Excitation of Toroidal Alfvén Eigenmodes in TFTR

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Deuterium neutral beams with energies up to 110 keV were injected into TFTR (Tokamak Fusion Test Reactor) plasmas at low magnetic field such that the beam injection velocities were comparable to the Alfvén velocity. Excitation of toroidal Alfvén eigenmodes was observed by Mirnov coils and beam emission spectroscopy.

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As the plasma parameters in large tokamaks approach the fusion reactor regime, α-particle physics becomes the focus of attention in controlled thermonuclear research.[1] The 3.5-MeV α particles from D-T reactions are born with velocities faster than the Alfvén velocity V_A and are expected to interact strongly with shear Alfvén waves.[2] In a tokamak, shear Alfvén waves which satisfy the Alfvén resonance condition ($\omega = k_\parallel V_A$) can only exist in specific frequency bands with gaps between them. This is analogous to the energy bands for valence electrons in a crystal lattice.[3] Recent theories show that toroidal Alfvén eigenmodes (TAE) can exist within a frequency gap[4] and have a very low instability threshold.[5-7] In ignited tokamaks, they can be driven unstable by the energetic α particles. These modes present an obvious danger to fusion reactors because they are predicted to be very effective in ejecting the high-energy α particles from the plasma. Numerical calculations[8] indicate that a low-amplitude TAE mode with $\tilde{B}/B = 5\times10^{-4}$ can remove the fast α particles from a tokamak before thermalization so that one may not be able to sustain the fusion burn. In addition, the present design of the International Thermonuclear Experimental Reactor (ITER) relies on 1.3-MeV neutral beams to drive the tokamak current. Expulsion of energetic particles by TAE modes driven by the fast-beam particles can substantially reduce current drive efficiency. Therefore, it is important to investigate the properties of this instability. A simulation experiment using neutral-beam injection into TFTR was first proposed[9] in 1988 with a narrow operating regime identified at low magnetic field near 10 kG such that the Alfvén velocity was comparable to the injection velocity V_b of 100-keV deuterium neutral-beam ions. This experiment was recently carried out in TFTR. The results are presented in this paper.

Up to 14 MW of nearly balanced (no net toroidal momentum input) deuterium neutral beams with 110-keV maximum energy were tangentially injected into plasmas with the following parameters: $B \geq 10$ kG, $q(a) \geq 2.8$, $R_0 = 240$ cm, $a = 75$ cm, $n_e \sim 3\times10^{13}$ cm^{-3}, $T_e(0) \sim 2$ keV, $\langle\beta\rangle \sim 1\%$. Bursts of magnetic fluctuations near the TAE frequency appeared in the Mirnov-coil signals when the beam power was above 5 MW and the plasma density was sufficiently high that $V_b/V_A > 0.7$. The Mirnov-coil signals were digitized at 500 kHz for fast-Fourier-transform analysis. Among various MHD activities, an easily identifiable peak near the TAE frequency showed up as depicted in Fig. 1(a). This peak faded away when the magnetic field was raised without changing $q(a)$. Figure 1(b) shows the variation of the frequency spectrum with neutral-beam power injected into plasmas at a fixed field of 10 kG. The mode excited at 82 kHz was identified as having a toroidal mode number $n = 2$. The TAE frequency can be estimated by[7] $\omega = V_A/2qR_0$, where the values of V_A and q should be taken on the flux surface at which the mode has maximum amplitude. In our experiment, the density profiles were quite flat and all the dominant ion species have a mass-to-charge ratio of 2. We calculated V_A with the electron density at $R = 280$ cm as deduced by Abel inversion of data from a ten-channel infrared interferometer. The uncertainty in V_A is small. However, the uncertainty in q is large. The value of q is expected to be between 1 and 2. The measured frequencies are plotted against their theoretical estimates in Fig. 1(c) with $q = 1.5$. Theoretically, the TAE frequency is proportional to the Alfvén speed. This was verified by changing the plasma density and the magnetic field. The measured frequencies are slightly higher than the theoretical values. There is good agreement with theory if we choose q to be 1.3. In these shots, the net toroidal momentum input from the neutral beams was small so that the plasma rotation velocity was small and the Doppler shift in frequency was not important. Helium-target plasmas were also used in the experiment, and the measured frequencies followed the same trend as shown in Fig. 1(c).

