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ALFVÉN EIGENMODES CAN LIMIT ACCESS TO HIGH FUSION GAIN STEADY-STATE TOKAMAK OPERATION

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Alfvén Eigenmodes Can Limit Access to High Fusion Gain, Steady-State Tokamak Operation

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Abstract. Experiments on the DIII-D tokamak show that Alfvén eigenmode (AE) activity degrades fast-ion confinement in many high β_N, high q_{min}, steady-state scenario discharges. (β_N is the normalized plasma pressure and q_{min} is the minimum value of the plasma safety factor.) An extensive set of diagnostics measure degraded fast-ion confinement: neutron detectors, fast-ion D$_\alpha$ (FIDA) spectrometers, neutral-particle analyzers, and fast-ion pressure inferred from the equilibrium. All fast-ion diagnostics that are sensitive to the co-passing population exhibit reductions relative to classical predictions. The increased fast-ion transport in discharges with strong AE activity accounts quantitatively for the previously observed reduction in global confinement with increasing q_{min}; however, not all high q_{min} discharges show appreciable degradation. We postulate that stochastic transport by multiple resonances with many small-amplitude AEs causes "stiff" fast-ion transport in this regime.

1. Introduction

Steady-state operation at high plasma pressure may improve the attractiveness of tokamak plasmas for fusion energy production [1]. In order to maintain the plasma in steady-state, the plasma current must be driven fully noninductively. Since the fraction of the total current carried by the intrinsic bootstrap current increases with the safety factor and normalized plasma pressure as $f_{BS} \propto q\beta_N$ [2,3], operation at high β_N minimizes the power required for externally driven current. For a strongly bootstrap-driven scenario in a power plant values of $\beta_N \gtrsim 4$ are anticipated. Values of β_N between 2.5-3.5 and edge safety factor $q_{95} \sim 5$ are envisioned for the steady-state ITER operating scenario [2].

Demonstration of a high β_N, steady-state operating scenario is a longstanding major goal of the DIII-D program [4]. In recent years, to achieve steady-state "high q_{min}" scenarios with broad current and pressure profiles, the facility has added additional gyrotron power for off-axis electron cyclotron current drive (ECCD) and tilted a beamline to inject off-axis. Recent publications have noted a tendency for reduced confinement with increasing q_{min} [5–8]. This observation motivates the experiments summarized here.

An empirical article on experiments conducted in 2013 was recently published [9]. The present paper summarizes those findings and includes additional data acquired in 2014. The paper concludes with the outlook for theoretical understanding of these results.

2. Summary of Published [9] Results

Discharges are formed using the techniques described in Refs [5] and [10] to achieve quasi-stationary, high β_N plasmas with minimal tearing-mode activity. Up to six co-injected deuterium neutral-beam sources are employed, usually with an injection energy of 81 keV. Nearly all of the discharges have an elongated, double-null divertor shape.

Many of the discharges with elevated q_{min} have degraded global confinement. Figure 1 compares the "H89" global confinement factor [11] for discharges in the present study with earlier data [8]. Although the correlation of confinement with q_{min} was strong in the earlier study, it is weaker in the present dataset. Nevertheless, many high q_{min} discharges do exhibit degraded confinement.

Virtually every discharge has AE activity and many also have unstable tearing modes. Typical AE toroidal mode numbers are $n = 2$–7. Usually a large number of AEs are observed; Fig. 2 shows a typical example.

Interferometer data such as that shown in Fig. 2 detect AE activity in the entire plasma. Data such as these from all available interferometer chord combinations are used to measure an "AE amplitude" that is a temporal

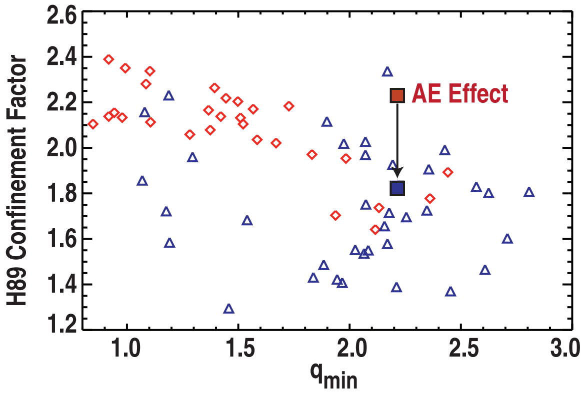

FIG. 1. "H98" global confinement scaling factor vs q_{min} for discharges in the steady-state scenario discharge database of Ref. [8] (diamond) and for the present study for discharges that are quasi-stationary for ≥0.4 s (triangle).The square symbol represents an extensively analyzed discharge, #153072, with degraded confinement of 1.8 [9]. If AEs were absent, estimates indicate that the global confinement factor for this discharge would exceed 2.2.

