High-Energy Fast Ions Drive BAEs Unstable but not BAAEs

W. W. Heidbrink[1], M. A. Van Zeeland[2], M. Austin[3], A. Bierwage[4], X. Du[2], P. Lauber[5], Z. Lin[1], and G. J. Choi[1]

[1]*University of California Irvine, CA 92697, USA*
[2]*General Atomics, San Diego, CA 92186, USA*
[3]*University of Texas at Austin, Austin, TX 78712, USA*
[4]*National Institutes for Quantum and Radiological Science and Technology (QST), Chiba-shi, Japan*
[5]*Max-Planck-Institut für Plasmaphysik, Garching, 85748 Germany*
Corresponding Author: W. W. Heidbrink, bill.heidbrink@uci.edu

Published as a journal article in Nuclear Fusion
http://iopscience.iop.org/article/10.1088/1741-4326/ac189d

HIGH-ENERGY FAST IONS DRIVE BAES UNSTABLE BUT NOT BAAES

W.W. HEIDBRINK
University of California, Irvine
Irvine, USA
Email: bill.heidbrink@uci.edu

M.A. VAN ZEELAND
General Atomics
San Diego, USA

M.E. AUSTIN
University of Texas, Austin
Austin, USA

A. BIERWAGE
National Institutes for Quantum and Radiological Science and Technology
Aomori, Japan

LIU CHEN
University of California, Irvine
Irvine, USA

G.J. CHOI
University of California, Irvine
Irvine, USA

N.A. CROCKER
University of California, Los Angeles
Los Angeles, USA

X.D. DU
General Atomics
San Diego, USA

P. LAUBER
Max Planck Institute for Plasma Physics
Garching, Germany

Z. LIN
University of California, Irvine
Irvine, USA

G.R. MCKEE
University of Wisconsin, Madison
Madison, USA

D.A. SPONG
Oak Ridge National Laboratory
Oak Ridge, USA

Abstract

Although the stability of ellipticity, toroidal and reversed-shear Alfvén eigenmodes (EAE, TAE, RSAE) is relatively well understood, less is known about the stability of lower-frequency modes such as the beta-induced Alfvén eigenmode (BAE) and the beta-induced Alfvén-acoustic eigenmode (BAAE). Because they are often unstable in present devices and are implicated in fast-ion transport, understanding their stability is vital. In a dedicated DIII-D experiment with unstable low frequency modes of both types, the beam and electron cyclotron heating powers are altered for 50-100~ms durations in reproducible discharges to isolate the effect of different driving gradients. As expected from the resonance condition, BAEs depend sensitively on the magnitude and direction of the beam power. In contrast, modes that were previously identified as BAAEs remain unstable when the beams are turned off; in fact, these modes are unstable in plasmas without any beam heating. These low frequency modes (LFM) are probably not the BAAE of theory but a reactive instability of predominately Alfvénic polarization. In both the dedicated experiment and a database of over 1000 beam-heated discharges, the LFMs are only unstable in plasmas with hot electrons but modest overall beta. In contrast, BAEs are most likely to be unstable in plasmas with appreciable beam power and poloidal beta. Stability trends in hydrogen plasmas are similar to deuterium. The results suggest that the LFMs may not jeopardize high-energy alpha confinement in future devices but BAEs remain a threat.

1. INTRODUCTION

The beta-induced Alfvén eigenmode [1] (BAE) and beta-induced Alfvén-acoustic eigenmode [2] (BAAE) are two instabilities with frequencies below that of toroidal Alfvén eigenmodes [3,4] (TAE) and reversed shear Alfvén eigenmodes [5] (RSAE). Both the BAE [1,6] and the BAAE [7] have been implicated in degraded fast-ion confinement. Although much attention has been devoted to predictions of TAE stability in future devices, these potentially dangerous lower-frequency modes have received far less attention. The purpose of the dedicated DIII-D experiment summarized here is to provide additional information on BAE and BAAE stability, with the ultimate goal of providing well-validated stability predictions for ITER and other future devices. More complete documentation appears in two longer articles, one on the BAE [8] and one on the instability that was formerly identified as the BAAE that is now called a low frequency mode (LFM) [9].

