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Theory and Observations of Low Frequency Eigenmodes due to Alfvén Acoustic Coupling in Toroidal Fusion Plasmas

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ABSTRACT.

New theory developments and experimental observations of two classes of energetic particle driven instabilities are reported. First is a new class of global MHD solutions resulting from coupling of the Alfvénic and acoustic fundamental MHD oscillations due to geodesic curvature. These modes, predicted theoretically and numerically and called Beta-induced Alfvén-Acoustic Eigenmodes (BAAEs), have been recently observed in low beta JET, DIII-D and high beta NSTX plasmas [1, 2]. The second class is the instability of Reversed Shear Alfvénic Eigenmodes (RSAEs), which are shown to be suppressed due to strong magnetic pressure in NSTX plasma. A kinetic theory is required if the modes strongly interact with the Alfvénic continuum. Both RSAEs and BAAEs can potentially deteriorate the fast ion confinement in next step fusion plasmas, especially if excited together with multiple global TAE instabilities [3]. At the same time they can be used as a diagnostic tool for fast ion and safety factor profiles, a technique known as MHD spectroscopy.

1. INTRODUCTION

Low frequency plasma oscillations due to coupling of two fundamental MHD branches, Alfvénic and acoustic, have attracted a lot of interest in recent years. They can have deleterious effects on plasma performance due to fast ion loss and wall heat load, but can be used for the so-called MHD spectroscopy to diagnose plasma parameters such as safety factor profiles. In a cylinder Alfvénic and acoustic branches do not interact and their solutions are uncoupled (see Fig.1) because of their polarization, which is purely compressional plasma displacement of the acoustic branch and incompressible of the Alfvénic branch. In a torus Alfvénic and acoustic waves couple due to the toroidal effect and their polarization is mixed. Various gaps in the continuum emerge (see Fig.1 (right figure)), such as TAE gap due to m and $m+1$ Alfvénic (poloidal) harmonics coupling, beta-induced Alfvénic gap (BAE) due to the GAM induced up shift of the Alfvénic continuum, and beta-induced Alfvén - acoustic (BAAE) gap due to m Alfvénic and $m\pm 1$ acoustic branches coupling, which was studied in detail recently [1, 2]. BAE and BAAE gaps are due to the geodesic curvature and finite plasma pressure. In each gap corresponding global eigenmode was found. In addition global modes are found near the extrema points of the continuum, such as formed at q_{min} location in the plasma with the reversed shear. Beta effects on two solutions shown in Fig.1, RSAE and BAAE are subject of this work.

2. PLASMA PRESSURE EFFECT ON RSAES

This is studied first by analyzing and modeling the experimental data from NSTX. RSAEs have been observed on many tokamak devices [4–6]. Most often RSAEs are observed with the frequency sweeping up as minimum $q(r)$ value, q_{min} , decreases. RSAE frequency is changing from a minimum stationary value to the TAE gap frequency [4]. Theoretically and numerically, it was found that sweeping up RSAEs exist in ideal MHD [7, 8]. RSAE instabilities with the frequency sweeping down, are also observed prior to reaching the minimum.

RSAE frequency is known to be determined by four following terms

$$\omega_{RSAE}^2 = k_{\parallel}^2 v_A^2 + \omega_{GAM}^2 + \Delta_{MHD}^2 + \Delta_h^2, \quad (1)$$

where $k_{\parallel} = m/q - n$ is parallel wavevector [9], n is toroidal mode number, $\omega_{GAM} = \omega_A \sqrt{\gamma \beta_{pl}/2}$ is GAM (or BAE) frequency [10–12], $-\Delta_{MHD}$ is a shift due to toroidicity and beta gradient (typically dominant) [13–15], and $-\Delta_h$ is the hot ion contribution [9]. It follows that plasma pressure has two ways to influence the eigenfrequency via finite pressure, ω_{GAM} , and its gradient, Δ_{MHD} . It is found that depending on plasma parameters the RSAE frequency pressure gradient contribution changes from zero up to [16]

$$\Delta_{MHD}^2 = -r \beta'_{pl} (1 - q^{-2}) \quad (2)$$

which is in agreement with numerical NOVA simulations for low beta, high aspect ratio plasma.

