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Attachment III

RF EXPERIMENTS ON PLT

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ABSTRACT

A variety of rf experiments are being conducted on PLT in order to explore rf techniques which could improve tokamak performance parameters. Of special importance are the studies of ion Bernstein wave (IBW) heating, lower hybrid MHD stabilization and electron heating, down-shifted electron cyclotron heating, and fast wave current drive. Ion Bernstein wave heating results at modest power indicate that the particle confinement time could be enhanced relative to that for fast wave heating in the ion cyclotron range of frequencies (ICRF) and neutral beam heating. At these power levels a conclusive determination of energy confinement scaling with power cannot yet be given. Central sawtooth and m=1 MHD stabilization is being obtained with centrally peaked lower hybrid (LH) current drive and the central electron temperature is peaking to values (~5 keV) well outside the bounds of "profile consistency". In this case the electron energy confinement is apparently increased relative to the ohmic value. The production of relativistic electrons via heating at the down-shifted electron cyclotron (EC) frequency is found to be consistent with theoretical predictions and lends support to the use of this method for heating in relatively high magnetic field devices. Finally, the study of fast wave current drive will begin in the near future to determine the efficacy of this method relative to that for the slow wave case and to determine if high density operation is feasible.

INTRODUCTION

Prior to this last year, the rf program on PLT was directed toward the evaluation of the physics feasibility of employing fast wave ICRF heating and slow wave LH current drive to heat and to sustain the current, respectively, in a fusion reactor. This program was successful in demonstrating the heating efficiencies for both the minority ion (Hosea, 1980; Hosea, 1982; Hwang, 1982) and second harmonic ion (Hwang, 1983; Wilson, 1985) resonance regimes, and the current drive efficiency for the slow wave LH regime (Bernabei, 1982; Motley, 1984) for densities up to the mid 10^{13} cm^{-3} range in PLT. During the past year, the emphasis of the PLT program has shifted to the study of other rf techniques which could affect the optimization of these previously studied schemes and/or which could lead to improved heating and current drive methods for enhancing the prospects of realizing a tokamak reactor concept. Specifically, studies of IBW heating, slow wave LH MHD stabilization and heating, and down-shifted EC heating of energetic electrons are ongoing, and fast wave current drive experiments are to begin in the near future. In this paper, we present the status of these studies and the prospects of achieving definitive results to support extrapolations to the reactor regime in the one-half year of operation remaining on PLT.

ION BERNSTEIN WAVE HEATING

The heating efficiency for fast wave ICRF heating as expressed in terms of the energy confinement time is found to drop to a lower, essentially constant level as P_{rf} is increased well above the ohmic power level P_{OH} in PLT (Mazzucato, 1984; Wilson, 1985). Similar results have been found for the second harmonic regime in the divertor discharges of ASDEX when P_{rf} is increased in combination with neutral beam power P_{NB} (Steinmetz, 1986) and in JET where extrapolations to higher power operation indicate a lower confinement level should be reached (Jacquinot, 1986). Thus, although the confinement does not continue to decrease with power indefinitely as has been suggested for the so-called L-mode of neutral beam heating (Kaye, 1985), the lower level of confinement observed is disconcerting with regard to efficiently heating a reactor plasma to ignition. Attempts are being made on ASDEX to push the confinement to a higher level with intense heating of the divertor plasma. However, even this so-called H-mode of operation may be too degraded for reactor level operation.

In order to optimize the fast wave ICRF heating method we are concentrating on the ability to deposit the rf power selectively in the core of the plasma where local energy confinement may be substantially improved relative to the global energy confinement, especially for large plasmas fueled with pellet injection as suggested for TFTR. Focalization of the rf waves with finite poloidal extent antennas and selection of proper $n_\parallel$ values to avoid surface damping in the electrons are important steps for achieving core heating. A six coil antenna system has been installed on PLT to study $n_\parallel$ effects. Another important consideration is the effect on power deposition of the generation of Bernstein waves at the antenna and at mode conversion surfaces within the plasma (Skiff, 1985). This comprises one of our reasons for studying the physics of ion Bernstein wave heating on PLT. Obviously, the other primary reasons is to determine the feasibility of employing IBW heating as an alternative to fast wave heating in the ICRF regime to more efficiently heat the reactor plasma to ignition (Ono, 1980; Puri, 1979).

