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INITIAL TMX CENTRAL-CELL ICRH EXPERIMENTS

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ABSTRACT

Four topics are discussed in this report: the feasibility of applying ion cyclotron resonance heating (ICRH) in the TMX central cell, some applications of heating, the results of preliminary experiments, and plans for further ICRH experiments. Fast-wave propagation and heating at $2\omega_{ci}$ becomes feasible at deuterium-ion densities exceeding $4 \times 10^{12} \text{ cm}^{-3}$ and slow-wave heating appears feasible at lower densities. Either technique is capable of coupling more than 200 kW into the plasma. Calculations of the ICRH power requirements for ion heating, beta limits, radial diffusion, and axial confinement experiments in the TMX central cell give encouraging results. We prepared an ICRH experiment at $2\omega_{ci}$ for the TMX central cell, and during preliminary experiments, solved three technical problems: interference with neutral beams, degradation of the antenna Q by titanium gettering, and development of diagnostics to measure the rf power and radiation resistance. A remaining technical problem, the shielding of rf magnetic as well as electric fields from the plasma with a Faraday shield, prevented the coupling of substantial rf power to the plasma. We propose a redesign of the Faraday shield that should solve the problem. No fundamental obstacles were found to the use of ICRH in tandem mirror machines. Finally, we discuss the use of ICRH to assist in the startup of thermal barriers in TMX Upgrade by heating the central-cell plasma to collisionless temperatures. Further experiments will be performed on Phaedrus, in collaboration with the University of Wisconsin group, to develop the necessary ICRH techniques.

EXECUTIVE SUMMARY

This report describes results of ion cyclotron resonance heating (ICRH) experiments carried out in the central cell of TMX. During these experiments, which were terminated when TMX was shut down for modification to TMX Upgrade, we successfully solved several technical problems. In our last series of experiments, plasma shorting of the Faraday shield limited us to 16 kW coupling to the plasma. Although we were able to measure plasma loading of the antenna, at this power level we could not detect plasma heating, which would have been 8% at best and would have been at the limits of our detectability. Central-cell ICRH experiments are now being continued on the Phaedrus experiment at the University of Wisconsin in order to evaluate the role of ICRH on TMX Upgrade.

This report includes a study of the feasibility of applying ICRH in tandem-mirror central cells, an evaluation of several applications of ion heating, the results of preliminary experiments in TMX, and plans for future experiments.

Both fast-wave and slow-wave propagation and heating appear feasible in tandem mirrors. The fast wave at $2\omega_{ci}$ requires hydrogen densities exceeding $2 \times 10^{12} \text{ cm}^{-3}$ for propagation of the $m = 0$ mode in a 25-cm-radius column. It has been successfully used in the Princeton Large Torus (PLT) at 130-kW levels. At ω_{ci} , the fast wave requires densities four times higher for propagation; however, Phaedrus has successfully heated plug plasmas with an evanescent fast wave in the near field of the antenna. These plug plasmas had densities and radii below the threshold for fast-wave propagation. Slow-wave heating in the Model C Stellarator coupled 2000 kW from the transmitter, and on RFC-XX at Nagoya slow waves have coupled 190 kW. But because the TMX central cell does not provide a uniform magnetic field falling off to a magnetic beach at either end, as in these two experiments, we cannot simply apply the already developed techniques. We discuss an antenna arrangement--a single half-turn coil at one end of the central cell--that will be tried on Phaedrus, and may couple either to the slow or the fast wave.

The first application of ICRH is obviously ion heating. We compute the power levels required in the TMX central cell. Coupling 100 kW into the ions is calculated to increase the ion temperature by 40 eV, at densities of about $5 \times 10^{12} \text{ cm}^{-3}$, which is readily detected with diamagnetic loops. By lowering

the plug beta to a few percent or by changing the magnetic field geometry to lower the theoretical interchange beta limit, we could begin to test beta limits with power levels of 100 to 200 kW. Tests at higher plug betas of 20 to 40%, where ballooning beta limits diverge from interchange beta limits, requires power levels of 500 to 1000 kW or more. In this range, ion temperatures exceed 300 eV, and radial diffusion is predicted to become significant, possibly limiting beta. We conclude that measuring global plasma properties at high ICRH power should permit determination of either beta limits or radial diffusion rates, but not both, although more detailed measurements may allow both to be determined. At temperatures below 300 eV and power levels below 400 kW, end losses dominate and we could study the scaling of axial electrostatic and magnetic confinement with the temperature.

On the basis of other ICRH experiments that coupled as much power into plasmas as we calculated was needed to produce significant effects in TMX, we were encouraged to attempt an ICRH experiment in TMX. The experiments that we performed during the last two months of TMX operation did not couple enough power to produce unambiguous indications of ion heating, but we did solve several technical problems and did not find any fundamental obstacles to successful use of ICRH in tandem-mirror central cells. The problems we solved were: (1) interference with neutral beams was eliminated by improving the rf-grounding system, (2) degradation of the antenna Q by titanium gettering was reduced to an insignificant level by covering the antenna with a Faraday shield, and (3) diagnostics were developed to measure the rf power and radiation resistance. The measured power was about 16 kW and the radiation resistance was less than 0.1 ohm. Both were reduced by a factor of about 36 from design levels by a fourth problem--shorting of the Faraday shield by the plasma. We propose the following solution to this problem, which has yet to be tested: by mounting each element of the Faraday shield from the wall rather than from an intermediate ring, we will enclose more magnetic flux between the antenna and its image currents (that will now be in the wall rather than the support ring), and thus we expect to couple substantially more power to the plasma.

Future plans include the use of ICRH to assist in the startup of thermal barriers, by heating the central-cell ions to a temperature where they will not collisionally fill the barrier faster than it can be pumped. We plan to develop the necessary techniques on Phaedrus, in collaboration with the University of Wisconsin group.

INTRODUCTION

Ion cyclotron resonance heating (ICRH) has been used successfully to heat ions in a number of toroidal and linear devices. Some of these experiments are listed in Tables 1 and 2. Of note are the products of the heating and coupling efficiencies (which range up to about 50% in the larger devices), the large number of different antenna designs, and the large number of heating mechanisms. The efficiencies of ICRH plasma heating can be similar to or higher than the efficiencies of neutral-beam heating, but the physics of the heating is more complicated.

In this report, we discuss various ICRH methods for use in a tandem-mirror central cell, evaluate the ICRH requirement for four physics experiments that are possible in TMX, outline the requirements for ICRH-assisted startup of TMX Upgrade, describe the ICRH hardware that was installed on TMX, and discuss preliminary results.

I. ICRH METHODS IN A TANDEM MIRROR CENTRAL CELL

ICRH has been used extensively and successfully in tokamaks, and to a lesser degree in mirror machines. In this section, we discuss the present theoretical and experimental knowledge of propagation and damping of fast and slow waves. Much of the existing knowledge is specialized to tokamaks; we will attempt to point out where such knowledge does not necessarily apply to mirror machines.

Two modes of ICRH appear most promising for heating ions in the TMX central cell. The first is the fast wave, also called the magneto-sonic wave, or Alfvén wave. It is used to heat hydrogen or deuterium ions at the fundamental or harmonics of the ion cyclotron frequency; in particular, $2\omega_{ci}$ heating is promising. Propagation and possible trapping of the fast wave is discussed in Sec. IA and heating is discussed in Sec. IB and IC. The second mode is the slow wave, also known as the ion cyclotron wave, or transverse Alfvén wave. It propagates below ω_{ci} , to a magnetic beach where resonance heating occurs at ω_{ci} . Section ID discusses successful heating of linear devices, or linear sections of devices, including the Model C Stellarator and RFC-XX. Section IE discusses magnetic beach designs for TMX.

