

Active feedback control of QSH in EXTRAP-T2R

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In recent years, significant 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 (I) the discovery of a spontaneous plasma regime, termed Quasi Single Helicity (QSH) regime, in which part of the plasma core is no longer stochastic and in (II) the development of techniques for active control of plasma instabilities.

(I) The QSH regime produces enhancement of plasma confinement [1]. Spontaneous QSH regimes in EXTRAP T2R are characterized by the presence of a magnetic island, generated by the spontaneous growth of one internally resonant tearing mode (the so-called dominant mode) and by the reduction of the other internally resonant tearing modes (secondary modes) [2]. The dominant mode is typically the first internal resonant and depends on the plasma equilibrium [2]. (II) Techniques for active control of plasma instabilities employ external coils that, through a feedback action, suppress the growth of multiple independent modes [3].

This work presents preliminary experiments of the application of the EXTRAP T2R feedback system to actively induce the QSH regime. The role of the amplitude of the dominant mode is studied in detail. In order to find the optimal conditions to induce the QSH, the technique is applied to several plasma equilibria; the effect of the amplification of different dominant modes is also tested.

EXTRAP T2R is a RFP device with minor radius $a=0.183\text{m}$ and major radius $R=1.24\text{m}$. The device is equipped with a feedback system for the active control of the magnetic modes. The system is composed of sensor saddle coils for the measurement of the radial magnetic fluctuations, of active saddle coils for the generation of external radial magnetic fields and of a digital controller that, from the field measured by the sensor coils, determines the input to the active coils in order to obtain the desired control; for more details, see Ref. [3]. The device is also equipped with a toroidal array of sensors for the measurement of the poloidal magnetic fluctuations; with the present settings, $m=1$ modes with toroidal resolution up to $|n|<32$ can be resolved.

In the present paper, the feedback system of EXTRAP T2R is applied using the mode control MC operation. In the MC operation, the radial magnetic field measured by the sensor coils is decomposed into spatial Fourier harmonics; then, the controller determines the input to the active coils to produce the external radial magnetic fields that will suppress the radial component of each Fourier harmonic separately; if $e(t)$ and $u(t)$ are the controller input and output signals, the effect of the controller in the present MC operation is: $u(t) = k_p e(t)$ where k_p is the proportional gain. The suppression of a mode is enhanced by increasing its corresponding k_p . Experimentally, the value to have the best mode suppression is $k_p=20$ for each mode; a lower value does not suppress the corresponding mode enough and a higher value produces instabilities in the

feedback system [4]. When not otherwise stated, in the present work the proportional gains will be set to 20 for each mode.

For a typical EXTRAP T2R discharge, with $F \approx -0.35$ and $I_p \approx 80 \text{ kA}$, the first internal resonant mode is $(m,n)=(1,-12)$. To actively induce a QSH regime, the best strategy could be to let the $n=-12$ mode grow freely by setting $k_p^{-12}=0$ and by suppressing all the other modes using $k_p^n=20$. The corresponding results are reported in Fig. 1. The radial component of the magnetic modes $b_r^{m,n}$ is shown in Fig. 1(b); while the secondary modes do not increase during the discharge, the $n=-12$ mode shows an increase that is approximately exponential; when its amplitude is too large, the discharge terminates, as shown by the time evolution of the current in Fig. 1(a). Since the feedback acts directly only on the $b_r^{m,n}$, to check if real QSHs are generated it is necessary to verify also the behaviour of at least the poloidal component of the magnetic modes, $b_\theta^{m,n}$; when also $b_\theta^{m,n}$ shows the typical QSH spectrum, then we can be confident that QSHs are generated in the plasma core. Even if $b_r^{1,-12}$ is very large during most part of the discharge, the behaviour of $b_\theta^{1,-12}$ is quite different: its amplitude is larger than that of the secondary modes only during very short periods; in Fig. 1(c) the $b_\theta^{1,n}$ are shown between 13ms and 14ms. The mode $n=-12$ is larger only at $t \approx 13.3 \text{ ms}$ and $t \approx 13.7 \text{ ms}$. To quantify the shape of the magnetic spectrum, the spectral index N_s is typically used. By definition, $N_s = \sum_n [b_{1,n}^2 / \sum_n b_{1,n}^2]^{-1}$. When $N_s=1$ only one mode is present in the plasma (single helicity SH), when all the modes have similar amplitudes then N_s is very large. A QSH regime is defined by the threshold $N_s < 2$. Hereafter, the presence and the duration of QSH regimes will be estimated using N_s calculated with the $b_\theta^{1,n}$ signals. The example of Fig. 1(d) shows that between 13ms and 14ms two QSHs are generated. It is interesting to note the regular patterns in the toroidal distribution of the poloidal field raw sensor signal during the QSHs, see Fig. 1(e), and to highlight the corresponding mode rotation. Fig. 1(f) shows the toroidal distribution of the raw poloidal fluctuations at the instant highlighted by the dashed line in frame (e); the periodicity $n=12$ confirms that the corresponding QSH has $n=-12$.