2. STUDY OF RSAES IN NSTX

Was focused on the plasma pressure effects, which stabilizes RSAE frequency sweep [6] via the GAM frequency up shift. Typical NSTX magnetic signal spectrum is shown in Fig.2. The spectrum is taken at the initial phase of the shot when the plasma beta was building up, but is still relatively low for NSTX. Other plasma parameters are $n_{e0} = 10^{19} \text{ cm}^{-3}$, $B = 4.5 \text{ kG}$ and plasma current of 0.8 MA . Conditions favorable for RSAE excitation were created with inverse q -profile and strong NBI heating with 2 MW of 90 keV beams. Instability of RSAEs have large upward frequency sweeps characteristic for observations in conventional tokamaks [5]. However at higher plasma beta RSAE frequency sweep is much reduced as can be seen from Fig.3(a). Corrected for the Doppler shift instability frequency points (Fig.3(b)) show familiar up and down sweeps which are bounded by the TAE frequency from above and by $\sqrt{\omega_{GAM}^2 + \Delta_{MHD}^2} \sim \beta_{pl}$ from below. For the comparison GAM frequency is also shown as black line in Fig.3(b). The value of Δ_{MHD} for different n -modes is compared at one time. Near $t = 0.25 \text{ sec}$ we find qualitatively Δ_{MHD} is smallest for lowest n values in agreement with predictions of Ref.[16], reaching maximum, Eq.(2), for high- n modes. At a later time, $t = 0.35 \text{ sec}$, q_{min} gets close to unity [6], so that Δ_{MHD} vanishes (see Eq.(2)). Further increase in plasma beta typically suppresses RSAE sweep.

RSAEs may induce significant beam ion losses in NSTX especially when their instability is excited at the same time as TAE and form the ‘‘avalanches’’ [17].

Since theoretical expressions for RSAE eigenfrequency can give only approximate value in a realistic plasma conditions we performed ideal MHD simulations using NOVA code [18]. In these simulations acoustic mode coupling was included by neglecting acoustic continuum resonances in MHD model [11]. Main effect of the acoustic mode coupling on Shear Alfvén Eigenmodes (SAEs) is retained resulting is a wider BAE gap (indicated in Fig.3(c)) and the up shift of each poloidal

harmonic continuum frequency proportional to ω_{GAM} . Such scheme simplifies numerical procedure to search for the eigenmodes by filtering out unphysical interactions with the acoustic continuum. Fig.3(c) shows results of such modeling. Alfvén continuum at q_{min} location (RSAE localization region) up shift by GAM frequency as expected is proportional to the plasma beta.

Thus q_{min} change can only modify the narrow continuum between BAE and TAE gaps and should not result in appreciable RSAE frequency sweep at high β_{pl} , i.e. the sweep is suppressed. Further modeling of RSAE structure and frequency suggested that ω_{GAM} and Δ_{MHD} are on the same order. This means that in NSTX RSAEs have frequencies inside TAE gap. The computed eigenmodes are formed by the coupling of TAEs and RSAE in NSTX because of strong coupling of corresponding poloidal harmonics of these modes. Notably global structure of RSAEs in ST devices are expected to be potentially dangerous for fast ion confinement. Thus RSAE sweep suppression is very important phenomena because it helps to reduce fast ion - wave resonance island transport in the phase space and thus to reduce radial transport of fast ions.

3. BAAE THEORY

This was recently developed to predict and describe observations of new global eigenmodes in toroidal plasma experiments, such as on presented here JET, DIII-D and NSTX devices. These modes appear near the continuum extrema points in the Alfvén - acoustic continuum gaps, which are formed by the interaction of Alfvén and acoustic branches mediated by finite pressure, plasma compressibility and geodesic curvature [19] (see illustration on Fig.1(b)). We have found numerically that global BAAEs may occur adjacent to these extrema points in both relatively low and high beta plasmas. The question posed in initial studies [2] is whether kinetic theory can explain frequency difference between the ideal MHD and observations. The latter were showing consistently lower values for the global BAAEs in the gap.

Qualitatively in the ideal MHD and low beta, high aspect ratio plasma BAAE gap is limited from above by a frequency which appears when $m \pm 1$ acoustic sideband frequencies match $\Omega_{a+} = \Omega_{a-}$, and is given by [1, 19]

$$\Omega^2 = \Omega_{+}^2 = 1/q^2, \quad (3)$$

where frequencies are normalized $\Omega^2 \equiv (\omega R_0/v_A)^2 / \delta$, $\delta \equiv \gamma\beta/2 \ll 1$, $\Omega_{a\pm} = k_{\pm}$, $k_j = (m + j - nq)/q$ and γ is the specific heat ratio. Near the rational magnetic surface another root, modified Alfvén branch, “shielded” by the acoustic sidebands was found

$$\Omega^2 = k_0^2 / \delta (1+2q^2) \quad (4)$$

Theory predicted that if q_{min} decreases at that location the modified modified Alfvén branch frequency sweeps up until it reaches the acoustic frequency, which approximately constitutes the lower BAAE

gap $\Omega_{\pm}^2 = k_{\pm}^2 = k_0^2 / \delta (1 + 2q^2)$ (see Fig.1(b)). Corresponding global solutions were found numerically. At $k_0^2 > \delta$ acoustic ± 1 sideband solutions exist.