TABLE 1. Summary of ICRH experiments, from PPPL-1610.¹

Device	f, MHz	P _{RF} , kW	Launching* structure	Coupling efficiency, ** %	Heating efficiency, ** %	T _i , * eV	Pulse length, ms	Heating mechanism*
ST	25	450	Two 1/2-coils (no Faraday shield)	90	20	200 D ⁺	1	Fundamental two-ion hybrid
ATC	25	200	1/3-turn copper strip (ceramic case, no shield)	90	40	200 D ⁺	10	Two-ion hybrid
T-4	23	50	3/4-turn coil			200 D ⁺	1	Direct minority heating
TFR	50-90	80	Tandem 1/2-turn coils (Faraday shielded)	80	70	150 D ⁺	30	Two-ion hybrid
PLT	25	350 (620) (1000)	1/2-turn coils (Faraday shielded)	70	70	500 (minor- ity up to 60 keV)	100 (5)	Two-ion hybrid D ⁺ (direct minority heating, D ⁺)
TM-1 Vch	7-35	150	Two asymmetric coils	80-90	30-40	100	0.8	Two-ion hybrid
DLVA	50	100	1/2-turn coil	65	20	100 H ⁺	1	Second harmonic
Macrotron	1-20	200	Rectangular loop			200	2-4	Off resonant
T0-1	48	5	Coil			50	20	

* Comments in parentheses were not in Ref. 1.

** These efficiencies are defined differently from those used in Sec. 4 of Ref. 1.

TABLE 2. Additional ICRH experiments.

Device	f, MHz	P _{rf} , kW	Launching structure	Heating efficiency, %	T _i , eV	Pulse length, ms	Heating mechanism
Model C Stellarator	25	2000	4-1 turn Stix coil	0.1-0.2	550	5	Slow wave fundamental resonance
TFR		50-100	Tandem 1/2-turn coils with ceramic but no Faraday shield	0.3-0.7	50-130	40-100	Minority and 2-ion hybrid
PLT	42	180	1/2-turn coils Faraday shielded	?			Second harmonic
Phaedrus		50	1-turn coil ceramic	0.1			Fast wave fundamental evanescent
Phaedrus		50	1/2-turn coil ceramic	≥0.3			Fast wave fundamental evanescent
Phaedrus		25	1/2-turn ceramic	~0.5			Second harmonic
RFC-XX	13.7	190	2 pair, phased Nagoya Type III	0.5	1000	3	Slow wave

A. Fast-Wave Propagation

Propagation of the fast wave requires large high-density devices that allow radial standing waves. Propagation of $m = 0$ waves in a conducting cylinder filled with plasma requires²

$$n a^2 (\text{cm}^{-1}) \geq 5 \times 10^{15} \left(\frac{m_i}{m_{iH}} \right) \left(\frac{\omega_{ci}}{\omega} \right)^2 \quad (1)$$

For the TMX central cell, where $a \approx 25$ cm, $(m_i/m_{iH}) = 2$, and $\omega = 2\omega_{ci}$, a density $n > 4 \times 10^{12}$ is required. This cutoff density varies with the azimuthal mode number m . If the plasma is surrounded by a vacuum annulus, the positive m -modes are not cut off, but propagate as a surface wave at very low densities.³ Note that the cutoff density for hydrogen is half of that for deuterium because of the mass ratio.

Hiro Takahashi⁴ points out that $m \leq 0$ modes may reach cutoff and perhaps reflect at the ends of the central cell, thereby exciting cavity resonances (eigenmodes). The resulting higher amplitude waves could provide very efficient coupling to the plasma, even if the damping is weak. We concluded that $m \leq 0$ waves will be cut off because, by flux conservation,

$$n a^2 = -\frac{2}{3} \frac{B_0}{B} \quad ,$$

which decreases by a factor of $B/B_0 = 20$ (for constant n) at the mirror. Furthermore, the ω_{ci}/ω term above adds another B^2 term for a total of $(B/B_0)^3 = 8000$ in the requirement for propagation. The major uncertainty is whether, at the cutoff, the wave will reflect or will mode convert to a propagating mode such as a slow wave. S. Yoshikawa predicts mode conversion at cutoff in the presence of minority ions.⁵

Brian McVey⁶ has modeled fast-wave propagation and heating (Fig. 1) with a code that includes fundamental damping, Landau damping, and collisions, but does not yet include $2\omega_{ci}$ damping. His results agree with Eq. (1)--he finds the lowest-density eigenmode at $n = 4 \times 10^{12} \text{ cm}^{-3}$ (Fig. 2). However, this mode deposits most of the power at the boundary of the plasma, where it will be quickly lost by radial diffusion or charge exchange (Fig. 3). By raising the density to $7 \times 10^{12} \text{ cm}^{-3}$ in deuterium, or $3.5 \times 10^{12} \text{ cm}^{-3}$ in hydrogen, the power deposition can be peaked at a radius of 15 cm, decreasing towards the

FIG. 1. The TTK central cell model used in McVey's code.

FIG. 2. The computed antenna loading resistance in a deuterium plasma versus central-cell density for 5%, 10%, and 20% concentrations of hydrogen. The solid line is for 5% H concentration.

FIG. 3. Computed radial power-deposition profiles for various densities (n_e) in the central cell. $s = 0.1$, $I_1 = I_2 = 50$ a, $B = 1$ kG, $T_e = 140$ eV; 5% H: $T_{||} = 200$ eV, $T_{\perp} = 1000$ eV; 95% D: $T_{||} = T_{\perp} = 50$ eV, $\omega = \omega_{cH}$. The dashed line is corrected for constant power input.

edge (Fig. 3). These densities also appear to be optimum for minimizing power requirements (Sec. III). The code assumes a square density profile. A diffuse profile may reduce the power deposition near the plasma boundary. These results are discussed further in Appendix A.

B. Fundamental Heating

Fast waves in a plasma that includes a minority-ion species with a higher cyclotron frequency are absorbed by three mechanisms: mode conversion, minority heating at the fundamental cyclotron frequency, and heating of the majority ions at the second harmonic.

In tokamaks, mode conversion occurs only with large concentrations of minority ions.⁷ Tokamak rules of thumb indicate that mode conversion is unlikely in TMX. However, this needs to be evaluated for the tandem geometry.

Enhanced minority heating occurs in tokamaks when the fundamental cyclotron frequency of the minority species is near the two-ion hybrid resonance. Y. Matsuda⁸ has evaluated this and concluded that this effect is absent in the central cell.

