GA–A27802

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

by
W.W. HEIDBRINK, J.R. FERRON, C.T. HOLCOMB, M. PODESTÀ,
M.A. VAN ZEELAND, and the DIII-D TEAM

AUGUST 2014

GENERAL ATOMICS

DISCLAIMER

GA–A27802

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

by

W.W. HEIDBRINK,* J.R. FERRON, C.T. HOLCOMB,† M. PODESTÀ,‡
M.A. VAN ZEELAND, and the DIII-D TEAM

This is a preprint of the synopsis for a paper to be presented at the Twenty-Fifth IAEA Fusion Energy Conf., October 13-18, 2014 in Saint Petersburg, Russia, and published in the *Proceedings*.

*University of California Irvine, Irvine, California.
†Lawrence Livermore National Laboratory, Livermore, California.
‡Princeton Plasma Physics Laboratory, Princeton, New Jersey.

Work supported by
the U.S. Department of Energy
under SC-G903402, DE-FC02-04ER54698,
DE-AC52-07NA27344, and DE-AC02-09CH11466

GENERAL ATOMICS PROJECT 30200
AUGUST 2014

GENERAL ATOMICS

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

EX-W

W.W. Heidbrink[1], J.R. Ferron[2], C.T. Holcomb[3], M. Podestà[4], M.A. Van Zeeland[2], and the DIII-D Team[2]
e-mail: Bill.Heidbrink@uci.edu

[1]University of California Irvine, University Dr., Irvine, CA 92697, USA
[2]General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, USA
[3]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550, USA
[4]Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543 USA

Fast-ion confinement is often adversely affected by Alfvén eigenmode (AE) activity in DIII-D steady-state scenario plasmas. A temporal correlation between AE modes and degradation in fast-ion confinement is often observed (Fig. 1). When the AE activity is strong, the measured neutron rate is reduced compared to "classical" predictions that ignore fast-ion transport by instabilities. Empirically, the degradation is quantified by an *ad hoc* fast-ion diffusion coefficient D_f. When the AE activity is weak or absent, the classical (D_f=0) prediction is consistent with experiment but when the AE activity is strong values of D_f as large as 3 m^2/s are needed to bring the predicted neutron rate into agreement with experiment.

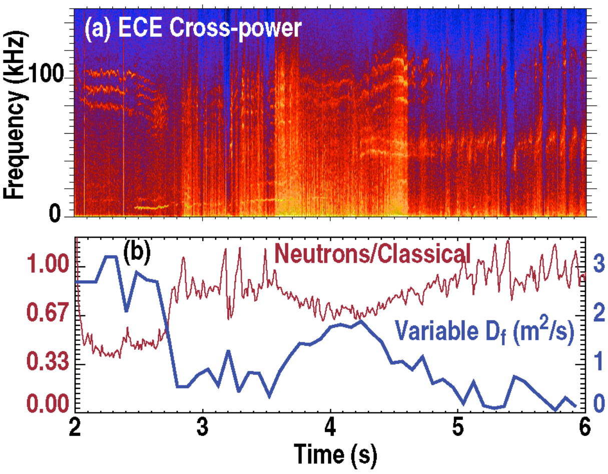

Fig. 1. (a) Fluctuations vs time in a high $q_{\min}$, steady-state scenario plasma. The modes above 60 kHz are AEs. (b) Measured neutron rate divided by a "classical" prediction that neglects transport by instabilities. The empirical value of fast-ion diffusion that gives agreement with the measured rate is also shown.

The experiments focus on the high $q_{\min}$, high β_N discharge scenario [1]. ($q_{\min}$ is the minimum value of the safety factor and β_N is the normalized plasma pressure.) In DIII-D, the noninductive current required for steady-state operation is provided by the combination of bootstrap current, off-axis electron cyclotron current drive (ECCD), and neutral beam current drive (NBCD) from 81 keV deuterium neutrals injected in the direction of the plasma current both on- and off-axis. However, in recent experiments [1], a degradation in overall confinement at elevated $q_{\min}$ lowered the fusion gain. The present experiments show that AEs caused the degraded confinement.

An extensive set of diagnostics measure degraded fast-ion confinement. These include: the volume-averaged neutron rate, fast-ion D_α (FIDA) profiles at four different angles with respect to the magnetic field, neutral-particle analyzer profiles of trapped ions, and fast-ion pressure and beam-current profiles inferred from the equilibrium. A pair of closely matched discharges with $q_{\min} \gtrsim 1$ and $q_{\min} \gtrsim 2$ are compared. The low $q_{\min}$ discharge has good confinement (normalized $H_{89} \simeq 2.3$), while the high $q_{\min}$ discharge has poorer confinement ($H_{89} \simeq 1.8$). In the low $q_{\min}$ discharge, the fast-ion signals agree well with classical predictions but, in the high $q_{\min}$ discharge, a fast-ion diffusion coefficient of $D_f \simeq 1.3$ m^2/s is needed to bring predicted signals close to experimental values.