Straightforward application of the ballooning formalism to the frequencies of interest based on the quasi-neutrality condition and Amper's law result in the general dispersion relation applicable for the Alfvén - acoustic continuum

$$2 - \sum_{\pm 1} k_{\pm 1}^{-2} \left\{ \frac{[\xi_{\pm 1i} + (\frac{1}{2} + \xi_{\pm 1i}^2) Z_{\pm 1}]^2}{\tau^{-1} + 1 + \xi_{\pm 1i} Z_{\pm 1}} - \left[\frac{3}{2} + \xi_{\pm 1i}^2 + \left(\frac{1}{2} + \xi_{\pm 1i}^2 + \xi_{\pm 1i}^4 \right) \frac{Z_{\pm 1}}{\xi_{\pm 1i}} \right] \right\} = \frac{2k_0^2}{\Omega^2 \delta_k} \quad (5)$$

which, if contributions from two acoustic sidebands are considered to be the same, $k_{+1}^2 \simeq k_{-1}^2$ or $k_0 \ll 1/q$, is reduced to the dispersion obtained in Ref.[20], where the derivation of Eq.(5) is described. Here $\tau = z_i^2 T_e n_i / z_e^2 T_e n_e$, $\delta k = \beta_i \tau / 2$, $\xi_{\pm 1i} = \omega / k_{\pm 1} v_{Ti}$, $Z = Z(\xi_{\pm 1i}) \equiv \pi^{-1/2} \int e^{-t} dt / (t - \xi_{\pm 1i})$, v_{Ti} is thermal ion velocity. We note that ± 1 sideband contributions should be separated to recover MHD results.

4. KINETIC DISPERSION OF MODIFIED ALFVÉN BRANCH

In a plasma with dominant electron beta recovers ideal MHD BAAE gap, Eq.(4), if $\tau > 2\xi_i^2 \gg 1$. In this case from Eq.(5) we find

$$\frac{k_0^2}{\Omega^2 \delta_k} \simeq 1 + \frac{2q^2}{1 - \xi_s^2} \left(1 + \xi_s^3 \tau^{3/2} e^{-\xi_s^2 \tau / 2} \frac{i \sqrt{\pi} \sigma}{4 \sqrt{2}} \right) \quad (6)$$

where we used $\xi_i = \omega q R / v_{Ti} = \omega q \sqrt{\tau} / \omega_A \sqrt{\beta e} \equiv \xi_s \sqrt{\tau / 2}$. If its imaginary part is neglected it is reduced to the MHD dispersion and corresponds to the sweeping up BAAE solution when q relaxes. The damping of this branch is exponentially small.

Another analytically treatable case is when ion temperature, or τ , is finite, and $\xi_{\pm i} \ll 1$. We find then

$$\frac{k_0^2}{\Omega^2 \delta_k} \simeq 1 + q^2 \left(\frac{1}{2} + \frac{\pi}{4} \frac{\tau}{1 + \tau} \right) + i e^{-\xi_s^2 \tau / 2} \frac{q^2 \sqrt{\pi}}{\xi_s \sqrt{2\tau}} \quad (7)$$

This solution is strongly ion Landau damped due to the acoustic branch assuming thermal ion parallel velocity is not changed over the characteristic time of the interaction with the mode. This is true if bounce frequency of thermal ions is smaller than the mode frequency, that is $\sqrt{\beta i \epsilon} < R k_{\parallel}$, which can be satisfied for sufficiently small ϵ and plasma pressure.

Eq.(5) also contains acoustic branches which correspond to zero denominator of the second term in the curl brackets on the LHS. This branch is the same as in MHD, Eq.(3), for $\tau \gg 1$, but should be obtained numerically otherwise. Figure 4 shows the comparison of these limit cases with MHD and with general dispersion. Numerical evaluation of Eq.(5) shows that the damping rate of its branches increases strongly at $\tau < 2$. Quantitatively in such a case the damping rate of the extremum points of the BAAE continuum is $\gamma / \omega > \sim 25\%$. The modified Alfvén branch damping becomes comparable to the frequency at smaller frequencies.

