Prospects for Alpha Channeling: Initial Results from TFTR

N. J. Fisch, M. C. Herrmann, D. S. Darrow, H. P. Furth,
R. F. Heeter, H. W. Herrmann, J. C. Hosea, R. Majeski,
C. K. Phillips, J. Rogers, G. Schilling and S. J. Zweben
Princeton Plasma Physics Laboratory, Princeton NJ USA

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Abstract

Numerical simulations show that for a reactor-sized tokamak, a combination of excited toroidal Alfven eigenmodes (TAE) and mode-converted ion Bernstein waves (IBW) might extract more than half the energy from a birth distribution of α particles in a tokamak DT reactor. Preliminary results on TFTR are analyzed with a view towards addressing the underlying assumptions in these simulations. The data, in fact, support several of the necessary conditions for realizing the alpha channeling effect.

1. Introduction

Tokamak reactors would be much improved by the alpha-channeling effect [1, 2], where α particles amplify waves that then damp on ions, thereby enabling hot-ion mode operation [3]. This effect, however, is likely to be realized only through a combination of waves [4]. Numerical simulations show that, for a reactor-sized tokamak, a combination of excited TAE and mode-converted IBW might extract more than half the energy from a birth distribution of α particles in a tokamak DT reactor [5]. An idealized model for both TAE and IBW spectra shows that 60% of the alpha power goes into the waves, with 20% going into high-n TAE (likely to damp on fuel ions), and with 40% going into a low-field-side IBW (which might damp on tritium fuel ions [6]).

This paper explores the experimental support for such speculations, obtained in a series of experiments on TFTR in 1995 [7] and 1996, emphasizing evidence relating to the use of the mode-converted ion-Bernstein wave. The experiments were carried out in D^3He plasmas, with fast magnetosonic waves at 43 MHz launched from the low-field periphery. These waves mode-convert to IBW waves at the D^3He ion-ion resonance, which was controlled by varying the minority ^3He fraction between 10 and 25% of the electron density. The plasma current was typically 1.4 MA, with the toroidal magnetic field ranging from 4.4 to 5.3 T, placing the mode-conversion layer within 25 cm of the magnetic axis.

In the presence of a mode-converted IBW wave, enhanced losses of energetic ions were observed. The lost ions impinge on a poloidal array of detectors [8, 9, 10]. These detectors are located at 90°, 60°, 45°, and 20° below the outer midplane and are each capable of resolving both the pitch-angle and gyroradius of lost energetic ions. Thus, 1.75 MeV deuterons, 1.16 MeV tritons, and 3.5 MeV α particles all have the same gyroradius signature, but the species might be inferred by other means. The resulting signature, in poloidal angle, pitch angle, and energy, is so detailed that only accurate assumptions about the wave physics allow the full data to be simulated numerically, thus revealing important details of both the wave propagation and the wave-particle interaction physics.

2. Fast Ion Interactions with the Mode-Converted IBW

Interactions of the mode-converted IBW wave both with fusion α particles and beam deuterons have been demonstrated. Among the experimental variables affecting these interactions is the placement of the mode conversion layer. In D^{3}He plasmas on TFTR, this placement has been accomplished routinely by varying the ^{3}He fraction, verified by observing the radius of the electron heating [11]. Controlling the location of the mode conversion layer is of major importance for channeling α power in a reactor.

The IBW wave interaction with beam deuterons has been deduced as follows: Enhanced losses were observed with deuterium beam heating only [12], with the mode conversion layer near the magnetic axis. In principle, the lost ions could be α particles, fusion tritons, or very much heated beam deuterons. The fusion tritons result from the interaction D + D $\rightarrow$ T (1 MeV) + p (3 MeV). In view of the other equally likely branch for DD, there is a neutron produced for every triton. The α particles result from the interaction D + ^{3}He $\rightarrow$ ^{4}He (3.6 MeV) + p (14.7 MeV). If the loss were accelerated deuterons, up to 2.1 MeV deuterons would be indicated, with about 2 MeV absorbed from the waves. If tritons or α particles, energies of 1.5 the birth energy would be indicated.

