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Confinement of Fusion Reaction Products during the Fishbone Instability

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The presence of fishbone events in the PDX tokamak is correlated with a reduction in the burnup of 0.8-MeV ^{3}He ions. This reduction is probably caused by distortion of the ^{3}He drift orbits in the helical magnetic fields associated with the instability, resulting in the loss of about 70% of the confined ^{3}He ions in a moderately strong fishbone. Such a nonresonant 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 $n=1$, $m=2,3,4$ magnetohydrodynamical (MHD) modes.[2,3] It was found theoretically that large losses of injected beam ions are expected because of 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 measurements[4–6] of beam-ion loss during fishbones.

Since a d-t plasma cannot ignite without alpha heating, fishbones would be extremely important if 3.5-MeV alphas produced in $d(t,n)\alpha$ fusion reactions were to induce a fishbonelike event or if they were to suffer losses when other energetic ions were exciting fishbones. In this paper, we present measurements of the $d(^3\mathrm{He},p)\alpha$ fusion reaction rate during $\mathrm{D}^0 \rightarrow \mathrm{D}^+$ neutral beam injection that suggest that nonresonant 0.8-MeV ^{3}He ions experience severe losses during fishbone activity.

The 0.8-MeV ^{3}He ions are produced by the $d(d,n)^3$He fusion reaction and their production rate is determined by measuring the 2.5-MeV neutron emission level. If a ^{3}He ion is confined, then it slows down through the peak of the $d(^3\mathrm{He},p)\alpha$ cross section at 550 keV in about 15 ms. The ^{3}He "burnup" [the ratio of 15-MeV protons produced in the $d(^3\mathrm{He},p)\alpha$ fusion reaction to 0.8-MeV ^{3}He ions produced in the $d(d,n)^3$He fusion reaction] is a sensitive measure of the 0.8-MeV ^{3}He ion confinement.[7] The absolute magnitude of the 15-MeV proton emission was detected with 10-ms time response by use of a horizontally inserted surface-barrier detector.[7,8] The absolute calibration was confirmed by puffing ^{3}He gas and taking the ^{3}He density to be one-half of the resulting rise in electron density.[7] The absolute accuracy of the measurement of the emission is about a factor of 2. The relative accuracy is determined primarily by counting statistics.

Most fusion-produced ^{3}He ions are born near the hot center of the plasma. In PDX, about half of the created 0.8-MeV ^{3}He 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 megaelectronvolt ions slow down predominantly as a result of collisions with electrons, losing energy in a time approximately proportional to $T_e^{3/2}/n_e$. The probability of a $d(^3\mathrm{He},p)\alpha$ reaction is proportional to the slowing-down time and to the density of target deuterons n_d, so that the classical burnup probability scales approximately as $n_d T_e^{3/2}/n_e$. Classically, the $d(^3\mathrm{He},p)\alpha$ reaction rate is expected to depend on the creation rate of ^{3}He ions (the 2.5-MeV neutron emission), on the poloidal field distribution (I_p), and on the electron temperature.[7] Reductions in the $d(^3\mathrm{He},p)\alpha$ reaction rate below the classical level indicate that the ^{3}He ions are more poorly confined than classically predicted, that the spatial distribution of $d(d,n)^3$He reactions is broader than predicted (resulting in increased classical losses), or that the ^{3}He ions lose energy more rapidly than classically predicted.[7]

The best 0.8-MeV ^{3}He 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 to 340 kA, with a resulting 25% drop in the poloidal beta and a termination of fishbone activity [Figs. 1(a) and 1(b)] at about 450 ms. The electron temperature ($\simeq 1.3$ 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 ^{3}He burnup,[7] the absolute magnitude of the 15-MeV proton emission [Fig. 1(c)] is roughly comparable to the levels expected for classical ^{3}He burnup through the discharge. Improved accuracy in the comparison of theory and experiment is obtained by normalizing the calculation and the experiment at 550 ms and examining the time evolution of the ^{3}He burnup. The magnitude of the ^{3}He burnup at 550 ms is close to the magnitude of the burnup measured previously in PDX discharges with sawtooth MHD activity in which the ^{3}He 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 ^{3}He burnup was about one-half of its usual 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 time[6] of 12–17 ms, while the instantaneous loss rate of the beam ions[6] (as measured by the neutron decay rate during the fishbone) was about 1 ms. The average ^{3}He confinement time[7] was about 5 ms, implying that $(70 \pm 20)\%$ of the 0.8-MeV ^{3}He ions were lost at each fishbone. Alternative interpretations for the reduction in ^{3}He burnup are that the $d(d,n)^3$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 $d(d,n)^3$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% drop in the neutron emission), the ^{3}He burnup was reduced about 25% during the fishbones (Fig. 3.18 of Ref. 8).

