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ECRH IN TANDEM MIRROR MACHINES

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1. INTRODUCTION

Microwave heating of electrons in mirror geometry has been carried out in many devices for a number of years. In Table I we summarize uses of rf heating in several types of mirror machines, both past and present, as well as in devices presently under construction.

Early experiments in single mirror cells used ECRH to create and heat electron plasmas to serve as a target for trapping energetic neutrals. These experiments generated low density ($n < 1 \times 10^{12} \text{ cm}^{-3}$), but very energetic plasmas (100's of keV).¹ In addition, high beta, hot electron annuli (rings) were observed which were MHD stable even in simple mirror traps with regions of unfavorable curvature.² These rings are a key component of toroidally linked mirror cells (bumpy tori) in which the high beta rings create an MHD stable configuration for a lower energy toroidal plasma.³

More recently, the need for rf electron heating in mirrors arose with the development of the tandem mirror confinement scheme which incorporates thermal barriers and potential plugs for confining ions.⁴

The plan of this paper is as follows: Section 2 describes the thermal barrier concept and the use of ECRH to generate the several electron populations required to establish confinement. In Section 3, important physics issues related to the microwave heating are discussed. Fokker-Planck calculations which model the heating processes are presented in Section 4, followed by recent experimental data on hot electron heating in Section 5. A summary is presented in Section 6.

Table I. ECRH Experiments in Mirror Machines

<u>Type of Device</u>	<u>Purpose of Electron Heating</u>	<u>Past & Present Machines</u>	<u>Machines under Construction</u>
Single mirror	Target plasmas, hot electron rings	Interim, CIRCE, TPM	
	RF heating studies	SM-1	
Bumpy torus	Toroidally linked mirrors with hot electron rings for MHD stability	EBT, NBT	
Tandem Mirror	Startup target plasma	TMX-U	MFTF-B
	Generation of potential for confinement - plug and thermal barrier	TMX-U	MFTF-B, TARA GAMMA-10
	Hot electron MHD anchor		TARA
Multiple mirror	RF heating studies	STM	
	Ion trapping in thermal barrier	MMX	

2. ELECTRON HEATING FOR THERMAL AND POTENTIAL BARRIERS

The principle of the tandem mirror with thermal barriers is illustrated in Fig. 1, where it is compared with basic tandem confinement. In the basic tandem mode⁵ the confining potential is created by a plug-electron population n_p whose density exceeds a much larger volume center-cell plasma of density n_c . With a uniform electron temperature T_e , the confining potential is given by a Boltzmann relation $\phi_c = T_e \ln (n_p/n_c)$.

In the thermal barrier mode, a depression in potential (thermal barrier) thermally isolates the plug electrons from the central cell population. The potential dip is created by a hot, mirror-trapped electron population, combined with removal (pumping by charge exchange on injected fast neutrals) of ions which are collisionally trapped in the potential depression. The potential drops in the barrier since ions have poorer confinement with pumping, in the absence of the potential dip, than the hot electrons. The confining potential is created at a peak in density, separated from the thermal barrier (density peak determined by energetic ions injected with neutral beams--the so-called "sloshing ions"). If ECRH is used to heat the electrons at the density peak, their increased loss rate (electron "pump out") causes the potential to rise until quasi-neutrality is reached between ions and electron densities. The confining potential can then be formed with $n_p < n_c$ for $T_{ep} > T_{ec}$. The reduced thermal contact between plug and center-cell electrons makes this possible at modest ECRH power levels.

For the thermal barrier mode the confining potential is given by,

$$\phi_c \approx T_{ep} \ln \left[\frac{n_p}{n_b} \left(\frac{T_{ec}}{T_{ep}} \right)^{1/2} \right] - T_{ec} \ln \left(\frac{n_c}{n_b} \right) \quad (1)$$

where subscripts p(c) for density and temperature refer to the plug (central cell).⁶ The quantity n_b is the passing density of central-cell electrons at the potential minimum in the barrier and equals the difference between the total density and the hot-electron density.

The reduced requirements on plug density to establish the confining potential significantly reduces the magnet and neutral beam technology constraints and power requirements for the end plug of a tandem-mirror reactor compared to a standard tandem.

