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## ABSTRACT

Toroidal Alfvén Eigenmodes and a new class of modes, the Alfvén cascades, excited by energetic ions are observed in the JET tokamak. Measurements of these Alfvén instabilities are used to solve the inverse problem of identifying the plasma parameters using the dependence of the Alfvén spectrum on equilibrium parameters.

PACs: 52.35.Bj; 52.55.Fa; 52.55.Pi

## 1. INTRODUCTION

The determination of the plasma parameters from measurements of magnetohydrodynamic (MHD) waves has been called MHD spectroscopy [1-3]. Alfvén waves, which constitute the most significant stable part of the MHD spectrum, and in particular the discrete spectra of Toroidal Alfvén Eigenmodes (TAEs), which exist in the toroidal geometry [4], were successfully used previously [2, 3] for the MHD spectroscopy of magnetically confined toroidal plasmas in the JET tokamak. The TAE eigenfrequency,  $\omega_{TAE}$ , lies within the toroidicity-induced gap [4] close to the frequency  $\omega_0$  determined by the degeneration of two cylindrical-geometry shear Alfvén modes with the poloidal mode numbers  $m$  and  $m+1$  (for the same toroidal mode number  $n$ ):

$$\omega_{TAE} \approx \omega_0 = k_{\parallel m}(r) V_A(r_m) = -k_{\parallel m+1}(r_m) V_A(r_m). \quad (1)$$

Here  $V_A(r)$  is the Alfvén velocity,  $k_{\parallel m}(r) = (1/B_0)(\mathbf{B}_0 \cdot \nabla) = [nq(r) - m]/Rq(r)$  is the component of the wave-vector parallel to the equilibrium magnetic field  $\mathbf{B}_0$ ,  $r$  and  $R$  are the minor radius and the major radius of the tokamak magnetic axis,  $r_m$  is the radial coordinate of the magnetic surface at which the degeneracy occurs, and  $q(r)$  is the safety factor.

The safety factor  $q(r)$  is a measure of the magnetic field line twist, i.e. this factor determines the ratio between the toroidal magnetic field  $B_T$  produced by external field coils and the poloidal field  $B_p$  produced by a toroidal current in plasma. In the simplest case of a low-pressure plasma with a circular cross-section and  $r/R \ll 1$ , the safety factor is given by  $q(r) = rB_T/RB_p$ . The profile  $q(r)$  is essential for determining the MHD stability of plasmas, but it is difficult to measure accurately, especially in the centre of the plasma. In the JET discharges with neutral beam injection (NBI) the ratio  $B_p/B_T$  is measured as a function of radius with the motional Stark effect (MSE) diagnostic [5]. However, in plasmas without NBI the safety factor profile  $q(r)$  is reconstructed with the EFIT code [6] using mainly external measurements of the axisymmetric magnetic field, and such EFIT reconstructions can have large error bars in the centre of the plasma. In this case as well as in cases where MSE measurements are available, independent determination of aspects of the  $q(r)$ -profile by MHD spectroscopy is very valuable.

The measurements of  $\omega_{TAE}$  can be used for determining local values of  $q(r_m)$  and increasing the accuracy of the EFIT equilibrium reconstruction, since the TAE frequency is determined by plasma parameters in a narrow region of width  $\Delta r \approx (r_m/R) \cdot (r_m/m)$ , which is associated with the magnetic surface  $r_m$  determined by

$$q(r_m) = (m+1/2)/n. \quad (2)$$

Expression (2) implies that one can associate measurements of  $\omega_{\text{TAE}}$  and the toroidal mode number  $n$  with a certain set of  $q(r_m)$  values only, e.g. TAEs with  $n=1$  are associated with  $q(r_m)=3/2$  ( $m=1$ ),  $5/2$  ( $m=1$ ),  $7/2$  ( $m=3$ ), etc. Thus, by measuring TAEs with  $n=1$  one can infer the relevant  $q(r_m)$  values providing the measurements of the plasma density profile are also available, so that  $V_A$  can be determined.

The problem of determining the safety factor in the plasma core by measuring the spectrum of *linearly stable* TAEs with low toroidal mode numbers,  $n=1-2$ , was analysed in [2, 3]. In this stable TAE technique, small amplitude currents were driven in an external antenna [7] and the synchronous measurements of the plasma response exhibited resonance behaviour at the eigenfrequencies of low- $n$  TAEs.

