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Reversed Shear Alfvén Eigenmodes: Experiment, Simulations and Theory

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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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ABSTRACT.

Analytical theory and ideal MagnetoHydroDynamic (MHD) simulations are applied to interpret and understand Alfvén eigenmode activity that can exist at the shear revearsal point in the magnetic safety factor, the Reversed shear Alfv en Eigenmodes (RSAE). The frequency behavior and the radial mode structure is studied for RSAEs associated with the TAE gap. From theory and simulations it was predicted that RSAE-like modes can also exist in higher order gaps in the Alfvén continuum. Experimental evidence is shown for RSAEs associated with the NAE gap.

1. INTRODUCTION

Plasma shaping and profile control are of paramount importance for advanced tokamak scenarios which are planned as high performance discharges in ITER. These high performance plasmas are highly elongated with a significant triangularity. The magnetic safety factor or q profile in two main operational scenarios, hybrid and advanced, is expected to be weakly to strongly reversed and/or has a large region of weak magnetic shear. Some of the important e effects of plasma shaping and reversed magnetic shear are microturbulence suppression, the absence of detrimental MHD activity such as Edge Localized Modes (ELM) and sawteeth. Internal transport barriers with high pressure gradients are likely to be formed in such plasmas.

Strong plasma shaping in the presence of low or reversed magnetic shear leads to large gaps in the shear Alfvén continuum spectrum. In these gaps various types of Alfvén Eigenmodes (AEs) can reside (such as the TAEs, EAEs, NAEs, BAEs, RSAEs, etc.) which are often excited by populations of super-Alfvén fast ions. Once excited, these modes can be very effective in transporting fast ions from the plasma core to the outer regions where they are lost. Understanding the behaviour of those modes is therefore of crucial importance for the development of advanced scenarios for ITER.

In this paper we present some results on the development of ideal MHD theory and the comparison to current experiments. The detailed study of geometry effects on ideal MHD modes is essential in order to establish a baseline from which non-ideal effects can be identified and understood.

2. FINITE PRESSURE EFFECTS ON RSAES

When the plasma pressure is finite the Alfvén and sound waves can couple and the beta-induced Alfvén eigenmode gap opens between zero and the GAM frequency. The effect of this coupling is that the minimum RSAE frequency increases to slightly above the GAM frequency. Such a shift is observed for low-n RSAEs in JET as can be seen in Fig. 1 where the observed RSAE frequency is compared with the simulated one [1].

The RSAEs are located above the top of the Alfvén continuum at the magnetic shear reversal point. The frequency spacing between the mode and the top of the Alfvén continuum increases with an increasing plasma pressure gradient as was shown analytically and from simulations in [2]. Analytical theory and NOVA [3, 4] simulations agree well with each other (see Fig.2 in the region where the analytical theory is valid (low pressure gradients). Details of the analytical theory can be found in [2, 5].

Due to the increased diagnostic capabilities, it is now possible to measure radially resolved density and temperature fluctuation profiles and compare those with theoretical predictions. In ideal MHD the electron density (ne) and temperature fluctuations (Te) are given in terms of the plasma displacement vector, ξ:

$$\frac{\delta n_e}{n_e} = -\left(\nabla \cdot \xi + \xi \cdot \frac{\nabla n_e}{n_e}\right)$$

$$\frac{\delta T_e}{T_e} = -\left((\gamma - 1)\nabla \cdot \xi + \xi \cdot \frac{\nabla T_e}{T_e}\right)$$

where is the adiabatic index of compression.

In DIIID both the density and temperature fluctuations due to TAEs and RSAEs have been measured and compared with NOVA predictions (Fig.3). The NOVA output was scaled to the ECE data and the same scaling factor was used for the density fluctuation data. From the above analysis we can conclude that radial fluctuation profiles as calculated from a ideal MHD model agree very well with the observed fluctuation profiles [7].