Considerable progress has been made over the past year in documenting the effects of Bernstein wave generation at ever increasing power levels. With the installation of a new antenna in January 1986, we have achieved a 500 kW level of power delivered to the antenna. The efficient ion heating that had been observed at lower powers (Hosea, 1985; Wilson, 1985) continues to be obtained up to the ~ 430 kW level of power which has now been transferred to the ion Bernstein waves. In order to make direct comparison with fast wave experiments much of the IBW experiments have been performed in the ^{3}He, and H minority regime.

Figure 1 shows the neutron flux approaching 10^{11} sec^{-1} for the highest power case conducted in the ^{3}He minority regime at a density of 3×10^{13} cm^{-3}. For this case $\Delta\bar{n}_e T_i(o)/P_{rf} = 5$

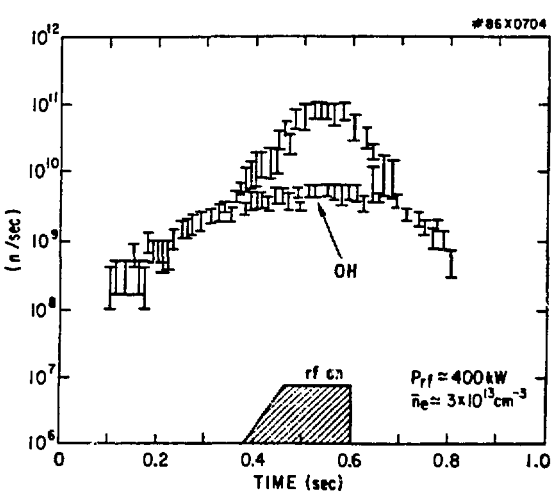

Fig. 1. Total neutron flux vs. time for P_{rf} = 430 kW and P_{rf} = 0. $\bar{n}_e = 3 \times 10^{13} cm^{-3}$, ^{3}He minority IBW heating.

eV/kW similar to the value obtained at this power level for the fast wave ^{3}He minority case during initial experiments on PLT (Hosea, 1980). Significant central electron energy increase $\Delta(n_e T_e(o))$ is obtained as well for this regime as shown in Fig. 2 for a power level of 330 kW. Ion temperature radial profiles for the ions in this case reveal the ion temperature increases over the cross section of the plasma. For the electrons, the temperature profile is essentially maintained constant in the face of a general increase of the plasma density ($\Delta\bar{n}_e = 8 \times 10^{12}$ cm^{-3}) over the plasma cross section. For fast wave heating a much smaller density increase is observed for this power level.

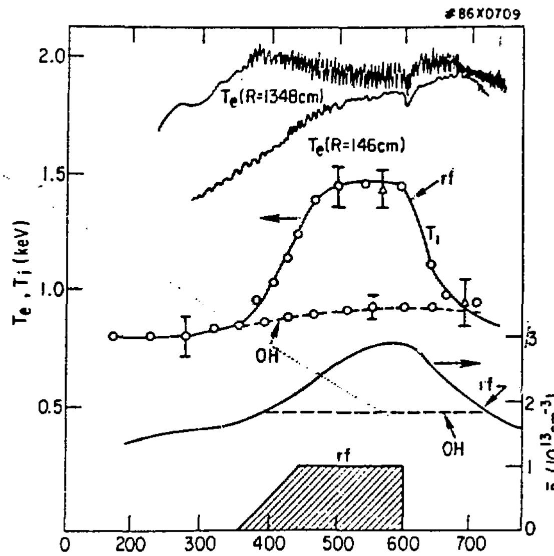

Fig. 2. Time evolutions of electron and ion temperature and electron density for P_{rf} = 330 kW.