5. JET EXPERIMENTS

Instabilities with basic BAAEs properties were observed [1] (shown in Fig.5(a)), where low frequency magnetic activity was observed with the characteristic frequency sweep up. However the frequency of $n = 4$ gap BAAE was found to be ~ 1.8 times higher than measured. In the original work it was assumed that q -profile is monotonic and $\tau = 1$. A rather simple way to resolve this frequency mismatch was suggested in Ref.[2]. It was proposed that local low (and perhaps reversed) shear region with $q_{min} = 1.5$ exists. In that case we evaluate $\Omega_+ \simeq 21kHz$, so that the inferred gap BAAE frequency $\sim 16kHz$ becomes sufficiently close to the Doppler shifted observed $f = 14kHz$. This conjecture is supported by the presence of only even toroidal mode numbers, which follows from the requirements that $m = q_{min}n$ must be integer. Kinetic expressions in JET plasma conditions agree with ideal MHD because $\delta_k = \beta_e/2 = \delta$, since $\beta \simeq \beta_e$ and $\gamma \simeq 1$ for strongly ICRF heated plasma, when most of the energy of H -minority is transferred to electrons. It is also consistent with our kinetic model because as can be seen from Fig.5(a) modes are observed with almost zero frequency when their damping is strongest unless $\tau \gg 1$.

6. MAGNETIC SPECTRUM IN NSTX

Shown in figure 5(b) at $n=2,4$. BAAE frequency sweeps up from the level of plasma rotation ($f_{rot} \simeq 15kHz$) at q_{min} surface to about $50kHz$ (for $n = 2$ mode) in the lab frame. In that shot following parameters were achieved (at $t = 0.26s$) $R_0 = 0.855m$, $a = 0.66m$, $\beta_{p10} \equiv a 2\pi p(0)/B_0^2 = 0.34$, vacuum magnetic field at the geometrical center $B_0 = 0.44T$, edge and central safety factor values are $q_1 \simeq 13.86$ and $q_0 \simeq 2.1$. After internal reconnection event (IRE) at $t = 0.275s$ BAAE frequency goes down to the level of plasma rotation frequency. This may indicate that q_{min} value is changed back to its value at $t = 0.262s$. Another interesting observation is that like in JET plasma only even n -number BAAEs have been observed at $t = 0.262-0.275s$. Independent MSE measurements indicate that q_{min} indeed is close to $3/2$ value. Detailed measurements of BAAE internal structure revealed the same radial localization, eigenfrequency (within measured accuracy) and their evolution as was predicted by ideal MHD theory. On the other hand, unlike JET observations, BAAEs in NSTX typically seem to stay near the modified Alfvén continuum frequency and do not enter the Alfvén - acoustic gap, which is predicted to be at $\sim 25kHz$ and is consistently above measured frequencies. In NSTX plasma $\tau \sim 1$ so that BAAE instability is possible only if the drive is strong. This is possible because fast ion pressure is comparable with the pressure of thermal ions. We note that the observed BAAEs in NSTX can form avalanches during which several modes are excited simultaneously and result in strong beam ion redistribution and loss of a neutron signal by 13%, which approximately indicate the beam ion loss [21].

In dedicated experiments on DIII-D BAAE oscillations were also observed. Detailed measurements of internal low frequency oscillations shown in figure 6(a) with the BES diagnostics reveal very low frequency peaks below the characteristic RSAE frequency signal, which we identified as BAAEs.

Experiments were conducted with the ECH applied at $0.8sec$ after which a strong broadband oscillations are seen in figure 6(a). At a later time when T_e increases sufficiently high narrow BAAE

peaks are seen in the both BES and ECE spectra. These modes have localized radial structure near q_{min} . At $t = 1.6sec$ plasma is characterized by $R_0 = 1.66m$, $a = 0.64m$, $\beta_{p/0} = 5\%$, $B_0 = 2T$, $q_1 \sim 6$.

