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Comparison of MHD-mode and Plasma Rotation Frequencies in TCV Ohmic and ECH Discharges

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Magnetohydrodynamic (MHD) instabilities often limit fusion plasma performance in magnetic confinement devices, such as tokamaks. In particular, tearing modes are thought to be responsible of the formation of helical magnetic islands, which brake and reconnect the magnetic field lines of nested flux surface allowing for a relatively fast radial transport of particle and heat. Important contributing terms to the stability of the tearing modes are found to strongly depend on the phase velocity of the magnetic island relatively to the ion and $\mathbf{E} \times \mathbf{B}$ flows [1], and it is thus important to develop theoretical and experimental knowledge of the relative island velocity to make reliable predictions on tearing modes stability. Although several attempts to self-consistently calculate the magnetic island phase velocity have been recently made [2], the issue is still under investigation and actively debated. In general, the magnetic island is embedded within ion and electron fluids, which flow at different velocities. The magnetic island is likely to propagate at some intermediate velocity.

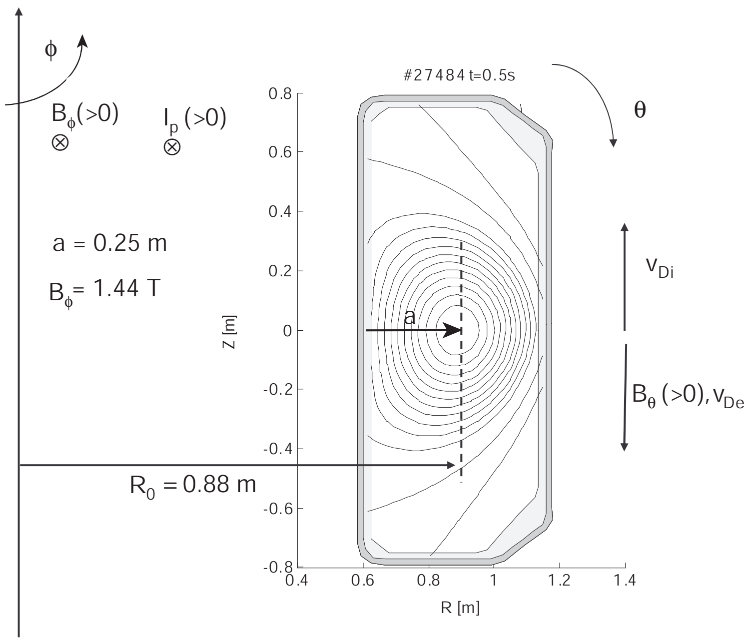

Figure 1: *Coordinate system and geometry defining the propagation directions. TCV vacuum vessel together with a plasma poloidal cross-section.*

Experimentally, in JET plasmas with strong momentum input the MHD modes are found to rotate with a frequency consistent with the toroidal ion rotation frequency [3], whereas in ASDEX-Upgrade the inclusion of diamagnetic drifts is needed to explain the mode rotation frequency, suggesting that the perturbation is, in this case, rotating with the electron fluid [4]. In this paper, we compare the MHD mode frequency, detected with magnetic coils, with the ion, the $\mathbf{E}\times\mathbf{B}$ and the electron rotation frequencies (defined below) calculated from experimental profiles in TCV plasmas with no external momentum injection. In particular, we are interested to know whether the MHD modes rotate closer to the ion or to the electron velocity.

Definitions and geometry

We note that owing to the fact that the magnetic perturbations are field-aligned, only flows perpendicular to the total magnetic field contribute to the Doppler-shifted mode frequency. We precisely define and measure: 1) the MHD (Mirnov) frequency ω_{MHD}, 2) the ion ω_i and electron ω_e rotation frequency respectively,

$$\omega_i = \vec{\mathrm{v}}_{i,\perp}\cdot\vec{k} \approx n\frac{(B_\theta \mathrm{v}_\phi - B_\phi \mathrm{v}_\theta)}{rB_\theta} \quad (1)$$

$$\omega_{E\times B} = \vec{\mathrm{v}}_{E\times B}\cdot\vec{k} \approx \frac{nE_r}{RB_\theta} \quad (2)$$

$$\omega_e = (\vec{\mathrm{v}}_{E\times B}+\vec{\mathrm{v}}_{D_e})\cdot\vec{k} \approx \frac{nE_r}{RB_\theta} + \frac{ndp_e/dr}{en_eRB_\theta} \quad \text{with} \quad (3)$$

$$E_r = \mathrm{v}_\phi B_\theta - \mathrm{v}_\theta B_\phi + \frac{dp_i/dr}{eZ_in_i}; \quad \vec{\mathrm{v}}_{D_j} = \frac{\vec{B}\times\nabla p_j}{Z_jn_jB^2},\ j=i,e$$