As shown in Table 1 several experiments with thermal barriers are operational, or under construction. At Livermore, experiments on TMX-U are underway to test the thermal barrier concept.⁷ Figure 2 shows the locations for ECRH in the experiment and a view of the microwave antennas in one end plug. For the thermal barrier $2\omega_{ce}$ heating is employed; fundamental heating at $\omega = \omega_{ce}$ is used in the potential peak. A 200 kW, 28 GHz pulsed gyrotron powers a set of antennas at each heating location.

A much larger scale experiment under construction at Livermore is MFTF-B, shown in Fig. 3.⁸ This experiment will employ electron heating at three frequencies: 28 and 35 GHz fundamental heating for plug electrons and 56 GHz at $2\omega_{ce}$ and higher harmonics in the thermal barrier.

3. REQUIREMENTS FOR ELECTRON HEATING

Table II lists important functions and requirements for ECRH in thermal barrier tandem mirrors. Computational methods which model various aspects of heating are noted.

Table II. Important Requirements for ECRH in Thermal Barrier Tandem Mirrors

<u>Function/Requirement</u>	<u>Issues</u>	<u>Analysis Methods</u>
Absorption of microwave power (Thermal barrier, potential plug)	<ul style="list-style-type: none"> • Mode (x/o) • Accessibility • Harmonic number • Relativistic effects • Core/edge heating 	Absorption theory, Ray tracing codes
Control of hot electron energy (T.B.)	Avoidance of hot electron runaway	Absorption theory, Fokker-Planck (F-P) and Monte-Carlo (M-C) codes
Control of hot electron anisotropy, $T_{\perp}/T_{\parallel}$ (T.B.)	Anisotropy drive of microinstabilities	Linear instability theory, F-P and M-C codes
Particle feed of trapped populations (T.B. and plug)	RF trapping of electrons from colder populations	F-P and M-C codes

3.1 MICROWAVE ABSORPTION

A fundamental requirement for heating is efficient absorption of the microwave power. This requirement determines the mode selected for launch of the wave, extraordinary(x) or ordinary(o), the position of launch for accessibility (high or low field side) and the harmonic number. In Table III we list the parameters for heating in the plug and thermal barriers for TMX-U and MFTF-B.

For calculating absorption ray-tracing codes are necessary.⁹ Results from such calculations for the potential plug of TMX-U are shown in Figs. 5 and 6. Figure 4 shows the magnetic field geometry of the minimum-B end plug. The plasma cross-section has the shape of a twisted bow tie, circular at the field minimum ($z \approx -5.7$ m) and becoming elliptical at higher fields. In Fig. 5a the effects of density on absorption at constant T_e are shown. As density increases, there is progressively greater ray bending and movement of the absorption peak from the plasma axis ($x \approx 0$) to the edge ($x \approx 5$ cm). Five cm at the $\omega = \Omega_e$ resonance corresponds to $r \approx 23$ cm at the field minimum. As shown in Fig. 5b, the absorption peak moves back to the axis as temperature increases at constant density. These effects are summarized in the power deposition curves of Fig. 6 for a plasma of 15 cm Gaussian radius at the midplane. Although the total fraction of antenna power absorbed in the plasma is near unity and almost independent of plasma parameter, the fraction absorbed within radii $R_0 = 5$ cm and $R_0 = 10$ cm (the plasma core) varies significantly. The calculations cover the range of parameters expected during plasma start-up and the transition to final equilibrium. To maximize absorption in the plasma core during startup, plasma density should be increased with electron temperature to avoid strong edge absorption.

Table III. Parameters for ECRH

<u>Parameter</u>	<u>TMX-U</u>	<u>MFTF-B</u>
Potential plug		
$n_{ep} \text{ (cm}^{-3}\text{)}$	7×10^{12}	5×10^{12}
$T_{ep} \text{ (keV)}$	1.4	60
$f \text{ (GHz)}$	28	28, 35
$\lambda = \frac{2\pi f}{\Omega e}$	1	1
Mode	X	x/o
Thermal barrier		
$n_{eh} \text{ (cm}^{-3}\text{)}$	$< 5 \times 10^{12}$	3×10^{12}
$E_{eh} \text{ (keV)}$	50	500
$f \text{ (GHz)}$	28	56
$\lambda = \frac{2\pi f}{\Omega e}$	2	≥ 2 (strongly relativistic)
Mode	x	x/o

