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Behaviour of MHD modes spectrum in the RFX Reversed Field Pinch

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Introduction

The sustainment of the Reversed Field Pinch (RFP) configuration implies the self-organisation of the plasma in a dynamical equilibrium state. The destabilisation and successive saturation of MHD resistive kink-tearing modes is the means by which the dynamo mechanism can sustain the RFP magnetic profiles. RFP experiments have already shown that some differences in the magnetic fluctuations spectra and amplitudes are possible, depending for example on the characteristics of the magnetic boundaries of the device such as the aspect ratio, the thickness of the conducting shell and its distance from the plasma, and different other experimental conditions [1, 2, 3]. This fact has stimulated detailed studies showing that on the same experiment the dynamo mechanism can be sustained by several magnetic spectral structures. Indeed, recently in the RFX device, experimental evidences of two different magnetic configurations have been found and correlated with SXR tomographic analysis [4, 5]. One is the usual Multiple Helicity state (MH), in which many MHD modes contribute to the total amplitude of the magnetic perturbation. The second is the Quasi Single Helicity (QSH) state, identified by the presence of one mode clearly dominating the spectrum, which resembles the ideal case of pure single helicity configurations.

In this work we analyse from a statistical point of view the parameters controlling in RFX the occurrence of very broad (more than the "normal" MH) or narrow MHD mode spectra. In this way we try to make a step further in understanding how to induce stationary QSH regimes with the final goal of studying the underlying physics of this new regime [6].

MHD modes spectra characterisation

The experimental studies presented in the following were performed on the RFX device [7]. The magnetic spectra were obtained by a double toroidal array of 72x2 toroidal field pickup coils placed in the inner surface of the thick shell. Those coils allow us to distinguish between even and odd poloidal modes (mainly m =0,1) and to calculate toroidal mode numbers n up to 36. In a previous study ([8]) it was already shown how average magnetic fluctuations amplitude scales with some plasma parameters and in particular with the magnetic Reynolds number S. In that work it was also shown that narrow stationary spectra usually correspond to amplitudes of magnetic fluctuations equal or slightly higher than the average [Fig. 1]. It is important to remember that the magnetic fluctuations amplitude is not necessarily in direct correlation with a higher level of stochasticity, as recently pointed out by a theoretical study [9], especially when only few modes are present.

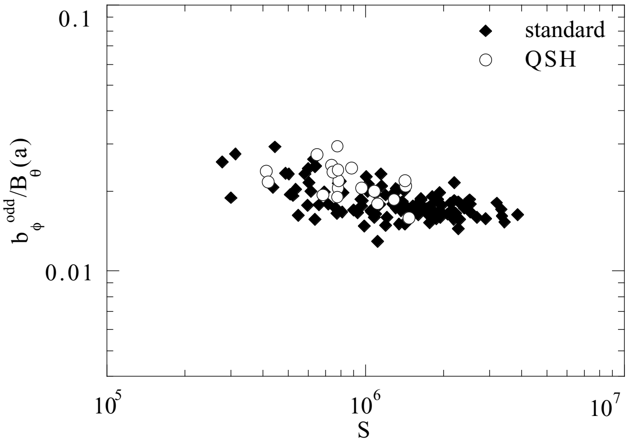

Fig. 1. Standard and QSH discharges vs. S.

In this paper we characterise stationary broad MH and QSH states, i.e. magnetic configurations lasting for times longer than the typical magnetic profile diffusion time. For this reason each point used in the calculations is a time average over a 5 milliseconds period during which the magnetic spectrum lies continuously in one of the two regimes. We compare in this way stationary states belonging to the two extreme cases of narrow (QSH) and very broad (broad MH) m=1 MHD spectrum. To select narrow and broad spectra, we used the spectral spread number, Ns, as defined in [2]:

