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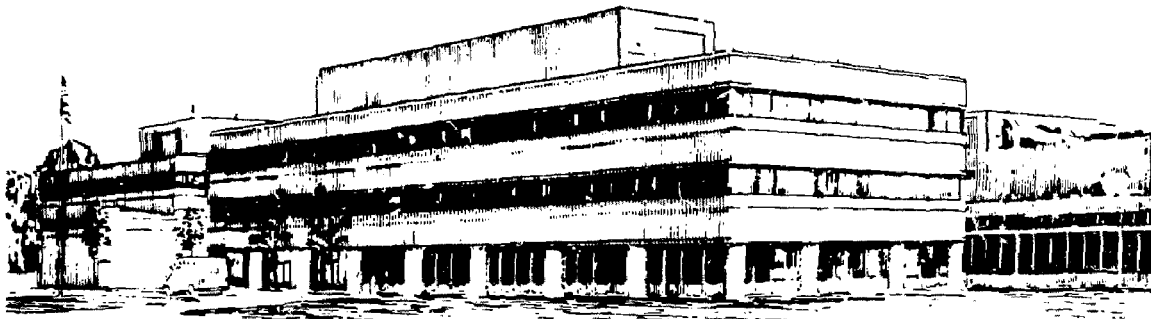
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EXCITATION OF TOROIDAL ALFVÉN EIGENMODES IN TFTR

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Abstract

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, alpha particle physics becomes the focus of attention in controlled thermonuclear research¹. The 3.5 MeV alpha 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 electrons in a crystal lattice. Recent theories show that toroidal Alfvén eigenmodes (TAE) can exist within a frequency gap³ and have very low instability threshold.⁴⁻⁶ In ignited tokamaks, they can be driven unstable by the energetic alpha particles. These modes present an obvious danger to fusion reactors because they are predicted to be very effective in ejecting the high energy alpha particles from the plasma. Numerical calculations⁷ indicate that a low amplitude TAE mode with $\tilde{B}/B = 5 \times 10^{-4}$ can remove the fast alpha 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 in 1988⁸ with a narrow operating regime identified at low magnetic field near 10kG 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, $n_e \sim 3 \times 10^{13} \text{ cm}^{-3}$, $T_e(0) \sim 2$ 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 $q(a)$. Fig.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 by⁶ $\omega = V_A/(2qR_0)$ 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 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 temperature, 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 spectroscopy⁹ (BES) system to measure the density oscillations associated with the TAE modes at $R>265$ cm with a radial resolution of 3 cm. Fig.2(a) shows the frequency spectrum of $(\tilde{n}/n)^2$ at two different locations on the horizontal mid-plane. 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 ($\tilde{n} \propto \xi \cdot \nabla n$). The BES system measured two local

maxima of \tilde{n}/n at $R=283$ cm 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. The BES channels approximately cover a range of 40 cm radially and 10 cm poloidally. Signals from all channels exhibit high coherence. Cross-phase spectrum 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 $m\sim 6$ and $m\sim 8$, respectively.

TAE modes are driven by the pressure gradient of the energetic circulating ions. When $V_b \sim V_A$, the growth rate can be estimated from the relation⁴:

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

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 was used to measure the neutron emission profile of the plasma. Each channel at a fixed major radius collects neutrons emitted along its sightline, similar to interferometer measurements of line-integrated electron density. After subtracted the background noise, the data for a 10kG plasma are shown in fig.3 . The radial profiles of neutron emissivity can be obtained by Abel inversion.¹⁰ With the assumption of a flat Z_{eff} profile and a dominant beam-target neutron production, 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 $\beta_b = 0.5\%$ and $\beta_e = 0.3\%$, eq.(1) yields $\gamma/\omega = 0.04$ 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 $\gamma/\omega = 0.03$. 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 $k_\theta \rho_b \approx 0.27$ for the beam ions with isotropic velocity $\langle v_b \rangle$. 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.⁶ 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 modes⁶ may be first to go unstable in reactors with high magnetic field where the energetic alpha particles have small gyroradii. More work is needed in this area for better understanding of this instability.

TAE modes are important because they can eject energetic particles from the plasma. Evidence for this was observed in our experiment. Fig.4 shows the correlation between the magnetic fluctuation amplitude, neutron emission rate and the soft x-ray signal. The plasma rotation frequency inferred from 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 $t=3.690s$ and the other at $3.701s$, 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 reduce L_D ; 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 beta was approximately 1%, about half the

Troyon limit. The poloidal beta was near unity so that the plasma was not near the ballooning stability limit. This avoids the ambiguity associated with pressure driven ballooning modes, and the low- β assumption employed in the theory³⁻⁶ can be justified. Fishbone instabilities driven by trapped energetic particles have much lower frequencies (below 20kHz) which can easily be differentiated from the TAE modes.

