DOE/ER-0070

Report of the Workshop on RF Heating in Mirror Systems

May 1980

Published August 1980

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U.S. Department of Energy
Office of Energy Research
Division of Mirror Confinement Systems

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James T. Woo, Rensselaer Polytechnic Institute

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Office of Energy Research
Division of Mirror Confinement Systems
Washington, D.C. 20545

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PREFACE

With the advance of the tandem mirror and the thermal barrier concepts, the application of RF power for heating and shaping the particle velocity distributions became an important element in the mirror program which can provide significant improvements to the reactor performance. To bring the important advances in RF-plasma interaction into the mirror program in a coherent fashion, a workshop was convened by the Division of Mirror Confinement Systems (DOE) to bring together scientists from both the magnetic mirror confinement and RF-plasma heating communities to exchange information on techniques, results and problems for potential tandem mirror applications. This report contains a summary of the workshop proceedings and concensus, and is intended to serve as the basis for further research.

Robert E. Price
Division of Mirror
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Office of Fusion Energy

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Executive Summary

During the ten month period from April 1979 to January 1980, the concepts of the tandem mirror reactor underwent a major evolution with the introduction of the electron thermal barrier idea. The thermal barriers permit the electron temperature in the tandem mirror end plugs to be raised above the central cell electron temperature by direct heating on the plug electrons only. As a result, the plug density required to maintain the potential barrier can be significantly reduced. This new concept when used in conceptual reactor design calculations gives every indication that a tandem mirror reactor could have an ignited center cell and that an energy amplification factor Q (energy produced divided by energy used to sustain the system) as high as 10-20 is realizable in a reasonable sized power plant. The development of this concept and its reactor implications combined with the results from TMX which verified the basic tandem mirror principles, excited the fusion scientific community as the first major evolution in magnetic fusion since the development of the tokamak concept. As a result, the Senior Mirror Review Panel recommended an agressive tandem mirror program to be pursued with upgrade of Phaedrus, TMX and MFTF as soon as programatically appropriate to incorporate thermal barriers and direct electron heating in the end plug.

It was recognized that many of the requirements to establish an improved tandem mirror reactor with thermal barrier can be

realized by the application of RF heating. Consequently, knowledge on the interaction of strong RF with mirror confined plasma is no longer of intellectual interest only, but is a matter of practical importance to the agressive pursuit of the tandem mirror program. For this reason, a Workshop on RF Heating in Mirror Systems was convened in Washington, D.C. on March 10-12. The goals of this workshop were multifold. First the workshop brought together scientists from both the mirror and tokamak RF communities to exchange information on techniques, results and problems. It was indeed profitable for the mirror scientists to receive comments from their tokamak counterparts. Secondly, the workshop provided a format from which the present understanding of RF heating could be delineated-i.e. the advantages and disadvantages of various ranges of RF heating and the relevant physics issues. Third, the workshop brought out areas of research needed for further advancement of RF heating that could benefit both Tokamak and Mirror research. Lastly, the workshop provided a technical review of the preliminary ideas on using RF to enhance the tandem mirror concept.

The workshop organized jointly by R.E. Price of DOE and J.T.Woo of Rensselaer Polytechnic Institute was attended by twenty-five scientists, identified in the list of attendees. The format was to have two days of presentations with adequate time for discussion. The last day was reserved for discussions only. The agenda is also attached. In addition to the benefits derived from strong interaction between the participants, the Workshop led to some general conclusions and recommendations.

The general consensus of the experimentalist at the workshop was that almost all RF experiments are very sensitive to details and generally the physics is more involved than first anticipated. These two concerns imply that before doing any major RF experiments, there should be greater emphasis for theoretical support in planning the design and operation of the experiments. This would be particularly true for mirror plasma applications because the physics of realizing phase space selective heating in non-axisymmetric geometry can be expected to be more complicated than Tokamak applications. While the prospect for using RF to improve the tandem mirror concept appears very promising, more thorough theoretical efforts must be made to understand the wave physics in three dimensionally inhomogeneous geometry and their coupling to non-Maxwellian particle distributions. There was consensus that the present plans of applying ECRH and ICRH to the current generation of experiments are the most promising approach because the corresponding physics is best understood. However, considerations of scaling RF systems to meet reactor needs and the possibilities of realizing further improvements to the tandem mirror concept that has already been identified suggest the need to aggressively pursue other approaches of RF heating. The projected needs of the mirror program for RF heating should also provide added inpetus for more technology efforts in development of gyrotrons, optimized coupling structures, polarizers, vacuum windows and lower cost power supplies of higher reliability. With regard to specific frequency ranges, the following observations were made.

LOWER HYBRID HEATING----This frequency range is potentially best suited to reactor applications. The principal issue is understanding the physics of wave coupling, which is the most complex and presently least understood among the three RF heating frequency ranges. It was the consensus of the Workshop that theory directly applied to mirror systems should be carried out to address the questions of wave penetration, taking into account such features as non-Maxwellian distributions, multiple density gradients and magnetic field inhomogenities. Although the planned high power experiments on a number of Tokamaks will provide some test for the theoretical efforts, there is also a great need for some smaller scaled mirror geometry experiments.

ION CYCLOTRON HEATING----Recent results from PLT and Pheadrus indicate that ICH can be expected to be effective on the planned TMX and Phaedrus upgrades. Additional theoretical and experimental works are needed on antenna loading, delineation of the absorption process and the energy balance. Innovative research should be done on using ICRF to heat electrons for barrier enhancement. Using ICRF for ion stoppering of end plugs and thermal barriers also need more detailed theory particularly in regard to reactor applications. The RF plugging experiments should be better diagnosed in order to distinguish the effect from nonadiabatic processes.

ELECTRON CYCLOTRON HEATING---Experiments on ISX-B and EBT have demonstrated that both beamed and cavity absorbing modes lead to perpendicular heating of the electrons. The beamed mode appears better suited to tandem mirror applications. However, the ray trajectory of the extraordinary mode is complicated and the wave is strongly absorbed. Hence the experiments must be done carefully to assure full coverage of plasma cross section. In contrast, ordinary wave propagation is more tractable, but in present day low density experiments, this mode is only weakly absorbed. Therefore, the effectiveness of ordinary wave heating in high density fusion parameter plasma requires further experimental investigation to verify the theoretical predictions.

CONCLUSIONS---The use of ECRF and ICRF in tandem mirros looks promising. LHRF heating still has many physics uncertainties associated with it but because of its availability and reactor compatibility, research on LHRF heating in mirrors should be initiated. Further detail is provided in the following chapters.

LIST OF ATTENDEES

Department of Energy

R. Price *
T. V. George
S. Staten

General Atomics

R. Harvey
J. Luxon

Jaycor

R. Gilgenbach

Lawrence Livermore Laboratory

B. Stallard
A. Molvik
Y. Matsuda

M.I.T.

M. Porkolab

McDonnell-Douglas

J. Muller

Oak Ridge National Laboratory

D. B. Batchelor

Princeton Plasma Physics Laboratory

R. Motley
N. Fisch
P. Colestock

Rensselaer Polytechnic Institute

J. Woo *

Science Applications Inc.

R. Aamodt

TRW

K. Moses
B. Quon
B. McVey
R. Meyer

United Technology

E. Szekilas

UCLA

G. Morales

University of Wisconsin

R. Post
D. Smith

* Workshop Organizers

Workshop on RF Heating in Mirror Systems

March 10-12, 1980
Room BE-069, Forrestal Building

Department of Energy
1000, Independence Avenue, N.W.
Washington, D.C.

AGENDA

Monday, March 10:

Morning--------------Tandem Mirror Program

R.E. Price (DOE)-----------------------Workshop Objectives

J.T. Woo (RPI)-------------------------Tandem Mirror Applications of RF Heating

B.W. Stallard (LLL)--------------------LLL Tandem Mirror Program

R.S. Post (Wisconsin)------------------Pheadrus Program

B.H. Quon (TRW)------------------------Symmetric Tandem Mirror Program

Afternoon-----------Mainly Electron Cyclotron Resonance Range

B.W. Stallard (LLL)--------------------ECRH in TMX Upgrade

D.B. Batchelor (ORNL)------------------ECRH in Simple Mirrors

M. Porkolab (MIT)----------------------ECRH in Tandem Mirrors

--------------------RF Heating in Alcator

P. Colestock (PPPL)--------------------Fast Wave ICRH in PLT

Tuesday, March 11:

Morning-------------Mainly Lower Hybrid Range

R.M. Gilgenbach(Jaycor)--------------ECRH in ISX-B

R.W. Motley (PPPL)-------------------Lower Hybrid Heating

J.L. Luxon (GA)----------------------Doublet II Results

G. Morales (UCLA)--------------------UCLA Results

Afternoon------------Mainly Ion Cyclotron Resonance Range

N.J. Fisch (PPPL)--------------------Magnctosonic Drive for Tokamaks and Mirrors

R.W. Harvey (GA)---------------------Lower Hybrid Penetration of Dense Hot Plasmas

D.B. Batchelor (ORNL)
J.T. Woo (RPI)----------------LHRF Applications to Tandem Mirrors

D. Smith (Wisconsin)-----------------ICRH in Pheadrus

A. Molvik (LLL)----------------------Applications of ICRH in TMX Center Cell

B. McVey (TRW)-----------------------Calculations of ICRH for TMX Center Cell

Wednesday, March 12:

E. Szekilas (United Technology)------R.F. Plugging in PSX

Y. Matsuda (LLL)---------------------R.F. Plugging for Thermal Barrier Applications

DISCUSSIONS

REPORT OF THE WORKSHOP ON RF HEATING IN MIRROR SYSTEMS

I. Introduction

The tandem mirror confinement concept (Dimov et al., 1976; Fowler and Logan, 1977) is potentially attractive as a fusion reactor for several important reasons. Firstly, the principle of the concept is based on classical plasma physics which is generally well understood. Secondly, the confinement time is scalable so that economically attractive energy balance can be realized. Finally, the reactor rendition of the concept appears to be very compatible with engineering and operational considerations. For these reasons, development of the tandem mirror reactor is being actively pursued.

Recently, a number of concepts and experiments have been advanced that can lead to further improvements in the performance of the tandem mirror reactor. The specific ideas are:

(1) Creation of a thermal barrier to limit electron conduction between end plug and center cell (Baldwin & Logan, 1979).
(2) Supplementary ion heating to control the ion temperature in the end plug (Post et al, 1977) and in the center cell (Molvik,1980).
(3) Pumping of the electrons out of the end plugs to amplify the potential barrier (Woo, 1978; 1979a).
(4) RF plugging to stabilize the end plug plasma against loss cone modes (First considered by Dow and Knetchli, 1959).