The global energy confinement time as a function of $\bar{n}_e$ with P_{rf} as a parameter is plotted in Fig. 3. Although τ_E is not exactly linear in density it is consistent with the ohmic value when measured at the same final density. This is an encouraging result, but it is still not possible at this power level, ($P_{rf} \lesssim 0.5\ P_{OH}$) within the accuracy of the data, to determine whether it will remain at the ohmic level as P_{rf} is pushed to the megawatt level. Note that fast wave heating for essentially the same conditions gives a comparable τ_E in Fig. 3 and that only a few milliseconds separates ohmic and the reduced confinement mode at this power level (Kaye, 1985) which is within the experimental uncertainties.

There are reasons to believe that confinement, both energy and particle, may be improved in the IBW heating case relative to the fast wave ICRF heating case. First, the energetic ion production in the IBW case should be minimal (Ono, 1984) and to the extent that such tails contribute to energy loss at higher rf power via some process such as loss of energetic ions or alteration of the plasma equilibrium potential, (Hosea, 1984) the energy confinement for IBW heating should be improved. That the IBW tail production is small is illustrated for the H-minority regime in Fig. 4. Note that the small remaining tail in the IBW regime could be due to a small component (~10%) of fast wave being generated by the IBW antenna. This amount of polarization contamination is not inconsistent with rf probe measurements of surface fields and has been predicted to be unavoidable (Skiff, 1985).

The evidence for improved particle confinement is the strong increase in density (Fig. 2) which is not accompanied by an enhancement of recycling in the impurities or deuterium according to spectroscopic measurements. In fact, low energy neutral flux measurements

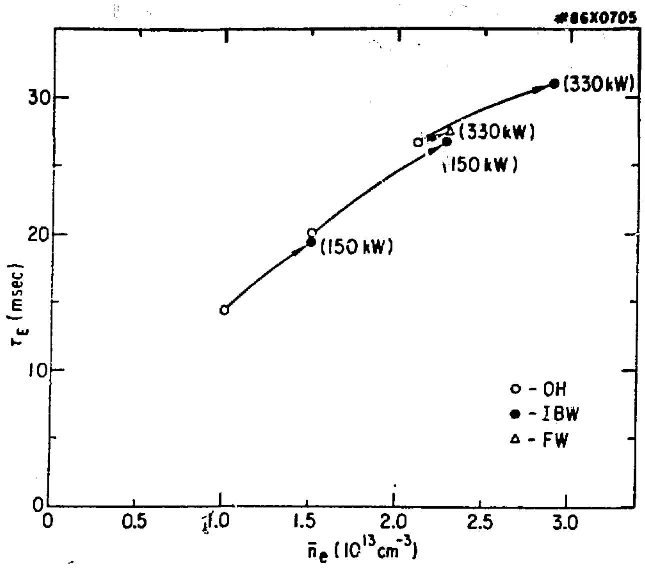

Fig. 3. Global energy confinement time vs density for several different powers. o-ohmic, •-IBW, Δ-fast wave.

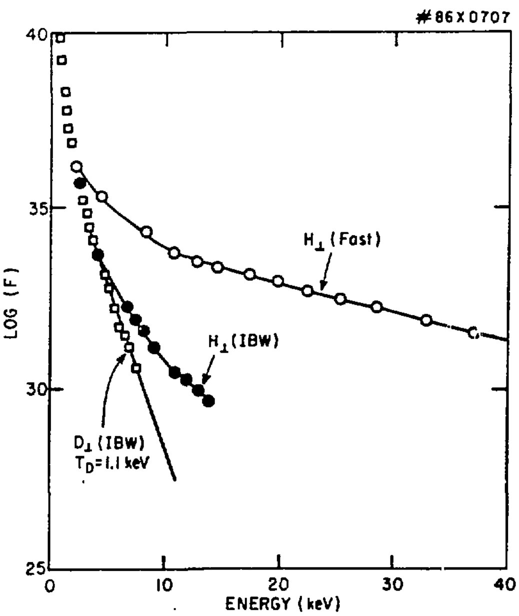

Fig. 4. Spectrum of charge exchange neutrals for H minority heating with IBW and fast wave. P_{rf} = 160 kW, $\bar{n}_e = 1.5 \times 10^{13}$.

indicate an actual reduction in recycling at moderate powers as indicated in Fig. 5 for the ^{3}He minority case. TVTS density profile measurements show that the increase is centrally peaked.