In order to identify the observed instabilities we have performed search for the eigenmodes using NOVA code and have found gap solutions with the frequencies shown in figure 6(b), which include the Doppler correction due to plasma rotation $12kHz$ at q_{min} . NOVA find solutions only as gap modes. During the sweeping up phase (modified Alfvén branch) all numerical solutions strongly interacted with the continuum and were discarded. Kinetic branch dispersion relation frequencies are also plotted, but for those values for which thermal ion Landau damping, Eq.7, satisfies $\gamma/\omega < 0.25$ and $0 < k_0 < 0.25$. Kinetic frequencies are plotted as a sweeping up solutions transitioning to the gap frequency. NOVA solutions turns out to be surprisingly close to the kinetic continuum gap frequency.

They also show similar time duration to those observed (see insert on Fig.6(a)). The sequence of instabilities is also reproduced. However in the experiments there was no measurements of BAAE activity done by the edge magnetics in order to determine the toroidal mode numbers. Thus one can only check how consistent the predictions are with the data. In the modeling the BAAE gap frequency is on the order $30-40kHz$. Additional analysis of BES poloidal wavevector measurements and the mode frequencies show that the instability frequency is in the range $0-30kHz$. (need to work out some more) FIDA measurements of the beam ion profiles suggest that the effect of BAAEs and RSAEs are similar.

SUMMARY

We have demonstrated the effects of the acoustic branch on the low frequency Alfvénic oscillations in toroidal plasmas with the reversed safety factor. We have shown that due large plasma beta in NSTX, characteristic frequency sweeping of RSAEs is suppressed. They are often stabilized by the finite pressure. New low frequency modes are studied and are observed in JET, NSTX and DIII-D. They exist in the BAAE gap with the frequency below GAM. With proper frequency normalization ideal MHD produces similar BAAE gap and can be used to simulate BAAE mode structure.

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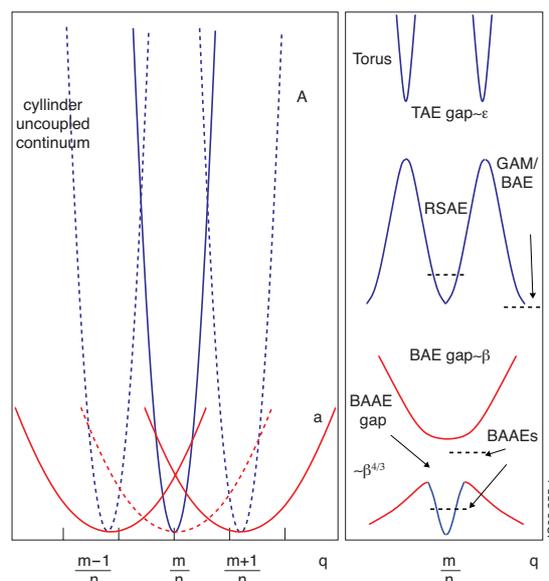


Figure 1: Schematic of the Alfvénic and acoustic continuum in a cylinder (left figure) and in a torus (right figure).

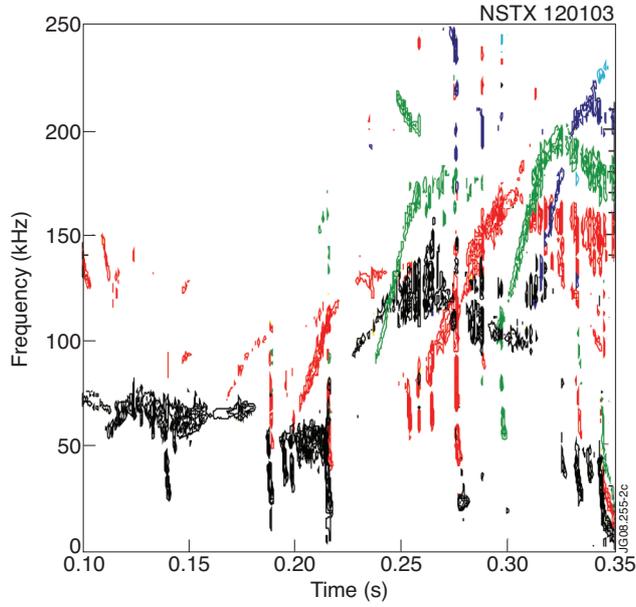


Figure 2: Edge magnetic spectrum of RSAE instabilities in NSTX with $\beta_{pl} = 6\%$ at $t = 0.27s$, $R = 1.25m$. Color coding is black for $n = 1$, red for $n = 2$, and green for $n = 3$.

