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Stationary Quasi Single Helicity States in RFX

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Recent experiments performed in the RFX Reversed Field Pinch (RFP) have demonstrated that the plasma can access a Quasi Single Helicity (QSH) state. In QSH regime the m=1 resistive mode toroidal spectrum, which usually includes a broad range of toroidal numbers n, shrinks around a dominant m=1,n=n_0 mode [1]. The standard condition with a broad n-spectrum is dubbed as Multiple Helicity (MH) state. When the plasma accesses a QSH state it makes a transition from a chaotic state, with stochastic magnetic field lines, to a more coherent and orderly state.

QSH states can be obtained either transiently or in a stationary fashion. Transient QSH states are the results of spontaneous transitions or of Pulsed Poloidal Current Drive (PPCD) and usually last for about 5 to 10 ms. With PPCD [2] a poloidal electric field is induced at the plasma edge in order to alleviate the resort to spontaneous dynamo. Under certain conditions, in particular a small magnetic field error level (of a few mT) and a relatively shallow reversal of the edge toroidal magnetic field, QSH states spontaneously reached early in the discharge can last until the end of the pulse, i.e. for tenths of ms, which corresponds to many energy confinement times ($\tau_E \approx 1$ ms).

In this paper we describe in particular the magnetic properties of experimental stationary QSH states.

The structure of MHD modes is quite different in QSH state with respect to MH state. As we shall see this difference concerns not only the m=1 modes, whose modification is the clearest magnetic signature of the transition, but also the m=0 modes which are originated by the nonlinear coupling between m=1 instabilities.

Fig.1 shows the time evolution of the m=1 n-modes from n=7 to n=12 for a QSH (top frame) and a MH (bottom frame) plasmas. In the QSH case it is evident the predominance of the (m=1,n=8) mode. On the contrary all the m=1 modes between n=7 and n=12 have comparable amplitude, within a factor of two, in the MH case.

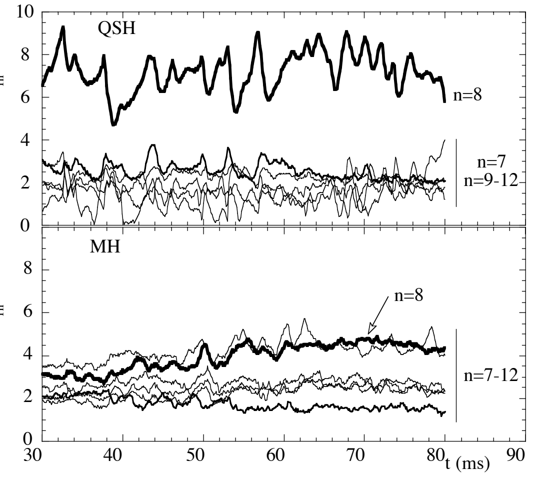

Fig.1

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The “width” of the m=1 spectrum can be measured by the spectral width w, which we define as $w=w_l+w_r$, where $w_l : \int_{n_{\max}-w_l}^{n_{\max}} b_{1n}^2 dn = \frac{1}{2}\int_{7}^{n_{\max}} b_{1n}^2$ and $w_r : \int_{n_{\max}}^{n_{\max}+w_r} b_{1n}^2 dn = \frac{1}{2}\int_{n_{\max}}^{20} b_{1n}^2$.

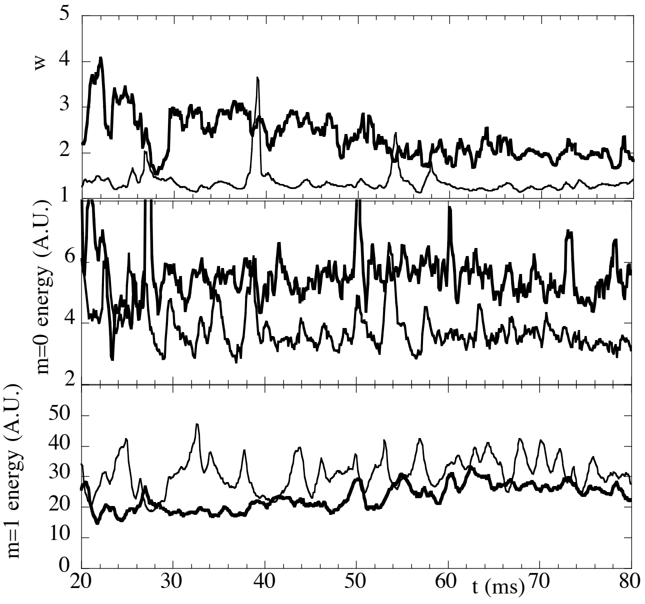

Fig.2

n_{max} is the dominant mode in the spectrum and b_{1n} is the amplitude of the (1, n) mode. Therefore the minimum value of w is 1, which corresponds to a pure SH spectrum. Fig. 2 (top frame) shows the time evolution of w for the two plasmas of Fig. 1.