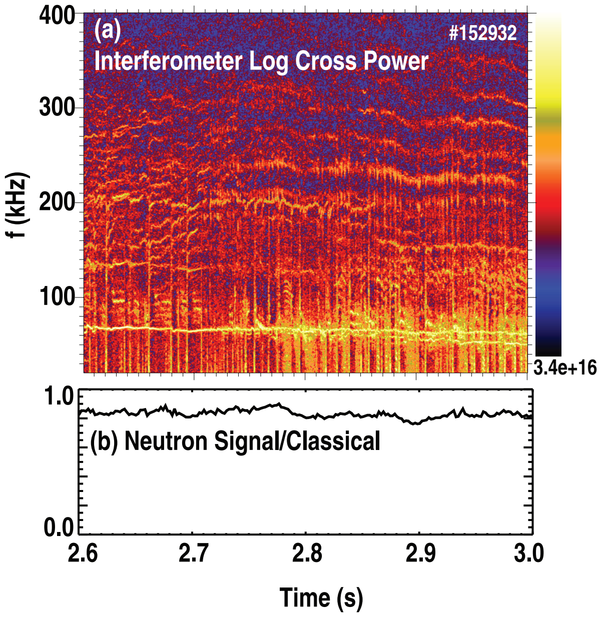

FIG. 2. (a) Cross-power of the two most central interferometer channels during the quasi-stationary period of a discharge with β_N = 2.8, q_{min} = 2.5, and H89 = 1.4. The "AE amplitude" during this period is 2.2 (au). (b) Ratio of measured neutron rate to classical calculation.

average of all coherent mode activity between the geodesic acoustic mode (GAM) frequency and the toroidal AE (TAE) frequency [9]. Local fluctuation diagnostics show that the AE activity occurs throughout much of the plasma volume. Figure 3 shows electron cyclotron emission (ECE) measurements of the AE profile for three of the modes in Fig. 2. The mode at 113 kHz is located near the q_{min} radius, which is at a normalized minor radius of $\rho \simeq 0.37$ in this discharge; this is probably a reversed shear AE (RSAE). The mode at 137 kHz is localized near the top of the H-mode pedestal. The mode at 153 kHz is a global mode at larger minor radius, probably a TAE.

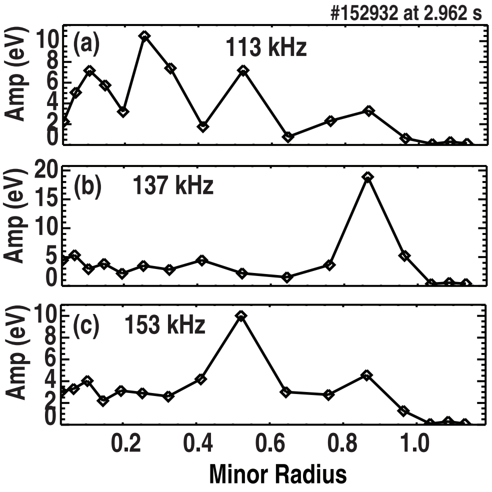

FIG. 3. ECE fluctuation amplitude vs ρ for three coherent modes at 2.962 s in the discharge of Fig. 2.

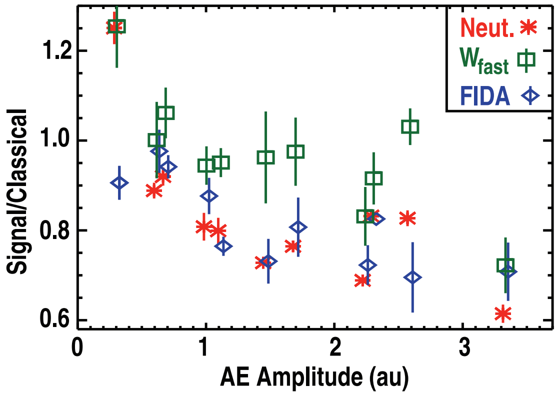

FIG. 4. Ratio of measured neutron (∗), fast-ion stored energy (square), and vertical FIDA (diamond) signals to classical predictions vs AE amplitude. The error bars represent the temporal variation during the stationary portion of the discharge.

