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Citation: Physics of Plasmas **13**, 056104 (2006); doi: 10.1063/1.2186049
View online: https://doi.org/10.1063/1.2186049
View Table of Contents: http://aip.scitation.org/toc/php/13/5
Published by the American Institute of Physics

Interpretation of core localized Alfvén eigenmodes in DIII-D and Joint European Torus reversed magnetic shear plasmas[a]

G. J. Kramer[b] and R. Nazikian
Princeton Plasma Physics Laboratories, P.O. Box 451, Princeton, New Jersey 08543

B. Alper and M. de Baar
Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, United Kingdom

H. L. Berk
Institute for Fusion Studies, Austin, Texas 78712

G.-Y. Fu and N. N. Gorelenkov
Princeton Plasma Physics Laboratories, P.O. Box 451, Princeton, New Jersey 08543

G. McKee
University of Wisconsin, Madison, Wisconsin 53706

S. D. Pinches
Max Planck Institute of Plasmaphysics, Euratom Association, Garching 85748, Germany

T. L. Rhodes
Institute of Plasma and Fusion Research, Electrical Engineering Department, University of California, Los Angeles, California 90024

S. E. Sharapov
Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, United Kingdom

W. M. Solomon
Princeton Plasma Physics Laboratories, P.O. Box 451, Princeton, New Jersey 08543

M. A. van Zeeland
Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee 37831

JET EFDA Contributors[c]
Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, United Kingdom

(Received 25 October 2005; accepted 20 February 2006; published online 8 May 2006)

Reversed shear Alfvén eigenmodes (RSAE) that were observed in the Joint European Torus (JET) [P. H. Rebut and B. E. Keen, Fusion Technol. **11**, 13 (1987)] and DIII-D [J. L. Luxon, Nucl. Fusion **42**, 614 (2002)] are studied with the ideal magnetohydrodynamic code NOVA-K [C. Z. Cheng, Phys. Rep. **211**, 1 (1992)]. It was found that the frequency behavior of the RSAEs can be described accurately by the NOVA-K code when plasma compressibility effects and toroidal plasma rotation are taken into account. For the mode activity on JET, the calculated drive exceeds the mode damping rate, consistent with experimental observations, while on DIII-D the growth rate from neutral beam ions for modes with high toroidal mode numbers is insufficient to account for the excitation of the modes and a major part of the drive comes from the background plasma.
 [DOI: 10.1063/1.2186049]

I. INTRODUCTION

In reversed magnetic shear configurations on tokamak plasmas, a special type of Alfvén eigenmode (AE) can occur: the reversed shear Alfvén eigenmode (RSAE). This mode resides at the zero shear point where the magnetic safety or q-profile has its minimum. The RSAEs reside just above the Alfvén continuum, and when the minimum of the q profile decreases, the RSAE frequency changes typically from about one-third of the TAE frequency to the TAE frequency in 10–500 ms. RSAEs have been reported as early as 1998 in the JT-60U tokamak[1,2] but at that time the identity of those modes was not clear. Soon after, RSAEs were found numerically[7] but no connection was made with experiments. Later on, RSAEs appeared in other Tokamaks: Alcator C-mod,[3] Joint European Torus (JET)[4] (where they are called Alfvén cascades), Tokamak Fusion Test Reactor (TFTR),[5] and DIII-D.[6] After the observation of RSAEs in JET, a theory has been developed to understand the nature of these modes[8–12] based on the role of energetic particles.

In this paper, we present experimental evidence for those modes in JET[13] and in DIII-D[14] and we investigate how accurately we can describe these RSAEs within the purely ideal magnetohydrodynamic (MHD) framework used in the

[a]Paper QI1 6, Bull. Am. Phys. Soc. **50**, 259 (2005).
[b]Invited speaker. Electronic address: gkramer@pppl.gov
[c]See Appendix of J. Pamela *et al.*, Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura, 2004) IAEA, Vienna (2004).

NOVA code[15] and its kinetic extensions in the NOVA-K code.[16] By validating these codes against experimental data, we can then determine the extent to which they can be used to extrapolate to ITER.

In Sec. II, a brief overview of the main diagnostic techniques for observing the RSAEs is given followed by some RSAE results from DIII-D and JET (Sec. III). In Sec. IV, the experimental results are compared with NOVA-K simulations and conclusions are drawn with topics for further study in Sec. V.