The ambiguity concerning the lost species is resolved by the data in Fig. 1, which shows very different loss signatures under co and counter deuterium beams, and π phased rf (both signs of n_ϕ present). Neither fusion product distribution would be affected significantly by the direction of the beams, thus identifying heated beam deuterons as the dominant lost species.

The interaction of α particles with the IBW waves has been demonstrated by tritium puffing in the presence of the deuterium beams, which produces a further enhanced loss, perhaps 5 times as much on the 45° and 60° detector, but not at the 90° and 20° detectors [13]. The puffing essentially changes only the presence of energetic α particles, through the DT fusion interaction, evidenced by a very much enhanced (25 times) neutron yield. Because these enhanced losses require both the puffing and the IBW, it follows that the lost species is in fact α particles.

These losses were observed for the mode conversion layer placed on axis (R=2.78 m), with the deuterium (or α) resonance layer at R=2.45 m, in contrast to the usual mode conversion shot, where the deuterium cyclotron layer is at R=2.25 m. It is of interest, and addressed below, that when tritium beams were used for heating, rather than deuterium beams, and with the mode conversion far from the deuterium resonance layer, these enhanced losses disappeared, although the neutron production increased by 30 times.

3. Modeling the Interaction with the IBW

Although successful identification of the lost species is made in either the presence or absence of tritium puffing, certain quizzical features of the data still remain. For example, why are lost beam tritons not observed, whereas beam deuterons are? Why are lost fusion α particles produced by tritium beams not observed when the mode conversion is far from the deuterium resonance, even while anomalous losses are observed in similar discharges driven by deuterium beams?

These questions have been addressed through numerical calculations of the wave-particle interactions. The detailed agreement with the experimental observations lends important support to the use of the same model in cases relevant to a reactor, for example when two waves are employed, and where the α cooling effect is predicted.

Particles interacting with the IBW wave are modeled as diffusing in the constants-of-motion space E-μ-P_ϕ along the trajectory

$$dP_\phi/dE = n_\phi/\omega \tag{1a}$$

$$d\mu/dE = en/(m\omega), \tag{1b}$$

where E is the energy, μ is the magnetic moment, P_ϕ is the canonical angular momentum, and n_ϕ is the toroidal mode number, ω is the IBW wave frequency, and n is the resonance order (for deuterons in a D^3He plasma, $n = 1$; for tritons, $n = 2$). With each traversal of the mode conversion region, resonant ions randomly jump to a nearby E-μ-P_ϕ coordinate along the trajectory described by Eqs. (1). Resonant ions satisfy

$$\omega - k_{||}v_{||} = n\Omega_i, \tag{2}$$

where Ω_i is the cyclotron frequency of the resonant ion.

Fig. 2a shows a counterpassing 100 keV deuteron heated to 2 MeV. By counterpassing, we mean ions traveling opposite to the plasma current. The innermost orbit shown is its initial orbit; each time it interacts with the IBW wave, it jumps to a wider orbit if it gains energy. If it loses energy, it jumps to an interior orbit (the orbits less than the initial energy are not shown). The widest orbit shown indicates that after it has gained 2 MeV, it becomes trapped, with an orbit intercepting the 90° detector. Fig. 2b shows a counterpassing 100 keV triton heated to 1 MeV. The innermost orbit shown is its initial orbit; the wider orbits shown are trapped orbits, but none intercept the tokamak periphery. Thus, whereas the 100 keV deuteron eventually is detected at the 90° detector, the 100 keV triton remains trapped in the plasma.