3. RSAES IN HIGHER ORDER ALFVEN GAPS

RSAEs are located at the local maximum of the Alfvén en continuum at the shear reversal point of the q profile. In higher-order gaps similar maxima exist as can be seen in Fig. 4We explore here the possibility of RSAE-like modes associated with those higher-order gaps. In NOVA simulations RSAEs associated with higher gaps can sometimes be found. Analytical theory [8] similar to the one for TAE-RSAEs [5] predicts a pressure-gradient threshold for modes in the higher order Alfvén gaps for large-aspect ratio plasmas with a circular cross section (Fig.5. The critical $\alpha = -dP/drRq^2/B^2$ (P plasma pressure, B magnetic field R major radius) for NAE-RSAEs de- creases with increasing values of qmin as is found from analytical theory and NOVA simulations (Fig.6. This implies that one should look for the NAE-RSAEs in data when qmin is still high. In JET NAE-RSAEs have been observed during the current ramp-up phase of highly elongated plasmas (κ = fluctuations of the RSAE compared to the NOVA results with the same scaling as for the temperature fluctuations. 1.8) when the q profile was reversed and had a very large region of weak shear as can be seen in Fig.7. In the spectrum of the magnetic fluctuations (Fig.8 measured with Mirnov coils at the plasma edge a rich spectrum of modes can be seen. The plasma is evolving rapidly during this period as can be seen from the time traces above, therefore, simulating this phase is tedious but with the NOVA code a good agreement between the measured and simulated spectrum was found. From the simulations TAE-RSAEs are positively identified ed at 2.6 to 2.8s end between 300 and 340kHz.

4. DOWN-CHIRPING RSAES

Normally, only RSAEs that chirp up in frequency are observed but on rare occasions down-chirping RSAEs are found experimentally. An example of down-chirping RSAEs in JET is shown in Fig.9 Down chirping RSAEs were observed in JET during the plasma ramp-up phase when the q-profile was reversed (Fig.10. MHD calculations with the NOVA-K code were successfully performed to simulate the observed frequency behaviour as can be seen in Fig.11 for the observed n = 1 and 2 RSAEs.

Experimentally down-chirping RSAEs have been observed and that can be simulated well with an ideal MHD code. E efforts are being made to develop an analytical theory which supports the simulations and studies are underway to clarify the role of the di different damping terms, where the continuum damping seems to be the dominant one, for the down-chirping modes.

CONCLUSIONS

In this paper we have compared in detail ideal MHD simulations of RSAEs with experimental results and analytical theory. This work is performed to gain understanding of RSAEs and predict their behaviour in among others ITER advanced tokamak scenarios.

It was shown that coupling effects between sound and Alfvén waves is important for understanding the minimum frequency of the RSAEs. Finite pressure gradient effects were found to be destabilizing for RSAEs by moving away the mode away from the Alfvén en continuum when the pressure gradient increases.

Another severe test for ideal MHD theory that passed successfully for RSAEs was the comparison between predicted and measured radial fluctuation profiles. Both temperature and density fluctuation pro profiles were found to be consistent with NOVA calculations.

From simulations and analytical theory it was found that RSAE-like modes can exist in higher order Alfvén gaps. For circular plasma cross sections these modes come only into existence when a critical plasma pressure gradient is passed. Elongating the plasma reduces this threshold as was found from simulations. These shaping effects are currently being studied in analytically. Experimentally, RSAEs associated with the RSAE gap were found in JET discharges and successfully simulated with ideal MHD.

RSAEs are mostly seen chirping up in frequency but there are rare observations of up and down chirping. Work is on going to understand this behaviour analytically. Simulations performed with NOVA were able to reproduce the observations but questions remain about the interaction of those modes with the Alfvén continuum.