where $\mathrm{v}_\phi, \mathrm{v}_\theta$ and B_ϕ, B_θ are the components of the velocity and magnetic fields, Z_j is the charge of specie j (Z_j=6 for carbon 6^+), n_j and p_j are the density and pressure of specie j and $\vec{k} = n/R\hat{e}_\phi + m/r\hat{e}_\theta$ is the wave vector of the instability with R and r the major and minor radius of the torus. The velocities are measured by active Charge eXchange Recombination Spectroscopy (CXRS) of the CVI emission lines [5], with a temporal resolution of typically 90 ms and a spatial resolution of 2.5 cm, allowing measurements in relatively stationary plasma with the present system. We make no difference, here, between the carbon impurity and the main ion (deuterium) velocities. In deriving equations $(1-3)$ we have neglected terms of the order of $(B_\theta/B_\phi)^2$ or smaller, which lead in total to an error of 5% maximum. The MHD mode is resonant on the flux surface $q = m/n$, with m and n being the poloidal and toroidal mode numbers and all quantities are calculated on this surface. Complete Mirnov probe arrays detecting $\tilde{B}_\theta$ determine m and n, while a Fourier transform determines ω_{MHD} with an accuracy of ±0.4 kHz. The MHD frequency is also cross-checked with the perturbation frequency in soft X-ray emissivity. The uncertainty on the velocity components is typically of ±3 km/s. The geometry of the TCV tokamak plasma and vacuum vessel with the conventions for the fields and current are shown in figure 1.

q=1 sawtooth precursors frequency

We now consider the sawtooth precursor oscillations frequency of ohmic L-mode discharges with different plasma currents. The edge safety factor ranges from 2.8 to 8.5 corresponding to a variation of the normalised sawtooth inversion radius, ρ_{inv}, (which is close to the q=1 radius) from 0.57 to 0.2. There is no momentum injection into these plasmas and the plasma rotation is thus sometimes called spontaneous or intrinsic. Toroidal rotation up to about 40 km/s at the q=1 surface is found in the negative (positive) direction for positive (negative) I_p (see figure 1), thus in the counter-current or electron diamagnetic drift direction [5]. The poloidal velocity is expected to be much smaller and to invert with the toroidal magnetic field. Experiments with positive and negative B_ϕ lead to an upper limit for v_θ of about +2.5 km/s. Although relatively small, this poloidal rotation can make a large contribution to ω_i and $\omega_{E\times B}$ because it is multiplied by B_ϕ in equations 2 and 3. We note that, under these conditions, the diamagnetic and velocity component contributions to the frequencies all add up, thus implying $\omega_i < \omega_{E\times B} < \omega_e$. In figure 2 we compare the MHD, the $\mathbf{E}\times\mathbf{B}$ and the ion frequencies calculated with the assumption $v_\theta = 0$, which correspond to a lower limit for ω_i and $\omega_{E\times B}$. Systematically, we have $\omega_i < \omega_{MHD} < \omega_{E\times B}$. The electron frequency ω_e (not plotted in figure 2) exceeds $\omega_{E\times B}$ by typically 3-6 kHz. Alternatively we can calculate the poloidal velocity to include in ω_i in order to match the sawtooth precursor frequency. We find very small v_θ, ranging from 0.25 to 1 km/s. Such velocities are at the limit of resolution with the present system. Hence, the possibility that $\omega_{MHD} \leq \omega_i$ cannot be excluded a priori and very accurate poloidal rotation measurements are needed. The MHD perturbations rotate, in this conditions, always much slower than the electron fluid.

