Energetic Particle Modes in JET Optimized Shear Experiments with non-Monotonic q-Profiles.

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Experimental Observations.

A new class of instabilities in the Alfvén frequency range, excited by ICRF-driven fast ions, is observed during the current ramp-up phase of JET Optimized Shear (OS) plasmas with a non-monotonic q-profile. Figure 1 shows a typical example of such measurements.

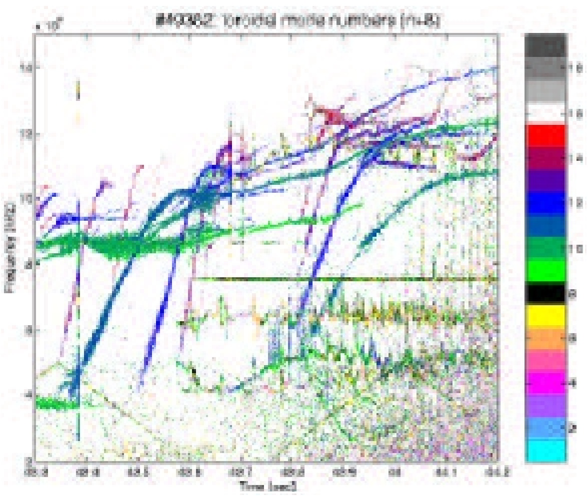

Figure 1. Magnetic spectrum in the preheating phase of an OS plasma with non monotonic q-profile.

These n=1-7 Alfvénic modes observed in OS plasmas with non-monotonic q-profile do not follow the scaling $f(t)\propto B/q\sqrt{n_i}+nf_{\phi TOR}$ typical of the ICRF-driven TAEs which appear in a plasma with monotonic q-profile. The modes originate in the Alfvén continuum around $r/a\approx 0.2$ at $f\approx 20\div 50kHz$, eventually merging after $\approx 100\div 400ms$ into a TAE at $f\approx f_{TAE}(q_{MIN})$ around $r/a=r/a(q_{MIN})\approx 0.5$. The chirping rate is proportional to the toroidal mode number, $df/dt\propto n$, and is independent on m.

Simulations and Theoretical Analysis of EPM Excitation.

We analyze here the JET discharge #49382 in the time interval $43.5<t(s)<44$ to discuss EPM excitation by ICRF driven fast ions [1-3] and the relation of the EPMs with other Alfvén modes [4]. The minority hydrogen fast ion population is modeled [5,6] using a bi-Maxwellian distribution function, with $T_{\perp H}/T_{//H}\approx 10$. The fast ions have potato orbits, $\omega_{orbit}<<\omega_{precession}$ [7]. The plasma parameters are $R_0/a=3.13$, $B_0=2.6T$, $n_{e0}=1.6\times 10^{19}m^{-3}$, $n_H/n_D=0.04$, $T_{\perp H}=210keV$, $\upsilon_{H,max}/\upsilon_{A0}=0.45$, $\rho_{*H}=1.9\times 10^{-2}$, $\beta_{i0}=0.2\%$, $\beta_{e0}=0.43\%$, $\beta_{H0}=0.8\%$. Radial profiles for q and β are given in fig.2; fig.3 gives those for the magnetic shear $s=rq'/q$ and $\alpha_H=-R_0q^2(\partial\beta_H/\partial r)$. The latter provides an indication of the strength of the fast ion drive on the EPMs, which is maximized at $r/a\approx 0.2$, as shown in fig.2. Numerical 1D-GK linear simulations [3] confirm this expectation, as shown in fig.4.

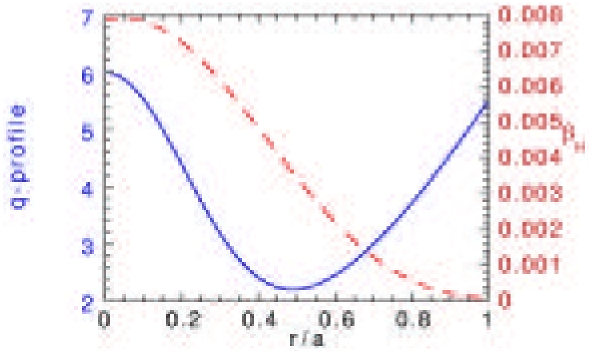

Figure 2 Radial profile for q (solid line) and β_H (broken line) for #49382 at 43.5<t(s)<44.0.