The strong enhancement of density with IBW heating with power is shown in Fig. 6 and is found to saturate for powers above ~300 kW at $\Delta\bar{n}_e \sim 9 \times 10^{12}$ cm^{-3}. The density rise for fast waves is $\sim\Delta\bar{n}_e \sim 2 \times 10^{12}$ cm^{-3} at 430 kW. This would suggest that a candidate for the cause

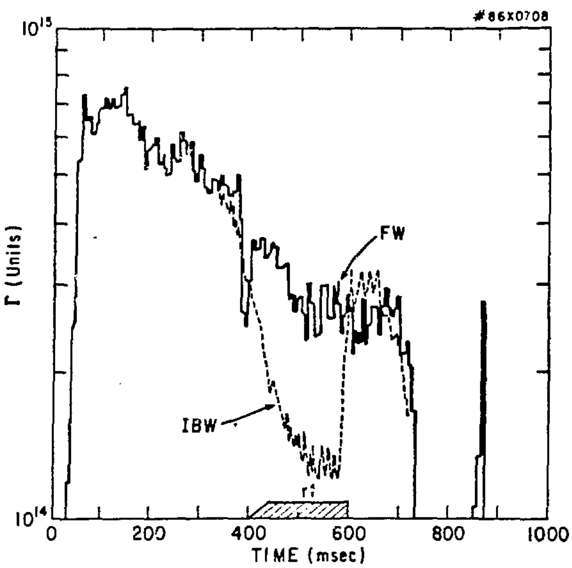

Fig. 5. Low energy (<1 keV) neutral flux for IBW and fast wave heating.

of the density increase during fast wave ICRF heating is the excitation of Bernstein waves at the antenna. The saturation of the density increase for the fast wave occurs at ~2 MW (Mazzacuto 1984) which would correspond to ~200 kW (10%) generation of Bernstein waves for the fast wave antennas on PLT (Skiff, 1985).

LOWER HYBRID CURRENT DRIVE STABILIZATION AND HEATING

The PLT lower hybrid current drive experiments are now directed toward suppression of sawtooth and m=1 oscillations in the core of the plasma and concurrently toward heating the core to unprecedented temperatures in the absence of sawteeth oscillations (Chu, 1986; Stevens, 1985). Recently a sixteen waveguide grill has been installed to better define the launched spectrum and possibly better define the phase space interaction region of the lower hybrid waves and, thereby possibly improve the current drive efficiency and stability control. The $n_\parallel$ spectra launched by the 16-waveguide coupler with a progressive phasing between adjacent waveguides $\Delta\phi = -75°$ is compared with the one launched by the 8-waveguide coupler with $\Delta\phi = -90°$ in Fig. 7.

Upon application of sufficient LH power in the central current drive mode ($\Delta\phi \sim -60°$ to $-90°$) the sawtooth oscillations are suppressed as indicated in the plot of electron cyclotron emission (ECE) in Fig. 8. The sawtooth oscillations in this figure can be attributed to the thermal electron population, as indicated by soft X-ray and Thomson scattering measurements, whereas the large background increase is due to the production of suprathermals upon application of the LH power. As the RF power is increased, at first the sawtooth oscillations increase in amplitude then decrease until disappearance. With further power increases the same phenomenology happens to the m=1 oscillation, which from being just a precursor to the sawtooth crash evolves into a non-growing continuous oscillation and eventually disappears at power levels of the order of 500 kW (Fig. 9).

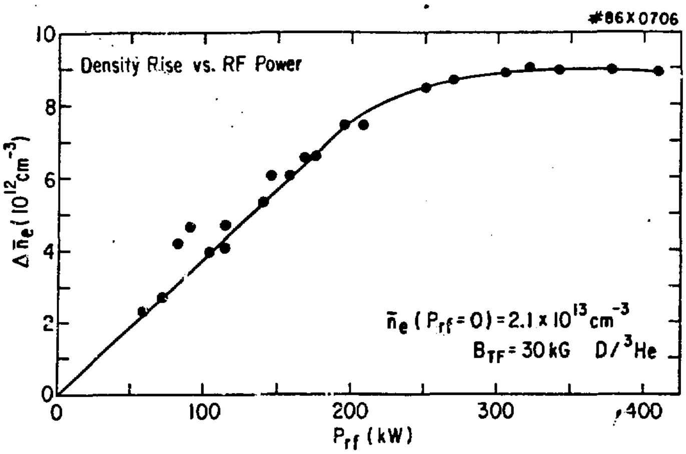

Fig. 6. Density rise vs. power for IBW heating in ^3He minority mode.