This very different behavior displayed by deuterium and tritium can be seen by considering trajectories in $v_{||}$–$v_\perp$ (or, equivalently, $\rho_{||}$–$\rho_\perp$, where ρ is the gyroradius) space, assuming that particles remain roughly on a flux surface during the interaction. In Fig. 3, the right side coordinates are for deuterium energies (in MeV), while the left side coordinates indicate tritium energies. The dotted line shows the passing–trapped boundary; this line is continued as a solid line for those trajectories that intersect the tokamak boundary. Thus, it can be seen that the deuterium ions (line D) are heated to about 2 MeV before being lost, whereas the tritium beam ions (line T) cannot reach the detector. However, it can also be seen that 1 MeV tritium, born of the DD reaction, can reach the loss region at around 1.5 MeV. Thus, the model of the IBW interaction supports both deuterium beam ions and energetic tritons as candidates for the 90° detector signal, while explaining the absence of a similar signal with tritium beams. The 1.5 MeV tritons, however, are evidently (from Fig. 1) not the dominant species.

To explain the absence of α-particle loss with tritium beams, note that in the case of tritium beams, the mode conversion layer is far from the α cyclotron resonance. From Eqs. (1b) and (2), we have $\Delta v_{||}/\Delta v_{\perp} = (v_{\perp}/v_{||})(\omega - \Omega_{\alpha})/\omega$. Hence, from Fig. 3 it can also be seen that α particles, far from the α resonance, move along too gentle a slope to intercept the trapped-passing boundary, except at very high energy, perhaps 8 MeV, which would be outside the gyroradius range of the lost–α detectors.

4. Deducing the $k_{||}$–flip

The numerical solutions that produce significant alpha channeling rely on the so-called "$k_{||}$–flip," which has been predicted theoretically [6], but never observed experimentally.

The $k_{||}$–flip occurs as follows: As the IBW wave emerges from the mode-conversion layer, there is a rapid increase, as a function of horizontal position, in k_x, the perpendicular wavenumber in the direction of the magnetic field gradient (here, the horizontal or $\hat{x}$-direction). Since the poloidal magnetic field has a component in the $\hat{x}$-direction, the parallel wavenumber can be written as

$$k_{||} = n_{\phi}/R + k_x \hat{x} \cdot \hat{B}, \tag{3}$$

where n_{ϕ}/R is the launched $k_{||}$, and where $\hat{B}$ is the direction of the magnetic field. For parameters of interest, $n_{\phi}/R \simeq .08$ cm^{-1}. At about 15 cm off the horizontal midplane, $\hat{x} \cdot \hat{B} \simeq .05$. In addition, from numerical calculations [6], one can expect $k_x \rho_t \simeq 1$, where ρ_t is the ion thermal gyroradius. Thus, either above or below the midplane, $k_{||}$ may change sign from the launched $k_{||}$.

This is a crucial feature of the mode-converted IBW in producing the α-channeling effect [5]. To see this, note that a particle moving from the center to the periphery of the plasma moves to lower P_{ϕ} (assuming its drift from its flux surface is small compared to the tokamak minor radius). Then, from Eq. (1a), α particles will cool as they leave the plasma only for $n_{\phi} > 0$. Repeated interactions of trapped α particles with the IBW, when the wave extracts energy from the α-particle, requires the wave-particle interaction to be on the outer leg (low-field side) of the trapped orbit, where the α-particle is comoving. From the resonance condition, we have $v_{||} = (\omega - \Omega_{\alpha})/k_{||} > 0$. Mode conversion in DT plasmas occurs to the high field side of the deuterium gyroresonance layer, so that $\omega < \Omega_{\alpha}$. Thus, where the wave particle interaction occurs, $k_{||}$ must be negative, which is necessarily opposite in sign to the launched $k_{||}$.

Fig. 4 shows large anomalous loss at the 45° detector for rf launched opposite to the direction of the current ($n_{\phi} < 0$, which is by convention called "$90°$ phasing"), in the presence of deuterium beams costreaming in the direction of the toroidal current. When $-90°$ rf is launched ($n_{\phi} > 0$) with costreaming beams, there is no rf-induced fast ion loss. Hence, the wave can be deduced to be well-directed and that this directivity is critical to the particle loss. In a D^{3}He plasma, the deuterium resonance is on the high field side of the mode conversion layer, so $\omega > \Omega_D$. Thus, to affect cogoing particles, $k_{||} > 0$, which is opposite in direction to n_{ϕ}, hence "flipped."

