*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.086 (2006)*

Spontaneous transition to quasi-single helicity states in RFX-mod and MST

P. Piovesan[1], A. Alfier[1], F. Bonomo[1], A. Cravotta[1], P. Franz[1], M. Gobbin[1], L. Marrelli[1], P. Martin[1], R. Pasqualotto[1], G. Spizzo[1], and the RFX-mod team, B.E. Chapman[2], D. Craig[2,3], S.C. Prager[2,3], J.S. Sarff[2]

[1] *Consorzio RFX, Euratom-ENEA Association, Padova, Italy*

[2] *Department of Physics, University of Wisconsin, Madison, WI, USA*

[3] *NSF Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas*

We present a study on the spontaneous transition to quasi-single helicity (QSH) in the European RFX-mod reversed-field pinch (RFP) and in the American MST. The optimization of QSH, where self-organization provides plasmas with reduced magnetic chaos, is one of the crucial issues to asses the fusion relevance of the RFP. In the last two years a variety of scenarios has been investigated in the rebuilt RFX-mod device, with and without active control of magnetic fluctuations, and up to plasma currents of 1MA [S. Ortolani, *Active mode control on RFX-mod*, invited oral, this conference]. A strong effort has been also spent to study QSH in MST [P. Franz, *et al.*, Phys. Plasmas **13**, 012510 (2006)]. Here a comparison will be made of the recent results obtained in these two machines.

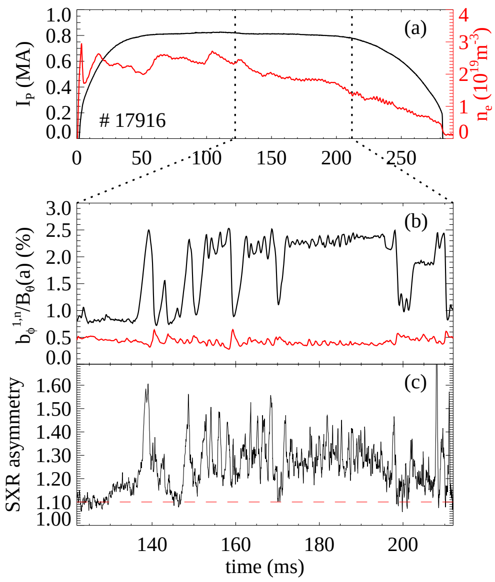

Figure 1: Virtual shell RFX-mod discharge with a quasi-stationary QSH.

In the initial operation of RFX-mod, mainly at low current $< 0.6MA$ and with no feedback control, long-lasting QSH states were reproducibly obtained, with characteristics similar to those previously observed in RFX [D.F. Escande, *et al.*, Phys. Rev. Lett. **85**, 3169 (2000)]. This was important to confirm the robustness and reproducibility of such states. Here we will compare these experiments with more advanced operations, both in RFX-mod and MST.

During the last year, we started using the new RFX-mod magnetic feedback system. This state-of-the-art tool consists of 192 active saddle coils providing a full coverage of the torus surface. A flexible control system permits one to explore a variety of schemes for magnetic feedback control. This allowed the exploration of completely new regimes in RFX-mod, characterized by a much better plasma control and reduced plasma-wall interaction. RFX-mod could thus access 1*MA* currents for longer periods than in the past, without excessive wall load.

The first feedback scheme investigated was the *virtual shell* (VS), in which each coil cancels the radial component of the magnetic field measured by its sensor. This realizes artificially an ideal wall similar to that obtained in MST with a thick Al shell. VS operation was proved to reduce significantly all the mode amplitudes. Though its effect extends up to the plasma core, it does not prevent the plasma to access QSH spectra. On the contrary even purer QSH spectra are associated with VS.

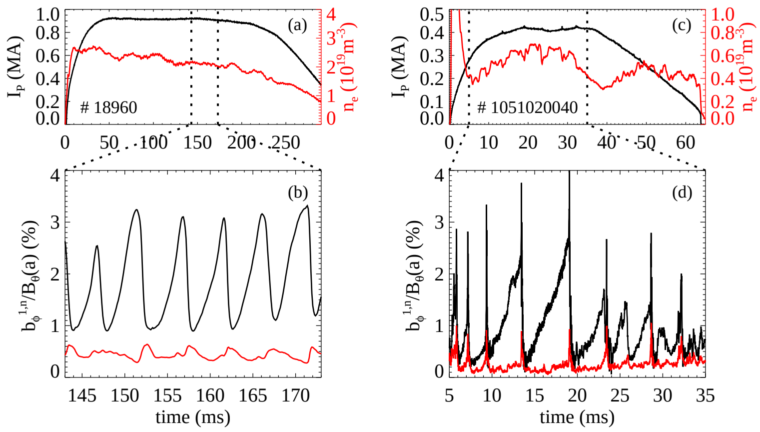

Figure 2: Oscillatory QSH in (a)-(b) RFX-mod and (c)-(d) MST.