II. DIAGNOSTICS

The observation of core localized MHD activity has become recently possible because of improvements to diagnostics that can detect high-frequency fluctuations, either as a local or as a line-integrated measurement. Therefore, we describe those diagnostic in this section.

High-frequency MHD activity in the range of RSAEs and TAEs (about 20–300 kHz) is traditionally observed with Mirnov coils that are mounted inside the vacuum vessel near the plasma edge. Modes that perturb the magnetic field near the plasma edge, such as global and low-n AEs, are readily observed with such a system but high-n core localized AEs are not observed. In order to observe those high-n modes, local measurements have to be made in the plasma core. Below we discuss briefly the diagnostic techniques that were used to observe such core localized modes.

One of the first techniques that was used to observe AEs near the plasma center was microwave reflectometry: a beam of microwaves is launched into the plasma and reflected off a cutoff layer inside the plasma, which depends on the microwave frequency and its polarization. The reflected signal carries information on the density fluctuations near the cutoff layer. This technique was used among others to observe low-n alpha-particle driven RSAEs and TAEs in TFTR, and a quantitative estimate of local density fluctuations was made.[5,17]

A related technique of observing core localized MHD activity was successfully employed on JET,[18] where a beam of microwaves was launched in O-mode polarization (the wave electrical field parallel to the magnetic field in the plasma) with a frequency somewhat higher than the cutoff frequency. In that case, the beam propagates through the plasma, reflects off the back wall, and returns back to the receiver antenna. The phase of the beam is modulated by core localized density fluctuations and the amplitude of the received beam is modulated due to refraction effects from those density variations. This interferometric technique provides a global survey of most core localized modes that do not readily show up on Mirnov coils.

Microwave radiation can also scatter off density perturbations that are formed by a correlated or "collective" motion of the electrons in the plasma. This method is successfully employed on DIII-D to measure the density component of the modes. Often frequencies in the range of 200–300 GHz are used to probe the plasma, and therefore this technique is called far-infrared (FIR) scattering.[19]

Fast sampled two-color interferometry has also proven useful for observing core localized MHD activity.[20] The difference with the microwave interferometer technique is that the wavelength of the launched waves, often 10.6 μm from a CO_2 laser, is far above the O-mode cutoff frequency. In this case, refraction effects are negligible and only phase fluctuations carry information on the density fluctuations. It was found recently on DIII-D that the interferometer sensitivity for different modes depends strongly on the geometry of the sight-line, a fact that was well explained using detailed NOVA modeling.[20]

With beam emission spectroscopy (BES), local density fluctuations can be detected by looking at the variations in H_α light that is generated when a neutral beam is injected into the plasma. BES spectroscopy is successfully employed on DIII-D for measuring the radial localization of density fluctuations and for the determination of local poloidal wave numbers.

Two other diagnostic techniques that do not observe the high frequency MHD activity but are very important for its interpretation are the motional Stark effect (MSE) and charge exchange recombination spectroscopy (CER) diagnostics. From MSE measurements, the evolution of the q profile is determined, which is very important for the modeling of the equilibrium of reversed shear plasmas. The measured mode frequencies are affected by a Doppler shift because of the toroidal plasma rotation. From CER measurements, the plasma rotation can be determined accurately from the Doppler shift of spectral lines that appear after charge exchange between plasma ions and neutral particles from an injected neutral particle beam. With this set of diagnostics, we are able to test theory against well diagnosed experimental data.

III. EXPERIMENTS

On both JET and DIII-D, RSAEs are observed frequently in plasmas with reversed magnetic shear. In this section, we present data on those modes from both machines. Reversed shear discharges in JET can be created with a combination of lower hybrid current drive (LHCD) and ion cyclotron resonance heating (ICRH), which do not introduce angular momentum to the plasma so the plasma rotation in the laboratory frame is negligible. In DIII-D discharges, however, unbalanced neutral beam injection (NBI) is used to create reversed magnetic shear. The unbalanced NBI introduces a substantial amount of plasma rotation. This creates a dramatic variation in the observed mode spectrum.