Enhanced minority heating has been successful on several tokamak experiments including the Princeton Large Torus (PLT),^{7,9} where up to 1 MW has been coupled into D-H and H-³He plasmas. The majority ions are heated collisionally by the hot tail of the rf-heated minority. We can estimate the H-D collisional power transfer for TMX from Spitzer equipartition of energy,¹⁰ using $\ln \lambda = 15$,

$$P = \frac{2.35 \times 10^{-6} q n_i^2 n_d^2 Z_i^2 Z_d^2 (T_i - T_d) V}{A_1 A_2 \left(\frac{T_i}{A_1} + \frac{T_d}{A_2} \right)^{3/2}} \quad (2)$$

where n is density (cm^{-3}), T is temperature (eV), V is volume (cm^3), and q is charge (1.6×10^{-19} C). For low concentrations of hydrogen, i.e., $n_h/n_d = 0.05$ and $n_d = 5 \times 10^{12} \text{ cm}^{-3}$, we find that optimum heating occurs for $T_h = 500$ eV and $T_d = 100$ eV, resulting in $P = 6.3$ kW. This is totally inadequate to heat to high beta. We can improve this situation somewhat by using D-³He, or by increasing the deuterium or minority densities, but the considerations of wave penetration and power requirements versus density make minority damping incapable of achieving high beta in the TMX central cell.

Fundamental ion-cyclotron heating has been successfully applied to the end plugs of Phaedrus.¹¹ This heating has been more successful with half-turn $m = 1$ antennas than with circular $m = 0$ antennas. This is attributed to the lack of a null rf field on axis with $m = 1$ antennas. The loading resistance has been found to be proportional to the plasma density, rather than independent of it, as predicted for slow waves, and is an order of magnitude larger than for slow waves. The decrease of the loading resistance with increasing ω_c/ω from 1.0 to 1.2, where 1.0 refers to resonance directly under the antenna, is also inconsistent with slow waves. This is interpreted as a result of moving the resonant zone farther from the antenna, where the

evanescent near field of the antenna is weaker. A recent theory of heating by evanescent fast waves¹² appears to fit the data quite well.

C. Second Harmonic Heating

The prospects are also promising for second harmonic damping. First, the wave energy is deposited directly into the majority deuterium ions. Second, the damping is enhanced over that in a tokamak because ions remain resonant in a large fraction of the central cell volume,¹³ rather than only while traversing a thin layer as in a tokamak. Third, we may be able to trap the fast wave in the central cell,⁴ as discussed in Sec. IA, to further enhance the heating efficiency.

Second harmonic damping has only recently been observed experimentally^{9,14} on PLT in a hydrogen discharge with up to 250 kW of rf power at 42 MHz. Tail heating to $T_i = 7$ keV was observed, consistent with Fokker-Planck computations of $2\omega_{ci}$ heating.

We estimate the heating to be expected at $2\omega_{ci}$ in the TMX central cell using the theory of Stix¹⁵ as evaluated by Scharer, et al.¹³ They calculate the power absorption by the ions per unit volume, $P(W/m^3)$, in mks units, as

$$P = \left(\frac{\pi^{1/2} \epsilon_0 \omega_{pi}^2}{4k_{\parallel} v_i} \right) \operatorname{Re} \left(\frac{k_{\perp}^2 c_i^2}{2} \right)^{l-1} |E_+|^2 \exp \left[- \left(\frac{\omega - l \omega_{ci}}{k_{\parallel} v_i} \right)^2 \right] \quad (3)$$

where l is the harmonic number ($\omega = l \omega_{ci}$). We used values of $k_{\parallel} = 6 \text{ m}^{-1}$ and $k_{\perp} = 12 \text{ m}^{-1}$ from results of McVey's code. At resonance the exponent term is unity and $\omega - l \omega_{ci} = 0$, but vacuum-field nonuniformity or finite beta cause this term to go to zero at 1% off resonance for $T_{ic} = 50$ eV or 5% off resonance for $T_i = 500$ eV. From the measured radius of 0.25 m and the computed magnetic-field plot, we estimate the resonant volume for $T_i = 500$ eV to be $V = 0.24 \text{ m}^3$. The total power absorbed into the TMX central cell is then

$$P(W) = 1.2 \times 10^{-10} n_e (\text{cm}^{-3}) A^{1/2} (\text{amu}) E_i^{1/2} (\text{eV}) B^{-2} (\text{kG}) \\ \times \left| E_+ \left(\frac{v}{cm} \right) \right|^2 V (\text{m}^3) .$$

(The units are included in the equation for convenience.) As an example, for

hydrogen at $n = 3.5 \times 10^{12} \text{ cm}^{-3}$, $E_i = 500 \text{ eV}$, $B = 1 \text{ kG}$, and $E_z = 10 \text{ V/cm}$, we obtain $P = 0.2 \text{ MW}$. Results from McVey's code indicate that electric fields of $E_z \approx 10 \text{ V/cm}$ are reasonable.

A well-known characteristic of second harmonic heating is that it heats the tail rather than the bulk of the ion-energy distribution, because the power absorption is proportional to $E_i^{1/2}$ or velocity. We estimate the maximum power level at which the tail ions can collisionally heat the bulk using Spitzer's equipartition of energy. For tail (t) ions interacting with the same charge and mass ions in the bulk (b) in a volume $V(\text{cm}^3) = 0.2 \times 10^5 / B(\text{kG})$ for TMX, we obtain

$$\tau_{eq}(\text{s}) = \frac{4.5 \times 10^5 A^{1/2} (\text{amu}) [T_b(\text{eV}) + T_t(\text{eV})]^{3/2}}{n_b (\text{cm}^{-3}) Z^4} \quad (4)$$

and

$$P(W) = \frac{1.0 \times 10^{-13} n_t [T_b(\text{eV}) - T_t(\text{eV})]}{B_c(\text{kG}) \tau_{eq}(\text{s})}$$

where P is the power that ions in the tail deliver to those in the bulk of the distribution. We can maximize the energy exchange, by setting $n_b = n_t = 5 \times 10^{12} \text{ cm}^{-3}$ and $T_b = 50 \text{ eV}$, to $P \leq 2.2 \times 10^5 \text{ W}$. Above this power level, ions will run away until they are limited by electron drag or lost, and effective heating of the bulk of the ion distribution will not occur.

We conclude that second-harmonic heating of either deuterium or hydrogen at $n \leq 5 \times 10^{12} \text{ cm}^{-3}$ is not effective at the power levels much above 10^5 W that are required to study radial diffusion or beta limits in the TMX central cell. However, it should be effective at maintaining central-cell ion temperatures of 1 keV in TMX Upgrade with a thermal barrier to reduce axial losses.

D. Slow-Wave Experiments

A large number of slow-wave heating experiments have been done in linear devices^{16,17} and in the straight sections of stellarators.^{15,18-20} These experiments successfully heated ions, with power levels up to 2 MW obtained in the Model C Stellarator.²⁰ In the ST Tokamak the heating was concentrated near the antenna, indicating that the slow wave did not propagate around a torus;²¹ hence slow-wave heating has not been used further in tokamaks.

The slow wave propagates for $\Omega \equiv \omega/\omega_{ci} < 1$ and resonantly heats ions at $\Omega = 1$. The two keys to successful slow-wave heating have been: (1) propagate from an antenna located in a higher magnetic field where $\Omega < 1$ to a magnetic beach where $\Omega \rightarrow 1$ and the wave energy is absorbed by the ions; (2) use a coil structure, such as a Stix coil or a Nagoya type-III antenna, that selects the optimum wavelength for propagation.²²

Recent experiments¹⁷ on RFC-XX at Nagoya have obtained successful slow-wave heating in a solenoidal magnetic field stoppered by cusps at either end. Slow waves were propagated from two pair of Nagoya type-III antennas to magnetic beaches at either end. (This is different from the TMX geometry, where the magnetic field strength increases at the ends.) The heating was optimized for a phase difference of 180° between pairs of antennas, at which they achieved a heating efficiency greater than 50%. Injection of 190 kW of rf into a hydrogen plasma $n = 1 \times 10^{12} \text{ cm}^{-3}$, $r_p \approx 5 \text{ cm}$, and $l \lesssim 2 \text{ m}$ raised the ion temperature to $T_{ic} \approx 1 \text{ keV}$.