2. SUMMARY OF RESULTS FROM THE DEDICATED EXPERIMENT

The dedicated experiment is conducted during the current ramp when the q profile is weakly reversed. Injection of ~80 keV deuterium neutral beams produces an anisotropic population of sub-Alfvénic fast ions that can potentially drive instability. Prior to the time of interest, the neutral beam injection and electron cyclotron heating (ECH) patterns remain identical on successive shots; consequently, the q profile and mode activity are highly reproducible shot-to-shot. At the time of interest, the beam and/or ECH patterns are modified to investigate the effect of fast-ion and thermal driving gradients on mode stability.

During the time of interest, three different types of instability occur, RSAEs, BAEs, and LFMs (Fig. 1). Electron cyclotron emission (ECE) data show that all three modes have radial eigenfunctions that peak near q_{min}, although there is some tendency for the BAE to peak closer to the magnetic axis (in the negative magnetic shear region) than the other two instabilities. All three modes depend sensitively on the value of q_{min}, which steadily decreases during the time of interest (Fig. 1b). RSAEs exhibit the "Alfvén cascades" first reported on JET [5]: at rational values of q_{min}, RSAEs with different toroidal mode numbers have similar frequencies in the plasma frame, then the frequencies sweep upward at different rates as time evolves. (The cascades when q_{min}=2 and 1.5 are marked in Fig. 1a.) In contrast, the LFMs are only unstable when q_{min} is close to an integer value; as a result, the LFMs appear in ascending patterns reminiscent of Christmas lights. The BAEs are also unstable when q_{min} approaches a rational value, although their appearance is less regular than for the LFMs (Fig. 1b). Another difference between the BAEs and the other instabilities is that, on a millisecond timescale, the BAE frequency chirps rapidly by ~10%, while the frequencies of LFMs and RSAEs hardly changes.

The toroidal rotation frequency at q_{min} and the temporal evolution of q_{min} are both known accurately, so the pattern of unstable BAEs and LFMs vs. time enables unique identification of poloidal and toroidal mode numbers *(m,n)* for each mode (Fig. 1a). The LFMs do not appear on magnetics so, for them, it is not possible to use the toroidal magnetics array to check the n number assignments; however, a set of discharges with high quality beam emission spectroscopy (BES) data confirm the correctness of the poloidal mode number assignments [9]. For the BAEs, data from the toroidal magnetics array confirm the toroidal mode number assignments for n=1-3 [8].

After correction for the Doppler shift, the LFM frequencies in the plasma frame are comparable to diamagnetic frequencies and are significantly lower than the frequency of the beta-induced Alfvén-acoustic gap in the continuum. For this reason, the modes are no longer identified as BAAEs [9]. The frequencies of the BAEs are close (typically within ~10%) of the BAE accumulation point in the Alfvén continuum [8].