ACKNOWLEDGEMENTS

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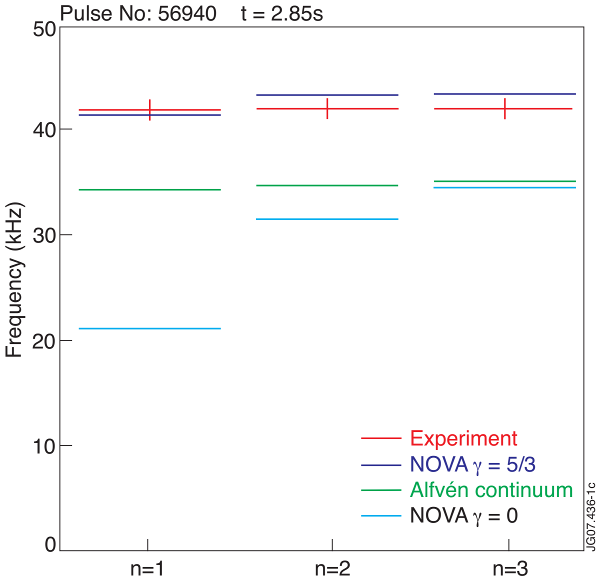

Figure 1: Experimentally observed minimum RSAE frequency (red) compared with simulations with (blue) and without (magenta) soundwave coupling. The up-shifted Alfvén continuum with soundwave coupling is indicated with the green lines.

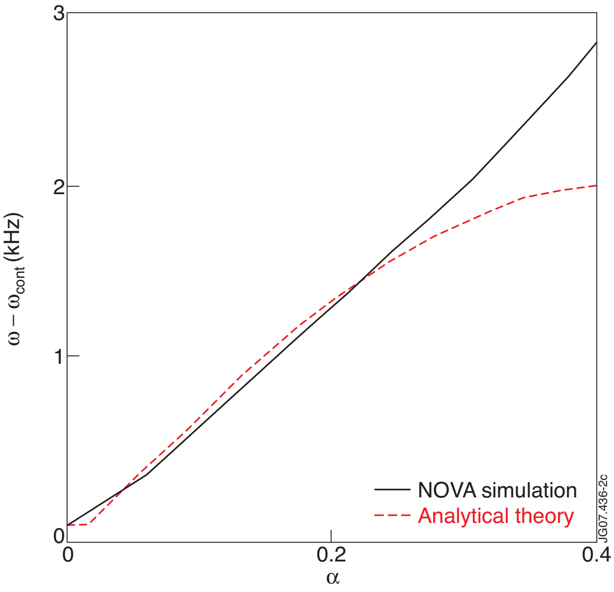

Figure 2: Difference between the RSAE frequency (ω) and the top of the Alfvén continuum at q_{min} *as a function of the normalized plasma pressure gradient,* $\alpha = -dP/drRq^2/B^2$ *(P plasma pressure, B magnetic field, R major radius).*