E. Magnetic Beach Designs for TMX

We have examined several geometries for producing wave absorption at a magnetic beach. The first geometry (Fig. 4) was initially attractive because waves could propagate in both directions from an antenna at the center, absorbing almost all the wave energy in beaches at either end. However, during discussions with Ron Cohen, it became clear that radial drifts could greatly reduce ion confinement. The calculated magnetic field is plotted in Fig. 4. We see that the B_θ field begins to increase, to about 70 g, at $z = 115 \text{ cm}$, where ions that are barely mirror-trapped at one end of the central cell would reflect. These ions would drift radially to the wall because they do not reach the opposite end of the central cell where they would experience equal but opposite radial drifts. Note that this is not a diffusion process, as the radial steps add rather than partially cancelling.

The standard TMX configuration is shown in Fig. 5. An antenna can be placed at position A or B. Either position allows the slow wave to propagate in both directions. With antenna A, the outer beach is near the plug midplane (similar to Don Smith's work on Phaedrus,²³ although this heating is now attributed to the evanescent fast wave in the near field of the antenna¹¹). With antenna B, the outer beach is beyond the mirror (not shown) and may heat

FIG. 4. MAFCO magnetic field calculations for a central antenna propagating slow waves to magnetic beaches at either end of TMX. (a) $|B|$ vs z , (b) B_θ vs z .

FIG. 5. Usual TMX configurations of $|B|$ vs z with possible antenna and magnetic beach positions indicated.

escaping ions, increasing the power deposition on the end wall. Plug heating, similar to case A, has not hurt the plug confinement of Phaedrus, where heating is applied at 30° to 40° from the loss cone; but because of collisional losses, central-cell containment for heating within 5.5° of the loss cone (as with antenna A) is unlikely to be much better than that found with drift-cyclotron loss cone (DCLC) rf in TMX,²⁴ so we reject this alternative.

Antenna B has several attractive features:

- The beach can be located anywhere from the midplane to the transition region near the antenna. This is very attractive from the point of view of controlling the plasma angular distribution: allowing high pressure to extend into ballooning regions or concentrating the pressure near the center (similar to radial neutral-beam injection).
- This mode of heating is applicable to TMX Upgrade, where hydrogen operation will exclude minority heating (although fast-wave second harmonic heating will be possible).

- Slow-wave experiments have coupled greater than 1 MW into plasmas with wave absorption at a beach.²⁰

- Evanescent near fields may produce efficient bulk heating at ω_{ci} , as on Phaedrus.^{11,23}

Antenna B also has some uncertainties or problems:

- Up to half of the power may be wasted in heating plasma outside the plugs. Besides being inefficient, heating plasma outside the plugs may increase gas refluxing, thereby decreasing T_e , and also may distort ion energy and power measurements at the end wall.

- Slow-wave coupling from an antenna to a plasma occurs only over a narrow range of approximately 10% in $\Omega = \omega/\omega_{ci}$.²² For optimum coupling from a multielement antenna such as a Stix coil, ω_{ci} must be held constant over the antenna array; i.e., the magnetic field must be constant. The magnetic field gradient at position B therefore prohibits the use of a Stix coil. However, Stix²⁵ suggested that a single coil in a magnetic field gradient may produce an effect similar to that of three-phased coils, because, for a cyclotron resonance under the antenna, to one side the wave-to-ion phase is $E_+ / (\omega + \Omega)$ and to the other side the phase is $E_+ / (\omega - \Omega)$. He added that while it is plausible that antenna B will couple efficiently to slow waves, the idea is untested.

II. APPLICATIONS OF ICRH FOR THE TMX CENTRAL CELL

The reasons for pursuing ICRH heating of tandem mirror central cells are to:

- Develop an alternative to neutral-beam heating.
- Study beta limits.
- Study radial diffusion.
- Test the scaling of axial electrostatic confinement with T_{ic} .
- Develop an alternative startup technique for TMX-Upgrade.

In this section, we calculate the ICRH power required to study the first four topics in the TMX central cell. The final topic is discussed in Sec. IV.

A. Alternative Heating Technique

Neutral beams are a very successful means of heating mirror machines and tokamaks, and are likely to remain an essential technique for heating mirror plugs, pumping thermal barriers, and injecting sloshing ions, because of the control that can be exercised over the phase space distribution of the trapped ions. However, in a tandem central cell, as in a torus, the major objective of heating is to provide the desired power to a roughly Maxwellian ion distribution on each flux tube, with no requirements on the angular distribution of the heated ions. For these purposes rf heating in general, and ICRH in particular, appears promising.

B. Theoretical Beta Limits

Tom Kaiser has computed beta limits in TMX for interchange and ballooning.²⁶ Figure 6 shows representative results. Tests of interchange beta limits can be made at very low betas, to determine the maximum ratio β_c/β_p . To test the ballooning limits we require a minimum of $\beta_c > 0.2$ and $\beta_p > 0.1$. Ideally we would achieve $\beta_c \gtrsim 0.4$ and $\beta_p \gtrsim 0.2$ so that the ballooning and interchange beta limits are sufficiently different to be easily distinguishable experimentally. Tom Kaiser and Bud Karmendy²⁷ have found that the theoretical beta limits can be varied by modifying the magnetic field geometry by changing currents in the TMX coils. This provides an opportunity to test the variation of the predicted beta limit with magnetic field geometry.

Since ballooning is caused by high plasma pressure in regions of bad curvature, we require a sufficiently wide angular distribution of ions to achieve this. Ballooning is expected where the central-cell field begins to bend in towards the fan, which occurs at 100 to 130 cm from the center of TMX, where the magnetic field has increased slightly (to 1.1 to 1.4 kG) from the 1 kG at the center. For the plasma pressure to extend to ballooning regions, the angular distribution must be at least 10° to 30° wide. We expect to control the angular distribution by adjusting the location of cyclotron resonance or by controlling the collisionality of the plasma through the density and temperature.

FIG. 6. Theoretical stability limits of TMX against ballooning.

C. Radial Diffusion

Resonant radial transport has been calculated by Ron Cohen and Tim Cutler.²⁸ They calculate diffusion caused only by density gradients τ_1 and also with contributions from ion-temperature and potential gradients τ_2 . Fig. 7 shows the power P required to sustain ions at a temperature T_i against losses due to radial diffusion in the TMX central cell,

$$P = 3/2 q n T_i V/\tau .$$

If T_ϕ is constant, Cohen and Cutler show that $\tau \propto T_i^{-3/2}$ so that $P \propto T_i^{5/2}$. Thus radial diffusion results in an upper limit to the ion temperature for a given power input; furthermore, it may truncate the ion energy distribution from the usual hot tail found with rf heating. In this case, either neutral beam or rf heating could be inefficient. Although the magnitude of radial diffusion, at a given temperature, depends critically on whether τ_1 or τ_2 properly describes the experiment, and on $(r_{\text{eff}}/r_c)^2$, large variations in the coefficient of radial diffusion have little effect on the temperature achievable with a given power input, as shown in Fig. 7.

