Stimulated Quasi Helical dynamics in pinch configurations

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Introduction. 3D MHD provides a powerful tool to interpret and predict the helical self-organization in toroidal pinches. In fact, in the last decade a paradigmatic change has occurred for the theoretical description of the Reversed Field Pinch (see for example [Cappello 2011]), promoted by experimental evidence in high current operation [Lorenzini 2009]. More recently, and in a similar way, 3D MHD helical equilibria as saturated kink states gained significant attention also for tokamak interpretation of experimental "snakes" [Cooper 2010, Delgado-A 2013]. A very recent milestone in the development of predictive/quantitative capability in the case of RFP modeling appears to be the use of helical boundary conditions [Bonfiglio 2011], schematically mimicking the action by the coils of the advanced feedback system available in RFX-mod experiment [Bonfiglio 2011, Piovesan 2011]. In fact, the use of an edge helical *Magnetic Perturbation* (**MP**) brings the comparison of nonlinear modeling and experimental phenomenology of *Quasi-Single Helicity* (**QSH**) to a quantitative level significantly enlarging the region of dimensionless parameter space (resistivity and viscosity) where QSH are obtained [Cappello 2012, Veranda 2013]. **In this paper we address** in particular the issue of helical regimes stimulated by the (nominally axis-symmetric) action of toroidal (magnetic) flux modulation, the so-called *Oscillating Parallel Current Drive* (**OPCD**) operation [Bolzonella 2001,Terranova 2007], successfully introduced in RFP experiments with the aim of prolonging the confinement improvements obtained with the Pulsed Parallel Current Drive [Sarff 1994, Sarff 2003].

Background. The RFX-mod machine demonstrated that the OPCD technique allows systematic QSH stimulation (with better confinement properties) out of fully 3D states (characterized by several resistive kink - tearing modes and chaotic magnetic field lines). Usually, the QSH dominant mode increases during the phase in which the toroidal field at the edge is decreased (*co-dynamo* phase). This is shown in [Terranova 2007], based on experiments performed at plasma currents I_P~600 kA. Later experimental activity, especially at higher currents ($I_P \geq 1.2$ MA), started to show more variability in temporal phasing between external action and plasma response, along with smaller advantage in QSH stimulated by OPCD with respect to the QSH spontaneously occurring at those larger plasma currents. On the numerical side, early 3D MHD modeling of PPCD showed that an important part of the dynamical process triggered by the flux modulation is plasma compression by pinch effect [Puiatti 2003]. Then, OPCD modeling reproduced the amplitude modulation effect of the dominant MHD mode in QSH states, but, differently from experimental evidences, only starting from a pre-established QSH state. An additional difference in MHD simulations is that the amplitude of the dominant mode increases during the increasing phase of the toroidal

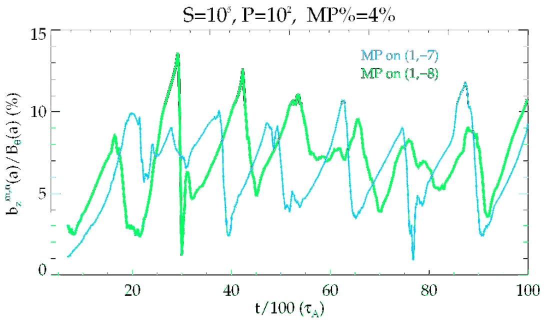

Figure (1a): Temporal behaviour of the stimulated MHD mode in two different simulations with n_{MP}=7,8. It is possible to notice that the (1,-8) MHD mode has higher peak amplitude, as is synthetized, averaging during the whole length of the simulation, in Fig.(1b) both at S=3·10^4 and S=10^5.

