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Imaging of magnetic chaos reduction and coherent structures in the MST reversed-field pinch

F. Bonomo[1], P. Franz[1], L. Frassinetti[1], M. Gobbin[1], L. Marrelli[1], P. Martin[1], P. Piovesan[1], I. Predebon[1], G. Spizzo[1], J.K. Anderson[2], B.E. Chapman[2], D. Craig[2], S.C. Prager[2], J. Sarff[2]

[1] *Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, Padova, Italy*

[2] *Department of Physics, University of Wisconsin, Madison, WI, USA*

Magnetic self-organization plays a fundamental role in the dynamics of reversed-field pinch (RFP) plasmas. In the standard multi-helical (MH) operation of the RFP, a broad spectrum of $m = 0, 1$ tearing modes with different n's is responsible for magnetic field sustainment through dynamo effects, but it also strongly affects the plasma confinement by inducing magnetic chaos over large portions of the plasma volume. Dynamo mode control and magnetic chaos reduction are thus key issues in the path towards the realization of enhanced confinement RFP regimes.

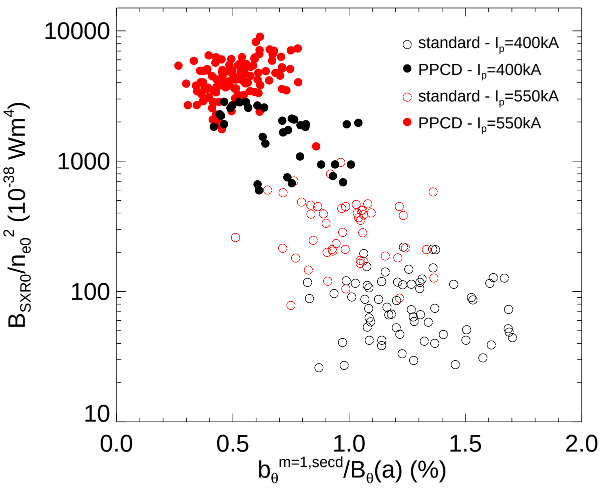

Figure 1: Core soft x-ray brightness divided by the core electron density squared as a function of the average $m = 1$ secondary mode amplitude normalized to the edge equilibrium magnetic field.

In this paper we present an experimental and numerical study of two different approaches to magnetic chaos reduction in the RFP, i.e. pulsed parallel current drive (PPCD) [1] and spontaneous quasi-single helicity (QSH) [2]. A detailed characterization of the topological and thermal properties of the plasma core confirms the magnetic chaos reduction expected in these plasmas and provides a direct imaging of it. Experiments have been done in the Madison Symmetric Torus (MST) device based at the University of Wisconsin, Madison, WI (USA). Advanced diagnostics and numerical codes have been employed to this scope: a high-resolution soft x-ray tomography recently installed in MST [5], a toroidal array of 32 pick-up coils, the guiding-center code ORBIT, and the toroidal equilibrium code MSTFit.

Following the inductive modification of the magnetic profiles due to PPCD, the dynamo modes and the associated magnetic chaos are strongly reduced. As a result, magnetic flux surfaces are at least partly restored in the plasma core, with a dramatic reduction of transport [3, 4].

Such a global effect is also confirmed by the present soft x-ray measurements. In Fig. 1 we report the core soft x-ray brightness divided by the core electron density squared as a function of the average $m = 1$ *secondary* mode amplitude normalized to the edge equilibrium magnetic field. Since during QSH the innermost resonant $(m = 1, n = 6)$ mode can have amplitudes ten times larger that the $(m = 1, n = 7-15)$ modes, we refer to them as *secondary* modes. Data from similar standard and PPCD discharges with plasma current $I_p = 400kA$ (black symbols) or $I_p = 550kA$ (red symbols) have been included in this analysis, each point corresponding to a different shot. We observe that a dramatic increase in the B_{SXR0}/n_{e0}^2 signal is associated with the secondary mode reduction due to PPCD. It has been recently shown [6] that the following dependence is valid in these plasmas: $B_{SXR0}/n_{e0}^2 \propto T_{e0}^{\alpha}$ with $\alpha \simeq 3$, the core electron temperature T_{e0} having been measured with double filter techniques. This result is in accordance with the confinement improvement due to PPCD observed in the past with other diagnostics [1].