FIG. 7. The power required to sustain TMX central cell against radial diffusion versus the ion temperature. (See Ref. 24 for a definition of parameters.)

D. Axial Power Balance

Steve Devoto calculated the TMX power balance with axial and electron drag losses, including auxiliary central-cell ion heating,²² to determine how much power is required to achieve a high central-cell ion temperature. These results apply to $T_{ic} > 1000$ eV only if radial diffusion is much weaker than predicted. His results, plotted in Fig. 8, show that axial losses do not limit beta for power levels above 400 kW absorbed by a plasma of $n_c = 5 \times 10^{12} \text{ cm}^{-3}$. The plug beta was arbitrarily set at 5%. Devoto pointed out that plug microstability must be assured, and evaluated two cases: (1) allowing T_{ep} to vary in order to achieve a power balance required $\beta_c < 14\%$, and (2) fixing $T_{ep} = 50$ eV required $\beta_c < 23\%$ so that central-cell losses could stream-stabilize the plugs. If we could stabilize TMX end plugs with external gas boxes as was done with 2XIIB, then the plug microstability would be independent of the central cell, β_p would be limited only by available neutral beam-power, and β_c would be limited by radial diffusion or MHD limits. An

FIG. 8. The power required to heat central-cell ions versus ion temperature T_{ic} (from Devoto²⁵).

additional case that includes electrostatic axial confinement is also plotted in Fig. 8. This results in slightly higher T_{ic} for a given input power.

The results of a more general power balance, including radial diffusion as well as axial losses and drag by 100-eV electrons, are plotted against beta in Fig. 9 for deuterium operation. The radial-diffusion power loss was computed as discussed in Sec. 1C. The power into electron drag was computed for $T_{ec} = 100$ eV. Electron heating to greater than 100 eV is probable, and will reduce the drag power. The axial power loss was calculated analytically as shown below, then normalized to Devoto's results at the same ion velocity, to include effects of charge-exchange losses due to gas puffing. We used the axial-loss formula recently implemented in the GFITS program by Correll:³⁰

$$n_c T_c = 10^6 T_c^{3/2} A^{1/2} \log(B_m/B_c) + 4 \times 10^{-4} n_c T_c^{-1/2} A^{1/2} B_m/B_c.$$

We ignored electrostatic confinement since it will be a small effect for $T_{ic} > 5$. We conclude that axial losses dominate at low ion temperatures (or betas), radial losses dominate at higher temperatures, and that electron drag is not an important energy loss mechanism for central-cell ions.

FIG. 9. Power loss versus ion beta in the TMX central cell for a deuterium ion density of 5×10^{12} for loss mechanisms including radial diffusion, electron drag, and axial collisional flow and collisionless mirror losses without electrostatic plugging. Beta does not include the electron contribution.

We have evaluated ion lifetime limitations due to charge exchange, with Gerry Cryczkowski's neutral-gas penetration code. The results (Figs. 10 and 11) show that gas puffer flow rates must be increased as T_{ic} increases in order to maintain the central density. This decreases the ion lifetime against charge exchange. Our conclusion is that ions diffusing radially will reach the wall as charge-exchange neutrals rather than as ions.

The optimum parameter range for experiments can be obtained from Figs. 7, 8, and 9. To accentuate radial diffusion, we operate at the lowest possible central-cell density in order to obtain the maximum ion temperature with the available power ($P_R \propto n_i^{5/2}$). To obtain maximum beta we must compromise between axial and radial losses. The density is constrained by $P_c \approx 10^{13}$ W by end losses that scale as n^a , where $1 \leq a \leq 2$, and by electron drag that scales as n^2 . But the density cannot be decreased indefinitely at high beta because radial diffusion becomes large at higher ion temperatures.

III. INITIAL TMX EXPERIMENTAL RESULTS

A. Experimental System

The ICRH system consists of a transmitter, controls, rf diagnostics, an antenna with parallel vacuum capacitors to form a resonant circuit, plasma limiters on either side of the antenna, and, for some of the experiments a Faraday shield.

The transmitter (Fig. 12) is a 1-MW class C amplifier powered by a capacitor bank of 560 μ fd and 25 kV to provide 70-ms-duration pulses with no more than 20% droop. The final amplifier is driven by a 1-kW driver that in turn is driven by a gated oscillator. The oscillator was operated in two modes: fixed and swept frequencies in the range of 1.3 to 2.2 MHz. The transmitter will be used on TMX Upgrade. The pulse duration of 70 ms is adequate for TMX Upgrade, and the transmitter can be easily retuned to other frequencies.

The vacuum capacitors include two remotely tunable 1000 pf, 35 kV units operated from the control room to provide fine tuning. Coarse tuning was achieved by installing or removing fixed 1000-pf capacitors. The antenna (Figs. 13 and 14) was a one-turn copper loop, 10 cm wide and with a 42-cm radius, surrounding the central-cell plasma. This design is based on the computed coupling to fast waves shown in Figs. 2 and 3.

FIG. 10. Charge-exchange ion lifetimes versus radius for various ion temperatures in the TMX central cell, calculated by G. Gryzkowski's neutral-gas penetration code. The gas flow is normalized to sustain $nT = 5 \times 10^{10} \text{ cm}^{-3} \text{ s}$ at $r = 0$, $n_c = 5 \times 10^{12} \text{ cm}^{-3}$, and $B_c = 1.0 \text{ kG}$.

FIG. 11. The gas puffer flow rate required for fueling versus the ion temperature $nT = 5 \times 10^{10} \text{ cm}^{-3}$ on axis.

FIG. 12. ICRH transmitter schematic.

FIG. 13. ICRH antenna-transmitter block diagram.

FIG. 14. The location of the ICRH antenna, Faraday shield, and limiters in the TMX central cell, and the magnetic field strength along the TMX central-cell axis.

Two copper limiters of 38-cm radius, on either side of the antenna, reduced the plasma flux to the antenna. They also shielded the octupole coils, diaphragmatic loops, and getter wires from the rf, and confined the gas from puffing experiments to the central cylindrical plasma. They were split into eight sectors to reduce circulating currents, and were grounded to the TMX vacuum-tank wall.

A Faraday shield was installed for a second series of experiments to reduce plasma bombardment of the antenna to a much greater degree than the limiters did and to shield the plasma from the rf electric field and protect the antenna from titanium gettering. Diagnostics were built to measure the power into the plasma and the radiation resistance (Figs. 13 and 15 and Table 3). The primary diagnostic was to measure the rf current and voltage and the

phase angle between them. The current and voltage were measured at the transmitter (I_1 , V_1), and at the input to the antenna-capacitor resonant circuit (I_2 , V_2). The circulating current through the antenna (I_3) was also measured. Taking rms values, the power from the transmitter is given by $P_i = I_1 V_1 \cos \theta_i$. The radiation resistance is $R_L = P/I_3^2$. These quantities are computed by the data-acquisition system. Initially, we used unshielded current transformers and voltage dividers. As the experiment progressed, we upgraded these with electrostatic shields, and measured their sensitivities and phase shifts with the shields in place.

Additional measurements of the input power from the capacitor bank to the final amplifier provided an easily measured upper limit to the output power and a measure of the efficiency of the amplifier.

