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OBSERVATIONS OF BEAM ION LOSSES IN TFTR DURING TAE MODES AND OTHER MHD ACTIVITY

BY

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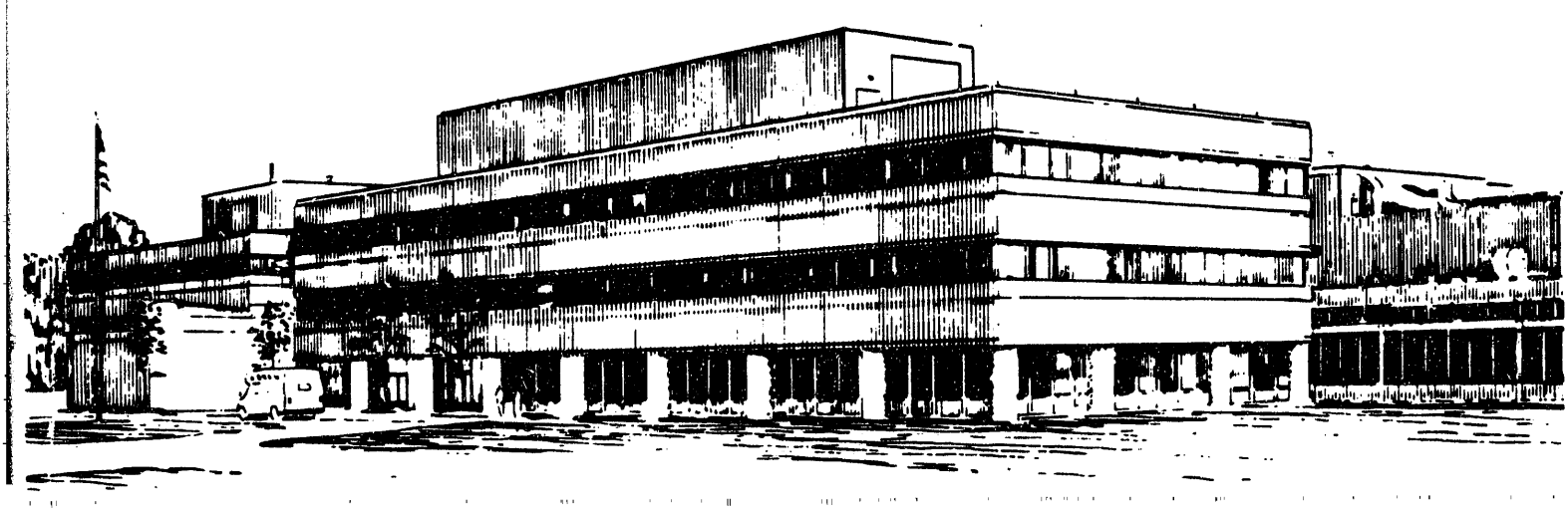

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MASTER

Observations of Beam Ion Losses in TFTR During TAE Modes and Other MHD Activity

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Abstract

Direct measurements of fast NBI ion losses have been made near the outer midplane during MHD activity in TFTR. Bursts of beam ion loss are seen coincident with the TAE mode activity. Particles lost during TAE activity are lost at the full injection energy of 100 keV, and only the total efflux of fast ions changes during the mode, not the pitch angle or energy of the lost ions. Reductions in neutron source strength indicate that $\sim$ 10 percent of the beam ions can be lost in a single burst, with a cumulative loss of as much as 50 percent. Other MHD activity can cause large losses of beam ions, including passing ions.

I. Introduction

Toroidal Alfvén Eigenmodes (TAEs) have become a topic of recent concern due to their potential impact upon tokamak reactors.[1-4] These are toroidal eigenmodes of the Alfvén wave which are driven unstable by resonances with toroidally-circulating particles whose velocity exceeds[5] $v_A/3$, where $v_A = \frac{B_T}{\sqrt{\mu_0 \rho}}$ is the Alfvén velocity. In a reactor, alpha particles are anticipated to provide the free energy to drive the mode. The mode is of importance due to its potential ability to expel fast ions of all sorts, including the alpha particles and beam ions.

