Viscosity profile studies in 3D non-linear MHD modeling of RFP fusion plasmas

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Aim of this work

Sensitivity study of the viscosity profile effects [1] in 3D non-linear magnetohydrodynamics (MHD) simulations of fusion plasmas, with reference to the RFP configuration, implementing a profile inspired to the Braginskii perpendicular viscosity coefficient in the code and studying the effects on the plasma dynamics and the viscosity anomaly.

Visco-resistive MHD model

SpeCyl [3] solves the visco-resistive MHD model. Hypothesis:

- constant mass density
- negligible pressure
- cylindrical geometry

Input parameters: dimensionless resistivity η and viscosity ν:

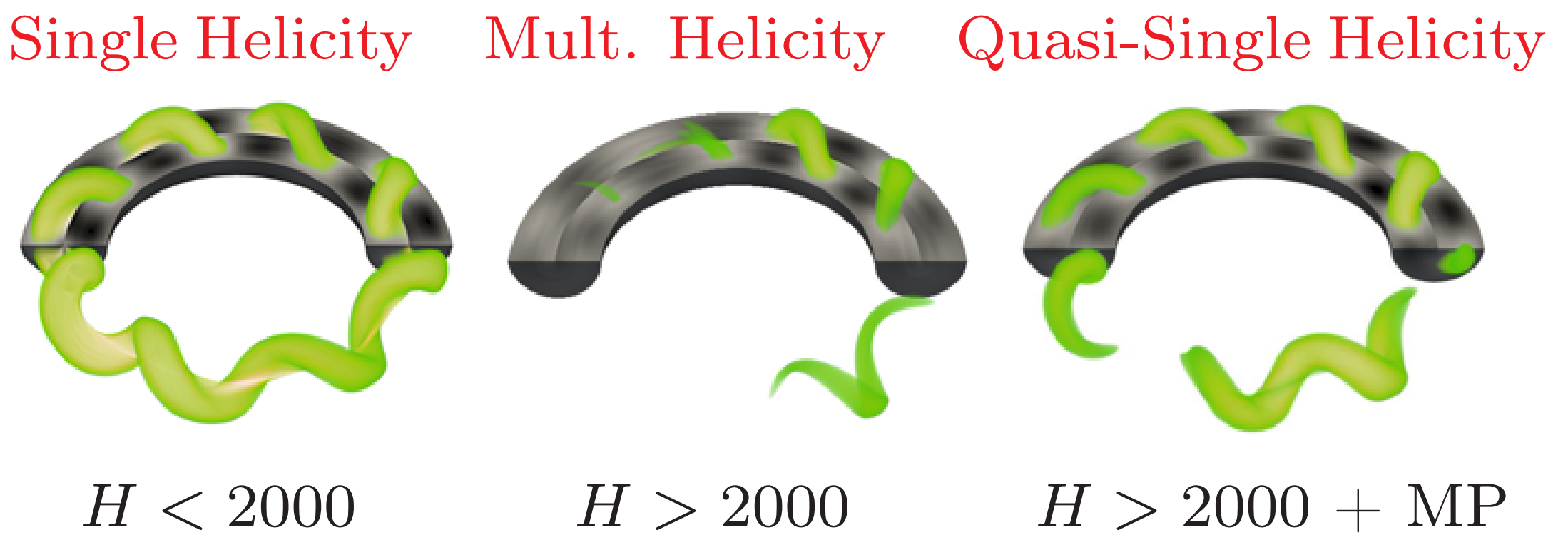
SpeCyl equations

$$\boxed{\begin{gathered}\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} = \mathbf{j}\times\mathbf{B} + \nu\nabla^2\mathbf{v} \\ \frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}) - \nabla\times(\eta\mathbf{j}) \\ \nabla\cdot\mathbf{B} = 0 \qquad \nabla\times\mathbf{B} = \mathbf{j}\end{gathered}}$$

Change of coordinates [4] $(\eta, \nu) \rightarrow (P, H)$, with $P = \nu/\eta$ magnetic Prandtl number and $H = 1/\sqrt{\eta\nu}$ Hartmann number:

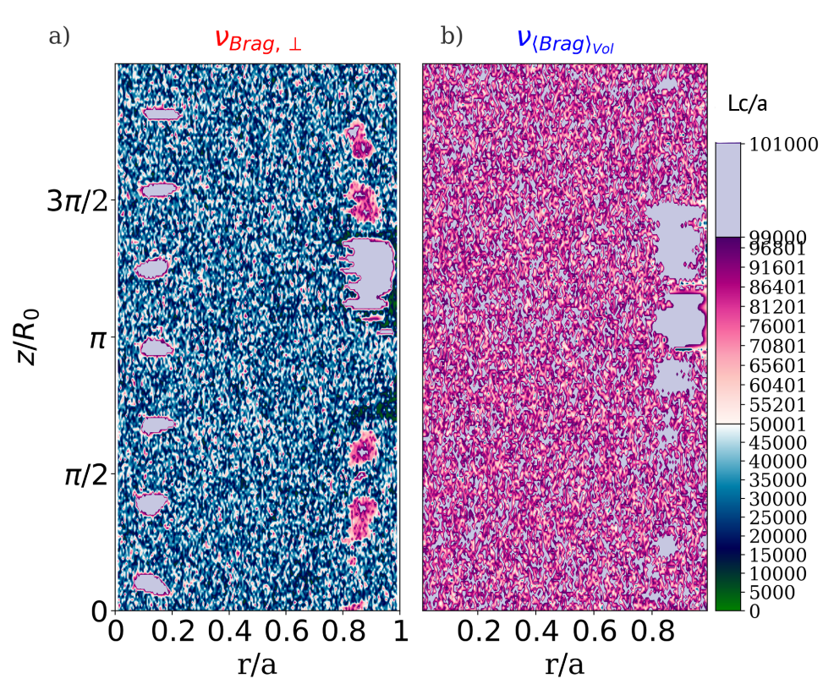
$\Rightarrow$ η and ν rule the plasma dynamics through H

$\Rightarrow$ H together with Magnetic Perturbation (finite $b_r(a)$, [5]) determines the plasma helical regime [6].



- **Resistivity η** profile: Spitzer-like $\eta \propto T_e^{-3/2}$, according to typical experimental temperature profiles: $\eta/\eta_0 = 1 + 20r^{10}$.
- **Viscosity ν** is the major uncertainty parameter among the transport coefficients [7]: different estimates exist according to classical [8] and turbulent theories [9].
  Profile: uniform in the majority of the simulations. Most relevant RFP instabilities are active in the direction perpendicular to the magnetic field [10] $\Rightarrow$ study of $\nu_{Brag,\perp}$ effects

Topology effects



$\nu_{Brag,\perp}$ increases MHD activity wrt $\nu_{\langle Brag\rangle_{Vol}}$

$\Rightarrow$ Negative effect on transport

$\Rightarrow$ lower connection length L_c

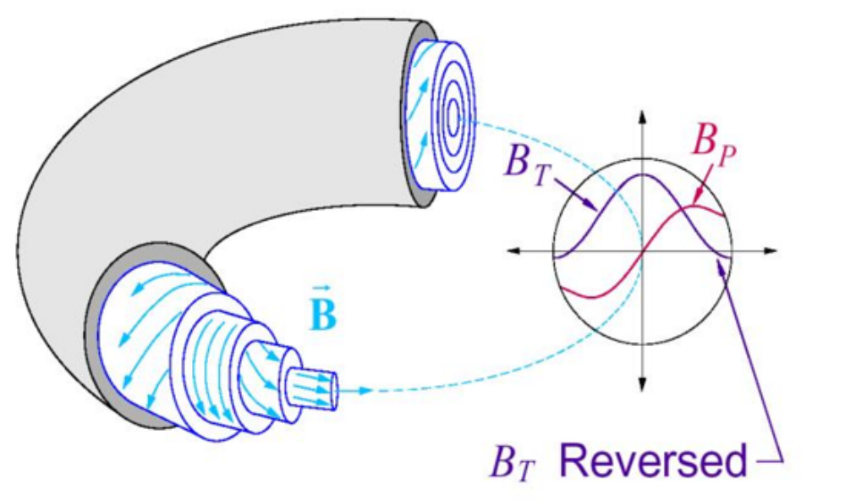
Conclusions

- a Bragiskii like viscosity profile results in damping the velocity field and enhancing magnetic field instabilities in the region where the viscosity is higher.
- the $\nu_{Brag,\perp}$ viscosity profile contributes in slightly reducing the anomaly

Reversed-field pinch configuration

Reversed-Field Pinch (RFP) configuration [2] is characterized by:

- small reversed edge toroidal field ($B_\phi(a) < 0$)
- large plasma current I_p (10 × stronger than tokamak with the same B_ϕ) $\Rightarrow$ high self-organization level
- same order of magnitude for magnetic fields: $B_\phi \approx B_\theta$.



