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Beam-driven energetic particle modes in advanced tokamak plasmas

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Abstract

A major goal of the DIII-D program is to study ‘advanced tokamak’ plasmas with good confinement, large normalized β , and a large fraction of self-sustained current. Many of these plasmas have large beam pressures ($\lesssim \frac{1}{3}$ of the total pressure) and weak magnetic shear; Alfvén instabilities with laboratory frequencies of 100–250 kHz are often observed. The instabilities correlate with reductions in the neutron rate below the classically expected value, complicating determination of the pressure and current profiles. Quantitative analysis of one case suggests that two types of energetic particle modes are destabilized: the resonant toroidicity-induced Alfvén eigenmode and the resonant kinetic ballooning mode. The strong dependence on neutral beam injection parameters and the variability in mode frequency are qualitatively consistent with this identification. Further analysis and measurements are planned.

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1. Introduction

Beam-driven instabilities with frequencies below the frequency of toroidicity-induced Alfvén eigenmodes (TAEs) but above the frequency of tearing modes and fishbones have been observed in DIII-D since 1991 [1]. Subsequent analysis failed to establish conclusively the identity of this instability [2], which was called the β -induced Alfvén eigenmode (BAE) in the initial publication. Around 1995, several theoretical groups [3–5] suggested that these modes could be a type of ‘energetic particle mode’. Energetic particle modes are waves that do not exist in the absence of a fast-ion population; they often resemble a normal mode of the background plasma but the frequency is determined primarily by a characteristic frequency of the fast-ion distribution function [3]. Two branches of energetic particle modes are potentially involved: a resonant TAE that has a lower frequency than the standard TAE and a resonant kinetic ballooning mode (KBM) that has a higher frequency than an ordinary ballooning mode.

This paper reviews recent work on this topic. An example of the degradation in beam-ion confinement associated with the Alfvén instabilities is given in section 2. Section 3 summarizes a recent paper that compares one representative case with energetic particle mode theory [6]. In section 4, data from a comprehensive study [2] of these instabilities are re-examined. Plans for future work are outlined in the final section.

2. Impact of Alfvén modes on projected performance of advanced tokamak plasmas

The current focus of the DIII-D program is the study of ‘advanced tokamak’ plasmas, i.e. potentially steady-state plasmas with large fusion reactivity in a small volume. Much attention is focused on plasmas with negative central magnetic shear and an internal transport barrier. In a planned demonstration of an advanced tokamak plasma, the plasma current will be sustained against resistive diffusion by electron cyclotron current drive; adequate efficiency requires a fairly low electron density ($\bar{n}_e \lesssim 5 \times 10^{19} \text{ m}^{-3}$). Deuterium 80 keV neutral beams are the primary heating source. In a high-temperature, low-density plasma the beam-ion pressure is large. This large beam pressure often destabilizes the Alfvén modes. Although less deleterious to performance than neoclassical tearing modes or resistive wall modes, the Alfvén instabilities complicate formation and control of advanced tokamak plasmas.

Extensive analysis of a representative discharge (#99411) was reported in [7]. This potential advanced tokamak target plasma (figure 1) had a $\beta_N H_{89P}$ product in excess of ~ 10 for two energy confinement times and the bootstrap current constituted $\sim 55\%$ of the total current. (Here $\beta_N = \beta/(I/aB)$ is the normalized beta and H_{89P} is the confinement time normalized to a standard scaling law [8].) The analysis

Figure 1. Time evolution of the 1.2 MA, 1.6 T discharge (#99411) analysed by Murakami *et al* [7].

Figure 2. The ratio of the measured neutron rate to the rate calculated by TRANSP for $D_B = 0$ and the spectrograph of magnetic fluctuations in discharge #99411. The nominal frequency of the centre of the TAE gap $v_A/4\pi qR$ and the toroidal rotation frequency (multiplied by a typical toroidal mode number of 4) are also shown; both quantities are evaluated near the minimum q surface.

suggested that, with adequate electron cyclotron power, the plasma pressure and current profiles could be sustained against resistive diffusion. Unfortunately, due to the Alfvén instabilities in this discharge, the beam-ion profile is highly uncertain, so the projections are of questionable validity.