All these ideas are mutually compatible and can be incorporated onto the original tandem mirror concept. In general, these improvements can in principle be realized by the selective application of RF power to the appropriate charge particle species in the various regions of the tandem mirror system. The purpose of this report is to survey the theoretical and experimental basis for such applications and identify the research needs. This report is prepared from the proceedings of the Workshop on RF Heating in Magnetic Mirror Systems held at DOE Headquarters in Washington, D.C. on March 10-12,1980. The workshop was organized into four consecutive half-day sessions of prepared talks and one half-day discussion. The first session on tandem mirror concepts and program plans served to identify the opportunities for the application of RF power and the specific approaches that are being pursued. A summary of the ideas presented in this session is given in Section II. The following three sessions of the Workshop were devoted to an exposition of current theoretical and experimental knowledge on the interaction of RF power with magnetically confined, dense, high temperature plasmas at frequencies near the electron cyclotron resonance, lower hybrid resonance and ion cyclotron resonance (including magnetosonic) ranges. The conclusions from these proceedings are presented in subsections A,B and C of Section III respectively. The discussion period, led by R.E. Price, seeks to identify the research needs. The recommendations are reported in Section IV.

II. Potential Applications of RF Heating

The tandem mirror concept utilizes magnetic mirrors to confine plasmas of different densities and potentials, suitably arranged in a linear configuration to form potential barriers for the confinement of both electrons and ions. The standard tandem mirror configuration as originally proposed for TMX (Coensgen, 1977) shown in Figure 1 consists of three cells: two high density mirror confined plasmas with large positive ambipolar potentials to form electrostatic end plugs for a center cell where the fusion plasma is confined at an intermediate potential. The plasma in the end plugs are sustained by energetic neutral injection and as in a standard mirror confined plasma, the magnitude of the positive space charge potential is determined by the ambipolar loss condition $\tau_i = \tau_e$, from which,

$$\frac{\phi_p}{T_e} \exp \left\{ \frac{\phi_p}{T_e} \right\} = \left(\frac{m_i}{m_e} \right)^{1/2} \left(\frac{T_i}{T_e} \right)^{3/2} \tag{1}$$

In the absence of supplementary heating, the electrons are heated by the energetic ions injected as neutrals and for Coulomb relaxation, the parameters are related approximately by $T_i \simeq 2\,\phi_p \simeq 10\,T_e$ (Baldwin, 1977). The positive ambipolar potential causes the ion distribution to possess an inverted population in $V_\perp$ which is a source of free energy for exciting microinstabilities (Post and Rosenbluth, 1966) that can enhance losses through particle-wave scattering. When this ambipolar

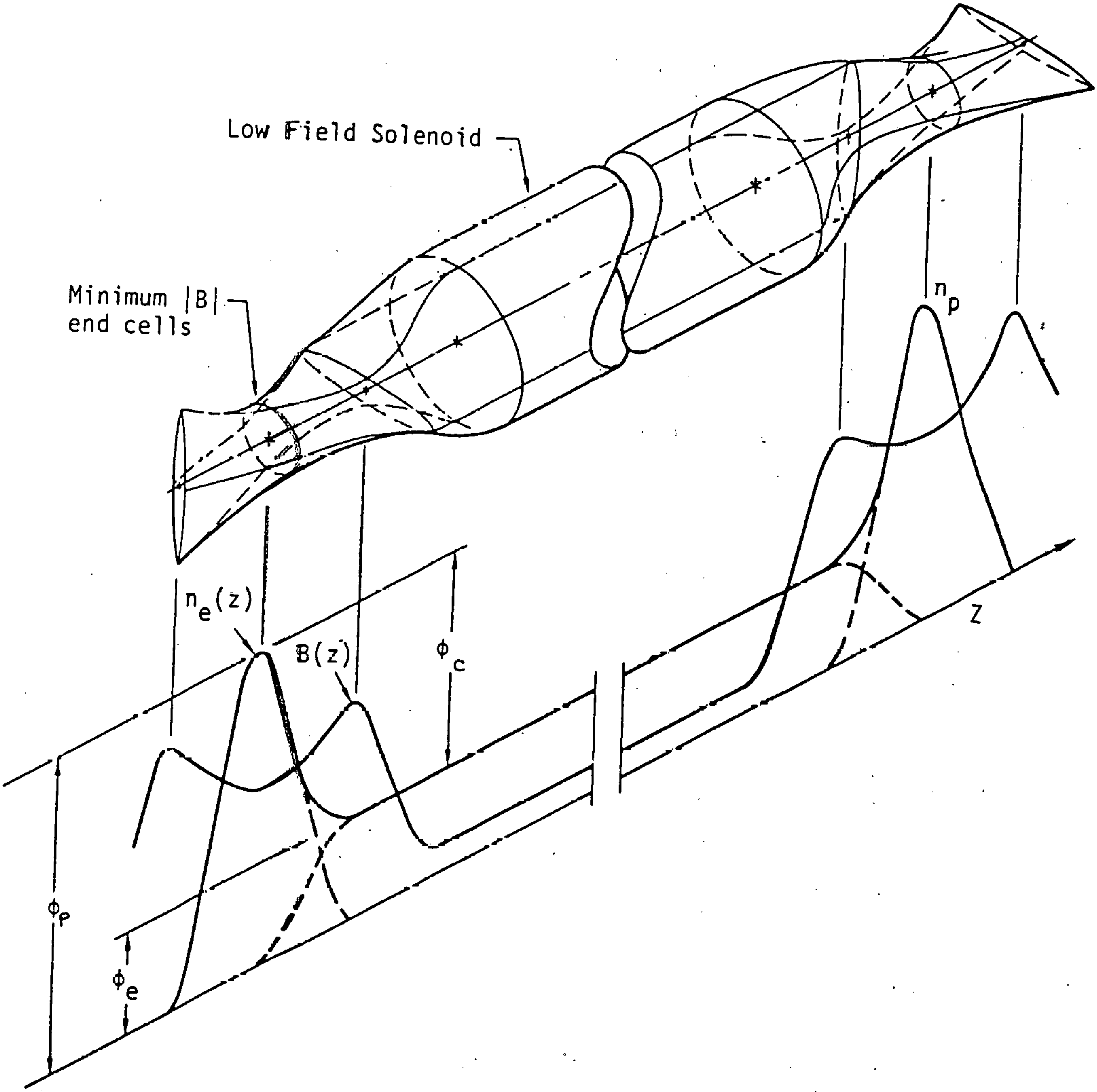


Figure 1 Standard Tandem Mirror Configuration

potential is utilized as end plugs for a center cell at an intermediate potential, then the ions in the center cell are locally confined by the barrier ϕ_c while the electrons, which are common to both regions, are confined by the overall positive potential well. Since the electrons in the plugs can penetrate into the center cell, the density in the two regions are related by the Boltzmann well relation

$$\phi_c/T_e = \ell n\ (n_p/n_c) \qquad (2)$$

The design of a tandem mirror reactor based on the original concept are **then** constrained by these relations.

RF heating can be utilized to improve the tandem mirror reactor concept significantly in the following ways:

(1) General Electron Heating--For a reactor, it is desirable that ϕ_c should be large to enhance center cell ion confinement while n_c/n_p should not be too small so that fusion yield from the center cell, proportional to n_c^2 is much greater than the input power for sustaining the plug density, which is proportional to n_p^2. In the standard tandem mirror, these values are constrained by equation (2). Accordingly, for a desired ϕ_c, a large value of n_c/n_p can be realized by heating the electrons in the end plugs. However, in order to avoid rapid electron heat conduction to the center cell, it will be desirable to introduce a thermal barrier (Baldwin & Logan, 1979) in the form of a local potential minimum between the end plug and the center cell. The thermal barrier concept will be tested in the planned TMX-Upgrade experiment to permit isolated heating of electrons in the end plugs.

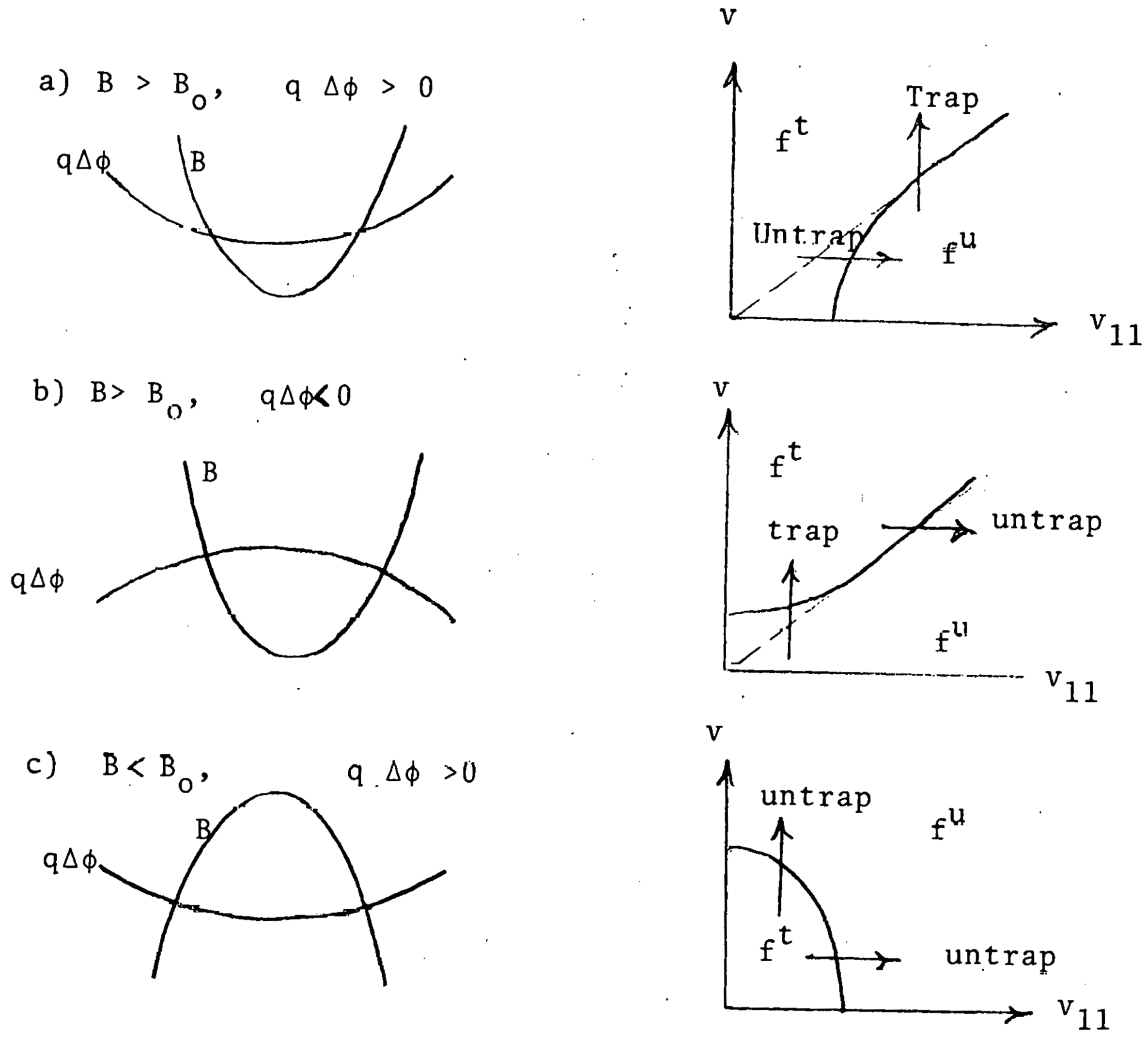


Figure 2 Velocity Space for Confined Particles Bounded by $V_{11}^{2} - \left(\frac{B}{B_o} - 1\right) V_{\perp}^{2} - \frac{2}{m} q\Delta\phi = 0$

(2) Trapping of Electrons by Perpendicular Heating--This form of heating can be realized by the electron cyclotron resonance process. When applied to particles in a mirror field in either a potential well (Fig. 2a) or a local maximum (Fig. 2b), electrons acquiring perpendicular energy are transported in velocity space to become better confined in the magnetic mirror field. Therefore, electron cyclotron heating at a resonance layer can create a localized electron rich region within a mirror cell to form a potential minimum. Such a localized potential minimum can modify the ambipolar potential of a mirror confined plasma and allow cold ions to be trapped so as to stabilize the loss cone modes. This mechanism has been postulated by Ioffe et al (1974) to explain the experimentally observed stabilization in the presence of applied RF power. With sufficiently high density of these electrons trapped deeply in the magnetic mirror, along with ion pumping, this mechanism can be expected to aid in the establishment of a potential minimum to form the thermal barrier. This approach will be examined on TMX-U.

