts of emission attributed to the UHLC mode. These occur with no apparent loss of confinement. The whistler instability has appeared either as bursts of emission or as a nearly continuous enhanced emission level. This mode is correlated with a broadening of the hot electron distribution, often without enhancing the loss rate. Some whistler instability bursts, however, do correlate with reductions in the midplane line density and enhanced axial losses. To date, we have observed microwave emission levels enhanced by instabilities above thermal level, but we have not experienced any hard limits to the hot electron density or temperature directly attributable to electron microinstabilities. We have, however, observed temporally localized limits that result in instability. The hot electron plasma generally recovers from instability with a broadened distribution and continues to build toward thermal-barrier level parameters. The available input energy sets the limits presently experienced.

As we increase the density of hot electrons in order to achieve thermal barrier operation, we approach a more convectively unstable operating regime. To produce the desired parameters, the experiment must advance toward the absolute-convective stability boundaries for both the whistler and UHLC modes. Therefore, during electron heating, we must pay careful attention to controlling the anisotropy and hot-to-cold electron density ratio, so that we prevent the more destructive absolute form of instability. Should the convective form of instability remain, we may experience loss rates enhanced above classical. This would require additional ECRH power or operation at reduced hot electron densities.

2. REVIEW OF PROBABLE ELECTRON MICROINSTABILITIES

When the hot electrons are micro-unstable, energy can be transferred from the hot electrons to waves which either radiate power away, enhance the classical loss rate by scattering particles into the loss cone, or alter the spatial electron distribution. Electron microinstability refers to waves that

are driven spontaneously unstable near the electron-cyclotron frequency by details of the velocity distribution. We have considered five possible instabilities with varying degrees of detail. These are summarized in Table 1. The upper-hybrid loss-cone (UHLC) mode and the whistler mode have been studied in greatest detail. For the parameters expected in TMX-U, the Timofeev mode⁶ should be more stable than the whistler mode. It is therefore believed that the whistler instability precludes the occurrence of the Timofeev mode. The possibility of parametric instabilities⁷ and their possibly beneficial effect on the formation of the hot electron population is in its formative state. The electron-cyclotron maser instability has only recently been studied⁸ as one we must contend with for confinement. We have not yet assessed its relevance to TMX-U.

Guest and Sigmar⁹ provided an early review of ECRH plasma microinstabilities. Those that led to the most stringent constraints on plasma parameters were the whistler and UHLC modes. This remains our viewpoint. We are currently performing additional theoretical analysis concerning both modes with a greater relevancy to the TMX-U experiment.^{10,11} Results from these studies indicate that wavelengths associated with high frequency electron modes are short in comparison with typical macroscopic scale lengths of the plasma. Hence, stability for these modes tends to constrain the electron distribution function rather than the configuration of the experimental plasma. Reference 12 gives a review of the early theory pertaining to the negative mode tandem operation of TMX-U. *The general conclusions apply to the present mode of TMX-U operation, in which only two electron species are present (hot and cold; no warm electrons).* The main conclusion of that study is that the UHLC mode will probably be convectively unstable. Thus, if these modes are present, we expect to operate with a scattering rate enhanced above the classical rate.

Reference 12 also reviews past hot electron experiments in the context of the Guest and Sigmar⁹ results. A fair agreement between the instabilities

Table 1. Electron microinstabilities.

Mode	Type	Alternate name	Drive
Upper hybrid loss cone ^a	Electrostatic	Two-component double distribution	Loss-cone
Whistler	Electromagnetic	Electron-cyclotron	Anisotropy beta
Timofeev	Electrostatic	Harris Half-harmonic	Anisotropy
Parametric	--	--	Mode coupling
Electron-cyclotron Maser	Electromagnetic	Relativistic	Relativistic bunching mechanism

^a The modes are found, in order from top to bottom, in Refs. 4-8.

reported and the theoretical stability boundaries was exhibited. In all cases, the frequency of microwave emission detected determined instability identity. For most of these experiments, microwave emission correlated well with axial bursts of hot electrons and, in a few cases, radial losses were also observed. The rapid loss of confinement was evidenced by a drop in plasma diamagnetism, with up to an 80% loss of hot electrons reported.¹³ Usually, however, the instabilities were much less violent, with correlated losses ranging from none to 20% of the hot electron beta reported. Driven experiments have exhibited multiple bursts of microwave radiation correlated with enhanced loss processes.

