Modeling of rotation and fast-ion effects on RWM stability in DIII-D plasmas

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Introduction

Operation at high normalised plasma pressure in tokamaks is usually limited by the destabilization of an external ideal kink instability (above the no-wall β_N limit), or – when the ideal kink is stabilized – by the triggering of a resistive instability close to the ideal with-wall β_N limit. In the presence of a realistically described (non-ideally conducting) wall, the ideal kink is slowly growing and it is defined as a Resistive Wall Mode (RWM). In plasmas with high toroidal rotation and a significant fraction of fast particles, it was postulated that kinetic wave-particle damping explains why the RWM is observed to be stable above the no-wall limit [1]. The damping depends on resonances between the plasma rotation and trapped ion motions, with additional non-resonant contributions from non-thermal (fast) beam ions. These conditions may extrapolate unfavourably to machines with low rotation and significantly smaller fractions of fast beam ions such as ITER [2–4]. Experiments were conducted at DIII-D to validate these hypotheses, tackling both the approach to the no-wall β_N limit in the presence of fast neutral beam ions and the role of toroidal rotation. In all the discharges described in this paper, the plasma stability is probed by active MHD spectroscopy with an external n=1 field at a frequency of 10–20 Hz, and the plasma response to this field is used as a proxy for RWM stability. We describe the comparison between the measured plasma response and that calculated by means of the MARS-K code [5], which includes both the toroidal rotation and the fast-ion resonances for the modeled plasmas.

Fast ions effects in the approach to the no-wall β_N limit

A series of plasmas were obtained in DIII-D at different β_N levels spanning 50%–110% of the no-wall limit, while keeping the rest of the characteristics fixed (shape, rotation, density...). Previous results have shown that ideal MHD only modeling of the RWM over-estimate the plasma response amplitude significantly when the pressure approaches the no-wall limit [6], and it was hypothesized that the inclusion of fast particles non-resonant damping in the model would decrease the calculated response amplitude, eliminating the exponential growth at higher β_N. In that study the experimental rotation was neglected, and new results that include the rotation profile in the ideal MHD modeling are shown in Fig. 1. The ideal no-wall plasma limit is calculated to be β_N~2.2–2.35. The inclusion of plasma

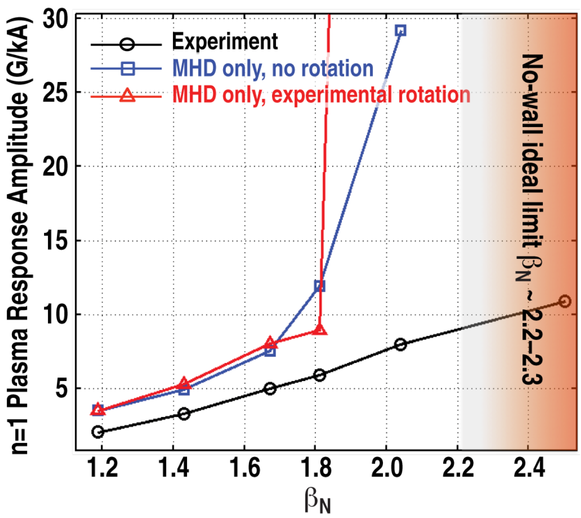

Fig. 1. Experimental β_N scan, and comparison with modeled plasma response amplitudes (blue: no rotation; red: experimental rotation profiles)

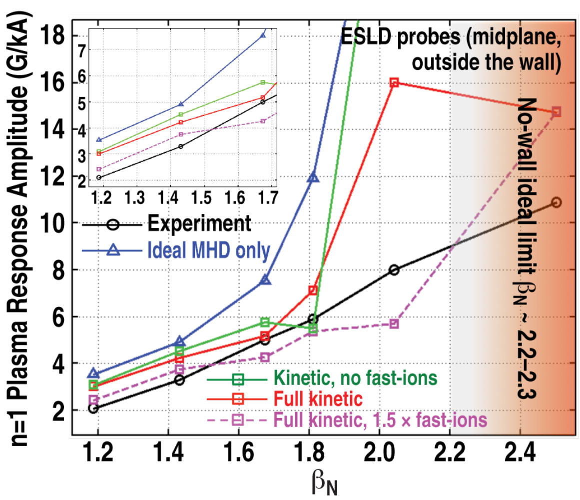

Fig. 2. Experimental (black) and modeled plasma response amplitude for a DIII-D β_N scan. Ideal MHD only model shown in blue, full kinetic model without fast-ion resonances in green, with fast-ions in red.

rotation has little effect at low β_N (<1.8), while it starts damping the response amplitude at ~80% of the no-wall β_N limit, before the pole in the response reappears at ~90% of the limit. This seems to confirm that rotation alone is not sufficient to achieve stabilization in the approach to a no-wall limit. Calculations with the MARS-K model, which includes rotation and all the damping terms of thermal and fast particle resonances (Fig. 2), show that (i) below 80% of the no-wall limit (β_N<1.8), the effects of the non-ideal damping terms (green and red curves vs. blue curve) is small, but visible, and it reduces the difference with the experimental data (black); (ii) the impact of fast-ion damping resonances is also small (difference between red and green curve); (iii) close to the no-wall limit, the growth in the response amplitude is greatly reduced by the presence of the non-ideal damping terms; (iv) excluding the fast-ion terms at high β_N makes the pole in the response amplitude reappear. The calculated mode structure is consistent with an n=1 character, and the main harmonics (m=2–6) indicate the presence of a global mode, radially distributed. While the inclusion of the new physics decreased the discrepancy with the experimental results at high β_N, the model still seems to overestimate the plasma response amplitude at ≳90% of the no-wall limit (β_N~2.05), and this discrepancy is being investigated. By artificially increasing the fast-ion damping terms, it is possible to estimate that the model presently overestimates the response amplitude by ~50% at this β_N level (Fig. 2, magenta curve). However, the calculated response is still overestimated by a factor of ~1.4 at the highest β_N point.

