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BY

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FAST WAVE HEATING IN THE PRINCETON LARGE TORUS*

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ABSTRACT

Fast wave heating in the ion cyclotron range of frequencies (ICRF) is being studied on the Princeton Large Torus (PLT) to evaluate its potential for heating large reactor-scale toroidal plasmas. Of primary interest are the two-ion and pure second harmonic heating regimes which, with proper control of the ion energy distribution and the rf power deposition profile, permit substantial energy glow into the bulk plasma ions. Initial heating experiments have been conducted with a single 1/2 turn antenna up to wave powers of $P_{rf} \simeq 350$ kW for durations of $\gtrsim 100$ ms in the two-ion regime under conditions for which direct fundamental cyclotron damping on the minority ion species dominates the wave absorption. Ion-ion coupling serves to heat the majority ions and for energetic minority ion energy distributions, energy flow to the electrons results from electron drag. Substantial ion heating is found for D-p mixtures; $\Delta T_d(0) \simeq 600$ eV for 350 kW with $\bar{n}_e \simeq 2 \times 10^{13}$ cm^{-3}. The deuteron heating efficiency is improved by about a factor of ~2 in D-^{3}he mixtures; $\Delta T_d(0) \simeq 500$ eV for 150 kW with $\bar{n}_e \simeq 2.1 \times 10^{13}$ cm^{-3}.

1. INTRODUCTION

The experimental ICRF program on PLT is directed toward optimizing the heating performance in the various wave regimes of possible interest for heating large reactor-scale tori and toward contributing to the understanding of the physics which will permit extrapolation of proven regimes to reactor conditions. Experimental conditions for determining the potential of ICRF heating are greatly improved in PLT over those previously employed in relatively small, low-current tokamaks (e.g., ST and ATC) (Hosea, 1976); in particular: 1. high current operation affords good energetic ion confinement; 2. the large minor radius permits a large number of modes to be excited from which those favoring bulk heating may be selected; and 3. wave conditions should be obtainable at high density, which are representative of machines of the size of TFTR and JET. Thus, the attainment of efficient heating of several keV without serious deleterious effects on the discharge in PLT,

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especially at higher densities, will readily demonstrate the applicability of ICRF heating to the next generation of tokamaks. Such a result, coupled with a thorough understanding of the heating process(es) and followed by an extensive effort to develop suitable wave generation structures, should qualify ICRF heating for use in a reactor.

Ultimately, ~5 MW of rf power will be applied to heat PLT in suitable wave regimes. Leading up to this application, Colestock (1978) and Hosea (1978) began the PLT program by exploring the wave properties for the various regimes and developing wave tracking techniques for conditions which support toroidal eigenmodes. More recently, we have begun un-optimized heating studies at moderate powers with a single 1/2 turn antenna in the two-ion regime, some of the results of which will be presented in this paper. Two-coil operation at higher power and with some $k_{\parallel}$ selection will be investigated in the near future as will heating for the other wave regimes, especially the pure second harmonic regime for which mode-tracking should permit rather precise $k_{\parallel}$ selection.

Subsequently, multiple array antennae suitably designed for adequate mode selectivity and power transfer will be employed in the more promising regimes at the maximum power level of ~5 MW. Such operation is projected to produce substantial heating at densities in the range of $\sim 10^{14}$ cm^{-3} and should serve as a definitive test of ICRF heating.

Pertinent theoretical considerations are discussed briefly in Section 2. The experimental conditions are presented in Section 3, and some of the heating results obtained for the two-ion regime are given in Sections 4 and 5. The implications of the heating results are discussed further in Section 6.

2. THEORETICAL CONSIDERATIONS

The ion heating wave regimes of primary interest in PLT are the pure second harmonic regime and the two-ion regime. For the former, second harmonic cyclotron damping dominates the wave absorption which results in the production of ion energy distributions having energetic "tails" (Adam, 1975; Stix, 1975). For the two-ion regime, the ion-ion hybrid resonance layer is located inside the plasma, causing either fast wave mode conversion to occur with electron Landau damping, minority ion fundamental cyclotron damping, and majority ion second harmonic damping (if present), competing in the wave absorption or, for sufficiently small concentrations of minority ions so that mode conversion is absent, an enhancement of direct minority ion fundamental cyclotron damping which then dominates the wave absorption and leads once again to ion (minority) energy distributions having energetic "tails" (Stix, 1975; Perkins, 1977; Jacquinot, 1978; Takahashi, 1977; Vdovin, 1977). For both regimes, efficient ion heating requires controlled deposition of the rf energy over the plasma cross-section and, in the cases for which energetic "tails" are produced, the controlled deposition must be coupled with appropriate plasma conditions to minimize the escape of the energetic ions via banana orbits which intercept the limiter or vessel (Hosea, 1976; Smith, 1975).