Since TMX-U is driven by intense beams of microwave radiation, we anticipate that the instability will occur either in bursts or possibly more continuously as we approach conditions of marginal stability. By marginal stability we imply a quasi-equilibrium between ECRH supporting an anisotropic loss-cone distribution and instability attempting to broaden the distribution to a Maxwellian-like form. Enhanced microwave emission levels exceeding those expected for "thermal" radiation from the hot electrons may be correlated with enhanced losses and drops in diamagnetism. This condition indicates a reduction in confinement from the classical level.

3. HOT ELECTRON EMISSION CHARACTERISTICS

The hot electron diagnostic with the best temporal resolution is the electron-cyclotron emission detector, designed at the University of Maryland. It detects microwave emissions from the hot electrons that are caused by both the thermal cyclotron emission and instability-generated waves. The cyclotron emission diagnostic measures microwave emissions either parallel to the magnetic field (in the whistler mode)¹⁴ or perpendicular to the field, as indicated schematically in Fig. 1. Two receivers are available; one detects radiation between 12 and 18 GHz, with a 50-MHz bandwidth and the other between 26 and 40 GHz, with a 400-MHz bandwidth. Typically, we detect instability bursts superimposed on a background thermal emission level. Since this is a relatively new diagnostic, not all signal characteristics are fully understood. This is particularly true for the absorption of hot electron radiation by a cold electron population. For the same reason, some conclusions are speculative. The data can best be described as preliminary, with analysis refinements forthcoming.

Data from a typical mode of monitoring cyclotron emission is shown in Fig. 2. In this mode we monitored parallel emissions using both receivers, one set to $f = 12.5$ GHz ($\Delta f = 50$ MHz) and the other to $f = 35$ GHz ($\Delta f = 400$ MHz). The slowly varying thermal signal at 12.5 GHz (Fig. 2a) is a result of Doppler-broadened emission from a region near the bottom of the well. It provides an estimate of the hot electron average energy from emitted power, which can be compared with x-ray measurements. Rapid variations of this signal result from nonthermal, instability-produced emissions. Noting that greater emission corresponds to a larger negative-going signal, we can conclude that the 35-GHz emission (Fig. 2b) comes from hot electrons that have sufficient parallel energy to approach the 12.5-kG resonance (35-GHz) location or sufficient parallel velocity to Doppler-broaden the spectrum to 35 GHz. Total emission at this frequency represents a combination of these effects. Emission at 12.5 GHz tends to be optically thick--at $T_{eh} = 10$ keV, thermal whistler mode emission from a Maxwellian plasma is optically thick if $n_{eh} > 10^{10} \text{ cm}^{-3}$ --and independent of density. On the other hand, emission at 35 GHz depends on n_{eh} and the hot electron axial length a_{eh} . In both cases, a significant cold electron density in the end fan region

results in attenuation of the signal (an error in measurement of average energy). Similarly, the 35-GHz emission experiences a resonant absorption inside the end-cell region and will have greater absorption whenever the cold electron population exists at high density in this region. Both signals are altered by the presence of cold electrons in the end cell as a result of variations in the whistler mode index of refraction. The magnitude of the receiver voltage output is directly proportional to the radiated power detected.

We will now discuss the time history of the 80-ms TMX-U shot exhibited in Fig. 2. We used a spark-plug neutral beam (Fig. 2h) to start up the experiment by providing an initial source of free electrons. Electrons are trapped and heated by ECRH using both fundamental (Fig. 2e) and second harmonic (Fig. 2j) heating. This initial plasma exhibits a rapid rise of the 35-GHz emission (Fig. 2b) as the cooler electrons are heated and created at the 28-GHz fundamental resonance. (The 28-GHz resonant location is only about 8 cm inward from the 35-GHz location for the TMX-U field profile.) Near $t = 15$ ms, the 35-GHz emission drops precipitously. This occurs before the spark-plug beam turns off and is therefore not related to beam shut-off. We believe that, during this interval, the hot electron population is forming its equilibrium axial distribution located at the bottom of the well. The hot electrons become mirror confined and move away from the 35-GHz resonant point; this results in a 35-GHz emission drop at a rate much faster than purely classical processes can explain.