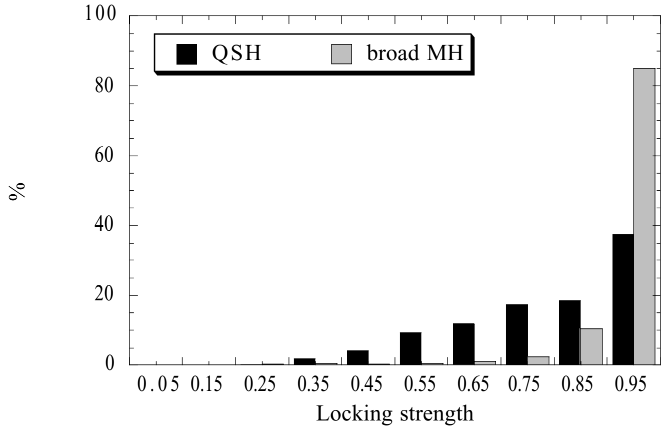

Fig.2. Locking strength frequencies for QSH and broad MH data.

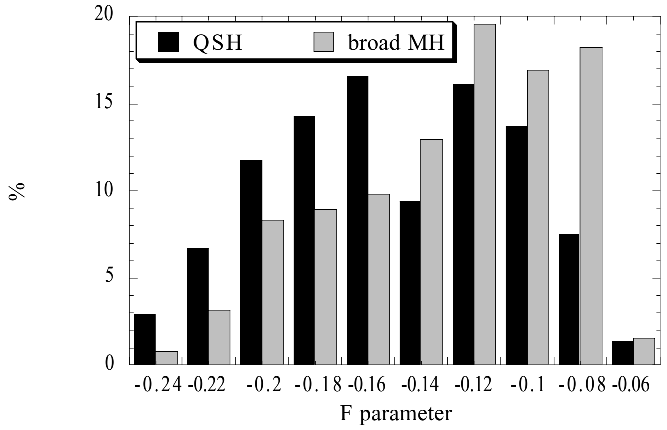

Fig. 3. F parameter frequencies for QSH and broad MH data.

$$N_S = \left[\sum_n \left(W_n \Big/ \sum_n W_n \right)^2 \right]^{-1}$$

where W_n is the energy of the (m=1,n) mode. In the sum modes with n from 7 to 20 were considered.

In the following we define as QSH points with N_s values smaller than 4 and broad MH points with N_s larger than 8. The total number of points in each set is approximately 1500. It is worth mentioning that the large majority of experimental data in RFX lies between these two values.

We also use in this analysis a parameter describing the phase locking of the MHD modes: in RFX all discharges show the locking of the MHD modes in phase and to the wall producing an enhancement of the plasma wall interaction and the worsening of the confinement properties of the discharge, especially at high plasma current levels ($I_t \approx 1$ MA). For this reason it is interesting to introduce a “locking strength” parameter by which we estimate the toroidal position where the MHD modes have the smaller phase difference. We calculate it as the normalised sum over the main interacting modes of the cosine of their phase difference. This parameter can be easily related to the more frequently used $1/\sigma$ parameter [10], but has the advantage of being upper limited in the case of perfect phase locking of the modes considered in the calculations. In Fig. 2 the frequency of a given value of the locking strength parameter is compared for the two kinds of spectra: it is easy to note how a broad spectrum corresponds almost always to a very high degree of phase locking while narrow spectra can exhibit with a much higher probability non perfectly phase locked MHD modes (it is interesting to note here that in some QSH cases with a low value of the locking strength parameter also the locking to the wall of the secondary modes is less evident).

MHD modes spectra analysis

We begin studying how the main plasma parameters such as plasma current, electron density and reversal parameter ($F = B_t(a)/<B_t>$) can affect amplitude and width of the toroidal magnetic field fluctuations spectrum. The most clear dependence comes from the F parameter (Fig. 3) and indicates how at deep reversal (more negative values of F) discharges with a narrow spectrum can be found more frequently than discharges with a very broad one. The same observation can be made by using the F and Θ ($\Theta = B_p(a)/<B_t>$) parameters to reconstruct the internal magnetic profiles by the α model [11], and leads to the consideration that at more peaked profiles (low values of the α parameter) correspond more frequently narrow spectra. A similar statistical analysis extended to other plasma parameters does not show any particular trend.

