Symmetry–breaking modes for helical states in RFX-mod

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Helical states are a common feature of the Reversed Field Pinch (RFP) configurations. These states are spontaneously observed in all experiments and can be described as equilibria characterized by a well defined periodicity that is linked to the machine aspect ratio and generally corresponds to the innermost resonant mode of an axisymmetric equilibrium. The spectrum of MHD fluctuations as measured at plasma edge is peaked on the main helicity with a quasi single helicity feature.

In the RFX-mod experiment [1] these states are routinely found [2] and show a helical core with a periodicity m=1,n=7 that is observed in all diagnostics both magnetic and kinetic (e.g. plasma temperature and density, SXR emissivity, plasma potential at the edge). However they do show back-transitions to multiple helicity states which can be only partially compensated by properly tuning the feedback laws of the real-time MHD mode active control system [3].

Previous linear-ideal MHD analyses have been performed with the Terpsichore code [4] running on 3D equilibria computed with the VMEC code [5] assuming internal profiles, such as pressure and safety factor, based on typical experimental profiles. These analyses showed that ideal MHD kink modes can be unstable leading to the breaking of the symmetry of the configuration, with a strong sensitivity to the internal profiles, indicating that more precise matching of equilibria with experimental data is mandatory. To this end we now use the V3FIT code [6] to calculate more precisely plasma equilibria from diagnostic information available on RFX-mod [7]. This is an important aspect in order to assess the role of current density and pressure gradients with respect to the level of ideal stability of MHD modes.

It is known that Terpsichore has some issues in dealing with the reversal surface, i.e. the surface where the toroidal magnetic field goes to zero and then reverses sign at the edge with respect to plasma core. However as helical states are favored by a very shallow reversal [2], we run the code artificially removing the reversal at the very edge. Though this has a very limited effect on the final equilibrium (e.g. flux surfaces shape and internal profiles), the effect on stability might be more significant.

Taking into account, as a first step, the axi-symmetric case, one finds the usual m/n=1/6 unstable mode that is a resistive wall mode easily controlled with the active control system for

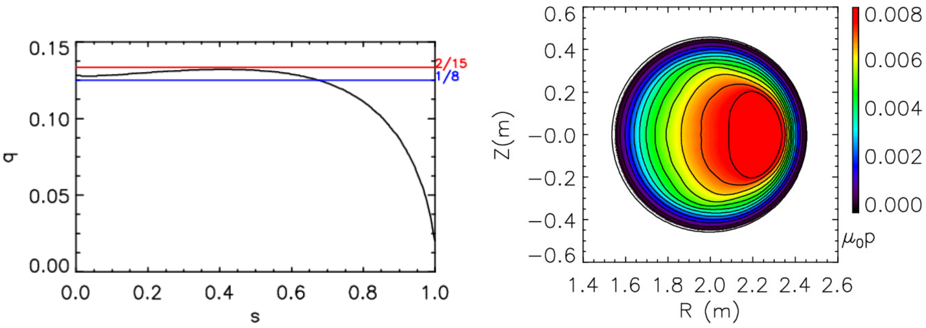

Figure 1: Left: q profile as a function of the normalized radial flux coordinate. Horizontal lines show the most unstable m/n modes for this case. Right: contour plot of plasma pressure, showing also flux surfaces. Quantities are shown in Boozer coordinates.

instabilities present on RFX-mod [8]. In the analysis of this paper, we assume that r_{shell}/a=1.067 (a=0.459 m is the minor radius of the first wall) as we considered as shell the vacuum vessel. This is the radius at which generally measurements are extrapolated for the realtime control of instabilities.

The next step is the study of fully 3D configurations and in particular the determination of symmetry breaking modes, i.e. unstable modes with a periodicity close to the dominant one.

In Terpsichore unstable modes are determined solving the eigenvalue problem for the energy of the system decomposed in terms of internal potential energy (W_P), vacuum energy (W_V) and kinetic energy (W_K): $\delta W_P + \delta W_V + \lambda \cdot \delta W_K = 0$, where the eigenvalue $\lambda < 0$ indicates instability. The eigenfunction associated to each mode is calculated by considering the MHD fluid displacement $\xi = \sqrt{g}\xi^s(\nabla\theta \times \nabla\phi) + \frac{B\times\nabla s}{B^2}\eta + \left[\frac{J(s)}{\Phi'(s)B^2}\eta - \mu\right]B$ calculated according to Boozer coordinate (Φ is the toroidal flux and the $'$ denotes derivative with respect to the radial flux coordinate). In particular we are interested in the radial component $\xi^s = \xi \cdot \nabla s$.

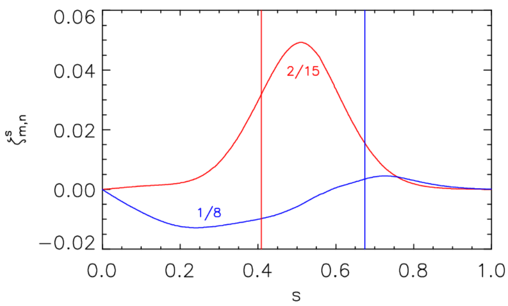

Figure 2: Eigenfunctions of the displacement associated to the two most unstable modes. Vertical lines correspond to the maximum of q (red) and the resonance of the 1/8 mode (blue).

For an experimental helical state, in figure 1 we show the q profile and plasma pressure contours (in Boozer coordinates). The two most unstable modes are found to be the 2/15 (non resonant) and 1/8 (resonant).