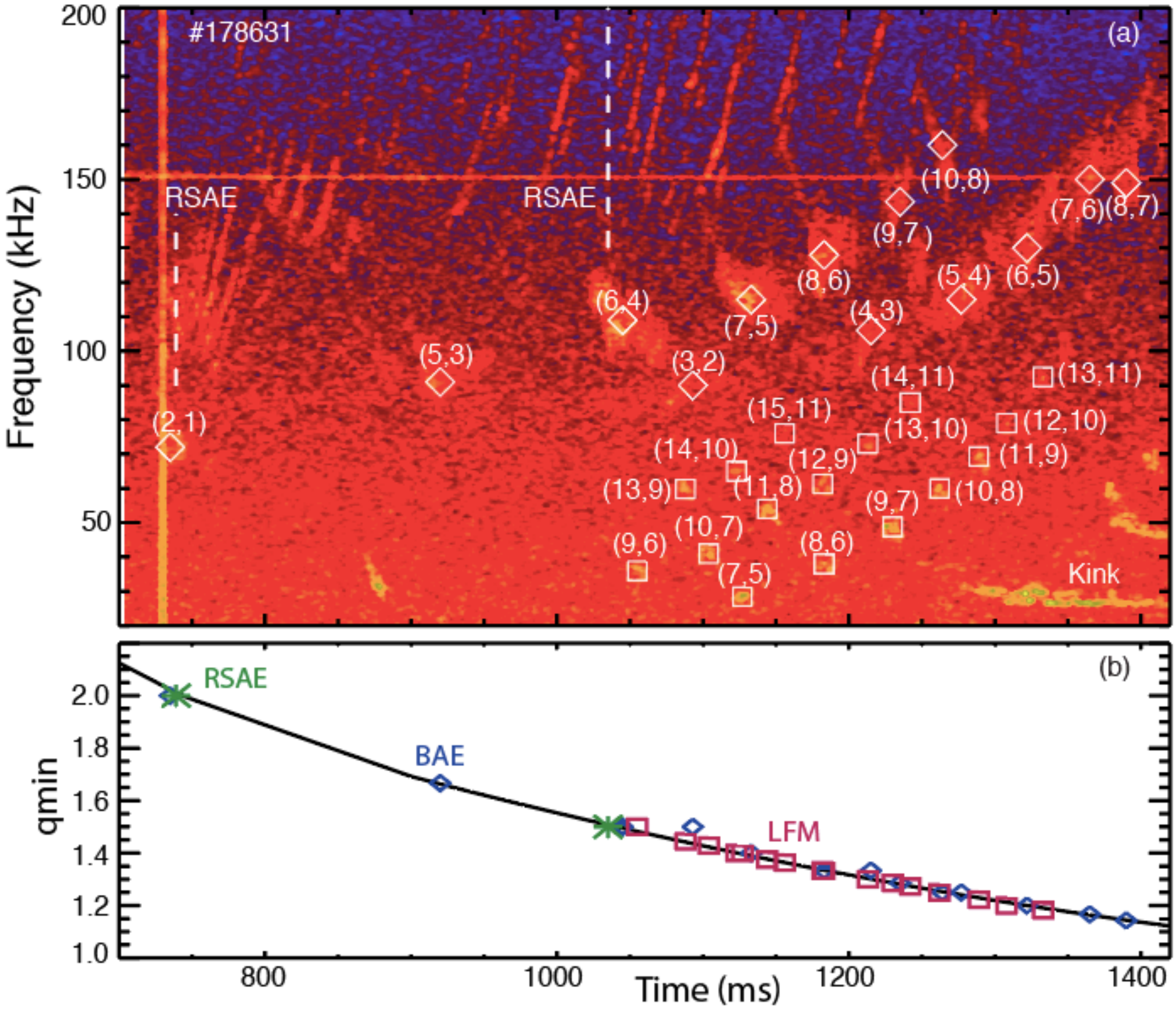

Figure 1. (a) Cross-power spectrogram in the reference shot of the dedicated experiment for ECE channels near q_{min}. The BAEs (diamonds) and LFMs (squares) are labelled by their (m,n) numbers. The dashed vertical lines are the times of q_{min}=2 and 1.5 crossings inferred from the RSAE activity on ECE and interferometer signals. (b) Measured q_{min} from EFIT reconstructions that use magnetics and motional stark effect (MSE) data vs. time. The RSAE (*), BAE (diamond), and LFM (square) symbols represent the values of m/n shown on the spectrogram.

The principal results of the dedicated experiment are illustrated in Fig. 2. When the tangential beams turn off, the BAE activity ceases in a time that is much shorter than the ~100 ms slowing-down time. In discharges where all of the beams turn off, RSAE activity also ceases, although it generally persists longer than BAE activity. In contrast, the activity in the lower frequency band persists unabated even in the absence of beam injection. Irrespective of the beam injection pattern, unstable LFMs are observed in all discharges of the dedicated experiment with sustained values of electron temperature T_e [9].

