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WAVE GENERATION AND HEATING IN THE ST TOKAMAK AT THE FUNDAMENTAL AND HARMONIC ION CYCLOTRON FREQUENCIES*

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ABSTRACT : We report here theoretical and experimental investigations of wave generation and heating at the fundamental and the first harmonic of the ion cyclotron frequency. General theoretical considerations are followed by a description of experiments on the ST Tokamak designed to test the feasibility of this heating scheme for providing the additional heating required for toroidal reactor operation.

Two R F coils were used in an enlarged section of the ST vacuum vessel to allow operation up to ~ 1 MW of R F power. Wave generation efficiencies of $\sim 90\%$ have been computed from theory and observed experimentally. The ion cyclotron (slow) wave is observed to be strongly damped but the fast hydro-magnetic wave is seen to propagate many times around the machine so that standing toroidal eigenmodes are generated. The dependence of the eigenmode resonances on the density and magnetic field agrees closely with a theory based on a cylindrical, cold-plasma model. At $\omega = 2\omega_{ic}$, with relatively short R F pulses, the ion temperature approximately doubles and increases by ~ 100 eV, corresponding to a heating efficiency of $\sim 20\%$. At $\omega = \omega_{ic}$ the ion temperature increases by only 25% under similar conditions. Longer R F pulses lead to a neutral particle influx which tends to constrict the current channel and leads to M H D instabilities. The impurity component of this influx also leads to enhanced ion heating by decreasing the ion-electron equipartition time. The temperature increases quoted are for conditions where the effect of this neutral influx was negligible.

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1 - INTRODUCTION.

The feasibility of employing wave heating at frequencies in the vicinity of the ion cyclotron frequency and its harmonics to supplement ohmic heating in future toroidal reactors is being investigated theoretically and with experiments on the ST Tokamak. This work demonstrates that heating by cyclotron absorption of fast magnetosonic waves is an efficient and attractive supplementary method from the viewpoint of both physics and the availability of high power rf generators.

Our initial experimental [1, 2] and theoretical [1, 3] work indicated that wave generation and heating in the ion cyclotron frequency regime would be effective, given an appropriate wave launching structure. In Reference 3 it was emphasized that toroidal eigenmodes should exist for the fast hydromagnetic wave which should be damped by linear processes at the fundamental or first harmonic of the ion cyclotron frequency.

This first study on ST was conducted at modest wave powers (~20 kW) and was directed toward ascertaining the wave generation properties for the hot toroidal plasma. A single half-turn loop was used to generate a flat axial spectrum of wave modes ($k_{||}$) with minor azimuthal mode numbers $m = 0$ and/or ± 1 . The dependence of coil loading resistance [$R_s \equiv P_{RF}/I_{RF}^2$] on $\Omega \equiv \omega_{RF}/\omega_{ci}$ was found to be in qualitative agreement with the cylindrical theory modified by the expected toroidal effects [1]. In this earlier work the efficiency of wave generation deduced from the coil loading (power going into waves as opposed to circuit losses) was 35-50 %.

Evidence of ion heating was also observed with CIV Doppler scans and perpendicular charge exchange neutral detection [2]. These measurements of $T_{||i}$ revealed bulk heating near $\Omega = 1$ and 2 (a few tens of eV) and considerable tail heating near $\Omega = 2$. However, the power level, and the uncertainty of the $T_{||i}$ spatial distribution precluded a reliable determination of the ion heating efficiency.

Encouraged by the results of our initial study, we have modified the coil system on ST in order to improve the wave generation efficiency, to increase the wave power level, and to discriminate against heating the exterior of the plasma. In addition, we have assembled a considerable array of diagnostics to allow us to monitor the wave generation and heating and, as well, the wave influence on the basic discharge characteristics ; e.g., equilibrium and stability.

2 - THEORY.