In figure 2 we show the eigenfunctions of the two most unstable modes (the most unstable mode has an eigenvalue λ =–0.0326 to be compared to the value λ=–1×10^{-4} representing marginal stability [4]). The colours are the same as in figure 1 and vertical lines correspond to the radius of the 1/8 resonance (blue) and the maximum of q (red). Already from this plot one can see how the eigenfunctions are larger near resonances (if present) and in regions where magnetic shear is

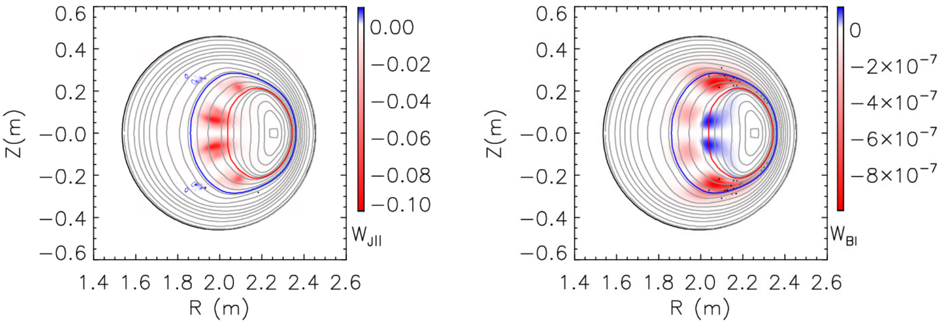

Figure 3: Contour plots of $W_{J||}$ (left) and W_{BI} (right). Flux surfaces are also shown. Coloured lines correspond to the maximum of q (red) and the resonance of the 1/8 mode (blue). Notice that W_{BI} is significantly smaller than $W_{J||}$, which is the destabilizing term.

lower (remember that the helicity of these modes is in some sense "close" to the main helicity of the configuration).

In studying stability it is also useful to determine which is the driving term for the unstable modes especially in cases where large gradients are also observed. Indeed helical states in RFX-mod do show a significant plasma pressure gradient in the region close to the maximum of q (associated to a transport barrier [2]) and this might also lead to pressure driven instabilites along with the ususal current driven modes of the RFP. In Terpischore the driving terms considered are essentially two: $W_{J||}$ describing the kink mode instability linked to the interaction of parallel current density with magnetic shear; and W_{BI} describing the ballooning-interchange instability due to the interaction of pressure with the magnetic field line curvature.

In figure 3 we show the contour plots of the two potential energies $W_{J||}$ and W_{BI} along with constant flux surfaces describing the equilibrium (in Boozer coordinates). Again coloured lines correspond to the resonance surface of the 1/8 (blue) and to the maximum q (red). W_{BI} is signficantly smaller that $W_{J||}$ so that these modes are always current driven kink instabilities. Also the destabilizing potential energy is concentrated in the helical core (inside the resonance of the 1/8) where 3D effects are more significant and magnetic shear is lower.

To address the effect of the q profile in the core, we have done a parametric study varying the q profile in order to obtain different values for magnetic shear in the core and removing resonances or allowing for double resonances. The equilibria obtained, have been studied with Terpsichore to assess the stability level of the configuration. As no role of pressure has been observed so far, the pressure profile has been kept constant in the scan.

As a first consideration, the changes in the q profile do not affect significantly the final equilibria: the shape of flux surfaces as well as internal profiles are not qualitatively different from each other. However in terms of stability, the differences are not negligible.

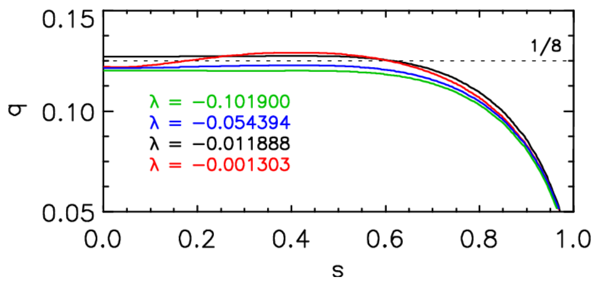

Figure 4: q profiles and corresponding eigenvalues λ. The most unstable mode is the 1/8 for all these cases.

In figure 4 we show a selection of q profiles from the scan data base, and a table with the eigenvalues associated to each case, zooming around the vaues of maximum q. Note that in all these cases the most unstable mode is the 1/8. The most unstable condition appears to be the flat q profile without the resonance radius (green profile). Increasing magnetic shear some level of stabilization is obtained (blue profile). Nonetheless an almost flat profile but with the resonance, provides a better stabilization (black profile). This comes from the fact that the resonance now appears in a region where some shear is present. The least unstable condition (from the linear-ideal point of view) is obtained with a reversed shear in the core associated to the presence of a double resonance for the 1/8 mode: again in this region some level of shear is present at the resonances. Notice that increasing the maximum value of q would simply change the most unstable mode (e.g. the mode 2/15), but the general features would still remain unchanged, an indication that the critical condition seems to involve the mode that is marginally resonant. It is not part of this work, but in this respect one should also consider the role of resistivity in defining the spectrum of unstable tearing modes (both current and pressure driven) as shown in [9].

The results presented show that from the linear-ideal point of view of stability, helical states are sensitive to the level of magnetic shear and marginal resonances in the core. As the helical state develops, one is expecting a larger fraction of current to flow in the hotter helical core and this will change the q profile accordingly. Also, as we are dealing with global modes, it is to be addressed the issue of resonant m=0 modes (hard to manage in Terpsichore) and their interaction with m=1 mode, as in the actual experiment these modes are marginally resonant (the discharges have a very shallow reversal).

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