The BAEs in the dedicated experiment are driven by co-passing fast ions that are injected by the tangential neutral beam sources [8]. When perpendicular beams substitute for tangential beams, the BAEs quickly cease. The BAEs are unstable when the condition for resonant interaction between recently deposited tangential beams and the mode is satisfied. As q_{min} evolves, the resonances shift away from the anisotropic fast-ion population in phase space; these shifts appear to be the primary factor that determine the duration of instability for each individual BAE.

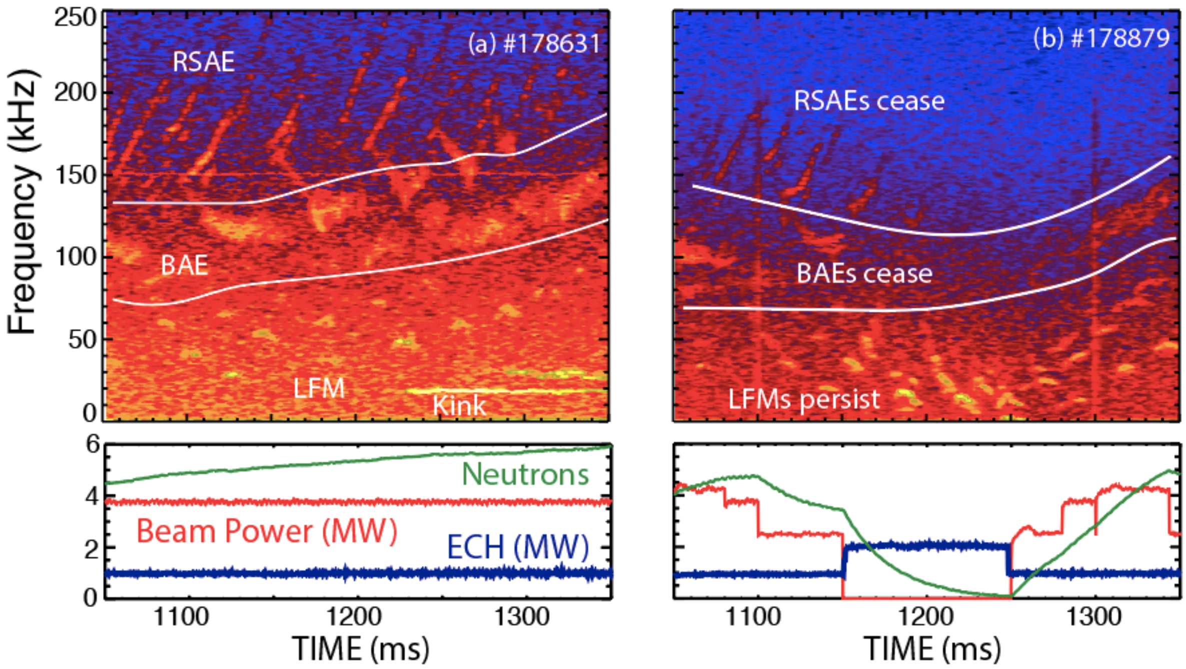

Figure 2. Cross-power ECE spectrograms in (a) the reference shot and (b) a discharge where the neutral beams temporarily turn off. When the beam power turns off, BAE activity ceases first, then RSAE activity ceases; the LFM activity persists throughout. (Because the plasma rotation slows when the beams are off, the Doppler-shifted LFM frequencies drop, then increase again when beam injection resumes.) The lower panels show the beam and ECH power traces and the neutron rate (in units of 10^{14} n/s).