Previous ICRF experiments on relatively small, low-current tokamaks were performed in the two-ion (deuteron-proton) regime and resulted in heating efficiencies in the range of 20-40% and an enhancement of particle recycling into the plasma (Adam, 1975; Takahashi, 1977). Relatively poor confinement of energetic ions and surface heating by the excitation of wave modes having large electric fields and field gradients at the plasma surface are suspected to be the primary factors limiting the ICRF performance in these experiments (Hosea, 1976). Projections to large high-current tokamaks such as PLT suggest that the energetic ion confinement should improve substantially, especially in the core of the plasma, and that the proper selection of propagating modes can be used to favor deposition of the rf power in the core of the plasma while minimizing the surface heating so that the true potential of ICRF heating for use in large tori may be established (Hosea, 1976).

We now turn our attention to the two-ion regime for which heating results will be presented. In recent years, the importance of the two-ion hybrid resonance on fast wave damping has been observed in several tokamaks (Takahashi, 1977; EQUIPE TFR, 1976; Vdovin, 1976) and has received considerable theoretical analysis (Perkins, 1977; Jacquinot, 1978; Takahashi, 1977; Vdovin, 1977; Jacquinot, 1977; Klima, 1975). Mode conversion occurs when the concentration of the ion minority specie, resonant at its fundamental cyclotron frequency, is sufficiently high as is illustrated for D-h and D-^{3}he mixtures in Figs. 1 and 2. Roughly, the concentrations required for mode conversion for these minorities are

$$\eta_h \gtrsim 5(\beta_e T_h/2T_e)^{1/2}\ S_{||}(4/3 + S_\phi^2) \tag{1a}$$

and

$$\eta_{^3He} \gtrsim 3(2\beta_e T_{^3He}/3\ T_e)^{1/2}\ (16/7 + S_\phi^2)\, S_{||} \tag{1b}$$

where $\eta = Zn\ (\text{minority})/n_e$, $S \equiv kC/\omega_{pd}$, and k_ϕ and $k_{||}$ are the wave numbers along the toroidal and total magnetic field, respectively. At lower concentrations than given by Eq. 1, mode conversion is absent, but the effect of the two-ion hybrid zone on wave polarization enhances the direct minority fundamental damping as shown. Upon application of rf power, the minority ions can receive sufficient energy even when mode conversion is present initially to heat up and push into the direct minority damping regime in accordance with Eq. 1.

The minority ion energy distribution will be governed by the Fokker-Planck theory, including the quasilinear diffusion produced by the power absorbed by the minority ions. The form of the distribution in the range of ion energies for which the distribution should be essentially isotropic ($E \lesssim 9kT_e$) has been evaluated in the absence of charge exchange to be (Stix, 1975)

$$\ell n\ f(E) = -\frac{E}{kT_e(1+\xi)}\left[1 + \frac{R_j(T_e - T_j + \xi T_e)}{T_j(1+R_j+\xi)}\ H\left(\frac{E}{E_j}\right)\right] \tag{2}$$

$$\xi = \frac{m\langle P\rangle}{8\pi^{1/2} n_e n Z^2 e^4\ \ell n\Lambda}\left(\frac{2k\,T_e}{m_e}\right)^{1/2} \tag{3}$$

and where the other terms are defined (Stix, 1975). To incorporate charge exchange we solve numerically the relation

$$\frac{\partial f}{\partial t} = \frac{1}{v^2}\frac{\partial}{\partial v}\left(-\alpha v^2 f + \frac{1}{2}\frac{\partial}{\partial v}\left[\beta v^2 f\right] + Kvf\right) - f n_0\langle\sigma_{cx} v\rangle + \frac{f_s}{\tau_s} \tag{4}$$

where σ_{cx} is the charge exchange cross-section, f_s is the assumed distribution of replacement minority ions, and τ_s is the replacement time.

By adjusting ξ to be sufficiently large to give the direct minority damping case (Eq. 1), all of the rf power will be transferred to the minority ions. If, in turn, ξ is not allowed to become too large, most of this power will be transferred via ion-ion coupling to the majority ions and very little power will be transferred through electron drag or lost by escaping energetic ions. Thus, the ξ parameter provides the prescription for proper control of the minority distribution for a given rf power level. These considerations are illustrated for a constant minority concentration in Fig. 3. The power per deuteron peaks at a given density where electron heating is diminished, and this critical density increases with rf power. In Fig. 3, charge exchange losses have been included for the proton case but are negligible for the helium-3 case.

In the heating experiments to be reported here, we have concentrated on the direct minority damping regime. At low densities, this regime favors majority ion heating. Also, it is of considerable importance when extrapolated to reactor conditions for substantial minority concentrations and for several minority species. However, the mode conversion regime is attractive as well at high densities where the electrons and ions are more tightly coupled.