The Mirnov coils are located outside the plasma. To be more specific about the mode structure, we need an internal measurement of these oscillations with good spatial resolution inside the plasma. Our experiment was operated at very low magnetic field and electron temper-

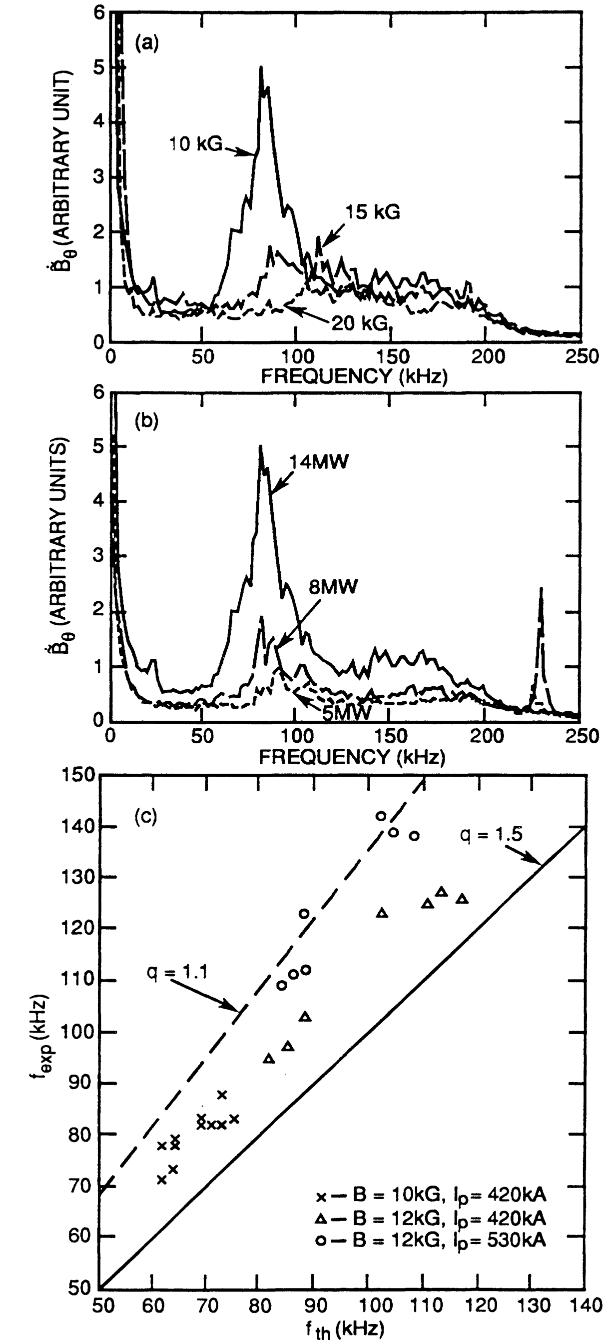

FIG. 1. (a) Frequency spectrum of Mirnov-coil signal from plasmas with $\langle\beta\rangle \sim 1\%$ at various magnetic fields. (b) Variation of frequency spectrum with neutral-beam power. (c) Comparison of experimentally measured frequencies with theoretically calculated TAE frequencies.