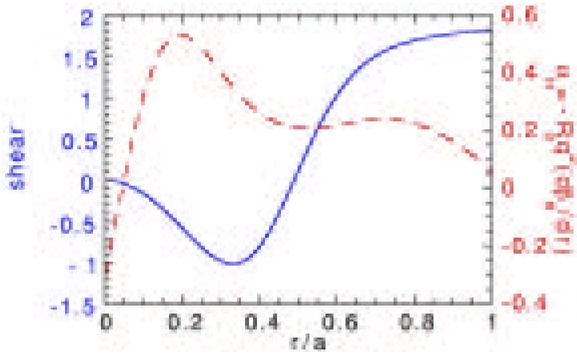

Figure 3. Radial profile for s=rq'/q (solid line) and α_H (broken line) for #49382 at 43.5<t(s)<44.0.

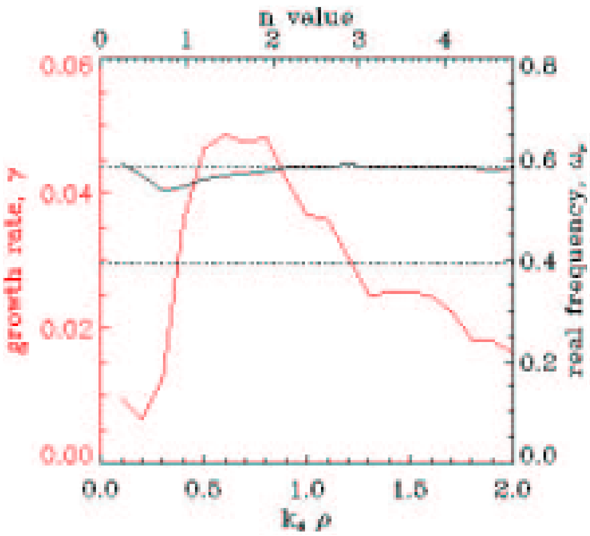

Figure 4. EPM growth rate γ (full line) and frequency ω_r (dotted line) at r/a=0.2. The TAE gap is also shown.

We identify this mode as a resonantly excited EPM and not as a TAE due to the strength of the growth rate, which is comparable with the gap width [3]. Non-linear simulations, using a 3D hybrid MHD-GK code [8], demonstrate strong resonant excitations of an EPM around $r/a=0.2$, where the fast ion resonant drive is maximized. For the simulations, $a/R=0.1$, and β_H has been rescaled such that α_H is constant. The fast ion velocity distribution function is taken as an isotropic Maxwellian.

Figure 5 shows that, after a transient phase, unstable EPMs appear at $r/a\approx 0.3$, causing rapid fast ion radial transport. The mode structure evolves as the source is radially displaced and weakened. The mode then merges into an Alfvén mode near the TAE gap at the position of the q-minimum surface at $r/a\approx 0.49$, as shown in fig.6. This rapid nonlinear evolution occurs on a time scale of $\approx 100\tau_A$ and explains why experimental observations of mode frequencies fit well with those of shear Alfvén waves localized near the q-minimum surface [4]. These modes have been recently interpreted as a variety of Global Alfvén Modes (GAE) [9] that exist near the local maximum of the Alfvén continuum at a q-minimum surface [4].

We consider now modes localized near r_0 (and $r_0/a=0.49$), where q has a minimum, q_0. The poloidal and toroidal mode numbers (m,n) are such that the normalized parallel wave vectors are $\Omega_{A,m}=nq_0-m<0$ and $\Omega_{A,m-1}=nq_0-m+1>0$. The continuum damping is therefore minimized for $-1/2<\Omega_{A,m}<0$ and $1/2<\Omega_{A,m-1}<1$. A gap exists in the continuum between the (m,n) mode, with a local maximum at r_0, and the $(m-1,n)$ mode, with a local minimum at r_0.