Previous experiments with ECRH in mirror systems have also shown that the finite β associated with the hot electron plasma can modify the vacuum magnetic field sufficiently to provide MHD stability in a simple mirror (Dandl et al.,1975). The symmetric tandem mirror (STM) experiment at TRW aims to investigate the application of intense ECRH at several frequencies to form a hot electron disk in a simple mirror which can serve both as a MHD anchor and to form a thermal barrier.

(3) Untrapping of Electrons by Perpendicular Heating--When applied to particles trapped in a potential barrier along a magnetic beach, as shown in Figure 2c, increasing the perpendicular energy generally tends to detrap the particles and drive them into regions of lower magnetic field. Therefore, by applying ECRH away from the midplane of a mirror cell, this process can detrap electrons and create a local positive potential. The process, therefore, has the same effect as general heating to amplify the ambipolar potential while maintaining n_c/n_p at sufficiently large values. This approach, together with ECRH at the midplane, can be used in the A-cell barrier concept (Baldwin, Logan, Simonen, 1980) to establish both the potential and thermal barrier in the same mirror cell. It is presently the reference design for TMX-U and MFTF-B.

(4) Untrapping of Electrons by Parallel Heating----The electric field components in the direction parallel to the confinement magnetic field is always subject to collisionless interactions with the streaming particles travelling in phase with the wave. The electron distribution confined in the tandem mirror system is expected to be approximately Maxwellian and therefore, will absorb energy by Landau damping. Parallel heating of electrons can thus be realized at any frequency. Regardless of the axial

potential and magnetic field distributions, this form of heating generally tends to detrap particles as shown in Figures 2a,b and c. Parallel heating is therefore most efficient for amplifying the potential barrier in the end plugs. For sufficiently intense heating, the electron distribution can be expected to assume a two temperature form with $T_{||} >> T_{\perp}$. It is then possible to establish a large ambipolar potential in the end plug with modest density in comparison to the center cell (Woo, 1979a). The heating power required to maintain this anisotropic two temperature distribution is determined by the self-scattering time for $V_{||}$ and scales as $(T_e^{\frac{1}{2}} n_p)^{-1}$. This approach may therefore be used to improve the tandem mirror by itself as well as in conjunction with thermal barriers.

(5) Perpendicular Heating of Ions----Supplementary ion heating provides additional control of the ion temperature. Although it is expected that the ions in the center cell of a tandem mirror reactor will not need supplementary heating to maintain thermonuclear conditions, and in fact, it is desirable to maintain a low ion temperature for better confinement, the process is of interest in hydrogen or deuterium experiments to attain reactor condition for the center cell ions. In the end plugs, supplementary ion heating relaxes the energy required for the injected neutrals to maintain the plasma in the end plugs. Perpendicular heating is preferred to general heating of the ions for maximizing the confinement time. ICRH is therefore naturally suited to these applications.

Supplementary heating of plug ions is being pursued in the Pheadrous tandem mirrors and incorporation of ICRH in the TMX-U center cell is also planned.

(6) Detrapping of Ions by Parallel Heating----This process is of interest to the creation of a local potential minimum as a thermal barrier (Baldwin and Logan, 1979). At present, the proposed approach for thermal barrier formation is to use charge exchange of neutrals injected in the loss cone of the confined ion distribution (Kesner, 1979) and supplemented with trapping of electrons by ECRH as described in paragraph (2) and (3) of this section. In principle however, it should also be possible to detrap ions with RF power through processes such as ion Landau damping and transit time pumping. The feasibility of these approaches have not been examined in detail at the present time.

(7) RF Plugging----The existance of the inverted ion distribution in the end plug is a source of free energy for the excitation of microinstabilities that degrades confinement both in the end plugs as well as the center cell. Therefore, RF plugging is of interest to at least partially fill the ion loss cones and suppress the microinstabilities. Because of the large skin loss, low frequency waves near the ion cyclotron resonance range appears most promising for this application. To minimize power requirement, plugging must be realized without heating. Evidence of such plugging has been reported previously (Watari et al., 1978) and further investigations are being planned on the Pheadrous and PSX experiment.

(8) RF Trapping and Detrapping----Recent results on TMX have shown that the self-excited RF from the end plugs can significantly degrade ion confinement in the center cell (Stallard, 1980; Rognlien, 1980). It is therefore of interest to consider the interaction of the self generated RF with the plasma which could lead to enhanced velocity space diffusion.

III. Survey of RF Heating Results

The potential applications of RF heating to tandem mirrors have been identified in the previous section along with the mechanism by which the desired effects can be realized. For implementation, it is necessary to consider the practicality of specific approaches and the overall effects in the presence of competing processes. The major portion of the Workshop was devoted to a review of RF heating results, both theoretical and experimental, relevant to the tandem mirror applications. For present generation experiments and ultimate reactor renditions, the frequencies of interest are on the order of 10^{11}Hz for the electron cyclotron range, 10^9-10^{10}Hz for the lower hybrid range and 10^8Hz for the ion cyclotron resonance range. Since the hardwares and the wave physics are distinct for each of these frequency ranges, they are considered separately in the following:

A. Electron Cyclotron Resonance Range

Electron cyclotron resonance heating of plasmas was first reported by Dandl et al (1962) by applying RF power to a cavity in a mirror magnetic field in which a resonance layer exists. Since then, this approach has been extensively utilized for electron heating in a series of experiments and is the basis of the Elmo Bumpy Torus (EBT) concept (Dandl et al., 1975) to utilize the finite-β of hot electrons for MHD stable confinement in simple mirrors. These experiments have shown that strong absorption occurs at resonance layers where $\omega = \Omega_e$ and $2\Omega_e$, the fundamental electron cyclotron frequency and its second harmonic. A limitation in considering the application of ECRH to thermonuclear systems has been the unavailability of high power sources at frequencies corresponding to electron cyclotron resonance at magnetic fields required for confinement of reactor plasmas. The development of the gyrotron concept (Zaytsev et al., 1974) has made it feasible to generate short wavelength RF at high power. Programs to develop sources with anticipated single tube CW power levels of $\sim 10^5$ watts at frequencies up to 110 GHz have been initiated. As a result, the feasibility of incorporating ECRH in various fusion reactor concepts has been greatly extended. Initial experiments with ECRH in Tokamaks have been carried out in

TM-3 (Alikaev et al., 1976) and ISX (Gilgenback et al., 1980). A variety of applications to the tandem mirror concept as described in the previous section have also been planned.

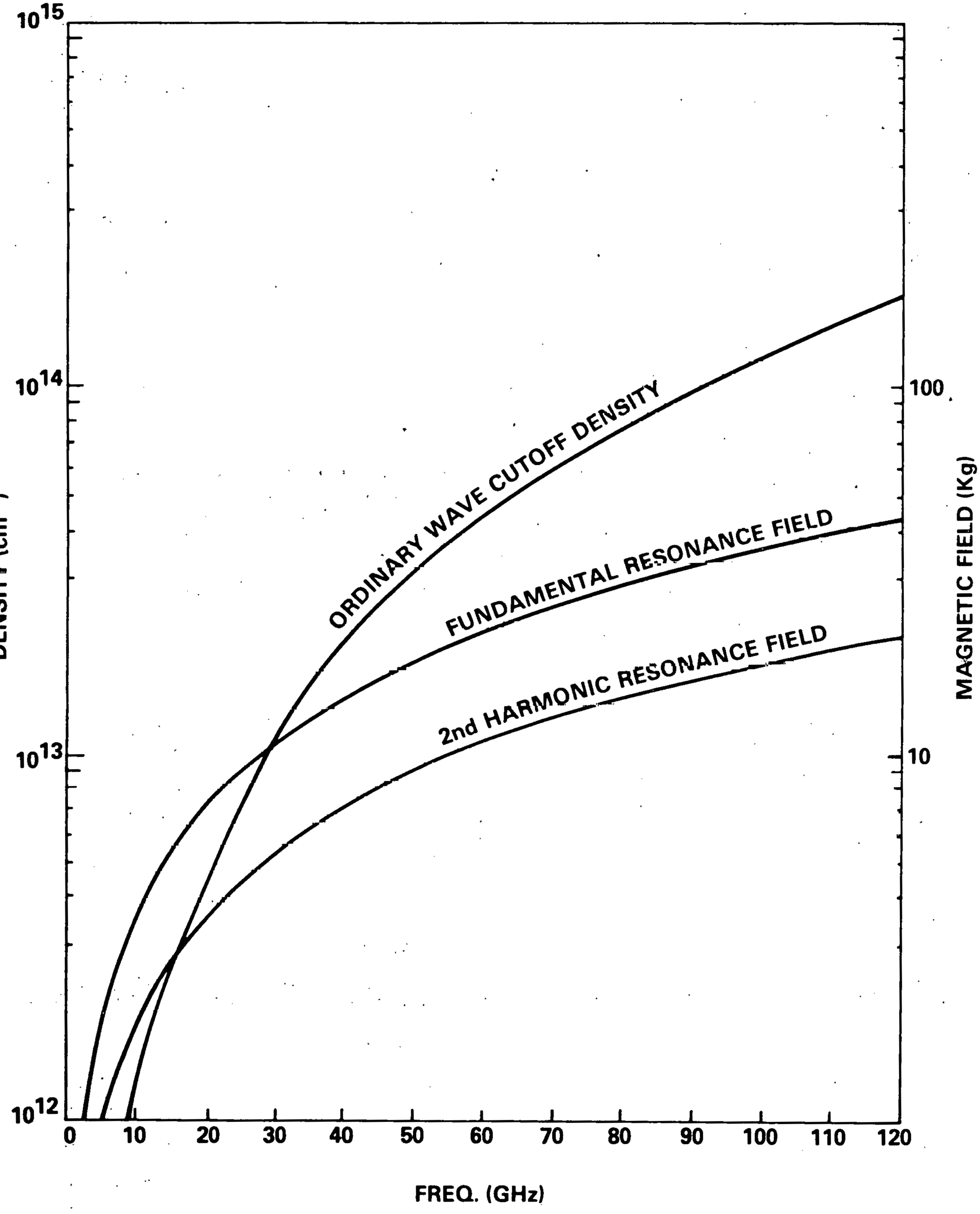
Although ECRH has been most extensively investigated in the EBT series of experiments, in considering the application to tandem mirrors with reactor grade plasmas, the conditions will be significantly different. In the EBT experiments, RF power is launched into an irregular shaped cavity from an oversized waveguide at the midplane of the mirror field and normally incident into a cold plasma with density of a few times 10^{12} cm^{-3}. In this configuration, the extraordinary mode propagating form the low field region will be cutoff before reaching the fundamental resonance layer and reflected while the ordinary mode is only very weakly absorbed. The observation of strong absorption and formation of high energy mirror confined electrons is interpreted as due to multiple reflection from the cavity wall and conversion to extraordinary mode in the high field mirror throat which is then strongly absorbed at the electron cyclotron resonance layers. For reactor grade plasmas in the EBT proof-of principle experiment under consideration and in tandem mirror and Tokamak applications, both the ordinary and extraordinary wave can be expected to be strongly absorbed in a single pass by the high density ($n \sim 10^{13} cm^{-3}$) hot plasma. However, the ordinary wave is cutoff when $\omega \leq \omega_{pe}$, and the extraordinary wave must be launched from the high field region for access to the resonance layer. Therefore, for proper deposition of the wave energy, as is required in tandem mirror applications, the questions of accessibility, wave energy transport and absorption must be evaluated in detail for specific cases. The recent result of ECRH on the ISX-Tokamak (Gilgenbach et al., 1980) with calculated single pass absorption of nearly 100% for the extraordinary wave and about 50% for the ordinary wave is relevant. In this experiment, microwave power at 35.08 GHz matched to the resonant field of 12.5 Kg at the major radius corresponding to the axis of the torus was launched in the TE_{01} circular mode from the inside (high field) of the torus. Electron temperature measurements indicate a 50% rise which corresponds to an estimated heating efficiency of 60%. This value is consistent with the theoretically predicted single pass absorption of the mixed modes.

