

## Spontaneous QSH in the EXTRAP T2R reversed-field pinch

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In recent years, good progress towards a better understanding and control of the plasma performance in Reversed-Field Pinch (RFP) devices has been made. These improvements consist both in (A) the discovery of spontaneous plasma regimes, termed Quasi Single Helicity (QSH) regime, with improved performance and in (B) the development of techniques for active control of plasma instabilities.

(A) In the QSH regime of a RFP, the dynamo mechanism is produced mainly by one tearing mode. The RFP configuration is sustained by the dynamo that, through the interaction of magnetic and velocity fluctuations, produces toroidal flux in the plasma core. In the standard scenario, called multiple helicity (MH), the dynamo is produced by the interaction of several core resonant tearing modes. As a consequence, the core magnetic field becomes stochastic and the transport of energy and particle is increased. However, theory [1] and experiments [2-4] have shown that the RFP dynamo can be produced also in a regime in which one tearing mode is large (the dominant mode) and the other modes are extremely low (secondary). In this scenario, called QSH regime, the magnetic chaos is reduced and part of the core is characterized by a magnetic island. The island is generally hotter than the surrounding plasma but the transport is reduced even in the chaotic region; in fact, it has been found that the combined effect of the growth of the dominant mode and the reduction of the secondary modes produces a global enhancement of the plasma confinement [5].

(B) Techniques for the active control of plasma instabilities employ external coils that, through feedback action, suppress the growth of all the multiple independent resistive wall modes; with this kind of operation, called virtual shell, the pulse duration is several times longer than the resistive wall time [6]. The feedback system can be used also to suppress some modes, keeping the others to a constant level (selective feedback). In principle, the application of the selective feedback could be able to induce and/or to control the QSH regime. For example, as later described, the QSH active control could be useful to extend the duration of the QSH itself. Therefore, the combination of the selective feedback and of the spontaneous QSH is very promising.

Detailed studies of spontaneous QSH have already been done in three RFP devices, MST [3], TPE-RX [4] and RFX-mod [7]; preliminary studies in EXTRAP T2R are reported in [8]. The aim of this paper is to present a detailed analysis of spontaneous QSH state in EXTRAP T2R when the virtual shell is applied. The analysis here presented will be helpful to understand the QSH underlying properties, in view of future applications of the QSH active control. The paper is organized as follows. First, we show an example of QSH plasma in EXTRAP T2R. Second, we confirm that these QSH plasmas are characterized by a magnetic island and by a rotating thermal structure which corresponds to the island itself. Finally, we will show the results of a scan in plasma current  $I_p$  and  $F$  parameter ( $F=B_\phi(a)/\langle B_\phi \rangle$ ) aimed to find the best experimental condition to obtain QSH plasmas and to study some QSH basilar properties from the statistical point of view.

In figure 1 we show an example of the behaviour of magnetic signals during a QSH regime. In frame (a), the toroidal distribution of the  $m=1$  component of the poloidal fluctuations is shown; the clear toroidal periodicity is the signature of a QSH regime. The time evolution of this signal is shown in frame (b); the periodic structure, i.e. the QSH, is located in the time interval between  $t=27.65\text{ms}$  and  $t=27.9\text{ms}$  and has a clear toroidal rotation. To quantify these characteristics, the results of the modal analysis are shown in frame (c); when the periodic structure is present, the mode with toroidal number  $n=-11$  becomes very large (this is the dominant mode). It is important to observe that, during the time interval in which the mode  $n=-11$  is large, the magnetic signals are characterized also by the reduction of all the others modes (the secondary). Concerning the mode rotation, frame (d), the dominant one has a rotation frequency  $\nu_{(1,-11)} \approx 5\text{kHz}$ . This value is in agreement with the typical rotation frequency of QSH plasma in MST device [3]. It is interesting to observe that the decrease of the dominant mode velocity is well correlated with the increase of the respective mode amplitude; this is probably due to an increase in the electromagnetic braking torque, as reported in [9].

