Scaling properties of Quasi-Single Helicity states in RFX-mod

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Quasi-Single Helicity (QSH) states are spontaneous or induced conditions achieved in high current reversed field pinch (RFP) discharges, characterized by the fact that one of the intrinsic MHD tearing modes dominates the spectrum while all the others are reduced in amplitude [1,2,3]. Thus, these states offer the potential of reduced magnetic chaos and enhanced confinement. QSH states are presently obtained intermittently, with back-transitions associated to the occurrence of a Discrete Relaxation Event (DRE).

In order to illustrate how the onset and back-transition of QSH states appear, waveforms recorded during the flat-top phase of a 1.5 MA discharge in the RFX-mod device are shown in Fig.1. From top to bottom, one can see the plasma current, the pinch parameter Θ (defined as $\Theta = B_\theta(a)/\langle B_\phi \rangle$, where B_θ and B_ϕ are the poloidal and toroidal magnetic field components, and <...> designates an average over the poloidal cross-section), and the amplitudes of the m=1 dominant and secondary modes. The dominant mode is the innermost resonant one (m=1/n=7 in RFX-mod), whereas the amplitude of the secondary modes is computed as the sum of the squared amplitudes of the modes with m=1 and n between 8 and 15, which are the most relevant of the spectrum. It is possible to observe the periodic transitions to conditions where the dominant mode is much larger than the secondary ones (QSH states) and the back-transitions to conditions where all the modes have similar

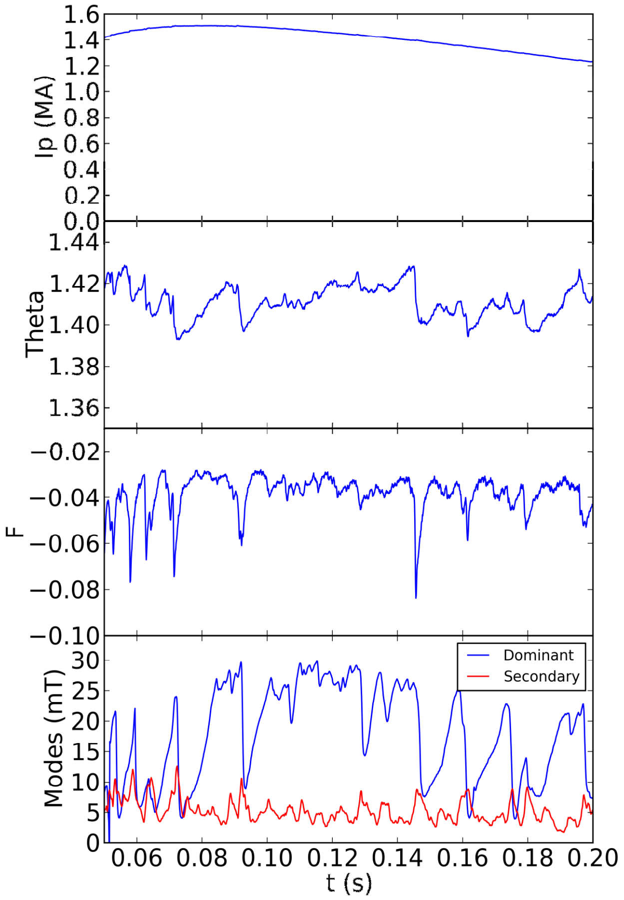

Figure 1: Example of high current discharge with intermittent transitions to QSH-

amplitudes (Multiple Helicity, MH states). It is important to observe that during the QSH phases the pinch parameter is monotonically increasing, indicating a systematic tendency of the current density profile to peak towards the center of the plasma column. This is not unexpected, as the transition to the QSH condition is accompanied by the onset of an internal transport barrier, with the consequent formation of a hotter core region. Thus, one would expect that the reduced central resistivity leads to a peaked current channel, which will form on a time scale dictated by the resistive diffusion time.

The fact that the QSH equilibrium is not stationary in time, but evolves on the resistive time scale, leads to the hypothesis that the back-transition to MH is due to the current density profile evolving to an unstable condition. Indeed, the duration of the QSH phases has been previously shown to be related to either the plasma current or the Lundquist number S (the two are strongly correlated, since raising the current the ohmic input power is increased, leading to higher electron temperature). In particular, the persistence of the QSH, defined as the fraction of the flat-top duration spent in QSH condition, was found to rise with S, hinting to the possibility of reaching 100%, i.e. a stationary QSH, at very high plasma current [3].