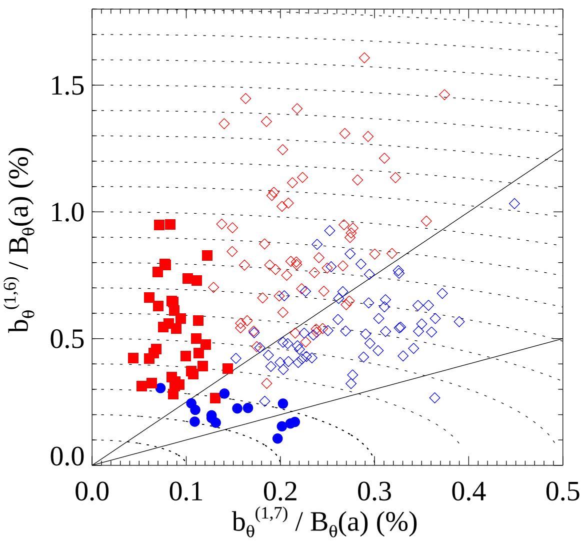

Figure 2: The $(1,6)$ *vs* $(1,7)$ normalized magnetic mode amplitudes for a set of $400kA$ standard (empty symbols) and PPCD (filled symbols) shots with MH (blue symbols) and QSH (red symbols) spectra.

As shown yet in [1], we also find that the PPCD effect is due to the reduction of all the *secondary* $m = 1$ modes, but it seems to be unaffected by the presence of a dominant $(1, n)$ mode. In other terms similar effects are produced with MH or QSH spectra, which are both observed during PPCD. We show in the following by using soft x-ray tomography and numerical modelling that a very different core topology is associated with these two types of spectra representing two different routes to magnetic chaos reduction.

In Fig. 2 we plot the normalized $(1,6)$ mode amplitude as a function of that of the $(1,7)$ mode, which is roughly proportional to the secondary mode amplitude, for a set of standard and PPCD shots with $I_p = 400kA$. For each discharge the plasma has been imaged with soft x-ray tomography and the following results have been obtained. QSH plasmas (red symbols) are always characterized by the presence in the core of a hot helical domain, which corresponds to the helical flux surfaces associated with the dominant $(1,6)$ mode. In standard MH plasmas (blue diamonds) no particular structures are observed, while separated helical flux domains are present in MH PPCD plasmas (blue circles).

The above observations are documented in Fig. 3 by tomographic and ORBIT reconstructions of the plasma core in a QSH and a MH PPCD discharge, respectively. During QSH a large hot helical structure emerges in the core associated with helical flux surfaces, while during MH distinct soft x-ray islands are present. The match between experimental and numerical reconstructions is rather good. In the MH case, the rational surfaces predicted by MSTFit are also superimposed to the tomographic reconstruction and a good match is found further confirming the validity of the present analysis. The two modes with the largest amplitudes are the $m = 1, n = 6, 8$ modes and the two soft x-ray islands observed here correspond to these helicities.

