n=0 VERTICAL DISPLACEMENTS, IMPACT OF MAGNETIC X-POINTS, AND VERTICAL DISPLACEMENT OSCILLATORY MODES DRIVEN BY FAST IONS IN TOKAMAK PLASMAS

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A new type of fast ion driven instability involving axisymmetric modes (with toroidal mode number n=0) in magnetically confined tokamak plasmas was discovered recently [1]. The relevant mode has been dubbed Vertical Displacement Oscillatory Mode (with acronym VDOM). The linear dispersion relation for this mode was obtained analytically in Refs. [1-4]. An estimate of the linear threshold for the destabilization of this mode in terms of critical fast ion density was discussed in Ref. [1].

Modes with toroidal mode number n=0 driven unstable by fast ions have been observed experimentally in recent JET discharges, see e.g. Fig. 3 of Ref. [5] and Fig. 12 of Ref. [6]. Simple extrapolations and numerical simulations discussed in this presentation suggest that these modes are likely to be observed also in future tokamak devices under construction, such as SPARC, DTT, and ITER. Since the VDOM instability relies on gradients of the fast ion distribution in velocity space, unstable VDOM may lead to a faster relaxation of fusion alpha particles in velocity space, rather than alpha particle radial transport and loss of confinement. In this sense, unstable VDOM should not pose a real danger for alpha particle confinement in fusion burning plasmas. Nevertheless, since VDOM are global in nature and can affect the edge plasma region through the production of current sheets in the vicinity of magnetic X-points of the divertor separatrix [7], they may give rise to an important coupling between the plasma core, where the fast particle drive is expected to be more important, and the plasma edge, with possible consequences on the stability of Edge Localized Modes and a potential impact on the plasma dynamics in the divertor region. These considerations motivate further studies of n=0 modes.

In this presentation, we will report on recent numerical simulations of the VDOM instability taking into account realistic tokamak geometry, with specific focus on JET geometry, which confirm the analytic predictions [8, 9], and the specific types of fast ion distribution functions that can give rise to the onset of this instability [10-12].

The linear dispersion relation for n=0 modes is cubic in the eigenfrequency and thus it involves three roots. Under conditions such that vertical displacements are subject to passive wall stabilization, one root of the dispersion relation has zero oscillation frequency and a relatively small growth rate scaling linearly with the inverse of the resistive wall time. We refer to this mode as the n=0 resistive wall mode. It is normally suppressed by active feedback stabilization in order to prevent the occurrence of Vertical Displacement Events leading to disruptions. However, in Ref. [3] it was shown that, if the conditions for passive wall stabilization are only marginally satisfied, the n=0 resistive wall mode can grow much faster, with a linear growth rate scaling with a fractional power of the inverse resistive wall time, posing more stringent conditions for active feedback stabilization.

The other two roots of the n=0 dispersion relation, which correspond to VDOM, oscillate with frequency

$$\omega = \pm\alpha\left(\kappa, \frac{b}{b_w}\right)\omega_{Ap}, \quad \text{where} \quad \omega_{Ap} = \frac{B_p'}{\sqrt{4\pi\rho_m}}$$

is the *poloidal Alfvén frequency,* B_p' is the radial derivative of the poloidal magnetic field on the magnetic axis, and α is a geometrical factor that depends on plasma elongation $\kappa = b/a > 1$, and on the plasma-wall distance as measured by the ratio between the major semi-axis of the nearly elliptical plasma boundary, b, and of the nearby nearly elliptical plasma wall, b_w (see, e.g., Eqs. 14 and 23 of Ref. [3] for a detailed derivation and definition of this factor). Thus, the VDOM frequency scales with the Alfvén frequency based on the poloidal magnetic field multiplied by a factor α, typically smaller than unity, that depends on κ and b_w/b, but is rather insensitive to details of the q profile. For typical JET parameters, this frequency ranges between 200 kHz and 500 kHz [9]. Normally, this frequency lies below the spectrum for continuum damping. Therefore, in the absence of fast ions, the mode is only weakly damped by wall resistivity. The VDOM has a global space structure, corresponding to a nearly rigid vertical shift of the plasma core, with a return flow localized near the plasma edge. As pointed out in Ref. [9], although the VDOM is a global plasma mode with a frequency of oscillation in the Alfvén frequency range, it should not be confused with a Global Alfvén Eigenmode (GAE), which is an internal plasma mode whose frequency of oscillation and spatial structure are sensitive to details of the q and plasma density profiles. Also, the VDOM, being an n=0 mode, is *resonant* at magnetic X-points of the divertor magnetic separatrix in a tokamak device, where the poloidal field vanishes, since n=0 perturbations are constant along the toroidal field line going through the magnetic X-point, as pointed out in Ref. [7]. As a consequence, in the ideal-MHD limit, n=0 perturbations tend to become singular near magnetic X-point. The singularity can be resolved by plasma resistivity, giving rise to the likely formation of current sheet structures peaking at the X-points and extending along the magnetic separatrix, as observed numerically in Ref. [8].

Vertical Displacement Oscillatory Modes can be driven unstable by a mode-particle resonance involving the transit and bounce frequency of fast ions with energies in the MeV range, as pointed out in Ref. [1]. However, the instability drive for n=0 modes requires a fast ion distribution function with a positive gradient of energy at constant magnetic moment μ, i.e.

$$\left.\frac{\partial F}{\partial E}\right|_{\mu} = \left.\frac{\partial F}{\partial E}\right|_{\Lambda} - \left.\frac{\Lambda}{E}\frac{\partial F}{\partial \Lambda}\right|_{\mathrm{E}} > 0, \qquad \text{where} \qquad \Lambda = \frac{\mu B_0}{E} \quad \text{is the pitch-angle variable in velocity space.}$$

In the isotropic limit ($\partial F/\partial\Lambda$ = 0), instability requires a positive slope in velocity space, i.e., a bump-on-tail kind of distribution function, which may occur transiently [10] when the source of fast ions is modulated on time scales that are shorter that the slowing-down time, τ_s. In Ref. [11], it was pointed out that rapid sawtooth relaxation oscillations with periods that are shorter than τ_s can also give rise to the required features for VDOM destabilization. When fusion alpha particles are considered, since the most energetic alphas with magnetically trapped (i.e., banana) orbits are not redistributed by sawtooth relaxations, anisotropy in velocity space may result on time intervals shorter than τ_s following a sawtooth crash [6]. Furthermore, recent results based on Fokker-Planck simulations suggest that intense ICRF heating may also lead to fast ion distribution functions satisfying the required conditions for VDOM destabilization, provided that the ion cyclotron resonance layer is placed on the high field side of the magnetic axis [12].

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