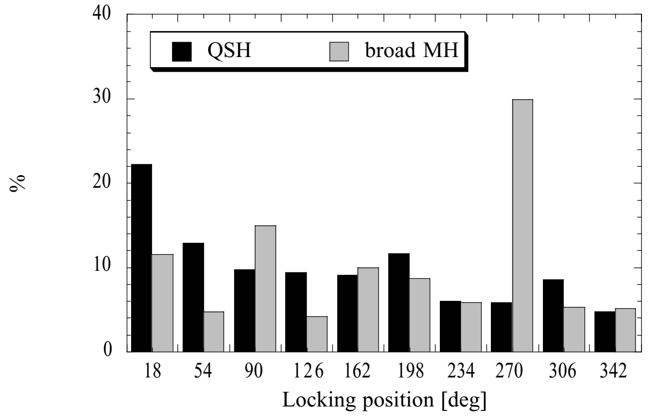

Fig. 4. Locking position frequencies for QSH and broad MH data.

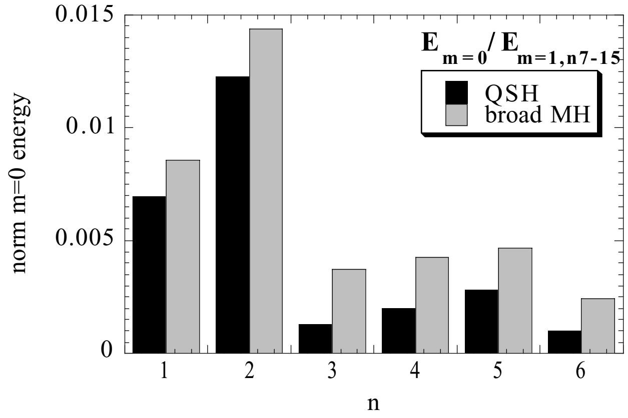

Fig. 5. m=0 normalised energy for different n modes.

The influence of the setting-up of the discharge (bias toroidal field, plasma current derivative, start-up phase, field errors control) on the magnetic spectrum composition was also experimentally investigated.

The position of the locked mode appears to be a very important parameter to get narrow or broad modes spectra. In Fig. 4 we compare the toroidal position of the wall locked modes for the two data sets. In RFX two poloidal gaps were originally present at ϕ=112.5° and 292.5°; the asymmetry in the MH position can be easily explained by the fact that the first poloidal gap (ϕ=112.5°) is now short circuited and that only very recently an effective feed-back control of the field error at the second one came into operation. It can be noted that QSH points do not show any particular "attractor", while broad spectra can be found more frequently around the open poloidal gap position. The interpretation of this correspondence in terms of field error control is at present under study.

Different setting-up conditions seem to affect in a less clear way the MHD flat-top spectra.

Discussion and conclusions

Despite a large variety of behaviours in the experiment we can draw in this work some connections with present status of theoretical and numerical modelling of the MH-QSH transition. An obvious analysis to perform would be about the incidence of QSH regimes in terms of the dissipative coefficients like resistivity and viscosity of the RFX plasma, which are known to control this kind of transition [5, 6 and references therein]. Unfortunately we do not have for these extended data sets complete diagnostic information to attempt an estimate of these coefficients like done in [8] for the total amplitude of magnetic fluctuations. Nonetheless we can find good indications concerning a number of additional points. First of all, we can now show on a statistical basis (see Fig. 5) that the experimental QSH states (as operationally defined in this work) display the expected characteristic of larger amplitude of m=1 modes and lower amplitude of the m=0 modes [5, 6, 12]. In this respect we should note that the degree of purity of the experimental QSH states obtained at present compared to the "ideal" helical symmetric regimes found in MHD modelling is still quite low. A second issue, which finds in our analysis a good statistical confirmation, is the influence of the pinch parameter Θ (or equivalently F as used in Fig. 3) on the dynamical transition. There are in fact numerical indications of easier achievement of QSH states at high Θ, at least for the occurrence of spontaneous transient transition to QSH regimes [9]. This is also in agreement with the experimental observation of the similar transient occurrence described in other experiments [1, 3, 13]. We can also show that already from a linear analysis we may find indications in this direction by comparing the instability spectrum for two typical magnetic configurations reconstructed from RFX data.