This necessarily short section on theory outlines where our recent work departs conceptually from previous approaches. To provide a basis for comparison, we recall that most of the previous theory [1, 4, 5] concentrated on calculating the radiation resistance R_s of a finite wave-launching antenna. The radiation resistance resulted from the rate at which energy propagated away from the antenna in the form of waves. The waves, in turn, were strongly absorbed elsewhere. The principal new concept is that weakly damped waves, which form toroidal eigenmodes in tokamak geometry, are more effective at plasma heating than strongly absorbed waves. As a particular example, let us consider the toroidal eigenmodes of the fast magnetosonic wave in tokamak geometry.

The waves are weakly damped by ion-cyclotron damping at the fundamental and second harmonic of the ion-cyclotron frequency and by transit-magnetic-pumping on electrons and resistive wall (vacuum chamber) effects at all frequencies in this range. The damping decrements have been calculated to be [3, 6, 7].

$$\gamma = \begin{cases} (R/a) (k_{\parallel}^2 T_i / M q \Omega_i) \sim 10^5 \text{ sec}^{-1}, & \omega = \Omega_i \\ (R/a) (q k_{\perp}^2 T_i / M \Omega_i) \sim 3 \cdot 10^5 \text{ sec}^{-1}, & \omega = 2\Omega_i \\ k_{\perp}^2 T_e / M \Omega_i \sim 3 \cdot 10^5 \text{ sec}^{-1}, & e\text{-TTMP}, \omega / k_{\parallel} \sim \bar{V}_e \\ (c/5a) (\omega/\sigma)^{1/2} \sim 10^4 \text{ sec}^{-1} & \text{wall} \end{cases}$$

where q is the concentration of the resonant species and the numerical values are typical of the ST experiments reported in the following sections.

The important point is this : Although the collisionless damping decrements are small compared to the wave frequency, what really matters is that they are large compared to the resistive losses in the wall and to the typical energy loss rates ($\sim 10^2 \text{ sec}^{-1}$). The first inequality guarantees that most of the wave energy goes into the plasma particles, while the second inequality means that the wave energy density can be much smaller than the thermal energy density and still achieve adequate heating. Indeed, using second harmonic damping and the approximate dispersion relation $\omega^2 = (2\Omega_i)^2 = k_{\perp}^2 V_A^2$,

$$\beta_{\text{waves}} \equiv \frac{|\delta B_z|^2}{B_0^2} \approx \frac{a}{R \Omega \tau_h} \sim 10^{-6} \ll \beta_{\text{plasma}} \sim 10^{-3}$$

With $\tau_h^{-1} = \dot{T}_i / T_i \sim 10^3 \text{ sec}^{-1}$. Such small wave intensities preclude any nonlinear wave effects aside from heating.

Eigenmode heating has several notable advantages : First, the weak damping permits ready penetration of the energy to the center of even a reactor plasma. Second, the roughly uniform distribution of wave amplitude throughout the torus produces heating that is roughly uniform. This contrasts with the spatially localized heating associated with the resonances of strongly absorbed waves. Third, both theory and the experiments reported herein demonstrate that the loading resistance R_s increases substantially for toroidal eigenmodes.

The principal disadvantage is the temporal variation of eigenmode frequencies caused by density variations. Wave generation systems with sufficient bandwidth to follow an eigenmode frequency [8] must be used. A 10 % bandwidth should be entirely adequate for large devices such as PLT or T-10 which will have many eigenmodes.

Let us next describe the mechanism of ion heating. In a tokamak, the location of a surface where $n \Omega_i(R) = \omega$ is a cylinder of constant major radius. Each time an ion crosses this surface, it receives an increment in perpendicular energy $\Delta E_{\perp}$ whose sign depends on relative phase between waves and particles. Hence all circulating ions and many trapped ones can participate in the heating process. Using the $\Delta E_{\perp}$ one can derive a Fokker-Plank equation governing the quasilinear evolution of the ion velocity distribution.

$$\frac{\partial}{\partial t} f(E_{\perp}, E_{\parallel}) = \Gamma_n \frac{\partial}{\partial E_{\perp}} E_{\perp}^n T^{2-n} \frac{\partial}{\partial E_{\perp}} f(E_{\perp}, E_{\parallel})$$