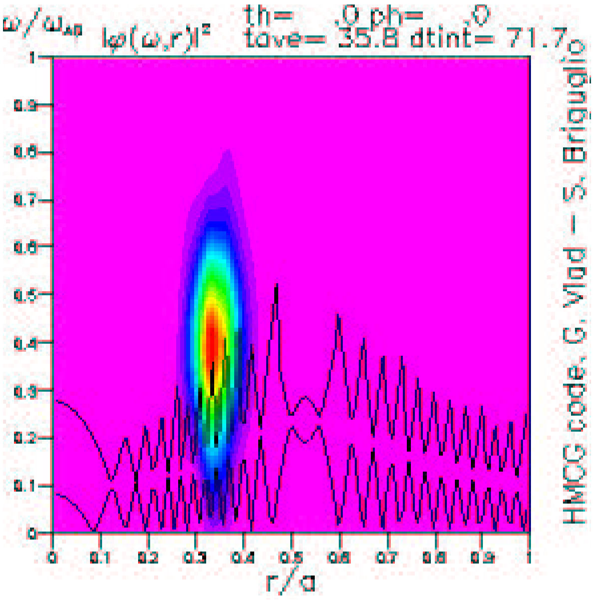

Figure 5. EPM amplitude in the (r/a,ω) plane in the linear destabilization phase at t=35.8τ_A.

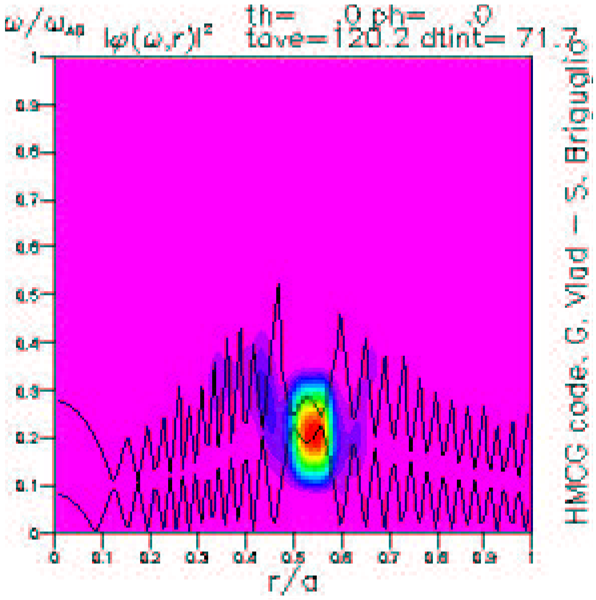

Figure 6. EPM amplitude in the (r/a,ω) plane in the nonlinearly saturated phase, at t=120.2τ_A.

For high-n's, no GAE [9] exist near an extremum of the Alfvén continuum, since the effect of the equilibrium current scales as $1/n$. Fast ions may also provide this localization effect. To show this, we start from eq.(23) of [2] that, for the (m,n) mode reads

$$\left\{ (e_\theta - e_r\xi)\bullet\left[\Omega^2 - \Omega^2_{A,m}\left(1+\frac{x^2}{\Omega_{A,m}}+\frac{x^4}{4\Omega^2_{A,m}}\right)\right](e_\theta - e_r\xi) + \Lambda_m \right\}\delta\psi_m = 0\,, \qquad (1)$$

Here $\Omega=\omega/\omega_A=qR_0\omega/\upsilon_A$, $x=[n(\partial^2 q/\partial r^2)_{r0}]^{1/2}(r-r_0)$, $\xi=(i/\sqrt{n})S(\partial/\partial x)$, $S=(r_0/q_0)[(\partial^2 q/\partial r^2)_{r0}]^{1/2}$; a similar equation can be written for the $(m-1,n)$ mode [2]. The term Λ_m in eq.(1) represents the fast ion contribution, whose non-resonant response can be approximated for $\omega_d>\omega_b>>\omega$ as:

$$\Lambda_m = -\frac{q^2R_0^2}{m^2/r_0^2}\frac{4\pi\omega}{c}\frac{e^2}{m_H}\left\langle J_0^2(\lambda_H)QF_{0H}\right\rangle, \qquad \lambda_H=\frac{k_\perp\upsilon_\perp}{\omega_{cH}}, \quad Q=\frac{2\omega\partial}{\partial\upsilon}+\frac{k\times b\bullet\nabla}{\omega_{cH}}\,. \qquad (2)$$