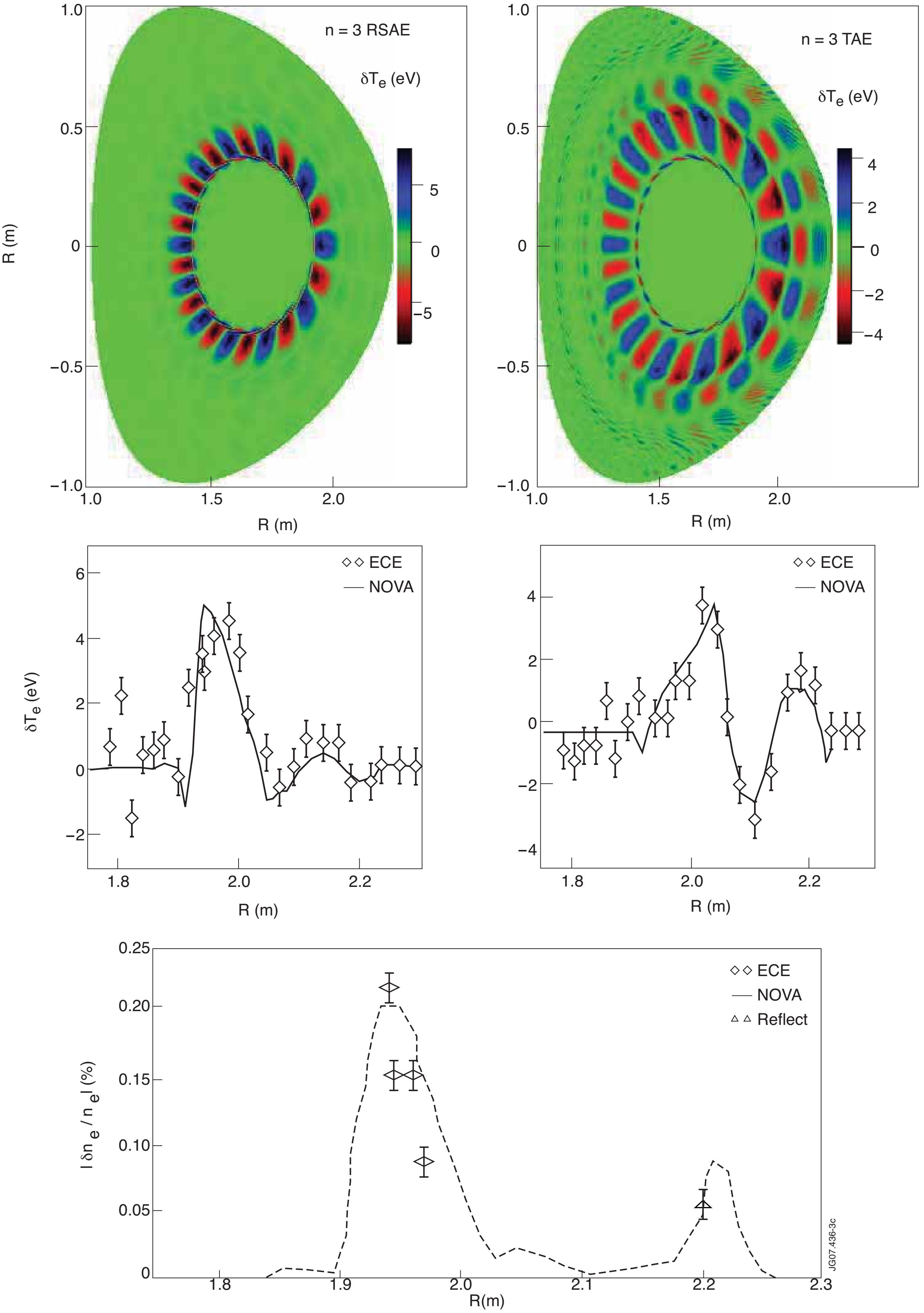

Figure 3: (Top) NOVA simulation of an n = 3 RSAE (left) and n = 3 TAE (right). (Middle) Measured temperature fluctuations at the plasma mid-plane for the same RSAE (left) and TAE (right). (Bottom) Measured density fluctuations of the RSAE compared to the NOVA results with the same scaling as for the temperature fluctuations.

