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# Vertical Displacement Oscillatory Modes driven by Fast Ions in Tokamak Plasmas

[1,2]F. Porcelli, [1]D. Banerjee, [1]S. Cavallero, [2]A.Yolbarsop, [3]L.-G. Eriksson, [4]C.C. Kim.

[1] Polytechnic University of Turin, Italy; [2] Univ. of Science and Technology of China, Hefei, China; Chalmers University of Technology, Gothenburg, Sweden; SLS2 Consulting, San Diego, USA

e-mail (speaker): francesco.porcelli@polito.it

A new type of fast ion driven instability involving axisymmetric modes (toroidal mode number n=0) in magnetically confined tokamak plasmas was discovered recently [1]. The relevant mode has been dubbed Vertical Displacement Oscillatory Mode (acronym VDOM). The linear dispersion relation for this mode was obtained analytically in Refs. [1-3]. 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 by fast ions have been observed experimentally in recent JET and TCV discharges, see e.g. Ref. [4]. Simple extrapolations and numerical simulations suggest that these modes are likely to be observed also in future tokamaks such as SPARC, DTT, and ITER. The VDOM instability relies on gradients of the fast ion distribution in velocity space. 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 [5], they may give rise to coupling between the plasma core, where the fast particle drive is expected to be more important, and the plasma edge, with a potential impact on the plasma dynamics in the divertor region. We will report on recent numerical simulations of the VDOM instability considering realistic tokamak geometry, with specific focus on JET geometry, and the specific types of fast ion distribution functions that can give rise to the onset of this instability [6-8].

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. This n=0 resistive wall mode is normally suppressed by active feedback stabilization 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 VDOM roots of the n=0 dispersion relation 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 on-axis radial derivative of the poloidal magnetic field, and the geometrical factor $\alpha$ depends on plasma elongation $\kappa = b/a > 1$, and on the plasma-wall distance $b/b_w$, with b the major semi-axis of the nearly elliptical plasma boundary, and $b_w$ that of the nearby nearly elliptical plasma wall (see, e.g., Eqs. 14 and 23 of Ref. [3]). For typical JET parameters, this frequency ranges between 200 kHz and 500 kHz [9]. In the absence of fast ions, the mode is weakly damped by wall resistivity. The VDOM space structure corresponds to a nearly rigid vertical shift of the plasma core, with a return flow localized near the plasma edge. 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. However, the instability drive for n=0 modes requires a fast ion distribution function with a positive gradient of energy at constant magnetic moment.

$$\left.\frac{\partial F}{\partial E}\right|_{\mu} = \left.\frac{\partial F}{\partial E}\right|_{\Lambda} - \frac{\Lambda}{E}\left.\frac{\partial F}{\partial \Lambda}\right|_{E} > 0, \quad \text{where} \quad \Lambda = \frac{\mu B_0}{E}$$

is the pitch-angle variable in velocity space. In the isotropic limit, 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, $\tau_s$. In Ref. [11], it was pointed out that rapid sawtooth relaxation oscillations with periods that are shorter than $\tau_s$ can also give rise to the required features for VDOM destabilization. Fast ions produced by NBI are anisotropic and can also drive VDOM, as well as intense ICRF heating where the ion cyclotron resonance layer is on the high field [12].

**References**

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