The multiplicity of AEs has an adverse impact on fast-ion confinement. Figure 2(b) shows the ratio of the measured neutron rate to the classical value predicted by the TRANSP NUBEAM [12] code in the absence of any wave-induced transport. In this discharge, the ratio is ∼0.83, a typical value for a discharge with this level of AE activity. The degradation is observed by every fast-ion diagnostic that is sensitive to the portion of velocity space populated by injected beams. Figure 4 shows the correlation between three of these fast-ion signals and the "AE amplitude" for eleven carefully analyzed discharges. The neutron rate, the fast-ion stored energy W_f inferred from the difference between the equilibrium stored energy and the thermal stored energy, and the intensity of fast-ion D_α (FIDA) light from vertically-viewing chords all decrease with increasing AE amplitude. Similar reductions are observed by tangentially and obliquely-viewing FIDA channels. In contrast, the correlation of degraded fast-ion signals with the amplitude of tearing mode activity is weak [9].

These trends are very reproducible. A convenient estimate of the classically expected neutron rate is given by a “zero-dimensional” (0D) neutron code [13]. Figure 5 shows the ratio of the measured neutron rate to 0D prediction vs “AE amplitude” for 77 different steady-state scenario plasmas from the 2013 and 2014 experimental campaigns. The degradation of the neutron rate in plasmas with strong AE activity is consistently observed.

Analysis with the TRANSP [14] code suggests that the degraded fast-ion confinement accounts for the observed reduction in global confinement. Inclusion of ad hoc fast-ion diffusion within TRANSP lowers the predicted fast-ion signals. The assumed fast-ion diffusion can target different portions of phase space. Values of diffusion that bring the predicted neutron rate into agreement with experiment predict similar reductions in power delivered to the thermal plasma, irrespective of the targeted portion of phase space [9]. The AEs degrade global confinement two ways: by reducing the fast-ion stored energy and by reducing the power delivered to the thermal plasma. When the degraded fast-ion confinement is taken into account, the global transport remains at typical H-mode levels in discharges with elevated q_{min} (Fig. 1).

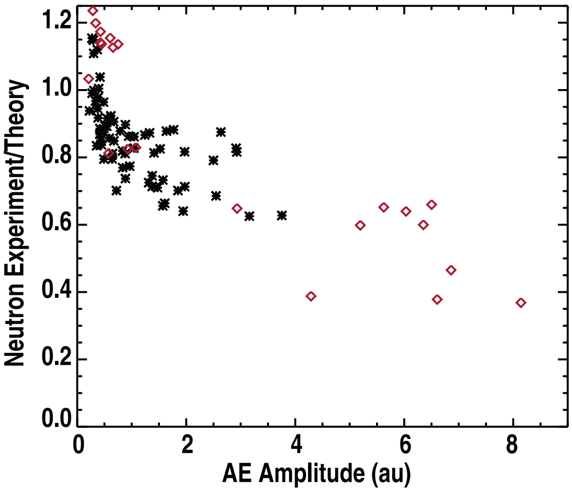

FIG. 5. Ratio of the measured neutron rate to the zero-dimensional prediction vs AE amplitude for the data in Ref. [9] (∗) and for new data collected during the 2014 campaign (diamonds).

3. Summary and Outlook

In conclusion, Alfvén eigenmodes degrade fast-ion confinement in many steady-state discharges with elevated q_{min}. This effect can account for the overall degradation in global confinement.

Calculations with the NOVA code [15] successfully predict linear AE instability in an analyzed high q_{min} discharge. Similar calculations with gyrofluid and gyrokinetic codes are underway. DIII-D results in L-mode plasmas suggest that the fast-ion transport becomes “stiff” above a critical gradient [16]. The likely physical mechanism is island overlap associated with the hundreds of resonances in high q_{min} plasmas with many unstable AEs [17]. The AE spectra in steady-state scenario plasmas resembles the L-mode spectra, suggesting that the same mechanism is operative here. One critical gradient model [18] has already achieved some success in predicting fast-ion profiles in L-mode plasmas [16,18]. Comparisons of this and other [19] critical gradient models with fast-ion data are planned.

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