ABSORPTION OF ION CYCLOTRON WAVES BY ONE COMPONENT OF A TWO-ION PLASMA*

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We have observed propagation of waves in a plasma containing two ion species (H^+ and $H_2{}^+$; H^+ and D^+), with subsequent absorption of the wave energy by those ions for which the wave frequency equals the ion cyclotron frequency at some point in the magnetic field. Using a plasma consisting of 10% deuterium in 90% hydrogen, measurement of plasma diamagnetism and observation of neutron production indicate that the minority ions may acquire large amounts of energy from the waves. This heating has been observed under conditions requiring the waves to propagate through a region of evanescence by "Budden tunneling."

The waves were produced in a toroidal plasma of known density created by Ohmic heating in the Model-C Stellarator.[1] Coupling of rf power to the plasma was accomplished by a two-wavelength induction (Stix) coil[2,3] at a fixed frequency of 25 MHz. The geometry of the experiment and the profile of the Stellarator confining magnetic field are shown in Fig. 1. The wave generated by the coil propagates around the machine and undergoes ion-cyclotron damping wherever the condition $\Omega = 1$ is met by one of the ion species. [Ω = (wave frequency)/(ion-cyclotron frequency). Subscripts H, H_2, and D will be used when referring to a particular ion.]

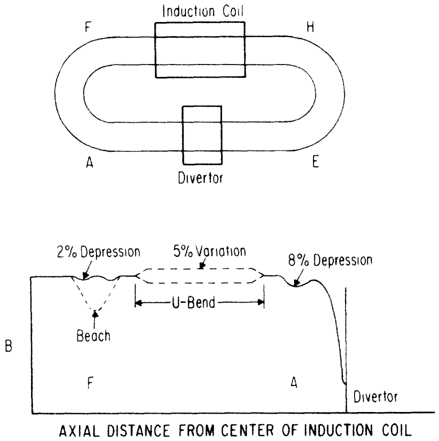

FIG. 1. Schematic view of the Model-C Stellarator, showing location of beaches and diamagnetic loops. The magnitude of the magnetic field as a function of axial distance around one U bend is shown. In addition to the normal variations of the field shown, the field can be reduced by as much as 25% at locations *F* and *H* (beach). The ±5% variation in the U bend is in the direction of the major radius of curvature.

It is important to take into account the minor local reductions in magnetic field strength shown in the diagram in order to explain the resonance effect observed. In addition to the small field depressions always occurring between the confining field coils, by shunting individual coils we can introduce reductions in magnetic field at locations *F* and *H* of up to 25% of the nominal field strength. These reductions are known as "beaches," for a wave propagating into such a region of reduced field will become evanescent if $\Omega > 1$ in that region. Such a local field reduction is also a magnetic mirror for those particles located within it.

Heating of the plasma was measured by diamagnetic loops located at *A*, *E*, *F*, and *H*, wound outside the stainless-steel vacuum vessel. The electron temperature always remained <30 eV. Large values of $p_\perp$, indicating high ion energies, were found only when the fields were such that for some ion species $\Omega = 1$ was satisfied within one of the local mirror regions at the diamagnetic loop being observed, indicating trapping of the accelerated ions in the mirror. With a hydrogen discharge, generation of waves and heating of plasma was found to be similar to that reported previously by Stix and Palladino,[2] and by Hooke et al.[4,5] at $0.7 < \Omega_H < 1.0$. (Since the magnetic field is a function of axial position, Ω varies with position.) This heating was observed at locations *F* and *H*, while no heating was found at *A* and *E*. However, at higher magnetic fields, so that $\Omega_H < 0.5$, additional heating was found, this time on both sides of the Stellarator.

Evidence for this heating is shown in Figs. 2(a) and 2(b), which gives $p_\perp$ measured on two sides of the Stellarator as a function of Ω_H measured at the induction coil, for two depths of "beach." The data can be explained by postulating the presence of a small concentration of $H_2{}^+$ ions in the plasma. (This effect has been noted previously by Nagao et al.[6] and was independently suggested by R. Palladino in connection with the present work.) The fields at which $\Omega_{H_2} = 1$ at a particular diamagnetic loop lie at the

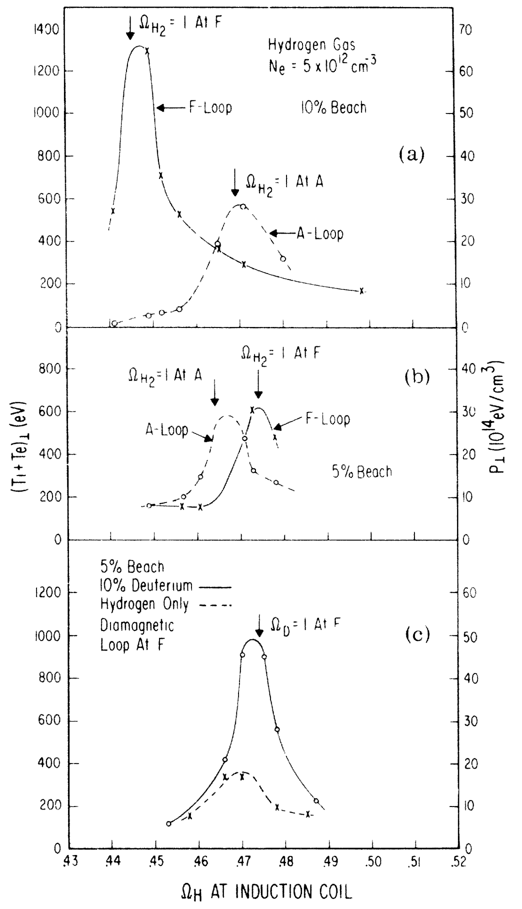

FIG. 2. (a) Diamagnetic pressures measured at locations A and F with hydrogen gas and 10% beach. (b) Same as (a) for 5% beach. (c) Diamagnetic pressures measured at location F, comparing 100% hydrogen with 90% hydrogen and 10% deuterium. (b) and (c) were obtained with different concentrations of H_2^+.