5. Diffusion Coefficient

The α channeling effect relies upon the extraction of the α-particle energy by waves in a time short compared to their slowing down time. Observations of the so-called "beam blip" losses on TFTR suggest that this collisionless limit has been very nearly reached experimentally with very modest rf power. Deuterium beams with duration of only 50 ms are fired into discharges with varying amounts of IBW power. The data is then quite quite rich in detail; in addition to the poloidal angle, energy, and pitch angle data, there is now the time-history of this data as a function of rf power.

A simple one-dimensional model of these losses suggests the following: in the limit of infinite rf power, the main losses should be observed at about time $\tau_D \equiv (\Delta v)^2/D_{\rm QL}$ after the beam blip, where Δv is the deuteron exit speed and $D_{\rm QL}$ is the rf diffusion coefficient. In the opposite limit, namely the collisional limit, $\nu\tau_D \gg 1$, the delay to the main loss should be about ν^{-1}, where ν is the collisional slowing down rate. The fraction of ions lost approaches one in the collisionless limit and zero in the collisional limit, since ions are presumed to interact with the wave only above a threshold velocity. This model suggests further that the dependence of the number of particles lost is extremely sensitive to the parameter $\nu\tau_D$ in the range $\nu\tau_D \simeq 1$.

Fig. 5 shows an estimate of the fraction of beam particles lost as a function of IBW power. The clearly very sensitive dependence on rf power suggests that the limit $\nu\tau_D \simeq 1$ has been attained; moreover, the large number of particles lost at 3 MW (about 0.5%) suggests that by increasing the rf power only by a factor of a few should access the fully collisionless limit. The data is sufficiently rich in detail that through comparisons with a more accurate simulation more quantitative predictions should be possible.

6. Mode Conversion in DT Plasmas

Recent modifications of the TFTR ICRF system now permit n_ϕ in the range 10–30, at 30 MHz, and with directed phasing. Thus, the IBW wave could be excited on axis or to the low-field side of the axis in DT plasmas, rather than in D^3He plasmas. However, experiments to date have not succeeded in efficient mode conversion in DT, apparently because of the presence of vigorous ^7Li minority heating [14]. It is thought that the presence of ^7Li can be avoided by conditioning exclusively with ^6Li, which has the same gyrofrequency as the deuterium.

If the mode conversion can indeed be made efficient, then several interesting directions of research are indicated. First, the observations in D^3He ought to be checked in DT. Second, according to numerical simulations, an IBW wave excited on axis in a reverse-shear DT plasma should exhibit cooling of certain α particles, even as other α particles are heated. Fig. 6 shows the predicted very distinctive lost-α signature, which shows the cooling effect observed on the 20° detector, well separated from the heated α particles, which are ejected only in the vicinity of the 90° detector.

7. Summary and Conclusions

Several key requirements for α channeling are supported by experiments with the mode-converted IBW wave on TFTR. In particular, we find that the IBW wave can be situated at will, that it can interact with either 3.5 MeV fusion α particles or 100 keV beam deuterons. and that the wave-particle diffusion coefficient is near the collisionless limit. Of major significance is the experimental verification of theoretical predictions that these interactions can take place with $k_{||}$ opposite in sign to n_ϕ. The agreement obtained between the very detailed experimental observations and computer modeling lends important support to the far-reaching predictions of α channeling in a reactor, based on the same numerical code. The results obtained suggest an important direction for further research, wherein the cooling of a significant population of fusion α particles could be observed in a reverse shear discharge on TFTR, if the mode conversion can be made efficient in a DT plasma.