The level of the edge toroidal field reversal plays a role in determining which mode emerges in a QSH state. A deeper reversal corresponds in fact to a lower on-axis safety factor; this can therefore eliminate the resonance of the lowest n numbers (n=7 with RFX aspect ratio). A relationship between $n_{\max}$ and the reversal parameter F, defined as $F = B_\varphi(a)/ < B_\varphi >$ is indeed experimentally observed, as shown in Fig. 3. This figure reports the percentiles of the values of F as a function of the measured dominant n mode for plasmas with $1 \le w \le 1.7$. For each n the bottom and the top of each box represents 5% and 95% of the data. The middle line represents the median value of the data, while the lower and upper dashed line represents 25% and 75% of the data. For deeper F plasmas the dominant n mode number increases. The predominance of an individual $(1,n_0)$ mode, measured at the plasma edge, finds a counterpart in the core, with the growth of an island detected with soft x-ray (SXR) tomography. A detailed description of the SXR emissivity profiles in QSH states can be found in [3]. The correlation between magnetic and SXR measurements is strong. In particular, there is good agreement between:

(i) the poloidal angle $\theta_{\rm SXR}$ where we find the SXR island,

(ii) the poloidal angle of the plasma column displacement, at the toroidal location where we perform SXR measurement, and

(iii) the poloidal phase angle $\theta_{\rm n}$ of the dominant $(1,n)$ mode. $\theta_{\rm dis}$ and $\theta_{\rm n}$ are reconstructed from magnetic measurements [3,4].

In Fig. 4 we show the time evolution of $\theta_{\rm n}$ (solid line) and of $\theta_{\rm SXR}$ (dotted line) for a stationary QSH discharge.

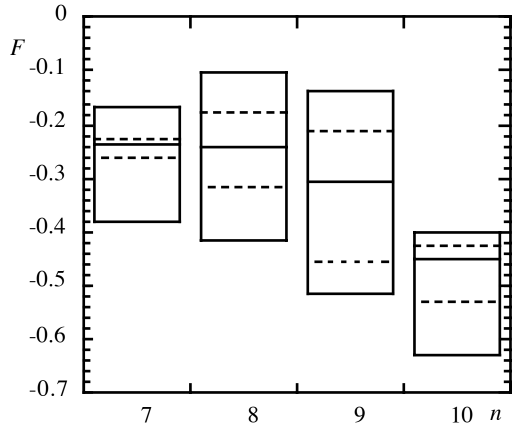

Fig.3

This helical shape has beneficial effect for the magnetic equilibrium. With a wide spectrum of modes we observe in fact that individual modes lock in phase among themselves and to the wall, producing a toroidally localised distortion of the equilibrium with severe consequences on the plasma-wall interaction [5]. Locked modes produce a distortion with a displacement of the plasma column up to ≈4 cm. On the contrary, the helical distortion associated to a QSH state is contained to less than 2 cm and, moreover, is not toroidally localised.

As previously mentioned the dominant *m*=1 mode in QSH states can range usually between *n*=7 and *n*=9. Sometime a transition between different dominant modes can happen in the same shot, as shown in Fig. 4, where we report the time evolution of the (1,7), (1,8) and (1,9) modes during one pulse. We can notice the interplay between the (1,7) and the (1,9) mode at *t*≈0.041 s. The two modes produce different islands, as shown in the SXR tomography inserts.

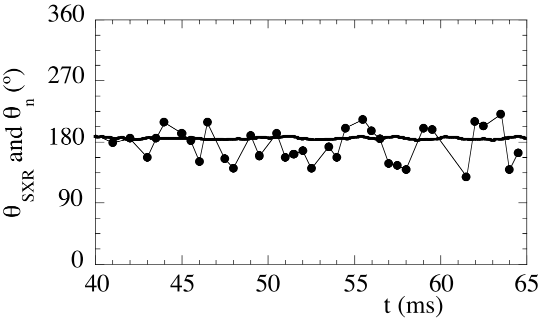

Fig.4

The role of *m*=0 modes in the RFP dynamics is also important. They typically have an amplitude which, within a factor of 2, is of the same order of magnitude of the *m*=1 modes and a spectrum which is relatively wide. Fig.2 shows the time evolution of the magnetic energy stored in the *m*=0 modes (middle frame) and of that stored in the *m*=1 modes (bottom frame). We note that the MH plasma is characterised by a relatively stronger role of the *m*=0 modes in comparison with the QSH plasma. This difference is even stronger considering that the energy of *m*=1 modes, which are the source of the *m*=0, is lower in the MH state. A particularly important role seems to be played by the (0,2) mode as shown in Fig.6, which displays the time averaged *n*-spectrum of the *m*=0 modes for the two discharges of Fig. 2. In the MH state a significant (0,2) mode amplitude is generated, which in the QSH is possibly lower due to the absence in the coupling process of the dominant *m*=1 modes. Further investigation on *m*=0 modes.is in progress.