Impact of rotation on RWM stability in the presence of fast ions

We report on two series of DIII-D discharges where the toroidal rotation was varied from shot to shot by increasing the fraction of neutral beam power injected in the direction opposite to the total plasma current direction, while β_N, plasma shape and density are kept fixed. New rotation levels, coupled with off-axis neutral beam injection (OANBI), were also obtained to expand the range of results above ~60 km/s analysed in [1] (Fig. 3, circles). The results for the discharges with higher rotation at mid-radius (circles) indicate that the decreasing trend observed in the past (Fig. 3, squares) stops at ~60 km/s, and the response amplitude has a very weak increasing trend at higher rotation. As reported in [7], OANBI causes the ideal no-wall limits to increase, and therefore the response amplitudes to decrease at fixed β_N, being farther away from the limit. This explains the overall lower values for the new discharges with OANBI power. Previous modeling [1] showed that RWM-unstable rotating equilibria are predicted to be stabilized if the fast-ions are included in the model. Moreover, the clear peak of the plasma response amplitude occurring in the experiments at ~0.8% of the normalized angular rotation ($\Omega_E\tau_A$, where τ_A is the Alfvén time) was reproduced using the MISK code to calculate the growth rate of the RWM, and the single mode model to estimate the corresponding plasma response for all the rotation levels. New results based on the original DIII-D equilibrium were obtained with the MARS-K code, which can calculate the plasma response directly, for a series of increasing rotation values, including the thermal and fast particles resonances in the model. The MARS-K modeling in this preliminary study shows the correct trend, but the plasma response amplitude is overestimated by a factor of ~2 (the model results, red circles in Fig. 4, are multiplied by 2, to be shown on the same plot as the experimental points). This is consistent with the modeled response amplitude at $\beta_N = 2.3$ in the β_N scan experiment, where the MARS-K results with fast-ion damping also seem to be overestimated.

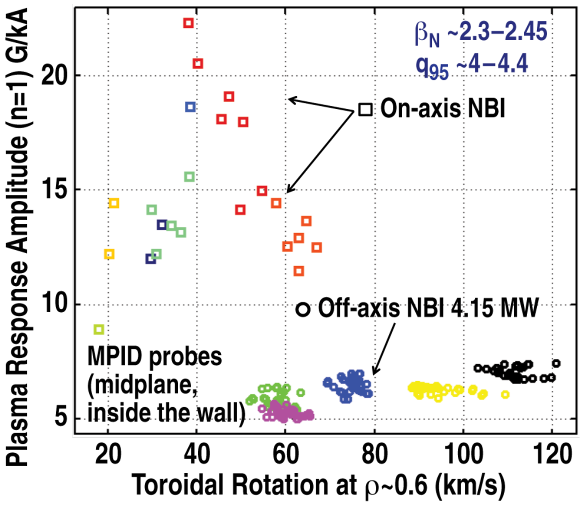

Fig. 3. Experimental measure of the plasma response amplitude in the rotation scan experiments. Data with all on-axis NBI power shown in squares, with ~4.2 MW of OANBI in circles.

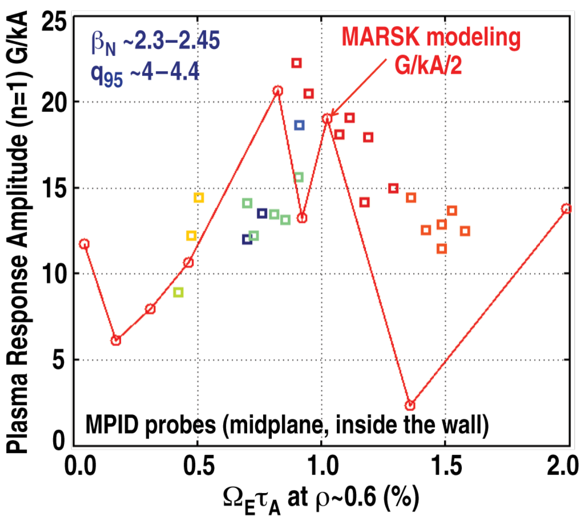

Fig. 4. MARS-K modeling of the plasma response amplitude obtained for a scan of the experimental rotation profile.

Conclusions

New modeling results have been obtained by means of the MARS-K code to validate the theory that links the stabilization of the RWM in DIII-D to the combined presence of significant plasma rotation and a large fraction of fast beam-driven ions. Rotation alone does not seem to be effective at stabilizing the mode above 90% of the no-wall limit, if non-ideal damping resonances are not taken into account. When thermal and fast particle resonances are included, the model obtains results that are a factor of ~2 closer to the experimental values, but the β_N level above 90% of the limit are still overestimated. New experimental data have been obtained for the toroidal rotation comparison, extending the rage of explored rotations by a factor of ~2. The results show that the downward trend observed previously stops at ~60 km/s and a slight increasing slope is present at higher rotation. The first modeling of the plasma response for this scan show that the MARS-K code reproduces the peak in the data correctly, but the amplitude of the response seem to be overestimated by a factor of ~5. The present effort is focussed on isolating the physics of bounce and precession resonances of trapped particles, as well as the transit frequency of passing particles, to assess which may be misevaluating the impact on the response amplitude. Moreover, the MARS code assumes a Maxwellian fast-ion distribution, while measurements show that the fast beam-ion distribution in DIII-D is significantly non-Maxwellian, which may contribute to the discrepancy observed in the results.

Work supported in part by the U.S. Department of Energy under DE-FG02-04ER54761, DE-AC02-09CH11466 and DE-FC02-04ER54698.

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