These studies are extended in the present Letter to measurements of *unstable* Alfvén waves excited in JET by energetic ions accelerated by ICRH. The high-resolution magnetic diagnostic [7, 8] installed in JET for the Alfvén frequency range facilitate measurements of the Alfvén instabilities, which are routinely observed in many JET discharges with ICRH. In this Letter, we demonstrate how to apply the detection of unstable Alfvén waves for the purposes of the MHD spectroscopy, and what advantages and disadvantages such a technique has as compared to the stable TAE technique [2, 3].

## 2. TAEs IN PLASMAS WITH TEMPORAL EVOLUTION OF MONOTONIC SAFETY FACTOR

The measurements of unstable Alfvén waves are performed using a toroidal set of high-resolution magnetic pick-up coils connected to an analog to digital converter with a sampling rate of 1MHz [7]. Magnetic fluctuation data,  $\partial(\delta B_p)/\partial t$ , are recorded with 12 bit resolution for up to 4 s during JET discharges. The toroidal set of three coils allows the determination of toroidal mode numbers from  $n = -17$  to  $n = 17$ . An impedance analysis technique to calibrate the pick-up coils remotely [8] allows an absolute determination of the mode amplitudes at the edge down to values of  $|\delta B_p/B_0| \leq 10^{-8}$ . Measurements of the poloidal mode numbers  $m$  had a limited frequency range (mostly up to 125 kHz, i.e. below  $\omega_{\text{TAE}}$ ) and a short time window, so that it was rarely possible to use the measurements of  $m$  for TAEs. Instead of  $m$ , the EFIT reconstruction is used as a first-order approximation for  $q$ .

In contrast to the technique based on external excitation of stable modes, limited to a single low  $n$ ,  $n=0, 1, 2$ , the wave numbers of unstable TAEs are determined by the distribution function of the energetic ions. Due to the spread in energy and the pitch-angle, the energetic ions excite simultaneously many TAEs with different toroidal mode numbers. The detection of unstable TAEs with different toroidal mode numbers can be directly used for determining the plasma current evolution during the discharge.

Consistency between TAE observations and the values  $q(r_m)$  determined by Equation (2) can be assessed first by analysing unstable TAEs (Fig.1) observed when  $q(r)$  significantly evolves

in time, so that the  $q(r_m)$ -values appear one after another at the plasma centre. As an example we consider TAEs measured during the “pre-heating” phase of a discharge (pulse #45848), when ICRH only was applied at constant power  $P_{ICRH} \approx 1.2$  MW, so that no significant toroidal rotation of plasma was present. During the time of analysis, from  $t = 3$  sec to  $t = 3.6$  sec, the plasma current was increasing from 1.55 MA to 1.8 MA, due to a current ramp-up 0.45 MA/s, and the safety factor was decreasing accordingly. At the same time, the plasma density was decreasing from  $\bar{n}_e \approx 1.05 \times 10^{19} \text{ m}^{-3}$  to  $0.85 \times 10^{19}$ , and the electron temperature was increasing from  $T_e(0) \approx 2.5$  keV to  $T_e(0) \approx 3.5$  keV. TAEs excited by ICRH-accelerated energetic ions were detected, as shown in Fig.1. The measured unstable TAEs last for about 0.2 sec. The toroidal mode numbers of TAEs with highest amplitude increase from  $n = 1$  to  $n = 3$ , with additional smaller amplitude signals showing unstable  $n = 6$  and  $n = 7$ .

The temporal evolution of  $q(r)$  as reconstructed by the EFIT code with magnetic measurements alone is shown in Fig.2, which we consider as a first order approximation for estimating  $q(r)$ . The ICRF-accelerated ions have been analysed in this discharge using the FIDO code [9], and the radial pressure profile of the energetic ions was found to have a significant pressure gradient within  $r/a \leq 0.5$ . Detection of an unstable TAE with  $n=1$  necessarily means that during the time of the TAE observation the magnetic surface associated with the value of  $q(r_m) = (m+1/2)/n$  is present in the plasma region with  $d\beta_{\text{hot}}/dr=0$ . Direct comparison of the EFIT-reconstructed profile in Fig.2 and Equation (2) shows that the  $n = 1$  mode can be only associated with the magnetic surface  $q=2.5$  ( $n/m=1/2$ ), since neither  $q=3.5$  nor  $q=1.5$  are good options for the initial guess from EFIT. Similarly, one concludes from the temporal sequence that the  $n = 2$  mode in Fig.1 can only be attributed to the magnetic surface  $q=2.25$  ( $n/m=2/4$ ), and the  $n = 3$  mode - to the magnetic surface  $q=2.17$  ( $n/m=3/6$ ).