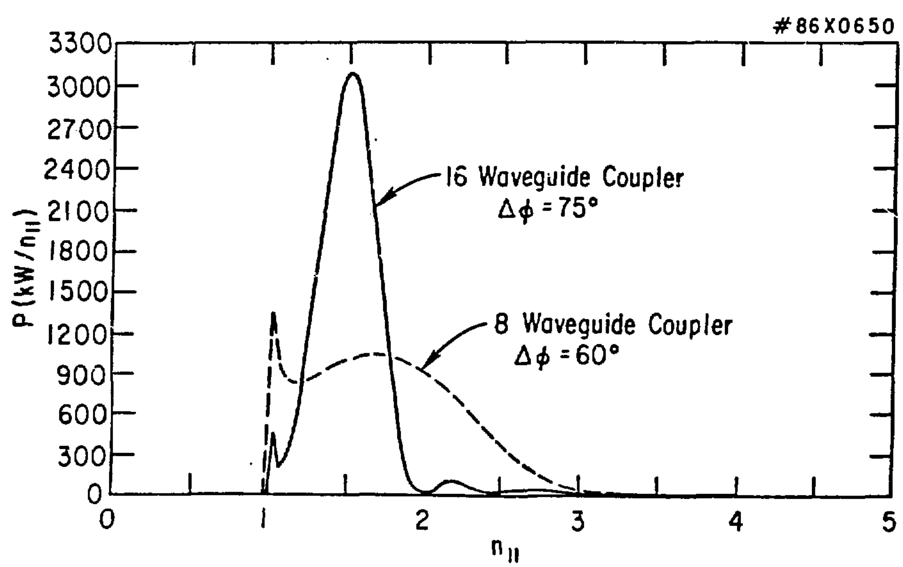

Fig. 7. Power spectrum for the new 16-waveguide coupler and the old 8-waveguide coupler for optimum current drive.

As the sawtooth nears extinction, the average central electron temperature separates strongly from the ohmic level as indicated in Fig. 9 for an experimental run using the 8-waveguide arrays. This effect has become very dramatic with the improvement of the Thomson Scattering to measure high temperatures more accurately and as the level of P_{rf} has been

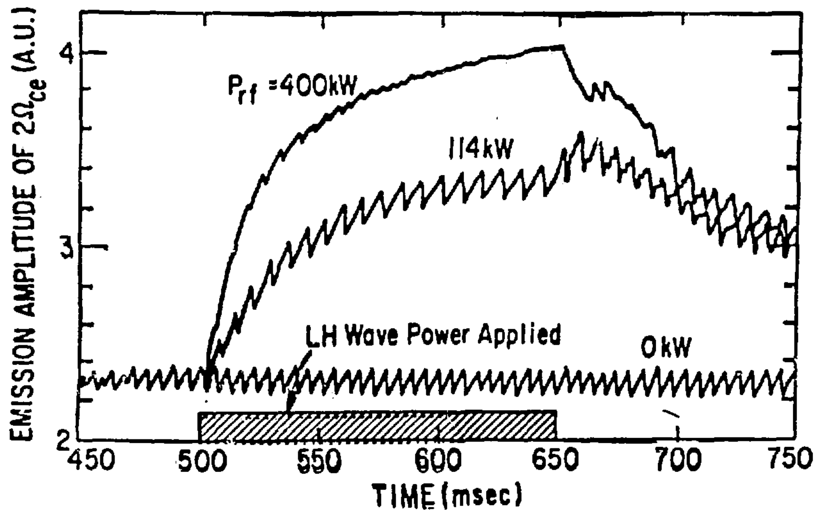

Fig. 8. Electron cyclotron emission vs. time for P_{rf} = 0, 114, 400 kW of LHCD.

