Effect of a realistic boundary on the helical self-organization of the RFP

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Introduction. The reversed-field pinch (RFP) is a configuration for the magnetic confinement of fusion plasmas, in which most of the toroidal field is generated by the plasma itself through a self-organized dynamo process, instead of being produced by external coils as in the tokamak. In the RFP, the nonlinear saturation of resistive-kink/tearing modes brings to the spontaneous emergence of helical states with improved confinement. This is observed both in nonlinear magnetohydrodynamics (MHD) modelling [1] and in RFP devices, especially at high current [2]. A major advance in the predictive capability of nonlinear MHD modelling for RFP plasmas was made possible by allowing helical perturbations of the radial magnetic field at the plasma boundary, which was suggested by analytical analysis of helical equilibrium equations [3]. A proper use of helical magnetic perturbations (MPs) in MHD modelling allowed to obtain experimental-like helical states [4] and to predict new helical states with chosen helical twist, successfully produced in RFX-mod [5].

In this paper, we study helical self-organization in the presence of a resistive shell at the plasma boundary $r = a$, surrounded by a vacuum layer and an ideal wall at $r = b$. First, we show single-mode simulations to test the effect of the new boundary. Then, we discuss multi-mode RFP simulations. Two main results are presented. On the one hand, by varying the distance between the plasma and the ideal wall it is possible to provide a nonlinear estimate for the decrease of secondary modes by increased shell proximity. This is of interest in view of the upgraded RFX-mod2 device (starting operation in 2021), in which the shell proximity will change from $b/a = 1.11$ to $b/a = 1.04$ [6, 7]. On the other hand, it is observed that with a proper choice for the resistive time of the conducting shell at $r = a$, helical states do emerge in a spontaneous and systematic way, as in the experiment, without the need of imposed MPs.

Numerical modelling is performed with the nonlinear 3D MHD code SpeCyl [8], a spectral code that solves visco-resistive MHD equations in cylindrical geometry. The standard boundary conditions of SpeCyl, corresponding to a perfectly conducting wall at $r = a$, have been modified similarly as in Refs. [9] to take into account a thin resistive wall with resistive diffusion time τ_W at $r = a$, and a vacuum region surrounded by an ideal wall at $r = b$.

Single-mode test cases. The wall at $r = a$ is assumed to be highly resistive ($\tau_W/\tau_R \ll 1$, with τ_R the plasma resistive diffusion time), so that currents induced into it are negligible on the simulation time scales. The effect of varying the ideal shell proximity is studied. The first test case is a $m = 2$, $n = 1$ external kink mode in a tokamak equilibrium with $q(a) \lesssim 2$ (Fig. 1). The mode is linearly stable with ideal wall at $r = a$ (standards BCs) as predicted by the energy principle [10]. It remains stable with ideal wall close to the plasma, then for $b/a > 1.3$ it becomes unstable and nonlinearly saturates at finite amplitude. For $b/a \gtrsim 2$ the solution is basically the same as with no ideal wall. The other three test cases deal with $m = 1$ modes in a RFP configuration with $q(0) = \frac{1}{8}$. The $m = 1$, $n = 6$ external kink mode (Fig. 2) shows the same qualitative behaviour as the external kink in the tokamak, but here a very narrow vacuum layer is sufficient to make the mode unstable, as discussed in Ref. [11]. We also note that the on-axis b_r value at saturation is maximum for $b/a = 1.05$ and decreases for larger b/a, in analogy with what found in Ref. [3]. The $m = 1$, $n = 10$ internal kink mode and the $m = 1$, $n = 21$ tearing mode (Fig. 3 and Fig. 4, respectively) are unstable even with ideal wall at $r = a$, and their growth rates and saturated profiles do not change significantly in the presence of a vacuum region between the plasma and the ideal wall, despite the significant increase of the $b_r(a)$ saturation value.

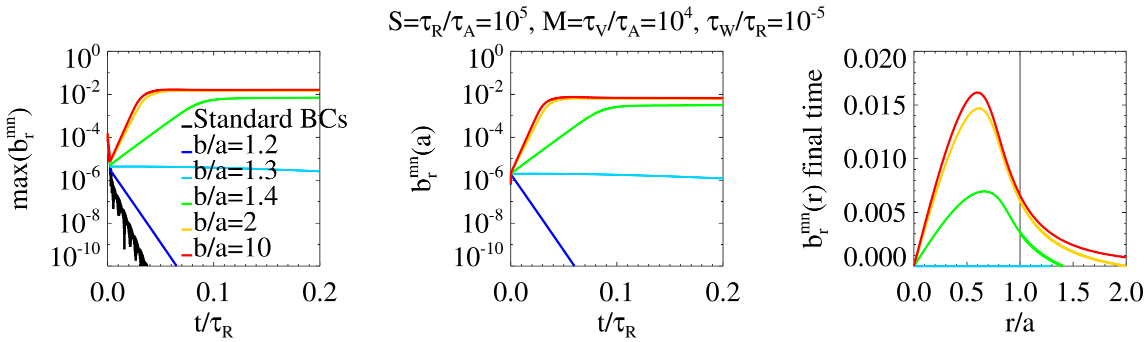

Figure 1: *Single-mode test case. $m = 2$, $n = 1$ external kink in the tokamak with $q(a) \lesssim 2$.*