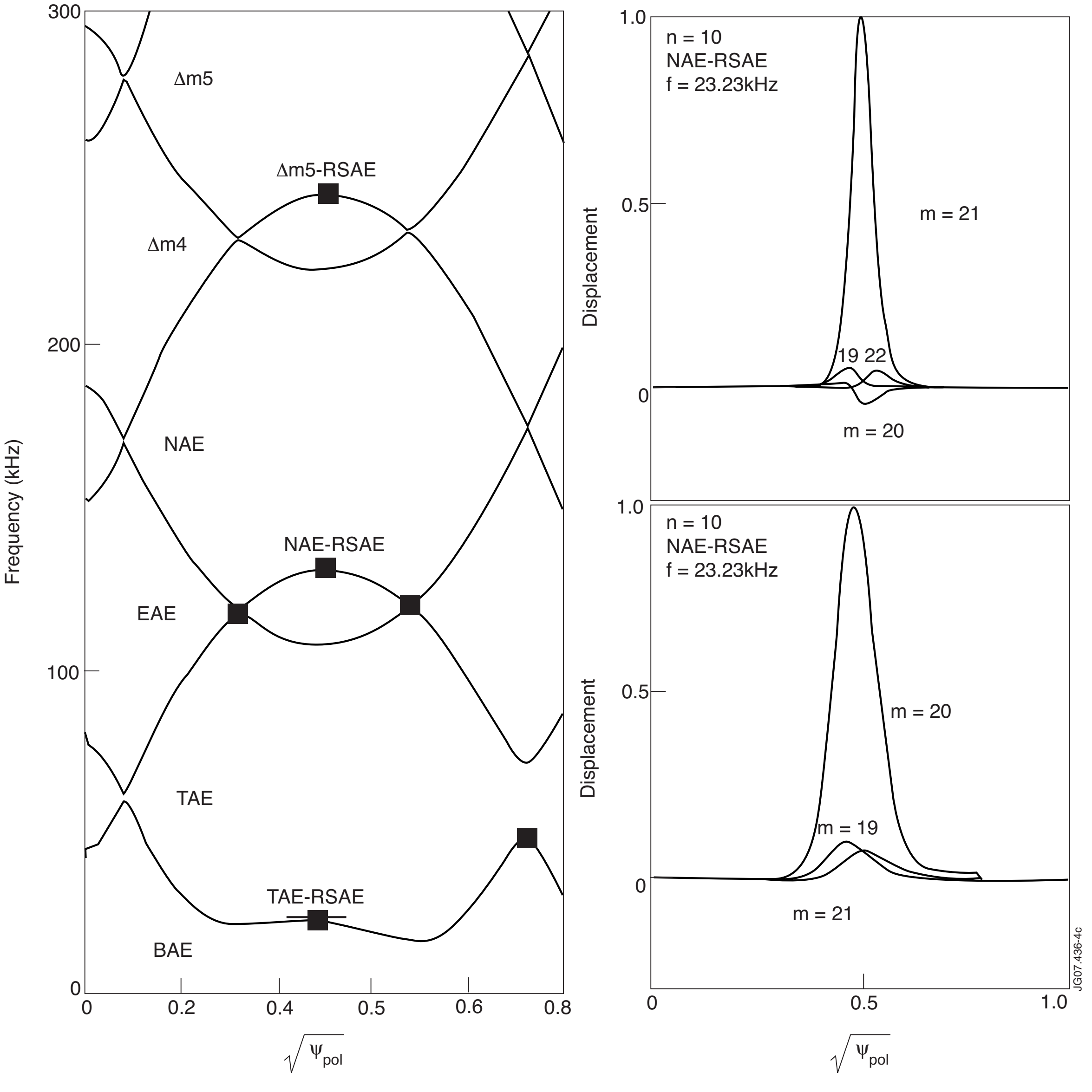

Figure 4: (Left) Alfvén continuum with the locations for RSAEs in the TAE, NAE and δm5 gaps. (Right) Eigenmode solutions for the TAE-RSAE (bottom) and the NAE-RSAE (top).