Estimates for absorption in the thermal barrier of TMX-U are plotted in Fig. 7. These curves, calculated for a Maxwellian plasma with $k_{||} = 0$,¹⁰ show relativistic broadening and a shift to higher magnetic field of the absorption peak as temperature increases. The theory used for Fig. 7 includes only the resonance term $\omega = 2 \Omega_e$, although higher order resonances also influence the absorption.¹¹ Doppler broadening ($k_{||} = 0$) of the resonance can also be important for the experiment. Inclusion of these effects does not alter the conclusion that strong single-pass absorption is to be expected. For a 15 cm radius the plasma is less than 10% transmitting to the axis for $\alpha > 0.2 \text{ cm}^{-1}$. As described below, we expect that energy limiting will be an important mechanism in affecting absorption and penetration of microwave power to the axis in the thermal barrier.

3.2 CONTROL OF HOT ELECTRON ENERGY AND ANISOTROPY

It is necessary to control the mean energy of the hot electron population in the thermal barrier. The magnitude of the required dip in the ambipolar potential, which forms the thermal barrier, is determined from power balance of the plug electron population. The required hot electron density is in turn determined by the magnitude of this potential dip through the quasi-neutrality condition. Magnetohydrodynamic (MHD) stability sets a limit on the hot electron pressure. At fixed density this constraint can be satisfied only by limiting the mean energy of the hot electron population. This limiting temperature is about 50 keV in TMX-U.

The problem of energy control is illustrated by the power balance relations described in Fig. 8. Hot electron runaway is a potential problem for the TMX-U energy range. The mean energy observed in several experiments

using ECRH in either single or linked mirrors (bumpy tori) appears to obey a non-adiabatic scaling law,¹² $\rho/L_B \approx 0.05$, where ρ is the gyroradius of the hot electrons and L_B is the magnetic field scale length. For TMX-U ($L_B \approx 1$ m) this scaling law predicts a mean energy for the hot electron population on the order of 10 MeV. Although other loss processes (e.g., synchrotron radiation) would limit the mean energy below 10 MeV, it is necessary to control the mean energy of the hot electron population in TMX-U by some other mechanism.

We believe that the mean energy of the hot electron population can be limited by localized heating with strong single-pass absorption.¹³ The experiments considered in Refs. 1-3 all employed cavity heating; i.e., there was a significant amplitude in the heating field at all spatial locations within the plasma. In TMX-U the microwave beam is well collimated. By spatially limiting the microwave fields, as shown in Fig. 9, the hot electrons are "detuned" from the cyclotron resonance as their energy becomes mildly relativistic. As the relativistic mass increase shifts the resonance to higher magnetic fields where the rf field is weaker, the heating rate will be considerably reduced. A consequence of energy limiting is reduced microwave absorption. Flattening of the electron velocity distribution should occur due to limiting, which in turn leads to reduced rf diffusion and less absorption from the wave. The absorption should adjust so that power input from the wave is balanced by hot electron loss processes. This effect should aid penetration for a strongly absorbing wave.

Control of hot-electron anisotropy, an important drive for instability¹⁴ should also be possible by varying the mirror ratio for off-midplane heating. In the experiment the mirror ratio for heating in the thermal barrier can be varied by means of movable microwave horns whose aiming

along the magnetic axis can be adjusted. Resonance is maintained by simultaneous adjustment of the magnetic field.

Spatially limited heating is described in Ref. 13. The existence of an energy gap ΔE separating $2\Omega_e$ heating from higher harmonics is most easily explained for the condition $N_{||} = k_{||}c/\omega \approx 0$. Plotted in Fig. 10a is a map in pitch angle-velocity space ($\theta_0 = \cos^{-1} v \cdot B/vB$ at the field minimum) of regions of allowed resonance. The resonances, shown shaded and satisfying $2\Omega_e(z)/\gamma = \omega_{rf}$, where γ is the relativistic mass factor, are determined by the extent in field B (or equivalently mirror ratio R_p) of the microwave fields. The large energy gap ΔE effectively limits electron heating to energies below E_M . In a practical device the parallel index $N_{||}$ for harmonic heating can be small but non-negligible. Also, for fundamental heating ($\ell = 1$) with the x mode $N_{||}$ can be large. An example of non-zero $N_{||}$ which leads to doppler broadening and narrowing of the energy gap ΔE , is shown in Fig. 10b. Large $N_{||}$ for $\ell = 1$ creates a "resonance bridge" to higher harmonics. The narrow width in pitch angle of the bridge, however, should reduce diffusion to higher energy.