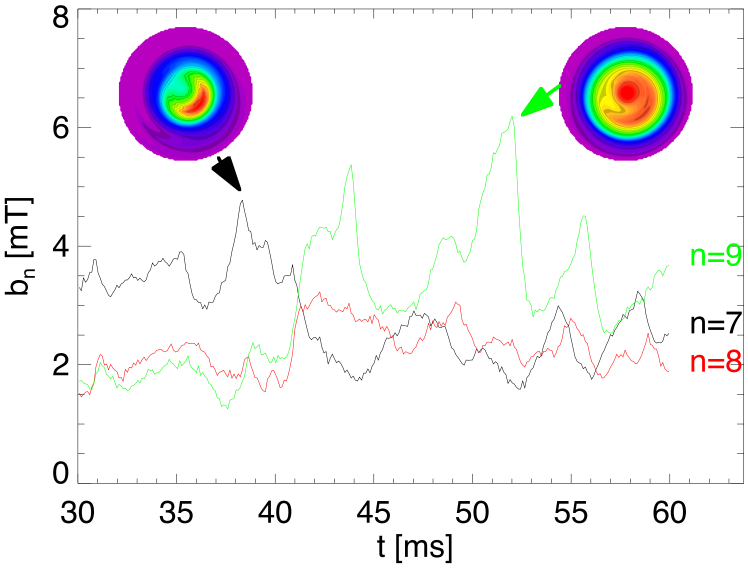

Fig.5

The *m*=0 modes experimental dynamics fits the results of 3D-MHD simulations, which have been done using the code described in [6] to study the difference between MH and QSH states. Fig. 7 show the time evolution of the energy stored in the *m*=0 and *m*=1 modes at the plasma edge (i.e. where experimental measurements are performed) for a MH and a QSH plasma. We see that while in the MH simulation the *m*=1 and *m*=0 amplitude are comparable within a factor of 3, in the QSH case the m=0 are lower in amplitude by more than a factor of 10. Stronger m=0 reduction is observed in the numerical QSH state since it is spectrally more "pure" than its experimental counterpart.

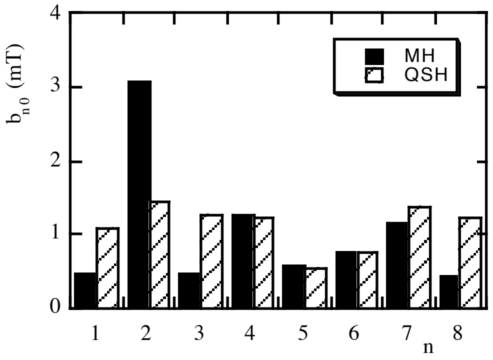

Fig.6

The magnetic properties of QSH states indicate that a lower degree of stochasticity might be present in the plasma core, with a reduction of the associated thermal losses. This is particularly evident when QSH are obtained transiently, i.e. during PPCD [7]. QSH characterise in fact those regimes, where up to now the best confinement performance has been obtained in RFX [7]. During PPCD we typically observe a reduction of the magnetic fluctuations level together with the growth of a m=1 island: the synergy between these two effects has therefore a strong impact on confinement. Moreover the best improvement of confinement is observed when the dominant mode is n=7, since a wider and more central plasma region corresponds to the generation of the helical magnetic flux surfaces. In this case the overall topology of the core plasma, as shown for example in Fig. 5, is observed to change and to assume a single helical magnetic axis. This result, experimentally observed, has also ben predicted by theoretical studies [8].When the dominant mode has higher n number the simultaneous presence of two "hot" cores is detected.

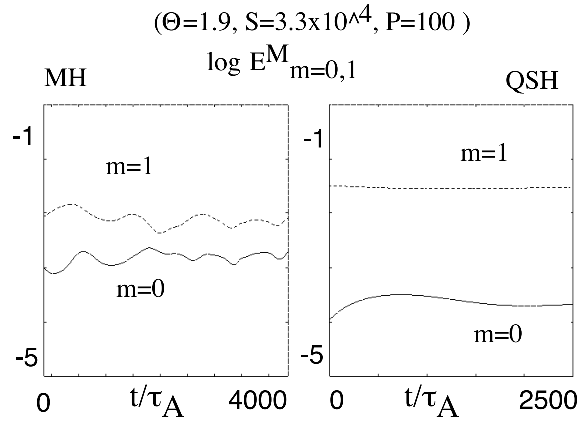

Fig.7

Stationary QSH do not show yet a comparable increase of the confinement. However , the achievement of QSH states lasting for the entire pulse duration with their corresponding coherent helical structure is by itself an important result in relation to the existence of helical non chaotic theoretical states. Furthermore their production in high current, high Lundquist number regimes, where the overall level of fluctuations is expected to be smaller, should benefit from the aforementioned synergy between fluctuation reduction and topology change.

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