Even if $b_\theta^{1,-12}$ is larger than the secondary modes only for short intervals, the percentage (or fraction) of the discharge characterized by QSH intervals is larger than in the case in which all modes are suppressed [(1,-12) included]. From a quantitative point of view, if $\tau_{QSH}^{i,j}$ is the duration of the QSH j in the discharge i and Δt_i is the duration of the discharge i , it is possible to define the quantity $P_{QSH}^i = \sum_j \tau_{QSH}^{i,j} / \Delta t_i$; P_{QSH}^i represents the percentage of the discharge i in

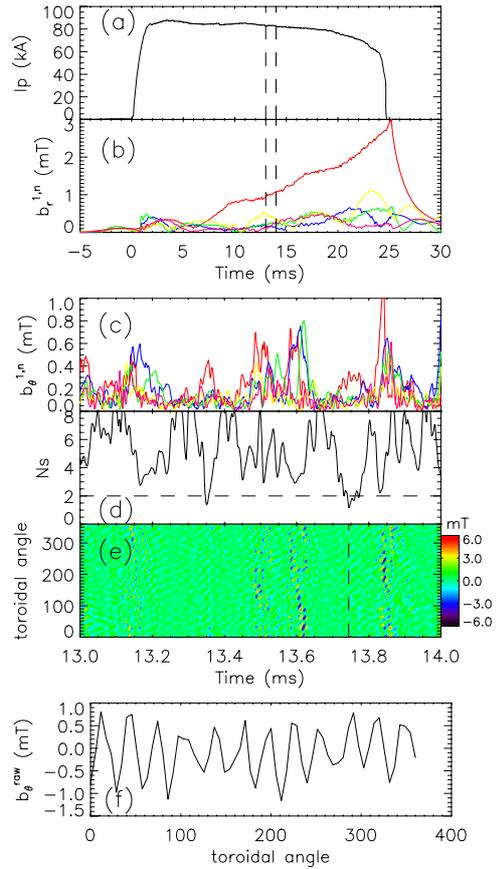


Figure 1. Example of active induction of a QSH by setting $k_p^{-12}=0$. (a) plasma current, (b) radial component of the magnetic modes, (c) poloidal component of the magnetic modes, (d) spectral index N_s , (e) poloidal field raw sensor signals and (f) toroidal distribution of the poloidal fluctuations from raw signals during a induced QSH.

which QSHs are present. For the case shown in Fig. 1 with $k_p^{-12}=0$, the result is $P_{QSH}^i \approx 1.5\%$. For a discharge in which $k_p^{-12}=20$ we have $P_{QSH}^i \approx 0.3\%$ only.

An interesting result is that when $k_p^{-12}=0$ is used, QSHs with $n \neq -12$ can be generated. To quantify this result, an ensemble of 10 discharges obtained with conditions similar to those of Fig. 1 (i.e. with $k_p^{-12} \approx 0$) are analysed. $P_{QSH} = \sum_{i,j} \tau_{QSH}^{i,j} / \sum_i \Delta t_i$ is then calculated considering only QSHs with specific n . The results are reported in Fig. 2(a). The fraction of time in which $n=-12$ QSHs are present is $\approx 1.2\%$; but a consistent part of the discharges also shows $n=-13$ QSHs ($\approx 0.5\%$). At present it is still not clear why QSHs with $n \neq -12$ are generated; possible explanations might be related to non-linear effects or to small changes in the plasma equilibrium. The total P_{QSH} for the ensemble of discharges of Fig. 2(a) is $P_{QSH} \approx 1.2+0.5 \approx 1.7\%$.

