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A Study of MHD Feedback Stabilization in Tokamaks with Lower Hybrid Waves

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Abstract.
Lower Hybrid Current Drive (LHCD) has been succesfully employed in current profile control experiments and can be utilized to prevent MHD instabilities by tailoring the profile. Similarly, theory has shown that LHCD can be very effective in stabilizing MHD instabilities by feedback techniques: this experiment has not been tried yet. This paper addresses some of the practical aspects of such an experiment.

INTRODUCTION

Feedback stabilization of the m=2, n=1 island with Lower Hybrid Current Drive has been theoretically proposed several years ago,[1,2,3,4] but never experimentally tried. Indeed, it has been often reported that in LHCD experiments, the m=2 mode was destabilized. This has been not because of any unique properties of LH waves that cause destabilization, but rather an indirect result of experimental requirements to date. So far, LHCD experiments have been designed to drive current efficiently, necessitating couplers which are able to launch the highest phase velocity waves compatible with accessibility; this has usually concentrated the rf-driven current inside q=2, thus steepening the current gradient at the rational surface. This is a way of destabilizing the m=2 mode.[5] For plasmas with moderate electron temperature, a LHCD feedback stabilization experiment might therefore require a dedicated coupler able to launch slow waves which are absorbed in the outer region of the plasma.

Feedback stabilization of the m=2 tearing mode can be effected by driving non-inductive current inside the magnetic island, in the same direction of the main current. A very attractive feature is that the stabilization is very rapid since it is caused by the reduction of the electric field which drives the mode: this is achieved with the back-emf induced by the non-inductive current.[6] In contrast, current profile modifications require much longer times, of the order of the resistive time.

Radial localization to a narrow region is not critical, provided that the driven current overlaps the island. The stabilization derives from the decrease of the electric field inside the island, so only the current which is localized inside is effective; the current which is deposited outside has only a minimal effect (provided it is not concentrated inside q=2). Therefore, the radial localization is not critical provided that the driven current overlaps the island.

Poloidal localization is not essential either, since the effect is dominant at the O-point: the current deposited at the X-point has relatively little effect.[6] However, a major advantage of a modulated current derives from the fact that up to a factor of 5 less current is required compared to a DC current.[6]

EXPERIMENTAL CONDITIONS FOR LHCD FEEDBACK STABILIZATION

The main experimental challenge is to be able to locate the rf-induced current inside the island. The ray trajectory intercepts the island, since it has been shown [7] that the perturbed magnetic field does not change appreciably the propagation of the LH waves; but it is practically impossible to rely on multiple passes of the waves through the plasma and $n_{||}$ upshift to "hit" the O-point of the island, so it is necessary to have previous knowledge of the radial location of the island and damp the rf-waves in first-pass. (See figure 1) (In principle it is also possible not to depend on the knowlegde of the radial location and scan the phase of the grill in order to optimize $n_{||}$, but as a proof-of-principle it is simpler to operate at a given $n_{||}$ throughout the pulse).

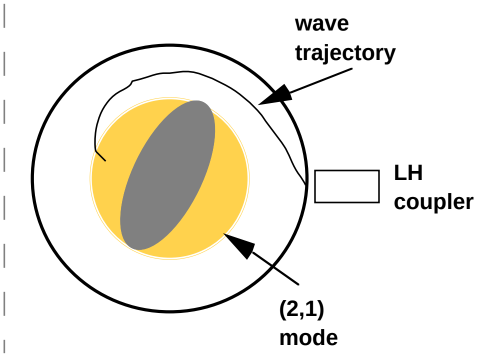

Fig.1 Schematic of the LH wave trajectory and of the m=2 magnetic island

Having to damp on first-pass has a consequence on the efficiency in moderate electron temperature experiments, because this requires launching moderately high $n_{||}$. The current drive efficiency is also reduced from the fact that a high $n_{||}$ requires small waveguides, which limit the maximum power that can be transmitted with a single coupler. Because of these cosiderations it is essential to evaluate the necessary current and the time required for stabilization .

As a reference, we take a D-shaped plasma[9] with 660 kA of current and 15 kG magnetic field on axis.

Following the treatment of Morris,[6] the threshold for the m=2 stabilization is found at approximately 15 kA of modulated current (compared to about 200 kA in case of steady-state current,and assuming the rf deposition to be ≈1/3 of the radius and the island width ≈0.1 the radius). The stabilization time depends on how much the driven current is above the threshold.Very interestingly, it is expected to be a few milliseconds.

Next it is necessary to phase the modulation so that the rf power is deposited inside the island: modulation of tens of kHz is well within the capability of any LH system and the driving signal can be obtained from Mirnov coils, BES or ECE. Since, as mentioned previously, the ray trajectory cannot be easily calculated easily in real time, a technique similar to that employed on Compass[10] can be applied with the added feature that the timing of the modulation is varied until the m=2 signal is seen to decrease.

It should be noted that, in situations in which the current drive efficiency is too low (due to the high $n_{||}$-spectrum used), it is possible to increase it by making use of a compound spectrum: one coupler launches a high $n_{||}$-spectrum which establishes a suprathermal tail, while another, launching a lower $n_{||}$, increases the efficiency. In this scenario it might prove convenient to launch the high $n_{||}$ DC, in order to keep an electron tail continuously centered around the m=2 island, and modulate the second coupler (the main contributor to the rf current) in order to increase the current at the O-point.

