Non-linear visco-resistive MHD modelling of reversed-field pinch fusion plasmas: viscosity coefficient studies

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Introduction: Non-linear magneto-hydrodynamics (MHD) simulations represent a fundamental tool in modelling magnetically confined fusion plasmas. In this framework, the momentum balance equation often includes a viscosity term, further simplified by considering a constant and uniform viscosity coefficient. However, there is no unique consent (neither in simulations nor in experiments) about the more appropriate form of the viscosity term [1] and different estimates of the viscosity coefficient exist, according to classical [2] or turbulent transport [3-5]. Although resistivity may also be anomalous [6], viscosity still represents the major uncertainty parameter, since recent papers [7, 8] (and ref. therein) have highlighted the existence of a two orders of magnitude difference, between classical and turbulent viscosity estimates in reversed-field pinch (RFP) fusion plasmas.

Aim of this work: We performed a sensitivity study on the effect of a non-uniform scalar viscosity on the helical self-organization processes in MHD modelling, according to classical (Braginskii) expression for typical RFP discharges in RFX-mod [9]. We finally evaluate also the impact of time dependent visco-resistive coefficients.

Numerical modelling: The numerical code used in this paper is SpeCyl [10], which solves the 3D non-linear visco-resistive MHD equations in dimensionless units and cylindrical geometry, exploiting a spectral formulation in the axial and azimuthal coordinates. In addition, a constant and uniform plasma density is considered and the effect of the pressure gradient is neglected (low β hypothesis). Two scalar coefficients rule the transport in this model: the dimensionless resistivity η and viscosity ν, adopting as reference case constant radial profiles as follows: $\eta(r) = \eta_0(1 + 20r^{10})$, $\nu(r) = \nu_0$.

3D nonlinear visco-resistive MHD successfully describes the helical self-organization processes observed in RFP configurations [11] jointly exploiting two features [9]: the dimensionless Hartmann number that rules the dynamics and is defined by the visco-resistive coefficients, $H =$

$(\eta\nu)^{-1/2}$ [12], and the impact of finite edge radial magnetic field (non-ideal magnetic field helical boundary conditions) [13], the so-called Magnetic Perturbations (MP).

Viscosity profiles effect: We have considered four different viscosity profiles in SpeCyl simulations, $\nu_{1,\dots,4}(r)$ (Fig. 1), inspired by the Braginskii perpendicular kinematic viscosity, $\nu_\perp \propto n^{3/2}/B^3T^{1/2}$, calculated considering n, T and B profiles compatible with the RFX-mod experimental findings.

<u>2D simulations</u> are performed with 20 harmonics (the fields are expressed by Fourier harmonics with m and n the poloidal and axial wave numbers) with fixed helicity ($h = n/m$). We have considered 4 SpeCyl simulations, with $h = -12$, $\eta_0 = 10^{-5}$, $\nu_0 = 10^{-2}$ and Hartmann $H \sim 3 \cdot 10^3$, distinguished by the viscosity profile $\nu_{1,\dots,4}(r)$ imposed. The linear growth rate γ of the magnetic energy decreases for profiles approaching the Braginskii one, characterized by a higher value of the volume average viscosity and of the viscosity at the resonance surface (Tab. 1). The set of 2D simulations with $h = -12$ and flat viscosity profile confirms qualitatively this trend displaying the scaling: $\gamma \propto \eta^{0.74}\nu^{-0.20}$, in qualitative agreement with [14, 15].

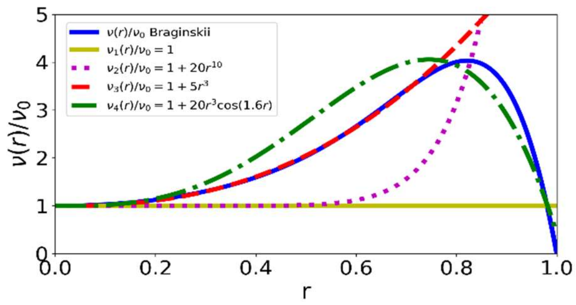


Figure 1: Comparison of the viscosity profiles tested in SpeCyl simulations.

Visco. prof.	$\gamma\tau_A$	$\nu(r_{res})$
$\nu_1(r)$	$8.90 \cdot 10^{-3}$	1
$\nu_2(r)$	$7.35 \cdot 10^{-3}$	1.04
$\nu_3(r)$	$7.21 \cdot 10^{-3}$	1.78
$\nu_4(r)$	$6.85 \cdot 10^{-3}$	3.11

Table 1: The dominant mode growth rate decreases as the viscosity at the resonanant surface is increased.

