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DURING THE FISHBONE INSTABILITY

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CONFINEMENT OF FUSION REACTION PRODUCTS DURING THE FISHBONE INSTABILITY

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ABSTRACT

The presence of fishbone events in the PDX tokamak is correlated with a reduction in the burnup of 0.8 MeV ^3He ions. This reduction is probably caused by distortion of the ^3He drift orbits in the helical magnetic fields associated with the instability, resulting in the loss of about 70% of the confined ^3He ions in a moderately strong fishbone. Such a non-resonant loss of particles with large orbits indicates that fishbone events may influence 3.5 MeV alphas in ignition experiments.

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In PDX neutral beam heated discharges a new instability called the "fishbone" instability was observed.^{1,2} The instability was associated with a significant loss of injected beam ions, resulting in the loss of as much as 20-40% of the total beam heating power.² The fishbone was identified as a large $n = 1$, $m = 1$ internal kink mode that also excites $n = 1$, $m = 2, 3, 4$ MHD modes.^{2,3} It was found theoretically that large losses of injected beam ions are expected due to a resonance between the toroidal precession of the beam ions and the rotation of the MHD modes.³ The theoretical predictions for mode-induced beam-ion loss are consistent with most features of the PDX measurements⁴⁻⁶ of beam-ion loss during fishbones.

Fishbones would be extremely important if 3.5 MeV alphas were to induce a fishbone-like event or if they were to suffer losses when other energetic ions were exciting fishbones. In this paper, we present measurements of the $d(^3\text{He}, p)\alpha$ fusion reaction rate during $D^0 \rightarrow D^+$ neutral beam injection that suggest that non-resonant 0.8 MeV ^3He ions experience severe losses during fishbone activity.

The 0.8 MeV ^3He ions are produced by the $d(d, n)^3\text{He}$ fusion reaction and their production rate is determined by measuring the 2.5 MeV neutron emission level. If a ^3He ion is confined, then it slows down through the peak of the $d(^3\text{He}, p)\alpha$ cross section. The ^3He 'burnup' (the ratio of 15 MeV protons produced in the $d(^3\text{He}, p)\alpha$ fusion reaction to 0.8 MeV ^3He ions produced in the $d(d, n)^3\text{He}$ fusion reaction) is a sensitive measure of the 0.8 MeV ^3He ion confinement.⁷ The absolute magnitude of the 15 MeV proton emission was detected with 10 ms time response using a horizontally inserted surface barrier detector.^{7,8} The absolute calibration was confirmed by puffing ^3He gas and taking the ^3He density to be $\frac{1}{2}$ of the resulting rise in electron density.⁷ The absolute accuracy of the measurement of the emission is about a factor of two. The relative accuracy is determined primarily by counting statistics.

Most fusion-produced ^3He ions are born near the hot center of the plasma. In PDX, about half of the created 0.8 MeV ^3He ions suffer classical orbit losses, with the majority of the losses occurring in the perpendicular part of velocity space.⁷ Because the poloidal gyroradius depends inversely on poloidal field, the magnitude of these classical losses drops with increasing plasma current. Classically, confined MeV ions slow down predominately due to collisions with electrons, losing energy in a time approximately proportional to $T_e^{3/2}/n_e$. The probability of a $d(^3\text{He}, p)\alpha$ reaction is proportional to the slowing-down time and to the density of target deuterons n_d , so the classical burnup probability scales approximately as $n_d T_e^{3/2}/n_e$. Classically, the $d(^3\text{He}, p)\alpha$ reaction rate is expected to depend on the creation rate of ^3He ions (the 2.5 MeV neutron emission), on the poloidal field

distribution (I_p), and on the electron temperature.⁷ Reductions in the $d(^3\text{He},p)\alpha$ reaction rate below the classical level indicate that the ^3He ions are more poorly confined than classically predicted, that the spatial distribution of $d(d,n)^3\text{He}$ reactions is broader than predicted (resulting in increased classical losses), or that the ^3He ions lose energy more rapidly than classically predicted.⁷

The best 0.8 MeV ^3He burnup data during fishbones are from two PDX run sequences during divertor operation. On one discharge sequence (Fig. 1), the plasma current rose from 250 kA to 340 kA, with a resulting 25% drop in the poloidal beta and a termination of fishbone activity (Fig. 1a,b) at about 450 ms. The electron temperature (≈ 1.3 keV) and beam power (4 MW) were approximately constant and the toroidal field was 14 kG. Within the experimental and theoretical uncertainties in measuring and predicting the ^3He burnup,⁷ the absolute magnitude of the 15 MeV proton emission (Fig. 1c) is roughly comparable to the levels expected for classical ^3He burnup throughout the discharge. Improved accuracy in the comparison of theory and experiment is obtained by normalizing the calculation and the experiment at 550 ms (i.e., saying the ^3He burnup is classical at 550 ms) and examining the time evolution of the ^3He burnup. The magnitude of the ^3He burnup at 550 ms is close to the magnitude of the burnup measured previously in PDX discharges with sawtooth MHD activity in which the ^3He burnup varied with plasma current and electron temperature approximately as expected,⁷ while the burnup earlier in the discharge falls below most of the previous observations. With this normalization, the measurements indicate that, in the presence of the fishbones, the ^3He burnup was about $\frac{1}{2}$ of the classical value. If we assume that a constant fraction of the beam ions was lost at each fishbone, then the 50 keV deuterons (beam ions) had an average confinement time⁶ of 12 $\rightarrow$ 17 ms, while the instantaneous loss rate of the beam ions⁶ (as measured by the neutron decay rate during the fishbone) was about 1 ms. The average ^3He confinement time⁷ was about 5 ms, implying that $70 \pm 20\%$ of the 0.8 MeV ^3He ions were lost at each fishbone. Alternative interpretations for the reduction in ^3He burnup are that the $d(d,n)^3\text{He}$ emission profile was a factor of 1.7 broader before 450 ms than after 450 ms or that about 70% of the ions rapidly decelerated during each fishbone. Although the $d(d,n)^3\text{He}$ emission profile may broaden instantaneously during a fishbone as beam-ions are expelled from the center of the plasma, for classical beam deposition, the average emission profile is not expected to be appreciably broader before 450 ms than after 450 ms.