Viscosity profiles test: settings

Simulation settings $\eta_0 = 10^{-6}$, $\nu_0 = 10^{-4}$, no MP

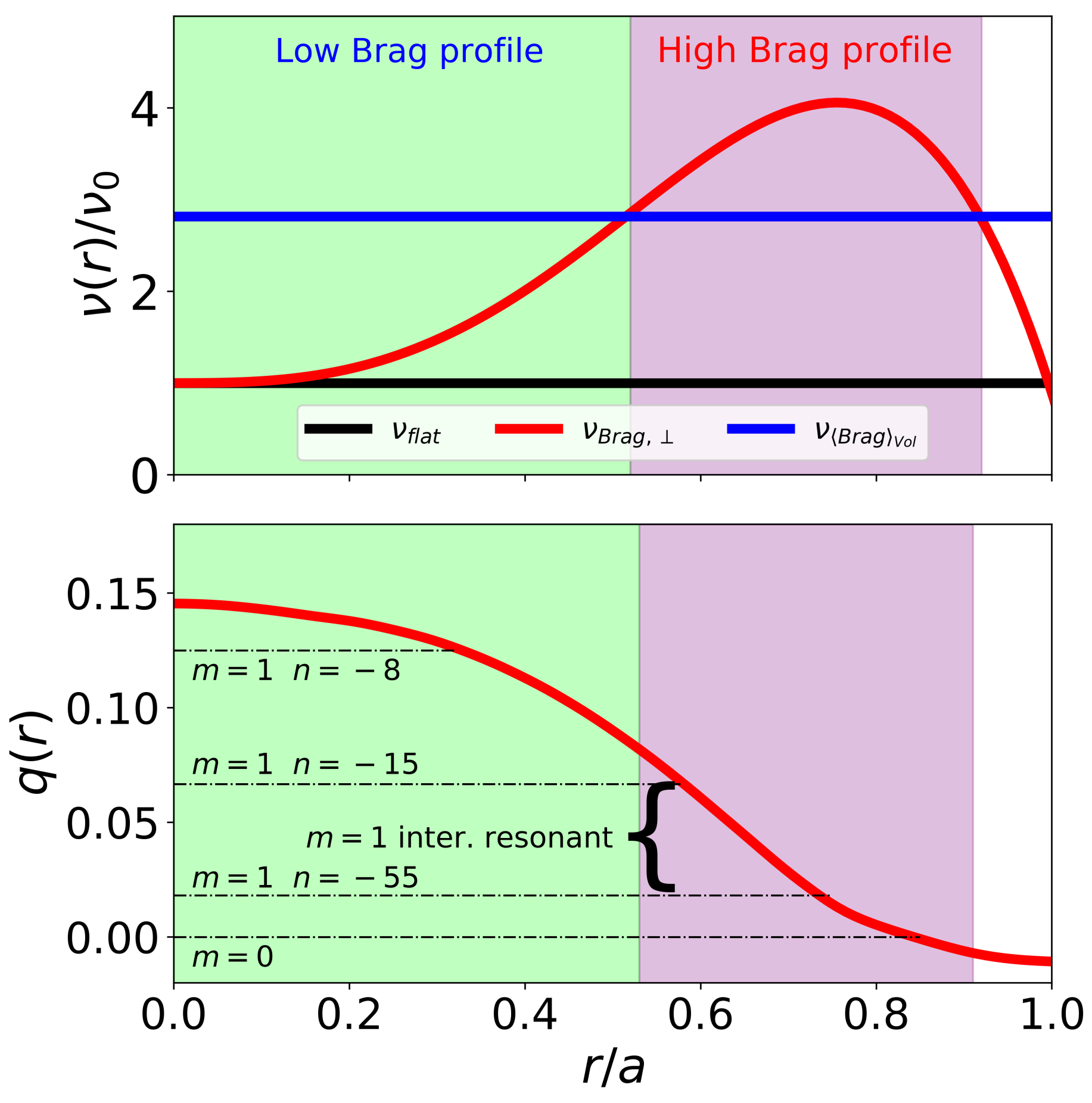
- ν_{flat}: most frequently used in previous studies
- $\nu_{Brag,\perp}$ inspired by $\nu_\perp^{Brag} \propto n^{3/2}/B^3T^{1/2}$ and reasonable profiles of T, n and B
- $\nu_{\langle Brag\rangle_{Vol}}$ with flat profile but the same volume average of Braginskii ($\sim 2.82\nu_{flat}$)