On the basis of present theoretical and experimental results, ECRH can be expected to be effective for application to tandem mirrors. The two principle modes of application are: heating by electron cyclotron damping at the fundamental and second harmonic of extraordinary waves launched from the high field region; and heating by resonance absorption of ordinary waves in plasmas with $\omega_{pe} < \omega$. Some of the other processes of possible interest are: cyclotron damping of whistler waves (Porkolab, 1978) and absorption of the extraordinary wave launched from low field side through Budden tunnelling and through conversion to electron plasma waves at the upper hybrid resonance layer (Batchelor, 1978). Ultimately, the usefulness of ECRH depends on the success in developing efficient high power sources at frequencies of interest, and on the device parameters to which it is to be applied. The ordinary wave cutoff density and the fundamental and second harmonic resonance magnetic field as a function of the wave frequency is plotted in Figure 3. For the standard tandem mirror reactor design (Moir et al., 1977), these values are below the anticipated parameters. However, effective electron heating is expected to lead to significant reduction in density and magnetic field intensity requirements in the end plug. It is therefore reasonable to expect that ECRH will be useful for electron heating not only in present day experiments but also be applicable to ultimate tandem mirror reactors.

Because of the anticipated strong single pass absorption for tandem mirror plasmas, the proper deposition of wave energy can be realized by directed beams of microwave power. This approach is preferable to the use of a cavity because it is more compatible with experimental and reactor designs. Ray tracing calculations in the minimum-B plug geometry showed the trajectories followed by the extraordinary mode for various launch conditions to be rather complex (Porkolab et al., 1980). The realization of the proper spatial heating profile by this mode of heating in the absence of a cavity is therefore a matter that requires careful design considerations. In contrast, the ray trajectory for the ordinary wave in the simple mirror field

FIGURE 3

Cutoff and Resonance Parameters for ECH



of the bumpy torus geometry have been shown to be virtual straight lines (Batchelor, 1978). Therefore, this mode of heating, may ultimately be simplier to apply. While the both modes are expected to be effective in electron heating, their effects on tandem mirror confinement is determined by the equilibrium electron distribution. There is, therefore, also the need for properly bounce averaged Fokker-Planck calculations to determine the relative merits of ordinary and extraordinary wave heating.

B. Lower Hybrid Range of Frequencies

The use of RF waves at the lower hybrid range was first suggested by Stix (1965) for heating ions in toroidal systems via mode conversion near the resonance layer. However, Landau damping by electrons along the field lines is always a competing process. It was subsequently recognized that this mechanism can be used to advantage in Tokamaks for modification of the current profile (Bers, 1976) to enhance MHD stability of the discharge, and to sustain the toroidal current (Fisch 1978) for steady state operations. For applications to the tandem mirror system, this form of electron heating could be the most efficient for enhancing the potential barrier in the end plugs (Woo, 1979b). The lower hybrid range of frequencies is therefore very versatile for plasma heating applications. Because the wave can couple strongly to both the ions and the electrons, the physics of wave propagation and absorption is also more complex and least understood in comparison to ECRH and ICRH range of frequencies. Technologically, the lower hybrid range of frequencies is attractive because of the availability of high power sources (up to megawatts at frequencies up to several GHz), and the fact that waveguides can be used to directionally couple the wave energy into the plasma in such a way that the system is compatible with reactor designs. Hence, there is a strong incentive for considering the use of lower hybrid waves.

Depending on the choice of wave frequency ω and the parallel index of refraction n_{11}, distinct effects of wave propagation and absorption can be realized as shown in Figure 4. (Harvey, et..al., 1978). The lower hybrid resonance occur when the wave frequency corresponds to $\omega_{LH} = [(\Omega_i^2 + \omega_{pi}^2) / (1 + (\Omega_i^2 + \omega_{pi}^2) / \Omega_i \Omega_e)]^{1/2}$ in the plasma. For access into a radially inhomogeneous column, a sufficient condition (Stix, 1962) is $n_{11}^2 > 1 + \omega_{pe}^2/\Omega_e^2$. The dispersion relation for the wave is given approximately by $k_\perp/k_{11} \simeq (\omega_{pe}/\omega) / (1 + \omega_{pe}^2/\Omega_e^2)^{1/2}$. From geometric optics, the wave energy is found to be transported along a trajectory $dr/dz \sim k_{11}/k_\perp$ in the azimuthally symmetric cylindrical (r,z) coordinate with the magnetic field aligned along the axis. Consequently, as the wave propagates into the high density interior, the ray trajectory bends towards the axis. In cylindrical geometry, the surface formed by azimuthal rotation of this curve along which

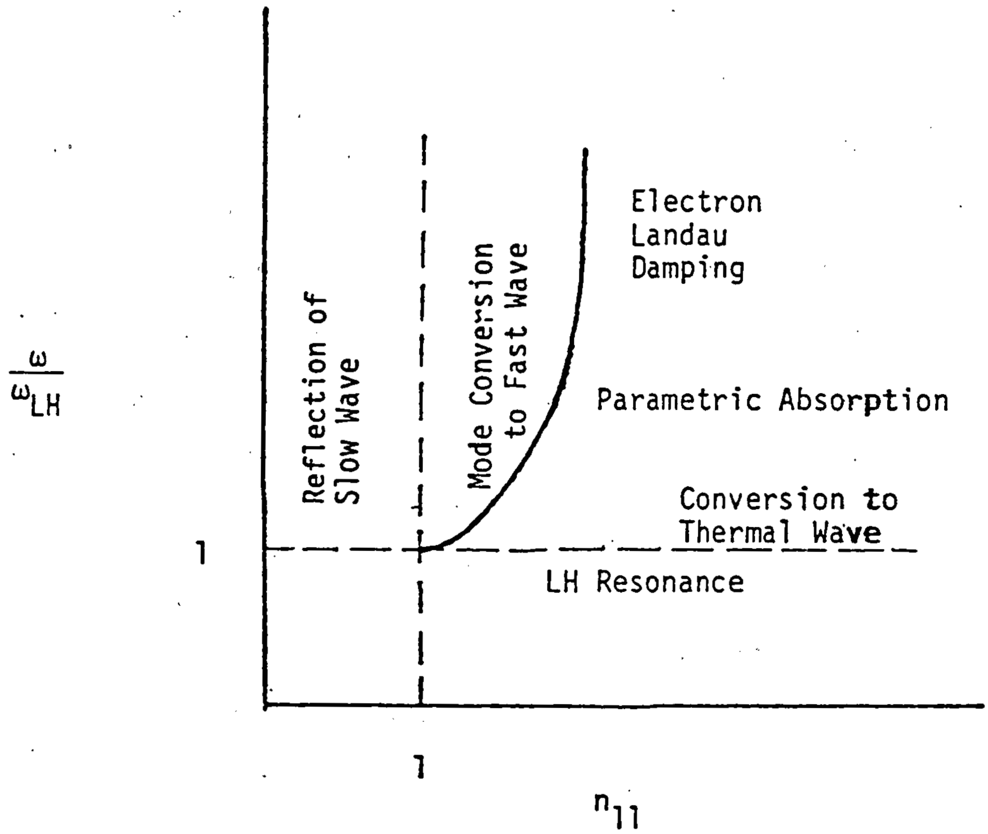


Figure 4 Wave Parameter Space for Lower Hybrid Heating

wave energy is transported is termed the resonance cone (Fisher & Gould, 1971). In a warm plasma, there is a confluence of the cold plasma ion wave near the region where $\omega \simeq \omega_{LH}$ and mode conversion will occur (Stix, 1965) leading to subsequent ion heating due to absorption at high multiples of the ion cyclotron frequency. If $\omega > \omega_{LH}$ throughout the plasma column, and provide the accessibility condition is satisfied, then the wave will propagate across the plasma column and the only linear absorption process expected is electron Landau damping. For parallel electron heating therefore, the wave frequency of interest extends continuously upward and absorption occurs when the phase velocity of the wave determined by the choice of wave parameters approaches the electron thermal speed. By the nature of the Landau damping process, the heating profile is dependent on the electron velocity distribution along the wave trajectory, which is modified by wave absorption balanced against collisional relaxation. It is also expected that thc threshold for parametric process, which can give rise to redistribution of the wave spectrum in the plasma, is relatively low. Consequently, the physics of plasma heating at the lower hybrid range of frequencies is a complex matter and a self-consistent description of the process requires inclusion of many basic effects which need to be better understood.