Comparing the frequencies of the modes with different  $n$  at the time of the mode appearances, we see that the modes follow the TAE-scaling with  $q$  and plasma density,  $f_0 = V_A / 4\pi q R \propto 1/q\rho_i^{1/2}$ , which confirms that these modes are TAEs. From the relevant  $q(r_m)$ -values for  $n = 1, 2$  and  $3$  at the observation times in Fig.2, one sees that the TAE observations in Fig.1 are consistent with the  $q(r)$ - evolution: each TAE moves radially together with corresponding  $q=2.5$ ,  $q=2.25$  or  $q=2.17$  from  $r/a \approx 0.2$  to  $r/a \approx 0.4$  and disappears then. The region of TAE instability,  $r/a \leq 0.4$ , is in agreement with the region of highest energetic ions pressure gradient. Note also that smaller amplitude TAEs with toroidal mode numbers  $n = 6$  and  $n = 7$  appear at  $t = 3.3$  sec and  $t = 3.4$  s correspondingly. This observation is consistent with the appearance of  $q \approx 2.25$ , which causes the existence of not only the mode  $n/m = 2/4$  as already discussed above, but also of the  $n/m = 6/13$  mode. The appearance of  $q \approx 2.21$  causes the existence of the  $n/m = 3/6$  and  $n/m = 7/15$  modes.

We conclude that in this particular case, the EFIT code shows a good accuracy consistent with the independent estimate of the  $q(r)$ -evolution from the TAE measurements. Possible future

use of the measurements of unstable TAEs for MHD spectroscopy is therefore encouraging, especially if direct measurements of the fast particle pressure profile will be performed.

### 3. ALFVÉN CASCADES IN PLASMAS WITH EVOLUTION OF NON-MONOTONIC SAFETY FACTOR

The information on the  $q(r)$ -profile and on its evolution in time is of even greater importance in the optimised shear or advanced tokamak scenarios. A very interesting example of Alfvén instabilities, differing from TAEs, are the Alfvén wave cascades observed for the first time on JT-60U [10], and now routinely detected in JET optimised shear experiments with strongly non-monotonic safety factor profiles, which significantly evolve in time [11]. These experiments are designed to generate internal transport barriers with non-monotonic  $q(r)$ -profiles created by lower hybrid heating and current drive before the main heating power is applied [12]. Appropriate tailoring of the  $q(r)$ -profile has been demonstrated to be the fundamental tool to reach favourable plasma stability and transport regimes [12]. MHD spectroscopy based on Alfvén instabilities has been applied to these scenarios for independent determination of the details of the  $q(r)$ -profile. This led to the necessity to interpret this new class of fast particle driven modes, the Alfvén cascades, in plasmas with shear reversed equilibria. In the rest of this section we briefly describe Alfvén cascades in JET plasmas without significant toroidal rotation, and subsequently focus on their application as diagnostic tools, while a full interpretation of the mode physics is beyond the scope of this Letter.

The Alfvén wave cascades with upward frequency sweeping, Fig.3, are driven by ICRH-accelerated energetic ions. Each cascade consists of many modes with different toroidal mode numbers and different frequencies. The toroidal mode numbers vary from values as low as  $n = 1$  (or  $n = 2$  in the particular case shown in Fig.3) to  $n = 6$ . The frequency of the Alfvén cascades starts from 20 to 60 kHz, i.e. well below the TAE frequency. During the cascade evolution, the frequency increases up to the frequency of the TAE-gap. One can observe this relation between the frequency of the cascades and the frequency of TAEs in Fig.3, where both Alfvén cascades and TAEs co-exist for  $t > 5.3$  s. The rate of increase in the Alfvén cascade frequency is proportional to the mode number  $n$  and modes of different  $n$  occur at different time slices.