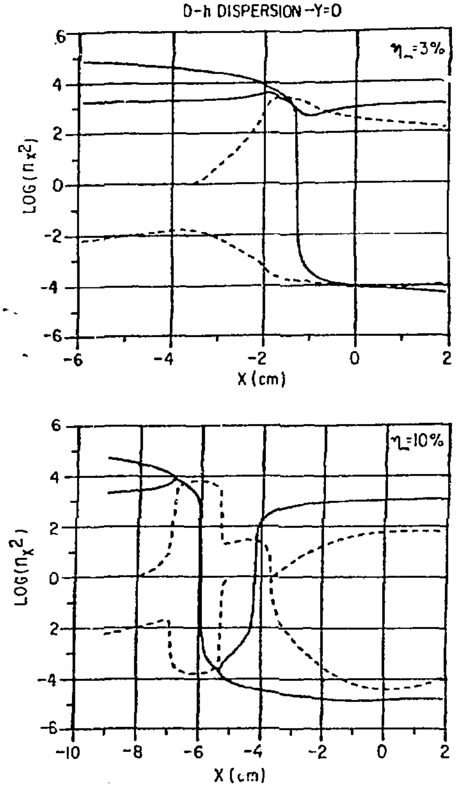
3. EXPERIMENTAL ARRANGEMENT

A single 1/2 turn coil located in PLT as shown in Fig. 4 has been employed to excite fast waves at 24.6 MHz in deuterium plasmas of moderate density - $\bar{n}_e \simeq 1\text{-}2.5 \times 10^{13}$ cm^{-3} - having resonant minority concentration of protons or helium-3. The design of this coil is similar to that developed for the ST Tokamak (Knutson, 1973). It favors m=0,±1 poloidal mode excitation (meaningful when the wave damping length is comparable to or longer than the coil diameter) but provides no spectral selection in $k_{\parallel}$. In the presence of toroidal eigenmodes, mode tracking can be employed for k selection. However, for most two-ion regimes studied, these modes are damped so that the coil loading by the waves is relatively constant. Modest $k_{\parallel}$ control in the two-ion regime has been exercised by adjusting the density to provide damped modes relatively near onset. The wave coupling efficiency in this latter case is found to be ~80% for the coil design now in use. This efficiency should improve when multiple coil arrays are employed in the future.

Feedback is currently used to hold the forward power to the coil system constant over the duration of the rf pulse. The coil measurements are illustrated in Fig. 5 where P_{NET} to the coil is ≃400 kW and P_{rf} to the waves is ≃300 kW. The nearly constant P_{rf} obtained in this manner facilitates the interpretation of the time behavior of the plasma response.

A large number of diagnostics are available on PLT which are well suited to the study of the plasma regime and its response to auxiliary heating (Bol and PLT Group, 1978; Eubank and PLT Group, 1978, 1979). These include several independent measurements of ion temperature, electron temperature, and stability characteristics. Also, impurity effects are monitored and controlled to the extent possible with the techniques developed for tokamaks over the past several years (Bol and PLT Group, 1978; Hosea, 1979a).

A mass discriminating charge exchange system (Davis, 1979), located on the opposite side of PLT from the rf coil and directed approximately toward the major axis of the torus, is of particular importance for studying the response of the individual species to the applied rf power. This system is complemented by a second horizontally scanning charge exchange system (without mass discrimination) located near the coil.



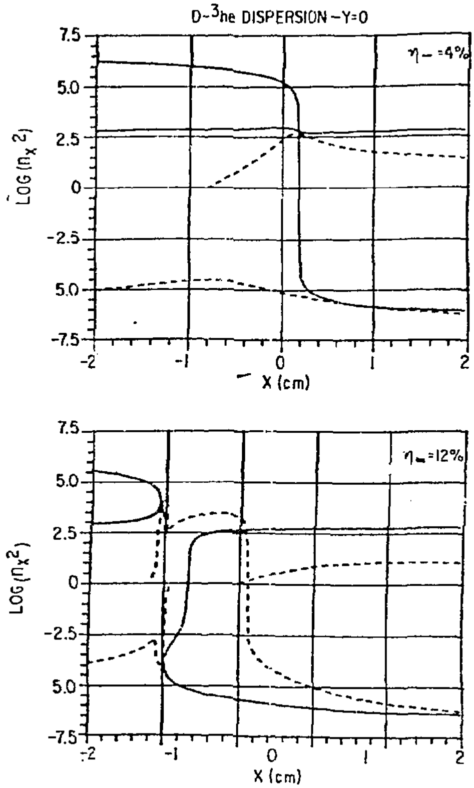


Fig. 1. Hot plasma dispersion relation roots in the mode conversion zone for the D-p case. $T_e = T_h = T_d = 1$ keV, $n_{eo} = 1.5 \times 10^{13}$ cm^{-3}, $k_\phi = 5$ m^{-1}, $B_T = 16.4$ kG, f = 24 MHz. (a) Direct damping regime. (b) Mode conversion regime. (PPPL 796009)