When the 35-GHz emission drops, the density at the bottom of the well (Fig. 2c) begins to build up, as does the line density at the 7.6-kG field location (Fig. 2d). We believe the potential dips as the mirror-confined population is created. Evidence for this is the rapid expulsion of low-to-moderate energy electrons, as detected by the sharp rise in net negative current collected on-axis (Fig. 2f). The net negative current implies an excess electron current on-axis and indicates that some cross-field transport is occurring. The loss current averaged over the radius adjusts itself to maintain an ambipolar loss rate. The Faraday cup end-loss current (Fig. 2g) is biased to repel low energy electrons. Its initially negative current indicates the loss of moderate energy electrons ($E > 1$ keV). The potential readily adjusts to form an ambipolar loss rate as the Faraday cup current swings positive. During the interval from 10 to 20 ms, the 12.5-GHz

Fig. 2. Temporal variation for the experiment with hot electrons and sloshing ions.

emission slowly grows as the electron heating provides sufficient Doppler spreading for us to detect emission at 12.5 GHz. At roughly 20 ms, the 12.5-GHz emission levels off, indicating an equilibrium in average energy has been reached, with $T_{eh} = 39$ keV from the 12.5-GHz power emitted and 65 keV from x-rays.

The axial profile and distribution shape of the hot electrons are, however, still evolving. At $t = 25$ ms, the previously flat density begins to rise, and the hot electrons begin to occupy a greater axial extent. We determine this by the increased 35-GHz emission and the rise in line density at the 7.6-kG field location (Fig. 2d). The broadened hot electron distribution results in more hot electrons scattering into the loss-cone. The loss of these moderate energy electrons results in a steady drop in the Faraday cup current. This evolution continues until about 35 ms, when sloshing-ion neutral beams are turned on in the end cells (Fig. 2i).

We need to form a sloshing-ion distribution using the end-cell neutral beams in order to achieve potential confinement of the central cell. We conducted these experiments to study the combination of these two building blocks with the ECRH power level presently restricted by available hardware. When the neutral beams are turned on, a rapid increase in total density is experienced. This reaches a limit at 40 ms. During this period of density growth, the 12.5-GHz signal exhibits strong nonthermal emissions (> 5 times thermal level). We believe these are evidence of the whistler instability, which can be more unstable in the presence of the cold electron population that is expected from the ionization of neutral beams.

Whistler wave effects on the hot electrons would be twofold: (1) wave-particle interaction would increase the effective scattering rate into the loss cone and (2) a broadening of the hot electron population would relieve the anisotropy drive. While we do observe enhanced end-losses, they appear to be a result only of the density rise due to beam injection rather than effects of whistler waves because the ion and electron losses respond in phase. Similarly, the lack of line density rise at the outer edge, i.e., at the 7.6-kG field location, and the damping of the 35-GHz emission seem to be inconsistent with a broadening of the hot electron distribution. We will discuss these points further in the next section.

Between 40 and 60 ms, the end-cell density is high, and some attenuation of the 35-GHz emission is evident. At $t = 70$ ms, the density has died away and the 35-GHz emission level rises to its thermal emission level. The difference between the 35-GHz emission at 80 ms and that at 42 ms indicates either a net loss of hot electrons from the axial edge of the hot electron profile or a reduction in the parallel velocity spread. Since the 12.5-GHz emission does not drop during beam injection, the hot electrons have not been significantly cooled. Note, however, that density may have been reduced since, under optically thick conditions, the radiated power depends only on the average energy rather than on the number of emitters. However, the optically thin edge, i.e., the 35-GHz emission, depends on both n_{eh} and T_{eh} .