Fig. 1 reports an example of a spontaneous transition to a quasi-stationary QSH in a VS discharge. The dominant mode is typically the innermost resonant one, $m = 1, n = -7$. The red line represents the normalized secondary mode amplitude, $m = 1, n = -8$ to -15. After a first oscillatory phase, the plasma settles down in a QSH state for about 30*ms*. The fast back-transitions to MH are not fully understood at the moment. They could be related to the intrinsic nonlinear plasma dynamics, but also to more technical reasons, such as a non perfect optimization of the error field control or of the VS algorithms. The optimization of these discharges, to obtain fully stationary QSH states, constitutes a very important challenge.

A hot helical core is present during quasi-stationary QSH states for a period much longer than the global energy confinement time $\tau_E \sim 0.5ms$. This good confinement region corresponds to the dominant mode helical flux surfaces, as observed by soft x-ray tomography and Thomson scattering. Fig. 1-c shows the ratio of the soft x-ray brightness from two opposite lines of sight, which represents the asymmetry of the brightness profile. A ratio of about 1.1 is due to the Shafranov shift, while higher ratios are associated with a hot helical core, as confirmed also by tomographic reconstructions. The profile asymmetry has very fast oscillations correlated with the mode amplitude at the beginning of the QSH transition, and reaches a more stationary value of about 1.3 during the long QSH period indicating the presence of a more stationary hot island.

In standard MST discharges QSH has typically a sawtooth dynamics. At the moment long-lasting QSH states have been observed in MST only under particular conditions, such as in pulsed poloidal current drive and $F = 0$ discharges [L. Marrelli, *et al.*, Phys. Plasmas **12**, 030701

(2005)]. A sawtooth dynamics similar to MST has been recently observed for the first time also in RFX-mod during VS operation. Fig. 2 shows such an example compared with a standard MST shot. These two shots have different plasma parameters, e.g. plasma current and density, but the mode dynamics is similar. The dominant mode is in both cases the innermost resonant one ($m = 1, n = -6$ in MST and $m = 1, n = -7$ in RFX-mod) and the average sawtooth period is comparable, $\tau_{saw} \simeq 5ms$. We also note some differences. The magnetic signals are smoother in RFX-mod than in MST. This is due to the fact that in RFX-mod the pick-up coils are placed outside the conducting shell, which has the effect to low-pass filter the signals, while in MST they are inside. Another difference is the absolute value of the mode amplitudes, which is lower in MST. This is likely due to the faster natural mode rotation in MST ($f \simeq 20kHz$) than in RFX-mod ($f \simeq 3Hz$), which can have a larger stabilizing effect. Other systematic differences could be introduced by the different radial position of the coils, by toroidal effects, or by a different Lundquist number, but they have not been accounted for accurately at the moment.

Studying the differences between long-lasting and intermittent QSH states is important to determine under which conditions a stationary QSH state can be reproducibly realized. To this purpose a database including all the VS discharges performed in the last year RFX-mod operation has been built. A large parameter range could be explored. The plasma current varies from 0.4 to $0.9MA$, density from 1 to $4 \times 10^{19} m^{-3}$, and the reversal parameter $F = B_\phi(a)/\langle B_\phi \rangle$ from -0.25 to -0.05. For each discharge, QSH periods are defined by the condition $N_S = \left[\sum_n (\tilde{b}^2_{1,n} / \sum_{n'} \tilde{b}^2_{1,n'})^2\right]^{-1} < 3$, where the spectral spread index $N_S = 1$ for a pure SH state and $N_S > 1$ when secondary modes are also present. We then defined for each discharge the *QSH probability* as the ratio between the sum of the QSH periods and the flat-top duration, and the *QSH duration* as its longest QSH period. We found that the strongest dependence of these two quantities in the database is on the plasma current.