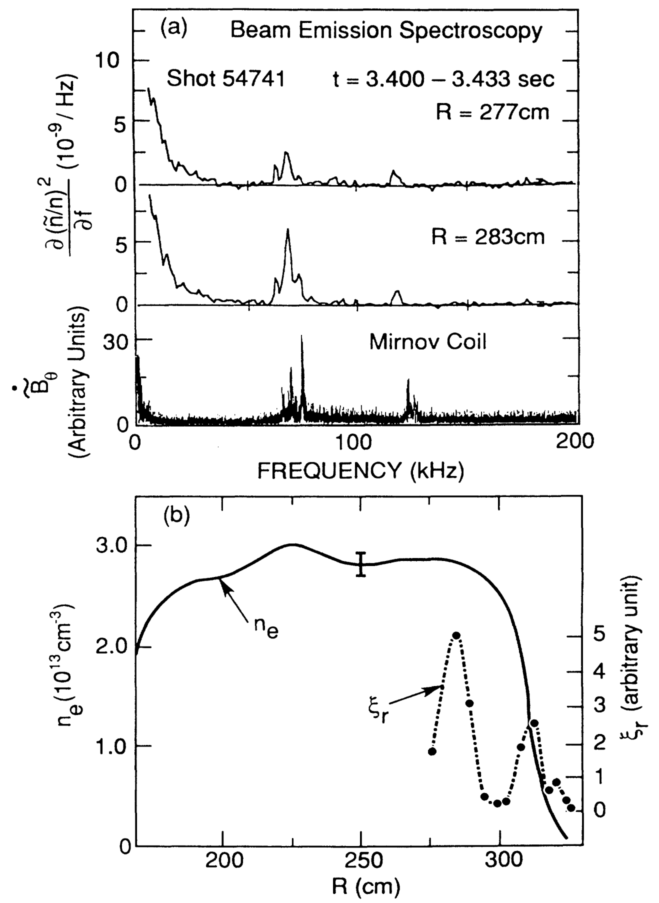

FIG. 2. (a) Comparison of fluctuation spectra from beam-emission-spectroscopy data and Mirnov-coil data. (b) Variation of inferred plasma radial displacement and electron-density profile.

ature, far away from the normal operating regime of TFTR. Many standard diagnostics, e.g., electron cyclotron emission, x-ray imaging system, microwave scattering, microwave reflectometer, etc., could not be used to study the TAE mode. Instead, we used the recently installed beam-emission-spectroscopy[10] (BES) system to measure the density oscillations associated with the TAE modes at $R > 265$ cm with a radial resolution of 3 cm. Figure 2(a) shows the frequency spectrum of $(\tilde{n}/n)^2$ at two different locations on the horizontal midplane. The frequency is very close to that observed on the Mirnov coils. The density-fluctuation level is proportional to the product of the plasma displacement and the density gradient ($\tilde{n} \propto \xi \nabla n$). The BES system measured two local maxima of $\tilde{n}/n$ at $R = 283$ and 315 cm with a node near $R = 300$ cm. The largest signal was at $R = 315$ cm where the density gradient was large. After dividing by the density gradient, we found that ξ_r, the radial component of ξ, had a radial standing-wave structure as depicted in Fig. 2(b). Although the error in the measurement of $\tilde{n}/n$ is within a few percent, large uncertainties in ξ_r at $R < 290$ cm result from the small density gradient associated with the flat density profile.

A cross-power spectral analysis shows coherence (significantly above noise level) between signals from the Mirnov coils and from various BES channels at the TAE frequency. Since these two diagnostics are triggered separately, it is important to make sure that we correlate signals at the same time. The coherence remains the same whether the TAE bursts correlate with a sawtooth crash or not. The BES channels approximately cover a range of 40 cm radially and 10 cm poloidally. Signals from all channels exhibit high coherence. Cross-phase spectra showed that there was no propagation in the radial direction, and a large phase shift was measured across the node at $R=300$ cm. Poloidal wavelengths of 36 cm at $R=291$ cm and 44 cm at $R=310$ cm were measured, corresponding to poloidal mode numbers of $m\sim6$ and $m\sim8$, respectively.