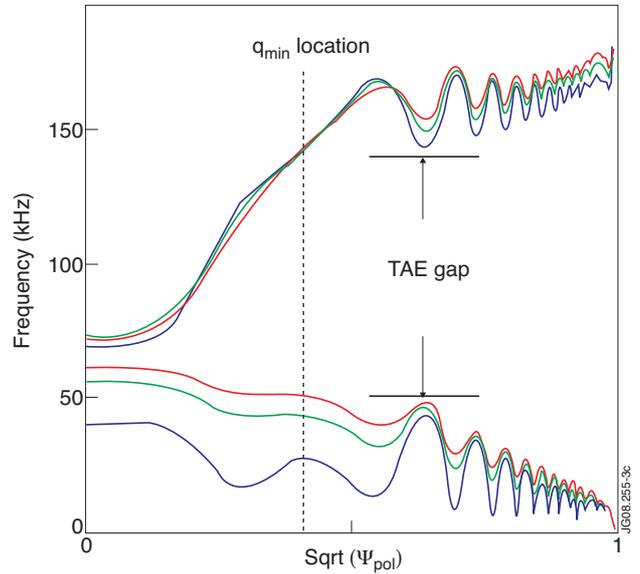
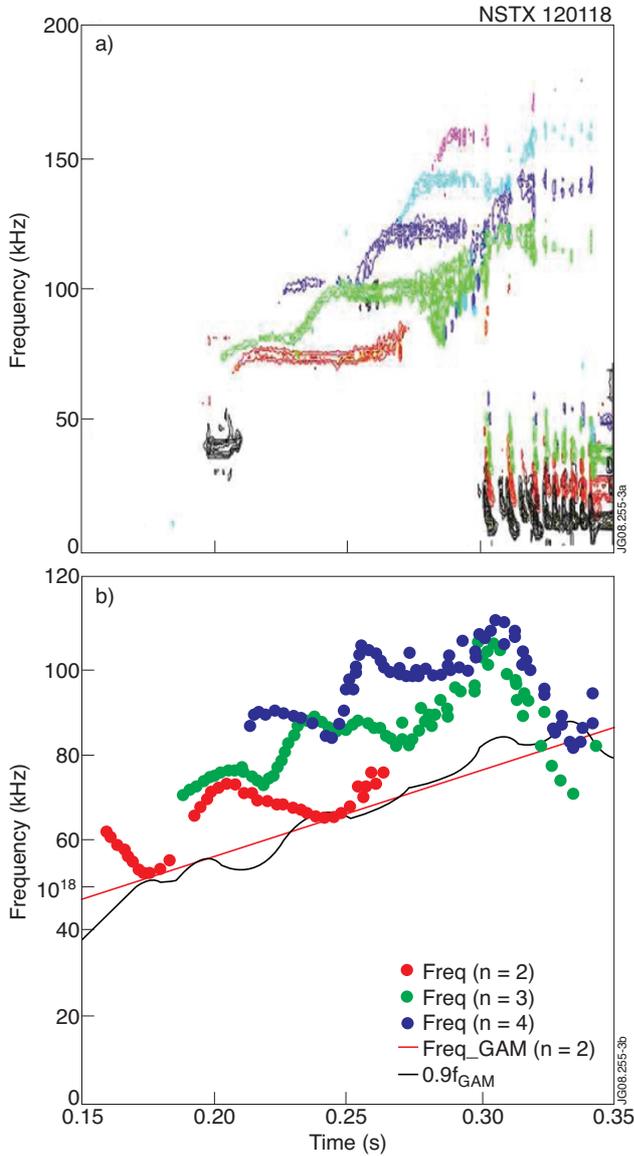


Figure 3: Figure (a) is the same as Fig.2, but for $\beta_{pl} = 11\%$. Figure (b) shows the same frequency points, but accounted for the Doppler rotation at q_{min} surface. Figure (c) presents NOVA continuum for different central plasma pressure as a function of plasma radius.