Fig. 2. Dispersion roots for the case of Fig. 1 but with a ^{3}he minority. (a) Direct damping regime. (b) Mode conversion regime. (PPPL 796019)

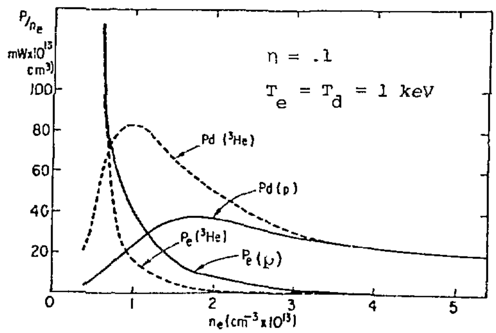


Fig. 3. Power per particle delivered by the energetic minority distribution on axis for D-h and D-^{3}he mixtures. (PPPL 796022)

4. HEATING RESULTS FOR THE D-h REGIME

Initial heating results were obtained first with a test 1/2 run coil with $P_{rf} \approx 30-70$ kW for D-h plasmas (Hosea, 1976). The proton concentrations were provided by the residual hydrogen and were typically $\eta_h \sim 3-10\%$. These results revealed that the proton energy distributions produced were very energetic T_{heff} (5 keV-40 keV) 7 keV , were consistent with the Fokker-Planck theory as prescribed by Stix $R_d \equiv Z_{eff}(m_h T_e/m_e T_d)$, and caused direct minority damping to dominate the wave absorption. Significant heating of the deuterons occurred via ion-ion coupling (~2 eV/kW at $\bar{n}_e = 1.5 \times 10^{13}$ cm^{-3}) and for some conditions electron heating could be sustained through the electron drag.

Preliminary measurements of the proton energy distributions versus the minor radius (Hwang, 1979) and coupled with the inclusion of charge exchange in the Fokker-Planck theory (Eq. 4) indicate that virtually all of the rf power is required to sustain the proton distributions. For example, analysis of the results of Hosea (1976) for $P_{rf} \approx 30$ kW gives 60%, 16%, and 24% as the split of the power between deuterons, charge exchange, and electrons, respectively.

Obviously, it is important to control the proton distribution (ξ of Eq. 3) in order to minimize the electron drag since energy can easily be radiated away from the electron channel for low density conditions. Bolometer measurements indicate that this is the case for the rf experiments which have been conducted. However, prior to optimizing the proton distribution as well as the antenna geometry, we have progressively increased the rf power to establish a reference from which optimization can follow. Thus, in the present experiments we have continued to utilize the residual hydrogen level and a single 1/2 turn coil. Heating results for P_{rf} levels up to ~260 kW are reported in Hwang (1979), and here results are discussed for P_{rf} levels up to ~350 kW which is comparable to the ohmic heating power for the discharge conditions studied. The discharge conditions selected had the parameters $B_\phi = 17$ kG, $I_p \approx 300$ kA, $V_\phi \approx 1.2$ V, $T_e(0) \approx 1400$ eV, $T_i(0) \approx 600$ eV, $\tau_{Ee} \approx 20$ ms, $\tau_{Ei} \approx 60$ ms, $Z_{eff} \approx 2-3$, and $\eta_h \approx 5-10\%$. P_{rf} values of $\approx$90, 200, and 350 kW were applied from $\approx$375 to ~380 ms in a consecutive series of experiments, and the deuterium gas programming was adjusted to give $\bar{n}_e \approx 2 \times 10^{13}$ cm^{-3} at the end of the rf pulse at each power.

Hydrogen and deuterium energy distributions obtained by perpendicular charge exchange measurements from the central core of the plasma at $P_{rf} \approx 350$ kW are presented in Fig. 6 and 7. The proton distribution is clearly observed up to E = 80 keV. The theoretical isotropic Fokker-Planck distribution (including charge exchange) is shown for comparison. Energetic protons are indeed confined to some extent in the center of the plasma up to 80 keV, but considerable energy is coupled to the electrons (see below). Significant deuteron heating is observed and there is no production of an observable energetic deuteron tail.

$T_d(0)$ versus time at $P_{rf} \approx 350$ kW is shown in Fig. 8. $T_d(0)$ is approximately doubled over the ohmic heating value. $T_d(0)$ versus $P/\bar{n}_e$ is plotted in Fig. 9 and is found to be approximately linear.