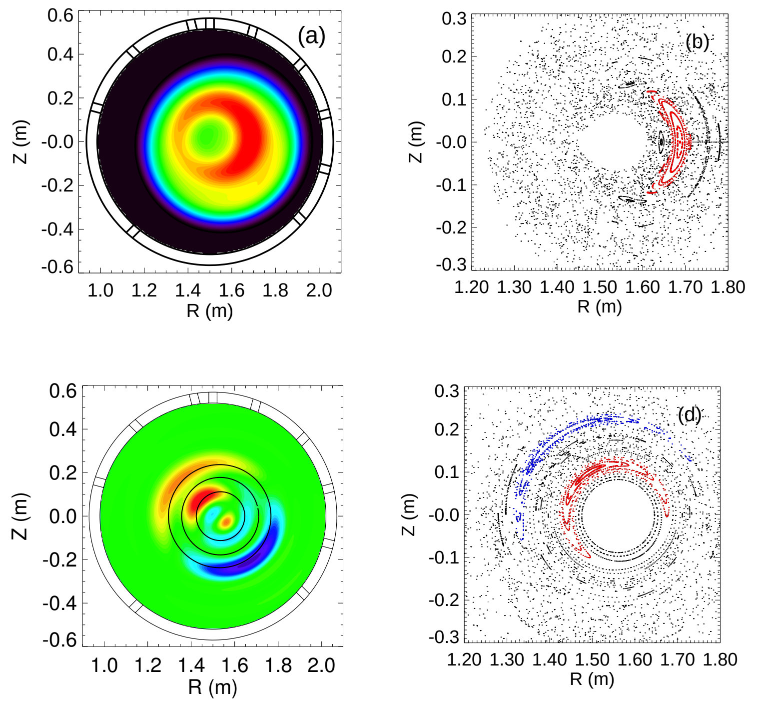

Figure 3: Tomographic and ORBIT reconstructions of PPCD shots with a QSH (a)-(b) and a MH (a)-(b) spectrum.

The above results can be interpreted as follows. In standard MH plasmas magnetic chaos develops since $m = 1$ islands with similar and relatively large widths overlap, which is well described by the Chirikov criterion. The magnetic mode amplitudes decrease to an unprecedented level during PPCD in MST, reducing the overlap of adjacent islands and allowing them to retain their individuality when an MH spectrum is present. The QSH case is somehow different, both for that regards standard and PPCD plasmas. As suggested in [7], the Chirikov criterion does not holds in this case, since one island is significantly larger than the nearby islands. In this case theory predicts that a relatively large helical flux domain associated with the dominant $m = 1$ mode can emerge out of a stochastic background when the island separatrix is expelled. This could explain the appearance of large soft x-ray islands during QSH.

As mentioned above QSH spectra have also been observed to emerge spontaneously in standard MST shots [2]. Also in this case, magnetic chaos is reduced inside the island domain and a hot helical structure is observed. The high spatiotemporal resolution of the MST tomography has permitted us to reconstruct the 3D structure of the soft x-ray island emerging during spontaneous QSH spectra. An example is reported in Fig. 4, where we plot the surface containing 60% of the island emissivity. This has been performed by composing several (60) tomographic reconstructions during a complete toroidal turn of the island. This is possible given the fact that the island does not change its amplitude significantly during one toroidal turn.

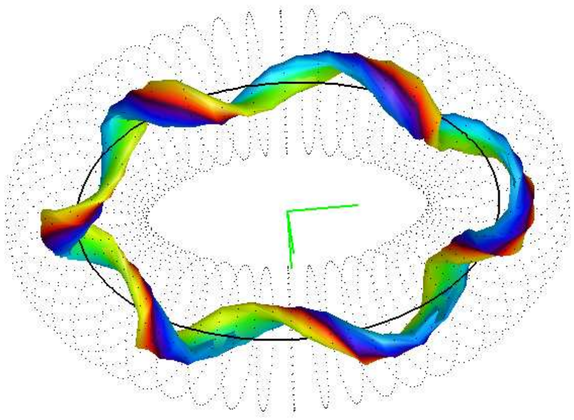

Figure 4: 3D reconstruction of a $(m = 1, n = 6)$ island during a spontaneous QSH state in a discharge with $I_p \simeq 400kA$.

Fig. 4 shows that spontaneous QSH spectra are associated with a significant deformation of the plasma column. This is now closer to a helical state, even though a finite level of secondary modes still limits the global confinement performance in the QSH plasmas obtained until now. The above evidence, along with the recent measurement of a significant dynamo electric field produced by the dominant mode during QSH in MST [8], provides good motivation for trying to bring these plasmas to a pure SH state. The optimization of QSH plasmas could be performed in the future by exploring plasma conditions that favor its occurrence, but also by employing active mode control, using for example the system of feedback coils now available in the RFX-mod device [9].

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