In Fig. 2(b), a similar analysis is repeated by setting all the gains to $k_p^n=20$ but $k_p^{-13}=0$. The same equilibrium of the discharges of Fig. 1 and Fig. 2(a) is used. QSHs with $n \neq -13$ are generated. QSHs with $n=-12$ occur even more frequently than QSHs with other modes. In this case, part of the explanation is due to the fact that the first internal resonant mode is still $n=-12$. In Fig. 2(c) the same analysis is repeated using $k_p^{-14}=0$. QSHs with $n=-12$ are again the most frequent. Finally, it is worth noticing that with this equilibrium the highest P_{QSH} is obtained with $k_p^{-12}=0$, i.e. when the system is trying to induce the QSH with the dominant mode corresponding to the first internal resonant one.

The maximum total P_{QSH} obtained up to now is $\approx 1.7\%$. To improve this result a systematic scan of k_p^{-12} has been performed. In Fig. 3(a) the time evolution of $b_r^{1,-12}$ is shown for discharges obtained with several values of k_p^{-12} . The increase of the proportional gain clearly produces a better suppression of the corresponding mode. To quantify this claim, in Fig. 3(b) the correlation between the growth rate $\gamma^{1,-12}$ of the mode $b_r^{1,-12}$ with k_p^{-12} is shown for an ensemble of 36 discharges obtained with the same equilibrium of the shots of Figs. 1 and 2. The growth rate is obtained with an exponential fit from $t \approx 10$ ms to the end of the discharge. It is worth noticing that below $k_p^{-12}=1$, the growth rate is almost constant ($\gamma^{1,-12} \approx 0.1 \text{ms}^{-1}$); the gain is so low that the mode grows almost freely. Due to the correlation between the growth rate and the gain, a similar correlation between P_{QSH} and k_p^{-12} might be expected. Actually, Fig. 3(c) shows that P_{QSH} has a maximum at $k_p^{-12} \approx 1.6$; for lower and higher gains, P_{QSH} is lower. This shows that a too large $b_r^{1,-12}$ does not increase the percentage of QSHs. The reason is still unclear but it is possible that due to some non-linear interactions, a very large dominant mode produces the increase of some secondary modes therefore deteriorating the optimal conditions for the QSH creation.

A further parameter that can affect the percentage of QSH is the equilibrium. In fact, a change in the equilibrium produces a modification in the safety factor profile and hence in the radial position of the resonant modes and ultimately in the value of the first internal resonant mode. Therefore, using the gain that maximizes P_{QSH} ($k_p^{-12} \approx 1.6$), a scan of the reversal parameter F has been performed. In total, 40 discharges have been analysed. The results are

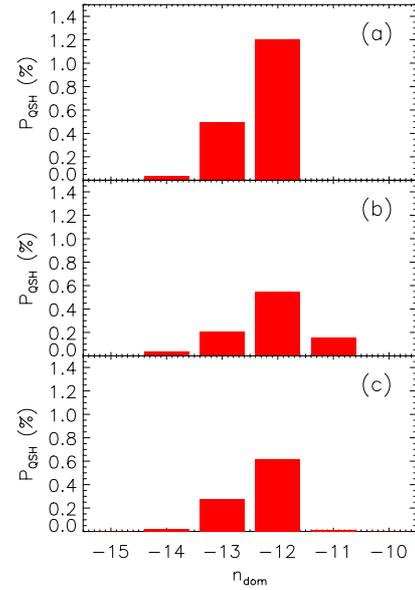


Figure 2. Fraction of the discharges characterized by QSHs with $n=-15,-14,-13,-12,-11$ and -10 . Frame (a) corresponds to discharges with $k_p^{-12}=0$, frame (b) $k_p^{-13}=0$ and frame (c) with $k_p^{-14}=0$.