Charge exchange, Doppler broadening of impurity radiation, and neutron measurements are combined to give the T_d profile of Fig. 10 for $P_{rf} \approx 350$ kW. The heating profile is broad and, based on the ohmic heating ion energy confinement time, indicates that ~40-50% of the rf power is coupled from the protons to the deuterons.

The neutron production accompanying the deuteron heating is shown in Fig. 11 f_n increases by a factor of ~50 to a level of ~2 × 10^{10} n/sec. Whereas the final temperature deduced from the neutrons is in reasonable agreement with other measurements, the initial temperature is ~100 eV higher. This probably results from the change in the T_d profile (not taken into account) and possibly to the assumption that $Z = 1$.

There are density and soft x-ray intensity increases with the application of the rf power as shown in Fig. 12. The density increases at 90 and 200 kW are larger than observed previously (Hwang, 1979) for similar discharge conditions, suggesting that the wall and limiter conditioning is playing a role. Δn_e versus P suggests a saturation at higher power. However, ΔI_x is apparently linear with P. With $\bar{n}_e$ at the end of the rf pulse essentially constant, the increase of I_x must in part be due to an observed increase in T_e and in part due to the influx of impurities – notably $\Delta I_i/I_i \sim$ 3-4 increases in Fe and Ti are estimated from impurity radiation measurements.

The escape of energetic protons (Fig. 6) is undoubtedly contributing to the influx of impurities into the plasma. However, as indicated by the soft x-ray measurements (Fig. 12), the application of rf power pushes the plasma into the strong sawtooth regime. Hence, the particle transport could be changing as well, favoring an enhanced influx of particles from the surface of the plasma, including deuterium, hydrogen, and impurities. The change of deuterium influx (density buildup) for the transition to the sawtooth regime for ohmic heating alone is dramatic (Hosea, 1979a).

It should be noted that the sawteeth can also be observed on the coil loading (Fig. 5). This indicates a dependence of the radiation resistance on the central density profile.

5. INITIAL HEATING RESULTS FOR THE D-^{3}he REGIME

As shown in Fig. 2, the dispersion characteristics for D-^{3}he are similar to those for D - h with the exception that the second harmonic resonance layer for d is no longer degenerate with the ^{3}He fundamental resonance layer. Therefore, we may employ the 24.6 MHz system to heat the deuterons via a helium-3 minority. This permits operation at higher B and I_p with improved energetic ion confinement. In addition, charge exchange losses should be negligible and better ion-ion coupling should ensue.

Initial D-^{3}he results have been obtained for discharge conditions similar to those for the D-h case of Section 4, except that B = 24.6 kG, $\eta_{3he} \sim$ 5-10%, and plasma currents up to ~500 kA have been used. The deuteron heating obtained at $P_{rf} \simeq 150$ kW and $\bar{n}_e \simeq 2.1 \times 10^{13}$ cm^{-3} is shown in Fig. 13. Similar heating has been observed for the protons as well, and no tails have been produced for either the deuterons or the protons. Again, a broad profile of heating has been observed. The deuterium heating efficiency is approximately twice that found for the 350 kW - 2 × 10^{13} cm^{-3} case in D-h. This is clearly illustrated in Fig. 14 where $\Delta T_d(0)$ is plotted versus $P_{rf}/\bar{n}_e$ for ^{3}He and H minorities (including the results of previous experiments for the latter) (Hosea, 1979; Hwang, 1979).

The T_d level reached with $P_{rf} \simeq 150$ kW as deduced from the neutron emission is plotted as a function of I_p in Fig. 15. This plot indicates that good minority ion confinement is achieved above ~300 kA. However, the density increase during the rf is comparable to that for the 350 kW D-h case as is the soft x-ray sawtooth behavior, even at the higher currents. Again, this suggests that a change of state may be occurring for the particle transport since the ^{3}He energy distribution should have been considerably less energetic than that obtained for the protons.

6. DISCUSSION

For a ~100 ms duration for the rf pulse, the deuterium heating approaches saturation to within ≲10%, as evidenced for longer pulses, indicating a heating time constant

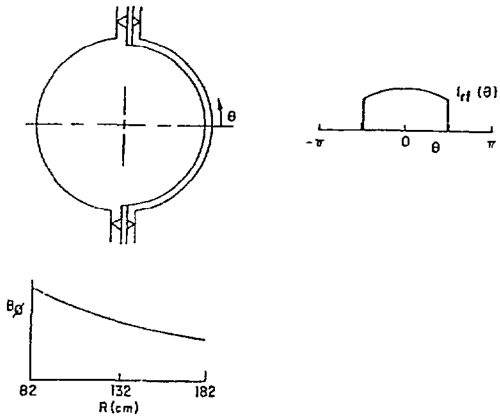


Fig. 4. Schematic representation of coil geometry with the rf current profile. (PPPL 796011)