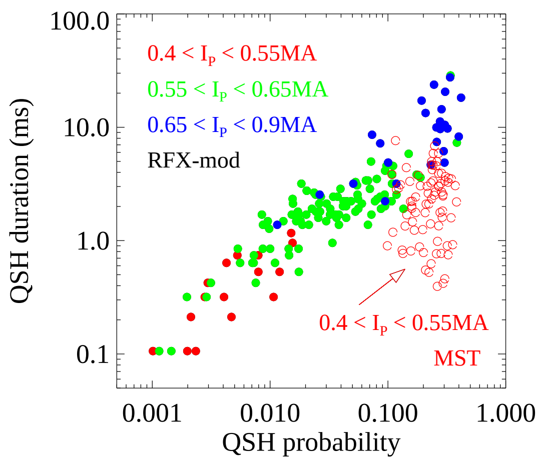

Figure 3: QSH duration *vs* probability for RFX-mod discharges at different plasma currents and for MST discharges.

Fig. 3 reports QSH duration as a function of QSH probability for three current ranges. The longest QSH periods are found in discharges with the highest QSH probability and the highest plasma current. An ensemble of standard MST discharges with $0.4 < I_P < 0.55MA$, the highest currents possible at the moment in MST, have been also analyzed. These discharges have a higher QSH duration and probability with respect to the RFX-mod discharges at the same current. This could be due to the lower MST aspect ratio, as predicted by MHD simulations. This result suggests that exploring even higher current regimes in MST could be beneficial for QSH states. A positive trend of the QSH transition probability with plasma current had been already observed in RFX [D. Terranova, *et al.*, Plasma Phys. Controll. Fusion **42**, 843 (2000)], MST, and TPE-RX [P. Piovesan, *et al.*, Phys. Plasmas **11**, 151 (2004)]. The present results not only confirm those findings, but extend them to a much broader parameter range. If high plasma current promotes the transition to long-lasting QSH states, a very promising perspective opens for the high-current $I_P > 1MA$ scenarios planned to be explored by RFX-mod in the near future.

A robust result of present and previous studies [L. Marrelli, *et al.*, Phys. Plasmas **12**, 030701 (2005); P. Piovesan, *et al.*, Phys. Plasmas **11**, 151 (2004)] is that a selection process among different modes in the spectrum takes place at the transition to QSH. Not only during QSH a dominant mode emerges from a bath of other modes, but a decrease in these secondary mode amplitude is also observed. This is shown in Fig. 4, which reports the dominant and secondary mode amplitudes, normalized to the equilibrium poloidal magnetic field, as a function of the spectral spread index N_S for two databases of RFX-mod discharges without and with VS. The VS database is the same as in Fig. 3, while the standard one only includes discharges with plasma current $0.4-0.6MA$, since VS makes high-current operation safer. The VS effect is also clear from Fig. 4. In fact not only the mode amplitude decreases with VS, but also N_S reaches values much closer to 1. This implies that purer QSH spectra can be obtained with VS. The same analysis has been made also for a database of standard MST discharges with $I_P \simeq 0.4MA$, which are indicated in blue in the figure. The same positive trend is also present in this device, where the mode amplitudes seem to reach even lower values. As commented above, this could be due to the fast mode rotation present in these discharges, which tends to further stabilize the modes.

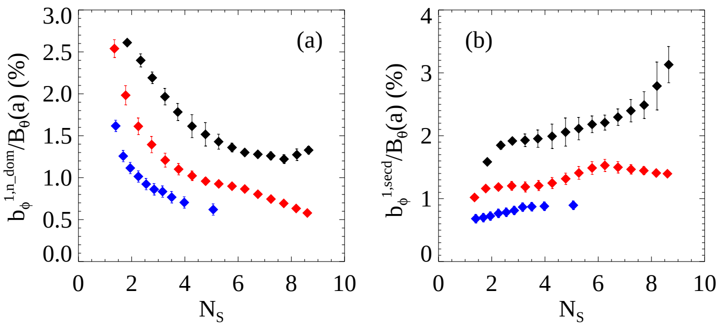

Figure 4: Dependence of the $m = 1$ dominant and secondary mode amplitudes on N_S in RFX-mod shots without (black) and with VS (red), and in MST shots (blue).

Acknowledgement. This work was supported by the European Communities under the contract of Association between EURATOM/ENEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.