Because of the potential advantages of the lower hybrid range, there is currently world wide interest in Tokamak heating at these frequencies. A number of basic experiments have established a basis for consideration of such applications. The condition for efficient coupling of wave energy into the plasma by phased waveguide arrays (Brambilla, 1976) have been demonstrated experimentally (Bernabei et al., 1977) at power levels up to where the ratio $\varepsilon E^2/nkT \gtrsim 0.1$, which is larger than would be expected in robust experiments. The transport of the wave energy along the resonance cone have been observed by Briggs and Parker (1972). Evidence for the existence of the lower hybrid resonance layer was found by Hooke and Bernabei (1972) through direct measurement of the index of refraction which peaks near the critical layer. The relative importance of the various absorption processes have been investigated by Raimbault and Shohet (1975). Recent experiments by Motley et al., (1979) on nonlinear effects have shown the threshold for parametric instabilities ($P < 1W/cm^2$) the formation of thermal eddies ($P \gtrsim 25\ W/cm^2$) and the excitation of ponder motive cavities near the mouth of the waveguide ($P \geq 300\ \omega/cm^2$) which could affect the coupling efficiency and need to be taken into consideration. Significant discripancy from linear theory predictions of accessibility and wave propagation was observed in the lower hybrid heating experiments on ALCATOR (Schuss et al., 1977; Surko et al., 1979). Experiments directed at electron heating have been carried out on Doublet II by Luxon et al., (1979). In this experiment, significant amount of RF power was coupled into the plasma. Both bulk and tail electron heating as well as ion tail formation were observed but not all of the input power have been accounted for from the available experimental data. Because of the complexity of possible physical processes involved, no definitive interpretation of the experimental observations is presently possible. In addition, a number of lower hybrid Tokamak heating experiments have been carried out as summarized in Table I and still higher power experiments are being initiated as shown in Table II (Motley, 1980). It can be expected that as more experimental results become available, better understanding of the important physics issues to permit effective heating will emerge.

In applying lower hybrid heating to tandem mirror systems, the situation is further complicated by the existence of axial as well as radial inhomogenities. It is to be noted also that for amplification of the ambipolar potential, parallel electron heating must be selectively applied to the portion of the electron distribution with small v_{11} that are locally trapped in the end plugs and avoid those that are already capable of escaping from the plug. Therefore, effective heating must be applied selectively in phase space. The spatial heating profile will depend on the geometry and plasma parameters chosen and extensive analysis will be required to determine the effective approaches for applying lower hybrid heating to tandem mirrors. Because of the significant difference in magnetic field geometry from Tokamak systems, there is also the need for dedicated experiments to address problems associated with heating in mirror configurations.

TABLE II. RECENT RESULTS OF LHH IN TOKAMAKS

Tokamak	Power	Frequency	Coupler	Ion Heating	Electron Heating
VEGA Grenoble	125 KW 10 msec	0.5 GHz	2 loops	$\Delta T_i \leq 100$ eV Ion Tail $T_{\parallel} \simeq T_{\perp}$	$\Delta T_e \leq 400$ eV
PETULA Grenoble	540 KW 2 msec	1.25 GHz	2 WG	$\Delta T_i \sim 150$ eV + Tail Parametric Decay	
ALCATOR A MIT	90 KW 20 msec	2.45 GHz	2 WG	$\Delta T_i \leq 100$ eV Ion Tail Neutron Production	$\Delta T_e / T_e \simeq 0.1$
JFT-2 Tokai	200 KW 20 msec	0.65 GHz 0.75 GHz	4 WG	$\Delta T_i \lesssim 300$ eV Ion tail observed Parametric Instability No Saturation in T_i	$\Delta T_e \simeq 150$ eV $\zeta > 55\%$
JIPPT-11 Kyushu	120 KW 20 msec	0.8 GHZ	2 WG	$\Delta T_i \leq 120$ eV No parallel tail	$\Delta T_e \simeq 0$

Table V. Planned Tokamak Lower Hybrid Heating Experiments

Tokamak	Radiator	Power	Frequency	Starting Date	Remarks
JT-60 Ibaragi	?	15 MW	1.5 GHz	?	
ALCATOR-C MIT	4 WG 4 Stacked	4MW	4.5 GHz	this year	High Density Regime
PLT Princeton	6 WG	1 MW	0.8 GHz	this year	Low Density Regime
FT Frascatti	2 WG	0.5- 1 MW	2.4 GHz	next year	
ASDEX Garching	4 WG	1 MW	0.8 GHz	next year	Low Density Regime
VEGA Grenoble	4 WG	0.8 MW	0.8 GHz	this year	Low Density Regime

C. ICRH

RF heating at the ion cyclotron resonance range of frequencies is of interest to the tandem mirror both for supplementary ion heating and RF plugging. Electron heating by Landau damping and by transit time pumping is also possible, for waves in the ICRH frequency range. The principal advantage of ICRF heating is the availability of high power sources. The relative bulk of the coupling structure is a matter of some concern to reactor applications. The physics of ICRH is however, considerably better understood than at the lower hybrid range.

Theoretically, ion heating can be realized by damping of the slow wave on a magnetic beach (Stix, 1958), heating of minority species at the fundamental or the bulk plasma at the second harmonic of the fast wave (Stix, 1975). Experimentally, the effectiveness of these forms of heating have been demonstrated in experiments such as the B-65 Stellarator (Stix and Palladino, 1958), in PLT (Hosea et al., 1979) and in Pheadrus tandem mirror (Post, 1980). Current interest in ICRH for Tokamak application focuses primarily on the use of fast waves (Colestock, 1980). Power is generally coupled to the plasma by means of loop antennas which are resonantly driven. The antenna loading depends on the matching of the wave damping length to the characteristic dimensions of the plasma column. Once the waves have been launched, damping can occur by a variety of mechanisms. In current devices, fundamental resonance absorption by the minority species is the most efficient process leading to bulk electron or ion heating via Coulomb collisions. For reactor regimes, absorption at the second harmonic also becomes feasible with the added advantage of considerable simplification of the coupling structure.

A primary objective of the Pheadrus experiment is to investigate all aspects of the application of ICRH to tandem mirrors. Significant bulk ion heating in the end plugs was observed for RF applied at 2 Ω_i in a pure hydrogen plasma. On the basis of the PLT and Pheadrus results, the use of ICRH in the center cell of TMX is being planned to explore the β-limit for MHD stable confinement, to study radial diffusion in the low collisionality regime of reactor interest and to study electrostatic confinement of energetic ions in the center cell. The exact approach for implementation in TMX is yet to be determined.

The use of RF at the ion cyclotron frequency range for end plugging is also being investigated both theoretically and experimentally. In tandem mirror applications, this effect is of interest both for suppressing loss cone instabilities in the end plugs and for preventing ions from falling into the thermal barrier. To minimize energy flow, it is important that RF plugging be accomplished without general heating. Experimentally, evidence of RF plugging has been observed in the form of reduction of losses from the plugged end, however, the results are not yet definitive. Theoretically, the field intensity required for plugging in a reactor plasma is expected to be large

($E \sim 10^5$ v/cm). A recent computational study on barrier formation in a TMX-like plasma by RF has shown that it is feasible to maintain a barrier with tolerable heating (Matsuda and Baldwin, 1979). However, further investigation is required to assess the feasibility in reactor grade plasmas. At present, ICRH is the most actively pursued form of RF heating in the mirror program and the critical issues are being addressed experimentally in the Phaedrus tandem mirror.

Recently, in connection with steady state operation of Tokamak reactors, the use of low frequency waves for current drive has been considered (Fisch, 1979). An advantage for using waves in the low frequency range is the fact that they have lower parallel phase velocity and higher momentum content. As a result, proportionally higher momentum is absorbed by the low energy electrons. This type of velocity space selectiveness is particularly well suited for untrapping electrons from the end plugs and therefore, of interest to tandem mirror applications. The steady state electron velocity distribution that can be realized is determined by the balance between resonant wave absorption and collisional relaxation. Since the low energy electrons are more collisional, the effectiveness of heating by low phase velocity waves in comparison to higher phase velocity waves with lower momentum content needs to be further evaluated theoretically and be subjected to experimental tests.

IV. Conclusions and Recommendations

The RF modes at the various frequency ranges that have been identified as candidates for heating are shown in Table III. Experience have shown that all RF heating experiments are very sensitive to details. Therefore, their implementation in specific applications require careful theoretical studies. This should include considerations of the accessibility condition due to radial and axial inhomogenities, ray tracing in realistic model of the configuration, calculations of the energy absorption profile based on particle velocity distributions consistent with the heating and collisional relaxation processes. Generally, the physics is complicated and not all the basic processes are satisfactorily understood at the present time. Therefore, additional experiments are needed to guide theory which in turn can suggest experimental approaches. Scaling of RF heating systems to meet reactor requirements suggests the need to develop new approaches as well as improved components. The most acute technology needs are in developing high power gyrotrons at higher frequencies, improved vacuum windows and optimized coupling structures. Programmatic recommendations regarding specific frequency ranges are as follows:

LOWER HYBRID RANGE

This frequency range is potentially best suited for reactor applications, but the physics is least understood at the present

Table III RF HEATING MODES

Frequency Range	Wave Mode	Absorption Mechanism	Heating Effect	Remarks
ECR	X-Mode	ECR	$T_{e\perp}$	Well understood and experimentally demonstrated
	O-Mode	Resonant Interaction	?	Expected to be strongly absorbed in dense hot plasma
	Bernstein Wave	?	?	Excited via mode conversion near the upper hybrid resonance layer
LH	Ion Plasma Wave	Perpendicular Landau damping	$T_{i\perp}$	Excited via mode conversion near the lower hybrid resonance layer
	Lower Hybrid Wave	Parallel Landau damping	$T_{e\parallel}$	Strongly absorbed by hot electrons
ICR	Slow Wave	ICR	$T_{i\perp}$	Bulk ion heating
	Fast Wave	Ion-ion hybrid resonance	$T_{i\perp}$	Minority heating
		ICR	$T_{i\perp}$	Tail heating at $2\Omega_i$
		Landau damping	$T_{e\parallel}$	
		Transit Time Pumping	$T_{e\parallel}$	

time. Therefore, theoretical efforts directed at applications to mirror systems should be initiated. The most critical issue is the penetration of the wave energy and their absorption in the desired regions of phase space by the self-consistent particle velocity distributions. An assessment based on detailed analysis of the relative importance of various competing absorption processes should also be made. Although a number of high powered lower hybrid heating experiments will be started in the near future, there are significant differences in details to invalidate general extrapolation to mirror applications. It would be prudent to carry out several smaller scaled experiments in mirror confined plasmas at this time to guide the theoretical efforts before attempting more robust experiments on major mirror facilities.

ION CYCLOTRON RANGE

The results of bulk heating on Pheadrus with fast wave at $2\ \Omega_i$ is encouraging. Options for slow wave ICRH and fast wave minority heating can be expected to be effective and should be checked experimentally. More theoretical effort is needed to provide a better picture of power flow in the steady state. The possibility of parallel electron heating by Landau and transit time damping should be investigated.