Experiments on TFTR[2] and DIII-D[3] have utilized neutral beam ions, under suitable conditions, as superalfvénic particles. In both experiments, repeated short bursts of high-frequency ($\sim$ 100 kHz) Mirnov activity were observed, which coincided with reductions in the neutron production rate. More recent experiments on DIII-D[6] have found significant sputtering of carbon tiles near the outside midplane during TAE-unstable discharges. This has been the most direct evidence of TAE-induced beam ion losses. The present work describes recent measurements of the beam ion losses due to TAE modes in TFTR, as well as losses from other MHD activity.

II. Beam Ion Loss During the TAE

To obtain conditions in which the 100 keV deuterium beam ions are super-alfvénic in TFTR ($v_b > v_A$), plasmas must be run at low toroidal field (1 to 1.5 T) and moderately high densities ($\geq 3 \times 10^{19}$ m^{-3}) so that the Alfvén speed is low.

Beam ion losses are detected with the TFTR midplane fast ion probe.[7-9] It is moveable radially, along a line 0.35 m below the midplane and, for plasmas in experiments reported here (R = 2.40 m, a = 0.75 m), can be positioned at minor radii varying from 1.04 m to 1.18 m. The probe detects fast ions which have trajectories such that they can pass through two collimating apertures and then strike a flat scintillator. The position of the light created identifies the gyroradius and pitch angle of the particle which produced it, and that light is recorded by an intensified videocamera (to obtain an image) and by a photomultiplier tube (to obtain the total intensity from the scintillator with fast time response). The probe detects only ions travelling in the direction of the plasma current, and only those with pitch angles (relative to the toroidal field) between 40° and 85°, and gyroradii between 2 cm and 12 cm.

Figure 1 shows data from a plasma with $R = 2.40$ m, $a = 0.75$ m, $B_T = 1.5$ T, $I_p = 500$ kA, $\bar{n}_e = 2.3 \times 10^{19}$ m^{-3}, and $P_{inj} = 10$ MW. The typical signatures[2] of a TAE are evident: periodic bursts of high-frequency magnetic activity, coincident with reductions in the neutron production rate, and increases in the beam ion loss. The frequency of the Mirnov signal within the bursts varies as expected from the mode frequency,[1] $\omega = \frac{v_A}{2qR}$. The beam ion loss is integrated over all pitch angles and energies that the probe can view; the only substantial contribution to the signal comes from 100 keV neutral beam ions. In addition, it is apparent that the magnitude of the ion loss is correlated with the amplitude of the magnetic activity, and that only the bursts with largest amplitude cause substantial dips in the neutron rate. In this figure it can be seen that the beam ion loss is sychronous with the mode activity, rising after the magnetic burst starts, and falling after the end of each burst. However, in some of the bursts, the ion loss does not peak until after the Mirnov activity has subsided, suggesting that the process of expulsion of the ions may take ~ 0.5 msec, although low-frequency Mirnov activity may also expel particles during the intervals between high-frequency bursts.

During the bursts, the rate of beam ion loss is approximately 1.5 times what it is without the mode activity. A SNAP calculation on a discharge similar to the one which produced the data in Fig. 1 indicates that 16% of the neutral beam ions escape the plasma due to first-orbit losses. First-orbit loss (and possibly stochastic TF ripple loss) most likely comprise the steady background loss rate. The 50% increase in the loss rate due to the bursts would then imply a loss of about 8% of the beam ions, which is of similar magnitude to the reduction in the neutron rate observed. Although the beam loss rate is seen to increase with every Mirnov burst, the neutron rate drops significantly only during some. This intermittency will be the subject of future investigations.

III. Energy and Pitch Angle of Ions Lost During TAEs

Figure 2 shows the sintillator image under two circumstances, for a discharge similar to that in Fig. 1. In 2(a), the image has been integrated over several bursts of the mode, and in 2(b), the image is that seen immediately after the neutral beams have been turned off, at which time the TAEs are no longer excited but the plasma parameters have not changed significantly from their values when the modes were present. The images show contours of constant intensity (the actual intensities of the contours differ between the two images). The maximum intensity corresponds to ions with a gyroradius of $\rho = 7 \pm 1$ cm, the gyroradius of the 100 keV deuterons at the probe position. The pitch angle at maximum intensity is $\chi = 57°$, while the boundary between trapped and passing particles is the line $\chi = 47°$. The images in Fig. 2 indicate that, although the total beam ion loss from the plasma seen by the probe is being increased by the TAE, the loss continues to occur at the same place in the energy/pitch angle space.