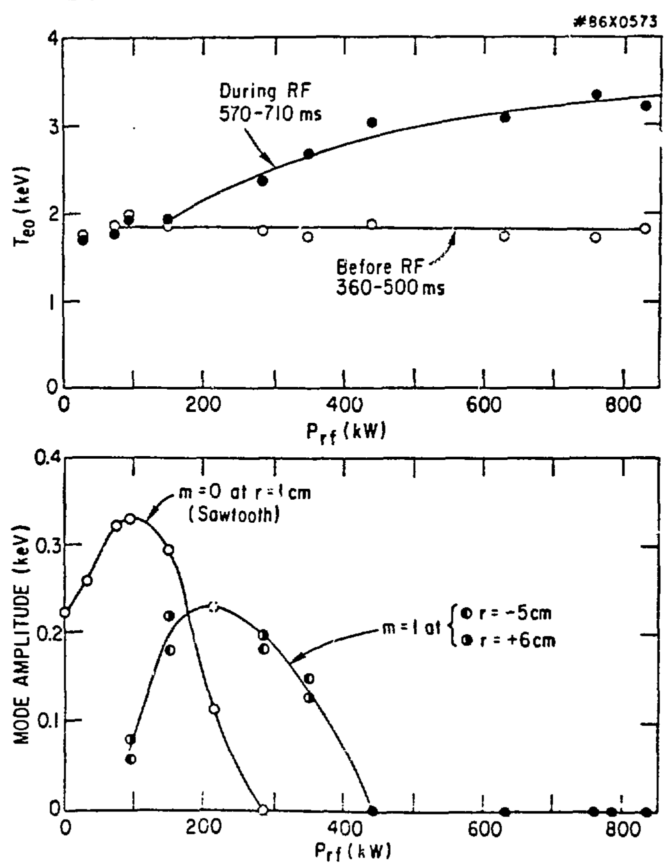

Fig. 9. a) Central electron temperature vs. power during LHCD.
b) Amplitude of MHD modes vs. power during LHCD.

increased. Figure 10 gives a recent result using the 8 and 16-waveguide arrays. It is thought that this strong central temperature increase is not accompanied by a concurrent construction of the current channel, but that the current driven in the energetic electrons is maintaining stable current "profile consistency" with a q profile which is similar to that in the ohmic case. This is in contrast to experiments on ASDEX where current broadening is measured (McCormick 1985). The m=1 MHD characteristics prior to their demise support this interpretation. If the thermal electron distribution were to be indicative of the current profile the central q for Fig. 10 would be 0.25 at P_{rf} = 660 kW. Inductance measurements in fact indicate that at these high powers well in excess of the amount required to stabilize sawteeth, the current profile if anything may broaden. Further longer pulse experiments are required to determine the steady state current distributions.

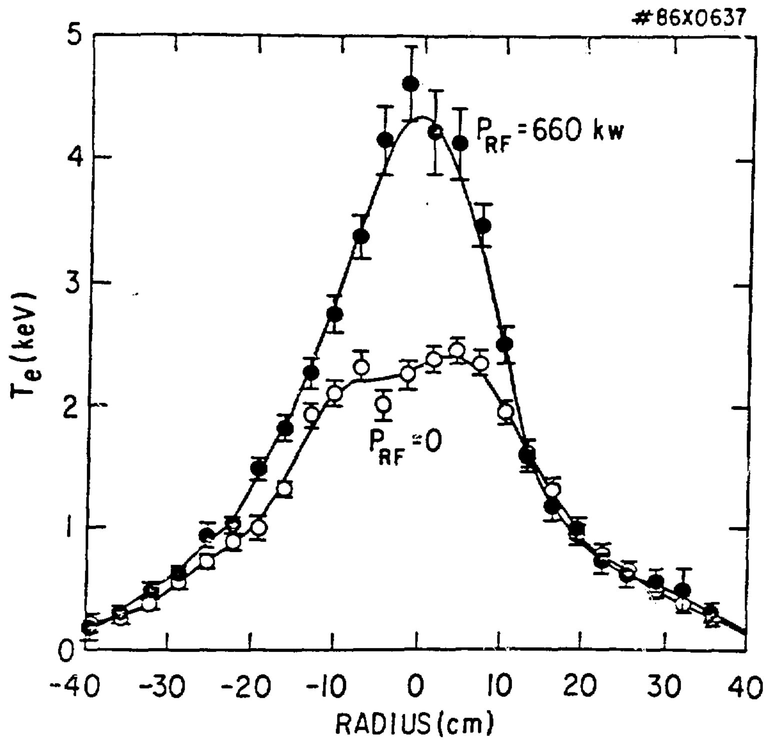

Fig. 10. Electron temperature profile from TVTS for P_{rf} = 0, 660 kW.