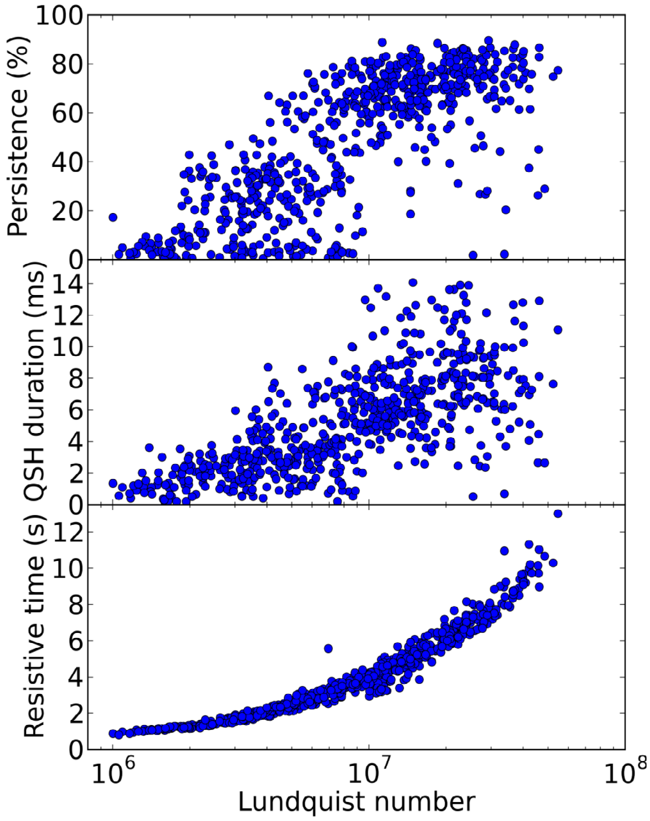

Figure 2: Scaling with Lundquist number of QSH persistence, average QSH duration and resistive diffusion time.

A re-evaluation of this trend, including recent experiments at plasma current of 2 MA (design value of the RFX-mod device) yields a different picture: as shown in Fig.2a, the persistence appears to saturate at a value of around 90%, and no stationary QSH is ever achieved. In order to better understand this behaviour, Fig.2b shows the average duration of QSH phases in the flat-top of each discharge as a function of the Lundquist number. This is found to grow without bounds with S, but has relatively small values, much lower than the discharge duration even at the highest S. Furthermore, as shown in Fig.2c, the resistive diffusion time displays a similar trend, thus confirming the idea that a resistive evolution of the QSH equilibrium towards instability is at the basis of the back-transition.

A detailed analysis of the back-transition to MH has been performed applying the conditional averaging technique to a database of 413 events occurring in a set of 1.5 MA discharges, using the back-transition as condition. The outcome is displayed in Fig.3, where the average plasma current, reversal parameter F ($F = B_\phi(a)/\langle B_\phi \rangle$), B_ϕ at the wall and average B_ϕ are displayed, together with the spatial pattern of the m = 0 (top) and m = 1 (bottom) magnetic field perturbations as given by sums and differences of the signals measured by two in-vessel Mirnov coil toroidal arrays. It can be seen that the back-transition is accompanied by a slight peak on the plasma current, crash in the reversal parameter and in the edge toroidal field and by a sudden increase of the toroidal magnetic field, all features typical of the Discrete Relaxation Events (DRE) well known in RFP plasmas. Furthermore, a toroidally localized m=0 structure is formed (third panel), which is associated to the current sheet driven by the magnetic field reconnection event [4]. The most striking observation is that the n = 7 pattern associated to the m = 1 dominant mode (fourth panel) is not lost at the back-transition; rather, the m=0 current sheet elicits, through the toroidal coupling, the formation of a further peak in the m = 1 pattern. This peak ruins the n = 7 symmetry, and gives rise to a much wider Fourier spectrum. Thus, the MH condition at high current is not fully disordered, but is still reminiscent of the n = 7 structure. It is also of interest the fact that after the back-transition the n = 7 pattern shifts toroidally until one of its peaks merges with