3. SUMMARY OF DATABASE STUDIES OF LFM AND BAE STABILITY

Three sets of data were assembled for deuterium plasmas [8,9]. For all three databases, in each time interval, the mode activity was classified as “stable,” “marginal,” or “unstable” in the LFM, BAE, RSAE, and TAE frequency bands. Also, all three databases are restricted to the first two seconds of the discharge, when the evolving q profile facilitates mode identification. For the 20 shots of the dedicated experiment, amplitudes of the coherent mode activity as measured by ECE was calculated in each of the frequency bands. The database for the dedicated experiment also includes TRANSP NUBEAM [10] calculations of plasma parameters, kinetic profile data, and data extracted from equilibrium reconstructions.

The second database contains over 2000 entries from over 1000 different discharges and spans a very wide range of plasma parameters.

Motivated by the insensitivity of the LFMs to neutral beam injection in the dedicated experiment, after these databases were assembled, a search was conducted of archival data for unstable LFMs in discharges without any beam injection. (Discharges in the first two databases all had deuterium beam injection.) In discharges with strong ECH and weakly reversed q profiles (but no beam heating), characteristic LFM instabilities can occur [9].

All three databases support the same conclusions. LFMs are unstable most often in plasmas with high electron temperature but relatively low beta (Fig. 3a). In contrast, unstable BAEs appear most often in high beta plasmas (Fig. 3b). The dependence on T_e (or its gradient) and on beta are the strongest dependencies in the databases for LFMs [8]. For BAEs, the strongest dependencies are on beta and beam parameters [9].

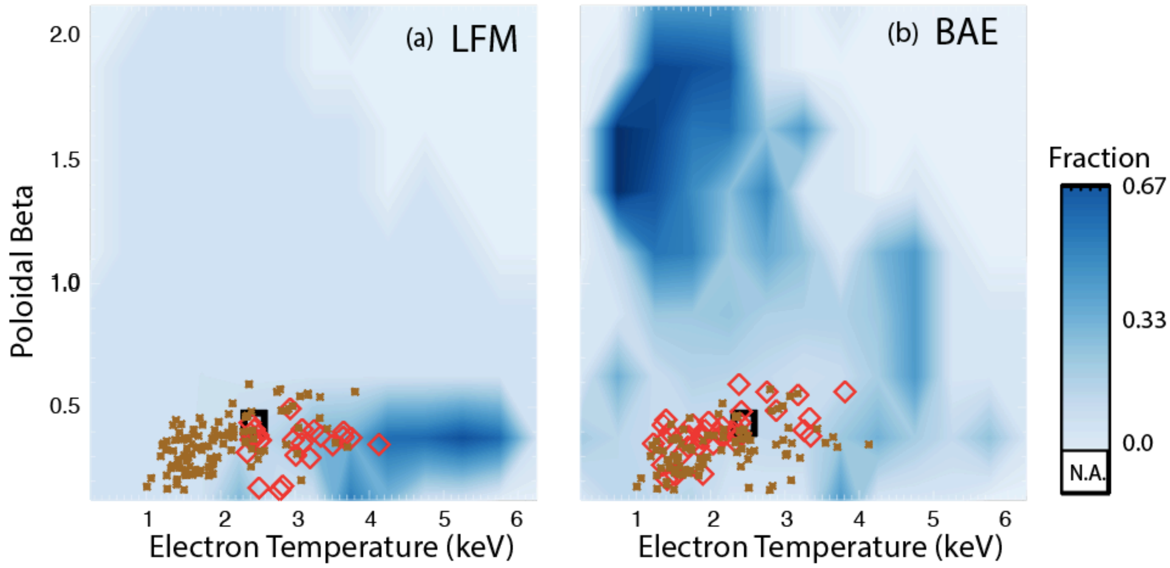

Figure 3. Occurrence of unstable (a) LFMs and (b) BAEs vs. central T_e and β_p. The blue shading indicates the fraction of entries with LFM or BAE activity per temperature-beta bin for the large deuterium plasma database. The black square represents the reference shot of Fig. 1. The red diamonds (small brown asterisks) represent unstable (stable) discharges during the isotope experiments with mixed H/D plasmas that are discussed in Sec. 5. White regions indicate a portion of parameter space without entries.

