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Experimental MHD studies of enhanced confinement reversed-field pinch plasmas

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The objective of this work was the clarification of some magnetohydrodynamic (MHD) dynamo and transport open problems, in improved confinement regimes of the reversed-field pinch (RFP), using advanced diagnostic and numerical tools. The RFP is a toroidal magnetically confined fusion plasma characterized by a high degree of magnetic self-organization. The magnetic configuration is sustained in time by a dynamo mechanism driven by helical MHD instabilities, which shares strong similarities with other laboratory and natural systems. The understanding of the RFP dynamo, and the related energy transport is crucial for the optimization of the RFP performance as a fusion relevant device. Moreover it allows to address very important issues in the field of magnetic self-organization and basic plasma physics.

The RFP dynamo is a non-linear process that produces an electric field $\mathbf{E}_{dyn}$, which adds to the inductively applied $\mathbf{E}_{ext}$ to balance the Ohm's law, $\mathbf{E}_{ext} + \mathbf{E}_{dyn} = \eta \mathbf{j}$. Without $\mathbf{E}_{dyn}$ the current density needed to produce the RFP magnetic field could not be driven. The field $\mathbf{E}_{dyn}$ is due to a velocity field $\mathbf{v}_{dyn}$ providing a $\mathbf{v}_{dyn} \times \mathbf{B}$ electromotive force. The simplest way to describe the RFP dynamo is through a *single-helicity* (SH) model. In the SH picture a single $m = 1$ resistive-kink mode grows unstable and then saturates nonlinearly at a value of few percents of the equilibrium magnetic field. The SH dynamo velocity field is an electrostatic drift related to a small charge separation caused by the helical deformation of the plasma due to the resistive-kink mode, and consistent with the quasineutrality approximation [Bonfiglio *et al.*, Phys. Rev. Lett. **94**, 1450001 (2005)]. SH provides a laminar dynamo mechanism and avoids the development of magnetic chaos due to the traditional *multiple helicity* (MH) dynamo. In MH a broad mode spectrum drives the dynamo, magnetic island overlap induces strong magnetic chaos throughout the plasma volume, and the confinement is severely limited. In this respect the SH RFP is a confinement concept, which might be very relevant in fusion perspective, and it is therefore one of the most relevant topics for the RFP community.

The existence of helical RFP states is robustly predicted by 3D visco-resistive MHD codes like SpeCyl and NIMROD [S. Cappello, Plasma Phys. Control. Fusion **46**, B313 (2004)], and their favorable confinement properties have been described with the Hamiltonian ORBIT code [I. Predebon *et al.*, Phys. Rev. Lett. **93**, 145001 (2004)]. Though pure SH states have not yet been obtained in experiments, regimes very close to SH, dubbed *Quasi-SH*, have been experimentally detected. In QSH a single $(m = 1, n)$ mode dominates the spectrum, but a finite low level of secondary modes is still present. A helical region, with closed flux surfaces and improved confinement, is present in the plasma core during QSH, but magnetic chaos is generated outside this helical domain by the other modes, which partially affects the transport properties of the system.

This work consists of two parts. The first one is dedicated to the measurement of the dynamo electric field during QSH. The second one deals with a different way to cope with magnetic chaos produced by the MH dynamo, i.e. the active control of the current profile with *pulsed poloidal current drive* (PPCD). PPCD drives transiently a poloidal electric field at the plasma edge, so to reduce the drive and amplitude of the dynamo modes. Though inherently transient in nature, PPCD has produced up to now the best confinement improvements in the RFP. In the following we describe an experimental analysis of magnetic chaos healing during PPCD. This work was made thanks to a tight collaboration among the RFX team in Padua, Italy, and the MST team at the University of Wisconsin, Madison, WI, USA. This collaboration was important to develop new diagnostics, and to design and realize common experiments.