IV. Losses During Other High-Frequency MHD Activity

Beam injection into plasma with densities $\sim 25\%$ lower than those used in the TAE experiments ($\bar{n}_e = 1.8 \times 10^{19}$ m^{-3}, $B_T = 2$ T, $I_p = 420$ kA, $P_{inj} = 10$ MW, $R = 2.40$ m, $a = 0.75$ m) can result in Mirnov bursts which have characteristics qualitatively similar to those of the TAEs: Mirnov activity at 25–50 kHz, neutron drops, and increased beam ion losses. These modes, however, do not fit the frequency scaling expected of TAE modes: $\omega = \frac{v_A}{2qR}$. These modes do, however, show similar radial distributions of frequency and amplitude in the beam emission spectroscopy (BES[10]) signals. Figure 3(a) shows the time-history of the midplane probe signal, with spikes of beam ion loss many times the MHD-quiescent background level. Figure 3(b) shows the image at the detector for a particularly intense burst of this sort. In this image, the loss of trapped particles is seen, approximately as in the TAE case (the intensity has saturated the camera at the center of the loss, preventing detection of the exact location of peak loss). It also, however, possesses an additional feature not seen in any of the TAE cases to date, the loss of passing particles (the feature with pitch angles below $\chi = 47°$).

V. Summary

Energy and pitch-angle resolved measurements of beam ions lost during TAEs indicate that particles are lost at the same energy and pitch angle both when the mode is present and absent. This observation

is most likely explicable by enhanced velocity-space diffusion of fast ions induced by the mode, or by stochastic ripple diffusion[7] of ions in the fields of the mode. Under similar conditions, but with lower density, intermediate frequency (25–50 kHz) MHD modes act to expel passing beam ions at their full injection energy.

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Figure Captions

Figure 1 Time histories of signals from Mirnov coil, neutron detector, and midplane fast ion probe during several TAE modes. Modes are designated by the enhanced high-frequency Mirnov signal. Note that the beam ion loss signal increases during each Mirnov burst, and that the amount of the increase varies in proportion to the Mirnov amplitude.

Figure 2 (a) Intensity pattern seen on midplane detector, integrated over an interval containing several TAE bursts. A gyroradius/pitch angle grid is overlaid on the pattern. The gyroradius is that the ion would have if all its velocity were perpendicular to B, i.e. this coordinate is the energy of the particle, not the actual radius of orbital motion. The pitch angle is $\chi = arccos(v_{tor}/v)$. (b) The pattern for similar plasma conditions immediately after beam injection has ended, so that TAE modes are no longer being excited. Note that the feature due to beam ion loss is at exactly the same position and has the same shape as the feature when TAEs are present.

Figure 3 (a) Beam ion loss signal versus time showing pronounced bursts of beam ion loss. (b) Intensity pattern seen on the detector during a Mirnov burst whose frequency scaling did not fit the TAE frequency, but under similar conditions. Note that, in this instance, passing particles are lost ($\chi < 47°$).

