

IBW and Fast Wave Launching and Damping on TFTR

J.C. Hosea, R. Bell, K. Hill, B. LeBlanc, R. Majeski,
 R. Nazikian, M. Ono, C.K. Phillips, J.H. Rogers, G. Schilling,
 J.R. Wilson, D.A. D'Ippolito*, J.R. Myra*, C.E. Bush†,
 G.R. Hanson†

Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543

*Lodestar Research Corporation, Boulder, CO 80301

†Oak Ridge National Laboratory, Oak Ridge, TN 37831-8071

Abstract. Antennas to provide direct IBW excitation and to improve the launched spectrum and power handling for mode converted (MC) IBW excitation have been installed on TFTR to support studies of transport barrier formation inside the TFTR plasma. Initial IBW launching/heating experiments have been performed at $f_{RF} = 76$ MHz and 50.6 MHz for several antenna and plasma positions, several magnetic fields (D, T, H, ^3He resonances), and with and without neutral beam injection. Although the measured surface density profiles in front of the antenna should theoretically support IBW launching to the plasma core via EPW excitation, loading resistance parameter dependence and heating results suggest that the wave energy is being deposited mostly in the plasma periphery. The potential roles of surface fast wave and near field excitation/damping on the IBW performance are discussed. Also MC IBW damping of the fast wave has been significantly improved through the removal of lithium 7 from the plasma.

INTRODUCTION

The motivation for studying direct launch ion Bernstein wave (IBW) heating and mode conversion IBW (MC IBW) heating and current drive on TFTR has been to explore these possibilities for providing pressure and current profile control in advanced tokamak D-T regimes. In particular, IBW poloidal sheared velocity flow generation has been proposed as a mechanism for producing an internal transport barrier (1) of the core H-mode (CH) type observed with direct launch IBW heating on PBX-M (2). Successful IBW implementation on TFTR should then have permitted control of the initiation and location of the internal transport barrier resulting in the enhanced reverse shear (ERS) (3) regime on TFTR. Theoretical projections of the PBX-M results to TFTR (4) suggest that PRF ≈ 1 -2 MW deposited over a sufficiently small radial extent (~ 10 cm) should produce the desired transport barrier. Additionally, modelling using TFTR reverse shear discharge parameters indicates that IBW barrier formation should produce the desired ERS regime at the moderate prelude neutral beam power levels ($P_{NB} \leq 10$ MW) (5) that preceded the high neutral beam power level required to produce the ERS regime in the absence of IBW barrier formation.

To support direct launch IBW experiments and to improve the spectrum and power launched for mode conversion IBW experiments, three of the RF antennas on TFTR were replaced with one IBW antenna and two four-strap, fast wave antennas. These installations were part of a major outage on TFTR for

antenna and diagnostic installations which was completed in a carefully planned manner to prevent tritium exposure and to minimize radiation exposure to a level of <6.6 person rem. (The tritium outgassing rate in the vacuum vessel was a few curies a day and the radiation level at the vessel was ~ 100 mR/hr.) The configuration of the IBW antenna is indicated in Fig. 1. It contains four poloidally-separated current straps which can be excited in different poloidal phasings and an edge reflectometer which can be used to measure the density profile in front of the antenna screen.

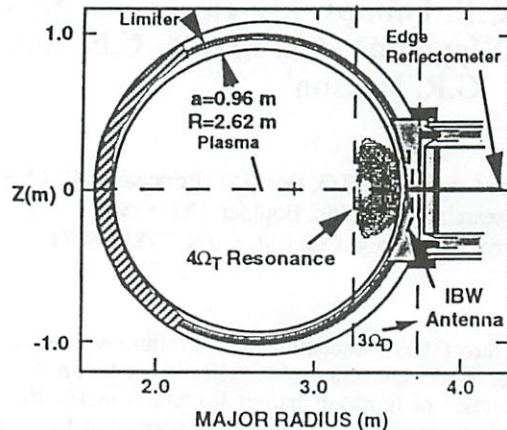


FIGURE 1. Direct launch IBW antenna configuration on TFTR. IBW ray tracing pattern is shown for damping at the $4\Omega_T$ resonance (76 MHz, 4.7 T at $R = 2.6$ m).

on lithium 7 that had plagued earlier experiments(7). Direct launch IBW powers of up to ~ 1.7 MW were delivered to the plasma, but only 20-40% of the RF power was observed to be deposited in the plasma core so that the threshold power for transport barrier formation was not obtained. For the mode conversion IBW heating regime, launched fast wave powers of up to ~ 2 MW were delivered to the plasma with $\sim 90\%$ of the power deposited in the plasma core in the absence of damping on lithium 7. (See Ref. 7 for further discussion of this case).

