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## Perspectives Gained from ICRF Physics Studies on TFTR

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**Abstract** Highlights from the ICRF program on TFTR are referenced, while recent results on rf-based profile control techniques are discussed in more detail.

### Introduction

The physics of ICRF heating and current drive has been studied on TFTR for over a decade. Following the early low power coupling studies, high power experiments resulted in sawtooth stabilization [a], the first observation of RF-driven excitation of toroidal Alfvén eigenmodes [b], and the discovery of a mode conversion scenario for localized off-axis electron heating [c]. The program culminated with the first studies of high power ICRF heating and profile control in tritium-rich high performance plasmas [d]. A significant part of the concluding experiments centered on the potential of ICRF to drive sheared flows [e] in order to suppress turbulence in the plasma core. Initial measurements taken with a novel poloidal velocity diagnostic [f] suggest that localized sheared poloidal flows can be driven with ion Bernstein waves excited directly [g] or else via mode conversion from a propagating fast magnetosonic wave. In this paper, recent results from TFTR on wave-based profile control techniques will be summarized along with suggestions for future studies elsewhere.

### Profile Control with Mode Conversion Heating and Current Drive

Steady state operation in advanced tokamak regimes will require the utilization of off-axis current profile control. In the early 90's, Majeski et al [c] suggested that localized electron Landau damping on ion Bernstein waves (IBW) excited via mode conversion (MC) of a launched fast magnetosonic wave (FW) might provide an efficient means of off-axis current profile control. Subsequent experiments on TFTR demonstrated highly efficient MC heating and current profile modifications [h]. The first tests of this process in D-T plasmas during the 1996 experimental campaign found that absorption was dominated by minority heating of a dilute lithium-7 (<sup>7</sup>Li) impurity intervening between the D cyclotron and MC layers [g]. The same problem would be caused by <sup>9</sup>Be impurity in ITER and <sup>11</sup>B impurity in

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Alcator CMod. The  ${}^7\text{Li}$  was present in the plasma due to Li pellet injection for wall conditioning. For the 1997 experimental campaign, deuterium-like  ${}^6\text{Li}$  was used for wall conditioning instead. Mode conversion experiments in beam-fueled D-T plasmas now exhibited localized heating near the mode conversion layer [g]. However, for high ion temperature supershot target plasmas, the localized heating was dominated by majority ion absorption. At target plasma temperatures below about 25 keV, a transition to dominant electron absorption was observed [i].

Modeling studies with 1D finite Larmor radius kinetic wave codes indicated that mode conversion becomes negligible in a device of the scale of ITER [j]. The large major radius and, to a lesser extent, the high density, contribute to a suppression of tunneling of the fast wave through the cutoff region to the mode conversion layer. For more compact devices such as KSTAR, TPX or BPX, mode conversion is predicted to be a viable off-axis wave absorber. Modeling studies with the METS95 full order Larmor radius code [k] indicates that energetic alpha particles in ITER may absorb a substantial fraction of the ICRF power in the D-T ion-ion hybrid regime. Since the energetic alpha particles slow down primarily on electrons, the fast wave absorption may produce enough of a perpendicular alpha particle beta to suppress sawteeth, analogous to observations on JET and TFTR in the minority heating regimes [a]. More detailed energetic particle stabilization studies are required to determine the potential of this process.

### Plasma Control via RF effects on poloidal and toroidal velocities

RF-driven sheared poloidal flows may provide a mechanism for transport suppression, leading to transport barrier formation and improved performance [e]. Localized poloidal flows have been observed in TFTR direct launch IBW experiments as well as in off-axis MC-IBW excitation [g]. Because the power coupled in these experiments was  $\leq 2$  MW, the magnitude of the driven flows was not sufficient to trigger transport barrier formation. However, the direction of the observed flows is in agreement with simple theory. The peak poloidal velocity observed in an off-axis MC experiment is displayed in Fig. 1. Note the modulation of the flow which correlates with the rf power modulation. Further studies are needed to improve power coupling to the IBW in these regimes.

Confinement enhancement in reversed shear (RS) discharges is associated with large core pressure gradients and large radial electric fields, as inferred from the radial force balance equation for a given plasma species:

$$E_r = \frac{\nabla p}{nZe} + v_\phi B_\theta - v_\theta B_\phi \quad (1)$$

where  $\nabla p$  is the pressure gradient,  $n$  is the density,  $Z$  is the charge number,  $v$  is velocity, and  $\theta$  and  $\phi$  refer to the poloidal and toroidal directions, respectively. The inferred sheared  $E \times B$

flows may suppress turbulence, thereby resulting in the observed confinement enhancement. Studies by Synakowski et al [1] have demonstrated that varying  $E_r$  by changing the NBI-induced toroidal velocity can optimize the duration of the enhanced performance phase of RS discharges. ICRF heating has been observed to substantially decrease both NBI-induced co and counter toroidal rotation in all regimes except for mode conversion on TFTR. The physical mechanism is not clear, but the rf tends to act like a viscosity rather than a torque. The utility of the rf effect on  $v_\phi$  for optimization of RS discharges remains to be determined.

