Dynamics of helical states in MST

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In the Reversed Field Pinch (RFP) configuration the Quasi Single Helicity (QSH) [1] state is of great interest due to its tendency to form at high Lundquist number. This state is characterized by the presence of a dominant tearing mode, usually the innermost resonant one, and by a three-dimensional "bean-like" structure. The QSH state is in contrast to the Multiple Helicity (MH) state characterized by a broad mode spectrum and an axisymmetric structure. The transition to a QSH state is common across RFP experiments [2,3,4] and its appearance and persistence are subject to sufficiently large plasma current I_p, at a Lundquist number $S > 6x10^5$ [5].

The temporal dynamics of the QSH state and its dependence on I_p have been captured in a predator-prey model [6]. In this model the helical structure is not an equilibrium but is considered as a coherent fluctuation structure that dominates other fluctuations due to the suppression of nonlinear coupling through shears in the magnetic and flow fields of the dominant structure [7]. If the dominant fluctuation is linearly unstable, then the suppression of the nonlinear coupling allows the dominant mode energy to rise, enhancing the amplitude of the dominant mode and decreasing the others. A minimal description of the suppression of mode coupling is constructed in reduced MHD assuming a turbulence closure. The governing equations are $d\omega/dt + \nabla_{\|} j = 0$ and $\partial\psi/\partial t + \nabla_{\|}\phi = 0$ where $\omega = \nabla_{\perp}^2\phi$ is the vorticity and $j = \nabla_{\perp}^2\psi$ the current, and the process is driven by the shearing rate $\Omega' = (im/r)\, Max\left[\partial\phi/\partial r|_{n_{min}}, \partial\psi/\partial r|_{n_{min}}\right]$, where m is the poloidal mode number and n_{min} the toroidal mode number of the innermost resonant tearing mode. The shear effect arises when the shear layer width $\Delta r = (\phi/r\Omega')^{1/2}$ is smaller than the magnetic island width $\omega_0 = \left(rqB_r^{tearing}/mq'B_\theta^{eq}\right)^{1/2}$. Including the shearing rate in the above MHD description, adding a minimal description of the nonlinear coupling, and assuming a slow time scale evolution of the dominant mode compared with the secondary modes, it is possible write the predator-pray model as

$$\frac{\partial D}{\partial t} = Q_D - \frac{(\sigma_1 S^2 + \sigma_2 SD)}{1+\epsilon(D/D_0)^{1/2}} - \alpha_D D; \qquad \frac{\partial S}{\partial t} = Q_S + \frac{(\sigma_1' DS + \sigma_2' D^2)}{1+\epsilon(D/D_0)^{1/2}} - \beta S^2 - \alpha_S S$$

where $D = |\psi_{n_{min}}|^2$ and $S = |\psi_{n>n_{min}}|^2$ are the dominant and secondary mode energies, Q_D and Q_S are driving terms with $Q_D > Q_S$ since the dominant mode is the primary unstable mode, α represents dissipation ($\alpha_D<\alpha_S$), and βS^2 represents the cascade of energy from larger scale to small scale among the secondary modes. The signs of the coupling terms are in agreement with the tearing mode cascade of energy from the dominant to the secondary modes. The $\epsilon(D/D_0)^{1/2}$ term is the suppression factor, with D_0 the dominant amplitude squared at the suppression threshold ($\omega_0/\Delta r = 1$) and ϵ is proportional to I_p.

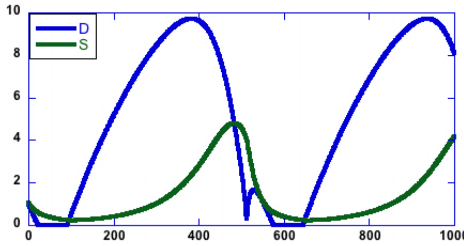

Figure 1: temporal behaviour of a limit cycle state.

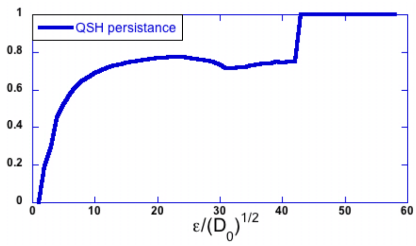

Figure 2: percent of time in QSH state as function of the shearing coefficient

If $\sigma_2 = \sigma_1' = 0$ the model leads to the limit cycle solution showed in Figure 1, where the blue trace is D and the green S. The time that the system spends in a QSH state (D>>S) scales with the suppression factor, as can be seen in Figure 2 providing a prediction consistent with the observed increase in persistence of the QSH with plasma current [6].

In the Madison Symmetric Torus (MST) the transition from the MH to the QSH is accompanied by wall locking [8]. MST has a shell surrounding the plasma with a cut (called poloidal gap) to allow the flux to enter the plasma. The poloidal gap is also the main source of static error field, which is minimized through active feedback. Other sources of static error fields are diagnostic portholes. The plasma tends to lock in alignment with the largest portholes, but this is not a favourable position for the diagnostics. To control the plasma locking position, a resonant m=1 magnetic perturbation with specified phase is applied through the active feedback system. Figure 3 shows the level of control afforded by this technique.