RSAE activity in DIII-D is often observed on the FIR diagnostic, as is shown in Fig. 1. The data were taken in a Quiescent Double Barrier discharge with the following parameters: toroidal magnetic field 2.0 T, plasma current 1.0 MA, minor radius 0.56 m, major radius 1.68 m, elongation 1.83, central electron density 5.4×10^{19} m^{-3}, central electron temperature 4.4 keV, central ion temperature 12.3 keV, and 12 MW of NBI power was injected opposite to the plasma current. Two bands of modes can be identified clearly in this figure. In general, modes in those bands chirp down in frequency and occur in the range up to about 1 MHz. We will study this phenomenon in the next section.

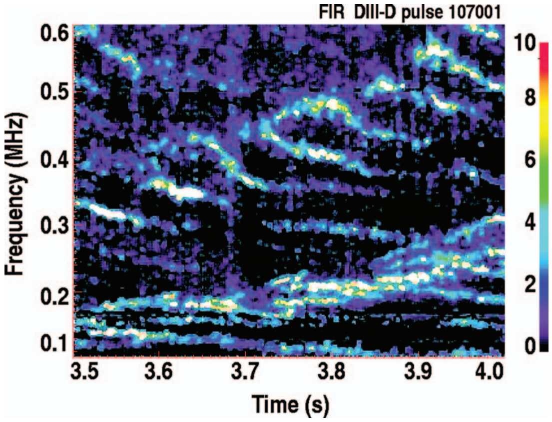

FIG. 1. (Color) A FIR spectrum from a DIII-D discharge showing bands of RSAE activity. Modes with different toroidal mode numbers are separated in frequency due to the toroidal plasma rotation. Toroidal mode numbers from $n\sim5$ at 0.1 MHz to $n\sim20$ at 0.6 MHz were obtained from Doppler shift measurements.

Because of the momentum input of the NBI, the plasma is rotating toroidally with a frequency of about 30 kHz.

An example of RSAE activity in JET is shown in Fig. 2 where a spectrum of the Mirnov coil fluctuations is shown. During this period $q_{\min}$ decreases from 4.0 at $t=2.0$ s to 1.9 at $t=4.0$ s. At $t=2.8$ s, when $q_{\min}$ passes the $q_{\min}=3$ rational surface, all the observed RSAEs reach their minimum frequency at 40 kHz while modes with different n reach the TAE frequency at different times. These modes were observed during the current ramp-up phase of pulse 65940 when the current increased from 1.0 to 1.8 MA. The line averaged electron density was 4×10^{19} m^{-3}, toroidal magnetic field 2.8 T, major radius 2.9 m, minor radius 0.97 m, elongation 1.7, and 2.0 MW of lower hybrid current drive, and 1.5 MW of ICRH was injected during this period. In Fig. 2, both the up- and down-chirping of the RSAEs are observed, which is very rarely seen in experiments. Usually only the up-chirping branch is seen (see, for example, Fig. 2 of Ref. 18).

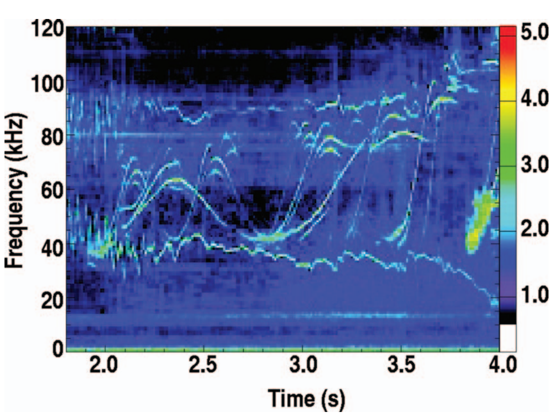

FIG. 2. (Color) A Mirnov coil spectrum from a JET discharge (pulse 56940) showing the RSAE activity as up- and down-chirping modes. The jagged signals below about 40 and above about 90 kHz are beat waves between different ICRH antennas.

