ALFVÉN CASCADES IN JET DISCHARGES WITH NON-MONOTONIC $q(r)$

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INTRODUCTION

Two main Optimised Shear (OS) scenarios were exploited on JET in order to generate Internal Transport Barriers (ITBs) [1]. In 1st scenario (Figure 1), an ITB is generated by high power NBI+ICRF applied to the plasma with a monotonic safety factor $q(r) > 1$. In 2nd scenario (Fig.1) an ITB can be triggered at smaller power of NBI+ICRF, when a non-monotonic $q(r)$ is generated by LHCD. Figure 2 shows the relevant $q(r)$ - profiles.

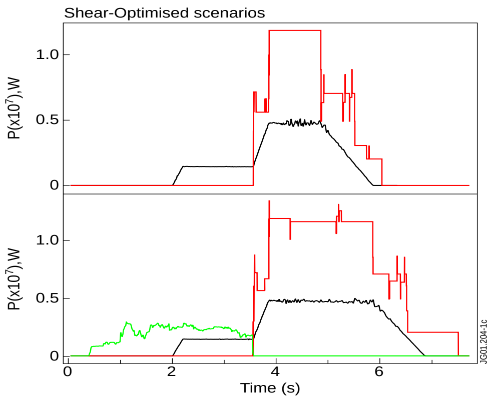

Fig.1 *Two OS discharges (pulses #49384 and #49382 with B_T=2.6 T and I_P^{max} = 2.2 MA) with the only difference in 2.5 MW of LHCD*

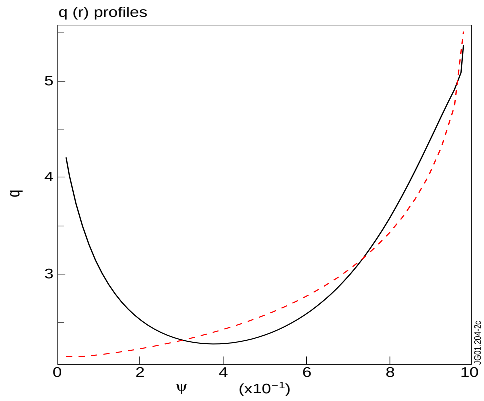

Fig.2 *Safety factor profiles $q(r)$ reconstructed from EFIT. MSE was used for reversed shear case #49382.*

ALFVÉN INSTABILITIES IN DIFFERENT OS PLASMAS

Measurements of magnetic perturbations in these different OS plasmas show that Alfvén instabilities driven by ICRH-accelerated ions are very different. In the plasmas with monotonic $q(r)$-profile ICRH ions drive TAEs (Fig. 3), while plasmas with non-monotonic $q(r)$ exhibit frequency sweeping phenomena below TAE frequency (Fig. 4). We shall call these frequency-sweeping Alfvén instabilities "Alfvén Cascades" (ACs).

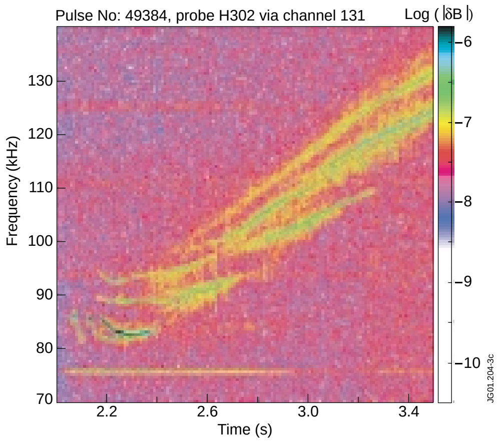

Fig.3 *Spectrogram of the magnetic perturbations,* δB_P *(Tesla), measured by Mirnov coils in plasma with* ***monotonic*** $q(r)$*. TAE modes are seen at frequencies* $f_{TAE} \cong$ *80-200 kHz.*

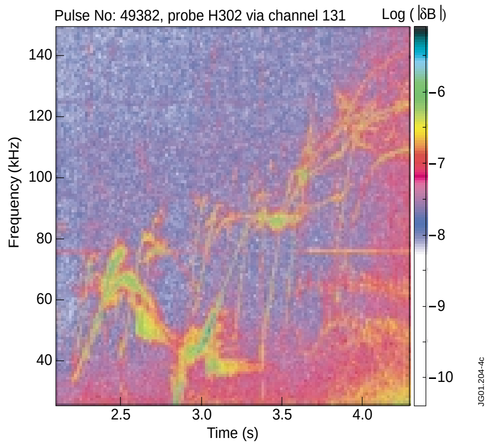

Fig.4 *Spectrogram of the magnetic perturbations in plasma with* ***non-monotonic*** $q(r)$*. Alfvén cascades are observed at frequencies below TAE frequency,* $f_{AC} \cong$ *30-100 kHz <* f_{TAE}*.*

