Tearing mode dynamics with two-fluid effects in tokamaks

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Introduction

Tearing modes are known to limit plasma performance in non inductive discharges in Tore Supra. Previous studies [1] using the non-linear MHD code XTOR-2F [2] show the possibility of full stabilization of these modes by combination of toroidal curvature and diamagnetic rotation. One of the fully non-inductive pulses on Tore Supra (TS-32299, $t = 234s$) is chosen as a test bed for these studies. In the present work we address the issue of extrapolation of the obtained results towards experimental S, since the stabilization threshold does not follow the classical scaling with Lundquist number (S). We study the effects of diamagnetic rotation and curvature on the metastability and saturation of the magnetic islands and apply our results to explain the abrupt transition to MHD regime in some experimental observations. The important issue of the toroidal curvature and diamagnetic rotation for ITER size machines is also discussed.

Linear stabilization by diamagnetic and curvature effects

In order to study numerically the impact of diamagnetic rotation on the $n = 1$, $m = 2$ mode we perform a scan of the linear growth rate with diamagnetic frequency. Simulations of linear growth regime show that diamagnetic rotation tends to destabilize the mode at low values, and to stabilize at higher values. The origin of the initial destabilization is the interplay of the electron diamagnetic rotation and curvature. Since there is still a significant difference in the values of the growth rate at high ω^* when a standard $S^{3/5}$ scaling for diamagnetic frequencies is applied (Fig. 1, right), it makes no sense to rescale the diamagnetic frequency this way and real values of diamagnetic frequency are used, see Fig. 1(left). The full procedure of the scan in ω^* and the choice of the input parameters is discussed in [1]. The complete stabilization point approaches experimental value of diamagnetic frequency as Lundquist number increases, see Fig. 1(left). If a power dependence of critical ω^* on Lundquist number is assumed, from Fig. 2 (upper curve) a full stabilization of the mode is predicted at $\omega^*_{crit} \approx 2\omega^*_{exp}$ for $S = S_{exp}$. The extrapolation curve can be fitted by the analytical expression $\omega^*_{crit} \propto S^{\alpha}$, with $\alpha \approx 0.26$. Linear mode dynamic is found to be sensitive to the details of the density profile due to contribution of ∇n to stabilization. Simulations with more accurate density profile give a more favourable result. Full stabilization is observed at lower value of the diamagnetic frequency. The extrapolation of

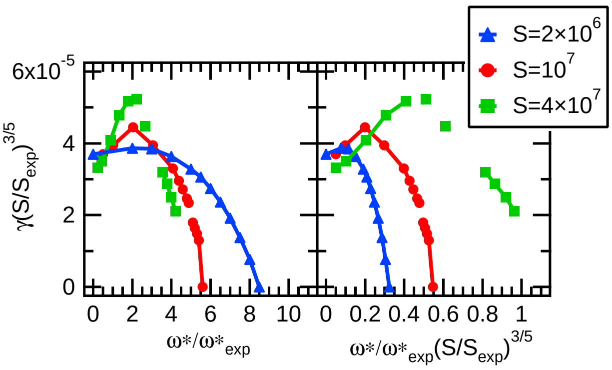

Figure 1: Linear growth rate as a function of diamagnetic frequency for different values of Lundquist number. With no scaling of ω_* (left). Scaling $\omega^* \propto \eta^{3/5}$ is used (right)

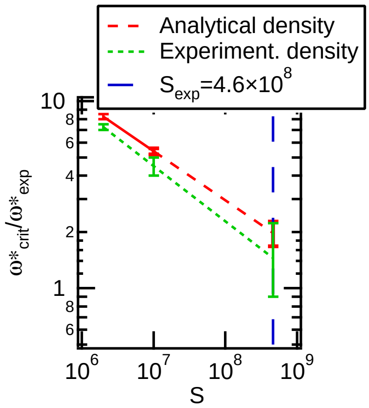

Figure 2: Extrapolation of linear stability threshold towards experimental Lundquist number.

this value towards experimental S number gives $\omega^*_{crit} \approx 1.45\omega^*_{exp}$, see Fig. 2 (lower curve). The experimental ω^* is found to be within the error bars. It means that full stabilization by diamagnetic rotation is a good candidate to explain the Tore Supra experiments.