The low $q_{\min}$ discharge has weak AE activity, while the high $q_{\min}$ discharge has strong AE activity. Fluctuations in the toroidal AE (TAE) band are measured by electron cyclotron emission, beam emission spectroscopy (BES), and interferometer diagnostics. Unstable AEs have toroidal mode numbers n=2-7 and, depending on the mode, eigenfunctions in the core, mid-radius, or edge. Here, the time-averaged sum of coherent peaks in the TAE band as measured by a combination of interferometer channels quantifies the strength of the AE activity. The high (low) $q_{\min}$ discharge has “AE amplitude”' of 3.7 (1.0).

Detailed analysis for 11 discharges finds a strong correlation between AE amplitude and the degradation in fast-ion signals (Fig. 2). The fast-ion signals are normalized by the classically-expected predictions. All fast-ion diagnostics that are sensitive to the co-passing population show a strong correlation with AE amplitude, while the correlation is weak for diagnostics that are sensitive exclusively to trapped or counter-circulating fast ions. These data strongly suggest that the intense co-circulating population both drives the AE activity and is most strongly affected by it.

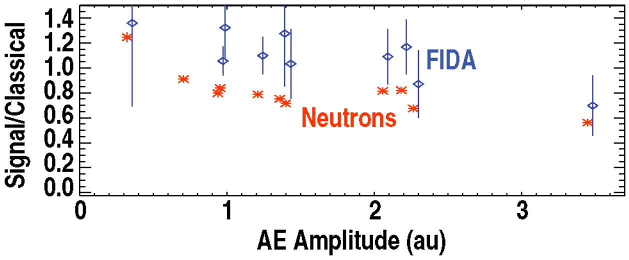

Fig. 2. Ratio of measured neutron and FIDA signals to the classical predictions vs the amplitude of AE. The FIDA data are for the sightline (~45°) that is most sensitive to the co-passing population.

A more extensive database of 65 discharges reinforces these conclusions. The correlation of degraded signals with tearing-mode activity is much weaker than the correlation with AE amplitude. Interestingly, the correlation with $q_{\min}$ is rather weak. Indeed, discharges with nearly classical fast-ion confinement exist that have $q_{\min}$ above 4 as long as the AE activity is weak.

There is no evidence that thermal confinement is degraded at high $q_{\min}$. Power-balance analysis of the carefully matched discharge pair with $q_{\min} \gtrsim 1$ and $q_{\min} \gtrsim 2$ shows that the enhanced fast-ion transport associated with the AEs can fully account for the reduction in overall confinement. Assuming that D_f=1.3 m^2/s, as needed to match the fast-ion measurements, the stored energy is directly reduced by ~10% due to the loss of fast-ion pressure and the beam power flow to the thermal plasma is ~37% smaller. These two effects account for the observed ~25% reduction in global confinement.

Stochastic transport by multiple resonances with many small-amplitude AEs probably causes the degraded fast-ion transport. The AE spectra in the steady-state plasmas resemble the spectra in DIII-D current-ramp plasmas. The latter have been studied extensively [2]. In current-ramp plasmas, the multiple, overlapping resonances cause the transport to be “stiff”; a critical gradient model appears to describe the fast-ion transport. As a result, a recent experiment found that, even though the linear AE stability is sensitive to changes in the fast-ion gradient, the achieved fast-ion profile is insensitive to the beam-deposition profile [2].

We postulate that a similar process occurs in the steady-state scenario plasmas. Theoretical analysis similar to that in Ref. [2] is underway. Linear MHD stability calculations find that AEs are more unstable in the $q_{\min} \gtrsim 2$ than in the $q_{\min} \gtrsim 1$ plasma, consistent with experimental trends. The first, preliminary, critical gradient calculations underpredict the fast-ion transport in the $q_{\min} \gtrsim 2$ plasma. Additional gyrofluid, gyrokinetic, and critical-gradient calculations are planned. A new fast-ion transport model that properly treats phase-space resonances is also modeling these plasmas.

This work was supported by the US Department of Energy under SC-G903402, DE-FC02-04ER54698, DE-AC52-07NA27344 and DE-AC02-09CH11466.

[1] J.R. Ferron, *et al.*, Phys. Plasmas **20**, 092504 (2013)
[2] W.W. Heidbrink, *et al.*, Nucl. Fusion **53**, 093006 and references therein (2013).