Where $n = 1, 2$ correspond to fundamental and second harmonic heating respectively, the formula for Γ_n are

$$\Gamma_1 = \frac{R}{\Omega(r + r_0)MT_i} |E_{\perp 1}|^2$$

$$\Gamma_2 = \frac{Re^2}{8(r + r_0)\Omega^3 M^2} |\nabla E_{\perp 2}|^2$$

where

$$r_0 \approx (R/a) (T_i/M)^{1/2} \Omega_i^{-1}$$

$$E_{\perp 1} = \frac{k_{\parallel}}{\sqrt{2Z}} \left(\frac{T_i}{M} \right)^{1/2} \frac{c^2}{\Omega_i \omega_{pi}^2} \left[\frac{\partial^2}{\partial r^2} E_{r1} - \frac{(2m-1)}{r} \frac{\partial}{\partial r} E_{r1} \right] + \frac{E_{r1}(m^2-1)}{r}$$

Z denotes the plasma dispersion function.

$$Z = Z \left[(\omega - \Omega_i)/k_{\parallel} V_i \right]$$

and $E_r, E_{\perp}$ are the right and left-hand electric field components.

Computational solutions show that these quasilinear diffusion operators yield high energy tails, the second harmonic operator producing a stronger tail.

3 - EXPERIMENT.

3.1. Coil system.

In upgrading the initial (Phase I) experiments to the present level (Phase II) (Fig. 1) three principal modifications have been made in the wave launching structure for the high power system: (i) two half-turn coils, separated along the plasma column by 43 cm, are used in place of the single coil launcher, (ii) the distance between the coils and the vessel has been increased from ~ 1.3 cm to ~ 4 cm, and (iii) the coil entrance port diameters have been enlarged from 3.5 cm to 7.6 cm. Alterations (i) and (ii) are predicted to raise the maximum generation efficiency $\left[\frac{P_{\text{waves}}}{P_{\text{waves}} + P_{\text{circuit loss}}} \right]$ to $\approx 80-90\%$. Alteration (iii) provides for greater voltage standoff which, coupled with the increased loading efficiency, permits operation at wave powers up to ~ 1 MW. In Fig. 2 we show the relative position of the RF coils and the diagnostics. The neutral detectors labeled $T_{\perp}/T_{\parallel}$ measure energy distributions of particles with velocity components primarily perpendicular/parallel to the toroidal magnetic field.

3.2. Coil loading, wave generation efficiency, and wave properties.

Figure 3 gives a typical loading curve obtained for the new system. The enhancement of $R_S (\equiv P_{\text{RF}}/I_{\text{RF}}^2)$ in the vicinity of $\Omega = \omega_{\text{rf}}/\Omega_i = 1$ (2) due to slow (fast) wave generation is ~ 10 times the circuit loss value, giving a wave generation efficiency of $\sim 90\%$ as predicted. R_S is found to depend on plasma parameters (e.g., n_e) as predicted by the cylindrical theory and

is independent of RF power level. The magnitude of the circuit resistance is indicated by the horizontal line at the 0.06 ohm level.

An array of 22 R F probes is used to identify the generated wave modes and to monitor axial (major azimuthal) attenuation. The theoretically predicted minor azimuthal modes are observed (Fig. 3). Axial attenuation is large ($\lambda \sim 1$ m) for the slow waves but the fast waves propagate many times around the machine. Toroidal eigenmodes are observed from loading and magnetic probe measurements. These toroidal modes lead to large peaks in the loading curves (Fig. 4) but are not seen in Fig. 3 because of the coarseness of the magnetic field scan. The observed and computed dependence of these modes on Ω and time (density) is seen in Fig. 5. The left side of this diagram is a computer read-out such that the dark lines indicate experimentally observed loading peaks, and the right side corresponds to a theory [9] which assumes that these peaks occur when an integral number (n) of wavelengths fit into the torus.

There is a tendency for these loading peaks to occur in pairs (Fig. 6). The right side of Fig. 6 shows a theoretical calculation of the load resistance wherein the splitting of the peaks is attributable to the poloidal magnetic field influence on propagation.