<u>3D simulations</u>: We have analysed the effect introduced by Braginskii-like viscosity profiles on the helical regimes observed in 3D simulations (225 Fourier harmonics with $m \leq 4$ and n up to 75 are evolved here) in the three dissipative regimes: **a)** <u>Single Helicity</u> ($H < 2000$), **b)** <u>Multiple Helicity</u> ($H > 2000$) and **c)** <u>Quasi-Single Helicity</u> ($H > 2000$, with applied Magnetic Perturbation).

a) For the <u>SH</u> regime (with $\eta_0 = 3.33 \cdot 10^{-5}$, $\nu_0 = 3.33 \cdot 10^{-2}$, $H \sim 9.5 \cdot 10^2$), an increase of viscosity produces a decrease of the modes linear growth rate (similar to the 2D case), which influences the helicity of the ensuing dominant mode between $h = -11$ and $h = -10$, Fig. 2.

b) In the low visco-resistive regime ($\eta_0 = 10^{-6}$, $\nu_0 = 10^{-4}$, $H = 10^5$) the <u>MH</u> regime is observed. This is a highly turbulent dynamics, characterized by magnetic chaos and by the absence of a dominant $m = 1$ mode. The effect introduced by the Braginskii-like viscosity profiles is to

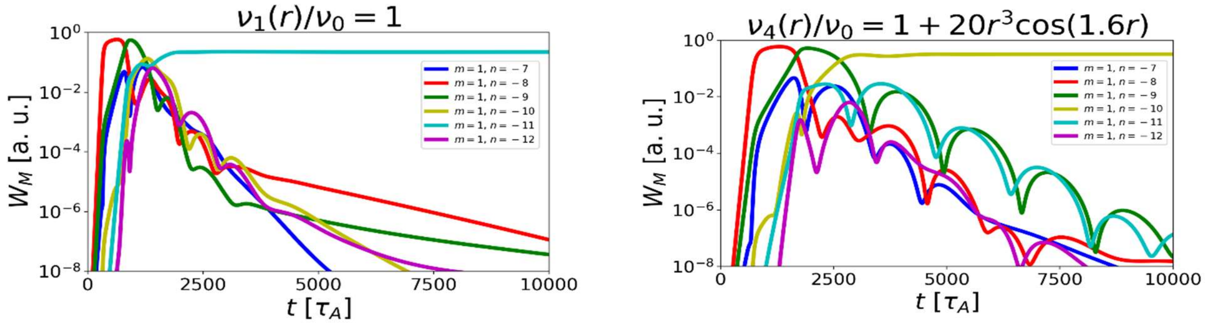


Figure 2: Magnetic energy evolution in 3D SpeCyl simulations. A volume average viscosity increase can cause the change of the dominant helicity.

damp the kinetic energy of $m = 1$, high n ($-25 \le n \le -15$) modes. This is expected, since the viscosity profiles analysed are higher in the region with $r/a \sim 0.6$, where the resonances of the high n modes occur. The kinetic energy damp of the modes with respect to the flat profile case, caused by the locally higher viscosity, triggers the growth of the correspondent magnetic energy modes [9], Fig. 3. This is consistent with an effect of plasma flows counteracting the growth of magnetic perturbations [16].

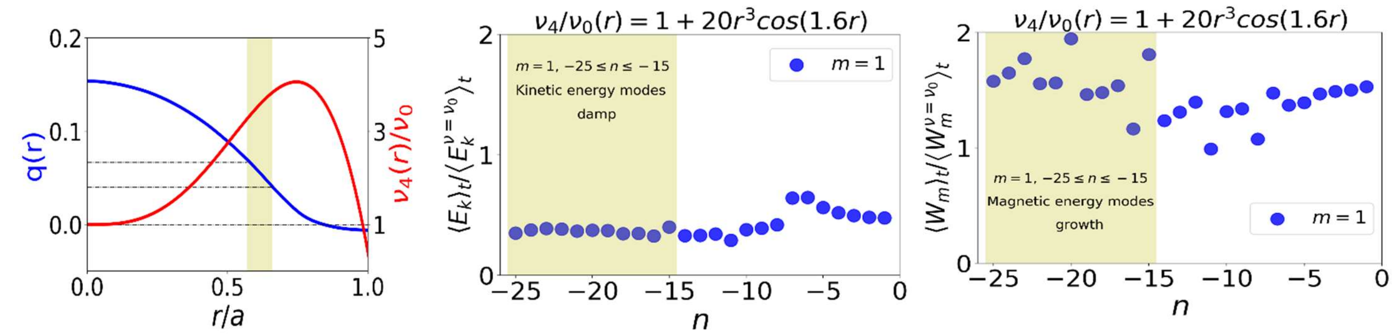
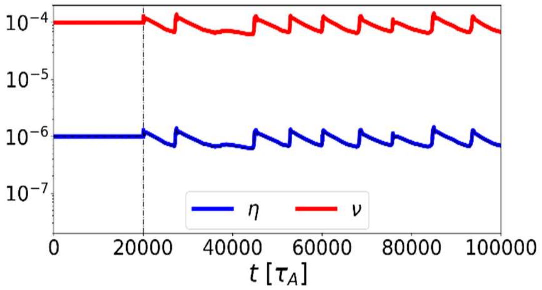