Since classical scattering rates of hot electrons are so low, they remain mirror-confined for extremely long times. Figure 3 shows the late-time (to 800 ms) emission characteristics of hot electrons for the shot shown in Fig. 2. The slow decay of the 12.5-GHz emission indicates a decay of hot, mirror-confined electrons. The rate changes abruptly at $t = 650$ ms because the TMX-U magnets begin to cycle off. During the slow decay, hot electrons are both slowly scattering into the loss cone and ionizing the background neutral gas. The low density $n_i \leq 10^{10} \text{ cm}^{-3}$ cold plasma produced attenuates the 35-GHz emission. As the neutral gas is pumped from the TMX-U chamber, the 35-GHz emission slowly rises, due to a reduction in cold plasma and attenuation of its emission. Classical scattering rates for 50-keV electrons on cold ions at low densities indicate scattering times of a few seconds. This is consistent with the slow decay of parallel emission. If, the plasma is optically thick, the emitted power is independent of density and the power received at the antenna can increase, even with a slowly decreasing density. Another possible explanation for the increased emission at 35-GHz is that the hot electrons are slowly broadening in space, as expected from Fokker-Planck studies, or in average parallel velocity and increasing the emission from the 35-GHz resonant location. We are now studying the relative importance of these effects.

The late-time emission variations are observed to change with frequency. Using a shot-to-shot scan of frequency, we show the emission characteristics for a similar data set in Fig. 4. Frequency-swept operation will be used at a later date; a limited set of single-shot, swept data agrees

Fig. 3. The late-time hot-electron cyclotron emission parallel to $\mathbf{B}$ for the shot shown in Fig. 2.

with the shot-to-shot results. We obtained the data from two receivers properly normalized for receiver gain variations. The "hole" in the data between 18 and 26 GHz represents a frequency range presently inaccessible using existing receivers. In addition, we cannot observe emission near 28 GHz because of ECRH heating at this frequency. Employing models for the hot and cold electrons and the TMX-U field profiles, we have generated a fit to similar data using a whistler emission code. This fit indicates that $T_{eh} = 62$ keV, with $n_{eh} = 2 \times 10^{10} \text{ cm}^{-3}$, $n_{ec} = 2 \times 10^9 \text{ cm}^{-3}$, and a hot electron length $a_{eh} = 25$ cm. As compared with earlier data (Fig. 2), the higher electron temperature achieved during the constant condition scan is a result of the availability of more ECRH power. Since these measurements are made at 100 ms, after all input power is removed, the density values are not totally representative of the sustained plasma density. In the shot presented, we see that the midplane density (Fig. 2c) has decayed to about 20% of its value before neutral beam injection. This represents a net loss of hot electrons during beam injection and subsequent plasma decay, during which hot electron lifetime is determined by scattering off cold plasma. Relaxation of the distribution after sustaining power is removed can result in variations of hot electron length. However, since scattering times are long (from more than several milliseconds at high density to seconds at low density) we use a_{eh} at 100 ms as one measure of the sustained hot electron length. The value of a_{eh} is important for a comparison with whistler emission in the next section.

In modeling cyclotron emission and comparing our models with the experiment, we find a value of a_{eh} of approximately 25 cm. Our conclusion is that we have, in fact, created a relatively short axial length hot electron population relative to Fokker-Planck results. We are currently addressing these topics in our investigation of hot electron emission.

4. EXPERIMENTAL OBSERVATIONS

During the initial operation of TMX-U, we have been studying the components required to produce a tandem mirror with thermal barriers. Two of these components are the sloshing-ion species and the mirror-confined hot electron species. We, therefore, have operated in basically two regimes;

- (a) The low n_{eh}/n_e regime, high total density n_e .
- (b) The high n_{eh}/n_e regime, low total density n_e .

Fig. 4. Comparison of experimentally measured emission with numerically calculated emission using TMX-U profiles.

where n_{eh} , n_{ec} are the hot and cold electron densities, respectively, and $n_e = n_{eh} + n_{ec}$. These two regimes tend to be susceptible to different instability modes and will be discussed separately.