A spectrograph from a magnetic coil (figure 2) indicates extensive coherent activity between 100 and 200 kHz both before and after the formation of the internal transport barrier. These modes have frequencies in the usual range for the Alfvén modes at DIII-D [2]. At the time of the peak in the neutron rate, the Doppler-corrected [9] mode frequency is $\sim 75\%$ of the frequency at the center of the TAE gap. Throughout the discharge, the experimentally measured volume-average neutron rate is significantly smaller than the rate calculated by the TRANSP code [10] under the assumption of classical beam deposition

Figure 3. Neutron rate calculated by TRANSP for various values of beam-ion diffusion coefficient D_B together with the measured neutron rate (discharge #99411).

and collisional thermalization (figure 2), suggesting appreciable beam-ion transport associated with this magnetic activity.

Figure 3 analyses the degradation of the beam-ion confinement in more detail. The TRANSP code permits introduction of an *ad hoc*, spatially constant, beam-ion diffusion coefficient that is independent of energy and pitch angle. Comparison with the measured neutron rate indicates that a diffusion coefficient of roughly $1 \text{ m}^2 \text{ s}^{-1}$ is needed to account for the measured rate. Comparison of the measured stored energy with the classical prediction provides a useful check on this conclusion [11]; an assumed beam-ion diffusion coefficient of $\sim 1 \text{ m}^2 \text{ s}^{-1}$ also improves the agreement with this measurement. Although this analysis is useful as an indication of the magnitude of the beam-ion transport, this *ad hoc* model cannot reliably predict the actual beam-ion profile, which depends on details of the resonant interaction between the instabilities and the beam ions.

The uncertainty in the beam-ion confinement implies large uncertainties in the plasma behaviour (figure 4). In the TRANSP modelling, the ion thermal diffusivity varies by a factor of two for different assumed values of D_B . Similarly, the

central beam-driven current density is uncertain by a factor of two. Obviously, our ability to extrapolate these results to other discharges is severely hampered by the beam-ion transport associated with the Alfvén modes. If the severity of the Alfvén modes changes significantly, the discharge evolution may change dramatically. Indeed, in recent experiments at higher toroidal field, the Alfvén activity is weaker and the discharge evolves differently.

3. Energetic particle mode analysis of a representative discharge

The instabilities discussed in the previous section were not identified theoretically. In this section, instabilities from a different advanced tokamak discharge are compared with the energetic particle mode theory embodied in the HINST [12] code. The analysis suggests that two types of energetic particle modes are observed in DIII-D plasmas: the resonant TAE and

the resonant KBM. As this comparison was already published [6], only a brief summary is given here.

The HINST code [12] is a non-perturbative, fully kinetic code that can reproduce both the resonant TAE and resonant KBM branches. A slowing-down distribution of passing beam ions is assumed, which is consistent with experimental observations [2] that passing beam ions are primarily responsible for mode excitation. The major limitation of the code is that it solves for a radially localized solution in ballooning coordinates so it cannot compute the full two-dimensional eigenfunction for conditions of low shear and medium mode numbers ($n = 3-5$).

The discharge selected for the comparison has modes with laboratory frequencies of ~ 100 kHz and ~ 200 kHz. The comparison is summarized in table 1. In light of the uncertainties in the comparison, the agreement is satisfactory, so we tentatively identify the lower-frequency mode as the resonant KBM and the higher-frequency mode as the resonant TAE.

Figure 4. Sensitivity of the inferred (a) ion (—) and electron (---) thermal diffusivities and the (b) beam-driven current density to the assumed value of beam-ion diffusion coefficient at 1.8 s in discharge #99411.

4. Re-examination of published BAE data

The apparently successful identification of the instabilities as energetic particle modes motivates a re-examination of the extensive observations reported in the paper entitled ‘What is the beta-induced Alfvén eigenmode?’ [2]. In [2], it was found that an extended database of observations did not scale with any basic parameter of the background plasma, including the Alfvén frequency, the ion diamagnetic frequency or the thermal ion transit frequency. If the instabilities are really energetic particle modes, this is expected for two reasons. First, the instabilities are *not* normal modes of the background plasma. Second, the theoretically predicted energetic particle mode frequency depends sensitively on the beam-ion distribution function, which differs greatly in different discharges.

Another feature that is consistent with identification as energetic particle modes is the extreme variability in frequency observed within a single discharge (figure 5). The measured frequencies appear to subdivide into two bands: the upper band is identified with the resonant TAE, while the lower band is identified with the resonant KBM. Even within a band, the frequency variation between subsequent bursts is quite large, typically four times larger than the estimated experimental error. Since the plasma parameters barely change between bursts, this variability is incompatible with identification of the instabilities as normal modes of the background plasma. On the other hand, because of anomalous beam-ion transport, the beam-ion distribution function almost certainly changes between bursts; so sudden changes in frequency are expected if the instabilities are energetic particle modes.

