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Effect of Alfvén resonances on the penetration of error fields on a rotating viscous plasma

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I – Introduction

The penetration and subsequent amplification of the intrinsic magnetic error field of a tokamak in the confined plasma may eventually lead to the plasma disruption [1]. When the plasma rotates, the plasma response to the static error field is influenced by the pair of Alfvén resonances (AR) located around the rational q-surface where magnetic reconnection takes place [2,3]. These resonances may potentially shield the external magnetic perturbations when the plasma is highly conducting and rotating at speeds above the 1kHz range, thereby avoiding amplified locked modes. However, experimental evidence suggests that these AR have little effect in preventing reconnection at the q=2. In this work we investigate the plasma response to a static m=2,n=1 error field component in both inviscid and viscous rotating plasmas, i.e. $Ga=\tau_R/\tau_V \ll 1$ and $Ga \gg 1$ where τ_R and τ_V are, respectively, the resistive and viscous diffusion time scales. The threshold in plasma rotation separating the forced reconnection (FR) and AR dominated regimes is found to have a strong dependence ($\omega_{thr} \propto 1/\tau_A S^{0.27}$) on the Magnetic Reynolds ($S=\tau_R/\tau_A$) and a very weak dependence on the Prandtl number (Ga). A discussion on the lack of experimental evidence of the AR dominated regime in present fusion machines is also made based on the role of plasma viscosity and on the plasma collisional regime.

II – Reduced MHD model for mode penetration

We assume a low-β, incompressible plasma with constant density (ρ), anomalous perpendicular viscosity (ν) and toroidal plasma rotation (V_{z0}), with aspect ratio $A=R_0/a=3$. The magnetic and velocity fields are given by $\mathbf{B} = \nabla\psi_0 \times \mathbf{z} + B_{0z}\mathbf{b} + g(r)\nabla\tilde{\psi}\times\mathbf{b}$ and $\mathbf{V} = V_{0z}\mathbf{z} + g(r)\nabla\tilde{u}\times\mathbf{b}$, where $\mathbf{b} = nr/mR_0\theta + \mathbf{z}$ and $g^{-1}(r) = |\hat{b}|^2 \sim 1$. The dimensionless linear time evolution equations for the perturbed flux and vorticity $\tilde{U} = \nabla_\perp^2\tilde{u}$ are given by [4]

$$\frac{\partial\tilde{\psi}}{\partial t} = \frac{\eta(x)}{S}\cdot\nabla_\perp^2\tilde{\psi} + i\cdot k_{//}\cdot\tilde{u} + i\frac{n}{A}v_{z0}\tilde{\psi} \quad (1)$$

$$\frac{\partial\tilde{U}}{\partial t} = i\frac{n}{A}v_{z0}\tilde{U} + i\cdot\nabla_\perp^2\tilde{\psi}\cdot k_{//} - i\frac{m}{x}\tilde{\psi}\cdot J'_{z0} + \frac{Ga}{S}\nabla_\perp^2\tilde{U} \quad (2)$$

where $k_{//} = (m - nq)/(Aq)$. Normalisation with respect to minor radius, toroidal magnetic field and Alfvén time ($\tau_A = a\sqrt{\mu_0\rho_0}/B_{0z}$) is assumed. The resistive and viscous times are given, respectively, by $\tau_R = a^2\mu_0/\eta(r=0)$ and $\tau_V = \rho_0 a^2/\nu$. A driving helical (m=2,n=1) current sheet is assumed in vacuum and a tearing stable q-profile is assumed ($-\Delta' a \sim 0.9$) $q(x) = q_0 a_1 \frac{\left(1+(2x)^{2\lambda}\right)^{a_2}}{a_1 + (2x)^{2\lambda}}$ with q_0=0.7, a_1=1.5, λ=1.8 and $a_2=(\lambda+1)/\lambda$. Since the mode is being driven by the static error field, away from the tearing layer and neglecting plasma resistivity, $\tilde{u} = -(nv_{z0})/(Ak_{//})\tilde{\psi}$ holds. Substituting in Eq. (2) (to dominant order) we identify the existence of the AR pair at both sides of the q=2 surface (where $(nv_{z0})^2 = (Ak_{//})^2$) : $\left[\frac{(nv_{z0})^2}{A^2 k_{//}} - k_{//}\right]\nabla_\perp^2\tilde{\psi} - \frac{m}{x}\tilde{\psi}\cdot J'_{z0} - i\frac{Ga}{S}\nabla_\perp^2(\nabla_\perp^2\tilde{u}) = 0$