THE LOW n_{eh}/n_e REGIME

A fairly high level of sloshing-ion neutral beam injection typifies this mode. The resulting high plasma density is mostly a result of the sloshing-ion component. This data is marked by rather low values of n_{eh}/n_e . It is in this regime that we have detected bursts of microwave radiation consistent with the UHLC instability.

This mode is driven unstable by a loss-cone distribution of hot, mirror-confined electrons. Even when the loss-cone is not too severe, $\{\partial f/\partial v_{\parallel}\}$ is not too great, a cold electron component can de-stabilize the mode.^{9,15} The cold plasma serves as a medium to support wave propagation with the wave energy derived from the hot electron loss-cone. The expected frequency is roughly equal to the upper-hybrid frequency $f_{UH} = (f_{pe}^2 + f_{ce}^2)^{1/2}$ determined from the cold electrons. During early TMX-U operation, we varied the frequency of the parallel-mode cyclotron-emission diagnostic on a shot-to-shot basis. We detected nonthermal bursts at frequencies above the minimum electron-cyclotron frequency ($f > 14$ GHz). Three such shots with comparable densities are shown in Fig. 5 for three different settings of the receiver frequency, $f = 15.0, 16.3$, and 17.8 GHz. Ignoring the initial bursts that are present at most frequencies, we observe nonthermal emissions during intervals when the density rises to a level in which f_{UH} is approximately equal to the receiver frequency. That is, the detected frequency about equals f_{UH} , as is expected for the UHLC mode with moderate levels of cold density. With estimates of the plasma parameters, as shown in Table 2, we used an electron microstability code¹⁶ to determine TMX-U stability relative to the UHLC mode. Theory predicted weak UHLC instability with $f_{wave} \approx 15$ GHz, consistent with the measurements. While instability activity is apparent, there was no evidence for density limits or enhanced end-loss rates. The density profiles are results of input power variation plus beam current, and ECRH duration. One can only surmise that the weak instability did not limit confinement for the conditions under which we operated TMX-U. However, it may have been providing some weak enhanced scattering.

Table 2. Experimental parameters estimated to occur during UHLC activity.

Parameter	Estimated value
Cold electron density	$n_c = 5 \times 10^{11} \text{ cm}^{-3}$
Hot electron density	$n_h = 0.5 \text{ to } 1 \times 10^{11} \text{ cm}^{-3}$
Hot electron temperature	$T_h \sim 20 \text{ to } 40 \text{ keV}$
Hot electron anisotropy	$(T_{\parallel}/T_{\perp})_h \sim 0.1 \text{ to } 0.4$
Cold electron temperature	$T_{\parallel c} = T_{\perp c} \sim 15 \text{ to } 20 \text{ eV}$
Frequency of enhanced emission ^a	$f_{\text{wave}} \sim 14 \text{ to } 16 \text{ GHz}$

^a Theory predicts $f \sim 15 \text{ GHz}$.

The operating regime for TMX-U during which we observed the UHLC mode is indicated in Fig. 6. We show numerically computed¹⁶ constant convective growth length curves for this mode, where ω_{ptot} is the plasma frequency using the total electron density and $\Omega_e = 2\pi f_{ce}$. We also show the worst case absolute-convective stability boundary that occurs for $n_{eh}/n_e \approx 0.6$. Density ratios either higher or lower than this value shift the stability boundary further to the right, that is, to higher densities. The TMX-U thermal barrier operating point lies close to this worst case boundary, indicating we must pass perilously close to absolute instability during thermal barrier buildup. Note that higher anisotropy (small $\langle T_{\parallel h} \rangle / \langle T_{\perp h} \rangle$) tends to be stabilizing to the UHLC mode and is consistent with its absence during the more recent experiments.