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 prediction. 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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FIGURE CAPTIONS

Figure 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.

Figure 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.

Figure 3. Neutron collimator data.

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

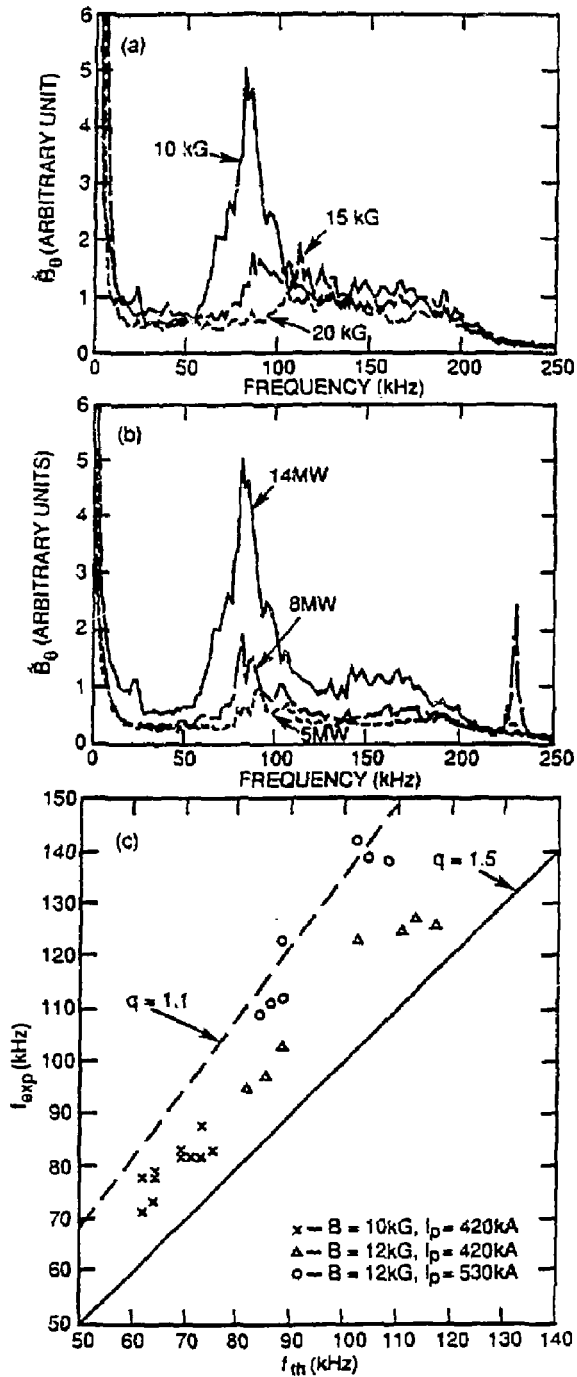


Fig. 1

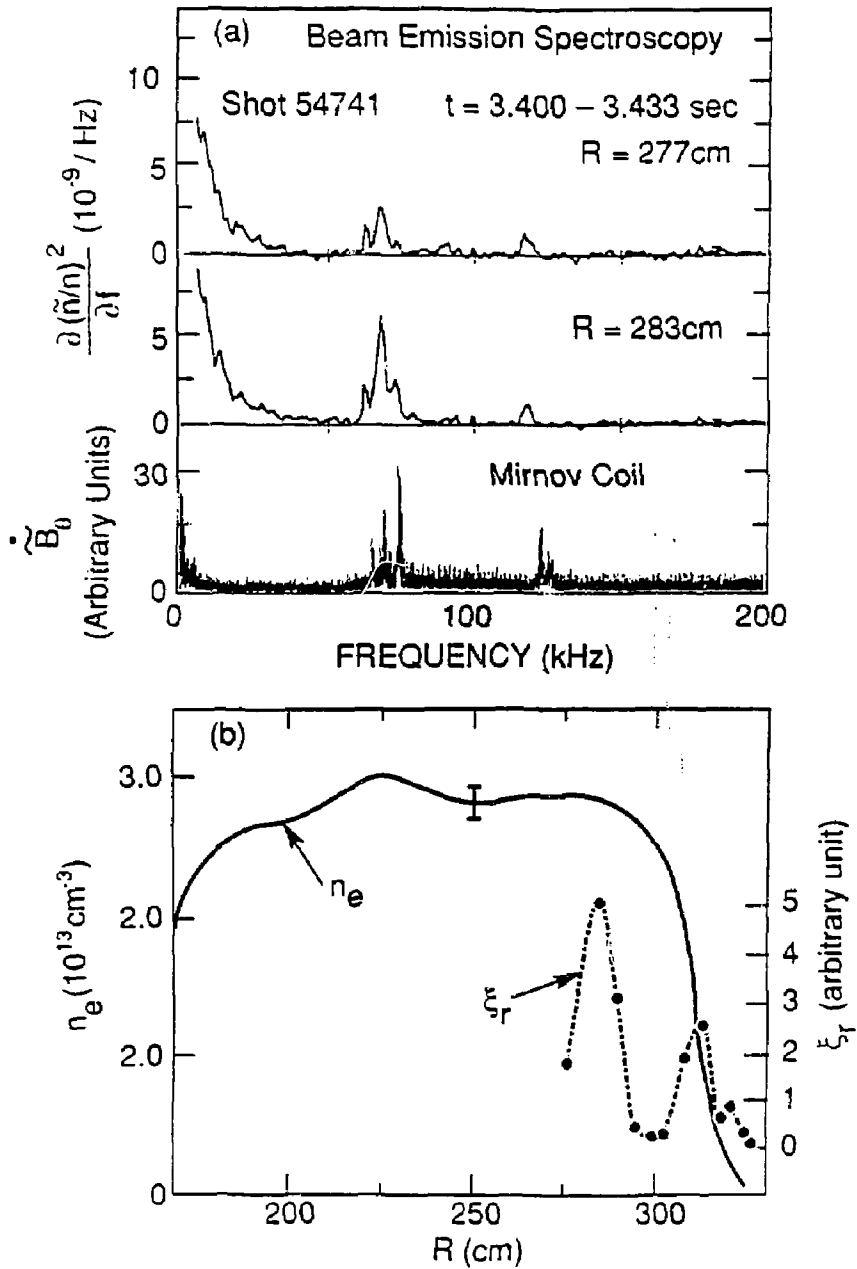


Fig. 2

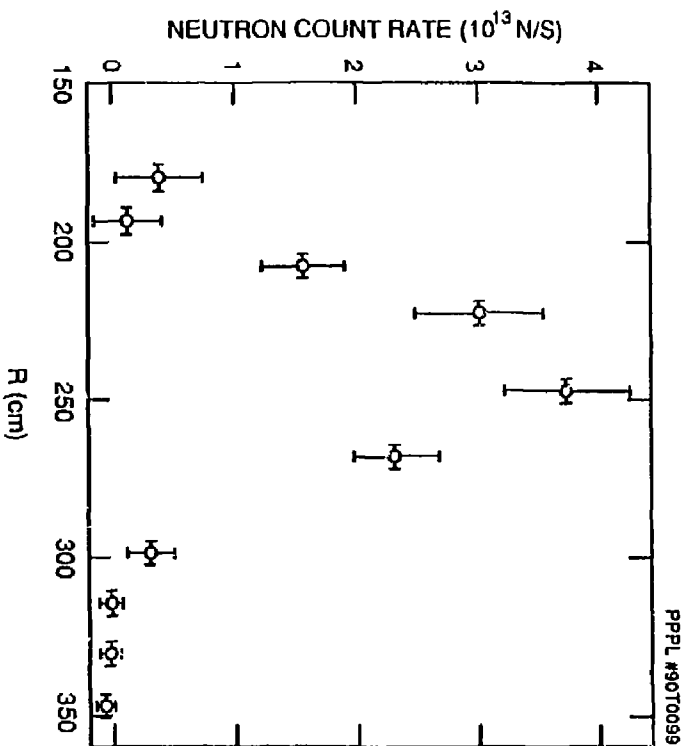


Fig. 3

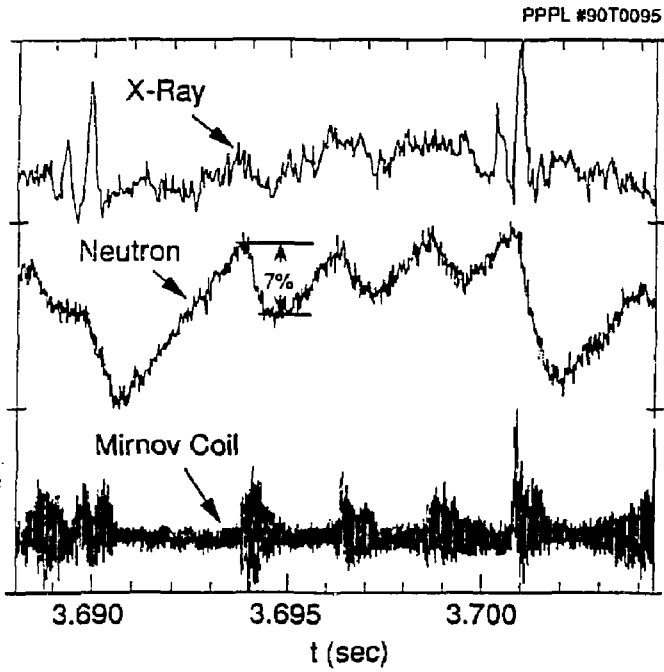


Fig. 4