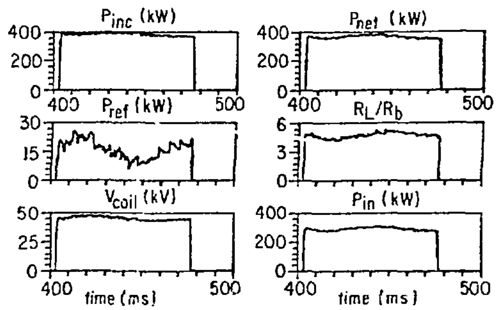


Fig. 5. Analog loading measurements for a single 1/2-turn coil. $P_{net} \approx 400$ kW, $P_{wave} \approx 300$ kW. (PPPL 796014)

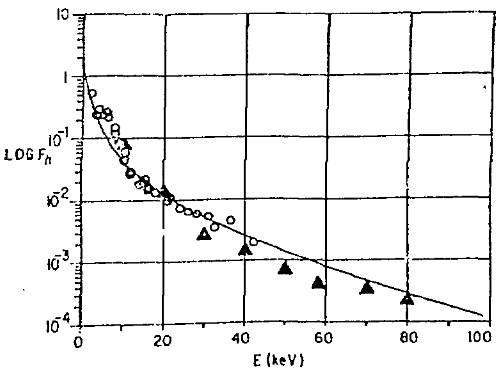


Fig. 6. Hydrogen charge exchange spectrum on axis with $P_{rf} \approx 350$ kW. o is the perpendicular cx analyzer; Δ is the fast ion diagnostic. (PPPL 796016)

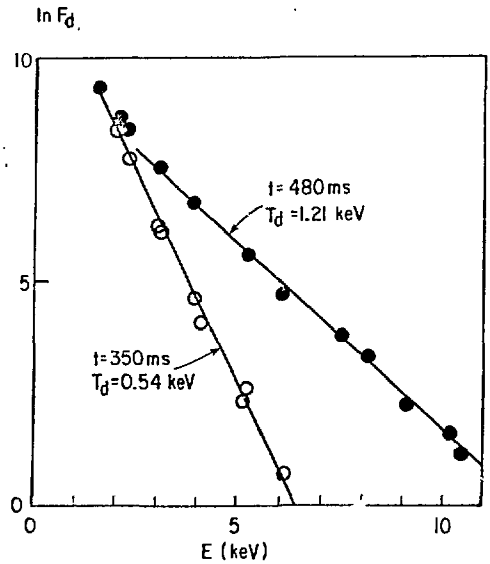


Fig. 7. Deuterium charge exchange spectrum for the case shown in Fig. 6. (PPPL 796017)

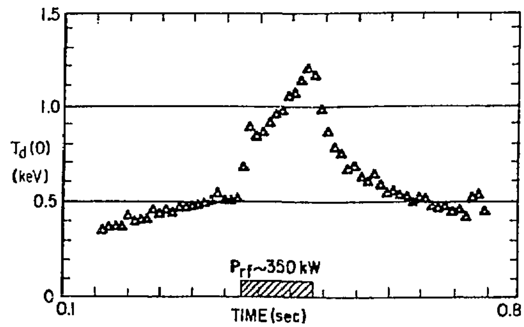


Fig. 8. Time evolution of the central deuteron temperature for P_{rf} ~ 350 kW. (PPPL 796020)

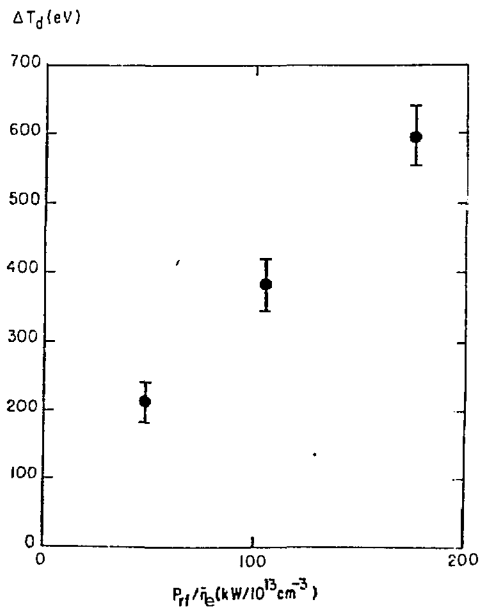


Fig. 9. Deuteron temperature increase as a function of normalized power. (PPPL 796012)