4. SUMMARY OF THEORY AND SIMULATIONS

The LFM observations motivated new analytical theory that appears in [9]. A reactive instability of Alfvénic polarization that is excited by steep electron temperature gradients near q_{min} has properties that are consistent with experiment.

Linear simulations of the reference case have been performed by the gyrofluid code FAR3d [11], the linear gyrokinetic code LIGKA [12], and the gyrokinetic code GTC [13]. Both FAR3d [10] and GTC [13] find unstable modes near q_{min} with frequencies comparable to LFM frequencies. In GTC, the mode is unstable in the absence of fast ions. As in experiment, the growth rate calculated by GTC increases with increasing T_e. A detailed report on the GTC simulations appears in [13].

FAR3d, LIGKA, and GTC all find unstable fast-ion driven modes that are located near q_{min} with frequencies comparable to the experimental BAEs [8]. In the GTC simulations, the BAE frequency is sensitive to the number of fast ions in a manner suggestive of an energetic particle mode, which may explain the frequency chirping observed experimentally. One difference from experiment is that the growth rate calculated by both FAR3d [8] and GTC [13] is rather insensitive to q_{min} while, in experiment, a given BAE is only unstable over a small range of q_{min}. All of the simulations to date employ an isotropic distribution function and it is well established experimentally that BAE stability is quite sensitive to the direction of beam injection, so the likely explanation for this discrepancy is the use of isotropic distribution functions in the simulations. Simulations with realistic anisotropic distribution functions are planned as future work.

5. OBSERVATIONS IN HYDROGEN PLASMAS

DIII-D recently completed several experiments with injection of both hydrogen and deuterium beams into plasmas with significant thermal hydrogen concentrations. Although none of these plasmas are an exact match of the conditions of the dedicated experiment, many include combined ECH and beam injection when the q profile is weakly reversed. The deuterium concentration in the available discharges ranges between approximately 10-60%.