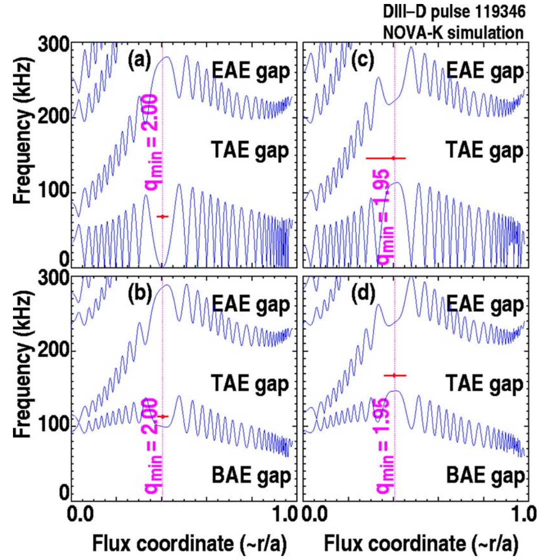

FIG. 3. Alfvén continua for an $n=10$ RSAE at $q_{\min}=2.0$ (a),(b) and an $n=10$ TAE at $q_{\min}=1.95$ (c),(d). In (a) and (c) the effects of plasma compressibility are neglected ($\gamma=0$) while in (b) and (d) these effects are included ($\gamma=5/3$).

IV. NOVA-K ANALYSIS

In the previous section, we have shown data on RSAEs from JET and DIII-D. In this section, we will use the NOVA code and its kinetic extensions for modeling these modes theoretically.

A. Plasma compressibility effects

When plasma compressibility is ignored, the Alfvén frequency can approach zero on the resonant surface where $k_{\parallel}m=[n-m/q(r)]/R$ vanishes. However, with the plasma compressibility taken into account,[12] it is found that the continuum frequency has a minimum at the geodesic acoustic mode frequency,[21] $\omega=\sqrt{2+1/q^2}c_s/R$, where $c_s=\sqrt{\gamma P/\rho}$ is the sound speed with P the equilibrium plasma pressure, ρ the equilibrium mass density, and γ the adiabatic index of compression (typically γ is chosen as 5/3) NOVA is able to take the plasma compressibility into account using a filtering technique similar to the one suggested in Ref. 22, where the continuum spectrum due to sound waves is removed under the assumption that the actual excitation frequency is much larger than the sound wave frequency, $\omega_s\sim k_{\parallel}mc_s$.

In Fig. 3, the Alfvén continua for an $n=10$ RSAE at the bottom of the chirp at $q_{\min}=2.0$ and a TAE at $q_{\min}=1.95$ are shown for a DIII-D reversed shear plasma. In those calculations, the plasma rotation was omitted for clarity. When plasma compressibility is not included, the lower Alfvén continuum goes to zero [Figs. 3(a) and 3(c)], an RSAE is found at 68 kHz, and a TAE at 146 kHz. When plasma compressibility is included ($\gamma=5/3$), the beta-induced Alfén eigenmode (BAE) gap appears below the lowest continuum and the RSAE moves up in frequency to 112 kHz while the TAE frequency changes to 168 kHz.

In order to compare these frequencies with experimental values, we have looked at the chirp range from the bottom of the RSAE frequency at $q_{\min}=2.0$ to the TAE frequency when

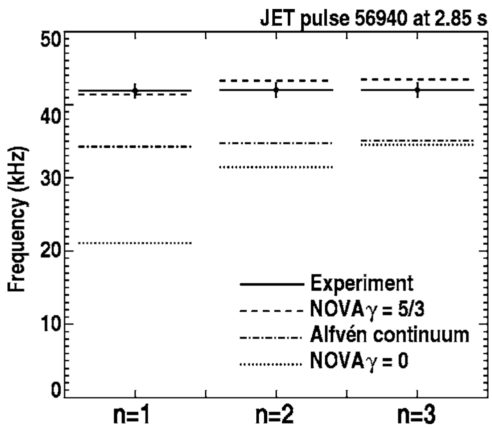

FIG. 4. Minimum RSAE frequencies when $q_{\min}=3.0$ for the $n=1$, 2, and 3 modes. The NOVA calculations that include the plasma compressibility effects ($\gamma=5/3$) (dashed lines) agree very well with the measured frequencies (solid lines). Ignoring the plasma compressibility effects decreases the calculated frequencies (dotted lines). The frequency of the Alfvén continuum at $q_{\min}$ for the $\gamma=5/3$ case is indicated with the dash-dotted lines.

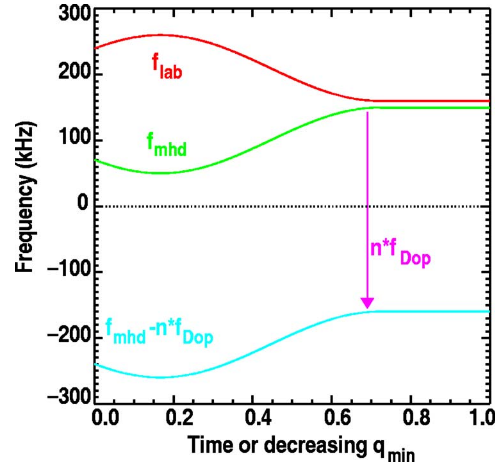

FIG. 5. The apparent down-chirp of RSAEs in DIII-D can be accounted for by a large Doppler shift generated by plasma rotation in the opposite direction to the mode propagation.