The duration of the QSH regime in the example of figure 1 is approximately  $\Delta t_{\text{QSH}} \approx 0.15\text{ms}$ . At present, the longest QSH obtained in EXTRAP T2R plasmas is only  $\approx 0.2\text{ms}$  and the average duration of all QSHs is  $\langle \Delta t_{\text{QSH}} \rangle \approx 0.05\text{ms}$ ; in other devices the typical QSH duration is at least one order of magnitude longer. It is not yet completely clear why in EXTRAP T2R such short QSH plasmas are obtained; however, two typical situations have been found: (1) the QSH termination can be ascribed to sawtooth crashes (not shown here) and (2) the QSH termination is to be correlated with the low rotation (or even wall locking) of the dominant mode (Fig. 1). Since the mode velocity is related to the mode amplitude, future experiments aimed to stabilize the dominant mode amplitude via the feedback system could be useful to extend the QSH duration.

The QSH regime is generally associated with the presence of a hot magnetic island in the plasma core. In Fig. 2 we show that, also in EXTRAP T2R, QSH state is characterized by a magnetic island and by a SXR structure (hereafter called “thermal” structure). A typical Poincaré map of the core magnetic field lines in EXTRAP T2R QSH plasma is shown in figure 2(a). The Poincaré map is obtained by solving the magnetic field line equations in cylindrical coordinates using a fourth order Runge-Kutta method; magnetic equilibrium is determined with the  $\alpha-\theta_0$  model and magnetic perturbations are determined by solving the Newcomb equation. In the figure, the dashed circle corresponds to the resonant radius of the dominant mode and the red points highlight one flux surface of the magnetic island. Note the presence of magnetic chaos outside the island.

Since magnetic modes are rotating, it is possible to verify if a localized thermal structure is associated with the island. This can be done by using the SXR diagnostic; it consists in a horizontal array of 10 chords located in the same poloidal plane at the toroidal angle  $\phi_{\text{SXR}} = 281^\circ$  [the geometry of 4 chords is shown in figure 2(a)]. SXR depends on impurity, density and electron temperature:  $\text{SXR} = f(Z_{\text{eff}}) n_e^2 T_e^\alpha$  and variations in SXR are often associated with variations in temperature. A “hot” rotating structure should produce

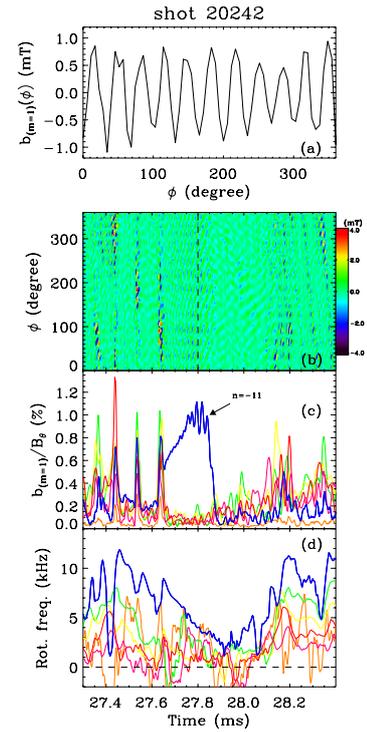


Figure 1. (a) Toroidal distribution of the  $m=1$  component of the  $B_\theta$  coil during a QSH state, at  $t=27.8\text{ms}$  and (b) respective time evolution. (c) Time evolution of  $m=1$  modes and (d) respective toroidal rotation frequency. Data are taken from shot 20242, with  $I_p \sim 75\text{kA}$  and  $F \sim 0.2$ .

sinusoidal SXR signals; signals measured at the bottom and at the top side of the plasma [points 1 and 4 in frame (a)] should have a phase shift  $\Delta\phi\approx 180^\circ$ . Moreover, since the structure should cross 2 times the central chords in one poloidal turn [points 3-5 and 2-6 in frame (a)], SXR measured from core chords should have a double oscillation frequency. In figure 2(b) we show the experimental SXR time evolution during a QSH regime. Since the signals in the outer chords have a clear phase shift and the double oscillation in the central chords is present, it is possible to conclude that a localized thermal structure is rotating inside the plasma.