Experiments on RF plugging at ICF still lacks definitive results. Critical test either by plugging both ends or by monitoring the difference in end losses when only one end is plugged should be carried out. A critical issue which needs to be addressed both experimentally and theoretically is the energy drain for plugging. The requirements for scaling to reactor applications should also be determined to assess the ultimate feasibility of this approach.

ELECTRON CYCLOTRON RANGE

Although the physics of ECRH is still not completely understood, the effectiveness of ECRH is well demonstrated and gives every indication that it is scalable for tandem mirror type of applications. The critical issue is the ultimate availability of high power sources at frequencies corresponding to reactor requirements. For present day experiments, absorption by beamed extraordinary mode appears most appropriate. However, the experiment must be designed with great carc because of the complexity of the ray trajectories. Heating by ordinary mode is of interest to advanced tandem mirror reactors and ultimately, may be simpler to implement. To realize the selectiveness, there is the need to develop polarizers. More definitive experiments for ordinary wave heating should also be carried out in appropriate plasma parameter regimes. In addition to ray tracing, theoretical effort directed at the relative effects of perpendicular and parallel electron heating in various tandem mirror concepts should also be carried out.

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TANDEM MIRROR APPLICATIONS OF RF HEATING

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Abstract

The tandem mirror reactor concept can be improved by manipulating the particle velocity distributions confined in various regions of the system. Basically, there are four types of situations characterized by the axial profiles of the magnetic field and electrostatic potential, for which different effects are realized by enhancing velocity space diffusion in different directions. The interaction of electromagnetic waves with plasma is well suited for shaping the particle velocity distributions because the interactions are generally directional and charge dependent as well as phase space selective. The type of effects that can be realized by manipulating the electron and ion velocity distributions in various situations for tandem mirror applications, and the RF process by which they can be realized are enumerated.

ABSTRACT OF WORKSHOP PRESENTATIONS

ECRH IN THERMAL BARRIER TANDEM MIRROR

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The tandem mirror confinement system makes use of positive potential mirror cells to electrostatically plug a long solenoid volume. Experiments on TMX at LLL have demonstrated increased confinement based upon this principle. Reactor studies for a simple tandem, however, show several unattractive technological requirements. The incorporation of thermal barriers lead to much more attractive designs. The proposed device MFTF-B is designed with thermal barriers to improve performance and achieve $Q \sim O(.5)$. As an advanced test of the thermal barrier concept the TMX upgrade is planned.

To create both the thermal barrier and the confining potential for solenoid ions of temperature T_c, heating several distinct, but spacially overlapping, populations of electrons is required. Hot mirror trapped electrons (E_{eh}) are required in the thermal barrier. A second group of electrons of temperature T_{ew} and satisfying $T_{ec} < T_{ew} << E_{eh}$ are potentially confined and create the potential barrier to confine the solenoid ions. For the TMX upgrade ECRH is planned. Tentative steady-state parameters are shown below.

Heating Region	n_e	T_e (keV)	Frequency
Thermal Barrier	4×10^{12}	34	$\omega = 2\omega_{ce}$
Potential barrier	4×10^{12} (total density 6×10^{12})	4	$\omega = \omega_{ce}$

The TMX microwave system will consist of four 200 kw, 28 GHz gyrotrons. One tube will feed each of four heating locations.

Important issues which must be addressed include the following:

- Start-up scenarios to establish the required electron distributions.
- Microwave-plasma coupling -- controlled heating and wave polarization are probably important.
- Control of T_e.
- Stability of electron distributions.

ICRH HEATING OF TANDEM MIRROR CENTER CELLS

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We have begun preparing for an ion cyclotron heating experiment in the center cell of TMX, following a suggestion of R. S. Post, and scoping ICRH for TMX-Upgrade and MFTF-B. ICRH is to supplement or replace neutral beam heating in the center cell. With this added heating in TMX, we hope to explore: ion heating, MHD beta limits, radial diffusion, microstability of the plug and center cell, and perhaps create or pump barriers and heat electrons by Landau damping and transit time magnetic pumping.

Electrostatic comfining potentials of 100-300eV in TMX are ineffective at confining ions above these energies. However, the center cell mirror ratio of 20 (for B_c = 1kG) provides sufficient confinement that average ion energies of 500eV are computed to be achievable with $n = 0.5 \times 10^{13} cm^{-3}$ and $P_{ICRH} \approx 400kW$. The power balance is computed with Devoto's TANDEM code. We require that end losses from the center cell be sufficient to stabilize the end plugs. This limits the ion energy. We are investigating supplying the stabilization externally to remove this limitation.

Electrostatic confinement is greatly improved with the tandem barrier experiment: TMX-Upgrade and MFTF-B. Thus, we calculate steady state ion heating requirements to be $P = q\, n^2\, V(E_i + \phi_c + T_e)/n\tau$. The ICRH power requirements for tentative TMX-U and MFTF-B parameters are 0.3 - 1.7MW absorbed at $2.2H_z$ and 3.3MW absorbed at $15MH_z$ respectively.

A number of issues in coupling R.F. power to the plasma are not settled.

- o Heat at w_{cd} or $2w_{cd}$, slow or fast wave?
- o Type of antenna: orient B parallel or perpendicular to B_0, couple to m = 0 or 1?
- o Use multiple phased antennas?
- o Effect of T_i gettering ($1\text{-}3 \times 10^{-3}$cm) on antenna.
- o Should antenna have electrostatic shield, ceramic sheath, or be bare?

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48.

Electron Cyclotron Resonant Heating on the TRW Symmetric Tandem Mirror (STM)

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TRW, Inc.

The Symmetric Tandem Mirror (STM) program has recently been developed under a contract between TRW, Inc. and the Department of Energy. As the initial phase of the STM program, TRW, Inc. has completed the construction of a single mirror cell facility which is designed to examine the use of diamagnetism of ECRH produced plasmas to modify unfavorable radial magnetic field gradient in symmetric mirror geometry. This modification can result in a magnetic configuration for stable mirror confinement of fusion plasmas. In the initial operations, we have demonstrated improved diamagnetic plasmas when several frequencies are applied. The spatial details of the magnetic modification and the high β plasma properties will be studied by an array of diagnostics presently under development. Tandom end cells will be added to existing mirror configuration and hot ion plasmas will be produced for MHD stability studies. (Presented by B. H. Quon)

Fast Wave Heating in Tokamaks

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The fast magnetosonic wave has been used successfully to heat ions in tokamak plasmas near the fundamental cyclotron frequency of a single ion in a multiple ion mixture. The basis of the heating mechanism is a change in the wave polarization near the cyclotron resonance although the precise mechanisms responsible for this change vary in several possible parameter regimes. The study of this method falls into three distinct but coupled areas: (1) antenna physics and wave coupling, (2) wave propagation and damping, and (3) wave-particle interaction and heating. Considerable progress has been made in recent years in bringing the theoretical pictures of each of these areas in closer agreement with experimental results.

Power is coupled to the plasma by means of poloidal loops which are resonantly driven. The observed antenna loading depends on whether or not the wave damping lengths are long compared to the plasma diameter and toroidal connection lengths. In the case of two-ion mixtures with an appreciable fraction of minority ions, the absorption in a single pass of the fast wave is sufficiently strong to eliminate any antenna reaction, reducing the loading impedance to the radiation resistance limit. For weak minority concentrations or higher harmonic excitation, well developed eigenmodes are formed, resulting in strong enhancement of the loading resistance. For this case, coupling to the plasma becomes a sensitive function of the plasma parameters and depends on the density of eigenmodes in the toroidal cavity.

Once the waves have been launched, damping can occur by a variety of mechanisms: majority second harmonic, minority fundamental cyclotron damping, electron Landau and transit time damping. The damping and wave propagation characteristics are functions of temperature, density, and parallel wavelengths. At sufficiently high density and minority concentration it is possible to couple power into ion Bernstein waves via linear mode conversion. However, for most parameter ranges of interest this process is not expected to play a major role. The dominant absorbtion mechanism is minority fundamental damping and this process is expected to scale to the reactor regime.

The interaction of minority ions with the wave in the resonant zone leads to RF diffusion of the minority distribution producing an energetic tail. If this tail can be sufficiently well confined, the power is equilibrated among electrons and ions in much the same fashion as energetic ions produced by neutral beams. It is the substantially better ion confinement in current experiments which has produced much improved heating efficiencies over earlier machines. The prognosis for using fast wave heating to heat denser, hotter plasmas seems good provided some technical problems, primarily related to coupler design, can be resolved.

TALK PRESENTED BY RONALD M. GILGENBACH - JAYCOR

ELECTRON CYCLOTRON HEATING AND PREIONIZATION EXPERIMENTS IN THE ISX-B TOKAMAK

Electron cyclotron heating experiments have been performed on a tokamak with large single pass absorption ($T_e \approx 850$eV, R = 93 cm). Unpolarized microwaves (80 kw, 35 GHz) from the NRL gyrotron were injected from the high field side of the tokamak to avoid the extraordinary wave cutoff. Wave transmission was in oversize (6 cm ID) circular waveguide with the low loss TE_{01}^{o} mode. The beamwidth of the reflecting plate antenna ($\pm 17^{o}$) was wide enough so that radiation not absorbed in a single pass through the hot plasma could be reflected from the wall to be absorbed in the cold plasma, and as such, would not be included in the energy balance calculations. Superheterodyne detection of the second harmonic cyclotron emission at $\sim$70 GHz and 58 GHz was employed as an electron temperature diagnostic.

The electron temperature and density profiles before and after ECH show a significant temperature increase (850 ev to $\sim$1300eV) with peaking at the center. This increase in Te agrees well with empirical heat transport code results. Electron density decreased during the ECH in all of our experiments. The gyrotron current was varied to demonstrate the dependence of electron temperature on microwave power. A linear heating rate (6 ev/kw) was found for the first time in a tokamak.

Preionization experiments were also performed by injecting microwaves prior to the tokamak discharge. Significant densities ($2\text{-}5 \times 10^{12}$ cm^{-3}) could be obtained prior to the onset of toroidal current, although the bulk electron temperature was low ($\sim$10eV). Savings in tokamak loop voltage were obtained with a more rapid rate of current rise in the preionized case.

Lower Hybrid Heating

R. W. Motley, Princeton U.

The basic concepts of lower hybrid heating of tokamak plasmas are outlined. Penetration of lower hybrid waves to the core is allowed only if one satisfies the accessibility criterion $N_{11}^2 > 1 + Wpe^2/Wce^2$. This requirement is especially stringent if the magnetic field is weak, as in the central mirror region of the tandem mirror. Even if this criterion is met, the group velocity vector assumes only a small angle, $\theta \sim w/ape$, with respect to the magnetic field. The entry trajectory in a tokamak plasma is a long 20-30m spiral. Such trajectories are not possible in a mirror device.

