Measuring and Modeling the Approach to Instability in the ITER Baseline Scenario (and beyond)

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The simple analysis of a >200 shot database for the ITER Baseline Scenario demonstration discharges in DIII-D (15 MA equivalent with scaled ITER shape and q_{95}=3.1) suggests operation at ITER relevant torque (T<=0.7 Nm) may be challenging, with less than 50% of the discharges remaining stable for more than 2 s. Even more concerning is that none are stable at 0-0.4 Nm of injected torque. Stable operation is generally found at T>3 Nm (all co-injected NBI), where nonetheless some of the discharges develop an instability at some point on the β_N flattop. This clearly indicates that the scenario is operated on a marginal stability point, as it is extremely sensitive to small perturbations. The active MHD spectroscopy technique applied to this scenario in the 2014 campaign yields interesting results that indicate the approach to an instability at low torque (fig. 1). Modelling of this effect with the MARS-K code shows a discrepancy with the experimental trends at the lowest values of rotation: resolving this issue is crucial to acquire predictive capability and scale these demonstration discharges to ITER.

A zoo of 2/1, 3/2, more rarely 4/3 tearing modes, and sometimes 2/1 borne-locked modes are triggered at different times during the discharges, and in most cases they modify the current and pressure profiles in a way that is not recoverable with the available heating systems. At low torque these instabilities most often lead to a disruption, due to the high normalised plasma current. However, evaluating the ideal no-wall and ideal-wall stability limits, presents us with a puzzle: the calculated no-wall β_N limit falls in the rage $\beta_{\text{no-wall}}$~2.5-3 and the ideal wall limit is β_{wall}>3.5, while the IBS is operated at β_N level of 1.8-2.2. Being so far below the ideal MHD β limit, all the while experiencing ubiquitous and disruptive instabilities in almost all the plasmas indicates that one or more non-ideal effects are at play. One obvious dependence is the correlation between injected torque and stability, which appears to indicate that a zero torque, and correspondingly low plasma rotation, large 2/1 tearing modes are triggered, which degrade the confinement, and most of the time slow and lock to the wall. The MSE measurements indicate that the current profile is evolving while the rotation is slowing down, mainly in the outer part of the plasma, and that can be another cause of the instabilities (the equilibrium may be evolving to a classically unstable state [1,2]).

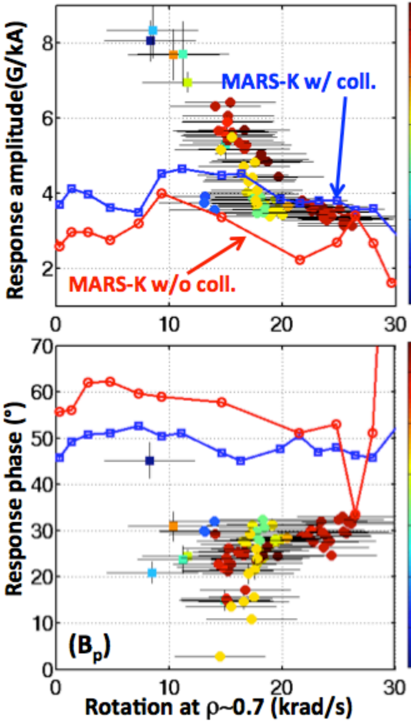

Fig. 1. Active MHD spectroscopy measurements of the plasma response amplitude (top) and phase (bottom) for a series of IBS discharges with varying input torque (color coded as in the colorbar). The full lines represent the MARS-K modelling of the rotation variation with fixed collisionality (blue) and zero collisionality (red).

MHD spectroscopy measurements (20 Hz, 240° phasing) were taken in several IBS discharges, while the torque was varied during the shot or from shot to shot, and an example of the results is shown in figure 1. The amplitude of the response picked up by the magnetic sensors increases rapidly with lower rotation, and the phase measurements show an abrupt change in the same range. This has been shown to be typical for this diagnostic when the plasma crosses an ideal limit ($\beta_{\text{no-wall}}$) [3], despite the fact that the scenario is run at a β_N level that is 55-65% of the no-wall limit. Moreover, the points at intermediate rotation exhibit a smooth increase of plasma response with $\beta_N/\beta_{\text{no-wall}}$, consistent with the usual ideal MHD trends, while the cases with highest and lowest rotation are completely off-trend (lower amplitude than the trend for the high rotation, much higher for the lowest rotation cases) [4]. These two observations strongly suggest that non-ideal effects are a crucial ingredient of the scenario stability.

Work has started to model these results, with the MARS-K code [5], which includes the plasma rotation, all the experimental kinetic profiles, collisionality (constant across the plasma minor radius in the present version), and all the drift kinetic frequency effects. The first results obtained with a single equilibrium and a rotation profile scan which spans the range of experimental rotations is reported in figure 1 (blue line). It is clear that collisionality is crucial for the model to reproduce the experiment, and the code captures the amplitude of the response very well in the range of high to moderate rotation. However, when the rotation drops below 15 krad/s and the measurements increase by twofold, the model does not reproduce this large increase. Also, the phase measurements are overestimated by the model 15-20° over the whole range of rotations, and hint at the potential of abrupt variations at low rotation that are not visible in the code results. Given that these abrupt phase changes at low rotation may be the most visible signal for the approach to a stability limit, it is crucial that the models be able to reproduce this part of the measurement precisely.

The low frequency MHD spectroscopy method usually indicates the degree of ideal instability of a plasma - therefore the large increase in the response amplitude, accompanied by an abrupt change in response phase, which characterises these IBS plasmas need to be interpreted in the light of potential non-ideal effects. Can these reduce the no-wall limit from $\beta_{\text{no-wall}} > 2.5$ to a value closer to the ITER β_N? Do these measurement indicate the importance of non-linear braking physics at zero injected torque, and an increased sensitivity of tearing stability to error fields? Are these effects generic (i.e. applicable to ITER) or are they due to a peculiarity of the present DIII-D construction? In order to acquire insights into these issues, it is crucial to investigate the cause of this correlation between injected torque, plasma response and onset of disruptive instabilities in this low q_{95}, low rotation scenario.

The model needs improvements at very low rotation, in order to resolve the discrepancy between the modelled and the measured response at zero torque. A more detailed collisionality model, with radial dependence of the profiles and energy dependence for the amplitude could improve the results. Moreover, finite ion orbits and a more precise fast-ion slowing down distribution may provide small variations. If we want to extrapolate the stability landscape of the plasmas produced in present machines to the plasmas in ITER and beyond, we need to acquire better understanding of the mechanisms at play: the present models need to be tested in these relevant conditions and the origin of the discrepancy between the experiment and the code results needs to be resolved. More integration between the experimental and the theory communities are necessary to add/correct the physics presently implemented in the models and to design experiments capable of validating all the components of the codes.

References

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