In the framework of the ideal MHD model, a close correlation has been found between the time evolution of the Alfvén cascades and the evolution of the Alfvén continuum frequency at the point of zero magnetic shear. An analysis of the Alfvén cascade frequency sweeping in time shows a very close correlation with the evolution of the local extremum,  $\omega'_A = 0$ , point (the “tip”) of Alfvén continuum associated with  $q_{\min}$ :

$$\omega(t) = \left| \frac{m}{q_{\min}(t)} - n \right| \cdot \frac{V_A(t)}{R_0} + \Delta\omega. \quad (3)$$

Here,  $q_{\min}(t)$  and  $V_A(t)$  vary in time in accordance with the experiment, and  $\Delta\omega$  is an offset frequency. Modelling of the Alfvén continuum evolution with the CSCAS code [13], shown



in Fig. 4, describes the temporal evolution of the value  $\omega(t) - \Delta\omega$  at fixed plasma density,  $V_A(t) = \text{const}$ , and at gradually decreasing  $q_{\min}(t)$ . It follows from Fig. 4 that the Alfvén cascade with upward frequency sweeping occurs when the Alfvén continuum has a *maximum* at  $q_{\min}$ . This is in contrast with the well-known case of Global Alfvén Eigenmodes, which exist at frequency below minimum of the Alfvén continuum [14].

The interpretation of the Alfvén cascades is given in [15] in terms of a new type of Energetic Particle Modes localized at the point where  $q(r)$  has a minimum. The eigenfrequency of this mode is given by

$$\omega_{\text{cascade}} = \omega(t) + \delta\omega(\beta_{\text{hot}}, d^2q/dr^2), \quad (4)$$

where  $\delta\omega$  ( $\delta\omega \ll \omega(t)$ ) is a small deviation of the cascade frequency from the Alfvén continuum (3). This deviation depends on the fast ion pressure  $\beta_{\text{hot}}$  and the second derivative  $d^2q/dr^2$  at  $q_{\min}$ , i.e. at the zero magnetic shear point,  $(dq/dr) = 0$ . Due to the finite value of  $\delta\omega$  the Alfvén cascade is not subject to significant continuum damping and is observed as a discrete eigenmode, which closely tracks the Alfvén continuum tip described by (3).

Considering Eq.(3) as a diagnostic tool for interpreting the Alfvén cascades in Fig.3, one sees that:

1. the rate of the Alfvén cascade frequency increase is proportional to  $n$ , in agreement with the experimental observation, and
2. modes of different  $n$  satisfy the condition  $m - nq_{\min}(t) = 0$  at different times as  $q_{\min}$  passes different sets of rational magnetic surfaces during the evolution. For example, the  $n = 1$  rational surfaces occur when  $q_{\min}$  passes integer values 1, 2, 3...; the  $n = 2$  rational surfaces occur when  $q_{\min}$  passes integer and half-integer values 1, 3/2, 2, 5/2...;  $n = 3$  rational surfaces occur when  $q_{\min}$  passes 1, 1.33, 1.67, 2, 2.33...etc.

Applying Equation (3) to the pattern of cascades in Fig.3, one can explain the simultaneous excitation of Alfvén cascades with all toroidal mode numbers from  $n = 1$  to  $n = 6$  at time slice  $t \approx 5.2$  s as an example of  $q_{\min}$  passing an integer value. From the MSE measurements performed with NBI blip at an earlier time,  $t \approx 3.1$  s, the value of  $q_{\min} = 2.8$  was found. Since  $q_{\min}$  in this discharge does not pass 1 (no sawtooth associated with  $q = 1$  was observed in this discharge), and the evolution of  $q_{\min}$  is a monotonically decreasing function of time, one concludes that  $q_{\min} = 2$  at  $t \approx 5.2$  s.

One can also explain that the Alfvén cascades with toroidal mode numbers, which keep increasing from  $n = 3$  to  $n = 6$ , during the time interval from  $t \approx 4.3$  s to  $t \approx 4.7$  s, correspond to  $q_{\min}$  passing values 2.33, 2.25 etc. (see Table I) while approaching  $q_{\min} = 2$ . On the other hand, the Alfvén cascades with toroidal mode numbers decreasing from  $n = 6$  to  $n = 3$  during the time interval from  $t \approx 5.6$  s to  $t \approx 6$  s, correspond to  $q_{\min}$  passing the values 1.82, 1.8 etc. on its way below  $q_{\min} = 2$ . Table I shows the summary of the Alfvén cascades observations with the relevant values of  $q_{\min}$  inferred from the toroidal mode number measurements.