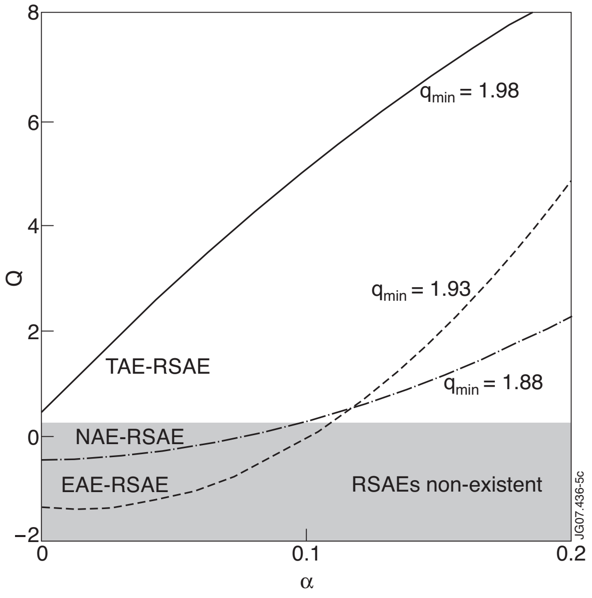

Figure 5: Q (as defined in [6] as function of the normalized pressure gradient, α, for a TAE-RSAE, NAE-RSAE, and an EAE-RSAE. When Q is smaller than 0.25 the no mode solution exist. The TAE-RSAE is always present while the NAE-RSAE and EAE-RSAE only come into existence when a critical pressure gradient is passed.

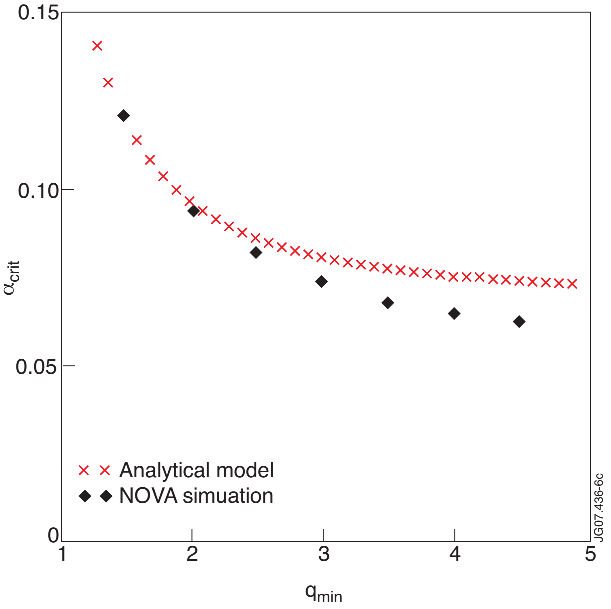

Figure 6: The critical pressure gradient, α, as function of q_{min} *calculated analytically (crosses) and with NOVA (diamonds). The critical increases with decreasing* q_{min}*.*