Effects

1. effect of viscosity volume average value (**global effect**) $\nu_{\langle Brag\rangle_{Vol}}$ Vs ν_{flat}
2. specific effects of the viscosity profile (**local effects**) $\nu_{Brag,\perp}$ Vs $\nu_{\langle Brag\rangle_{Vol}}$

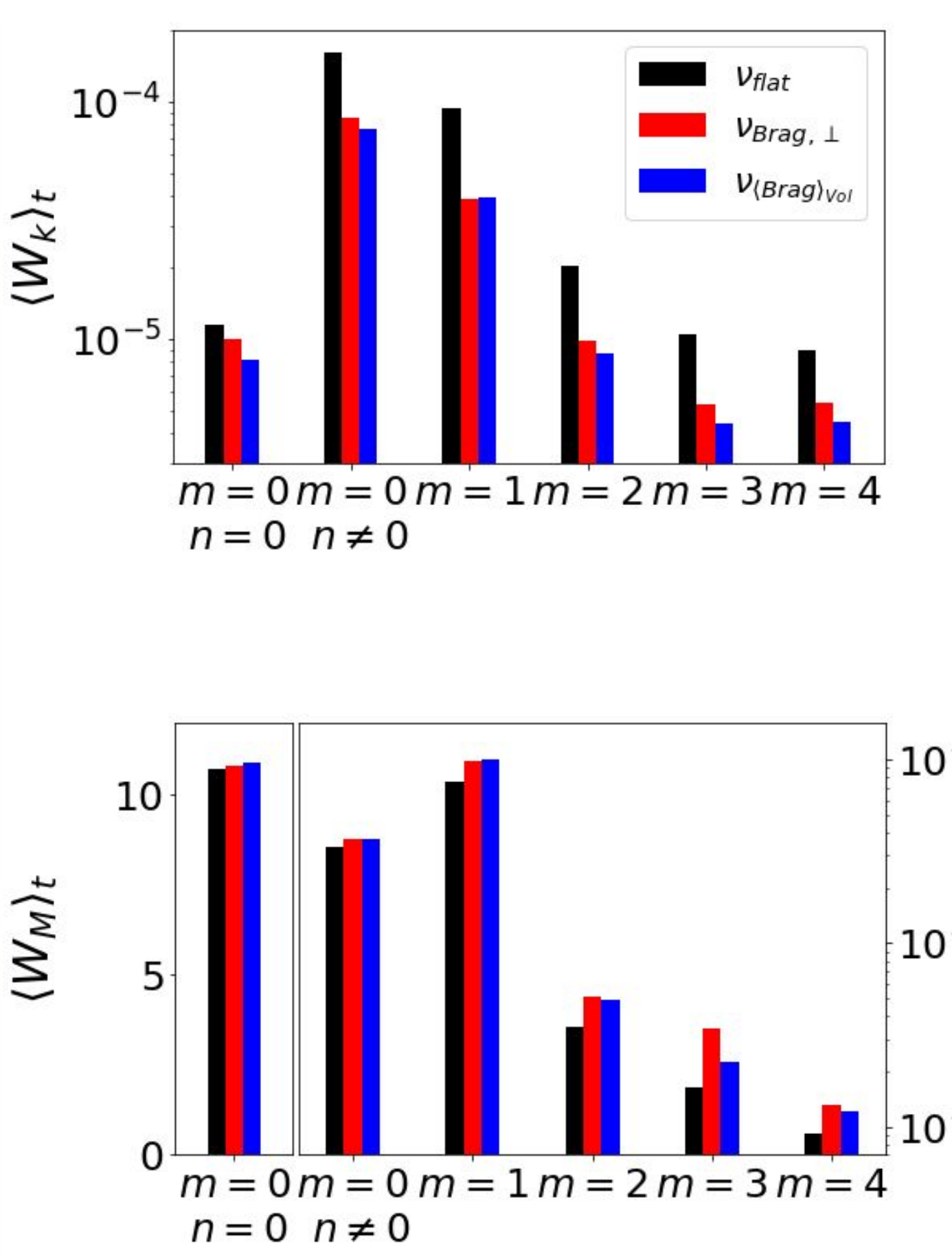
$\nu_{Brag,\perp} < \nu_{\langle Brag\rangle_{Vol}} \rightarrow$ $m = 1$ core res modes