**Table I**

Time, s	4.3	4.5	4.6	4.65	5.2	5.6	5.7	5.9
$n$	3, 6	4	5	6	2-6	6	5	4
$q_{\min}$	2.33	2.25	2.2	2.18	2	1.82	1.8	1.75

In contrast to the higher frequency TAEs, measurements of the poloidal mode numbers and internal measurements showing the mode structure are available at certain time slices for the lower-frequency Alfvén cascades. Figure 5 shows that the  $n = 4$  Alfvén cascade observed at  $t \approx 5.9$  s has the poloidal mode numbers  $m \approx 7-8$ , while Fig. 6 shows that this Alfvén cascade is highly localized at  $r/a \approx 0.4$ . These values are consistent with both the value of  $q_{\min} = 1.75$  estimated above for  $t \approx 5.9$  s and with the point of zero magnetic shear measured by the MSE at earlier time  $t \approx 3.1$  s.

We conclude that this evolution of  $q_{\min}$  above is consistent with the temporal evolution of  $q(r)$  from EFIT and the use of Alfvén cascades for diagnostic purposes is a promising aspect of the MHD spectroscopy. Future dedicated experiments must be performed with combined MSE measurements and the MHD spectroscopy, in order to benchmark the results obtained from the MSE with the MHD spectroscopy. The need for a better understanding of the properties of the Alfvén cascades also motivate measurements of the fast ion pressure profile in future experiments.

#### 4. TAEs in toroidally rotating plasmas

In contrast to the previous two Sections, we now consider observations of weakly-unstable TAEs in JET discharges with a significant differential toroidal rotation of the plasma,  $f_{rot}(r)$ , driven by uni-directional NBI. The Doppler shift caused by the toroidal plasma rotation is taken into account to relate the mode frequency measured in the laboratory reference frame,  $f_n^{LAB}$ , and the mode frequency in the plasma reference frame,  $f_n^0$ , as follows:

$$f_n^{LAB} = f_n^0 + n f_{rot}(r). \quad (5)$$

Since the Doppler shift,  $n f_{rot}(r)$ , separating different toroidal modes in frequency is a function of radius, one can use this frequency separation to identify the radial location of the modes [16]. We apply this Doppler shift technique to a typical H-mode JET discharge (pulse #40369) with measurements of TAEs shown in Fig.7 around the time slice  $t = 12.53$  s. The toroidal mode numbers of TAEs are  $n = 6, 7, 8, 9, 10$  and  $11$ , with corresponding frequency separations between the modes

$$\Omega_{rot}(r) = 2\pi f_{rot}(r) = 1.124 \times 10^5, 1.02 \times 10^5, 0.95 \times 10^5, 0.894 \times 10^5, 0.894 \times 10^5 \text{ rad/s}. \quad (6)$$

From the EFIT reconstructed profile of  $q(r)$  shown in Fig.6 we associate the observed TAEs with  $q(r_m)$ -values as follows:  $q = 0.92$  ( $n/m = 6/5$ ),  $q = 0.93$  ( $n/m = 7/6$ ),  $q = 0.94$  ( $n/m = 8/7$ ),  $q = 0.94$  ( $n/m = 9/8$ ) and  $q = 0.95$  ( $n/m = 10/9$ ). The radial profile of the toroidal

plasma rotation,  $\Omega_{rot}(r)$ , is measured by a charge-exchange diagnostic as shown in Fig. 8. From the measurements of the toroidal plasma rotation and the Doppler shifts for TAEs (2) we estimate the radial location of TAEs and associated  $q(r_m)$ -values as shown in Fig.8 by the crosses. These measurements indicate that the values of the  $q(r)$ - profile in the plasma centre estimated with the EFIT technique alone are somewhat lower than found with the use of TAEs in toroidally rotating plasma.