$q_{\min}=1.95$ rather than comparing absolute frequencies. The plasma rotation does not change on the time scale that the $n=10$ mode chirps up so the comparison with the chirp range is more accurate than the absolute frequency, which is affected by Doppler shifts due to plasma rotation.[6] Including the effects of plasma compressibility in the NOVA analysis reduces the chirp range from 78 to 56 kHz. Experimentally, a chirp range of 60 kHz was observed when averaged over multiple modes in Fig. 1, so the inclusion of the plasma compressibility effects is consistent with the data on DIII-D.

In JET, RSAE toroidal mode numbers between 1 and 3 were observed in an ICRH heated reversed shear plasma on the Mirnov coils (Fig. 2). These RSAEs appeared on the Mirnov coil diagnostic beacause these low-n modes have a broader radial eigenmode structure than the high-n modes. In this case, the plasma rotation is negligible compared to the Alfvén velocity and we can compare the observed minimum RSAE frequencies with the NOVA calculations. In Fig. 4, the measured frequency (solid line) is compared with NOVA simulations without (dotted line) and with (dashed line) the plasma compressibility effects for the $n=1,2$, and 3 RSAEs. The frequency of the Alfvén continuum at $q_{\min}$ with the plasma compressibility effects included is indicated with the dash-dotted line. From this figure, it can be seen that there is very good agreement between the experimental and calculated NOVA frequencies when $\gamma=5/3$. When $\gamma=0$, the NOVA frequencies are too low and depend strongly on the toroidal mode number, which is not observed experimentally. Even for low-n modes, plasma compressibility effects are very important for obtaining the correct RSAE frequencies in the simulations.

B. Mode existence in ideal MHD

Numerical results from NOVA show that including pressure gradient terms into the eigenmode calculation produces a minimum nonzero frequency for the modes when $q_{\min}$ is at a rational surface, even when $\gamma=0$. However, a consistent analytic explanation for why a finite frequency mode should exist in this limit has not as yet been established.[23] Nonetheless, the NOVA calculations show that when the pressure gradient is sufficiently large, the effect of including a pressure gradient can be competitive with the adiabatic index term in establishing a finite frequency of an RSAE at a rational surface.

C. Toroidal plasma rotation

The measured RSAE and TAE frequencies can be strongly affected by the toroidal plasma rotation. The measured frequency in the laboratory frame, ω_{lab}, is the sum of the AE frequency in the plasma frame, ω_{MHD}, and the toroidal plasma rotation, ω_{Dop},

$$\omega_{\text{lab}} = \omega_{\text{MHD}} + n\omega_{\text{Dop}}. \tag{1}$$

The Doppler shift is proportional to the toroidal mode number and for high n the observed frequency is dominated by the Doppler shift as was shown in DIII-D. The effects of the diamagnetic drift term has been ignored because $n\omega_{\text{Dop}}$ is substantially larger than the diamagnetic drift frequency for the data presented in this paper.

MHD theory predicts the RSAE frequency to chirp up from its minimum frequency at a rational q-surface to the TAE frequency. This up-chirp was observed in the JET discharges in Ref. 4, but for the DIII-D discharges a down-chirp was observed for the RSAEs when $q_{\min}$ was decreasing (see Fig. 2). This down-shift can be explained by the large toroidal plasma rotation that is present in DIII-D. The RSAEs propagate in the direction of the plasma current and for the discharge shown opposite to the plasma rotation so ω_{Dop} is negative in Eq. (1) and for sufficiently large n, ω_{lab} becomes negative (or ω_{lab} gets a 180 degree phase shift). Experimentally, the sign of ω_{lab} is not determined so the negative frequencies are aliased to the positive ones and the MHD-frequency up-chirp appears as down-chirps in the experiment (see Fig. 5).

Toroidal plasma rotation can be the dominant contribution to the observed frequency, but in the NOVA code plasma rotation is not taken into account. We have applied the following approximation to include toroidal rotation in NOVA.