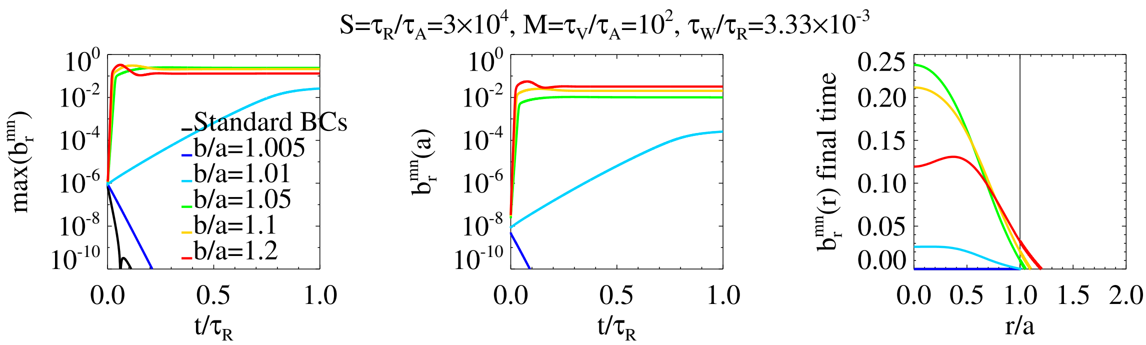

Figure 2: *Single-mode test case. $m = 1$, $n = 6$ external kink in the RFP with $q(0) = \frac{1}{8}$.*

Multi-mode RFP simulations. Two sets of multi-mode RFP simulations have been performed in the low dissipation regime with quasi-periodic reconnection events (in this regime, applied MPs produce experimental-like helical states [4]). The first set of multi-mode RFP sim-

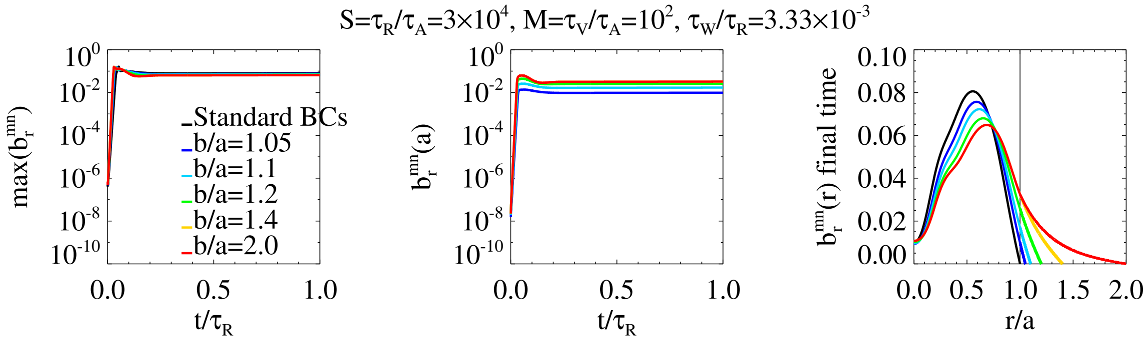

Figure 3: *Single-mode test case.* $m = 1$, $n = 10$ *internal kink in the RFP with* $q(0) = \frac{1}{8}$.

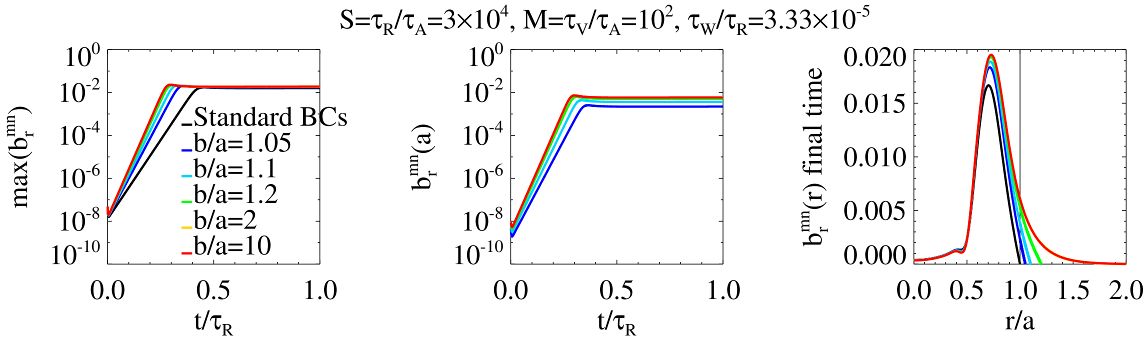

Figure 4: *Single-mode test case.* $m = 1$, $n = 21$ *tearing mode in the RFP with* $q(0) = \frac{1}{8}$.