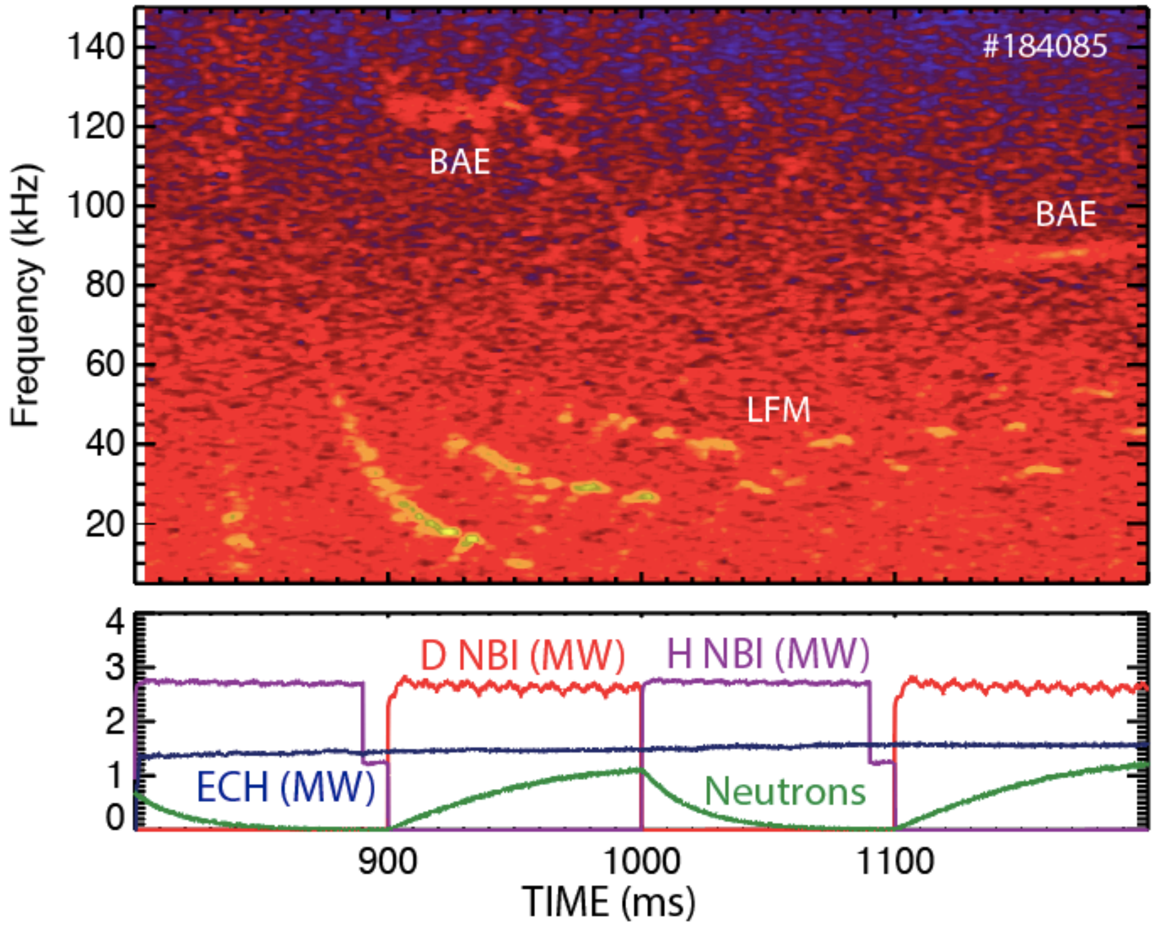

Figure 4. Cross-power ECE spectrogram from a discharge with roughly equal concentrations of hydrogen and deuterium and alternating injection of hydrogen and deuterium neutral beams. The units of the neutron signal are 10^{14} n/s, as in Fig. 2. Magnetics data show that the unstable BAE at 1160 ms has toroidal mode number n=2. Parameters at 1060 ms: central electron density n_e=1.8 x 10^{19} m^{-3}, central electron and ion temperatures T_e=2.5 keV and T_i=1.9 keV, q_{min}=1.3, $\beta_p = 0.37$, plasma current I_p=0.8 MA, central toroidal field B_T=2.0 T.

Many discharges have unstable LFMs, BAEs, or both. Figure 4 shows an example. Notice that the BAEs only appear during deuterium neutral beam injection; hydrogen injection did not destabilize BAEs in any discharge in the recent isotope campaign. In contrast, as expected, the occurrence of unstable LFMs is independent of beam type.

The discharge conditions in the isotope campaign do not exactly match the conditions of the deuterium dedicated experiment, so a direct comparison of LFM and BAE stability in matched discharges with different thermal plasma isotopic composition is not possible. However, comparison of the large deuterium database with a database of 83 discharges with appreciable hydrogen concentration illuminates general trends. For the LFM, instability requires $T_e > 2$ keV and modest poloidal beta, just as in deuterium discharges (Fig. 3a). (Actually, owing to limited hydrogen beam power and poorer confinement in hydrogen, all of the discharges in the isotope campaign have relatively low β_p in the first two seconds of the discharge.) For the BAE, as in deuterium discharges, the occurrence of instability correlates positively with β_p but is uncorrelated with T_e (Fig. 3b). For these isotope campaign shots, the β_p dependence may actually reflect an underlying dependence on deuterium beam power P_B^D, as β_p and P_B^D are strongly correlated in this dataset. Indeed, unstable BAEs are not observed unless P_B^D exceeds 2.0 MW.