For a given plasma equilibrium, the NOVA code searches for eigenfrequencies, ω_{MHD}, of the MHD modes. If the plasma behaves as a rigid rotator without any rotational shear, then Eq. (1) can be used to transform the frequencies obtained in the laboratory frame to the ones in the plasma frame. In tokamak plasmas, however, a significant shear in the toroidal rotation can be observed, and only for modes that are localized in a narrow region where the rotation shear is small can Eq. (1) be applied. Let the toroidal rotation be given as a function of the normalized minor radius, $\omega_{\mathrm{Dop}}(\rho)$, and approximate it with a flux function. Then instead of searching for ω_{MHD} we can search for ω_{lab}, which is calculated as

$$\omega_{\mathrm{lab}}^2 = [\omega_{\mathrm{MHD}} + n\omega_{\mathrm{Dop}}(\rho)]^2. \tag{2}$$

For a plasma rotating rigidly in the toroidal direction and for highly localized modes, this procedure gives the same results as Eq. (1). For global modes in plasmas with a significant toroidal rotation shear, a weighted Doppler shift is obtained in agreement with the experimental data.

D. Mode numbers

The determination of toroidal and poloidal mode numbers is crucial for the theoretical interpretation of the measured spectra. In the case in which the modes are observed on a number of Mirnov coils distributed in the toroidal and/or poloidal direction, mode numbers can be obtained reliably from the phase differences between the measured signals. Unfortunately, Mirnov coils only pick-up modes that have a significant magnetic perturbation at the plasma edge. Most of the high-n RSAE activity is located in the plasma core near $q_{\min}$ and goes unnoticed by the Mirnov coils. Only internal diagnostics register these modes, but extracting information on mode numbers is difficult.

In plasmas with toroidal rotation, the different n numbers have Doppler shifts that are proportional to n [see Eq. (1)]. Mode numbers can then be inferred from the measured Doppler shifts. This method works especially well at integer-q crossings because a large range of successive n numbers are present. However, at half integer-q a very similar pattern is observed near the minimum RSAE frequency, but there only the even n numbers are present. This method gives the range of n numbers, and absolute values may be deduced if the plasma rotation near $q_{\min}$ is known accurately.

Poloidal wave numbers have been measured with the BES diagnostic using a poloidal array of viewing chords. In DIII-D, such BES measurements were performed for RSAEs at the location of $q_{\min}$, and local poloidal wave numbers, k_θ, were deduced (see Fig. 6). The straightforward transformation from measured k_θ to poloidal mode number, $m=k_\theta l/2\pi$ (l is the length of the flux surface in the poloidal direction), is not accurate for D-shaped tokamaks. With NOVA, however, we can calculate the local k_θ for RSAEs and TAEs along a poloidal path. These calculations show that k_θ varies by almost a factor of 2 on a flux surface, as can be seen in Fig. 7. At the low-field side where BES is measuring k_θ has its minimum. In the calculations for Fig. 7, $q_{\min}$ was 1.40 with $n=40$ and $m=56$. The simple approach with $k_\theta=1.92$ would have given $m=38$, which is a significant underestimation of the true mode number.

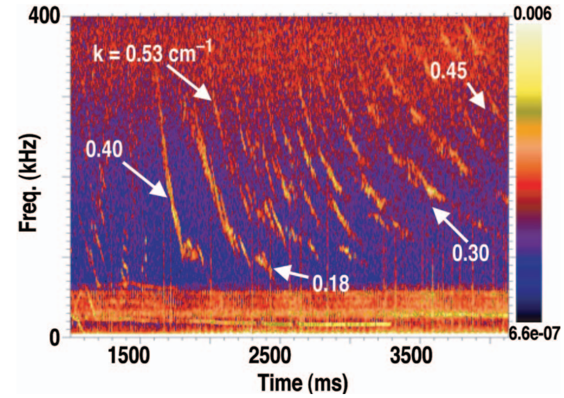

FIG. 6. (Color) BES spectrum from a DIII-D discharge. Poloidal wave numbers for a number of selected modes are indicated with the white arrows. The $q_{\min}=2$ surface appeared in the plasma at 1500 ms.