### Confinement Studies

One of the most important unresolved questions in transport studies is the whether or not energy confinement follows the gyro-Bohm scaling model originally suggested by Kadomtsev [m]. In this model, the thermal conductivity is proportional to a simple power of the normalized gyroradius:

$$\chi \sim \chi_B \rho_*^m F \quad (2)$$

where  $\chi_B$  is the Bohm diffusion coefficient,  $F$  is a function of dimensionless parameters that characterize the discharge, and  $\rho_* \sim (T_e M_i)^{0.5}/B$ , with  $T_e$  the electron temperature,  $M_i$  the effective ion mass, and  $B$  the magnetic field. Comparison of matched rf-only heated D(H) and DT(H) discharges indicated that  $\chi$  decreases as  $\rho_*$  increases [n]. This improvement is in the opposite direction to that found in dimensionless scaling experiments on DIII-D and JET when  $B$  was varied [o]. By comparing confinement of rf-only heated D(H) and DT(H) discharges at two different  $B$  fields in JET, resolution of this disagreement may be achieved.

### Summary and Open Questions

Wave-based methods for control of plasma stability and transport were studied over the last 5 years on TFTR. Efficient, localized off-axis heating and current drive via mode conversion was proposed and observed. The viability of this technique for steady-state sustainment of advanced tokamak operational regimes or instability suppression remains to be demonstrated. Sheared poloidal rotation driven during both direct launch and mode conversion excitation of ion Bernstein waves was observed. Efficient methods for direct launch IBW remain a topic for further research. Whether or not this approach will lead to a reliable technique for core transport barrier formation is uncertain. Fast wave heating has been observed to reduce neutral-beam induced toroidal plasma rotation in all regimes except mode conversion. The use of this effect for the optimization of reversed shear discharges remains to be studied experimentally. Finally, isotopic confinement studies in rf-only heated D(H) and DT(H) discharges in TFTR revealed a decrease in the electron thermal conductivity, a result in direct opposition to  $\rho_*$  scaling studies based on variation of  $B$ .

Favorable resolution of these issues by further studies by the international tokamak community may provide a cost-effective path to a tokamak-based fusion reactor.

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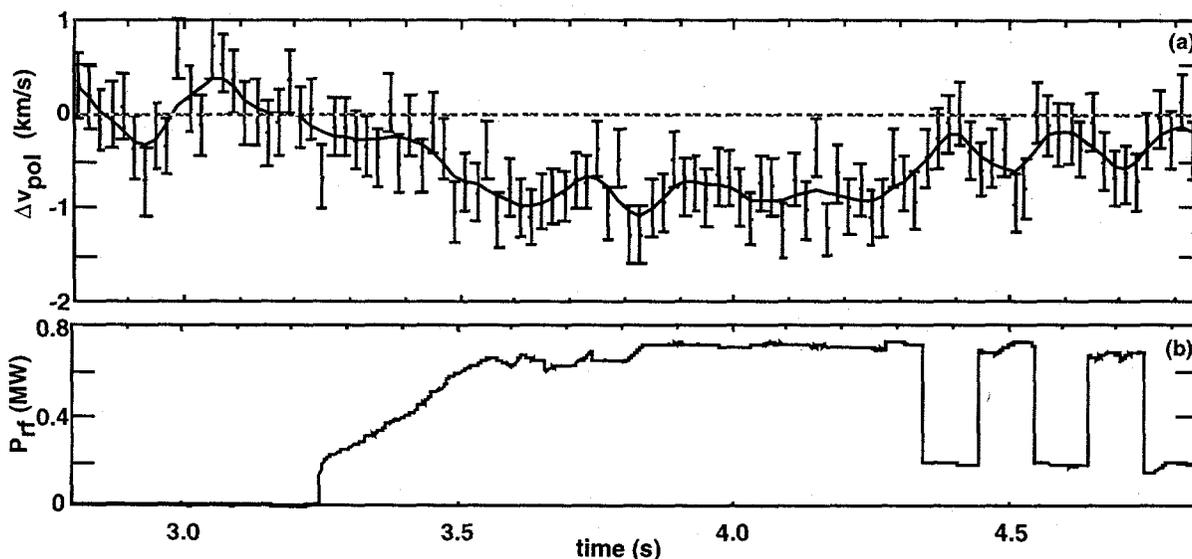


Figure 1 The change in the peak poloidal velocity during ICRF, measured relative to the 400 msec prior to the rf turn on is shown in (a), while the time evolution of the applied rf power is shown in (b).