A directional coupler to measure forward and reflected power was designed, but not built.

B. Results with a Bare Copper Antenna

Initially the neutral-beam system interrupted off for the duration of the ICRH pulse in the presence of plasmas. This problem occurred because the antenna was grounded to the TMX tank through the transmitter so that rf currents flowed through the plasma from the antenna to the TMX tank during a shot, resulting in an rf ground loop. This interference problem was eliminated by grounding the antenna at the vacuum vessel wall and grounding the transmitter only through the shield of the coaxial cable between the transmitter and antenna.

No rf interference with diagnostics was observed except with adjacent diamagnetic loops that, like the antenna, encircled the plasma and coupled to the antenna through mutual inductance. This coupling was reduced to a tolerable level with 50 μ s RC integrators on the diamagnetic loop signals. Rf probes in the plugs as well as those in the central cell detected the rf of higher amplitude than DCLC. This indicated that a wave was propagating, although perhaps only on the surface of the plasma.

The Q of the antenna-matching capacitor-coaxial cable system was measured by the ratio of rf input current to circulating current (I_3/I_1). An alternative, and more accurate, method was to sweep the driving frequency and measure the width of the resonance, $Q = f/\Delta f$. The initial Q, in vacuum, was greater

FIG. 15. RF diagnostics and data system.

FIG. 15. Continued.

TABLE 3. Summary of rf diagnostic system.

Calculated parameter	Measured parameters	Measurement device	Measurement location	Software calculations
dc power into transmitter, P_{dc}	dc voltage, V_{dc} dc current, I_{dc}	Voltage-to-frequency converter Current transformer and low-pass filter	Capacitor bank High voltage input to transmitter	$P_{dc} = V_{dc} I_{dc}$
Peak rf power, P_{pk1}	rf voltage, V_{rf1}	Resistive voltage divider and band-pass filter	At output of rf transmitter	$P_{pk1} = \frac{V_{pk1} I_{pk1}}{2} \cos \theta_1$
rms rf power, P_{rms1}	rf current, I_{rf1}	Unshielded current transformer and band-pass filter		$P_{rms1} = V_{rms1} I_{rms1} \cos \theta_1$
Loading resistance, R_{L1}	Phase angle, θ_1	Phase detector: zero-crossing type		$R_{L1} = \frac{V_{pk1} \cos \theta_1}{2 I_{pk1}}$
Peak rf power, P_{pk2}	rf voltage, V_{rf2}	Electrostatically shielded capacitive voltage divider and band-pass filter	Input of impedance-matching circuit, at the antenna	$P_{pk2} = \frac{V_{pk2} I_{pk2}}{2} \cos \theta_2$
rms rf power, P_{rms2}	rf current, I_{rf2}	Electrostatically shielded current transformer and band-pass filter		$P_{rms2} = V_{rms2} I_{rms2} \cos \theta_2$
Loading resistance, R_{L2}	Phase angle, θ_2	Phase detector: zero-crossing type		$R_{L2} = \frac{V_{pk2} \cos \theta_2}{2 I_{pk2}}$

TABLE 3. Continued.

Calculated parameter	Measured parameters	Measurement device	Measurement location	Software calculations*
Peak rf power, P_{pk3}	rf voltage, V_{rf2}	Electrostatically shielded voltage divider and band-pass filter	At antenna	$P_{pk3} = \frac{V_{pk2} I_{pk3}}{2} \cos \theta_3$
rms rf power, P_{rms3}	rf current, I_{rf3}	Unshielded current transformer and band-pass filter		$P_{rms3} = V_{rms2} I_{rms3} \cos \theta_3$
Loading resistance, R_{L3}	phase angle, θ_3	Phase detector: zero crossing type		$R_{L3} = \frac{V_{pk2} \cos \theta_3}{2 I_{pk3}}$
Q	rf circulating current, I_{pk3}	Unshielded current transformer	In antenna	$Q = \frac{I_{pk3}}{I_{pk1}}$
	rf current, I_{pk1}	Unshielded current transformer	At transmitter output	

NOTE: rms value of voltage and current are obtained by a mean-squaring circuit with the square root carried out in software. Peak values are obtained by a peak detector circuit.

* The voltages at the matching circuit (V_2) and at the antenna (V_3) are the same, as shown in Fig. 13.

than 100 (Fig. 1a) but dropped to less than 20 as a result of the deposition of titanium on the antenna surface. This problem made a bare copper antenna unusable for ICRH experiments in TMX and prompted the design of a Faraday shield.

FIG. 1b. An $\dot{B}$ loop signal (b) versus time when swept through resonance (a) with plasma, (b) in vacuum. The frequency is swept from 1.25 MHz to 1.75 MHz four times during the plasma pulse. The system Q can be determined from the width of the resonance and a knowledge of the frequency during the sweep.

C. Results with a Faraday-Shielded Antenna

We installed a Faraday shield, shown in Figs. 1b and 1c, after the August 1980 run. The shield's purpose was to reduce capacitive coupling to the plasma, reduce plasma bombardment of the antenna, and keep titanium pattering off of the antenna. It accomplished these goals: the vacuum Q remained near 10, even after the September 1980 run which coated the shield with titanium. The shielded antenna was free of titanium except for a few isolated patches. The Faraday shield was oriented so that ion orbits could not reach the antenna before hitting the shield.

During installation of the shield, we measured $\dot{B} = dB/dt$ at the axis of the antenna with a loop probe, driving the antenna at 50 W with a known current and frequency. We found that the Faraday shield reduced $\dot{B}$ by a factor of 6 (power by a factor of 36) compared with the bare antennas, and reduced the antenna inductance. This reduction was caused by rf image currents in the support rings for the Faraday shield (Fig. 13) cancelling most of the antenna's magnetic field. We installed an insulated break between each quadrant of the shield, which brought $\dot{B}$ back to within a factor of 2 of a bare antenna.

However, with plasma, the Faraday shield again apparently shorted at the four insulated breaks (it was essentially a four-section shield). The results were similar to those with the original shorted turn shield: the inductance was decreased, the resonant frequency shifted upwards, and the rf magnetic fields were largely shielded from the plasma.

The basic problem with this Faraday shield can be solved by supporting each element of the shield from the wall rather than from a ring between the wall and the antenna. This moves the rf image currents from a ring just outside the antenna radius to the wall at about twice the antenna radius. The increased area between the antenna and the return conductors greatly increases the amount of rf magnetic flux available to couple to the plasma. The antenna inductance should then be essentially unchanged by a Faraday shield.

Since the antenna resonance was shifted by the plasma, we succeeded in locating the antenna-capacitor resonance with plasma only by sweeping the frequency ± 0.2 MHz (Fig. 16). The resonance is seen clearly in the vacuum shot [Fig. 16(b)], where the antenna Q is about 100, and is not obvious with plasma [Fig. 16(a)], where Q is perhaps 20 and is difficult to separate from the transmitter output power that varies over this frequency range. However, the resonant frequency changed as a function of plasma density, even during a single shot; therefore, we could not stay on resonance to heat the plasma.