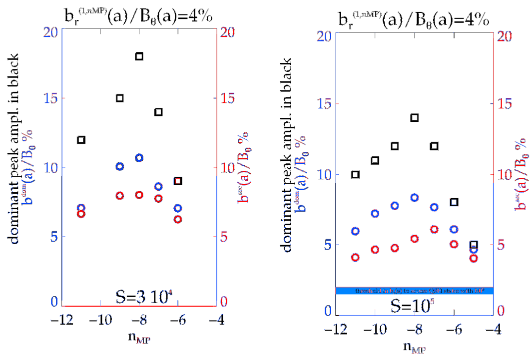

Figure (1b): Response of the dominant mode (blue dots) to the applied n_{MP} (x axis). Cumulated amplitude of the secondary modes (red dots). Peak amplitude of the dominant mode (black squares).

field at the edge (*counter-dynamo* phase), which has been only seldom observed in experiments [Bonfiglio 2007]. **We present here results of a study in its initial stage** focused on the impact on MHD dynamics of MPs together with OPCD action.

Numerical tools. The numerical simulation of the RFP configuration is performed through the non-linear spectral 3D MHD code SpeCyl [Cappello 1996], that solves the visco-resistive MHD model in cylindrical geometry (periodical boundary conditions in the *z* direction and aspect ratio R_o/a=4). SpeCyl has been benchmarked against PIXIE3D [Bonfiglio 2010].

Results: Response to MP (without OCPD). We first analyse the effect of the application of MPs with different helicities on the spontaneous MHD dynamics, without OPCD action. The simulation setup is the same as in [Veranda 2013], with pinch parameter set to $\Theta = B_\theta(a)/\langle B_\theta(a)\rangle$=1.6. Two sets of simulations are considered here with different values of the Lundquist number S (inverse normalized resistivity η), namely $S=\eta^{-1}=3\times10^4$ and $S=10^5$; the inverse normalized viscosity, M, is fixed to $M=\nu^{-1}=10^4$ for both sets. MPs are applied with poloidal and toroidal periodicities: m_{MP}=1 and 5≤n_{MP}≤11. The perturbed $b_r(a)$ amplitude shown here is 4% of the mean edge poloidal field. In figure (1a) the MHD dynamics of the stimulated MHD modes is shown for the S=10^5 case, using n_{MP}=7, 8. In both cases, the dominant mode undergoes quasi periodic sawtooth cycles; however, the *response* of the n=8 mode to the MP is bigger, as shown by the larger average and peak values. The result from the full sets of simulations $5 \leq n_{MP} \leq 11$ is reported in fig.(1b): the largest *response* to MPs is obtained using $n_{MP}=8$ for both the values $S=3\times10^4$, 10^5. **Response to MP and OPCD.** The combined effect of MP and OPCD action has been analyzed for the simulation set with $S=3\times10^4$. OPCD has been applied using MP with $n_{MP}=7$, 9, 11. The amplitude of the OPCD action is fixed, resulting in reversal parameter oscillations from $F\cong0$ to $F\cong-0.3$ ($F=B_z(a)/\langle B_\theta(a)\rangle$). Two different OPCD (toroidal flux modulation) periods are considered: $\tau_{OPCD}=800$, 4000 τ_A, i.e. about 2 and 8 times the spontaneous sawtooth period τ_F, similarly to the experimental choices. Figures (2a) and (2b) show the effect of OPCD on the $n_{MP}=7$ case: notice that the 4% MP is not strong enough to stimulate the QSH state. The OPCD (applied starting from t=4400 τ_A) appears to be temporarily effective in the amplification of the dominant mode, whose peak amplitudes are larger than without OPCD. In addition, the quality of the resulting QSH states depends on the OPCD period: the shorter period is more efficient in modulating the dominant mode amplitude, while the longer one extends to the co-dynamo phase the laminar conditions appearing in counter-dynamo. Figures (3a) and (3b) show the effect of OPCD on the $n_{MP}=9$ case, where the 4% MP is effective in stimulating the