The first contribution here described is the direct measurement of the MHD dynamo electric field during QSH states [P. Piovesan, D. Craig, L. Marrelli *et al.*, Phys. Rev. Lett. **93**, 235001 (2004)]. Before this, clear experimental proofs that one single dominant mode in a QSH spectrum can produce a dynamo electric field large enough to sustain the RFP configuration were lacking. This was a crucial result to prove the relevance of SH for future RFP operation. Experiments and data analysis were done in collaboration with the MST team. We used a fast ion Doppler spectrometer to measure the CV ion fluid velocity, and an array of 32 magnetic probes to compute the $(m = 1, n)$ mode spectrum. The high spatio-temporal resolution of the spectrometer, with six lines of sight spanning the entire poloidal section and frequency resolution up to 50kHz, allowed to measure with sufficient accuracy both the mean fluid velocity and its fluctuations due to the dynamo mode rotation. Cross-correlation algorithms were then developed to extract from the velocity signals

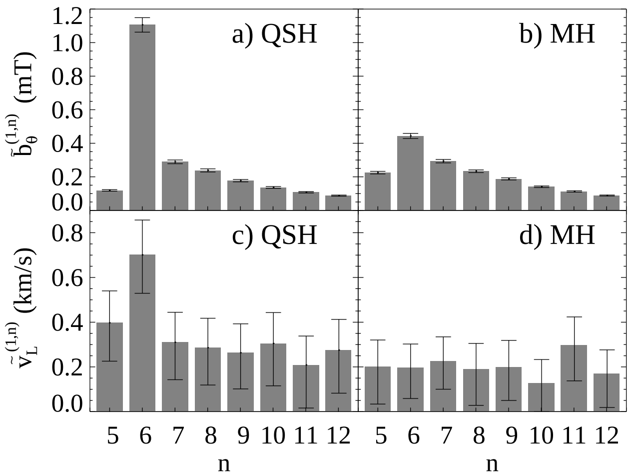

Figure 1: Magnetic and flow velocity $(m = 1, n)$ spectra measured during QSH and MH periods in the MST experiment.

the part coherent with each magnetic mode, and to separate it from the uncorrelated noise. This analysis was applied to an ensemble of about 580 similar MST shots to have good statistics. Since MH and QSH periods alternate randomly along a discharge, an algorithm was written to separate them and produce two ensembles of MH and QSH events. The ensemble-averaged spectra of the velocity $v_\theta^{(1,n)}$ and magnetic $b_r^{(1,n)}$ fluctuations in MH and QSH were thus measured, and are reported in Fig. 1.

The first important result is that during QSH both the velocity and magnetic fluctuations are dominated by a single Fourier harmonic with a well-defined helicity, while a turbulent spectrum is observed in MH. This was previously known only for the magnetic part. This further evidence has an important implication: QSH states are more laminar than MH states, since a global helical flow pattern emerges during QSH from an otherwise turbulent MH velocity field, as predicted also by theory. Since passive spectroscopy gives an estimate of the fluid velocity averaged along a line of sight, modelling of the measurements was necessary to validate these results. To this aim the fluctuation spatial profiles associated with the $(m = 1, n)$ modes were compared with those computed using the MHD SpeCyl code. A “virtual" spectroscopic diagnostic similar to that used in the experiment was applied to SH and QSH simulations, using as input the measured CV emissivity profiles, and an excellent agreement with the measurements was found. Due to the fact that the mode eigenfunctions are not localized around their rational surface, but are quite global, the line average effect can be taken into account in a simple manner and does not significantly affect the conclusions.

These velocity and magnetic spectra were then used to compute the dynamo electric field $E_\phi^{(1,n)} = \langle v_\theta^{(1,n)} b_r^{(1,n)} \rangle$ produced by each individual $(m = 1, n)$ mode at different radii. Fig. 2 reports this quantity at the radius $r/a = 0.34$. In QSH states the dominant mode alone produces a dynamo electric field greater than that from all the secondary modes and of the same order as the inductively driven electric field, $\sim 1V/m$. This provides the first experimental proof that it is possible to drive the RFP dynamo with only one dominant mode. Further experiments will be necessary to obtain purer spectra, but in any case this shows for the first time that a turbulent dynamo is not necessary for the RFP.