We estimate the rf energy coupled into the plasma during the time Δt that the antenna is in resonance during the frequency sweep, and obtain the maximum change that might be produced in the diamagnetic signals. The $2\omega_{ci}$ resonant region was located at $z = 112$ cm and was about 10 cm long. The rf energy is given by

$$\Delta E_{rf} = P \Delta t .$$

From shot 16 on September 27, 1980, we obtain the rf power at the resonance at

19.5 ms from $P_2 = I_2 V_2 \cos \theta_2 = 3.6 \text{ kW}$. There is an uncertainty in this number due to the fact that calibrations changed with frequency. The error is no more than a factor of 2 for the worst case and is more likely less than 20%. If we use $\Delta t = 10^{-3} \text{ s}$, obtained from the duration of the rf peak on the central-cell rf probes, then $E_{rf} = 3.6 \text{ J}$. The energy of the central-cell plasma is

$$E_c = \frac{3}{2} q n (T_{ic} + T_{ec}) \pi r_p^2 L = 45 \text{ J} .$$

If the rf heated with 100% efficiency, we could obtain

$$\left. \frac{\Delta E}{E} \right|_{rf} = 0.08 .$$

Variations of 0.05 in the plasma energy derived from four central-cell diamagnetic loop signals showed some correlation with the time of the antenna resonance. This could indicate rf heating efficiencies exceeding 50%. Future experiments with a redesigned Faraday shield are expected to maintain resonance at a fixed frequency, and so provide longer heating times. This, together with the higher power coupling expected, should produce strong and unambiguous ion heating.

An example of data from the rf diagnostics is shown in Fig. 17. Theta 2 is defined only during the rf pulse when the rf voltage and current both exceed a threshold level. The peak rf current was measured with an electrostatically shielded current transformer. The peak rf voltage of about 800 V (not shown) was measured with a capacitive voltage divider that required careful calibration and installation because its division ratio and phase shift were sensitive to both frequency and its termination impedance. The phase angle was obtained by measuring the time interval between zero crossings of the rf voltage and current. A positive phase angle represents the voltage leading the current.

We evaluate the rms power by the equation $P_{rms} = 0.5 V_{p2} I_{p2} \cos \theta_2$, where peak values of the rf voltage and current, measured at the input to the antenna, are used. Both signals were filtered to remove harmonics. With an improved Faraday shield, we expect to couple much higher power levels than the 16 kW measured here for two reasons: (1) The attenuation of the rf magnetic field by the shield should be much less than 2 rather than 36 as in these data. We will be able to adjust the antenna circuit to be at, or near, resonance for the duration of the plasma. (2) We also expect the radiation resistance,

FIG. 17. Diagnostic signals at maximum power and fixed frequency. (Diagnostic shot 61 on 10/4/80; background: shot 52, diagnostic no. 30.)

$R = P/(I_3^2 \cos \theta_3)$, to increase to the order of 1Ω from the value $R = 0.1 \Omega$ measured here

For the shot shown, the ICRH was turned on at 15 ms, after the plasma had been formed, and was turned off at 34 ms, after the plasma had decayed. The antenna circuit was not in resonance either with or without plasma in this shot. The comparable power levels observed with and without plasma are believed to be a consequence of the out-of-resonance condition.

IV. ICRH ASSISTED STARTUP OF TMX UPGRADE

Startup of TMX Upgrade requires heating the central-cell ions to a high temperature in order to reduce collisional filling of the thermal barrier to a level that can be pumped. This section discusses the use of ICRH rather than neutral beams to accomplish this heating. Open issues are listed that are amenable to either experimental tests or theoretical evaluation.

A. Startup Scenario

The startup of the TMX Upgrade with ICRH is sketched in Fig. 18. The central-cell density is initially kept low (perhaps 1 to $2 \times 10^{12} \text{ cm}^{-3}$) to minimize axial losses and hence the heating power required. The ions are magnetic mirror confined until the end-plug potential becomes high. The plugs provide an MHD anchor and should be absolutely or marginally microstable, without depending on central cell end losses. As the central-cell ion temperature increases, formation of the thermal barrier becomes possible and the plug potential can be increased to provide electrostatic confinement for the central cell so that its density can now be increased, while maintaining a moderate heating power.

B. Theoretical Issues

The first issue is specific to ICRH, the rest apply to any central cell startup and heating technique:

- Slow-wave vs fast-wave heating: Efficiency, range of applicability, overlap of density ranges (if any), bulk or tail heating.
- Axial and radial power balance: How much power is required to heat, build up, and sustain the central-cell ions?

FIG. 18. ICRH-assisted startup of TMX Upgrade.

• Gas puffing requirement: How much gas is required to sustain central cell and how much gas can the barrier and plug tolerate?

C. Experimental Issues

We will study ICRH in the Phaedrus central cell in a cooperative effort with that group. The experimental program will address several questions:

• Antenna design and location: The first antenna-transmitter configuration will be similar to those used in Phaedrus plugs. Slow-wave propagation from a half-turn antenna in the transition region to a magnetic beach near the midplane appears promising for initial heating from very low densities to densities near $n_c = 10^{13} \text{ cm}^{-3}$. A promising alternative heating technique (from recent Phaedrus end-plug results) is to use fundamental heating from evanescent fast waves in the near field of the antenna.

• Transmitter design: Either an oscillator with an antenna in the resonant circuit or a fixed-frequency amplifier will be used. The former stays in resonance, the latter must be slightly retuned for resonance in the presence of plasma.

• Ion-heating efficiency.

• Tail or bulk ion heating: Ion energy spectra obtained with a neutral analyzer and average ion energies obtained with diamagnetic loops will be the primary diagnostics.

• Optimum plasma density range.

• Wave propagation toward both plug and central cell or only to the central cell. The latter is preferable and probable if we use evanescent fast waves rather than slow waves. Rf probes in the plugs will measure the wave propagation. An end-loss analyzer will measure any increase in the energy of end-loss ions.

The goal of the above program is to learn how to heat a central-cell plasma sufficiently for a thermal barrier to be established. Maintenance of the central-cell ion temperature as the density is increased to $2 \times 10^{13} \text{ cm}^{-3}$ is a separate problem, less well suited to testing in Phaedrus for two reasons: First, fast-wave heating appears to be more effective at high densities, because a hot tail can more rapidly equilibrate with the bulk ions and the wave does not propagate at low densities. The plasma densities expected in Phaedrus are marginal for propagation whereas those in TMX Upgrade are adequate.

Secondly, without thermal barriers, poor axial confinement will require more input power to the ions than can be collisionally exchanged between the tail and bulk ions. Thus, at power levels adequate to maintain $T_{ic} = 900$ eV in TMX Upgrade, much lower temperatures could be achieved in Phaedrus.