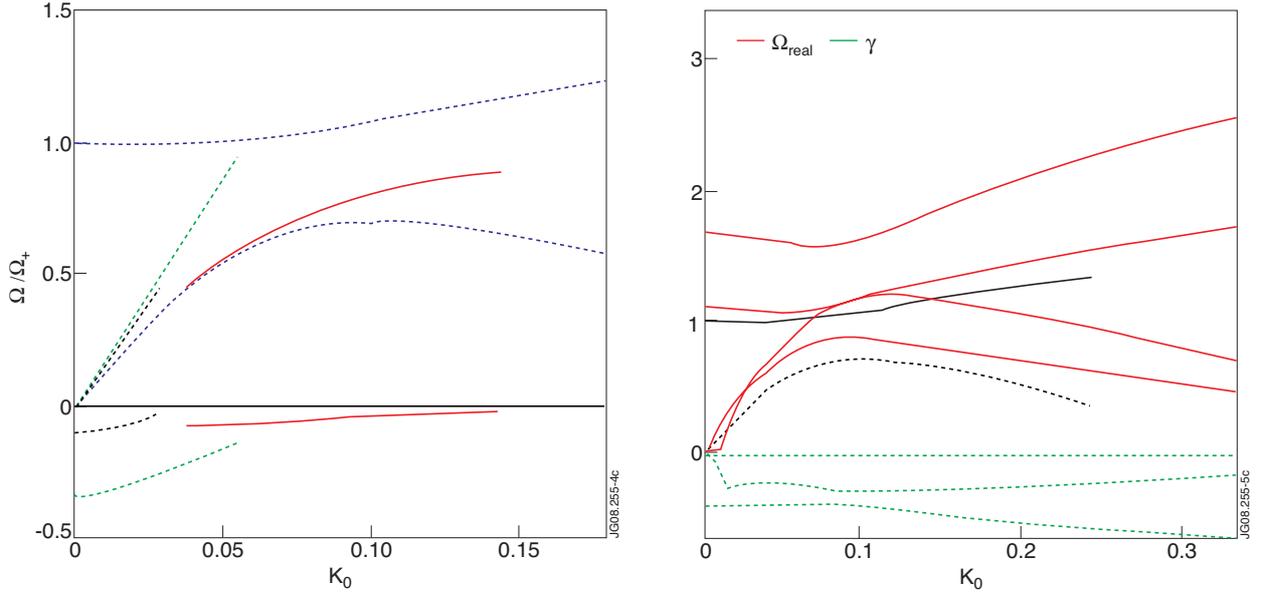


Figure 4: BAAE continuum solutions comparison with the MHD solution as indicated. All real solution frequencies are positive and their imaginary parts are negative. Frequencies are normalized to $\Omega_+ = \omega_A \sqrt{\tau\beta_i/2}q$ for kinetic solution. MHD frequencies are normalized to $\Omega_+ = \omega_A \sqrt{\tau\beta_i/2}q$. On figure (a) two kinetic branches are shown for $\tau = 15$, lower frequency, Eq.(7), and higher frequency, Eq.(6) solutions. Eq.(7) dispersion is also shown for $\tau = 2$. Figure (b) presents frequencies evaluated using general dispersion relation, Eq.(5). Results are shown for $n = 12$, $m = 21$ and $\delta = \delta_k = 0.25\%$.