The stability code uses a uniform plasma model and velocity distributions that model Fokker-Planck results. We expect nonuniform effects to be stabilizing, since they favorably alter the stability by reducing the convective growth length and may eliminate the normal mode structure.¹² It is also suggested that instability waves are unable to mode-convert in TMX-U and will be reabsorbed¹⁷ before they propagate out of the end cell. It is presently not clear whether this will result in an increased heating efficiency for hot electrons or in a channel to transfer power from hot electrons to cold and/or warm electrons. This channel would be a power drain on hot electrons, which could be offset by proper control and distribution of

Fig. 5. Nonthermal emission bursts near the upper-hybrid frequency. The receiver frequencies used were (a) 15 GHz, (b) 16.3 GHz, and (c) 17.8 GHz. The line density was measured at the end-cell midplane.

Fig. 6. Constant convective growth length L curves and worst-case ($n_{eh}/n = 0.6$) absolute-convective stability boundary for the UHLC instability for $T_{eh} = 40$ keV, $T_{ih} = 3$ keV, and $B = 5$ kG. The worst-case boundary is represented by the dashed line.

ECRH power. In any event, if UHLC waves grow (convectively), they may enhance the scattering rate of hot electrons into the loss-cone over that expected for classical processes. Thus, we may require additional ECRH power or operation at lower hot electron density. As we approach the proposed operating point by increasing density, we expect to become more unstable to the UHLC mode, and we anticipate higher amplitude waves caused by increased convected growth (shorter growth length). Whether we experience a density limit or not depends on the form the instability takes and the nature of the wave-particle interactions that are present. We anticipate possible problems with this mode above densities of about $2 \text{ to } 3 \times 10^{12} \text{ cm}^{-3}$, where the instability drive becomes very strong and we approach absolute instability. We note, however, that this is very close to our design density of $4.0 \times 10^{12} \text{ cm}^{-3}$.

THE HIGH n_{eh}/n_e REGIME

During early 1983 we operated with 60- to 150-kW ECRH power levels (design level is 200 kW) and studied the creation of hot electrons. In these experiments we generally used a short pulse of neutral beam current as a spark plug to get initial ionization and startup with ECRH. We could turn on the remainder of the neutral beams later during the shot to study the effects of sloshing-ion buildup on the hot electron population. With this mode of operation, lower beam current levels are available for creating the sloshing-ion distribution.

The experiments are characterized by a hot ($T_{eh} \sim 50 \text{ to } 70 \text{ keV}$), dense ($n_{eh} \sim 5 \times 10^{17}$) electron population with larger values of $n_{eh}/n_e < 0.9$. As we discussed in Sec. 3, this population appears to be more anisotropic (shorter in length) than anticipated from Fokker-Planck calculations and is expected to be more unstable to the whistler instability. Figure 7 shows the TMX-U operating range under these conditions, with the convective growth length curves¹⁶ for the whistler mode. At high anisotropy, located in the lower part of the plot, we expect the whistler mode to be absolutely unstable.

We observed two variations in whistler mode (identified by $f < 14.0 \text{ GHz}$) activity: (a) short burst and (b) continuous enhanced radiation. We believe that (a) represents absolute instability, whereas (b) represents

weakly unstable convective wave growth. Depending on the virulence of the mode, it may or may not result in enhanced losses. To minimize confusion introduced by competing effects, we present examples of whistler activity in TMX-U taken from shots with hot electrons only. That is, we made no attempt to create a sloshing-ion population by neutral beam injection. Injecting sloshing-ion beams, as shown in Fig. 2, or changing the hot electron feed can considerably alter the hot electron distribution and stability. In Figs. 8-10, we show the power input to the east end-cell plasma in plots f (the spark-plug beam), g (the fundamental ECRH power at the 10-kG field), and h (the second harmonic heating pulse at the bottom of the well).

Figure 8 presents a representative case in which we detect the hypothesized absolute version of the whistler mode. There are two rather sharp bursts of emission detected at 12.5 GHz parallel to the magnetic field (Fig. 8a). Correlated with these bursts are rapid increases in the 35-GHz emission (Fig. 8b). These increases are much too rapid to be attributed to electron heating and are therefore associated with rapid spreading of the hot electrons. During the first burst at $t = 23$ ms, the density at the east end-cell midplane (Fig. 8c) flattens, but there are no enhanced end-losses. The density is free to build up further after the distribution has broadened.