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REFERENCES

1. D. L. Jassby, et al., Plasma Heating R&D Assessment, Plasma Physics Laboratory, Princeton University, Princeton, NJ, PPPL-1610 (1979).
2. Niklos Porkolob, Review of RF Heating, International School of Plasma Physics, Varenna, Italy, Sept. 1-10, 1977. Preprint PFC/JA-70-3.
3. H. Takahashi, ICRF Heating and Wave Generation in the ATC Tokamak. Part I: Wave Generation, Propagation and Absorption, Plasma Physics Laboratory, Princeton University, Princeton, NJ, PPPL-1345, (1979) p. 26.
4. H. Takahashi, Princeton University, Princeton, NJ, private communication (1980).
5. S. Yoshikawa, Ion Cyclotron Heating of Plasmas with Two-Ion Components, Plasma Physics Laboratory, Princeton University, Princeton, NJ, PPPL-1713 (1980).
6. Brian McVey, Excitation Theory of the Inductive Drive, TRW Report Task II, 2740 (1980).
7. Joel Hosea, et al., Fast Wave Heating in the Princeton Large Torus, Plasma Physics Laboratory, Princeton University, Princeton, NJ, PPPL-1588 (1979).
8. Y. Matsuda, Lawrence Livermore National Laboratory, Livermore, CA, internal document MFE/TC-80-1984t (July 10, 1980). Readers outside the Laboratory who desire further information on LLNL internal documents should address their inquiries to the Technical Information Department, Lawrence Livermore National Laboratory, Livermore, CA 94550.
9. P. L. Colestock, S. L. Davis, D. Q. Hwang, and H. R. Thompson, "High Power ICRF Experiments in the Princeton Large Torus," in IEEE International Conference on Plasma Science (1980), paper 2B8.
10. Lyman Spitzer, Jr., Physics of Fully Ionized Gases, (Interscience, New York, 1962).
11. D. K. Smith, "Results From the Phaedrus Tandem Mirror," Bull. Am. Phys. Soc. 25, 1016 (1980).
12. D. K. Smith, et al., "ICRH at the Fundamental Resonance on Phaedrus," Bull. Am. Phys. Soc. 25, 859 (1980).
13. J. E. Scharer, B. D. McVey, and T. K. Mau, "Fast-wave Ion-Cyclotron and First-Harmonic Heating of Large Tokamaks," Nuc. Fusion 17, 297 (1977).
14. H. R. Thompson, et al., "Heating at the Second Ion Cyclotron Harmonic in a Single Species Plasma in PLT," Bull. Am. Phys. Soc. 25, 1018 (1980).

15. T. H. Stix, The Theory of Plasma Waves (McGraw-Hill, New York 1962).
16. R. W. Clark, D. G. Swanson, P. Korn, F. Sandel, S. Robertson, and C. B. Wharton, "High Power Fundamental and Harmonic Resonant Ion Cyclotron Heating in a Mirror Machine," Phys. Fluids **17**, 1322 (1974).
17. K. Adati, et al., RFC-XX Plasma Confinement and Heating Experiments, IAEA, Vienna, Austria, IAEA-CN-38/F-5 (1980).
18. W. M. Hooke and M. A. Rothman, "A Survey of Experiments on Ion Cyclotron Resonance in Plasmas," Nuc. Fusion **4**, 33 (1964).
19. S. Yoshikawa, R. M. Sinclair, M. A. Rothman, "Ion Heating in the C Stellarator," in Plasma Physics and Controlled Nuclear Fusion Research (IAEA, 1966).
20. M. A. Rothman, R. M. Sinclair, I. G. Brown, and J. C. Hosea, "Ion Cyclotron Heating in the Model C Stellarator," Phys. Fluids **12**, 2211 (1969).
21. H. Takahashi, Wave Generation and Heating Near Ion Cyclotron Frequency in the ST Tokamak, Plasma Physics Laboratory, Princeton University, Princeton, NJ, MATT-1140 (1975), p. 8.
22. J. C. Hosea and R. M. Sinclair, "Ion Cyclotron Wave Generation in the Model C Stellarator," Phys. Fluids **13**, 701 (1970), and H. Takahashi, "Optimum Wavelength of Stix Coil," Plasma Phys. **16**, 29 (1974).
23. R. Breun, et al., Initial Results from the Tandem Mirror, Phaedrus, IAEA-CN-38/F-2-1 (1980).
24. T. D. Rognlien and Y. Matsuda, Tandem Mirror Confinement in the Presence of Ion Cyclotron Fluctuations, Lawrence Livermore Laboratory, Livermore, CA, UCRL-84571 (1980).
25. T. Stix, private communication, 1980.
26. T. Kaiser, Lawrence Livermore National Laboratory, Livermore, CA, private communication (1980).
27. C. Karmendy, Lawrence Livermore National Laboratory, Livermore, CA, private communication (1980).
28. R. Cohen and T. Cutler, Lawrence Livermore National Laboratory, Livermore, CA, internal document MFE/TC/80-1475 (April 8, 1980).
29. S. Devoto, Lawrence Livermore National Laboratory, Livermore, CA, internal document MFE/80-1323X:00X (March 27, 1980 and July 10, 1980).
30. D. Correll, Lawrence Livermore National Laboratory, Livermore, CA, internal document TMX Memo (May 9, 1980).

APPENDIX A

Brian McVey

Preliminary results have been obtained using a computer code which models ICKH of a plasma confined by solenoidal fields.⁶ Figure 1 illustrates the geometry assumed in the computer code. The plasma has a uniform density out to radius $a = 25$ cm, where it abruptly drops to zero. Each plasma species is assumed to have a bi-Maxwellian velocity distribution. The assumed plasma parameters (unless explicitly stated otherwise) are listed in Table A-1. The linearized plasma response to the rf fields is computed via kinetic theory,¹⁵ neglecting finite gyroradius effects.

The plasma response includes fundamental ion-cyclotron damping, electron Landau damping, and collision effects which are simply modeled by using a particle-conserving Krook collision operator. The present computer code is being modified to incorporate second harmonic heating. Referring again to Fig. 1, the rf fields are generated from an antenna consisting of two filamentary current loops positioned as shown. The plasma-antenna system is enclosed by an outer vacuum chamber of infinite conductivity and by two end-plates. The boundary condition imposed at the end plates is $E_z = 0$, preserving the quasi-neutrality of the equilibrium plasma.

Figure 1 represents a well-posed boundary-value problem in which the linearized self-consistent plasma fields can be computed for the specified current source. Once the fields are determined, quantities such as the effective antenna loading resistance due to plasma absorption can be calculated. Figure 2 is a plot of the antenna loading resistances as a function of fast wave modes. The solid curve is for minority heating of 5% H, the crosses for 10% H, and the dots for 20% H. The eigenmode becomes more sharply peaked for the larger concentrations of H, however, it is still sufficiently broad to provide a large power transfer to the plasma as the density changes slowly. Direct fundamental heating of a relatively large concentration of H by the fast wave appears feasible. The radial power absorption profiles for the two peaks in plasma loading are shown in Fig. 3. The lower density peak corresponds to the lowest order radial eigenmode. For this mode the power absorption tends to peak at the plasma surface. At the larger density, the next higher order radial mode is obtained with the power absorption peaking well within the plasma boundary. The solid curves assume constant current in the antenna. The

dashed curve corrects the power-deposition profile of the low-density mode to correspond to the same power input to the plasma as the high-density mode. In Fig. 3, the power absorption on axis is zero, since the assumed antenna exclusively excites $n = 0$ modes. We are in the process of evaluating the radial power-deposition profile of a half-turn loop which may improve the radial profile at the lower densities.

TABLE A-1. TMX plasma parameters used to compute Figs. 2 and 3.

$$B = 1 \text{ KG}$$

$$T_e = 140 \text{ eV}$$

$$95\% \text{ D, } T_{||} = T_{\perp} = 50 \text{ eV}$$

$$5\% \text{ H, } T_{||} = 200 \text{ eV}$$

$$T_{\perp} = 1 \text{ keV}$$

$$\omega = \omega_{cH}$$

n_e is listed in Figs. 2 and 3

$$I_1 = I_2 = 50 \text{ A peak}$$