One hypothesis prior to the isotope experiment was that, owing to stronger ion Landau damping with a faster thermal species, the LFMs and BAEs might be more stable in hydrogen plasmas. The experimental results prove this hypothesis incorrect, however. If anything, the data indicate that both LFMs and BAEs tend to be slightly more unstable in plasmas with significant hydrogen concentrations. Following the experiment, GTC and FAR3d repeated linear simulations of the reference case of the dedicated deuterium experiment with a single change of input parameters: the thermal mass was switched from deuterium to hydrogen. In GTC, for the $n=3$ BAE, both the growth rate and the frequency increased ~ 30% in hydrogen and the relative growth rate γ/ω decreased slightly (~6%). In GTC, for the $n=6$ LFM, the mode frequency hardly changed and the growth rate increased ~60%. In FAR3d simulations, replacing the thermal deuterium with thermal hydrogen made only modest changes in growth rate for modes in both the LFM and BAE bands.

6. CONCLUSIONS

This paper summarizes two longer papers on the stability of LFMs [9] and BAE [8] in DIII-D discharges with evolving q profiles that have reversed shear. The main conclusion of the LFM studies is that the modes previously called BAAE were misidentified and are more likely a very low frequency reactive instability of predominately Alfvénic polarization, possibly driven by steep electron temperature gradients near q_{min}. It is speculated that, because the LFMs do not resonate with high energy fast ions, they are less dangerous for fast-ion transport than resonant instabilities.

In contrast, the BAE instability interacts strongly with the highest energy fast ions. Their relatively short duration of instability in these evolving discharges occurs because the anisotropic beam population only interacts strongly with modes over a relatively narrow range of q. As published in both old [6] and new [8] papers, BAEs can adversely impact fast ion confinement. Quantitative calculations of BAE stability with realistic distribution functions is needed for detailed understanding of stability trends in DIII-D and to predict BAE stability in ITER and beyond.

This paper also reports new observations of unstable LFMs and BAEs in DIII-D plasmas with large hydrogen concentrations. Both modes appear to be as unstable in plasmas with significant hydrogen fractions as they are in deuterium.

ACKNOWLEDGEMENTS

Helpful discussions with Nate Ferraro, Nikolai Gorelenkov, Gerrit Kramer, Craig Petty, Mario Podesta, and Fulvio Zonca are gratefully acknowledged, as is the vital assistance of the DIII-D team. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Award(s) DE-SC0020337, DE-FC02-04ER54698, and DE-SC0019352.

 This work has been partially carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1] HEIDBRINK, W. W., STRAIT, E. J., CHU, M. S., and TURNBULL, M. S., Phys. Rev. Lett. 71 (1993) 855.
[2] GORELENKOV, N. N., BERK, H. L., FREDRICKSON, E., et al., Phys. Lett. A 370 (2007) 70.
[3] WONG, K. L., FONCK, R. J., PAUL, S. F., et al., Phys. Rev. Lett. 66 (1991) 1874.
[4] HEIDBRINK, W. W., STRAIT, E. J., DOYLE, E., SAGER, G., and SNIDER, R. T., Nucl. Fusion 31 (1991) 1635.
[5] SHARAPOV, S. E., TESTA, D., ALPER, B., et al., Physics Letters A 289 (2001) 127.
[6] DUONG, H. H., HEIDBRINK, W. W., STRAIT, E. J., et al., Nucl. Fusion 33 (1993) 749.
[7] GORELENKOV, N. N., VAN ZEELAND, M. A., BERK, H. L., et al., Phys. Pl. 16 (2009) 056107.
[8] HEIDBRINK, W. W., VAN ZEELAND, M. A., et al., Nucl. Fusion 61 (2021) submitted.
[9] HEIDBRINK, W. W., VAN ZEELAND, M. A., et al., Nucl. Fusion 61 (2021) 016029.
[10] PANKIN, A., MCCUNE, D., ANDRE, R., BATEMAN, G., and KRITZ, A., Comp. Phys. Comm. 159 (2004) 157.
[11] VARELA, J., SPONG, D. A., et al., Nucl. Fusion 58 (2018) 076017.

[12] LAUBER, P., GUNTER, S., KONIES, A., and PINCHES, S. D., Journal of Computational Physics 226 (2007) 447.
[13] CHOI, G. et al., Nucl. Fusion 61 (2021) submitted.