Note that the 35-GHz emission slowly decreases after the burst. We interpret this as evidence that the distribution is narrowing in parallel velocity and moving axially away from the 35-GHz resonant location. At 36 ms, another burst of radiation occurs along with rapid spreading of the distribution (the 35-GHz emission increases rapidly again). This time the east end-cell midplane density dips because electrons are lost. These losses are also detected by the on-axis net current collectors at the end wall (Fig. 8d). We observe little change, however, by the on-axis Faraday cup (Fig. 8e). This implies that the escaping electrons have sufficiently low energy and do not exceed the electron-repeller voltage of this diagnostic. The loss of only low-energy electrons is also confirmed in the relatively small changes in plasma diamagnetism. After the burst is over, the density rebuilds at roughly its initial rate.

Figure 9 shows multiple bursts of whistler instability. During each burst of radiation at 12.5-GHz (Fig. 9a), we observe a dip in the line density at the midplane (Fig. 9c) and a rapid rise of 35-GHz emission. This again

Fig. 7. Constant convective growth length L curves for the whistler instability for $n_h/n_{tot} = 0.6$, $T_{hl} = 40$ keV, and $T_{cl} = 3$ keV.

Fig. 8. Experimental conditions resulting in nonthermal bursts with 5- and 10-kG heating.

Fig. 9. Experimental conditions resulting in multiple nonthermal emission bursts with 10-kG heating only.

Fig. 10. Experimental conditions resulting in continuous enhanced emission at 12.5 GHz.

indicates a rapid spreading of the hot electrons by the instability. In each instance we see enhanced end-losses, but after each burst the density is allowed to rise to a higher level. The enhanced electron losses appear as reductions in the on-axis net current detected (Fig. 9d). During these bursts, the on-axis Faraday cup current detected also drops, indicating that the escaping electrons have energies in excess of the 1-keV retarding potential. That is, the enhanced losses on this shot are derived from the hot electron population and indicate that we must take great caution in forming the hot electrons with respect to marginal stability. Note, however, that in spite of the instability activity, there is a general trend toward higher line density at the midplane and greater 12.5-GHz emission as the hot electron beta increases throughout the shot without an absolute limit. During this heating, there is a trend toward higher 35-GHz emission, indicating that with the increased β_{eh} , the distribution broadens in parallel velocity and axial extent. This is very encouraging, since without the benefit of a complete ensemble of heating hardware [we presently lack any ion-cyclotron resonant heating (ICRH) and some ECRH power], we are still capable of producing hot electron distributions approaching those required for thermal barriers. This data represents operation at somewhat higher anisotropy levels than those expected at equilibrium. Thus, the instability, rather than the proper mix of heating, must do the work of spreading the distribution.

As a final example of whistler activity, Fig. 10 presents an example of nearly continuous enhanced 12.5-GHz emission. We believe it is evidence of a convective form of the instability. As the midplane density rises rapidly (Fig. 10c), whistler waves go unstable and produce bursts of substantial amplitude at a frequency of 12.5 GHz at 16 and 19 ms (Fig. 10a). As evidenced by the 35-GHz emission (Fig. 10b) the hot electrons spread rapidly and reduce the level of whistler instability. A quasi-equilibrium is reached, in which we detect an enhanced (above thermal) radiation level at 12.5 GHz. The midplane density for this case remains essentially constant. The drop in 35-GHz emission is a result of self absorption by a cold electron component inside the end cell, in the end-fan region, or both. This is evidenced by the increased emission at late times, $t > 75$ ms. Since the 35-GHz emission rises back to its level at 20 to 28 ms, we infer that the dip between 28 and 70 ms is due to signal attenuation by absorption. A final point worth noting

is that the constant line density level at $1.6 \times 10^{13} \text{ cm}^{-2}$ is not a hard density threshold since, on this shot, the west end-cell line density rises to a significantly higher level, $2.2 \times 10^{13} \text{ cm}^{-2}$ (see Fig. 10i).