When $q_{\min}$ decreases, RSAEs evolve into TAEs and new RSAEs appear when $q_{\min}$ reaches the next rational q surface. During this evolution k_θ at the low-field side also decreases as is shown in Fig. 8 for several $n=10$ RSAEs and TAEs. This can be understood as follows: when $q_{\min}$ decreases, m decreases by 1 when the next rational surface is reached. Therefore, the poloidal wavelength increases (or k_θ decreases). When $q_{\min}$ decreases, both the minimum RSAE and TAE frequency increase.

A detailed analysis of the band of modes pointed to with the arrow labeled with 0.40 shown in Fig. 6 revealed that when the modes appear just after 1500 ms at around 400 kHz, $k_\theta=0.75$ cm^{-1}. At the end of that same band at 1900 ms when the frequency is 80 kHz, $k_\theta=0.25$ cm^{-1}. The combination these results with a NOVA analysis resulted in poloidal mode numbers from $m=36$ at the start to $m=12$ at the end of that band. From MSE measurements, it was found that $q_{\min}$ passes the $q_{\min}=2$ surface at 1500 ms. Therefore, we can assign toroidal mode numbers in the range of $n=19$ to the high-frequency RSAEs down to $n=6$ for the low-frequency RSAEs, which is consistent with results expected from the Doppler shifts.

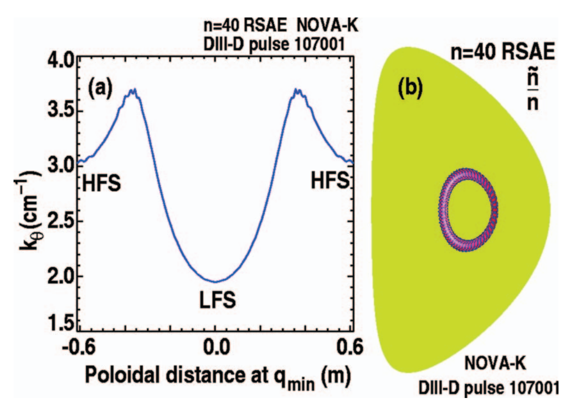

FIG. 7. (Color) (a) Variation of k_θ as a function of the poloidal distance from the low-field side (LFS) for an $n=40$ RSAE (b).

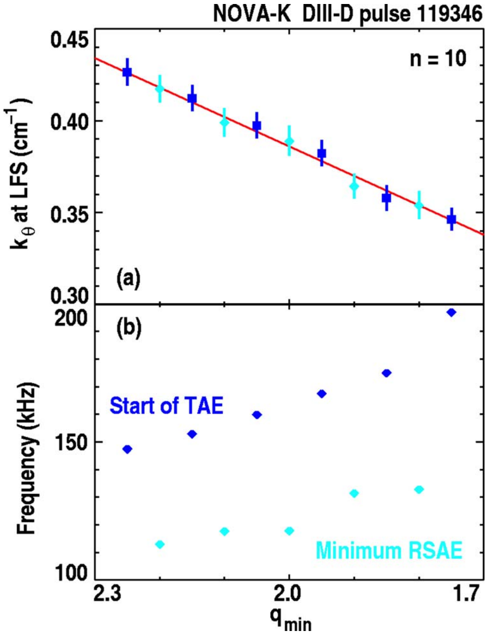

FIG. 8. (a) Variation of k_θ at the low-field side and (b) the change in the minimum RSAE and TAE frequency as a function of $q_{\min}$ for $n=10$ RSAEs and TAEs.

From the above analysis, we conclude that the diagnostic combination of BES (local k_θ) and MSE (q profile and $q_{\min}$) together with a NOVA analysis is a very powerful combination to extract poloidal and toroidal mode number information for core-localized AE activity even if the activity does not appear on Mirnov coils.

E. Stability analysis

In current tokamaks, a large number of RSAEs and TAEs have been observed and their stability is studied in order to predict their behavior in ITER and determine if those modes can be harmful to plasma performance.

The usual TAEs in normal shear discharges are driven unstable by a population of fast ions which can be created among others by neutral beam injection,[24] ICRH heating,[25] and fusion alpha particles.[26] For these discharges, the NOVA-K code has been successfully validated against experimental results from several tokamaks[27–29] and it has been used to predict the stability of TAEs in normal shear discharges for the proposed next generation of tokamaks, ITER, FIRE, and IGNITOR.[28] Recently, we have started a similar study to validate NOVA-K for RSAEs and to understand its predictive capability and limitations for RSAEs. Below, we present results from JET and DIII-D.