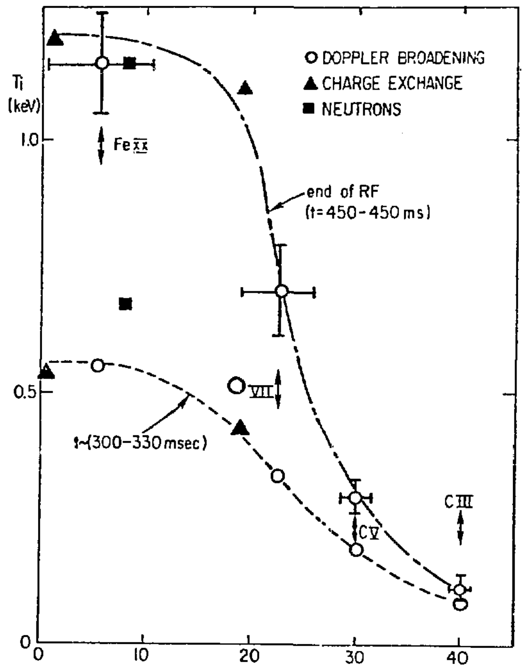


Fig. 10. Radial ion temperature profile for P_{rf} ~ 350 kW via charge exchange, neutrons, and spectroscopic measurements. (PPPL 796013)

τ_{rf} of ~40 ms on the average. This τ_{rf} is expected to be shorter than the energy confinement time τ_{Ei}, as defined for the ohmic heating discharge prior to heating with rf power since the ohmic heating power transfer to the ions decreases as T_d increases: $\langle P_{OH} \rangle \propto (1 - T_d/T_e)$. A particularly simple illustration of this effect is obtained when density, T_e, and $\langle P_{rf} \rangle$ are assumed constant:

$$T_d = T_{do}\left[1 + \frac{\langle P_{rf}\rangle}{K}\left(1 - e^{-t/\tau_{rf}}\right)\right] \qquad (5)$$

where T_{do} is the starting T_d, $\langle P_{OH} \rangle = K(1 - T_d/T_e)$, and

$$\tau_{rf} = \tau_{Ei}\left(1 - \frac{T_{do}}{T_e}\right) \qquad (6)$$

The observed values of τ_{rf} are then consistent with the longer τ_{Ei} (care must be taken to include changes in n_e and T_e for specific cases).

The heating results obtained in the d-h two-ion regime are comparable with those obtained under the same discharge conditions with counter beam injection. Ion heating efficiency, density and I_x increases, and impurity influxes track similarly. For both cases, energetic ions are produced which are more subject to banana orbit losses than for co-beam injection (Eubank and PLT Group, 1978).

For the D-^{3}he regime, the heating efficiency is approximately doubled. This indicates that higher ohmic heating current operation in the D-h regime, with higher densities to reduce charge exchange losses and with better control of the energetic proton distribution, should result in higher ion heating efficiency as well.

The net power delivered to a single 1/2 turn coil on PLT has been sustained at $P_{NET} \approx 500$ kW for durations exceeding 100 ms. Two of these coils coupled together should provide wave powers in excess of 1 MW, approaching 2 MW to the extent that wave interference between the coils occurs. This will permit scaling of the heating to higher powers with the additional advantage of some antenna $k_\parallel$ selection to enhance the rf power deposition in the core of the plasma. Based on the present results, the prognosis for the feasibility of achieving efficient ICRF heating in the two-ion regime at large powers on PLT is quite optimistic. As the power is increased, the density will be increased as well so that greater control over the density during the heating should be possible with feedback programming of the gas injection. Also, the frequency of the rf system will be increased to provide for higher field, higher plasma current D-h operation to ensure adequate confinement of the minority ions.

The direct minority damping case scales favorably to the large, hot, dense plasmas of the reactor, utilizing a number of minority species - D, He, H, etc. in tritium, for example. For the reactor, single pass absorption through the resonance layer should be strong, causing this minority damping case to be essentially equivalent to the black-body ECRH case. Control over the power deposition pattern must then be designed into the antenna.

In principle, many ICRF regimes may prove to be of potential use for heating the reactor plasma. If the second harmonic regime proves to be satisfactory, this regime (or a higher harmonic regime which has similar dispersion characteristics) may be preferred for heating the reactor plasma since higher frequency operation may facilitate the design of a suitable antenna structure. Also, ICRF heating may prove useful for purposes other than bulk heating in a reactor, e.g., preferential