In a second run sequence with weaker fishbones (15% drops in the neutron emission), the ^3He burnup was about $\frac{3}{4}$ of the expected classical value (Fig. 3.18 of Ref. 8).

The effect of fishbones on the drift orbits of 0.8 MeV ^3He ions was studied numerically

using a Monte Carlo code.³ The fishbone magnetic field structure was modeled by helical $n = 1$, $m = 1, 2, 3$ modes rotating toroidally at 16 kHz. The radial distribution of $d(d,n)^3\text{He}$ fusion reactions that produce the ^3He ions and the unperturbed field structure were chosen to approximate the experimental conditions of Fig. 1. The perturbed field structure was modeled as a square pulse of duration 500 μs and the fraction of ^3He ions lost during the "fishbone" pulse was calculated as a function of mode amplitude (Fig. 2a). For a given mode amplitude, the predicted losses of 0.8 MeV ^3He ions exceed the losses predicted for 50 keV beam ions by about a factor of two. This is in agreement with the experimental observations. Unlike the beam-ion losses, the computed ^3He losses are insensitive both to the duration of the fishbone and to the mode precession frequency in the range of 10-20 kHz (Fig. 2b), indicating that the ^3He losses are not due to a resonance with the mode. Both co-going and counter-going ^3He ions are lost in roughly equal amounts. (Trapped ^3He ions are lost classically.) The radial distortion of the ^3He drift orbits is generally several times larger than the radial distortion of the flux surfaces alone. The numerical calculations suggest that the observed reduction in ^3He burnup is due primarily to additional orbit losses to the PDX vessel caused by distortion of ^3He drift orbits in the three-dimensional field created by the fishbone instability.

For field perturbations $\delta B_\theta/B_\theta$ of equal amplitude, the losses of fusion products on larger devices are expected to be less severe than on PDX since the ratio of poloidal gyroradius to plasma minor radius is smaller. In near-term ignition ($Q \simeq 1$) experiments, however, the losses still are expected to be appreciable. For example, on TFTR ($a = 80$ cm, $R = 270$ cm) near $Q = 1$ ($B_T = 40$ kG, $I_p = 1.9$ MA) the presence of field perturbations as large as those observed in our PDX experiments ($\delta B_\theta/B_T = 2 \times 10^{-3}$) is predicted to increase the losses of 3.5 MeV alphas from 8% in the absence of instabilities to 49% in the presence of fishbones.

In conclusion, the observed reduction in the 0.8 MeV ^3He burnup in the presence of PDX fishbones suggests that non-resonant fusion products can be lost in an MHD mode of sufficient amplitude. 3.5 MeV alphas in an ignition experiment may experience losses even if the alpha population does not destabilize any modes.

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Figure Captions

Fig. 1 Time evolution of (a) the magnetic fluctuations from a Mirnov coil mounted near the outer wall, (b) the neutron emission measured by an NE102A scintillator, and (c) the 15 MeV proton emission from the $d(^3\text{He},p)\alpha$ fusion reaction for a PDX plasma which evolved out of large fishbone activity at about 450 ms. The shaded region in (c) is the calculated 15 MeV proton emission based upon classical 0.8 MeV ^3He ion production, confinement, and slowing down using measurements of the time evolution of the plasma current and of the electron temperature (PHA). The calculation is normalized to experiment at about 550 ms. The proton data are the average of four similar discharges.

Fig. 2 (a) Fractional loss of 0.8 MeV ^3He ions in a fishbone of $n = 1$, $m = 1$ mode amplitude $\delta B_\theta/B_T$. The open points are the results of Monte Carlo simulations with 3000 particles. The curve is a fit to the calculated points. The solid points are the ^3He losses deduced assuming that the measured reduction in ^3He burnup is due to fishbone losses of ^3He ions. The vertical error bars represent the uncertainty in relating the burnup reduction to the losses per fishbone. The mode amplitude for the ^3He burnup data was determined by selecting the amplitude that correctly predicts the experimentally observed reduction in neutron emission; the horizontal error bars represent uncertainties in this amplitude due to uncertainties in the beam deposition and q profiles. The amplitudes of the $m = 1, 2, 3$ modes are assumed to be in the ratio 3.8:2:1 and the mode rotates toroidally at 16 kHz. (b) Fractional loss of 0.8 MeV ^3He ions as a function of mode precession frequency in a fishbone with mode amplitude $\delta B_\theta/B_T$ of 2.2×10^{-3} . Compared to beam ions (Fig. 4 of Ref. 3), the ^3He ions are insensitive to changes in precession frequency, indicating that the ^3He losses are not due to mode-particle pumping.

Fig. 1

Fig. 2

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