DIRECT LAUNCH IBW COUPLING/HEATING

The relatively weak core heating results obtained with direct launch IBW over a large range of parameters on TFTR demonstrate that a large fraction of the launched power was deposited in the periphery of the plasma. Apparently, the edge heating cannot be attributed to reflection of the electron plasma wave (EPW) in the edge density gradient which would interfere with coupling to the IBW wave inside the plasma. Edge reflectometer density measurements (Fig 2) show that the density profile in front of the antenna is modified in a manner consistent with the ponderomotive force and should support efficient EPW coupling to the core IBW since the WKB factor $(dk_r/dr/k^2)$ should remain less than 1 in the vicinity of $\omega = \omega_{lh}$ (8). Thus, the edge heating must be due to other mechanisms in the plasma surface possibly including fast wave excitation, near field reactive wave excitation (supporting the antenna image currents), sheath effect (9), and parametric decay instability (PDI) excitation (10).

A preliminary examination of the data obtained on TFTR lends support to surface wave excitation being a major contributor to the edge heating observed. A

RF experiments were conducted over the final three months of TFTR operation and the major goals of this curtailed campaign were 1) to explore parameter space [R_p , R_{ANT} , $n(a)$, $T(a)$, with and without neutral beam heating, antenna phasing and frequency, etc.) to optimize IBW coupling/heating leading to a study of barrier formation if adequate P_{RF} could be deposited at the desired location (6) and 2) to demonstrate that mode conversion IBW barrier formation might be possible in principle in D-T plasma without the wave absorption

drop in antenna loading by approximately a factor of two was measured for a change in antenna poloidal current phasing from 0000 to $00\pi\pi$ (Fig. 3), whereas no significant loading dependence on toroidal field, plasma radius, antenna radius, and plasma parameters was observed. In addition, the core heating efficiency increased by approximately a factor of two for the two for the out-of-phase case (Fig. 4).

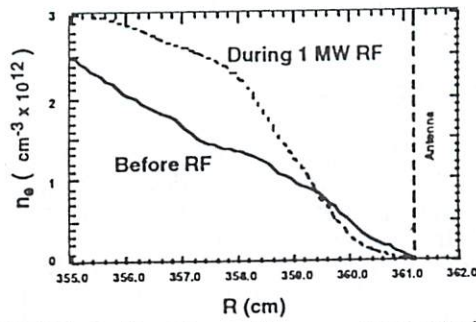


FIGURE 2. Density profile measurements in front of the antenna for the $4\Omega_T$ resonance case at 76 MHz.

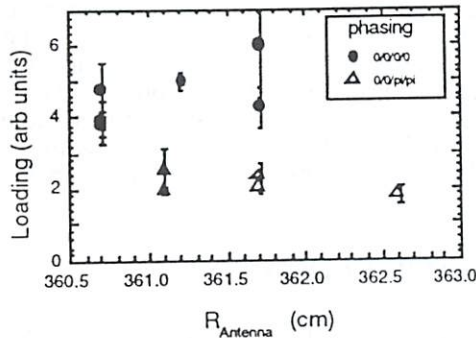


FIGURE 3. Antenna loading versus antenna radius for two poloidal phasings under a variety of conditions: $0/0/0/0$ -ohmic and neutral injection $2.58 \text{ m} \leq R_p \leq 2.61 \text{ m}$, $B_o = 4.7 \text{ T}$, and 3.6 T ; $0/0/\pi/\pi$ -ohmic, $R_p = 2.61 \text{ m}$, $B_o = 2.4 \text{ T}$.