Properties of Alfvén cascades:

1) Frequencies of ACs start from 20-40 kHz, well below TAE frequency range. **2)** Each AC consists of many branches of perturbations with different n and different frequencies. **3)** Toroidal numbers of ACs vary from n =+1 to n =+6 (Figure 5). **4)** ACs of different n appear with different periodicity in time.

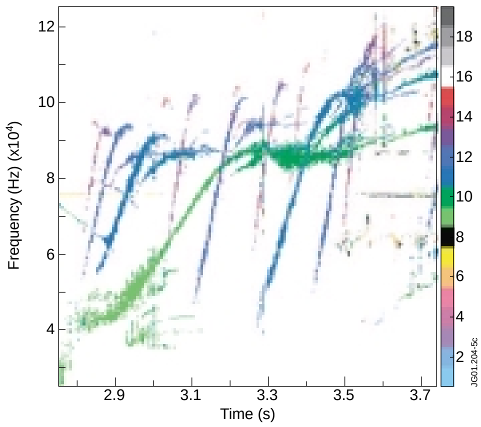

Fig.5 *Toroidal mode numbers of ACs shown in Figure 4*

5) Frequency of AC increases up to TAE gap, with rate of the increaser, $df/dt \propto n$. **7)** AC of low mode numbers, sweeps on time scale 0.5–1 sec typical of evolution of $q(r)$-profile. This time scale is much longer than frequency sweep in "chirping" modes observed in JET [2]. **6)** ECE and SXR measurements show that ACs are located close to $q_{\min}$, the location region is nearly the same for all n and it does not change in time.

NOVEL TYPE OF ENERGETIC PARTICLE MODE ASSOCIATED WITH $q_{\min}$

Analysis of AC frequency sweeping shows close correlation with the evolution of the local extremum $\omega_A' = 0$ point of the Alfvén continuum as is also the case with the Global Alfvén Eigenmode [4,5]. This point is very close to $q_{\min}$:

$$\omega(t) = \left(\frac{m}{q_{\min}(t)} - n \right) \frac{V_A}{R_0} + \Delta\omega \cdot \qquad (1)$$

Here, $q_{\min}$ varies in time in accordance with experiment, *m* is poloidal number, $\Delta\omega$ is an off-set frequency. Modelling of the Alfvén continuum evolution with the CSCAS code [3] shows that AC occurs when the Alfvén continuum has a *maximum* at $q_{\min}$ (in contrast with results from the standard treatment of GAE [4,5]). Fig.6 shows evolution of Alfvén continuum in reversed shear JET discharge with $q_{\min}(t)$ evolving from $q_{\min} = 3$ down to $q_{\min} = 2.4$. Sequence of the continuum tips associated with $q_{\min}$ is shown by numbers 1 through 7. By mapping each of the frequency points and the relevant value of $q_{\min}$ and keeping only the upward sweeping branches, we obtain a graph with a characteristic "cascading" behaviour (Figure 7).

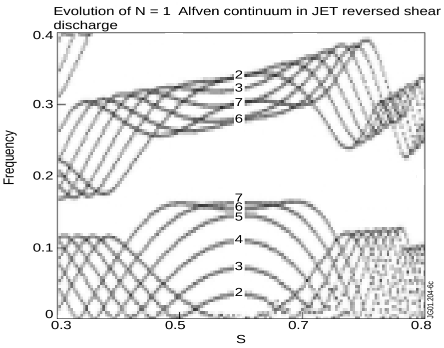

Fig.6 *CSCAS code: frequency* $\omega R_0 / V_A(0)$ *of Alfvén continuum as a function of radius* $s = \left(\psi_P / \psi_P^{edge}\right)^{1/2}$

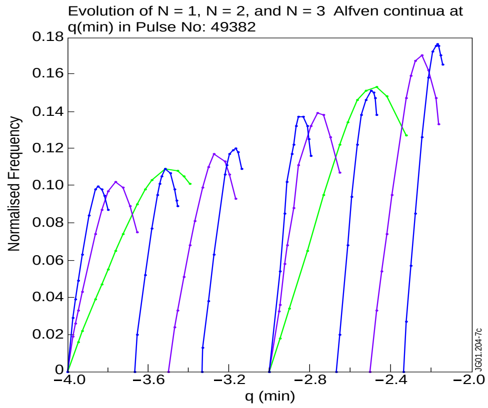

Fig.7 *Modelling of the Alfvén cascades of different toroidal mode numbers n=1 (green), n=2(red) and n=3(blue) in #49382 with gradually decreasing* $q_{\min}$.