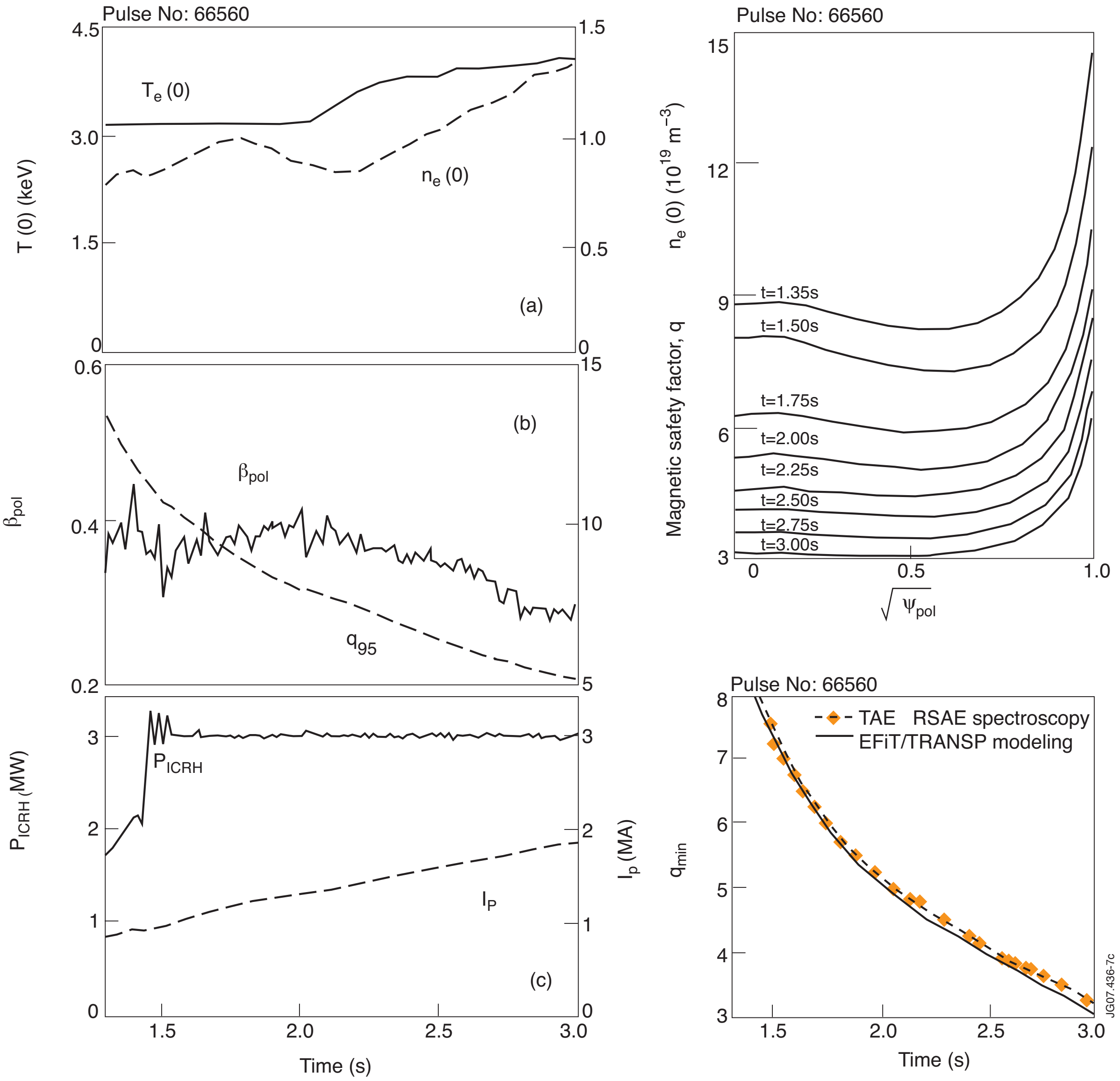

Figure 7: (Left) Time traces for a JET discharge (Pulse No: 66560) in which NAE-RSAEs were observed. (Right) The q profile at several times during the current ramp-up (top) and the evolution of q_{min} as deduced from RSAE spectroscopy compared to the one from EFIT/TRANSP modeling (bottom).

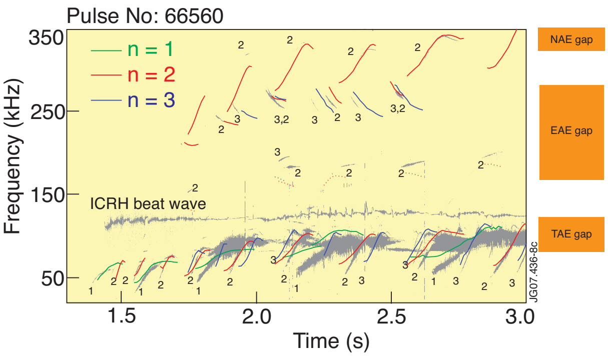

Figure 8: Mirnov coil spectrum of magneti fluctuations of a JET discharge (Pulse No: 66560) in which NAE-RSAEs were observed (Gray contours) overlayed in color are NOVA simulations for n = 1 (green), n = 2 (red), and n = 3 modes. The NAE-RSAEs can be seen above 300kHz.