## CONCLUSIONS

It has been shown that the detection of Alfvén instabilities excited by energetic ions in different types of JET plasmas provides important information on the safety factor  $q(r)$  in the plasma core. The use of linearly unstable Alfvén waves has additional physics insights, which lead to important new aspects as compared to the MHD spectroscopy based on linearly stable Alfvén waves [2, 3]:

1. A broader spectrum of toroidal mode numbers of TAEs excited by energetic particles serves in itself as an indicator of the presence of the relevant  $q$ -values in the region of energetic particle gradient. This broader spectrum can be also used for Doppler shift measurements in toroidally rotating plasmas.
2. The Alfvén cascades are new types of eigenmodes not explored in the linearly stable spectrum studied in [2, 3]. These modes are shown to have a good diagnostic potential, in addition to the TAE modes.

It is important to note that diagnostic uses of the Alfvén instabilities are naturally limited by the non-linear regimes of the modes. For large values of the energetic ion drive, the amplitude of Alfvén waves may exhibit an oscillatory or chaotic behaviour [17, 18], thus reducing the accuracy of the spectroscopic measurements. Therefore, simultaneous measurement of both stable and unstable Alfvén waves is the best option for the MHD spectroscopy.

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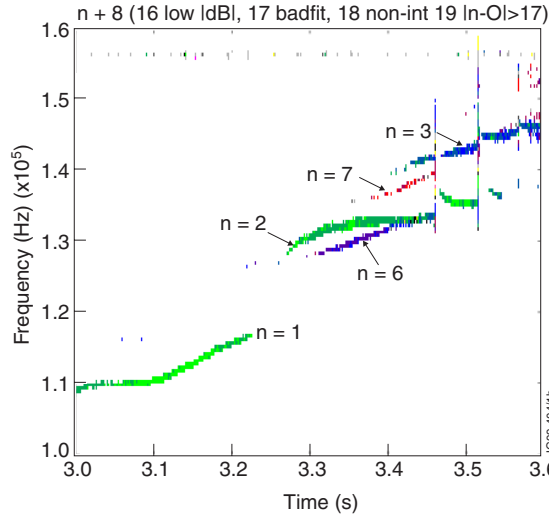


Fig.1: Phase spectrogram of magnetic perturbations showing the toroidal mode numbers  $n$ , measured by the external Mirnov coils during the pre-heating phase of discharge #45848

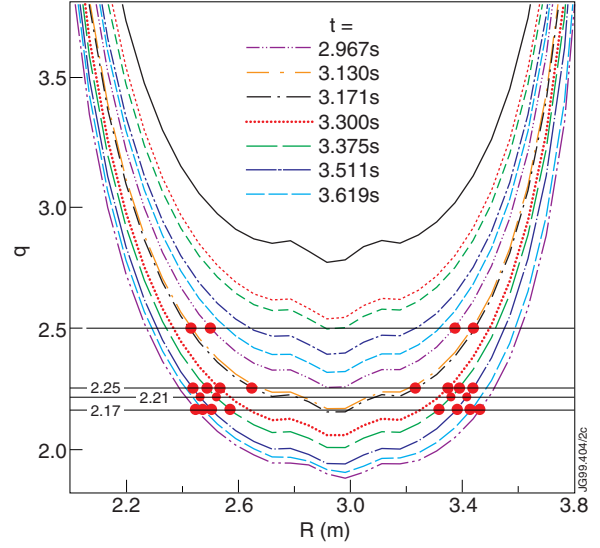


Fig.2: Temporal evolution of the  $q(r)$  profile reconstructed by EFIT.  $q$ -values associated with TAEs with toroidal mode numbers  $n=1, 2, 3$  and  $6, 7$  are shown. The points show the time slices when corresponding TAEs are observed.