MODELLING

An equilibrium modelling code with a LH ray tracing package[11] has been used to determine the conditions required to perform an experiment in a plasma with the following characteristics[9]:

major radius R_0=160 cm
aspect ratio A=3.38
elongation κ=1.58
triangularity δ_t=0.67
β_{pol}=1.57

magnetic field on axis B_0=1.4 T
plasma current I_p=660 KA
safety factor on axis q_0=1.14
q_{95}=3.65

From the magnetic equilibrium we find that $\psi(q=2)=0.7$ (corresponding to $r/a \approx 0.8$) and that the electron temperature at this location is $T_e \approx 1400$ eV.

In order to determine which $n_{||}$-spectrum to launch, the damping location of individual values of $n_{||}$ have been evaluated with the ray tracing package of the code: it is easy to show that a spectrum with $5.0 \leq n_{||} \leq 5.5$ is necessary to first-pass damp at $T_e \approx 1400$ eV. Such a $n_{||}$-spectrum can be launched by an array of 32 waveguides, at the frequency of 4.6 GHz.

The radial distribution of rf current density generated by such spectrum, carrying 200 kW, is shown in figure 2. 40 kA of current are generated near ψ=0.7, of which approximately 20 kA directly inside the magnetic island. Since the poloidal spread of the rf-current is $\Delta\theta \approx 10°$, the spatial resolution is more than sufficient for the feedback modulation stabilization scheme. Toroidal localization is not needed, since LH waves follow the field lines, but a calculated spread of $\Delta\varphi \approx 5°$ illustrates well the localization of the damping.

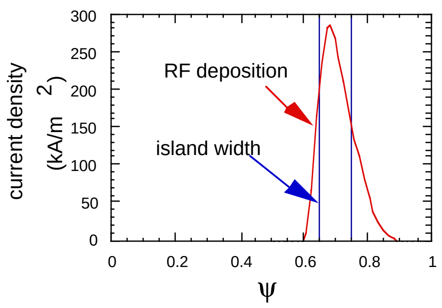

Fig.2 Calculated radial distribution of the rf current.

It is interesting to note that a broadening of the launched spectrum (such as one launched by an array of 16 waveguides) does not result in a broader power deposition, but mainly in a shift of the damping toward lower electron temperature. This is because the higher "content" of large $n_{||}$ in the spectrum requires lower T_e for damping.

The necessity of a high number of waveguides derives from their narrowness, which implies lower power per waveguide (this limitation is largely removed in a machine like ITER, because of the high electron temperature).

Some spread of the rf current is caused by radial diffusion of the fast electrons: the very fact that high $n_{||}$ are used, insures that the effect of diffusion is minimal. Figure 3 (obtained by means of the 3D Fokker-Planck code of Ref.8) shows the rf current for different values of the diffusion coefficient D_r. Another source of spread of the rf current could derive from the finite poloidal size of the coupler: ray tracing calculations show that the trajectories diverge somewhat only after the first pass through the plasma.

CONCLUSIONS

The practical feasibility of a feedback stabilization experiment using LHCD has been investigated. It is found that even in moderate temperature plasmas MHD instability can be stabilized by a modest amount of power: the principal requirement of the LHCD is the condition of first-pass damping. It is found that localization of the rf current and diffusion do not constitute a problem to the stabilization, which appears to be very fast.

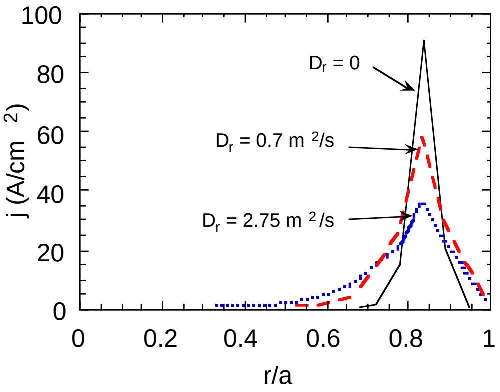

Fig. 3 RF current broadening due to the fast electrons diffusion for 2 values of the diffusion coefficient D_r.

The relevance of demonstrating the stabilization of the m=2 mode with LHCD is obvious when we consider that such experiment would be much easier in a machine like ITER: the much higher electron temperature in the vicinity of the mode and the much larger radius allow a far better localization and efficiency than in present tokamaks, without the need of using thin waveguides. A feedback stabilization with LHCD would be of great value, in comparison with an equivalent experiment with ECCD. In fact, in the latter scheme, a somewhat better localization is balanced by a very low efficiency, especially in the outer portion of the plasma (owing to trapped electrons). It should also be noted that for ECCD, at a given magnetic field, the mode resonant surface should be tracked by mechanical movements of the mirrors which constitute the antenna. Conversely, for LH waves, the power deposition profile can be spatially shifted by changing the phase velocity of the waves (i.e. by changing the phasing of the waveguides in the coupler). In a machine like ITER, this can be accomplished in real time.

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