Hot electron lengths indicate that these heating experiments have been generating distributions with too great an anisotropy. In Sec. 3, we estimated this length to be roughly $a_{eh} = 25 \text{ cm}$. Using the following relation as an estimate length of anisotropy¹⁸:

$$A = \frac{T_{\perp}}{T_{\parallel}} = 2(1 - \beta) \left[\frac{\beta}{2} + \left(\frac{2a_{eh}}{L_v} \right)^2 \right]^{-1},$$

we calculate $A \approx 23$ for $\beta = 0.04$ and the vacuum field scale length $L_v = 200$. Since the whistler instability is excited with a frequency $f_w = f_{ce} (1 - T_{\parallel}/T_{\perp})$, this anisotropy predicts that excited waves should have frequencies near 13 GHz. During frequency scans of the 12-18 GHz parallel cyclotron emission diagnostic, we observed that instability burst activity maximized near 13 GHz. This provides additional evidence that the mode is the whistler instability and that we must maintain control of hot electron anisotropy.

These anisotropy estimates are fairly rough and somewhat high. To improve them we need refinements to the codes and a better comparison with experimentally measured parameters. Length measurements from similar data using a spatial array of diamagnetic loops indicate the hot electrons are 2 to 3 times longer than the measurements we obtained above and provide anisotropy estimates in the range of 4 to 5. Together, however, these two measurements do indicate that we are creating hot electron distributions that are too peaked in perpendicular velocity. We expect to operate with $A \sim 2$ to 3, during which the whistler mode should, at worst, be convectively unstable, as shown in Fig. 7.

The importance of controlling anisotropy is obvious from the data presented here. Thus, in future experiments we will control the mix of ECRH heating power at the two axial locations and generate the proper hot electron feed with ICRH. In addition, we will optimize heating efficiency and anisotropy by (1) adjusting the aim of the ECRH horns and (2) varying the position of the resonant surface by changing the vacuum magnetic field.

5. SUMMARY

During the initial operation of TMX-U, we created hot electron populations in the end cells with parameters approaching those required for a thermal barrier. These experiments have been limited mainly by the amount of ECRH power available: 60-150 kW. However, we did observe nonthermal bursts of microwave emission at frequencies near the electron-cyclotron frequency of the minimum end-cell magnetic field. These emissions can only be derived from instability of the hot electron distribution.

Tentatively, we identify these modes by the frequency of enhanced emission as follows:

Table 2. Modes observed in the initial TMX-U experiments.

<u>Mode</u>	<u>Frequency</u>	<u>Condition</u>	<u>Effects</u>
UHLC	$f/f_{ce} \approx 1.1$	$n_{eh}/n_e \ll 1$; high n_e	None
Whistler	$f/f_{ce} \approx 0.9$	$n_{eh}/n_e \sim 1$; low n_e high anisotropy	Occasional drop in midplane line density and en- hanced axial losses.

While we observed temporally localized effects on confinement during whistler-like emissions, we saw no absolute limit to hot electron density or temperature that was directly attributable to instability activity. Estimates of anisotropy and hot electron length indicate that we formed distributions too peaked in perpendicular velocity and thereby susceptible to the whistler instability. In future experiments we will take greater care to control anisotropy to minimize the occurrence of whistler activity without driving the UHLC mode.

In spite of these effects, we do anticipate that a convectively unstable form of one of these instabilities will be present at equilibrium as indicated in Figs. 6 and 7. The exact effects on confinement at mode saturation depend on the method of saturation and wave amplitudes, that is, the temporal and

spatial growth rates. Some degree of wave-particle scattering is expected to enhance the loss rate over that due to classical processes. If so, additional ECRH power or reduced density operation may be required. It is also possible that instability wave energy may be reabsorbed internally in the end cell. If this energy is reabsorbed by the hot electrons, a velocity-space redistribution of energy will result; this may be beneficial, since it may reduce anisotropy. Reabsorption of wave energy in either the warm or cold electron population, however, would result in a mechanism for power loss from the hot electrons. We must include this possibility in power flow calculations and in electron heating control.

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