3.3 PARTICLE FEED OF TRAPPED ELECTRON POPULATIONS

In addition to providing energy input, ECRH also provides the particle source which sustains the trapped electron populations. A flow diagram illustrating this process is sketched in Fig. 11. Current feed to the hot electrons is a several-step process. Starting with the central cell population, electrons with enough energy to penetrate the thermal barriers pass through the potential plug. Both collision and rf "velocity kicks" from fundamental heating trap a fraction of these electrons, providing currents

J_{coll} and J_{rf} which then fuel the potential trapped electrons. Cold electrons from ionization of injected neutrals and cold gas can also be an important source of current for the plug.

As described in the introduction, rf diffusion of electrons to higher energy (rf "pumpout") generates a current J_{rf} escaping out of the potential. It is this same current which establishes the confining plug potential required for quasi-neutrality. The escaping energetic electrons join the mirror trapped, thermal-barrier population where their energy is further increased by harmonic heating. Particle balance of the thermal barrier electrons is achieved by losses into the mirror loss cone at higher energy, which are driven by collisions and rf diffusion.

4. FOKKER-PLANCK CALCULATIONS OF HEATING

4.1 HOT ELECTRON STARTUP

We have calculated rf heating of electrons using a time-dependent, bounce-averaged Fokker-Planck code. The processes modeled by the code are listed in Fig. 12. Since potentials are not included in the calculation, the results are relevant for hot electron startup when potential variations are small within the end plug mirrors. The details of the calculation are given in Ref. 13.

The midplane (field minimum) velocity space is depicted in Fig. 13. The particle source for mirror-trapped electrons is a low temperature Maxwellian plasma source of density n_s and temperature T_s that fills the loss cone. Electrons become trapped at low energy by both collisions and rf diffusion

across the loss-cone boundary. Both processes determine losses into the loss cone over the entire energy range and across a $v_0 = v_{\max}$ boundary.

For the rf driven currents shown in Fig. 11, strong trapping and heating are expected when rf diffusion for fundamental heating exceeds collisional losses into the loss cone. The strong trapping condition, given by the formula in Fig. 14, is sensitively dependent upon the magnitude of the rf electric field.

An example calculation for plasma-source parameters $n_s = 5 \times 10^{11} \text{ cm}^{-3}$, $T_s = 400 \text{ eV}$ and rf electric field $\epsilon = 100 \text{ V/cm}$ is shown in Fig. 15a. We show the axial profiles of density, mean-electron energy, and parallel and perpendicular plasma pressure.

The current and power fluxes across the loss-cone boundary due to collisions (dotted curves) and rf diffusion (solid curves) are shown in Fig. 15b. For this example the dominant current flow is at low energy. A cold electron initially trapped by ECRH near the loss cone has a small probability of reaching high energy compared to the probability of loss during heating. Consequently, the overall particle balance is determined at low energy $E \sim T_s$. On the other hand, the major component of power flow occurs at higher energy. For parameters such that $n_h/n_c \gg 1$ (strong trapping), the required rf power can be estimated from the collisional and diffusion losses of the hot electrons.

Contour plots of the steady state distribution function $f(v_0, \theta_0)$ at the midplane are shown in Fig. 16a. At moderate energies, f is distorted along the resonant heating lines. At higher energy where the rf diffusion is reduced because of the relativistic detuning, the contours are weak functions of θ_0 , since Coulomb collisions are the dominant processes. The same distribution function, integrated over the pitch angle θ_0 , is plotted as a

function of energy in Fig. 16b. The distribution is clearly non-Maxwellian. The stream component is visible at low energy. A break in the curve at an energy near $E_{10} = 63$ keV shows the effect of the relativistic detuning.

From the Fokker-Planck equation we define a quantity χ , relating rf electric field, rf frequency and plasma source density n_s . The solutions for the calculation scale with this parameter. The variation with χ of density, mean energy, required rf power and the fraction of hot electrons is shown in Fig. 17. The hot-electron fraction is defined as the number of electrons with energies exceeding 2 keV, the approximate depth of the thermal barrier expected in the TMX-U experiment. Electrons with lower energy would be expelled by the potential.