Figure 3: The resonance of the m=1 high n modes, takes place at radial coordinates characterized by high values of the viscosity (left). As a consequence, the m=1 spectrum is characterized by a damp of the kinetic energy modes with respect to the flat profile case(center) and a consequent growth of the correspondent magnetic energy modes (right).

c) In the low visco-resistive regime with applied Magnetic Perturbations (MP) [13] ($\eta_0 = 10^{-6}$, $\nu_0 = 10^{-4}$, $H = 10^5$ and $b_r^{1,-7}(a)/B_\theta(a) = 3.5\%$ as fixed MP), the QSH phase is observed. QSH is characterized by quasi-periodical ordered phases, during which a single dominant mode is amplified due to the imposed boundary conditions. Despite a slight increase in the $m = 1$, high n magnetic energy modes, (as in case **b)**) no significant effects on the helical organization are found, the latter remaining strongly determined by the small applied MP.

Time dependent visco-resistive dissipation: We finally evaluate the impact of a time dependent visco-resistive dissipation (with uniform viscosity profile). In particular, we present a 3D simulation (with applied MP $b_r^{1,-7}(a)/B_\theta(a) = 3.5\%$), where the central resistivity and viscosity are evolved keeping their ratio constant ($\nu_0/\eta_0 = 100$) with fixed profile and according to the relation: $\eta_0 = 1.75 \cdot 10^{-7}\left(W_M^{1,-7}(t)\right)^{-1/2}$. This relation is motivated qualitatively by considering that high confinement and temperature (large $W_M^{1,-7}$ in QSH) correspond to a low visco-resistive dissipation and vice versa. In practice, a variation of 1.6 in T and 1.1 in n during QSH cycles in RFX-mod [11] gives rise to a dissipation variation excursion of ~ 2.5, which is used here. As shown in Fig. 4, the introduction of such dependence results in a general slowdown of the RFP sawtooth activity [9]. In fact, the typical oscillation period (τ_{saw}) increases by a factor 1.14, from $7200\tau_A$ to $8200\tau_A$.



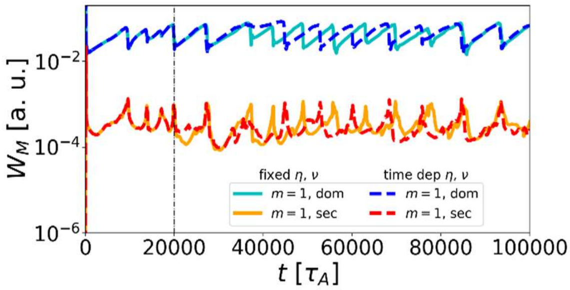


Figure 4: Time-dependent resistivity and viscosity, calculated according to the dominant mode magnetic energy (left). A slow down of the RFP sawtooth dynamics takes place with time dependent visco-resistive dissipation (right).

Conclusions: the introduction of "Braginskii-like" viscosity profiles (larger by a factor 2.8 in the edge region) produces a moderate damp (× 0.5) of the plasma flow spectral components resonating in spatial regions where the viscosity profile is higher. This causes those spectral components to show an increased (× 1.8) MHD magnetic activity, as a simple picture of the interplay between plasma flow and magnetic field predicts – i.e. an increase of the former causes a damp of the latter [16]. A first rough estimate of a self-consistent evolution of visco-resistive dissipation during the typical RFP sawtoothing cycles is also performed: a time dependent central value of the dissipation, linked to the $h = -7$ helical amplitude and inspired to RFX-mod experimental values excursion, slows down the RFP sawtooth activity, without significantly altering the dynamical regime. Further studies with the PIXIE3D code solving an extended-MHD model [10] for full self-consistency are foreseen.

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