The effect of fishbones on the drift orbits of 0.8-MeV ^{3}He ions was studied numerically with use of 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 dis-

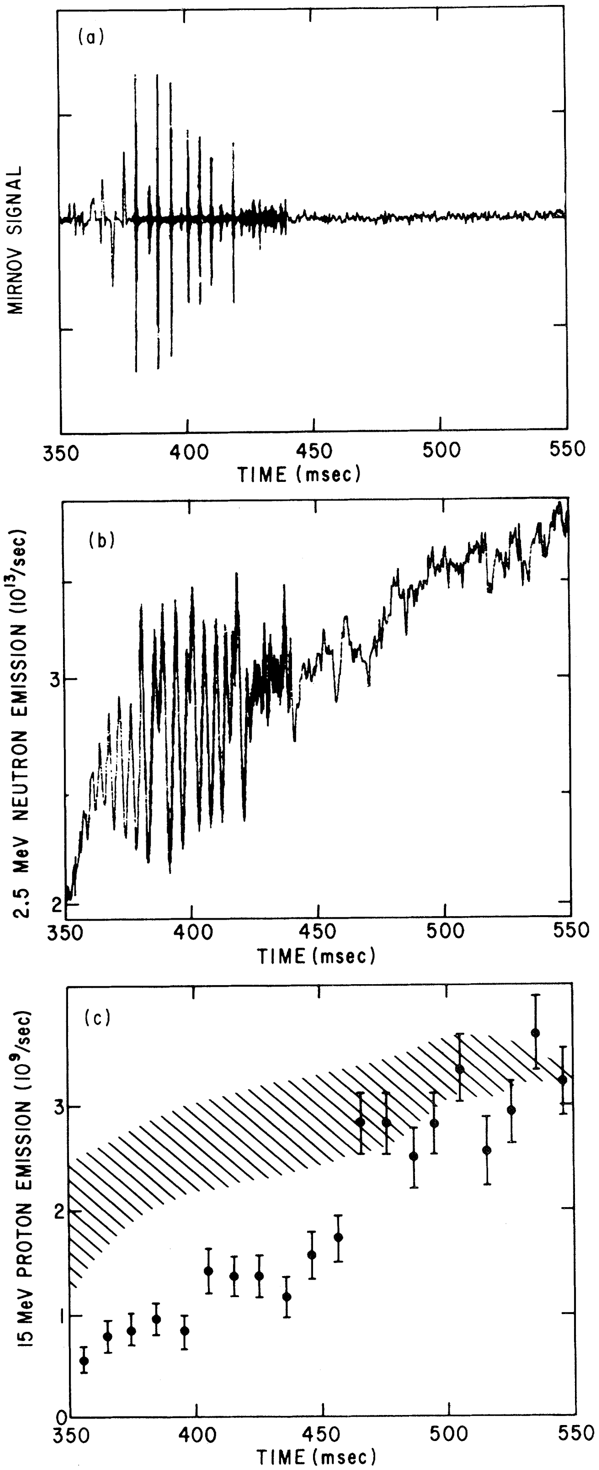

FIG. 1. Time evolution of (a) the magnetic fluctuations from a Mirnov coil mounted near the outer wall, (b) the neutron emission measured by an NE102A scintillator, and (c) the 15-MeV proton emission from the fusion reaction $d(^3\mathrm{He},p)\alpha$ for a PDX plasma which evolved out of large fishbone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

tribution of $d(d,n)^3$He fusion reactions that produce the ^{3}He 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 ^{3}He ions lost during the "fishbone" pulse was calculated as a function of mode amplitude [Fig. 2(a)]. For a given mode amplitude, the predicted losses of 0.8-MeV ^{3}He ions exceed the losses predicted for 50-keV beam ions by about a factor of 2. This is in agreement with the experimental observations. Unlike the beam-ion losses, the computed ^{3}He losses are insensitive both to the duration of the fishbone and to the mode precession frequency in the range of 10–20 kHz [Fig. 2(b)], indicating that the ^{3}He losses are not due to a resonance with the mode. Both copropagating and counterpropagating ^{3}He ions are lost in roughly equal amounts. (Trapped ^{3}He ions are lost classically.) The radial distortion of the ^{3}He 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 ^{3}He burnup is due primarily to additional orbit losses to the PDX vessel caused by distortion of ^{3}He 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 ^{3}He burnup in the presence of PDX fishbones suggests that nonresonant 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