TAE modes are mainly driven by the pressure gradient of the energetic circulating ions. When $V_b\sim V_A$, the growth rate can be estimated from the following relation:[5]

$$\gamma/\omega=\tfrac{9}{4}\,[\beta_b(\omega_{*b}/\omega-\tfrac{1}{2})F-\beta_e V_A/V_{Te}]\,, \qquad (1)$$

where ω is the TAE frequency, ω_{*b} is the diamagnetic drift frequency of the energetic particles, V_{Te} is the electron thermal velocity, $F=x(1+2x^2+2x^4)\exp(-x^2)$ with $x=V_A/\langle V_b\rangle$, $\langle V_b\rangle$ is the average beam particle velocity, and β_b and β_e are the ratios of particle pressure to magnetic-field pressure for the energetic particles and the electrons, respectively. A ten-channel neutron collimator[11] was used to measure the neutron-emission profile of the plasma. Each channel at a fixed major radius collects neutrons emitted along its sight line, similar to interferometer measurements of line-integrated electron density. After substraction of the background noise, the data for a 10-kG plasma are shown in Fig. 3. The radial profiles of neutron emissivity can be obtained by Abel inversion.[12] With the assumption of a flat $Z_{\rm eff}$ profile and a dominant beam-target neutron production by the same beam velocity distribution, we obtained the beam-density profile with an e-folding length L_b of 18 cm at $R=280$ cm. The addition of beam-beam neutron production would increase L_b. Analysis of the Mirnov-coil data reveals that the dominant instability is an $n=2$ mode and the frequency can be correctly estimated given $q=1.3$. For estimated values of $\beta_b\approx0.5\%$ and $\beta_e\approx0.3\%$, Eq. (1) yields $\gamma/\omega\approx0.04$ which is clearly unstable, even if β_b is much lower. When we raised the magnetic field to 12 kG, the $n=3$ mode became dominant and $\gamma/\omega\approx0.03$. In both cases, the driving term in Eq. (1) is an order of magnitude larger than the damping term. It is quite possible that there are other more important stabilizing mechanisms not included in Eq. (1), for instance, finite-ion-Larmor-radius (FLR) effects. For $B=12$ kG, $m=3.5$, we have $k_\theta\rho_b\approx0.27$ for the beam ions with isotropic average energy of 30 keV. Velocity anisotropy tends to reduce $k\rho_b$, but inclusion of the radial component k_r will make $k\rho_b$ larger. Nevertheless, we expect FLR effects to play an important role. The FLR effects enter through the guiding-center drift velocity which can detune the transit resonance.[7] This is not included in the derivation of Eq. (1). Since the driving term increases linearly with m which increases with n for a fixed q value, FLR effects may be the mechanism which sets upper limits on the mode numbers m,n that can go unstable. This is consistent with our experimental observations. It leads us to speculate that the high-n modes[7] may be first to go unstable in reactors with high magnetic field where the energetic α particles have small gyroradii. More work is needed in this area for better understanding of this instability.

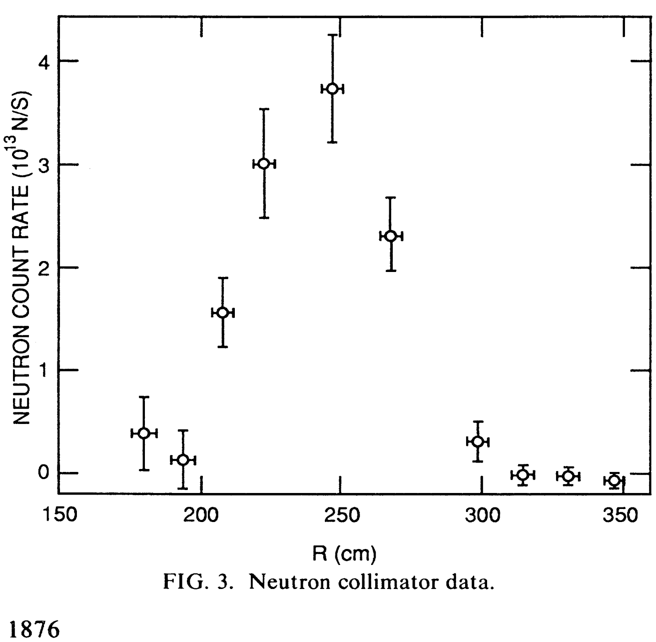

FIG. 3. Neutron collimator data.