For this study, we have performed a stability analysis on JET with NOVA-K for the $n=1$ mode that was observed in the discharge shown in Fig. 2 at different times when the mode evolves from TAE to RSAE (down-chirp) and back to TAE (up-chirp). Because the RSAE resides inside the Alfvén continuum, continuum damping is the dominant damping, and it was found that when the mode chirps down, the continuum damping becomes the main damping mechanism. At the minimum of the RSAE frequency, the continuum damping was found to be $\gamma/\omega=4\%$. The continuum damping decreased during the up-chirp and virtually disappeared when the mode transforms into a TAE. For the TAE, radiative damping was the dominant mechanism ($\gamma/\omega\approx 0.5\%$). The continuum damping was calculated perturbatively with the NOVA code along the lines given in Ref. 30. These results were found to be in good agreement with fully nonperturbative NOVA-KN and kinetic calculations.[31]

In the JET case, ICRH generated fast ions drove those modes unstable and we have used the fast ion distribution calculated with the TRANSP code[32] for estimating the strength of the drive. In these calculations, finite orbit width and finite Lamor radius effects were taken into account.[33–35] The drive for the $n=1$ TAE at 2.5 s was 70% stronger than the calculated damping rate so the mode was calculated to be unstable. During the down-chirp, the drive decreased significantly because the decreasing $q_{\min}$ changed the mode structure. The minimum drive was found about halfway through down-chirp, and when the minimum RSAE frequency was approached the drive increased again and continued to increase during the up-chirp. The weakened drive during the down-chirp may contribute significantly to the question of why down-chirping RSAEs are seldom observed.

In this discharge it was found for the $n=1$ that during the down-chirp and near the minimum frequency of the RSAE, the calculated drive was up to 40% weaker than the calculated damping. It is, however, quite possible that those modes are excited experimentally because there are large uncertainties of at least 50% in the drive and damping calculations. These uncertainties arise from uncertainties in the q profile, fast-ion distribution, and from nonlinear effects. Another explanation for the observation of the down-chirping RSAEs is that the perturbative analysis as performed with NOVA-K breaks down. Energetic particles may modify the mode[36] in such a way that the eigenmode changes its structure and interacts differently with the drive and damping mechanisms.

In DIIID discharges presented in this paper 80 keV neutral beams were injected in the counter current direction for creating and sustaining the reversed magnetic shear configuration. The velocity of the particles in the beam was 40% of the Alfvén velocity. Therefore, it is expected that the 1/3 side band resonance[37] is of importance to excite the TAEs in this case. However, initial calculations do not show a significant drive from the beam ions for high-n modes. The same calculations also indicate that a major part of the drive comes from the thermal particles in the Maxwellian tail of the plasma,[38] but more work is needed in this area to understand the stability properties of those high-n modes.

V. CONCLUSIONS AND OUTLOOK

Reversed shear Alfvén eigenmodes have been observed on different tokamaks where those modes reside near the shear reversal point. In order to detect the RSAEs, internal fluctuation measurements near $q_{\min}$ have been performed using interferometric, spectroscopic, and scattering techniques. Only modes with low toroidal mode numbers can sometimes be detected with Mirnov coils. We have compared data from DIII-D and JET with results from calculations performed with the NOVA-K code. Eigenmode solutions were found in the simulations for both machines and the calculated frequencies agreed well with the experiments after including Doppler shifts due to toroidal plasma rotation and effects of plasma compressibility that persist after filtering out direct sound wave excitations. The apparent down-chirp of the RSAEs in DIII-D could be explained by the strong toroidal plasma rotation; in the plasma frame those modes chirp up as is expected from theory.

From the results that we have obtained so far, ideal MHD theory with its kinetic extensions (NOVA-K), simulated, and experimental mode frequencies agreed very well and the first results of a stability analysis indicated that within the margin of error, the modes are unstable. There are, however, indications that down-chirping RSAEs are not pure ideal MHD modes but that fast particles modify the mode structure in such a way that the interaction with the Alfvén continuum is altered. These effects will be studied further.

Because ideal MHD works well for up-chirping RSAEs in JET and DIII-D, RSAE excitation in reversed shear scenarios for ITER might be studied with confidence using the NOVA-K code.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Contracts No. DE-AC02-76-CH0373 and No. DE-AC03-99ER54463.

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