Combining information from magnetic and SXR measurements, it is possible to conclude that the thermal structure detected with the SXR camera coincides with the magnetic island. The radial position of the thermal structure can be estimated from the amplitude of the SXR oscillation,  $A$  [see frame (b)]; by decomposing the SXR into a “slow” term  $S_{\text{slow}}$  and a “fast” oscillating term due to the thermal structure rotation,  $A$  can be defined as follows:

$$\text{SXR}(r,t)\approx S_{\text{slow}}(r,t)+A(r,t)\cos[\omega t+\alpha(r)].$$

The chords that have an impact parameter equal to the radial position of the structure will have a large oscillation  $A$ ; in an ideal case,  $A(r)$  will be perfectly symmetric. In Fig. 2(c), we show the  $A$  radial profile in two QSH plasma with dominant mode  $n=-13$  and  $n=-12$ . In the first case, the thermal structure seems to be more external than in the second case. We also plot the radial position of the respective magnetic islands calculated with the  $\alpha-\theta_0$  model (dashed line); the radial positions of the thermal structure and of the magnetic island are qualitatively in agreement.

Moreover, it is possible to compare the poloidal position of the magnetic island  $\theta_{\text{isl}}$  and that of the thermal structure  $\theta_{\text{SXR}}$ .  $\theta_{\text{isl}}$  can be determined from the phase of the dominant mode  $\alpha_{\text{DOM}}$ :

$$b_{(1,n_{\text{DOM}})} = b(t) \times \cos[\theta - n_{\text{DOM}}\phi - \alpha_{\text{DOM}}(t)].$$

At the toroidal position of the SXR diagnostic, the poloidal position of the magnetic island is  $\theta_{\text{isl}} = n_{\text{DOM}}\phi_{\text{sxr}} + \alpha_{\text{DOM}}$ .  $\theta_{\text{SXR}}$  can be determined from the phase of the SXR signals. The comparison of  $\theta_{\text{SXR}}$  and  $\theta_{\text{isl}}$ , frame (d), shows that the poloidal position of the island and that of the thermal structure are similar. Therefore, it is possible to conclude that the thermal and magnetic structures coincide.

To determine the best operative condition to obtain spontaneous QSH, an ensemble of 167 discharges, obtained by changing  $I_p$  and  $F$  in a wide range, has been analysed. Figures 3(a) and 3(b) summarize the results. The distribution in the  $I_p$ - $F$  plane of all the data points is shown in frame (a); black dots correspond to MH plasma and red dots to QSH. To distinguish between MH and QSH, the spectral index  $N_s = \sum_n [b_{(1,n)}^2 / \sum_n b_{(1,n)}^2]^{-1}$  is used; a pure

