Helical RFP states in 3D nonlinear MHD: intermittency and magnetic topology

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Introduction. The qualitative study of magnetic field topology and the quantitative evaluation of transport coefficients are fundamental techniques for the study of transport. In this paper we tackle this problem in the framework of the numerical solution of the 3D nonlinear visco-resistive magnetohydrodynamics (MHD) model. The tools built for this kind of analysis will be here applied to the study of the global quasi-helical (QSH) states that are achieved both in MHD numerical simulations and in experimental activity performed on the reversed-field pinch (RFP) magnetic configuration.

Helical states. 3D nonlinear visco-resistive MHD numerical simulations of RFP with the cylindrical and spectral code SpeCyl [1] predicted the possibility that a single MHD mode of resistive-kink tearing nature could saturate and dominate the other MHD modes, creating a QSH state [2]. A similar state was indeed observed in high current operations (up to 2MA in RFX-mod). It is characterized by large thermal structures, by internal transport barrier [3] and by quasi-periodic reconnection events that intermittently bring the system back to a fully 3D field configuration. Another theoretical prediction is that the helicity (i.e. the toroidal wave number of the dominant MHD mode) of the QSH state can be externally forced by the use of a suitable helical magnetic boundary condition, a simple helical edge perturbation to the radial component of the field, called magnetic perturbation, MP [4,5]. This theoretical prediction was indeed verified in the RFX-mod experiment [6].

In this paper we will describe the MHD dynamics of forced helical states. Values of helicity different from n=-7, the one spontaneously occurring at high current in the RFX-mod machine in Padova, numerically studied in [7], will be investigated. We will show that forced QSH states built upon non-resonant MHD modes (non-resonant with respect to the safety factor profile) have better topological properties than QSH states built upon resonant MHD modes: bigger areas of conserved surfaces are detected and lower transport coefficients values are computed. On the other hand, as shown in [8] and under experimental validation in RFX-mod, the plasma responds better to forced resonant QSH states.

MHD dynamics. The dynamics of the RFP states in the visco-resistive 3D MHD model depends on four main parameters (and on the initial equilibrium): two parameters are related with plasma dissipation, normalized resistivity ($\eta=S^{-1}$) and viscosity ($\nu=M^{-1}$) and two are related with the features of the boundary conditions, MP helicity (n_{MP}) and MP intensity (MP%). Depending on the value of the four parameters different dynamical regimes are possible. At high dissipation independently of b.c. stationary 2D helical states are observed. At low dissipation, low MP%, intrinsically 3D states are observed. At low dissipation and over a threshold in MP% quasi-helical states with a helicity equal to n_{MP} are found. In this paper we study the low-dissipation over-threshold MP% area of the parameter space, characterized by intermittent QSH phases with a preferred dominant mode (with poloidal wave number m=1 and toroidal wave number $n=n_{MP}$) in between sawtooth crashes and by a high level of resemblance with experimental measurements [6]. Figure 1) shows the features of the RFP equilibrium in different dynamical situations, whose pinch parameter is set to $\Theta= B_\theta(a)/\langle B_z(a)\rangle=1.6$, with $S=10^6$ and $M=10^4$. The evolution of a wide spectrum of MHD modes with $0\leq m\leq 4$ is studied. MPs are applied with $m_{MP}=1$ and with $-11\leq n_{MP}\leq -5$. The perturbed $b_r(a)$ amplitude considered here is 4% or 6% of the mean edge poloidal field. In figure 2) the MHD dynamics of a simulation with $n_{MP}=-5$ is shown.

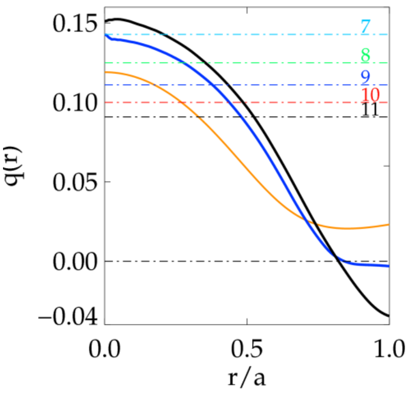

Figure 1: Safety factor profile of the equilibrium used as initial state for the MHD simulation (orange). In black and blue two profiles modified by the non-linear dynamics (blue before a reconnection event, black after)