Saturated states

In order to study the improvement of confinement by diamagnetic rotation we measure saturated island width in the simulations with different values of diamagnetic frequency. Since transport in presence of an island is increased due to reconnection, deterioration of confinement increases with island size. The results of simulations for non-linear saturation are shown in Fig. 3. Saturated island width is found to be strongly decaying as diamagnetic frequency and Lundquist number are increased. In the stable domain (i.e. $\omega^*/\omega^*_{exp} > 5.5$, for $S = 10^7$) results are obtained by introducing a seed into the plasma. In order to discriminate the impacts of the diamagnetic and curvature effects we reduced impact of curvature. To this end, the major radius was increased by a factor of ten ($R = 10R_{exp}$). All aspect ratio dependent quantities were rescaled accordingly. These simulations show that higher curvature makes the reduction of saturated size by diamagnetic effect more efficient (Fig. 4). In the lower curvature (large R) case, the reduction of the saturated width by diamagnetic frequency takes the form of a jump reminiscent of multiple states as found in [3].

In the simulation for $\omega^* = 0$ island did not reach the full saturation, so an arrow indicates that saturated width is expected to be higher. Effect on the plasma pressure is illustrated on Fig. 5. One finds dramatic pressure drop in the case $\omega^* = 0$ and no significant confinement degradation at $\omega^*/\omega^*_{exp} \approx 5$. This raises the question of our ability to detect magnetic island if it saturates at low amplitude in experimental conditions. Synthetic ECE diagnostic is used to estimate minimum detectable island size. Assuming an experimental noise level of 1%, the de-

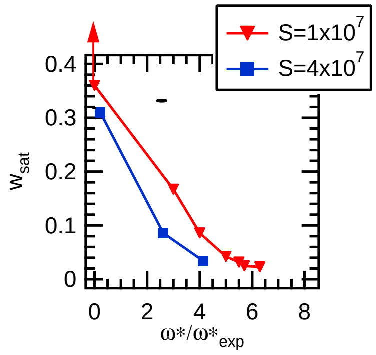

Figure 3: Decay of saturated island width with diamagnetic frequency ω^* for different values of Lundquist number.

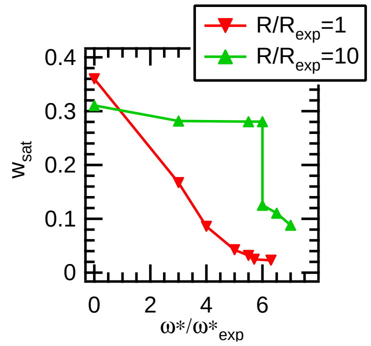

Figure 4: Decay of saturated island width with diamagnetic frequency ω^* for different values of major radius.

tection threshold is $w_{detection} = 0.018a$, where a - is the minor radius (fig. 6). The extrapolation of the saturated island width towards experimental S and ω^* is shown on fig. 7. For this purpose the power-law dependence $w_{sat} \propto \omega^{*\alpha} S^{\beta}$ is assumed. After its saturation the island is expected to be detectable and moreover it can lead to a strong degradation of confinement.