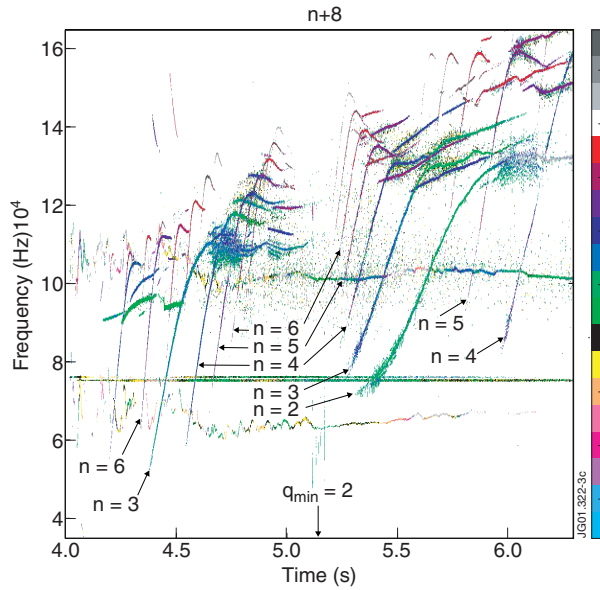


Fig.3: Alfvén wave cascades observed in JET discharge with deep shear reversed equilibrium (pulse #53488). TAE modes are also observed in the frequency range 120-160 kHz at  $t > 5.3$  s.

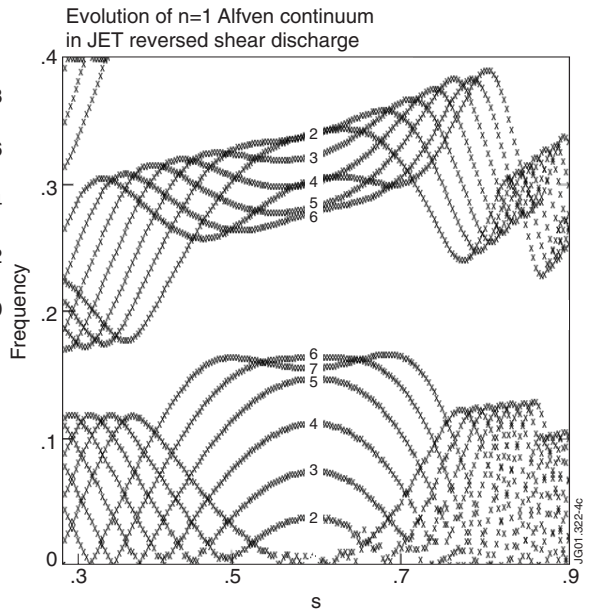


Fig.4: Modelling with the CSCAS code of the Alfvén spectrum: normalized frequency  $\omega R_0 / V_A(0)$  of Alfvén continuum as a function of radius  $s = (\psi_P / \psi_P^{edge})^{1/2}$ . An example ( $n=1$ ) of evolution of Alfvén continuum in reversed shear JET discharge with  $q_{min}(t)$  evolving from  $q_{min} = 3$  down to  $q_{min} = 2.4$  is shown here. The sequence of Alfvén continuum tips associated with  $q_{min} = 3, 2.9, \dots, 2.4$  is shown by numbers 1, ..., 7. These local extremum points are located at  $s \approx 0.6$ , where the magnetic shear is zero.

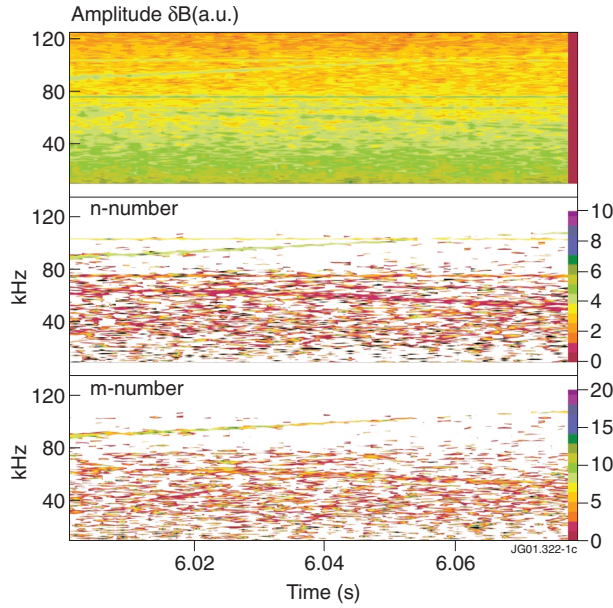


Fig.5: Zoom of the Alfvén wave cascades shown in Fig.3. The amplitude (top), toroidal (middle) and poloidal (bottom) mode numbers are shown for this time interval.