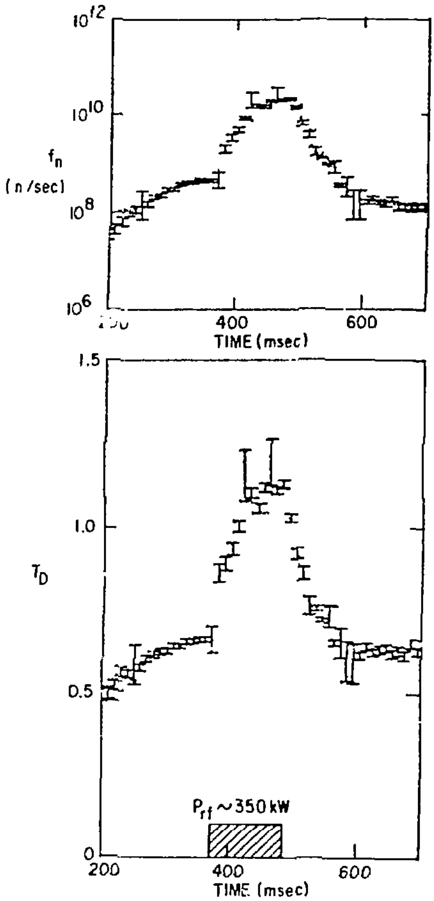


Fig. 11. Neutron flux and corresponding deduced ion temperature during rf pulse. (PPPL 796023)

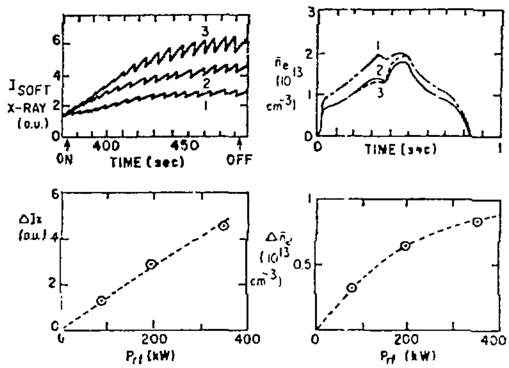


Fig. 12. (a) Soft x-ray measurements during rf pulse and increase in level with P_{rf}.
(b) Time evolution of the density during the rf heating and $\Delta\bar{n}_e$ as a function of the applied rf power. (PPPL 796008)

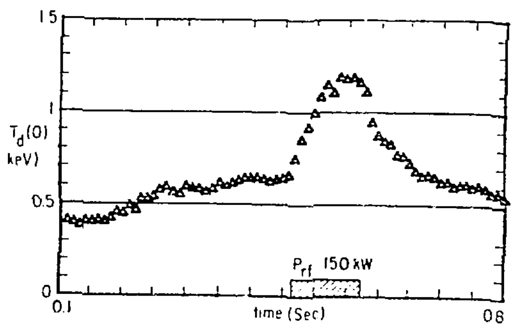


Fig. 13. Deuteron temperature during the rf pulse for the D-^{3}he case with $P_{rf} \sim 150$ kW, $\bar{n}_e \sim 2.1 \times 10^{13}$ cm^{-3}. (PPPL 796010)

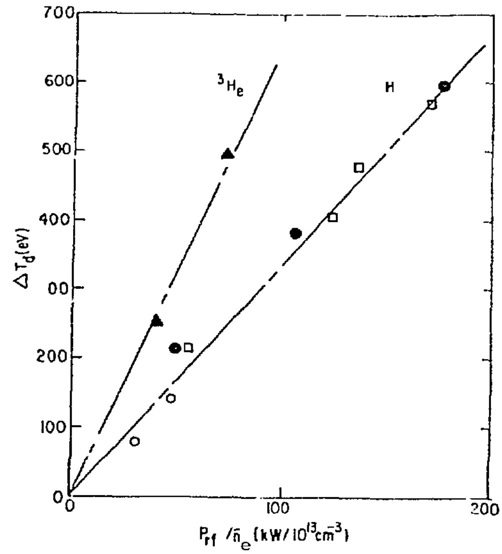


Fig. 14. Deuteron temperature increase on axis for the proton and ^3He minority cases versus the normalized rf wave power. (PPPL 796021)

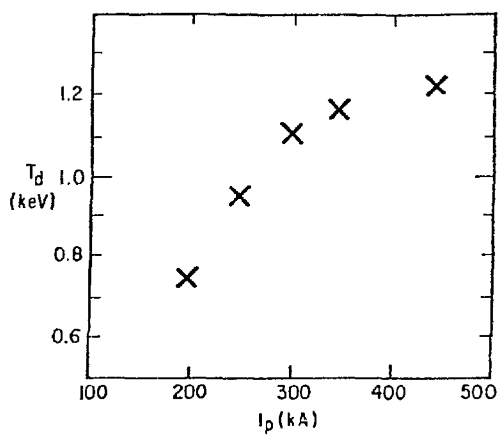


Fig. 15. Peak deuteron temperature as a function of the plasma current for P_{rf} ~ 150 kW. (PPPL 796018)

heating of alpha particles in the surface of the plasma might force them out of the plasma along banana orbits and help reduce their recycling into the plasma core.

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