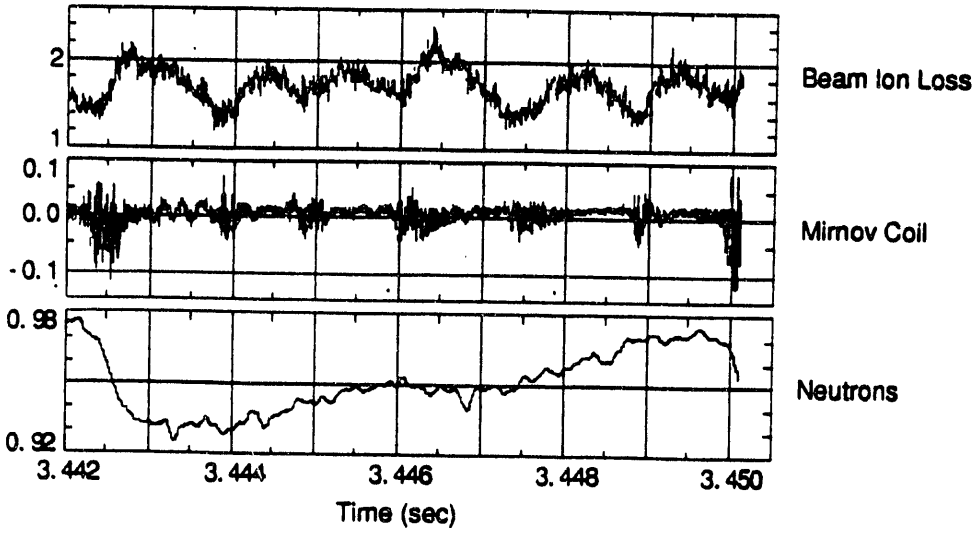

Figure 1

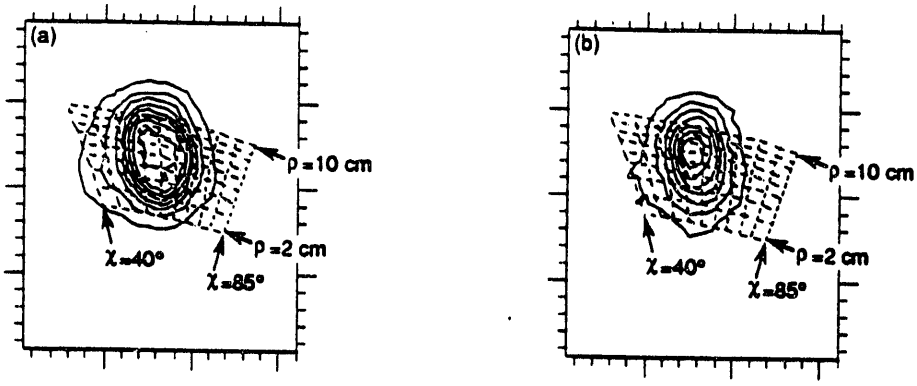

Figure 2

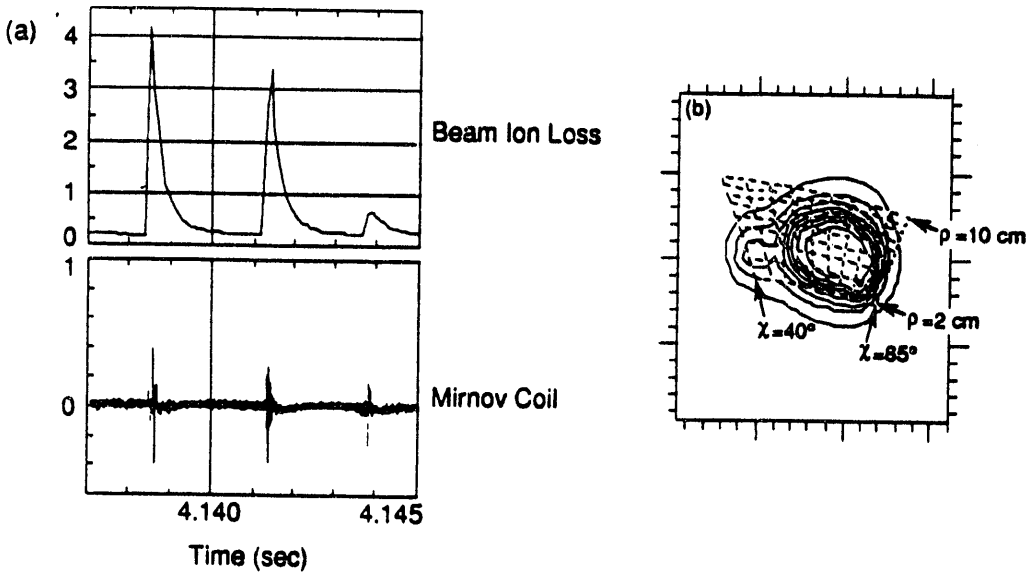

Figure 3

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