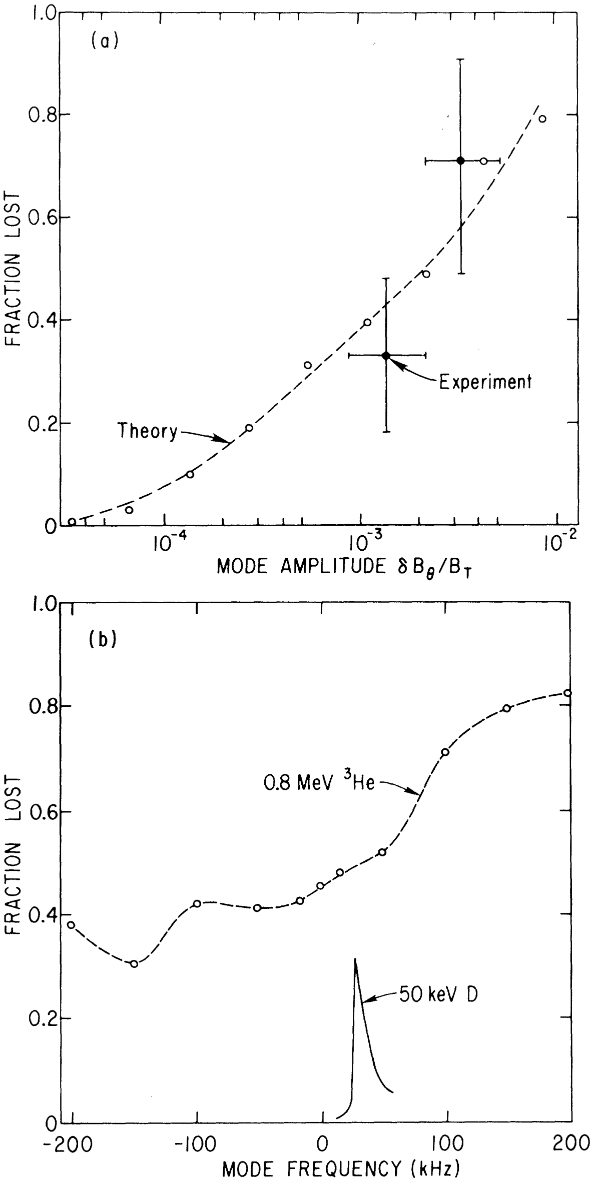

FIG. 2. (a) Fractional loss of 0.8-MeV ^{3}He ions in a fishbone of $n = 1$, $m = 1$ mode amplitude $\delta B_\theta/B_T$. The open points are the results of Monte Carlo simulations with 3000 particles. The curve is a fit to the calculated points. The solid points are the ^{3}He losses deduced under the assumption that the measured reduction in ^{3}He burnup is due to fishbone losses of ^{3}He ions. The vertical error bars represent the uncertainty in relating the burnup reduction to the losses per fishbone. The mode amplitude for the ^{3}He 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 modes rotate toroidally at 16 kHz. (b) Fractional loss of 0.8-MeV ^{3}He ions as a function of mode precession frequency in a fishbone with mode amplitude $\delta B_\theta/B_T$ of 2.2×10^{-3}. A positive mode frequency indicates that the modes rotate in the direction of beam-ion precession. Compared to beam ions (solid curve) (Ref. 3), the ^{3}He ions are insensitive to changes in precession frequency, indicating that the ^{3}He losses are not due to mode-particle pumping.

destabilize any modes.

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[1] D. Johnson *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research* (International Atomic Energy Agency, Baltimore, 1983), Vol. 1, p. 9.

[2] K. McGuire *et al.*, Phys. Rev. Lett. **50**, 891 (1983).

[3] R. B. White, R. J. Goldston, K. McGuire, A. H. Boozer, D. A. Monticello, and W. Park, Phys. Fluids **26**, 2958 (1983).

[4] P. Beiersdorfer, R. Kaita, and R. J. Goldston, Nucl. Fusion **24**, 487 (1984).

[5] D. Buchenauer, D. Q. Hwang, K. McGuire, and R. J. Goldston, "MHD Effects on Beam Ion Loss During Near Perpendicular Neutral Beam Injection," in Proceedings of the Fourth International Symposium on Heating in Toroidal Plasmas, Rome, 1984 (to be published).

[6] J. D. Strachan, B. Grek, W. Heidbrink, D. Johnson, S. Kaye, H. Kugel, B. LeBlanc, and K. McGuire, Princeton Plasma Physics Laboratory Report No. PPPL-2165, 1984 (unpublished).

[7] W. W. Heidbrink, R. E. Chrien, and J. D. Strachan, Nucl. Fusion **23**, 917 (1983).

[8] W. W. Heidbrink, "Tokamak Diagnostics Using Fusion Products," Ph.D. thesis, Princeton University, 1984 (unpublished), p. 66.