The high magnetic fields and copious α-particle population place TFTR as the only experiment capable of establishing the low-field-side IBW-α interaction physics. Studies of the TAE mode, which has been driven directly in JET using beat waves or a saddle coil antenna [15, 16], help to complete the physics basis for the full α-channeling effect. Establishing, even separately, the effects of the central TAE and low-field-side IBW lends confidence to the very promising numerical simulation of their combined effect.

Acknowledgment

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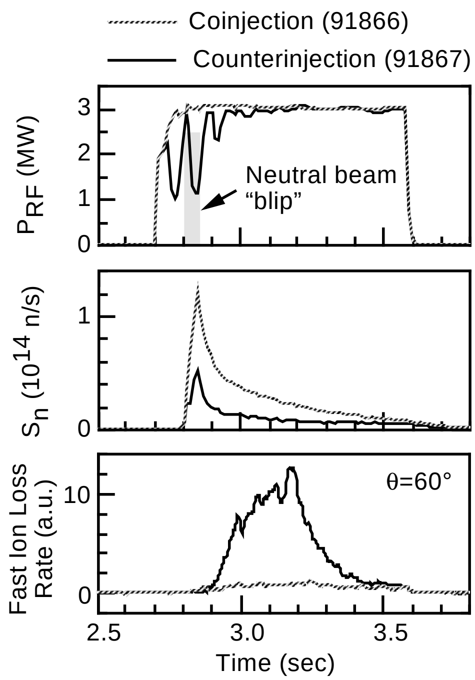

Fig. 1 Losses of co and counter deuterium beam ions in the presence of π phased rf. Discharge at 4.8 T, 1.4 MA with mode conversion layer on axis.

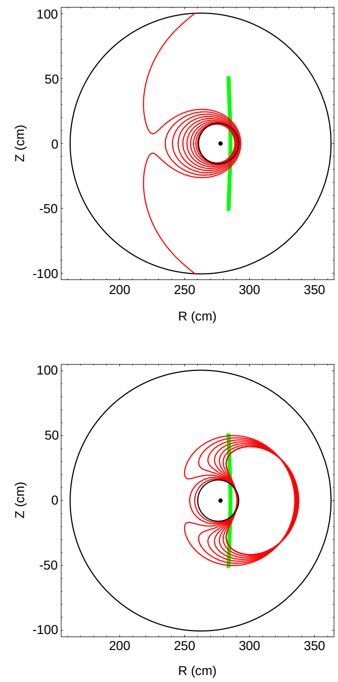

Fig. 2 A deuteron (top) and a triton (bottom) interacting with an IBW (shaded strip). The 100 keV particles are initially passing near the center, later becoming trapped.

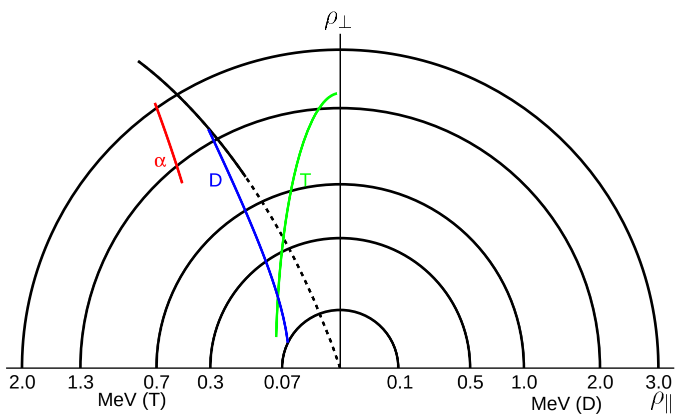

Fig. 3: Passing/trapped boundary and trajectories of 100 keV D, 100 keV T and 3.5 MeV α particles diffused by IBW vs. $\rho_{||}$ and $\rho_\perp$.