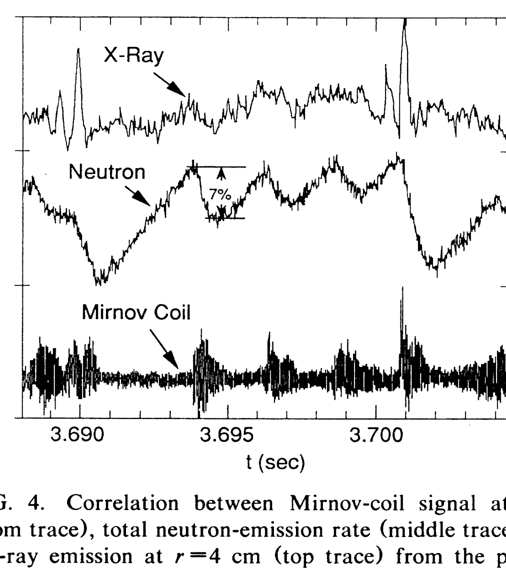

FIG. 4. Correlation between Mirnov-coil signal at $\theta=0$ (bottom trace), total neutron-emission rate (middle trace), and soft-x-ray emission at $r=4$ cm (top trace) from the plasma. The vertical scale is linear with zeros suppressed.

TAE modes are important because they can eject energetic particles from the plasma. Evidence for this was observed in our experiment. Figure 4 shows the correlation between the magnetic-fluctuation amplitude, neutron-emission rate, and the soft-x-ray signal. The toroidal plasma rotation frequency inferred from those $m=1$ oscillations in the x-ray signal is 1.5 kHz, negligible compared with the TAE frequency. There were two sawtooth crashes during the sampling interval, one at $t=3.690$ s and the other as 3.701 s, which apparently triggered the corresponding high-frequency oscillations. This can be understood as follows: a sawtooth crash expels energetic ions from the center and temporarily reduces L_b; moreover, it generates a broad spectrum of magnetic perturbations and the plasma behaves like a narrow-band amplifier which selects the resonant Fourier component and amplifies it. The central three bursts of oscillations were probably triggered by events not detected by the x-ray detector. Each burst was accompanied by a drop in the neutron emission, indicating transport of energetic particles from the plasma core. In this experiment, the plasma total β was approximately 1%, about half the Troyon and Gruber limit.[13] The poloidal β was near unity so that the plasma was not near the ballooning-stability limit. This avoids the ambiguity associated with pressure-driven ballooning modes,[14] and the low-β assumption employed in the theory[4-7] can be justified. Fishbone instabilities[15] driven by trapped energetic particles have much lower frequencies (below 20 kHz) which can easily be differentiated from the TAE modes. The high-frequency events observed during neutral-beam injection in the PDX[16] and PBX[17] experiments exhibit some features similar to the TAE modes described in this paper.

In conclusion, we have demonstrated that energetic ions with velocities comparable to the Alfvén velocity can excite magnetic fluctuations near the theoretical TAE frequency. The threshold appears to be higher than existing theoretical predictions. These fluctuations disappear at high magnetic field. The variation of frequency with Alfvén velocity and the radial standing-wave structure measured by beam-emission spectroscopy support the conclusion that these are TAE modes. The corresponding decrease in neutron emission during bursts indicates that some energetic particles are ejected from the plasma core by these modes. This may cause difficulties for sustaining the fusion burn in an ignited tokamak, or achieving neutral-beam current drive with super-Alfvénic beams.

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