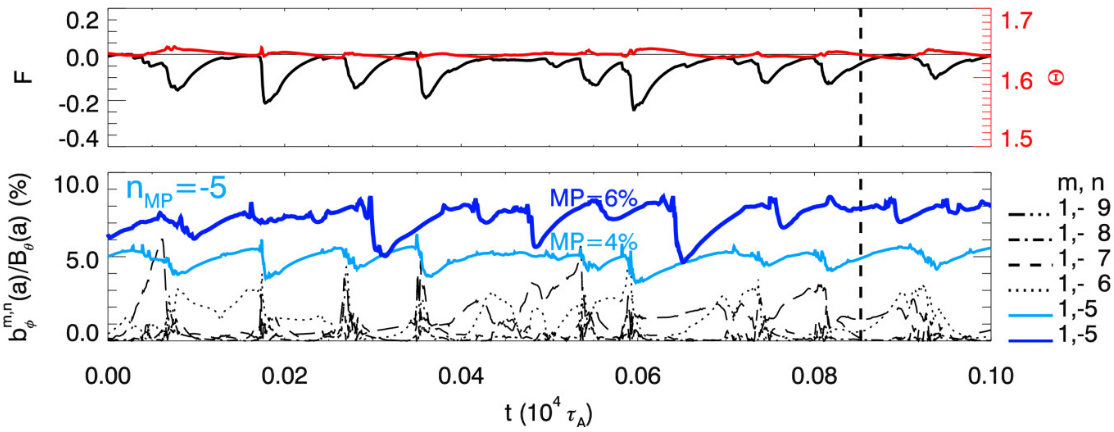

Figure 2: MHD dynamics when MP%=4% and n_{MP}=-5. Top: temporal evolution of the pinch parameter and of the reversal parameter $F= B_z(a)/\langle B_z(a)\rangle$: drops of F are correlated with reconnection events. Bottom: temporal evolution of the most important MHD modes. The (1,-5) is clearly dominant, apart during the abrupt reconnection events. In dark blue the temporal evolution of the (1,-5) MHD mode, for a different simulation, when higher MP are imposed (MP%=6%): the dynamics is qualitatively the same.

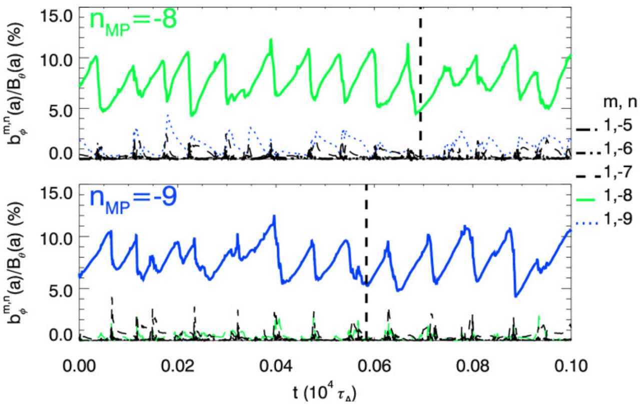

Figure 3: MHD dynamics when MP%=4% and nMP=-8 (top) and nMP=-9 (bottom). The (1,n_{MP}) mode is dominant, independently of the value of n_{MP}.

In figure 3) simulations with n_{MP}=-8 and n_{MP}=-9 are shown. Qualitatively the MHD dynamics in the three cases is the same, with long-lasting QSH phases interrupted by reconnection events characterized by a sudden rise in the value of perturbations to the helical equilibrium and the formation of current sheets.

Magnetic topology. The magnetic field topology is studied with the field line tracing code NEMATO [9,10]. The time instants highlighted in figures 2),3) are analyzed: these states have the same adimensional parameters (only different n_{MP}) and a similar value of secondary perturbations to the helical equilibrium; more in detail, the time instants chosen have a ratio between dominant and cumulated secondary modes amplitude that is equal to 1.5 and the cumulated secondary modes amplitude was divided by a factor of 3 to match the values measured in RFX-mod and.