A linear stability analysis could also help in characterising MH and QSH states. It has been already shown [14, 15] that in RFX the reconstructed cylindrical symmetric equilibria lie near the marginal stability curve for internal resonant m=1 modes.

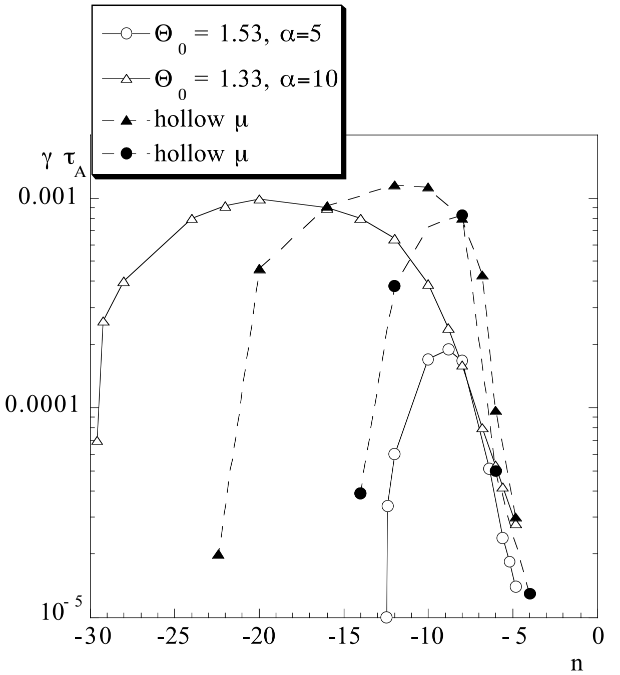

Fig. 6. Linear unstable spectra: monotonic μ profile (empty symbols), and hollow μ profile (full symbols).

As far as MH and QSH states are concerned, this fact is also confirmed, with the QSH states being generally located at relatively low α's and high Θ_0 in comparison with MH cases (this is true at least in a statistical sense). Therefore we compare the linear unstable spectra for equilibria of the MH and QSH type. The stability calculations are done considering two resistive walls surrounding the plasma as in [15] with values of the wall penetration times tuned on the RFX case. The linear results confirm quantitatively, as shown in Fig. 6, that the low α case corresponds to a narrower *n* spectrum (empty and full circles). Since there are uncertainties on the reconstructed equilibria, the linear spectrum is also analysed for neighbour equilibria of slightly hollow μ profiles (full symbols) with the same F and Θ values. Even considering these uncertainties, the QSH cases correspond to narrower spectra. It is also interesting to note, from Fig. 6, that the MH type spectrum could be narrowed by permitting some degree of hollowness of the equilibrium while the QSH could not, and the effect on the spectrum of hollowness is less strong in this last case. These features suggest, also in accordance with single helicity equilibrium calculations [9], that an MH state could evolve towards a QSH state, through the developing of a resonant mode which produces a hollow μ and narrows the unstable spectrum. The further increase in amplitude of this mode produces a saddle-node bifurcation [9] and a final monotonic and stable μ profile is achieved.

In conclusion, a statistical analysis of experimental data points out that F parameter and locking position are key ingredients to characterise narrow magnetic fluctuations spectra in RFX. The importance of the magnetic field profile is also confirmed by both theoretical and numerical studies. The relation between magnetic spectrum and field errors still requires more careful investigations from both the numerical and the experimental sides.

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