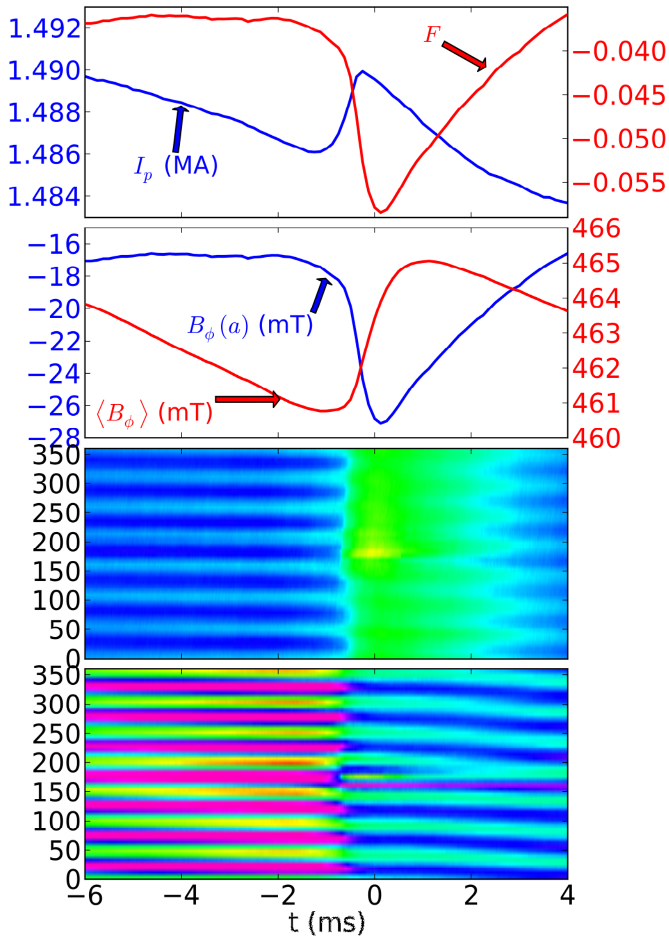

Figure 3: Conditional averages of (from topo to bottom): plasma current and F; average toroidal field and toroidal field at the edge; m=0 magnetic field pattern; m=1 magnetic field pattern.

the spurious peak induced by the reconnection event, and this leads to the rebirth of the QSH condition.

The QSH states are preferentially obtained at high plasma current and shallow toroidal field reversal. The reason can be understood by looking at fig.4, which shows a typical high current discharge (in blue), a discharge with much lower current and similar F (in red) and a discharge with deeper F (in green). It can be seen how at reduced current and deeper F the frequency of the DRE, observed as negative spikes on the F signal, is much higher. Since the DRE induce the back-transition to MH, this justifies the preference for the high current, shallow F condition.

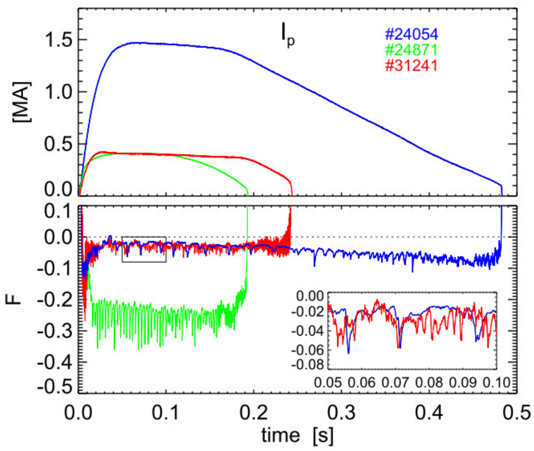

Figure 4: Plasma current and F waveforms for three different discharges.

As already mentioned, the formation of the high temperature core in QSH states is related to the onset of internal transport barriers. This is particularly relevant in the QSH flavour which has been dubbed Single Helical Axis (SHAx) state, where the X-point of the magnetic island formed by the dominant mode annihilates with the discharge magnetic axis, and the island O-point emerges as the only remaining critical point, becoming the helical magnetic axis of the discharge [2]. The physical origin of these transport barriers has been investigated in several papers [5,6]. A crucial result is that their strength, defined as the average T_e gradient in the barrier region, is found to scale with the normalized amplitude of the secondary modes, as shown in Fig.5. This suggests that even in the best cases the residual chaos induced by these modes is still the dominant factor ruling the energy transport.

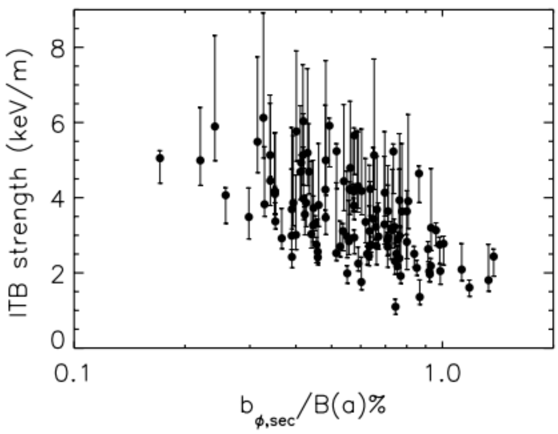

Figure 5: Scaling of thermal barrier strength with secondary mode amplitude.

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