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Magnetic order improvement through high current and MHD feedback control in RFX-mod

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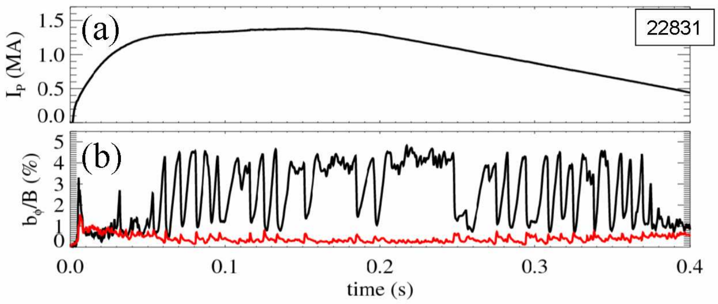

Figure 1. (a) Plasma current and (c) dominant and secondary mode amplitudes in a high-current RFX-mod discharge.

The RFX-mod device [1], based at the Consorzio RFX, Padua, Italy, has recently reached high plasma currents up to 1.5MA for the first time in a reversed-field pinch (RFP). This was made possible by exploiting a new system for magnetic feedback control, which is constituted by 192 saddle coils fully covering the toroidal surface and by 192 respective sensor coils measuring the magnetic field radial component at the same positions [2]. Each saddle coil is independently driven by a programmable digital controller. Various feedback schemes have been tested under different plasma conditions. The two control schemes most relevant to the experiments analyzed in this paper are the so called Virtual Shell (VS), in which each coil cancels the radial magnetic flux linked by it, and the Clean Mode Control (CMC). In CMC the poloidal (m=0,1) and toroidal (n=-23 to 23, here negative n refer to modes resonant inside the reversal surface) mode number spectrum of the radial magnetic field is computed by a real-time fast Fourier transform and the feedback algorithm is applied to each harmonic in the Fourier space. It is thus possible with CMC to limit the control to a subset of modes, e.g. to the most unstable ones, and to compensate for the different wall-penetration time of each mode. Moreover the CMC algorithm computes in real-time the sideband harmonics entering the measurements due to the sensor coil geometry and “cleans” them from this spurious contribution [3]. Up to now the CMC has given the best results in terms of radial magnetic field control at the wall and reduction of the plasma-wall interaction. Thanks to CMC high-current regimes up to 1.5MA could be explored.

The high-current experiments recently performed in RFX-mod are raising new physics issues and are opening routes for magnetic order improvement. Among these new findings is the observation of robust transitions to helical states, which are main subject of this work. These correspond to a RFP regime predicted by MHD computations [4] and recently observed in several RFPs, though at lower currents [5]. Such regime is called quasi-single helicity (QSH), since a single mode dominates the magnetic spectrum, but secondary modes at lower amplitude still exist and back-transitions to turbulent multi-helical states are observed.

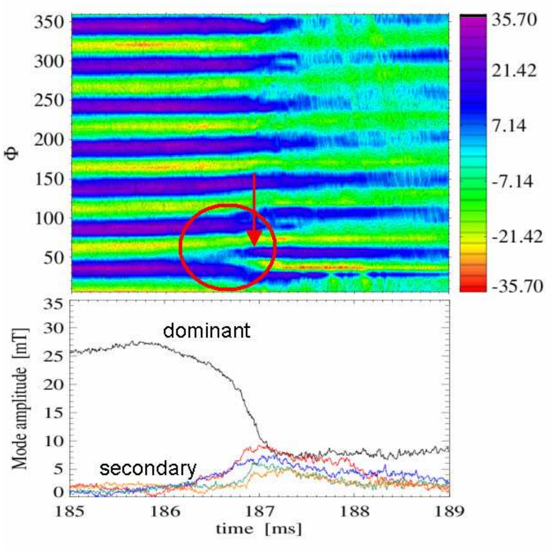

Figure 2. a) Contour plot of the time evolution of magnetic b_ϕ signals in 48 toroidal positions (color scale in mT; arrow indicates the formation of a poloidal current sheet); b) time evolution of the m=1 mode amplitudes.

The new features of the QSH states at high current is their long duration, exceeding several energy confinement times, the strong reduction of the secondary mode amplitude, and a sizable effect on the thermal energy content. This is due both to the emergence of large plasma volumes with strongly reduced thermal conductivity, associated with the dominant mode helical flux surfaces, but also to an overall magnetic order improvement due to a strong decrease of the secondary mode amplitudes, reaching record low values of about $b_\phi/B(a) \sim 0.1\%$.

Fig. 1-(a) shows the current waveform of a typical high current discharge. Several transitions to QSH can be seen in Fig. 1-(b), which reports the dominant mode (m=1, n=-7) amplitude and the average amplitude of the secondary modes (m=1, n from -8 to -16). QSH periods lasting up to 50ms are observed, which correspond to more than 10 energy confinement times. Back-transitions to multi-helical states are also present, which are due very likely to the nonlinear interaction with the secondary modes and with residual error-fields not completely compensated for. The optimization of the error field control is a matter of active research and could very likely contribute to improve the QSH performance.

The initial phase of the back-transitions to multi-helical states is not a global phenomenon, but it is characterised by the fast growth of a toroidally localized magnetic perturbation, with the rest of the (1,-7) helical structure remaining almost unaffected. This can be clearly seen in in Fig. 2-(a), where a contour plot of the m=1 b_ϕ component measured in 48 toroidal positions as a function of time is shown. These data are collected by a highly-resolved system of magnetic coils located inside the vacuum chamber. The growth of the localised perturbation, which triggers the crash of the (1, -7) dominant mode, is followed by reconnection of magnetic field lines, recognised by the formation at the same toroidal position of a poloidal current sheet, a phenomenon strongly resembling the discrete relaxation events observed in RFX-mod [6].