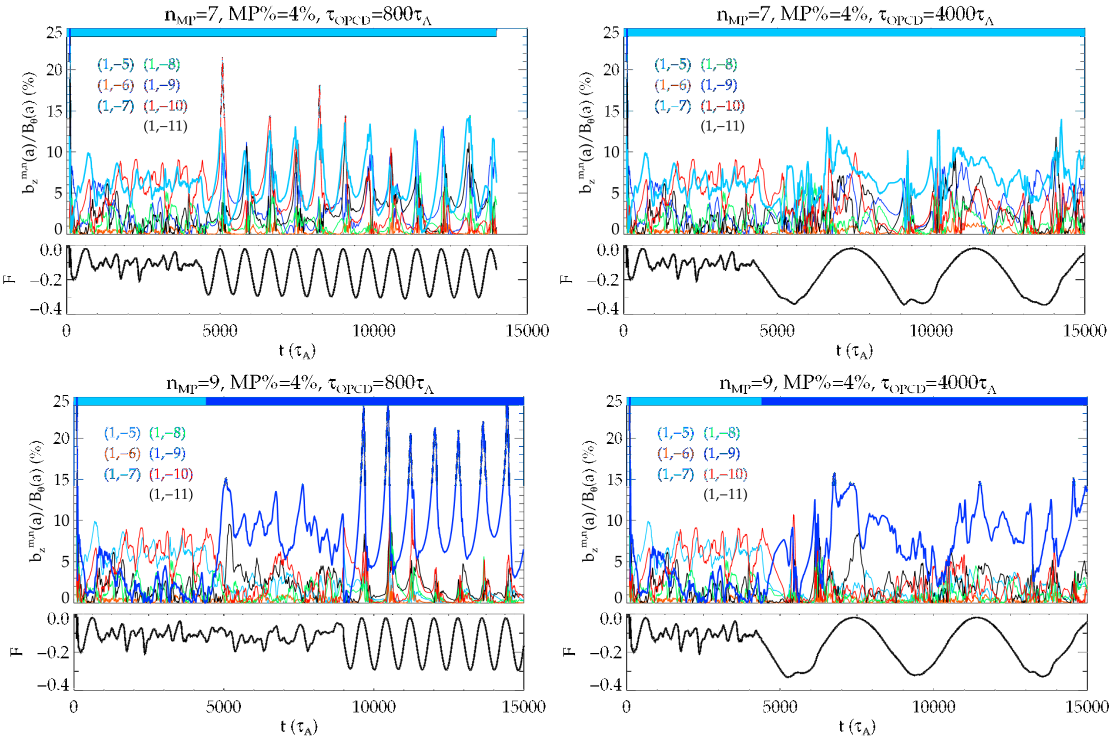

Figure (2a,2b) *(first row)* **(3a,3b)** *(second row)*: Temporal behaviour of the most important MHD modes and of the reversal parameter F. Lundquist number is $S=3\cdot10^4$. Notice that the value of MP%=4% on the (1,-7) MHD mode is less effective in the stimulation of a QSH than the same MP on the (1,-9) MHD mode in fig.(3a). Colored bands in top of the top plot indicate the mode externally stimulated by MP.

QSH state (as seen in fig.(3a) during the time interval 4400≤t≤9000 τ_A). Again, a dependence on the OPCD period is observed, with similar features as the previous n_{MP}=7 case. It is important to notice that in all the cases analysed in this study there is a clear correlation between the increase of the dominant mode and the shallowing of the reversal parameter (counter-dynamo phase). As mentioned above, this numerical result seems to be in contrast with the results published in [Terranova 2007], while it is consistent with some other cases [Bonfiglio 2007]. **Conclusions.** The action of OPCD proves to be effective in periodically amplifying the amplitude of the mode selected by MP. Such a response strongly depends on the chosen MP helicity. Sensitivity to the OPCD period is also observed: the shorter period ($2\times\tau_F$) results in a temporal phasing with dominant mode increasing in counter-dynamo (in experiment seldom observed at lower plasma currents). The longer ($8\times\tau_F$) is less effective in amplitude modulation, but extends the “laminar” dynamics also during the co-dynamo phase, when a MH dynamics would be otherwise observed with the shorter period. These first promising indications strongly encourage the continuation of these studies, both on the numerical and the experimental side.

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