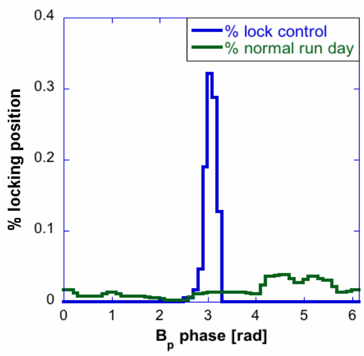

Figure 3: normalized histogram of the locking position with and without applied error field

This locking control allows the construction of large ensemble of pulses with the magnetic structure aligned to the Thomson Scattering (TS) [9] and FIR Interferometry systems [10]. The n_e and T_e radial profiles are mapped to helical flux coordinates ρ using the NCT-SHEq code [11]. Three different regimes are observed during the growth, saturation and crash of QSH states associated with the amplitude of the *m=1, n=5* magnetic field perturbation. It is shown in Figure 4. The topmost plot is the time trace of the amplitude of the 4 innermost tearing modes amplitude. The second plot represents the time evolution of the T_e profile obtained from TS measurements every 2/3 ms. The third plot is the time evolution of the n_e profile obtained by inverting the interferometry measurements on the helical flux surfaces. When the mode is growing (from 20ms to 23.5ms) a thermal structure forms along the helical axis. During the flat-top phase (from 23.5ms to 28.5ms) the temperature structure becomes intermittent and a density structure appears. At the crash (between 28.5 ms to 29 ms) the density structure disappears and the temperature profile shows evidence of a heat pulse.

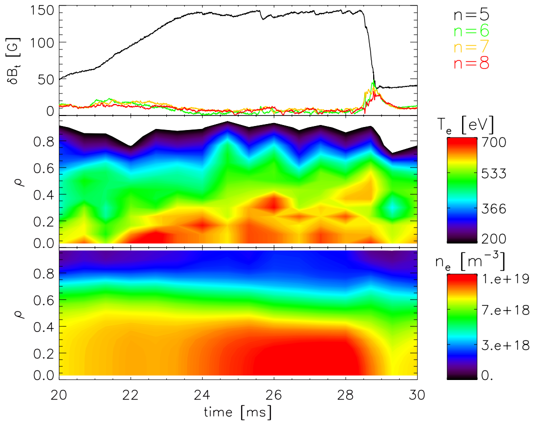

Figure 4: from the top, time evolution of the innermost tearing modes amplitude; of the T_e as function of flux surfaces; of n_e as function of flux surfaces

The time evolution of the electron pressure profile created from n_e and T_e recontructions are compared with profiles of soft X-ray emission reconstructed on the NCT-SHEq equilibrium in Figure 5, highlighting good agreement.

Different mechanisms related to the crash phase of the QSH structure are tested by quantifying the behaviour of the electron pressure during the flat-top phase of the QSH.

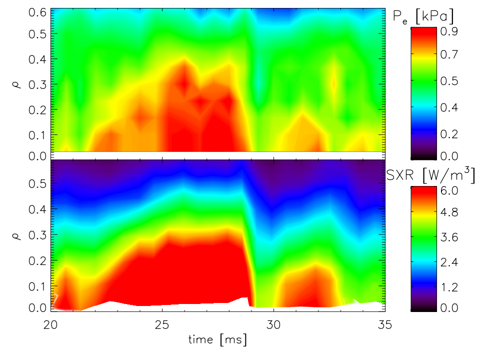

Figure 5: comparison between the electron pressure and SXR brightness time evolution as function of the flux surfaces

The radial profile of β_e has been reconstructed from the electron pressure profile and the magnetic field profiles coming from the NCT-SHEq reconstructions. In Figure 6 the top plot shows the average value of β_e in black and the average value of $\nabla\beta_e/\beta_e$ in red. The time evolution of the electron presure profile is shown below. Neither β_e nor $\nabla\beta_e/\beta_e$ show limiting behavior in the dataset.

The second pursued way is the non-linear coupling of the tearing modes. One of the causes of momentum transport during normal plasma operation is through nonlinear mode coupling, when two m=1 modes are coupled through a resonant m=0. To maximize the probability of transition to a QSH state, the main plasma parameters are $I_p \geq 400kA$, $n_e \approx 0.5{\times}10^{19}m^{-3}$ and $F = 0$. The m=0 mode is excluded from the plasma, so the nonlinear interaction could be through the m=2 modes. In the middle plot of Figure 6 the nonlinear mode triple products between n=5, 6 and 11 are shown in black and the amplitude of the innermost resonant tearing mode amplitude in green. Also in this case there is not any clear relation between the QSH dynamics and the nonlinear mode triple products. This suggest that some other mechanism is responsible for the dithering between QSH and multihelicity states.

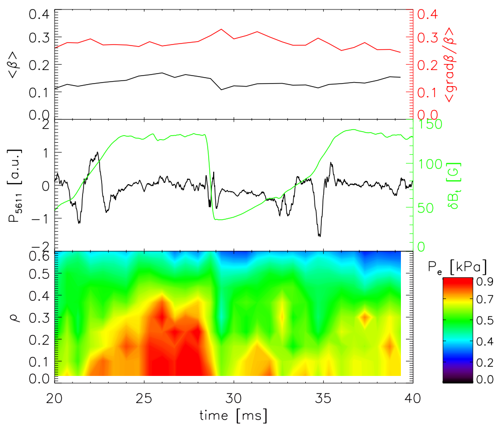

Figure 6: time evolution of $<\boldsymbol{\beta}>$ and $<\nabla\boldsymbol{\beta}/\boldsymbol{\beta}>$ (top); of the correlated triple product and the n=5 mode amplitude (middle); of P_e radial profile (bottom)

Another reconstruction of the equilibrium and of the radial profile of several quantities is performed using V3FIT coupled with VMEC [12], a three dimensional code that assumes the flux surfaces as isobars and then reconstructs them in order to better fit all the desired diagnostics. The reconstruction of the magnetic flux surfaces in a fix boundary simulation is in good agreement with the one provided from NCT-SHEq.

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