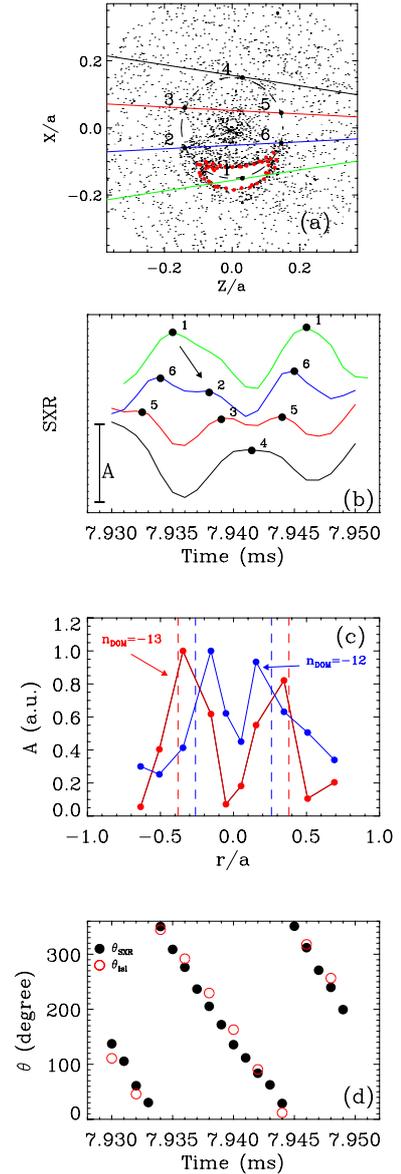


Figure 2. (a) Poincaré map of the magnetic field line in a QSH plasma. Part of the geometry of the SXR diagnostic geometry is shown. (b) SXR time evolution for shot 20380. Numbered points correspond to the positions of the island highlighted in frame (a). Frame (c), radial profile of the SXR fluctuation amplitude. Dashed lines correspond to the resonant radius calculated with the  $\alpha-\theta_0$  model. (d) Time evolution of the poloidal position of the magnetic island and of the SXR structure [same shot of (b)].

single helicity state has  $N_s=1$  and QSH are defined with  $N_s < 2$ . To determine the best region to have QSH, frame (b) shows the probability  $P_{\text{QSH}} = (\text{QSH events}) / (\text{total events})$  versus  $I_p$  and  $F$ . QSH occurs with the highest probability for  $I_p \approx 70 \text{ kA}$  and  $F \approx -0.15$ . These levels of  $I_p$  and  $F$  turn out to be also the best to have the longest QSH regimes, as shown in frame (c); however, note that the average length is shown and not the maximum length.

We already discussed in Fig. 1 that QSH regimes are characterized by the increase of the dominant mode, but also with the reduction of the secondary modes. This conclusion is confirmed by a statistical analysis made over the shots of the database; in Fig. 3(d), we show the correlation of the dominant mode and of the total energy of the secondary modes versus  $N_s$  (only discharges with  $I_p \approx 80 \text{ kA}$  and  $F \approx -0.2$  are considered). The reduction of  $N_s$  is correlated with the increase of the dominant mode and with the reduction of the secondary modes; note that this trend is in agreement with those found in other RFPs [3,4,7].

In conclusion, QSH regimes are present also in EXTRAP T2R device. In agreement with the results obtained in other devices, QSH regimes are characterized by a magnetic island; the island has a SXR emission higher than the bulk plasma. Moreover, these regimes are produced by the cooperative effect of the reduction of the secondary modes and of the increase of the dominant mode. These results are an essential starting point for future experiments aimed to actively control the QSH with the feedback system in EXTRAP T2R.

## References

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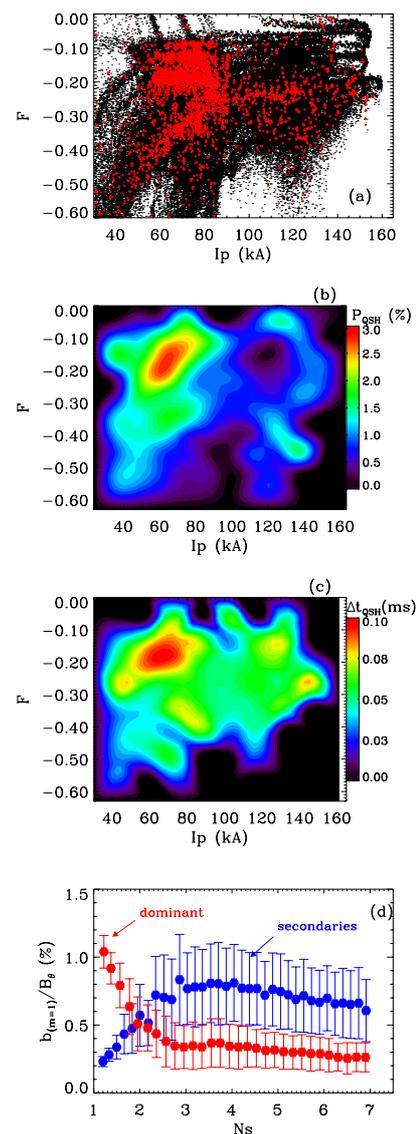


Figure 3. (a) Distribution of the data points; every point is an average in a time interval 0.04ms long (black: MH, red: QSH). (b) Distribution of QSH probability and (c) distribution of QSH length. (d) correlation between mode amplitudes and  $N_s$ .