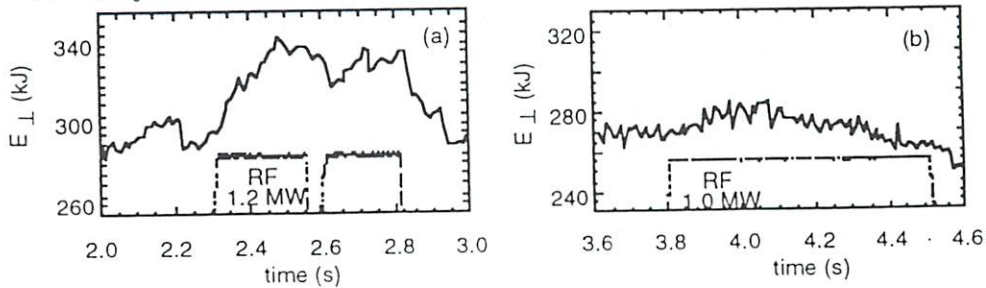


FIGURE 4. Transverse energy measured with diagnostic loops for the $3\Omega_D$ resonance IBW case for (a) 50.65 MHz, $B_o = 2.4 \text{ T}$ with $0/0/\pi/\pi$ phasing and (b) 76 MHz, $B_o = 3.6 \text{ T}$ with $0/0/0/0$ phasing.

These results suggest that the poloidal phase change reduced coupling to surface waves while maintaining coupling to the EPW which continued to drive the IBW. [A similar conclusion applies for out-of-phase coupling to IBW via the electrostatic ion cyclotron wave (ESICW) reported in Ref. 6.]

Out-of-phase drive should reduce collisional and sheath damping of the antenna reactive fields to the extent that cross field currents connect oppositely directed image currents to reduce the magnitude and range of the image currents over the plasma surface. Also, coupling to low m coaxial transmission line modes and surface fast wave modes via E_θ should be reduced leading to less edge power deposition by these modes through damping on ion cyclotron resonances in the plasma periphery, by collisions, and in sheaths.

Weak parametric decay instability (PDI) signals have been observed with probes at the plasma boundary. The signal amplitudes are at or below (≤ -35 db from the pump wave signal) the levels reported for the IBW experiments on DIII-D (11), but vary dramatically pulse-to-pulse and do not appear to be correlated to the core heating efficiency. However, the pump wave signal is found to encircle the plasma and to attenuate slowly as it propagates away from the antenna, consistent with surface wave excitation.

CONCLUSIONS

It remains clear that the major challenge for using IBW heating to create a transport barrier in the interior of the plasma is the development of a wave launcher which can couple sufficient power to the IBW through the plasma periphery. The new reflectometer measurements reported here support the model that the ponderomotive force should provide a density profile amenable to the EPW conduit of power to the core IBW wave and indeed TRANSP modelling (11) shows that up to ~40% of the power was delivered to the plasma core. Substantial power continues to be deposited in the edge of the plasma, but it is encouraging that the amount of power reaching the core of the plasma is found to depend strongly on the poloidal phasing of the antenna current elements. This suggests that surface wave loading is involved and that such loading might be minimized with further antenna development incorporating both poloidal and toroidal phasing or new antenna geometries such as the folded waveguide which could reduce surface wave coupling. With adequate understanding of the launching physics, it may prove possible to develop an antenna which can deliver IBW powers above the threshold required for producing a barrier in reactor grade plasmas.

ACKNOWLEDGMENTS

The authors would like to thank the PPPL engineering and technical staff who made these experiments possible and R.J. Hawryluk for his support. This work is supported by US Department of Energy contract # DE-AC02-76CH03073.

REFERENCES

1. Biglari, H. et al., in Proceedings of the 9th Topical Conference on RF Powers in Plasmas, AIP 244 1992, p. 376.
2. Ono, M. et al., Plasma Physics and Contr. Nuc. Fusion Vol. 1 (IAEA, Seville, 1994) 469.
3. Levinton, F.M. et al., Phys. Rev. Lett. 75, 4417 (1995).
4. LeBlanc, B. et al., Proceedings of the 11th Topical Conf. on RF Power in Plasmas, 1996, AIP 355 pp. 483.
5. LeBlanc, B. et al., Plasma Phys. Contr. Nuc. Fusion 38 1445 (1996).
6. Rogers, J. et al., this conference.
7. Majeski, R. et al., this conference.
8. Ono, M. et al., this conference.
9. Myra, J. et al., this conference.
10. Pinsker, R.I. et al., Nucl. Fus. 33 777 (1993).
11. LeBlanc, B. et al., this conference.