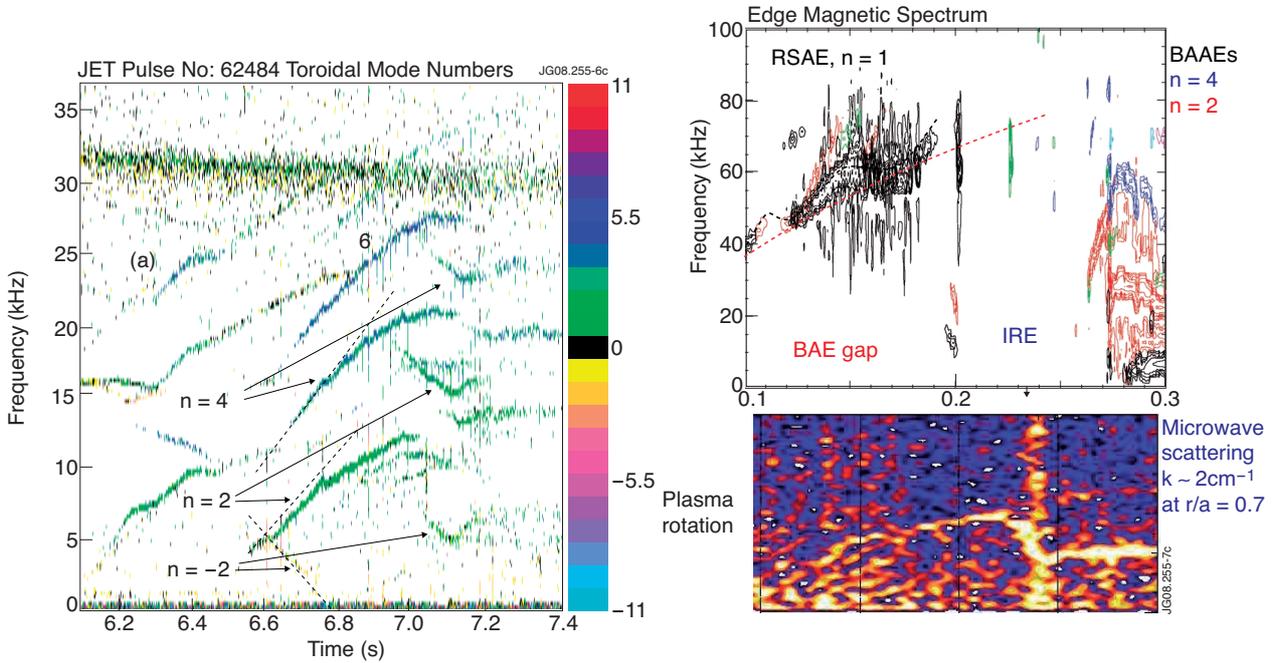


Figure 5: Magnetic signal frequency spectrum in JET (a) and NSTX (b). Different colors represent toroidal mode numbers according to the color chart on the right (figure (a)). Black dashed lines are tangential to the signal initial evolution at $t = 6.6$ sec. In NSTX after RSAEs with slow evolving activity suppressed at $t = 0.18$ s, BAAE becomes unstable at $t = 0.26$ s, such as $n = 2$ (red) and $n = 4$ (blue). BAAEs are also observed on high- k scattering diagnostic shown in the insert.

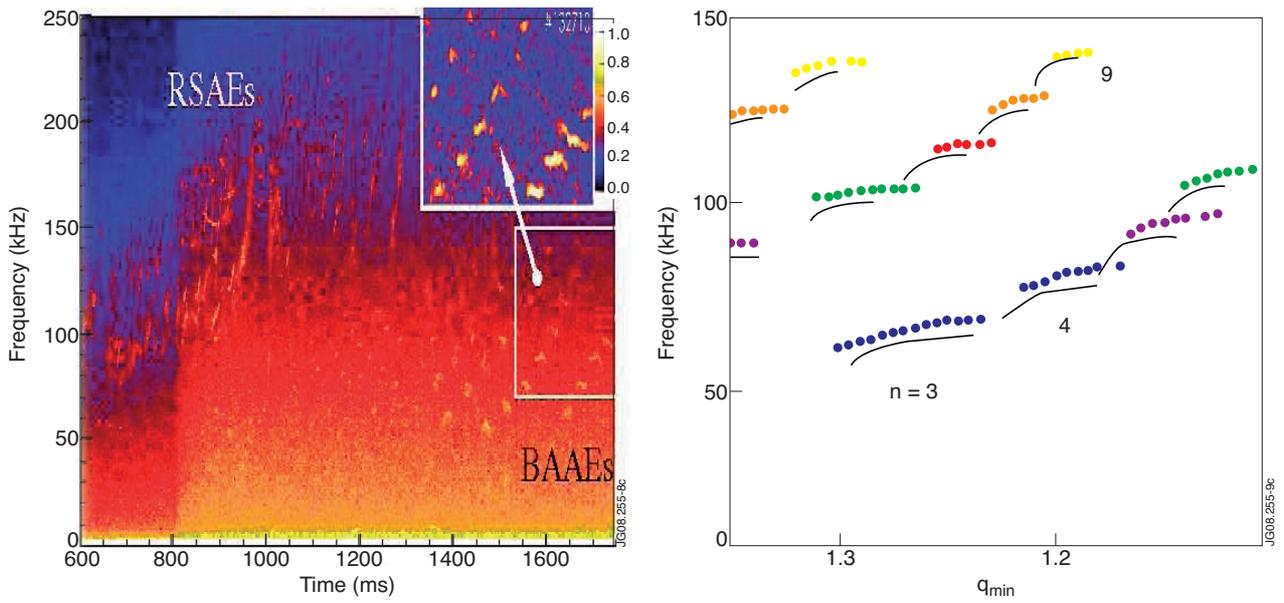


Figure 6: BES measured frequency spectrum (a) DIII-D Pulse No: 132710 and a zoom of a narrow region of several BES channels cross correlation shown in the insert. Figure (b) shows results of NOVA simulations (points) of different n modes as indicated. Under each mode points shown in black line is the lower continuum gap frequency from kinetic dispersion.