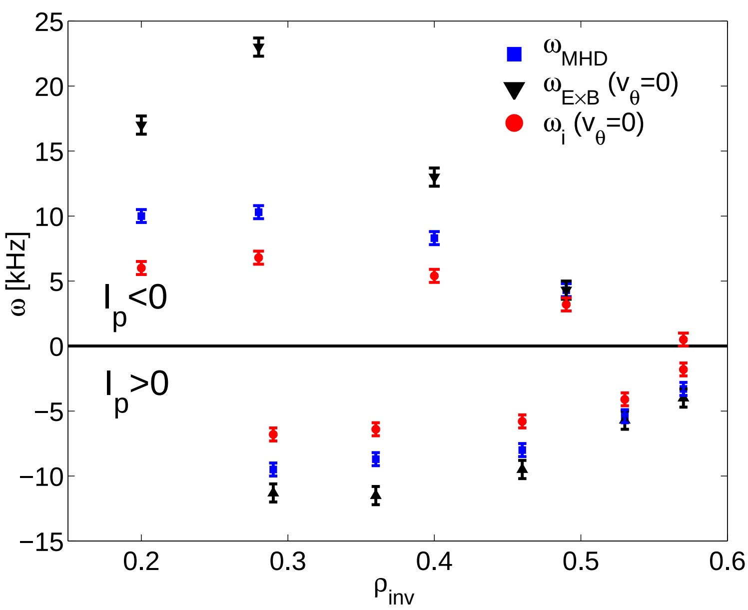

Figure 2: *Comparison, in a safety factor scan, of the sawtooth precursors frequency ω_{MHD} with the expected Doppler shift from the* $\mathbf{E}\times\mathbf{B}$ *flow $\omega_{E\times B}$ and the ion flow ω_i (in case of pure toroidal rotation). Negative (positive) frequencies correspond to positive (negative) plasma current I_p.*

Tearing modes

Let us consider the case of tearing modes (TM). Experimentally we have to distinguish between isolated single island TM, non-isolated single island TM and coupled multiple islands TM.

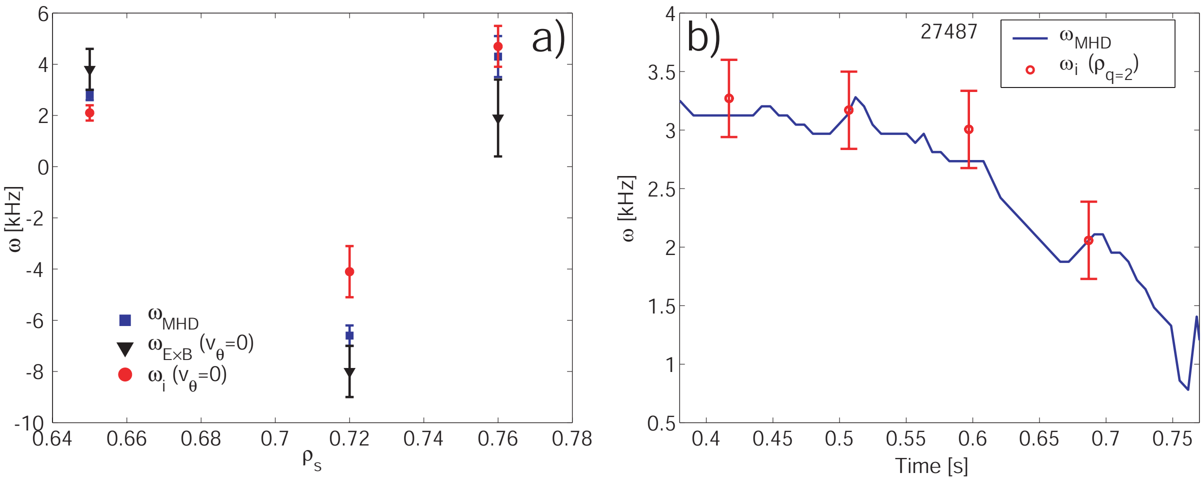

Figure 3: *a) Comparison of TM and plasma flows rotation frequencies in case of isolated magnetic islands resonant with magnetic surfaces located at ρ_s. In details, m/n=2/1 TM in L-mode with ohmic ($\rho_s = 0.65$) and ECRH heating ($\rho_s = 0.72$) and a m/n=4/3 TM in H-mode with ECRH ($\rho_s = 0.76$). b) a m/n=2/1 TM in ohmic L-mode locking to the conducting wall.*

Only single island TM are considered in this paper. With isolated TM we intend a magnetic island which does not appear to interact with any external structure (e.g. conducting walls) and have a relatively constant rotating frequency. In L-mode Ohmic and ECH discharges we find, similarly to the case of sawtooth precursors, that $\omega_i < \omega_{MHD} < \omega_{E\times B}$ (figure 3a) if zero poloidal rotation is admitted. The case of an H-mode discharge (mode at $\rho_s = 0.76$ in fig. 3a) appears to be somewhat different. The plasma and the magnetic island rotate in the co-current direction at the same speed. Although only toroidal rotation measurements were available for the analysis and not even an upper limit of the poloidal rotation is known in this case. In case of non-isolated islands (locked mode), which may reach a width of up to 8 cm in TCV, there is a strong plasma-island interaction with the conducting wall. The toroidal rotation profile is usually flat within the unstable flux surface [6], which rotates toroidally at the same speed as the magnetic island (figure 3). While locking to the metallic wall, the magnetic island may brake completely the core plasma rotation. In all the cases presented here, the MHD modes rotates with a frequency much closer to the ion than to the electron frequency. Diamagnetic contributions to ω_{MHD} may exist but extremely accurate measurements of the ion poloidal rotation are needed for a precise evaluation of the plasma flows.

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