Table 1. Comparison between EPM theory and experiment for discharge #98549.

Property	Experiment	Theory	Comment
Plasma frequency	15 ± 9 kHz 108 ± 9 kHz	29 kHz (r-KBM) 96 kHz (r-TAE)	Lower β_B lowers theory Lower β_B raises theory
Radial location	Near q_{min} radius	Near q_{min} radius	For both modes
Growth rate	Both unstable r-KBM slightly more	Both unstable r-TAE slightly more	
Most unstable n	5 (15 kHz) 3–6 (108 kHz)	≤ 4 ≤ 4	Theory unreliable for $n \lesssim 5$

Figure 5. Mode frequency in the plasma frame normalized by the frequency at the centre of the TAE gap for six discharges with BAE activity (from [2]). The evolution of the β_N is also shown. Identification of the upper frequency band as the resonant TAE, the lower frequency band as the resonant KBM and the relatively large variability within a frequency band are indicated. The uncertainty in the frequency measurement is comparable to the symbol size. The absolute value of the nominal TAE frequency is approximately 65 kHz in 71524, 70 kHz in 77328, 80 kHz in 71517, 85 kHz in 75784 and 90 kHz in 71495 and 71496.

Experimentally, the mode stability is extraordinarily sensitive to beam injection parameters such as the injection energy and angle of injection. An example from [2] is shown in figure 6. In nearly identical discharges (figure 7), when 80% of the source power was injected by the more tangential (left) beams, the BAEs were quite unstable. When 60% of the source power was injected by the more tangential beams, the BAEs were barely observed. Within the framework of normal mode theory, this change in beam injection angle should reduce the instability drive $<25\%$, which is unlikely to stabilize a mode that apparently was driven strongly past marginal stability. On the other hand, within the framework of energetic particle mode theory, stronger than linear dependence on beam parameters is possible, so the stabilization of the activity is unsurprising.

In summary, a retrospective view of the data in [2] is compatible with identification of these instabilities as energetic particle modes.

5. Future plans

To date, quantitative comparisons of DIII-D data with energetic particle mode theory were only completed for a single discharge (section 3). In the near future, we plan to analyse

Figure 6. Spectra of magnetic activity for similar discharges with different angles of beam injection at 1.74 s for the discharge shown in figure 7 (from [2]). The numbers above the peaks are the toroidal mode numbers. The peaks imply [2] that the mode is most strongly excited near the minimum in q at $\rho \simeq 0.45$ and that the mode frequency in the plasma frame is approximately 10% of the frequency in the centre of the TAE gap, as expected for a resonant KBM. (Here ρ is the normalized square root of the toroidal flux.)

Figure 7. Comparison of plasma parameters for the two discharges in figure 6. The discharge with $\langle v_{\parallel}/v \rangle = 0.61$ is represented by the thin line; the thick line represents the discharge with $\langle v_{\parallel}/v \rangle = 0.57$. The toroidal field is 2.1 T. The fifth panel is the fraction of beam power injected by the more-tangential (left) beam sources. (The left beams on DIII-D inject at a tangency radius of $R_{\text{tan}} \simeq 1.10$ m, while the right beams inject at $R_{\text{tan}} \simeq 0.76$ m.)

nearly identical discharges with different beam injection parameters, including the pair illustrated in figures 6 and 7. Since energetic particle mode theory predicts a sensitive dependence on the beam-distribution function, this should be a stringent test of the applicability of the theory.

The anomalous beam-ion transport documented in section 2 motivates new diagnostics to measure the beam-ion profile. Two concepts are under consideration. In the first, an array of natural diamond detectors [13] will measure the active charge exchange flux from a modulated heating beam to infer the beam-ion density as a function of radius. In the second (figure 8), detection of 3 MeV protons as a function of pitch angle will be used to reconstruct the d–d emission profile [14]. Since beam–plasma reactions constitute $\sim \frac{2}{3}$ of the total number of fusion reactions in discharges such as the one shown in figure 1, the beam-ion density profile can be inferred from the d–d emission profile.

In addition to these immediate plans, a comparison of internal eigenfunction measurements with the predictions of a global code is highly desirable.

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Figure 8. (a) Calculated signal as a function of toroidal angle $\cos^{-1}(v_{\parallel}/v)$ for a 3 MeV proton detector at the bottom of the DIII-D vacuum vessel in discharge #99411. A d–d emission profile of the form $s \propto (1 - \rho)^3$ is assumed. (b)–(d) Poloidal projection of three of the orbits measured by the detector. This detector geometry is sensitive to beam-ion transport in the R direction.

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