Nonlinear effects of the coupling between electromagnetic waves in guides and electrostatic plasma waves are discussed, with emphasis on results from the 13 kG H-1 test plasma at Princeton. Parametric instabilities are omnipresent, by virtue of their low $< 1W/cm^2$ threshold power, but do not appear to block transfer of power past the surface plasma. Vortices form just outside the mouth of the guide when $P > 20W/cm^2$ and shift the plasma load to the top or bottom of the waveguide. Reflectivity rises moderately to $\sim$12%. At higher power levels ($>300W/cm^2$) cavitation by the rf pressure exerted by the evanescent E_z field can raise the reflectivity significantly under some conditions. Past the surface plasma layers one must consider outscattering of the lower hybrid waves by density fluctuations from drift waves.

Results of the past year from tokamak heating experiments and future plans for high power irradiation of tokamak plasmas are reviewed.

RF HEATING AT TWICE THE LOWER HYBRID FREQUENCY ON DOUBLET IIA

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Experiments have been carried out on Doublet IIA to evaluate the heating of electrons in a tokamak plasma at twice the lower hybrid frequency. Such heating would offer an economical alternative to neutral beam heating for tokamaks. Economical sources at these frequencies (1 - 2 GHz) are already available and the use of standard transmission lines would allow them to be located at a convenient location remote from the device.

The slow wave structures used to launch the waves are described in detail elsewhere.[1] The apparatus and early results have also been given previously.[2] The theory of quasi linear Landau damping has been addressed in a number of references.[3-5]

The experimental observations may be summarized as follows: The power was coupled to the charged particles, but was poorly confined. The presence of the launched wave was observed in the plasma, but the amount of power in this wave is unknown. Superthermal electron and ion components were both generally produced by the application of rf power. Increases in the central electron bulk temperature were observed sporadically when the wave phase velocity was approximately 1.9 times the central electron thermal velocity.

Two models for the heating and loss mechanism are being studied. First, the power is coupled to superthermal electrons by Landau damping as expected but it is lost via anomolous electron transport instead of thermalizing to the plasma bulk. Second, the power is coupled to the superthermal ions via a parametric decay process and is lost through banana losses before it can thermalize.

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A PERSPECTIVE ON RF HEATING

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Over the past few years our group at UCLA has been engaged in a broad study of RF heating spanning various frequencies and research tools. In this communication a personal perspective of the general results obtained is presented. The areas in which we have focused our attention are as follows. Experiments: 1) (R. Taylor) ICRF Heating in the Microtor and Macrotor Tokamaks, 2) (G. Dimonte) Heating of Perfect Confinement Systems, e.g., pure ion plasmas and 3) (R. Stenzel, W. Gekelman) Nonlinear effects in LH cones. Computer Simulation: (V. Decyk, J. Dawson) 1) LH heating and wave coupling, and 2) current drive by LH waves. Theory: 1) Nonlinear surface effects in LHH, 2) Kinetic plasma effects in antenna loading, 3) (K. Whang) Effect of ICRF on ion confinement in tokamaks, and 4) (K. Nozaki) Alfven wave heating in multipoles.

Some of the important issues of general interest that have emerged are: 1) RF heating experiments are sensitive to details. Successful studies require a high quality confinement device with inert walls. Several man-years of effort and complete plasma diagnostic support are essential to begin to understand the complex RF-plasma energy exchange. 2) RF heating changes the zero order confinement. At the power levels of interest the externally driven waves alter the zero order transport in a serious manner. Implementation of significant RF heating requires a total design approach in which the machine operation and the RF conditions can coexist. 3) Behavior of RF couplers is not understood. The sheath-like effects produced by the tenuous plasma surrounding RF wave launchers and the role played by return currents influence the loading properties in a major way. These effects need to be considered in planning and interpreting experiments. 4) Difficult to RF heat electrons in a tokamak. Due to the existence of a large (but not understood) zero order electron heat transport, the RF power absorbed can be totally masked; in some instances the RF can produce cooling. 5) Nonlinearities at the plasma edge are important. In LHH the coupling efficiency can decrease at large power levels and spectral distortion takes place, while in ICRF the ponderomotive force can produce a useful self-shielding of the antenna. 6) Theoretical linear absorption mechanisms not validated. Theoretical calculations based on uniform ideal plasma conditions have not been validated in experiments and simulations. However, the plasma appears to provide an unexpected favorable heating of ions. 7) Implementation of RF current drive must be consistent with confinement. In selecting a frequency to drive plasma currents, utmost care must be exercised in generating current profiles which are favorable from the confinement and transport point of view. This requires a good knowledge of wave profiles. From these considerations it appears that LH waves are poor candidates for current drive, while high frequency ($\omega \sim 5\Omega_i$) fast Alfven waves may be useful.

We next proceed to outline the highlights of specific studies. In the Microtor/Macrotor experiments a universal nonresonant loading of the antennae structures has been observed and can be as large as 1 Ω. The loading is proportional to density, frequency, and antenna length. Heating experiments with fast Alfven waves at $P_{RF} \sim 4\text{-}5\ P_{OH}$ have resulted in excellent ion heating $\Delta T_i/T_i \sim 5$. This heating is frequency insensitive over $\Omega_i \leq \omega \leq 4\Omega_i$ and its dynamics is not understood. The narrow minority heating regime has been observed and it exhibits the expected sensitivity on concentration and frequency. The electrons, however, do not show any sign of heating. At large power levels the RF induces a non-disruptive plasma pump-out that reduces the density by a factor of 5 and limits the heating efficiency. The detailed mechanisms for pump-out are not understood, but several candidates have been identified. The pump-out can be overcome by additional gas puffing, or by the more sophisticated method of external manipulation of the ambipolar potential. Theoretically, the latter procedure can be shown to produce enhanced confinement of ion orbits.

Heating studies in perfect confinement systems such as pure ion plasmas are at the preliminary stage. However, it has already been observed that externally launched standing waves can give rise to strong heating consistent with stochastic bounce absorption. An enhanced radial diffusion accompanies the heating and severely reduces the long confinement times set by conservaion of canonical momentum constraints.

The particle simulations of LHH show the existence of strongly nonlinear effects at the plasma edge. Energetic electron tails are created at the edge and density cavities due to the ponderomotive force appear in front of the RF antenna. Electron Landau damping produces a strong filtering of the externally impossed spectrum; only the fastest wave penetrates to the plasma center. Due to the nonlinearities at the plasma edge a rich multiharmonic spectrum (in ω and k) is generated. It is found that the frequencies which actually penetrate to the plasma center are not the ones that are externally excited. For $T_i/T_e \sim 0.1$ no mode conversion to ion modes is observed at the plasma center, hence no central ion heating takes place. For $T_i/T_e \sim 1$, recent runs show evidence of central ion heating, although it is still small compared to ion heating at the plasma egde. The simulation of current drive by travelling LH waves indeed shows the existence of a DC current. Part of this current is carried by tail electrons undergoing trapping/detrapping in the wave troughs. Due to the strong surface coupling of LH waves, the current profiles are peaked at the plasma edge.

Experiments on nonlinear LH cone propagation have demonstrated the reality of the ponderomotive force in this frequency regime and the associated production of density cavities. In the process of creating the density cavities fast ion bursts arise. Theoretical studies of nonlinear LH cone propagation have qualitatively described the experimental observations.

Self-consistent studies of nonlinear coupling of slow electromagnetic waves at the plasma edge have shown a decrease in the coupling to LH waves due to the modification of the density profile as the power level is increased.

A recent theoretical study has been undertaken of the self-consistent heating and spatial diffusion of single ions in a tokamak due to ICRF. The preferential increase in perpendicular ion energy gives rise to random transitions between passing and trapped particles which results in an enhanced banana diffusion rate. Applications of this effect in the areas of exhaust control by RF and modification of trapped particle instabilities by RF merit further study.

A theoretical study of kinetic effects in the loading of RF conductors has demonstrated that significant power can be absorbed by electrons due to transit time and stochastic bounce absorption. The reality of stochastic bounce absorption has been demonstrated and it is found that the electrons can attain energies comparable to the peak RF potential applied to the conductor. For inductive couplers typical loading Q values of the order of 30 arise due to the anomalous skin effect.

A preliminary theoretical investigation of Alfven wave heating in multipoles suggest the possibility of core heating by a penetrating magnetosonic mode. The role of the surface heating produced by the unavoidable Alfven resonance needs to be considered.

The experience derived from these investigations points to the need to emphasize studies in the areas of 1) Effect of RF on confinement, 2) Antenna design in a plasma environment, 3) RF-machine operation integral design, and 4) Wave absorption in zero order turbulent media.

Possibilities with Waves in Tokamaks and Mirrors

N. J. Fisch

Subjecting electrons or ions to rf waves offers exciting possibilities in tokamak and other confinement geometries. A number of wave concepts that have proved useful in approaching tokamak problems may also be relevant to mirror problems.

In tokamaks, the usual means of accelerating electrons is by means of a dc electric field. Electric fields that are dc accelerate particles of both species without discrimination of particle velocities. In contrast, by heating with rf waves, control (which is possibly advantageous) may be exercised over which particles are accelerated. In Landau damping of electrostatic waves, particles with specific parallel velocities absorb the wave energy, although there is no discrimination of perpendicular velocities. Using transit-time magnetic pumping, however, allows preferential acceleration of particles with large perpendicular velocities, while retaining the selectivity in parallel velocity. In both cases, particles are accelerated in a diffusive manner in the parallel direction.

Alternatively, use may be made of the cyclotron resonance to diffuse particles either in perpendicular velocity only or partly in perpendicular and partly in parallel velocity. The diffusion path is always the constant energy contour in the wave frame of reference. Thus, for example, by using waves with slow parallel phase velocity to interact with fast particles, it is possible to diffuse particles nearly along their contours of constant energy.

One of the interesting applications for waves in tokamaks is to continuously drive the toroidal current. The above concepts may be applied to seek ways to achieve the current at acceptable power cost. Thus, it may be found that power requirements are minimized either by employing high-momentum-content (slow parallel phase velocity) waves to transfer momentum to thermal electrons or by employing low-momentum-content waves to interact with fast electrons which are nearly collisionless. The former method additionally benefits from preferentially accelerating high-perpendicular-velocity electrons. Diffusing electrons nearly along their contours of constant energy would incur far less power dissipation than either method. However, unfortunately it is difficult to launch suitable waves in reactors to utilize this effect.

In tandem mirrors, it may be desirable to drive electrons out of the end plugs. In this case, to reduce the power requirements, it may be best to preferentially diffuse high-perpendicular-velocity electrons in parallel energy, as can be achieved with magnetic pumping. The benefits of this scheme are as follows: Since the trapped electron temperature is greater than the untrapped electron temperature, more favorable gradients in phase space exist at higher perpendicular velocity. Furthermore, these faster electrons are relatively collisionless, so the collisional filling-in, which reverses the wave effect, occurs more slowly. Finally, by choosing the proper parallel phase velocity, it is possible to select waves that interact primarily with the marginally trapped electrons, which require the least energy to untrap. Collisions may then be relied upon to produce more marginally trapped electrons out of deeply trapped ones.