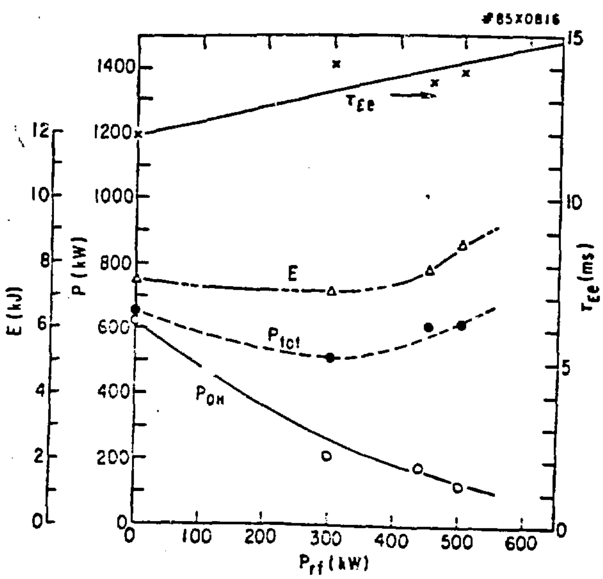

Fig. 11. Electron stored energy, power input and electron confinement timer vs. rf power.

within the range of LH power applied at present the global electron energy confinement time shows no degradation and possibly some improvement. This result is illustrated in Fig. 11 over the range of power shown. The global τ_{Ec} for the thermal electrons alone is found to increase somewhat with power even without including the energy stored in the energetic electrons. Most of the additional stored thermal energy is at the center of the discharge (Fig. 10) which indicates that the confinement is improved in the absence of MHD activity. The density fluctuations measured with microwave scattering at r = 10 cm show a monotonic decrease in amplitude with rf power (factor of 2 decrease at P_{LH} ~400 kW as shown in Fig. 12) whereas those at 20 cm do not change. These results suggest that if these fluctuations are associated with enhanced transport then the central electron heating may be accompanied with improved central confinement due to their suppression as well.

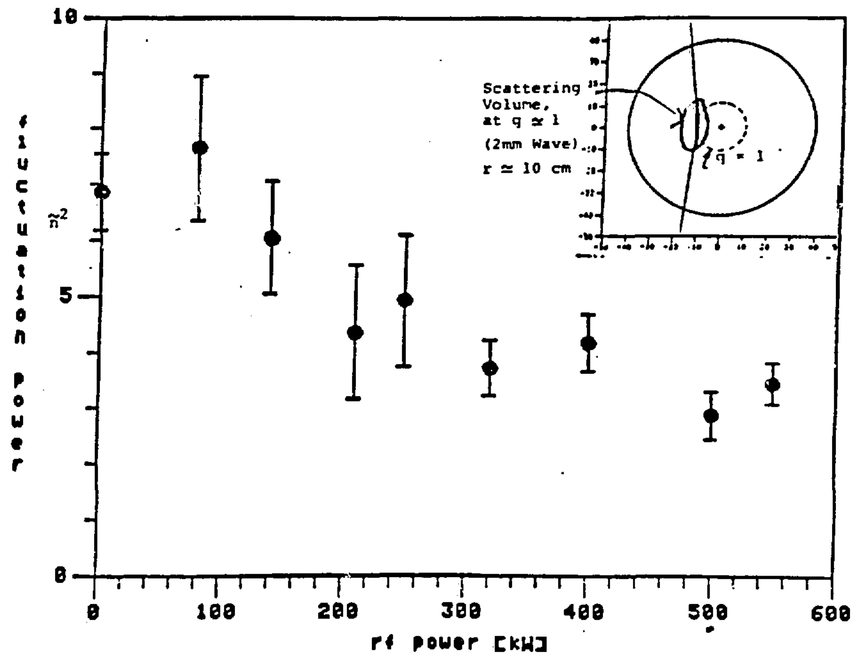

Fig. 12. Magnitude of density fluctuation with wave vector $k = 7\ cm^{-1}$ at r = 10 cm vs. rf power.