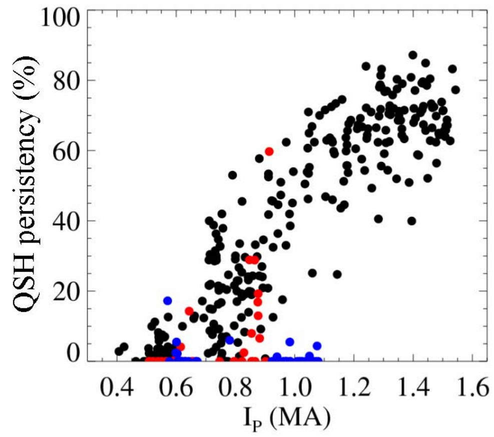

Figure 3. QSH persistency as a function of plasma current for CMC (black), VS (red), and VS+rotating perturbation (blue) discharges.

The QSH persistency, defined as the ratio among the total time in which the plasma stays in QSH and the flattop duration, is observed to strongly increase with plasma current, as shown in Fig. 3. This quantity reaches values of about 85% at the highest current levels achieved. Such a strong, spontaneous tendency to produce robust QSH states by increasing the current may be explained by analyzing the mode dynamics as a function of non-dimensional parameters such as the Lundquist number, $S = \tau_R/\tau_A$. In fact, the electron temperature increases with current in RFX-mod and hence S increases as well. Higher currents mean higher S values, or, in other terms, less-collisional plasmas.

Fig. 4 shows the dependence of the dominant and the secondary mode amplitudes as a function of S. It is interesting to note the opposite behaviour of these modes. The secondary mode amplitude shows a clear power low decay as a function of S, which has been already observed in several previous experiments and numerical simulations, though in a less extended S range. The new result is the behaviour of the dominant mode, which first increases with S and then tends to saturate (or increases with a much lower slope) at a value of about 5%. This may indicate the reaching of a helical equilibrium independent on the Lundquist number, which is consistent with 3D visco-resistive nonlinear MHD simulations, where a similar saturation is observed in pure single helicity states. Given the above dependence of the mode amplitudes on S, it may be concluded that the helical state is progressively less perturbed by the secondary modes as S increases, which may explain the longer QSH persistency at high current.

The QSH transition at high current has also positive effects on the plasma thermal content. Figs. 4-(c) and (d) show two typical electron temperature profiles measured by

Thomson scattering during QSH at high current. In both cases, regions of increased electron temperature are observed, which correspond to the helical flux surfaces of the dominant mode. The good confinement region in the profile of Fig. 4-(d) is much broader than in the case of Fig. 4-(c), which is more similar to previous results obtained in other RFPs at lower current. This can be explained in terms of the dominant and secondary mode amplitudes at these times, which are marked with red and green circles in Figs. 4-(a) and (b). The broader profile in Fig. 4-(d) corresponds to a purer QSH at a higher S, with larger dominant mode amplitude and record low level of secondary modes.

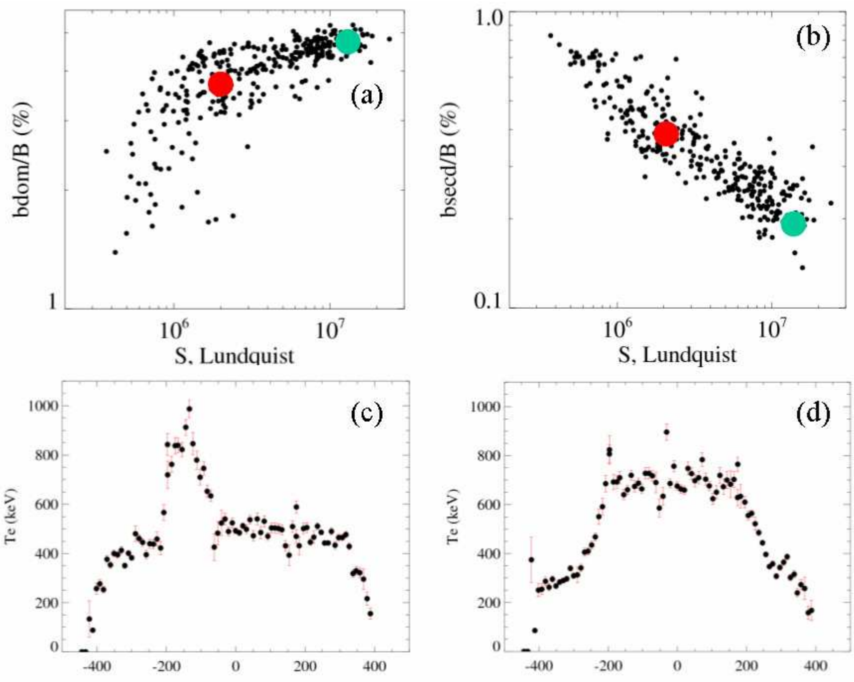

Figure 4. (a) Dominant and (b) secondary mode amplitude *vs* the Lundquist number for CMC plasmas and (c)-(d) electron temperature profiles corresponding to the discharges indicated with red (profile (c)) and green (profile (d)) circles in (a) and (b).

In the high-current experiments recently performed in RFX-mod, thanks to advanced MHD feedback control schemes, new observations on the transition to helical states with improved magnetic order have been made, which significantly extend the knowledge on QSH obtained with previous lower current experiments. The QSH pureness is improved by increasing S. The plasma spontaneously accesses a state with improved magnetic order characterized by long lasting QSH states, more resilient to external perturbations caused by secondary modes or error fields, and characterized by broad regions of good confinement.

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