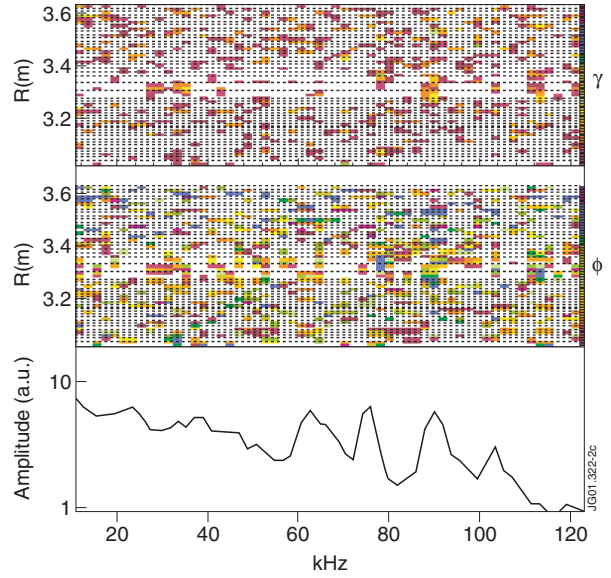


Fig.6: Cross-correlation spectrogram for the amplitude  $\gamma$  and the phase  $\phi$  of the Alfvén cascade shown in Fig.5. The radial location of the perturbation at  $R \approx 3.3$  m (which corresponds to  $r/a \approx 0.4$ ) can be inferred from the cross-correlation between the external magnetics and the 48-channel electron cyclotron emission (ECE) diagnostic.

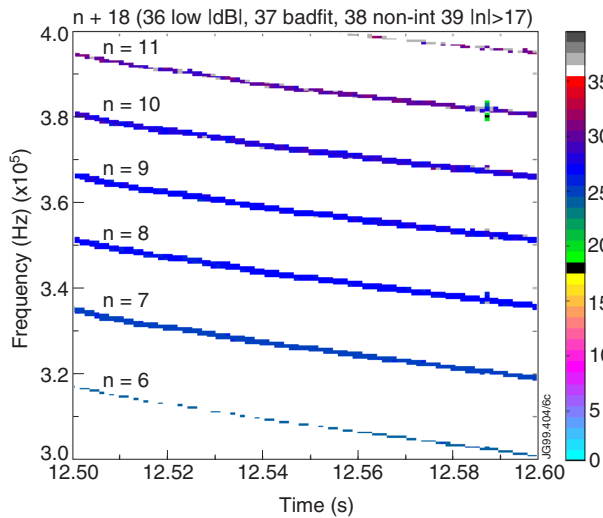


Fig.7: Zoomed phase spectrogram of magnetic perturbations for determination of the toroidal mode numbers of TAEs in #40369.

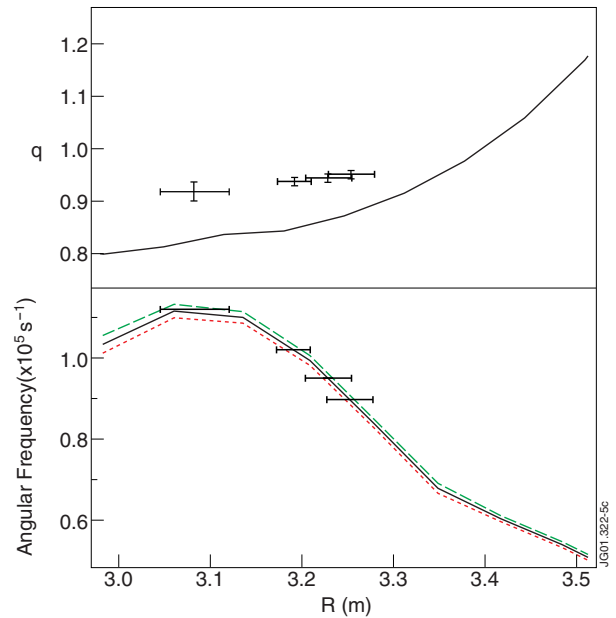


Fig.8:  $q(r)$ - profile from EFIT and plasma toroidal rotation profile measured by the charge-exchange diagnostics in #40369. Upper and lower limits of the rotation measurements are shown. Further increase of the error bars is associated with the finite radial width,  $\Delta r \approx 3$  cm, of the plasma volume over which the measurements are averaged.