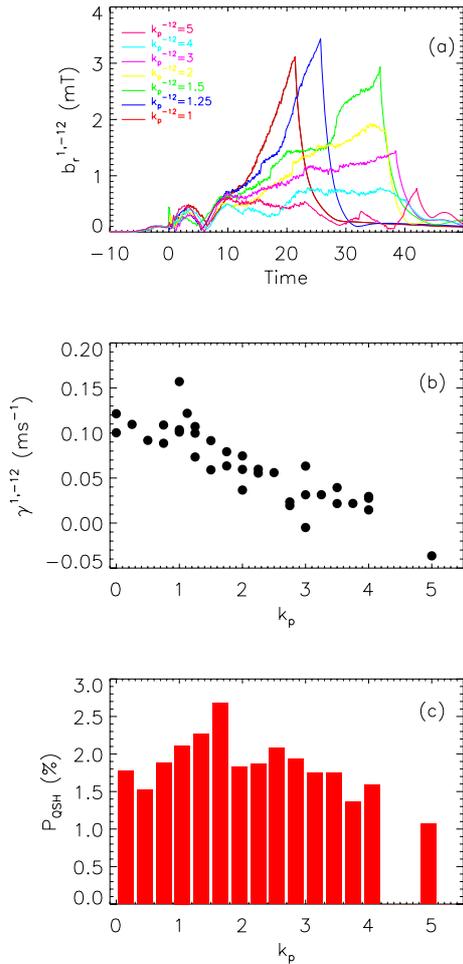


Figure 3. (a) Evolution of $b_r^{1,-12}$ for different gains. (b) Correlation of the growth rate of mode $(m,n)=(1,-12)$ with the gain. (c) Percentage of QSHs for different gains.

is calculated using the $\alpha-\Theta_0$ model with $\beta_0=10\%$ for several values of F (for each F the corresponding experimental pinch parameter is used). For values of F extremely different from -0.35 , the mode $n=-12$ is not the first resonant mode or is not resonant anymore and P_{QSH} drops.

In conclusion, in this paper we have shown that it is possible to actively induce the QSH regime by using the feedback system in the mode control operation with only the proportional gain. When all modes are suppressed with the optimal gains then the percentage of QSH is only $P_{QSH}\approx 0.3\%$. By letting the first resonant mode grow freely using $k_p^{-12}=0$ the percentage increases up to $P_{QSH}\approx 1.7\%$. The optimization of k_p^{-12} allows P_{QSH} to $\approx 2.7\%$ to increase and the optimization of the equilibrium to $P_{QSH}\approx 3.5\%$. Future work will consist in the implementation of the integral and proportional gains in the MC operation in order to further increase the percentage of the induced QSHs. Active control of QSH is also useful during the EXTRAP T2R improved confinement regimes; for details see Ref. [5].

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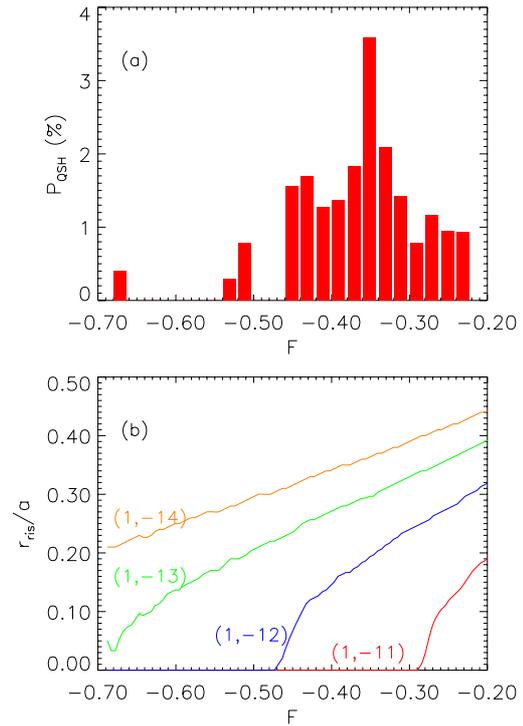


Figure 4. (a) Percentage of QSHs at different values of the reversal parameter. (b) Resonant radius of internal modes for several F values.

summarized in Fig. 4. At $F\approx -0.35$ the percentage of QSHs is maximized. This value corresponds to the equilibrium in which the mode $n=-12$ is the first internal resonant. In Fig. 4(b) the resonant radius r_{res} of several internal modes is shown. r_{res}