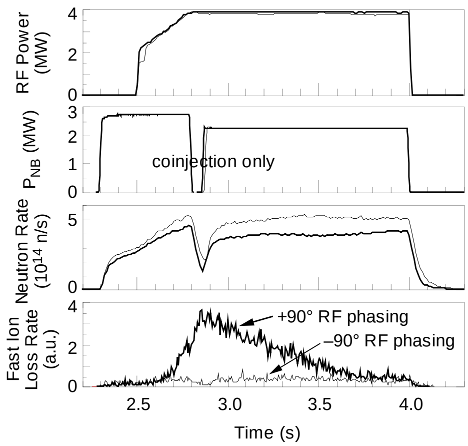

Fig. 4 Losses of co deuterium beams in the presence of phased rf. +90° phasing (counter to the current) results in significantly enhanced losses, whereas -90° phasing (co to the current) shows first orbit losses of fusion products only.

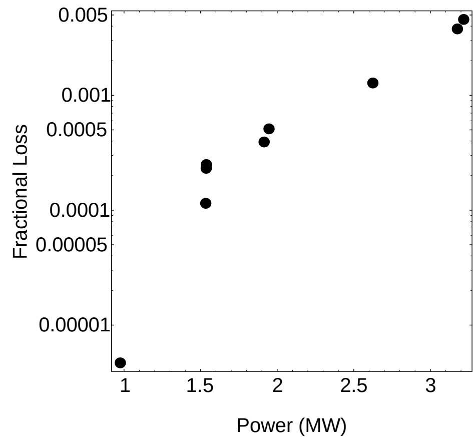

Fig. 5 Approximate losses of deuterium ions (fraction of beam ions) vs. rf power. The measured loss is assumed to be constant over a portion of the outer midplane.

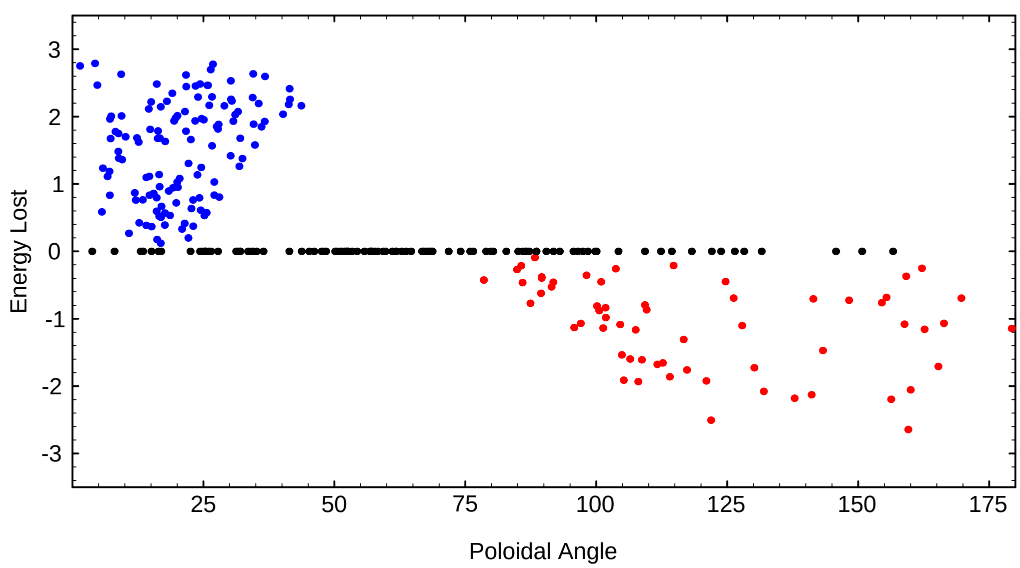

Fig. 6: Energy lost to the wave (MeV) and poloidal exit angle of α particles in simulated reverse shear TFTR discharge with B = 5.3 T, I = 1.85 MA (scaled shot #84011). 1000 particles are simulated. Particles exiting with zero energy lost correspond to first orbit losses (11%). 13.7% of the α particles are cooled, exiting near the outer midplane. 3.8% are heated exiting between the inner midplane and the bottom.