ulations is performed by decreasing b/a from 1.2 to 1 at fixed $\tau_W/\tau_R = 10^{-2}$. The aim of this scan is to provide a nonlinear prediction for the reduction of radial magnetic field fluctuations in the upgraded RFX-mod2 device (starting operation in 2021, with $b/a = 1.04$) with respect to RFX-mod ($b/a = 1.11$). Indeed, at present the only predictions for the reduction of the edge b_r amplitudes in RFX-mod2 are provided by the RFXLocking code [12] which includes a realistic feedback control system, but is based on a linear Newcomb approach with the conservative assumption that the internal amplitude of MHD modes will remain the same as in RFX-mod. On the other hand, the present version of SpeCyl, with an ideal shell at given distance from the plasma, can be considered as a best-case scenario of the real feedback performance (because an ideal shell behaves as an ideal feedback system which perfectly cancels b_r at its surface) [6].

The result of the nonlinear multi-mode scan in b/a is shown in Fig. 5. It is observed that the edge b_r (directly related to the deformation of the last closed magnetic surface) grows linearly with b/a. In particular, more than a factor of 2 reduction of the edge b_r is expected going from $b/a = 1.11$ to $b/a = 1.04$. As a consequence, a milder plasma wall interaction is expected in RFX-

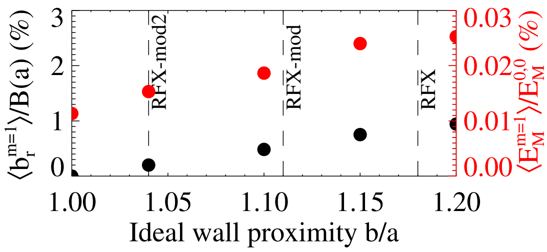

Figure 5: *Time-averaged edge* b_r *amplitude (black) and total magnetic energy (red) of* $m = 1$ *modes for a set of nonlinear MHD simulations of the RFP with varying proximity of the ideal wall to the plasma.*

mod2. The volume-integrated magnetic energy is also predicted to decrease by moving the ideal shell closer to the plasma. More precisely, SpeCyl predicts a reduction of overall mode energy of about 30% for RFX-mod2 compared to RFX-mod, suggesting a decrease of internal transport due to the related reduced magnetic field stochasticity.

The second set of multi-mode RFP simulations is performed by varying τ_W at fixed $b/a = 1.2$. As shown in Fig. 6, a regime is observed in which QSH states with $n = 7$ dominant mode spontaneously and systematically emerge in between reconnection events, as observed in RFX-mod, without the need of any ad-hoc external perturbation. This regime can be found in MHD modelling when τ_W is comparable with the characteristic period between reconnection events. This preliminary observation suggests that the self-consistent interplay between MHD dynamics and a realistic magnetic boundary, providing a "memory" effect, might be a key element for the emergence of QSH states in the RFP.

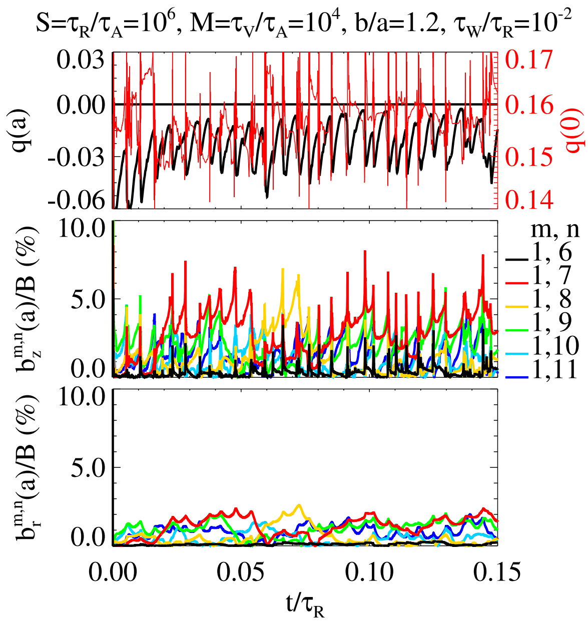

Figure 6: *Multi-mode RFP simulation with* $\tau_W/\tau_R = 10^{-2}$*, showing the spontaneous emergence of the* $m = 1$*,* $n = 7$ *mode as in RFX-mod.*

Future extensions of this work include SpeCyl simulations with a second resistive shell at $r = b$ (recently implemented in the code) to study resistive-wall modes, modelling of a feedback control system for MHD modes as in RFX-mod2, and the coupling with finite plasma rotation.

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