The plasma energy and density are seen to be increasing functions of χ and plasma-source temperature, as expected, since rf diffusion becomes relatively stronger compared to collisional losses. The saturation in mean-electron energy shown in Fig. 11(b) results from the relativistic detuning of the rf diffusion. The dashed curves are a plot of the strong trapping condition given in Fig. 14.

4.2 THERMAL BARRIER AND POTENTIAL PLUG EQUILIBRIUM

We have also used the Fokker-Planck equation to calculate equilibria which include the effects of a potential profile.¹⁵ The code, although more general than the calculation described in 4.1, assumes a fixed (in time) potential and does not calculate a self-consistent, time-dependent solution.

Results of calculations simulating the steady-state of TMX-U are shown in Fig. 19 for the assumed magnetic field and potential profiles plotted in Fig. 18.

By varying the rf electric field for fundamental heating, while holding constant the thermal barrier second harmonic electric field, we find solutions for the axial density profile shown in Fig. 19. As the electric field at the fundamental increases, the density at the fixed potential peak decreases. This illustrates the rf "pumpout" mechanism previously described. An rf electric field in the range $\epsilon_1 \sim 10$ V/cm reproduces a density peak in the plug which satisfies Eq. 1 and thus, the density and potentials are consistent. This value of electric field is smaller than that which we can apply in the experiment. Monte-Carlo calculations of heating in the same potential and magnetic well agree with the Fokker-Planck results.¹⁵

An important consequence of rf "pumpout" is that, as the rf field is further increased for fixed plug density (determined by energetic, neutral-beam-injected ions) the plug potential will rise to greater values than that assumed in Fig. 18. This strong rf result leads to a more favorable scaling of plug potential with density than described by Eq. 1.¹⁶

5. HOT ELECTRON STARTUP EXPERIMENTS IN TMX-U

The TMX-U experiment is sketched in Fig. 20. Recent experiments on hot-electron startup have been carried out.¹⁷ These experiments were in preparation for startup of the full thermal barrier equilibrium which combines ECRH, sloshing and pumping neutral beams and central cell ICRH. The startup experiments were performed at low density as motivated by the Fokker-Planck results shown in Fig. 17. During startup T_e is initially low ($T_e \leq 50$ eV) and efficient trapping and heating occurs only for large χ . Large χ is obtained for a low source plasma density, n_s , generated in the TMX-U central cell with low gas feed.

We show in Fig. 21 a typical diamagnetic loop signal showing time dependent buildup of hot electron pressure. Hot electron density up to $8 \times 10^{11} \text{ cm}^{-3}$ at 40 keV mean energy has been obtained for a 40 ms rf pulse. Good heating efficiency has been demonstrated. The hot electrons are not at steady state after 40 ms for such low startup density, consistent with Fokker-Planck estimates of 60-80 ms to approach equilibrium.

Data for a shot with a complete set of diagnostics is shown in Fig. 22. In addition to diamagnetism, midplane interferometric measurements of line density and x-ray Bremsstrahlung and axial measurements of plasma emission,¹⁸ were made. For this data buildup occurred late in time with power injected only in the thermal barrier, although at low density some power may have reached the fundamental resonance (cavity heating).

The hot electron density increases nearly linearly in time as shown by the x-rays and diamagnetism. A warm plasma (probable temperature $\sim$ few keV) is apparently mirror-trapped early during the pulse.

An important result is the energy limiting of the hot electron energy as measured by the mean energy of x-ray photons above 5 keV (foil filter) and also by the radiometer. The energy clamping is consistent with spatially limited heating as described in Sec. 3.2, although this result has not been clearly proven experimentally. There is some evidence for hot electron energy scaling proportional to rf power.

Measurements of hot electron length are shown in Fig. 23. The normalized diamagnetic pressure is compared with a Fokker-Planck result. We believe the shorter length measured experimentally may be due to non-equilibrium of the distribution as well as the possible difference in relative rf electric fields in the experiment compared to the calculation (100 V/cm assumed).

We attempt a comparison between experiment and theory in Fig. 24. The plasma source parameters n_s and T_s , which are used to calculate hot electron beta from the theory, are determined from a model of power balance between ECRH power input and end losses. The experimental results are estimated to lie in the shaded region, a factor 2 or so below the theoretical curve. Since the theoretical curves are for steady-state, the differences between theory and experiment are smaller.