Here F_{0H} is the fast hydrogen tail distribution function and we have assumed deeply trapped potato orbits [7], for which the mode drive is expected to be strongest. Toroidal coupling between (m,n) and $(m-1,n)$ modes can be neglected for $\Omega_{A,m}+\Omega_{A,m-1}>>r_0/R$. The two modes satisfy the approximate dispersion relations, derived from a variational principle [2]:

$$\sqrt{\Omega_{A,m}+\Omega}-\frac{S\pi}{2^{5/2}n^{1/2}}\left(\frac{2n}{S^2}\frac{\Lambda_m}{\Omega_{A,m}}-1\right)=0\,, \qquad \sqrt{\Omega_{A,m-1}-\Omega}-\frac{S\pi}{2^{5/2}n^{1/2}}\left(\frac{2n}{S^2}\frac{\Lambda_{m-1}}{\Omega_{A,m-1}}-1\right)=0\,. \qquad (3)$$

Moreover, $\Lambda_{m-1}\approx\Lambda_m<0$ since $\omega_d>\omega_b>>\omega$: thus the fast ions behave as nearly massless and are characterized by negative compressibility, which shifts upward the mode frequency, contrary to the general case for which fast ion compression shifts the mode frequency downward

[1,2,3]. For this reason, only the *(m,n)* mode can exist just above the local maximum of the Alfvén continuum at r_0, but not the *(m-1,n)* mode, just below the local minimum in the continuum. The condition for the existence of the *(m,n)* mode is $\Lambda_m/\Omega_{A,m}>S^2/2n$, which, as a consequence of eq.(2) is independent on n and on the mode frequency. This condition imposes a lower bound on the fast hydrogen tail density. For the present parameters, this gives $n_H/n_D>3.1\%$, consistent with the experimental value $n_H/n_D\approx 4\%$. As $\Omega_{A,m}+\Omega_{A,m-1}\rightarrow 0^+$ (which may occur when, as in the experiment, q_0 drops), toroidal coupling effects become more important. Two branches are present as in eq.(3), one of which strongly continuum damped (odd mode); the other (even mode) satisfies the modified dispersion relation [2]:

$$\left[\varepsilon_0^2\Omega^4-\left(\Omega^2-1/4\right)\right]^{1/4}-\frac{S\pi}{2^{3/2}n^{1/2}}\left(\frac{2n}{S^2}\frac{\Lambda_m}{\Omega_{A,m}}-1\right)=0\,,\ \varepsilon_0=2\left(\frac{r_0}{R}+\Delta'\right),\qquad \Omega_{A,m}\approx -1/2. \tag{4}$$

On the LHS of eq.(4), the fourth root of the quantity in parentheses appears due to the local minimum in the q-profile, and not the square root as in the usual TAE case [2]. In both cases, the exponentially small continuum damping, due to the non-local interaction with the *(m,n)* mode, and other kinetic damping mechanisms, must be evaluated and compared with the fast ion resonant drive before the existence of such modes is demonstrated on a rigorous basis. When $\Omega_{A,m}+\Omega_{A,m-1}<<-r_0/R$, due to a further drop in q_0, the local interaction with the Alfvén continuum cannot be avoided for both *(m,n)* and *(m-1,n)* modes that are strongly damped. This explains why, after reaching the TAE frequency, the modes observed disappear.

Summary and Conclusions.

A class of chirping modes observed in JET OS plasmas with non monotonic q-profile have been identified as EPMs originating in the Alfvén continuum at $r/a\approx 0.2$, where the fast ion drive is larger. Radial redistribution in the resonant fast ion source occurs when the EPM excitation threshold is exceeded: this causes the EPM to shift outwards, following the source. As the fast ions are displaced, the source is weakened: the EPM localizes at the q-minimum surface where continuum damping is minimized. This surface acts as insulator region for the fast ion transport and as an Alfvén accumulation point: here the EPMs land softly onto TAEs.

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References.

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