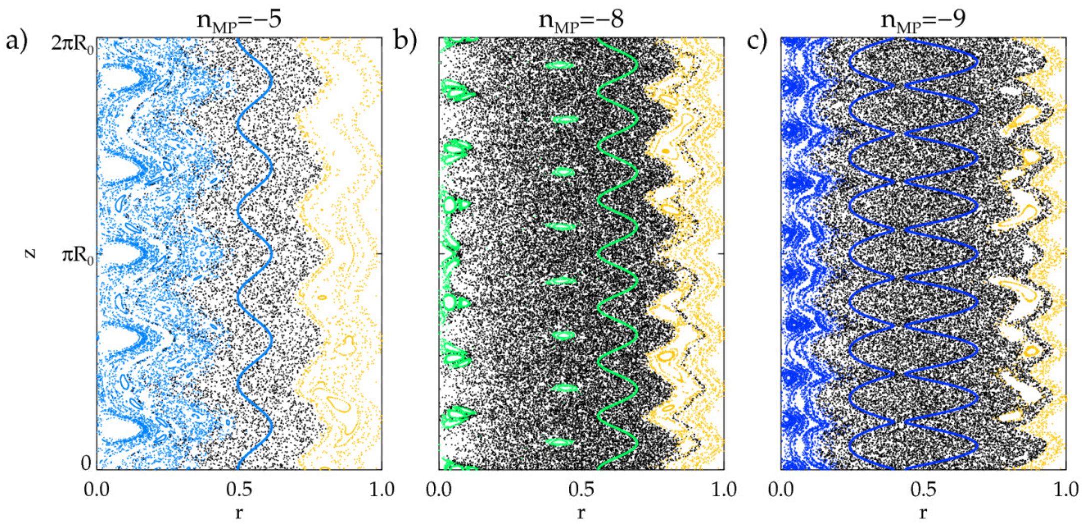

Figure 4: The QSH states built upon the non-resonant MHD mode, panel a), is characterized by two large regions of conserved magnetic surfaces at the core r/a=0.3 and around the reversal r/a=0.85. The colored/ordered area is much bigger than the corresponding areas in panel b) and c). Thick lines represent unperturbed flux surfaces used to compute the diffusion coefficients described later in the paper.

It is evident from figure 4) that states with lower helicity are characterized by higher areas of conserved magnetic surfaces, probably due to the non-resonant nature of the dominant mode: in fact a non-resonant mode does not create a magnetic island, whose separatrix represents a seed for magnetic chaos [10,11].

Transport coefficients. The problem of cross-field transport in the presence of a static and stochastic magnetic field is usually addressed considering average transport characteristics; in particular magnetic field lines diffusion coefficients [12]. The Lyapunov exponent, λ, quantifies the exponential separation between two initially close magnetic field lines and is a measure of the local stochasticity of the magnetic field. It is computed averaging on a set of couples of magnetic field lines with initial points radially separated by a quantity $\delta \rightarrow 0$. The diffusion coefficient, D_{st}, can be defined as an average rate of change of the quadratic mean square displacement (perpendicular to the unperturbed flux surfaces) of a set of magnetic field lines starting from the same flux surface (that is plotted in each panel of figure 4). The behavior of these two physical quantities with n_{MP}, figure 5), supports the thesis that non-resonant QSH states have better topological properties. In figure 5) the values of D_{st} and of λ normalized to the n_{MP}=-7 case are shown. One may notice that the QSH states built upon resonant MHD modes have a much higher diffusion coefficient (up to three times) and a higher Lyapunov exponent (up to five times). The first non-resonant MHD mode (n_{MP}=-6) seems to represent the best option to achieve a reduction of the level of transport due to the stochastic magnetic field.

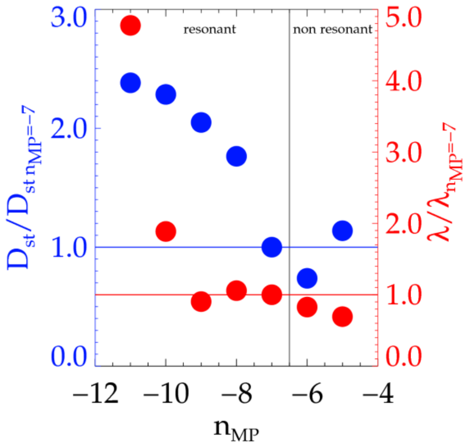

Figure 5: Values of D_{st} (left axis) normalized to the n_{MP}=-7 case. Value of the Lyapunov exponent (right) relative to the n_{MP}=-7 case. Higher values are computed for forced resonant QSH states.

Conclusion. Non-resonant QSH states seem to have similar dynamical properties to the resonant-QSH states, but better topological properties. This feature can be linked to the lack of magnetic islands associated with the MHD mode and to the possibility for the MP to influence the plasma up to the core; this influence may be affected by the addition of a self-consistently computed plasma flow [13], a feature that will be added soon to the model.

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