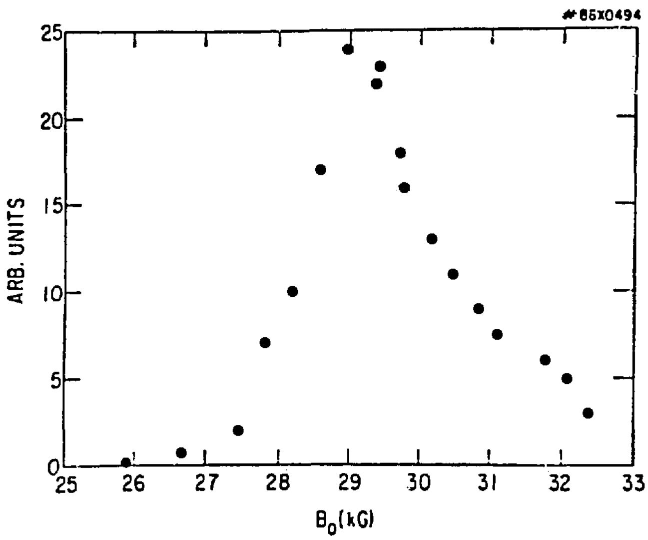

Fig. 13. Amplitude of the electron cyclotron emission as a function of toroidal field during electron cyclotron heating.

ECRH

The damping of electron cyclotron waves at down-shifted frequencies has been investigated (Mazzucato, 1986). One advantage of down-shifted absorption is the ability to use lower frequency sources at a given magnetic field. An additional advantage is that the absorption takes place on the tail electrons allowing an influence on the plasma current. A 60 GHz extraordinary wave was launched vertically downward at an angle of 30° to the toroidal field over a range of toroidal fields from 26 to 33 kG. Experiments were performed in plasmas with line average density $\bar{n}_e = 1.2 \times 10^{13} cm^{-3}$, central electron temperatures $T_{eo} = 1.8-2.0$ keV and plasma current $I_p = 500$ kA utilizing rf powers up to 50 kW. In Fig. 13 the amplitude of the electron cyclotron emission (ECE) with a frequency corresponding to a major radius R=200 cm, which is outside the PLT vacuum vessel, is shown versus magnetic field. These photons must be emitted by energetic electrons. Measurements of the hard (30-700 keV) x-rays indicate that the electrons are located at the center of the PLT discharge. From this and the frequency of emission it can be concluded that these electrons must have energies in the range of 200-300 keV. The peak in emission at 29 kG indicates that these energetic electrons are produced most efficiently for a magnetic field were the wave frequency is much smaller than the electron cyclotron frequency. This data supports a scenario where the absorption of the electron cyclotron waves leads to a perpendicular acceleration of the electrons making them less collisional and allowing increased acceleration by the DC electric field. At low values of toroidal field this is prevented by the high collisionality of the resonant electrons. On the other hand, at high values of toroidal field, the energy of the resonant electrons is too large for the ohmic tail to yield significant wave absorption.

FUTURE WORK

In the remaining months of PLT operation definitive results on IBW at powers up to 1 MW are expected to be obtained. At this power level the question of confinement scaling with power should be answerable. In addition other modes of IBW heating such as three halves and third harmonic deuterium will be further investigated. Combined operation of LHCD with fast wave ICRF will be explored to exploit the sawtooth free, hot electron regime with ion heating. In addition long-pulse LHCD experiments will be performed to determine the steady state current profile and MHD response. Fast wave ICRF experiments include the use of six phased antennas for better k selection and a prototype waveguide. Fast wave current drive at lower hybrid frequencies is also being explored. It is hoped that these results will be encouraging enough to apply these concepts to future experiments.

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