Numerical analysis of unperturbed orbits of ICRH ions in deeply-reversed shear equilibrium was performed with the HAGIS code [6] and with the CASTOR-K code [7]. Due to hollow plasma current profiles at the plasma centre, very large drift orbits were found for ICRH-ions. For ions of energy around 500 keV orbit frequency is smaller than toroidal precession drift frequency ("potato" orbits). Ordering $\omega_{dh} > \omega_{bh} \approx \omega$ is relevant.

Two main factors are important for ACs: **1)** The widths of orbits of ICRH-accelerated ions are larger than AC scale; **2)** Hot ion drifts past the eigenfunction at faster rate than hot ion orbit frequency or mode frequency. Under these conditions, the hot ion response is spatially local, in contrast to theories for EPM with a non-local hot ion response [8].

Reduced MHD model for shear Alfvén waves is combined with drift kinetic description of energetic ions to give AC equation:

$$\frac{m^2}{r^2}\left(\frac{\omega^2}{V_A^2}-k_\parallel^2\right)\phi-\frac{\partial}{\partial r}\left(\frac{\omega^2}{V_A^2}-k_\parallel^2\right)\frac{\partial\phi}{\partial r}=-\frac{4\pi e}{cB}\frac{m}{r}\phi\frac{\partial}{\partial r}\left[\omega\langle n_{hot}\rangle-k_\parallel\left\langle\frac{1}{e}j_{\parallel hot}\right\rangle\right],$$

Real (non-resonant) parts of fast ion contributions, $\langle n_{hot}\rangle$ and $\langle j_{\parallel hot}\rangle$ play a dominant role in formation of the novel type Energetic Particle Mode associated with local maximum of Alfvén continuum. This equation has a solution for AC frequency and threshold for AC emergence from the Alfvén continuum:

$$\omega_{AC}=\frac{V_A}{R}\left|n-\frac{m}{q_{\min}}\right|;\quad -\frac{4\pi e}{c}\frac{Rq_{\min}^2}{Br_{\min}q''_{\min}}\frac{\partial}{\partial r}\left[\frac{V_A|m-nq_{\min}|}{(m-nq_{\min})}\langle n_{hot}\rangle+\left\langle\frac{1}{e}j_{\parallel hot}\right\rangle\right]_{r=r_{\min}}=\frac{1}{2}.$$

The threshold is independent of *m* and *n*, in agreement with the experimental data where many modes are seen simultaneously. For a given ratio ω/ω_{Dh} <<1 and the negative hot ion pressure gradient, only ACs of upward sweeping frequency exist.

SUMMARY

Alfvén cascades observed in JET were found to be associated with a novel type of Energetic Particle Mode existing at $q_{\min}$ due to large orbits of ICRH-accelerated ions, which cause the observed Alfvén modes to be shifted slightly upward from the maximum of the Alfvén continuum. We found that the effect of the hot ions was the only mechanism that correlates with the experimental data while other conceivable mechanisms conflicted with the data. Sweeping frequency of ACs is mainly caused by evolution of $q_{\min}$ in time. Threshold for AC emergence from the continuum does not depend on mode number and the frequency of AC is given by Equation (1). Direct measurements of Alfvén cascades can provide information about evolution of $q_{\min}$.

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References: [1] C.Challis et al., Plasma Phys. Contr. Fusion, to be published (2001); [2] S.E.Sharapov et al., Nuclear Fusion 39 (1999) 373; [3] S.Poedts, E.Schwartz, J.Comput. Phys 105 (1993) 165; [4] K.Appert et al., Plasma Phys. Contr. Fusion 24 (1982) 1147; [5] D.W.Ross et al., Phys. Fluids 25 (1982) 652; [6] S.D.Pinches et al., Computer Phys. Comm. 111 (1998) 133; [7] D.Borba. PhD Thesis, Ins. Superior Tecnico, Lisboa (1996); [8] F.Zonca, L.Chen, Phys. Plasmas 3 (1996) 323; D.Testa et al., EPS, Madeira (2001).