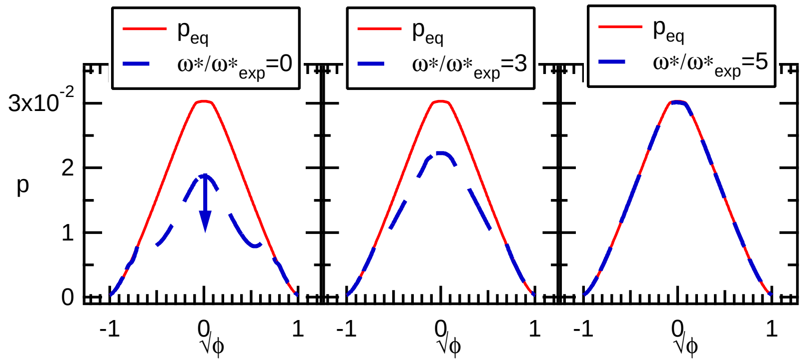

Figure 5: Saturated pressure profiles for different ω^*

The typical Tore Supra and ITER (Table 1) parameters are used in order to compare the importance of the diamagnetic (measured by α) and the curvature (D_R) effects for these machines. If similar gradients are assumed, diamagnetic rotation is expected to be weaker in ITER, since $\alpha_{ITER}/\alpha_{TS} \approx 0.2$ (see Table 2). However due to the much higher Lundquist numbers and cur-

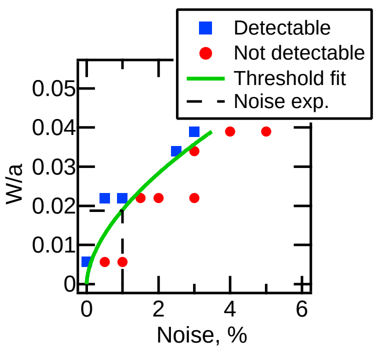

Figure 6: Minimal detectable island size as a function of experimental noise level.

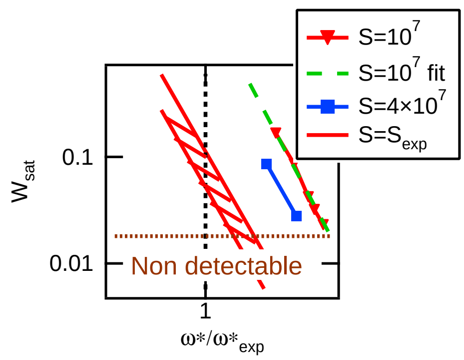

Figure 7: Extrapolation of saturated island width towards experimental S.

vature, lower ω^*_{crit} is expected. If this value is below experimental diamagnetic frequency it can introduce a new mechanism for a metastability along with curvature and bootstrap current.

Table 1: Typical Tore Supra and ITER parameters

	a	R	B_0	T	n
Tore Supra	$0.72\,m$	$2.28\,m$	$3.4\,T$	$3\,keV$	$3\times10^{19}\,m^{-3}$
Typical ITER	$2\,m$	$6.2\,m$	$5.3\,T$	$30\,keV$	$10^{20}\,m^{-3}$

Table 2: Extrapolation to ITER

$D_R(ITER)/D_R(TS)$	S_{ITER}/S_{TS}	$\alpha_{ITER}/\alpha_{TS}$
$10-20$	≈ 60	≈ 0.2

Conclusions

The dependence of tearing mode stability on diamagnetic rotation and toroidal curvature has been studied. Our simulations show that diamagnetic rotation can fully stabilize the (2,1) tearing mode and curvature plays an important role for this stabilization. The full stabilization extrapolated to experimental resistivity and is found to be consistent, within the error bars, with the absence of an island in the experiment considered. Thus, the proposed mechanism is a plausible candidate to explain the absence of $n=1, m=2$ mode in some of mentioned experiments on Tore Supra. In the non linear regime, the saturation of n=1, m=2 mode is found to be strongly reduced by diamagnetic rotation. However extrapolation towards experimental situation shows the possibility of island saturation at a level sufficient to degrade confinement significantly. These facts: marginal stability, metastability reported before [1] and high saturated width of the (2,1) mode could explain abrupt transition to MHD regime. For ITER size machines, the toroidal curvature is expected to be more important in the linear regime due to higher β. Lower non-linear saturation is predicted thanks to the higher values of Lundquist number typical for such devices and favourable scaling with S.

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