Theoretical work on the rotating plasma response to resonant static fields has identified two dominant regimes [5] : a visco-resistive regime where the constant-ψ approximation is valid inside the tearing layer and $\Delta'_{layer}(\omega_\phi) \propto i(\omega_\phi\tau_{rec})$; an ideal-viscous regime with $\Delta'_{layer} \propto \omega_\phi^{-1/4} e^{i\sigma\frac{7}{8}\pi}, \sigma = \mathrm{sgn}(\omega_\phi)$ where ω_ϕ/n and τ_{rec} are the toroidal plasma rotation frequency and reconnection time scale. The threshold for the transition between the two regimes occurs at $\omega_\phi/n \sim 1/\tau_A\,(Ga.S)^{1/3}$ and sets also a transition from a decreasing to an increasing (with plasma rotation frequency) toroidal braking torque induced by the external fields [5]. A novel interpretation of these two regimes, yielding the same frequency threshold but independent of Ga and based on the competition between resistive dissipation at the q=2 surface and magnetic energy accumulation at the AR, is given in Ref.3.

III – Numerical results

Plasma rotation scans at different values of S were done to characterise and obtain scaling laws for the transition from FR to AR regimes. Rigid plasma rotation avoids effect of shear flow on mode stability. We adopt (as in Ref. 5 for the transition between the visco-resistive and ideal-viscous regimes) as a criteria for the transition between the two regimes a local extremum in the flux surface averaged torque in the plasma. In the FR regime the torque, localised around the q=2, decreases with the plasma toroidal rotation (for rotation frequencies above the inverse of the reconnection time [5]), whereas when the plasma response becomes increasingly dominant at the AR, the toroidal force (locally at the AR), increases with plasma rotation. This is shown in Figure 1a, for $S = 9\times10^7$ and Ga=0.005. The transition between the two regimes is more apparent in Figure 1b, showing a contour plot of the toroidal force profile as a function of plasma rotation frequency.

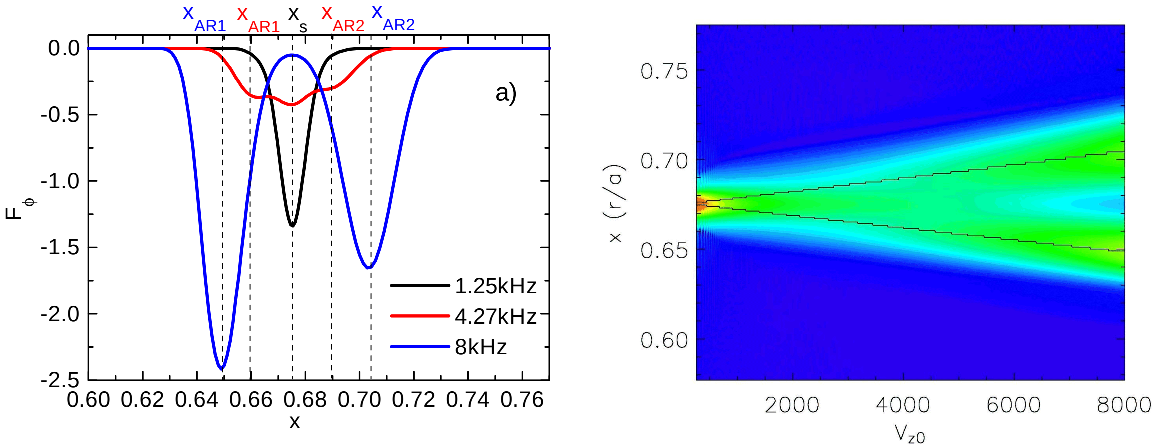

Figure 1 – a) Radial profile of toroidal torque prior (black), short (red) and well after (blue) the transition between regimes; the two black lines in b) indicate the location of the AR according to $(nv_{z0})^2 = (Ak_{//})^2$.