The hot Electron beta scaling with density and power predicted by Fig. 24 assumes no potential plugging of central cell ions. Once plugging with neutral beam injection is achieved, the beta scaling with density is more favorable.

6. SUMMARY

We have described several aspects of ECRH in tandem mirrors. To create the desired electron populations requires careful attention to details of absorption. Among these are relativistic effects and non-Maxwellian distributions. Relativity plays an important role in both wave propagation (ray bending or refraction and wave accessibility or cutoffs) and absorption (harmonic overlap). These effects become even more important for higher energy machines such as MFTF-B and reactors.

Since the electrons are strongly driven by rf diffusion, their distribution in energy can depart from Maxwellian. This affects both absorption and plasma potentials. A self-consistent treatment of the coupling between rf diffusion and the effect on absorption is highly desirable. Fokker-Planck, Monte-Carlo and ray-tracing codes are useful for examining these issues. A complete treatment of these effects remains a goal for the calculations.

Experimentally, results for low density heating of hot electrons in TMX-U have shown good efficiency and have produced hot electron energies desired for a thermal barrier. The next step of experiments, currently underway, is to form a barrier by combining hot electrons with neutral-beam-injected hot ions and to build up the plasma density to the desired steady-state.

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FIGURE CAPTIONS

- Fig. 1. Comparison of axial potential profiles for the basic tandem and a tandem incorporating a thermal barrier. ECRH is used to create both the barrier and the plug potential, which confines center cell ions.
- Fig. 2. Heating locations in TMX-U and an axial view of the antennas in one end plug.
- Fig. 3. Sketch of the MFIF-B Axicell tandem mirror under construction at Livermore. ECRH is used in each end plug.
- Fig. 4. Field lines and mod-B surfaces in TMX-U showing locations of rf heating.
- Fig. 5. Ray bending and absorption in the potential plug of TMX-U for the extraordinary mode at $\omega = \Omega_e$. The surfaces for right-hand cutoff, upper-hybrid resonance and electron resonance are shown. The ray bundle at peak power is highlighted.
- Fig. 6. Fraction of antenna power absorbed within radius R_0 in the TMX-U potential plug. The plasma radial density profile is a 15 cm scale-length Gaussian.
- Fig. 7. Absorption coefficient for a Maxwellian plasma for $k_{\parallel} = 0$ and $\omega = 1.76 \times 10^{11} \text{ s}^{-1}$.

Fig. 8. Power balance for thermal barrier, hot electrons in TMX-U. Runaway to high energy ($\gg 50$ keV) must be avoided.

Fig. 9. A scheme to control hot electron energy and anisotropy in the thermal barrier by spatially-limited heating. The relativistic mass shift of the resonance to higher magnetic field limits heating.

Fig. 10. Allowed resonance (shaded areas) in midplane velocity space for spatially restricted rf electric fields for a) $N_{||} = 0$ and b) $N_{||} = 0.8$ in the potential plug ($\ell=1$) and $N_{||} = 0.25$ with thermal barrier ($\ell=2$). Higher order harmonic heating exists at high energy. (From Ref. 13.)

Fig. 11. Diagram for rf driven particle flow in the plug and thermal barrier.

Fig. 12. Fokker-Planck model for hot-electron startup.

Fig. 13. Midplane (magnetic minimum) velocity space for the Fokker-Planck code showing resonance lines and imposed boundary conditions.

Fig. 14. Condition for strong trapping and heating at the fundamental when potential effects may be neglected.

Fig. 15. a) Calculated axial profiles of density, mean electron energy and plasma pressure for TMX-U; b) Electron current and energy fluxes out one end across loss-cone boundary due to rf diffusion (solid) and collisions (dotted). Negative fluxes refer to flow out of the trapped space. Plasma source parameters are $n_s = 5 \times 10^{11} \text{ cm}^{-3}$, $3/2 T_s = 0.6 \text{ keV}$ and rf electric field $\epsilon = 100 \text{ V/cm}$.

Fig. 16. a) Contour plot of the distribution function in midplane phase space. The distribution function decreases by a factor 0.58 between contours; b) Energy distribution function $F(E)$ at the midplane.

Fig. 17. Plots of (a) plasma density, (b) mean electron energy, (c) fraction of hot electrons, and (d) required ECRH power, normalized to source density squared, as a function of χ with relativistic detuning. The parameter for the curves is source energy $3/2 T_s$. Plasma potential is assumed zero.