3.3. Ion heating and overall discharge response.

We began our heating studies with relatively long (5-10 msec) R F pulses. Charge-exchange neutral scans of $T_{i\perp}$ revealed considerable ion "body" (~ 100 eV) and "tail" heating (large signals at 8 kV) at both $\Omega = 1$ and $\Omega = 2$. $T_{i\perp}$ increased quickly (< 1 msec) to a saturation level whereas $T_{i\parallel}$ (obtained from tangential scans on the opposite side of the machine from the R F coil system) increased throughout the R F pulse (Fig. 7). Both $T_{i\perp}$ and $T_{i\parallel}$ decayed much slower than expected. (Doppler broadening measurements gave similar heating curves.)

At supplementary powers comparable to the ohmic heating power, we expect and find significant perturbations of the equilibrium conditions. These perturbations can be attributed to the ion heating and to an increase in neutral influx. The neutral influx is troublesome in two respects.

First, it tends to constrict the current channel and can lead to MHD instability. Secondly, impurity influx can increase the electron-ion equipartition rate and thereby enhance the ohmic heating of the ions. Simulation of the R F produced density increase with pulsed gas injection give no additional ion heating for a D_2 pulse but gives considerable ion heating for Ne (Fig. 8) on a time scale of ~ 10 msec. In fact, most of the $T_{i\parallel}$ increase for $\Omega \sim 1$ is due to impurity influx for long R F pulse operation.

The influx has been markedly reduced by decreasing the machine base pressure and by using shorter R F pulses. Removal of the influx effect on ion temperature reveals that $T_{i\parallel}$ approximately doubles during an R F pulse with $P_{\text{wave}} \sim 70$ kW at $\Omega \sim 2$ (Fig. 9) but only increases a factor of ~ 1.25 at $\Omega \sim 1$. In both cases $T_{i\parallel}$ decays back to its initial value in ~ 2 msec.

The wave heating efficiency ($\Delta W_{\text{ion}} / \Delta W_{\text{wave}}$) at $\Omega \sim 2$ is $\sim 20\%$ and appears to be consistent with the observed containment time and energetic ion tail orbit loss.

In Fig. 10 we show a typical ion energy distribution showing the "tail" which occurs for $\Omega = 2$. The quoted temperatures in this paper always refer to the temperature of the "body" of the distribution. The lower efficiency at $\Omega \sim 1$ is thought to be due to the peculiarities of the slow wave in a torus (which could result in considerable energy deposition in the surface of the plasma).

4 - DISCUSSION.

The experiments here demonstrate that the physical process involved in wave generation and absorption in the ion cyclotron frequency regime is understood, e.g., the magnitude of the coil loading, mode characteristics, and the formation of high energy tails. In future, larger devices (PLT, PDX, T-10, etc...) a variety of eigenmodes may be excited and fast wave generation will be optimized. Because the plasma current will be roughly 40 times that of the modest ST discharges studied here, the confinement of the ions and especially the energetic ion tails will be dramatically improved. This should result in higher heating efficiency and reduced neutral influx.

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Fig.1 - The RF COIL CONFIGURATION.
The upper half of the figure represents the initial or Phase I experiments. Phase II, on the lower half refers to the present experiment.

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Fig.2 - Schematic representation of the ST Tokamak showing the relative position of the RF coils, magnetic probes and charge-exchange neutral detectors.

↑
Fig.3 - Loading resistance, R_s , vs. $\Omega = \omega/\omega_{ci}$ for helium.
($I_{oh} = 21$ kA, $n_e = 10^{13} \text{ cm}^{-3}$, $P_{RF} = 10$ kW, $\omega = 2\pi \cdot 25$ MHz).

↑
Fig.4 - Loading resistance vs. time (density) and vs Ω showing toroidal eigenmodes in a H plasma traces represent input data for the Ω -time plots in Fig. 5.

←**Fig.5 - Plots of the occurrence of eigenmodes in Ω -time space ; theoretical (R), experimental (L). The time dependence comes from the density variation in Fig. 4.**

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