Increasing plasma viscosity (Ga=20 results are shown in Figure 2a) affects mainly the profile of the toroidal force but not the plasma rotation threshold for the transition. This is shown in Figure 2b, where the obtained numerical scaling (with S) for such threshold in V_{0z} is shown for Ga=0.005,2 and 20. Also shown is the threshold $1/\tau_A S^{1/3}$ derived in Ref.3.

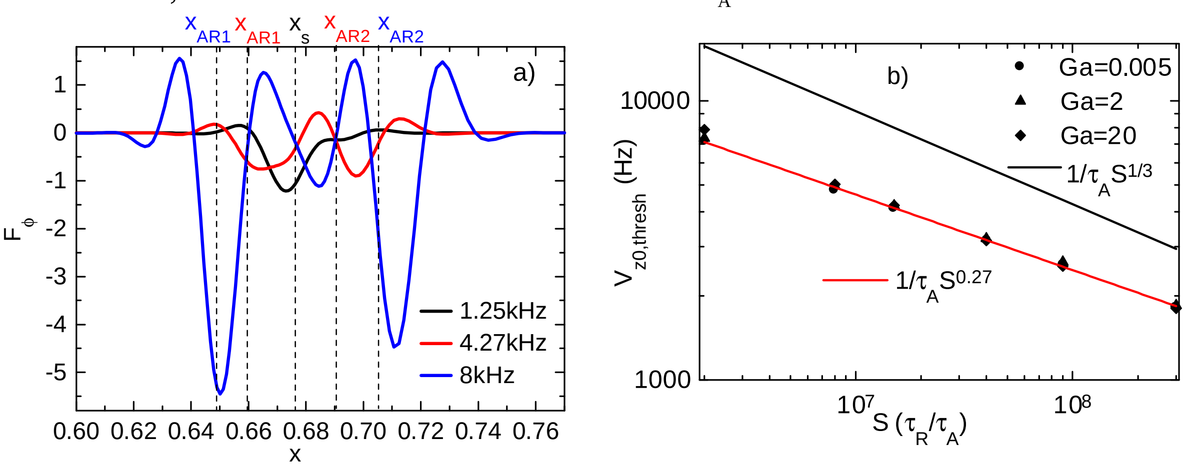

Figure 2 – Toroidal force evolution in viscous plasmas (a) and S-scaling of plasma rotation threshold for regime transition (b); threshold is roughly independent of Ga and smaller compared to theoretical prediction (see Ref.3 and also Ref.5 with Ga=1)

IV – Conclusions

We have investigated the penetration of static external magnetic fields on rotating magnetically confined fusion plasmas. During the transition from a forced reconnection regime to an AR regime, the toroidal induced braking force becomes an increasing function of plasma rotation frequency as a direct consequence of the emerging contributions at the AR locations (contrasting the decrease in the localised force at the q=2 surface). The threshold in plasma rotation for this regimes' transition scales as $\omega_{thr} \propto 1/\tau_A S^{0.27}$ and has a weak dependence on the anomalous plasma viscosity. The lack of experimental evidence of a AR dominated regime in tokamaks operating at large S (ω_{thr}<1.8kHz for S>3x10^8) may be due to an effective drag on plasma rotation caused by viscosity, implying that the braking forces, localised at the AR, through viscosity, also brake plasma rotation at the q=2 surface, favouring a forced reconnection dominated regime. On the other hand, considering as in Ref.3 the plasma rotation threshold ω_{thr} as a measure of the inverse time for equilibration between pumping of energy to the AR and dissipation at the q=2 surface, we should extend such an interpretation to a collisionless high temperature plasma. In fact, for such a plasma magnetic reconnection is known to be evolve on much faster time scales [6], implying a much larger threshold plasma rotation to enter the AR regime.

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