Fig. 18. Axial profiles of magnetic field and plasma potential assumed for Fokker-Planck and Monte-Carlo calculations.

Fig. 19. Fokker-Planck equilibria calculated for several values of plug electric field E_1 , and constant thermal barrier field $E_2 = 90 \text{ V/cm}$.

Fig. 20. TMX-U thermal barrier experiment.

Fig. 21. ECRH generation of hot electron plasma in TMX-U.

Fig. 22. Data sequence illustrating hot electron startup in TMX-U.

Fig. 23. Measured axial profile of hot electrons in TMX-U and comparison with Fokker-Planck calculation.

Fig. 24. Comparison of experiment and Fokker-Planck calculation of hot electron beta.

TANDEM MIRROR OPERATING MODES

Input power	Potential confinement	End cell ion microstability (source of low energy ions)
<p>Original tandem mode</p>	90° beams	$\phi_c = T_e \ln \left(\frac{n_p}{n_c} \right)$	Center cell ion losses
<p>Sloshing ion mode</p>	47° beams	$\phi_c = T_e \ln \left(\frac{n_p}{n_c} \right)$	Potential trapped ions and central cell ion losses
<p>Thermal barrier mode</p>	ECRH 47° beams pump beams	$\phi = T_{ep} \ln \left(\frac{n_p}{n_b} \right) \left(\frac{T_{ec}}{T_{ep}} \right)^{1/2}$ $- T_{ec} \ln \left(\frac{n_c}{n_b} \right)$	Potential trapped ions and passing center cell ions

Fig 1

MICROWAVE ANTENNAS IN TMX-U

End view

Fig 2

THE MFTF-B AXICELL

Fig 3

FIELD LINES AND MOD-B IN PLUG, EAST END, ELEVATION TMX-U

Fig 4

RAY BENDING AND ABSORPTION IN THE POTENTIAL PLUG OF TMX-U

Greater ray bending at higher density ($T_e = 50 \text{ eV}$)

Fig. 5

Movement of absorption to $x = 0$ at higher T_e ($n = 4 \times 10^{12} \text{ cm}^{-3}$)

POWER DEPOSITION IN THE TMX-U PLUG. HIGH DENSITY AND
LOW TEMPERATURE CAN LEAD TO EDGE ABSORPTION

Fig. 6.

ABSORPTION IS STRONG AT $\omega = 2\Omega_e$ IN THE THERMAL BARRIER OF TMX-U

Fig. 7

CONTROL OF HOT ELECTRON RUNAWAY

Problem: What controls are available to limit electron energy and prevent runaway?

Hot electron power balance

$$\begin{aligned} \frac{d}{dt} (n_e^h E_e^h V) &= P_{\text{ECRH}} - P_{\text{SYNC}} - P_{\text{BREM}} - P_{\text{SCATT}} - P_{\text{DRAG}} \\ &\sim n_e^h E_e^h \sim n_e^h n_i (E_e^h)^{1/2} \sim \frac{n_e^h (n_e + n_i)}{(E_e^h)^{1/2}} \sim \frac{n_e^h n_e^c}{(E_e^h)^{3/2}} (E_{eh} - 3/2 T_e^c) \end{aligned}$$

For range of interest ($\langle E_e^h \rangle > 50 \text{ keV}$, $n_e^h > n_e^c$),

$$P_{\text{SCATT}} > P_{\text{DRAG}} \gg P_{\text{SYNC}} > P_{\text{BREM}}$$

Since $P_{\text{SCATT}} \sim \frac{1}{(E_e^h)^{1/2}}$, what will prevent runaway?