indicated points, taking into account the known axial variation of magnetic field. These points coincide with the maxima in $p_\perp$, indicating that we are observing resonance acceleration and trapping of the H_2^+ ions. The fact that the peak at location F is greater for the 10% beach than for the 5% beach indicates that the deeper beach is more efficient at trapping energetic ions. (A 5% beach means that the field at the minimum of the beach is 5% lower than at the induction coil.) The heating at A shows that some of the wave energy goes through evanescent regions at F and H and around the U bend. Such transmission can be explained by "Budden tunnelling."[7] When the concentration of H_2^+ is small, the wave equation may be approximated, near resonance, by

$$\frac{d^2E}{dx^2} + k_\parallel^{\,2}\left(1 + g\frac{l_B}{x - x_0}\right)E = 0,$$

where E is the wave electric field. The direction of propagation and of the static magnetic field are in the x direction, x_0 is the point for which $\Omega_{H_2} = 1$, $l_B = [d(\ln B)/dx]^{-1}$, $g = H_2^+/H^+$ concentration, and $\lambda_\parallel = 2\pi k_\parallel$ is the wavelength at that x for which $gl_B/(x - x_0) \ll 1$. For g small compared to unity, Budden found that the wave would be transmitted through the evanescent region with only a small amount of absorption and reflection. The amount of transmission is proportional to $\exp[-\pi g k_\parallel l_B]$.

As a test of this hypothesis the amount of Ohmic heating was reduced so that the hydrogen was only 25% ionized, and consequently the concentration of H_2^+ was increased. There was little effect on $p_\perp$ at location F, while $p_\perp$ at A was reduced by a factor of 10, indicating greater absorption of the waves before they reach A.

One presumes the H_2^+ is formed from neutral hydrogen emerging from the large divertor volume during the Ohmic heating pulse.[1] Even though the H_2^+ ions which are accelerated by ion-cyclotron resonance may soon be dissociated, the resulting H^+ ions will remain trapped in the local mirror fields. If these energetic ions amount to 10% of the total measured density, then the average energy of these ions is in the neighborhood of 10 keV, rather than the 1 keV calculated using the total ion density.

To test this conclusion, 10% of deuterium was added to the hydrogen producing a two-ion plasma of the type discussed by Buchsbaum.[8] As shown in Fig. 2(c), this addition gave an increase in $p_\perp$ seen at location F. If we attribute the observed $p_\perp$ to the 10% D^+ ions, the average D^+ ion energy is ~9 keV.

By use of a BF_3 counter with polyethylene moderator, neturon production was observed when the magnetic field was such as to give the maximum diamagnetic signal. Neutron yields with 10% deuterium and 100% deuterium are compared in Table I. Although the possibility of wall production of neutrons makes a quantitative assessment difficult, one may state that the magnitudes of the observed neutron yield supports our hypothesis that it is only the resonant particles (deuterons) which are accelerated, and that it is the $p_\perp$ for these par-

Table I. Generation of suprathermal ions. ($n_e = 5 \times 10^{12}/\mathrm{cm}^3$. 5% beach at H and F.)

Gas	rf power (MW)	$P_\perp = \langle n_e K T_i \rangle$ (eV/cm^3)	Neutrons/ discharge
100% D_2	1.9	3.6×10^{15}	2×10^4
10% D_2 and 90% H_2	0.55	3.1×10^{15}	2.5×10^5

ticles which is detected by the diamagnetic loop.

The preferential heating of resonant particles which we have observed is accompanied by tunneling through the evanescent region on the far side (the weak-magnetic-field side) of the point $\Omega_D = 1$ in the magnetic beach. This configuration could therefore be used to heat a plasma simultaneously at several beaches, thus spreading the energy out more uniformly. There is the alternative possibility which is to approach the point $\Omega_D = 1$ from the weak-magnetic-field side—coupling power into the plasma waves at a magnetic field such that $0.5 < \Omega_H < 1.0$, tunneling through the evanescent region, and then damping the waves near a local maximum in the magnetic field (a "magnetic mountain") where $\Omega_H = 0.5$ or $\Omega_D = 1.0$ is satisfied. This avoids trapping of the ions in a mirror and converts some of the $v_\perp$ into $v_\parallel$ as the ions are repelled from the field maximum. The method of heating described in this paper appears to be especially suitable for heating a mixture of deuterium and tritium to fusion temperatures since then both ion species are active participants in the fusion reaction and neither is merely a passive carrier of wave energy.

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[1] For the recent Stellerator experimental configuration see, e.g., R. M. Sinclair, S. Yoshikawa, W. L. Harries, K. M. Young, K. E. Weimer, and J. L. Johnson, to be published.

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[8] S. J. Buchsbaum, Phys. Fluids 3, 418 (1960).