Analogous considerations apply to choosing waves to push ions out of the heat barrier in the most power-efficient manner. Again magnetic pumping is attractive, however, now the requirement on high plasma beta is somewhat more stringent. (High beta assures wave propagation at an Alfvėn speed on the order of only several times the ion thermal speed.)

The use of accelerating waves offers even more exotic possibilities. By ramping the wave frequency in time or employing a spatially varying parallel wavenumber, waves with parallel phase velocities that vary in time or position may be launched. In mirror fields, particles in different portions of phase space respond differently to the magnetic and potential gradients. By tailoring the wave phase velocity so that the wave follows a single particle, i.e. the wave maintains the same phase with respect to the particle, very selective particle acceleration may be achieved. This is a coherent wave-particle interaction. An interesting application is when a mirror throat separates two collisional regions. By aplying properly phased waves to the mirror throat an asymmetry may be introduced. The waves may selectively transmit particles that ordinarily would be reflected. This allows the construction of a temperature differential between the two collisional regions. This "heat pump" is an active version of a "heat barrier," and may have similar applications.

Lower Hybrid Wave Penetration of Hot, Dense Plasmas.
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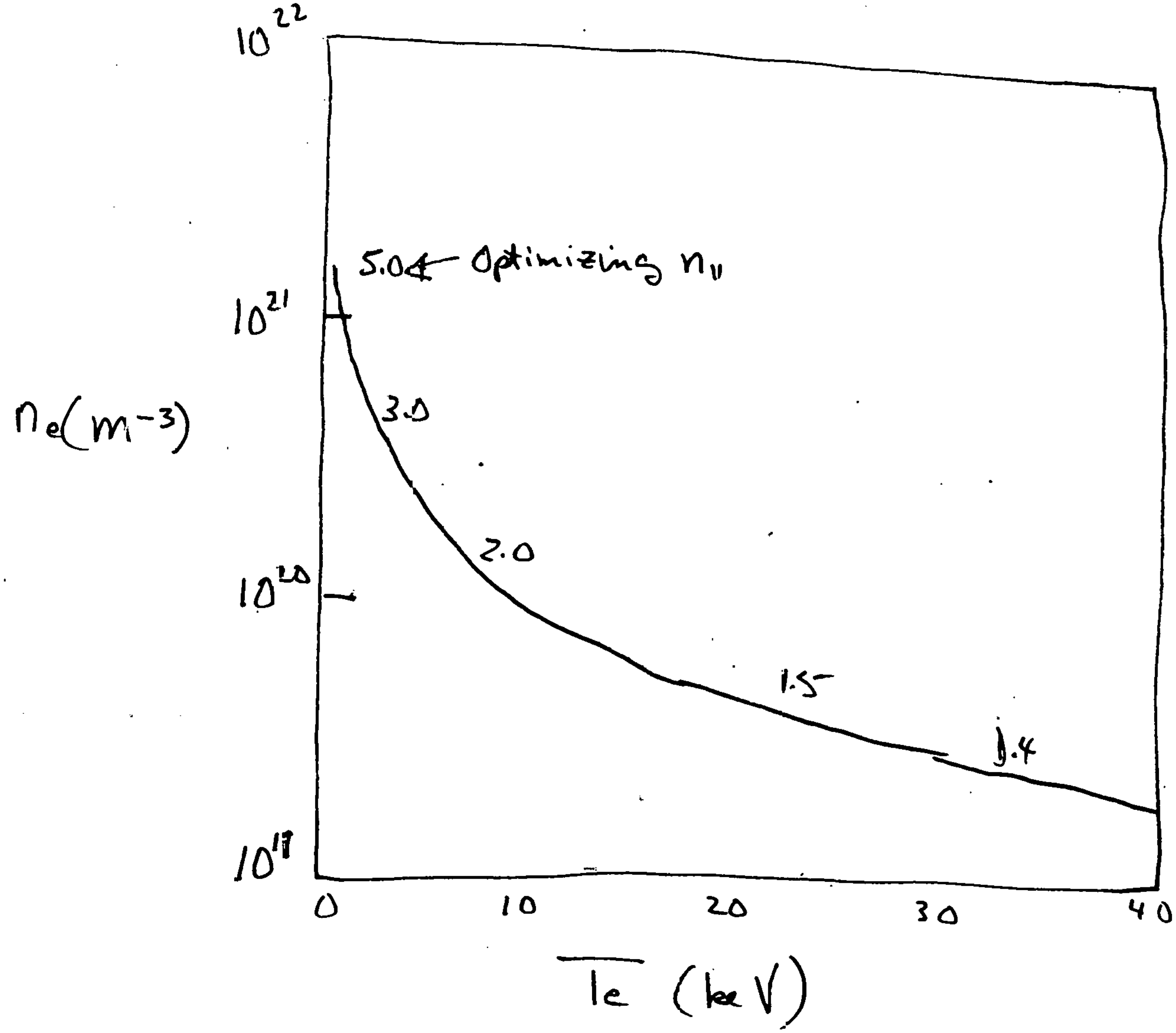
A primary consideration in determining lower hybrid wave penetration of hot, dense plasmas is that the wave parallel refractive index be large enough so that the wave can propagate to a given density without mode conversion to fast waves, yet small enough to avoid excessive Landau damping. Assuming plateau formation in a quasilinear model of Landau damping on a zeroth order Maxwellian distribution of electrons and a magnetic field of 5 tesla, then the penetrable density varies from 5×10^{19} m^{-3} to 2×10^{19} m^{-3}, as the temperature varies from 20 keV to 40 keV.

DENSITY – TEMPERATURE LIMIT

- QL Damping and no fast mode conversion
- S_{APP} = 100 kW/m^2; $\Delta k_{\parallel}/k_{\parallel} = 0.1$, $B = 5$ tesla
- $L = .2$m



CALCULATIONS OF ICRH IN TMX CENTER CELL

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Abstract

Preliminary calculations are presented for the loading resistance and electric field patterns of a two-turn loop for the TMX center cell geometry and plasma parameters. The plasma model assumed in the calculations is a hot-collisionless plasma and loading resistances are computed by integrating the radial component of the Poynting vector over the plasma surface. The model further assumes a uniform plasma density and confining magnetic field, an abrupt plasma-vacuum boundary, finite me theory is used, and finite gyroradius effects are neglected.

Coupling to both the ion cyclotron wave ($\omega < \omega_{ci}$), and the fast wave were investigated. It is found that the lowest fast wave eigenmodes occur for $\omega < \omega_{ci}$, and coupling to these modes dwarf the loading resistance due to excitation of the ion cyclotron wave. This result is for a single turn current loop, and it is not expected that a more elaborate slow wave structure will appreciably improve the coupling to the ion cyclotron wave. The loading resistance of minority hydrogen (5 - 10%) heating in a deuterium plasma is typically 1 to 4 ohms for a series two-turn loop. Use of a single turn loop would result in R_L = .25 to 1 Ω. For 500 amp-turns in the coil, $|E_+|$ field strengths of approximately 1 V/cm are obtained which exceeds the electric field strength necessary ($\sim$ .5 V/cm) to runaway from H-D Coulomb collisions.

For pure deuterium, high Q eigenmodes are observed with a reduction in the heating rate per ion. In this case, the $|E_+|$ field strengths are reduced by a factor of ten from the minority case.

Simulation of Barrier Generation by a Pondermotive Force in a Tandem Mirror

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Introduction of thermal barriers is expected to greatly improve the performance of tandem mirror machines and lead to a reactor with much reduced technological requirements compared to a conventional tandem mirror. A key question is how to generate and maintain the barriers and how much power is required to do so.

We consider a use of rf electromagnetic fields near ion cyclotron frequency to generate such barriers between the central cell and the plugs. This is based on the well-known effect of pondermotive potential given by $\psi = E^2E_1{}^2/2m\omega(\omega-\omega_c)$ where e and m are the ion charge and mass. E_1 is the amplitude of perpendicular of electric field with a left-hand circular polarization, ω is the rf frequency, and Wc is the ion cyclotron frequency. For $\omega > \omega_c$ ions will be reflected away from a region where the rf field is applied, resulting in a density depression, i.e., a barrier. In theory, this occurs adiabatically. In practice, however, we may not avoid a certain amount of heating which will degrade the ion confinement and cost us additional power. To obtain quantitative results on the density depression and the ion heating we have carried out numerical simulations using a single particle orbit code. The code solves the following set of time-averaged equations of motion,

$$\frac{d\mu}{dt} = \left(\frac{2\mu}{B}\right)^{1/2} \frac{eE_\perp}{m} \sin\zeta - \frac{v_\parallel}{\omega}\left(\frac{2\mu}{B}\right)^{1/2} \frac{e}{m}\frac{\partial E_\perp}{\partial s}\cos\zeta$$

$$\frac{d\zeta}{dt} = \omega - \omega_c + \frac{eE_\perp}{m(2\mu B)^{1/2}}\cos\zeta + \frac{v_\parallel}{\omega(2\mu B)^{1/2}}\frac{e}{m}\frac{\partial E_\perp}{\partial s}\sin\zeta$$

$$\frac{dv_\parallel}{dt} = -\mu\frac{\partial B}{\partial s} + \frac{(2\mu B)^{1/2}}{\omega}\frac{e}{m}\frac{\partial E_\perp}{\partial s}\cos\zeta - \frac{e}{m}\frac{\partial \Phi}{\partial s} \quad ; \quad \frac{ds}{dt} = v_\parallel$$

where $M(=V_{\perp}^{2}/2B)$ is the magnetic moment, $\xi(=wt+\phi)$ is the relative gyrophase, I is the electrostatic potential, V_{11} is the parallel velocity, and S is the axial position.

We have found that in a TMX-like plasma it is possible to generate thermal barriers with $Nb/Nc \lesssim 1$ (Nb = barrier density, Nc = central cell density) by applying a localized rf field at $W \simeq 1.2Wc$ and $E_{\perp} \simeq 300$ v/cm in the region where the magnetic field $Bo \simeq 2$ kG. The associated power absorption by the central cell ions can be made substantially smaller than the trapped neutral beam power in the plugs and would not cause a significant degradation of the ion confinement. We have also studied the effects of gyrophase scattering due to Coulomb collisions. For a central plasma in the present TMX experiments the collisional effects may be significant because the collision mean free path is about twice the central cell length. The simulation results so far indicate an enhanced heating by up to a factor of 2.

Electron Cyclotron Resonance Heating of Plasmas in Tandem Mirrors.

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and

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Abstract

The feasibility of heating tandem mirror devices with microwaves near the electron cyclotron frequency or its harmonic is examined. Ray tracing calculations are performed to find the optimum angle of wave launching for maximum absorption. It is found that the mirror plugs of present day tandem mirror devices can be heated effectively via the extraordinary mode, and that in the next generation of devices, both the ordinary and the extraordinary mode of propagation can be used. Presently available gyrotrons can be used as sources of microwave energy in these experiments.

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