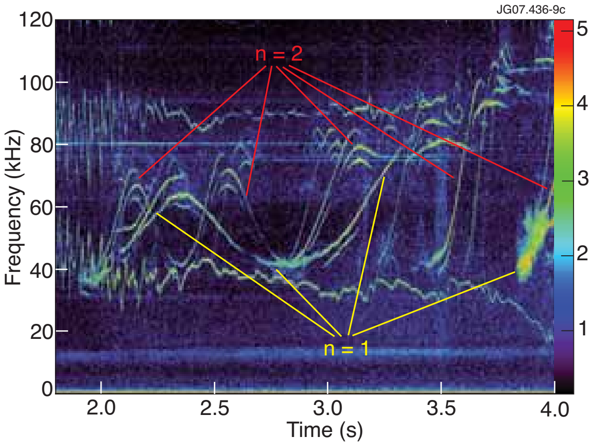

Figure 9: Mirnov coil spectrum of magnetic fluctuations of a JET discharge (Pulse No: 56940) in which up- and down-chirping RSAEs were found. The n=1 and n=2 modes which were simulated with NOVA are indicated with the yellow and red arrows.

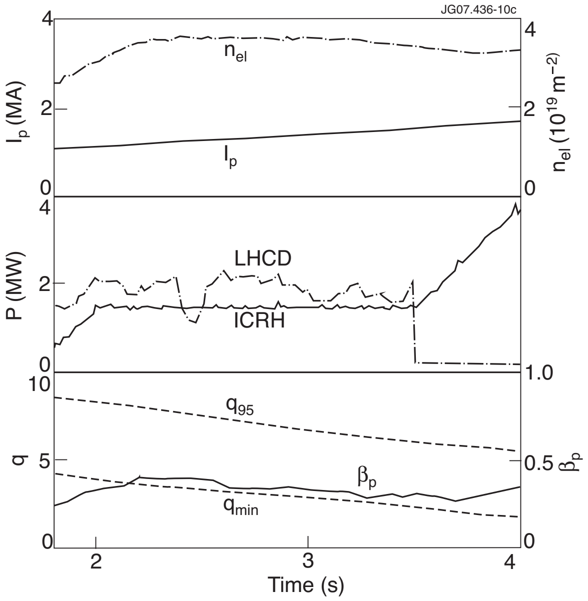

Figure 10: Time traces for a JET discharge (Pulse No: 56940) in which up- and down-chirping RSAEs were found.

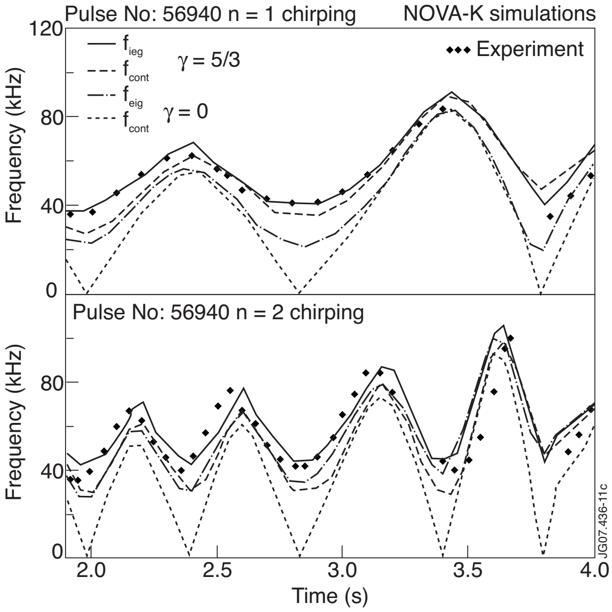

Figure 11: Nova simulations of the n = 1 (top) and n = 2 (bottom) up-down chirping RSAEs. Diamonds: experimental frequency, Solid (dash-dotted) lines simulated eigenfrequencies with (without) the inclusion of soundwave coupling. Dashed (dotted) lines the frequency of the Alfvén continuum at qmin with (without) the inclusion of soundwave coupling.