Possible solution:

Limit on electron heating by control of heating zone and $N_{\parallel}$

Fig 8

CONTROL OF THERMAL BARRIER HOT ELECTRON ENERGY AND ANISOTROPY DRIVEN INSTABILITY

Fig 9

ENERGY G/P BETWEEN ALLOWED RESONANCES FOR
THERMAL BARRIER ELECTRONS IN TMX-U

Fig. 10

**Current Feed to Plug and Thermal Barrier
due to RF and collisions**

Fig 11

BOUNCE – AVERAGED, ELECTRON FOKKER-PLANCK CODE WITH RF HEATING (ECRH)

- Time dependent calculation
- v, θ coordinates; non-relativistic
- Symmetric axial profiles
- Coulomb collisions: electron-electron and electron-ion (fixed ions)
- Electron heating at $\omega = \omega_{ce}, 2\omega_{ce}$
Quasi-linear rf diffusion — $E_1^- (k_{||} = 0)$
- Pseudo-relativistic: Magnetic field dependent rf profile with mass dependent shift of the resonance
- PLASMA POTENTIAL, $\phi = 0$

FOKKER-PLANCK MIDPLANE PITCH-ANGLE AND VELOCITY SPACE

Fig. 13

RF TRAPPING AND HEATING FROM A PLASMA STREAM SOURCE

$$\left. \begin{array}{l} \text{RF heating} \\ \text{at } \omega = \omega_c \end{array} \right\} \nu_{\text{RF}} \sim \frac{1}{v^2} \frac{dv^2}{dt} \sim \frac{D_{\text{RF}}}{v^2} \sim \frac{\mathcal{E}_1^2}{v^2 \omega}$$

Strong trapping and heating occurs when RF diffusion is competitive with coulomb losses, i.e.,

$$\nu_{\text{RF}} > \nu_c (\Delta\theta)^2 \quad \left[\text{Matsuda, Nevins, and Cohen} \right]$$

[UCRL 85826]

For a plasma stream of density and temperature n_s and T_s , the strong trapping condition is,

$$E_s (\text{keV}) = \frac{3}{2} T_s \gtrsim \left[\frac{n_s \times 10^{-11} (\text{cm}^{-3}) f(\text{GHz})}{\Delta\theta^2 \mathcal{E}_1^2 (\text{V/cm})} \right]^2$$

Fig 14

FOKKER-PLANCK CALCULATIONS FOR TMX-U

AXIAL PROFILES

(a)

PARTICLE AND POWER LOSS-CONE FLUXES

(b)

Fig. 15

FOKER-PLANCK HOT ELECTRON DISTRIBUTION

Fig. 16

FOKKER PLANCK CALCULATIONS ARE USED TO PREDICT ECRH HEATING EFFICIENCY

$$\chi = \frac{\mathcal{E}^2 (\text{V-cm}^{-1})}{n_s (10^{11} \text{cm}^{-3}) f (\text{GHz})}$$

$$R_r (\omega_{ce}) = 2.3 \quad \phi_p = 0$$

$$R_r (2\omega_{ce}) = 1.15 \quad E_{10} = 63 \text{ keV}$$

$$\mathcal{E} (\omega_{ce}) = \mathcal{E} (2\omega_{ce}) = 100 \text{ V-cm}^{-1}$$

Fig 17

MAGNETIC FIELD AND POTENTIAL PROFILES IN TMX-U END CELL

Fig. 18

RF CONTROLLED DENSITY IN TMX-U POTENTIAL PLUG

density profiles : $E_{rf}(n=2) = 90 \text{ v/cm}$

Fig. 19

TANDEM MIRROR EXPERIMENT

ATMNA

Fig 20

ECRH FORMATION OF HOT ELECTRON PLASMA

- Required to displace thermal electrons by magnetically trapped electrons to form thermal barrier
- Parameters to date — heating in absense of dense plasma

$$T_{e, \text{ hot}} = 40 \text{ keV}$$

$$n_{e, \text{ hot}} = 0.8 \times 10^{12} \text{ cm}^{-3}$$

$$\beta_{e, \text{ hot}} = 6\%$$

$$W_{\text{ hot}} = 460 \text{ J}$$

- Hot electron formation during low gas (start-up) conditions
— Electron source is central cell plasma

Diamagnetism at plug midplane

Stored energy: $W_{\perp} = 460 \text{ J}$

Rate of rise: $P_{\perp} = 20 \text{ kJ/s}$

Power incident: $P = 60 \text{ kW}$

Efficiency = 33%

Ref. B.W. Stallard, et al., UCID-19665 (1983)

Fig 21

HOT ELECTRON STARTUP AT LOW DENSITY IN TMX-U

Fig 22

AXIAL PRESSURE PROFILE OF HOT ELECTRONS IN TMX-U

Fig. 23

COMPARISON OF OCTOBER 82 TMX-U RESULTS WITH STEADY STATE FOKKER-PLANCK CODE

Fig 24