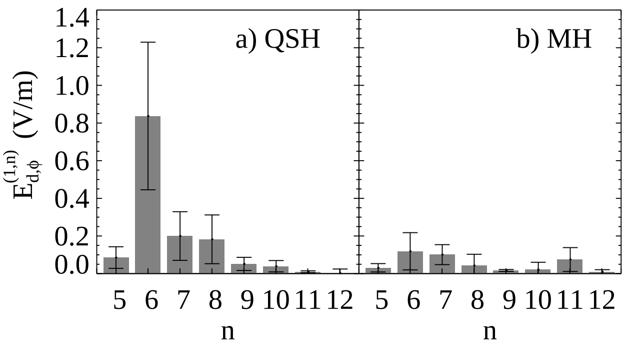

Figure 2: Dynamo electric field produced by each $(m = 1, n)$ dynamo mode measured during QSH and MH periods in the MST experiment.

The second RFP scenario studied here is produced with the PPCD technique. This study was conducted in collaboration with the MST team. The aim was to investigate with high spatio-temporal resolution the local magnetic chaos healing associated with improved confinement in the core. This was made possible by the novel x-ray tomography built in collaboration with the MST team, which is mentioned above. First of all a detailed statistical characterization of many similar PPCD discharges was made using magnetic and x-ray measurements. PPCD produces two possible different final states starting from the same initial conditions, with similar probabilities and confinement improvement. In about half of the cases PPCD acts so as to reduce all the modes and produce a MH spectrum of modes with record low amplitude. In the second half of cases PPCD induces very pure QSH spectra. In both cases a strong magnetic chaos reduction is obtained.

The first important result is that during MH-PPCD plasmas multiple islands appear in the plasma core, as shown in Fig. 3. This is observed for the first time in a RFP, and is a new result in fusion and plasma physics [P. Franz, L. Marrelli, P. Piovesan *et al.*, Phys. Rev. Lett. **92**, 125001 (2004)]. This effect was modelled with the toroidal equilibrium code MSTFit and the field line tracing code ORBIT. In standard MH the individual island widths are so large that they overlap and magnetic chaos destroys the flux surfaces. To the contrary, during PPCD the island widths are low enough to avoid overlap. This represents the first direct imaging of the chaos reduction process ultimately responsible for the sizable confinement improvement observed in PPCD. On the other hand, by imaging QSH-PPCD plasmas it could be shown that the whole plasma column is helically deformed, with a maximum of emissivity corresponding to the O-point of the dominant mode. Hence this mode does not simply produce a local effect, but deforms the whole plasma into a different macroscopic state. Since no evident differences in the confinement of MH and QSH PPCD plasmas could be found, this constitutes a strong hint that a helical RFP may be compatible with improved confinement.

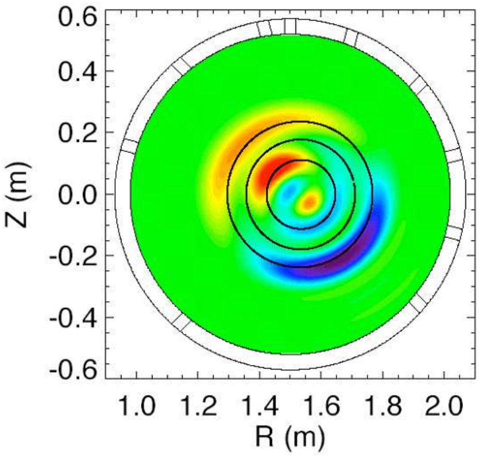

Figure 3: Tomographic reconstruction of multiple islands during PPCD in MST and $m = 1, n = 6, 7, 8$ rational surfaces predicted by MSTFit.

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