$\nu_{Brag,\perp} > \nu_{\langle Brag\rangle_{Vol}} \rightarrow$ $m = 1$ inter res modes



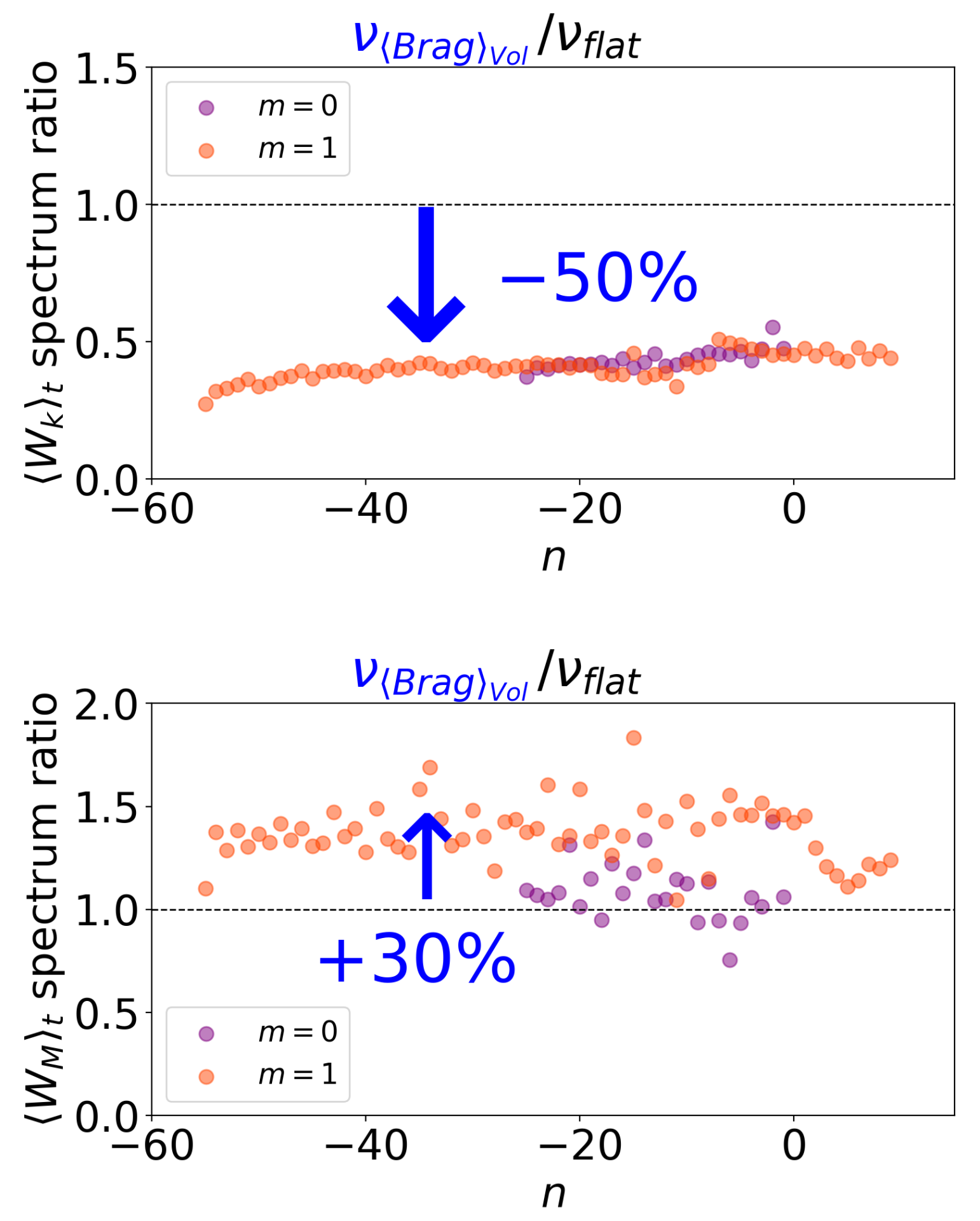
Plasma dynamics effects

Modes energy absolute value



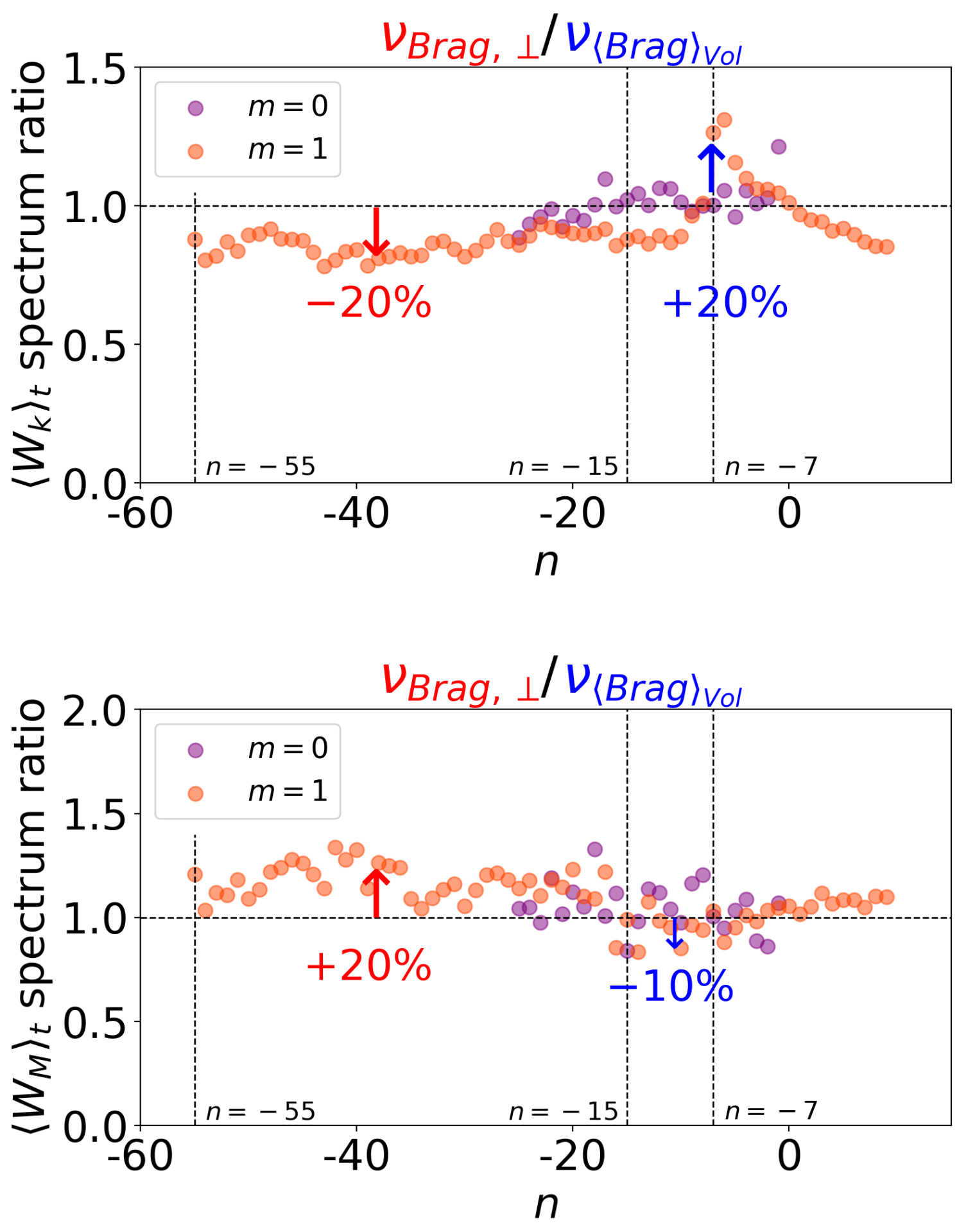
No viscosity effect on the axisymmetric comp. of the magnetic field. Wave numbers considered: $m \leq 4$, $|n| \leq 70$.

Global effects of higher viscosity



"Order 0" effect. Kinetic energy W_k damp, enhancement of the magnetic energy W_M, for the majority of $m = 0, 1$ modes.

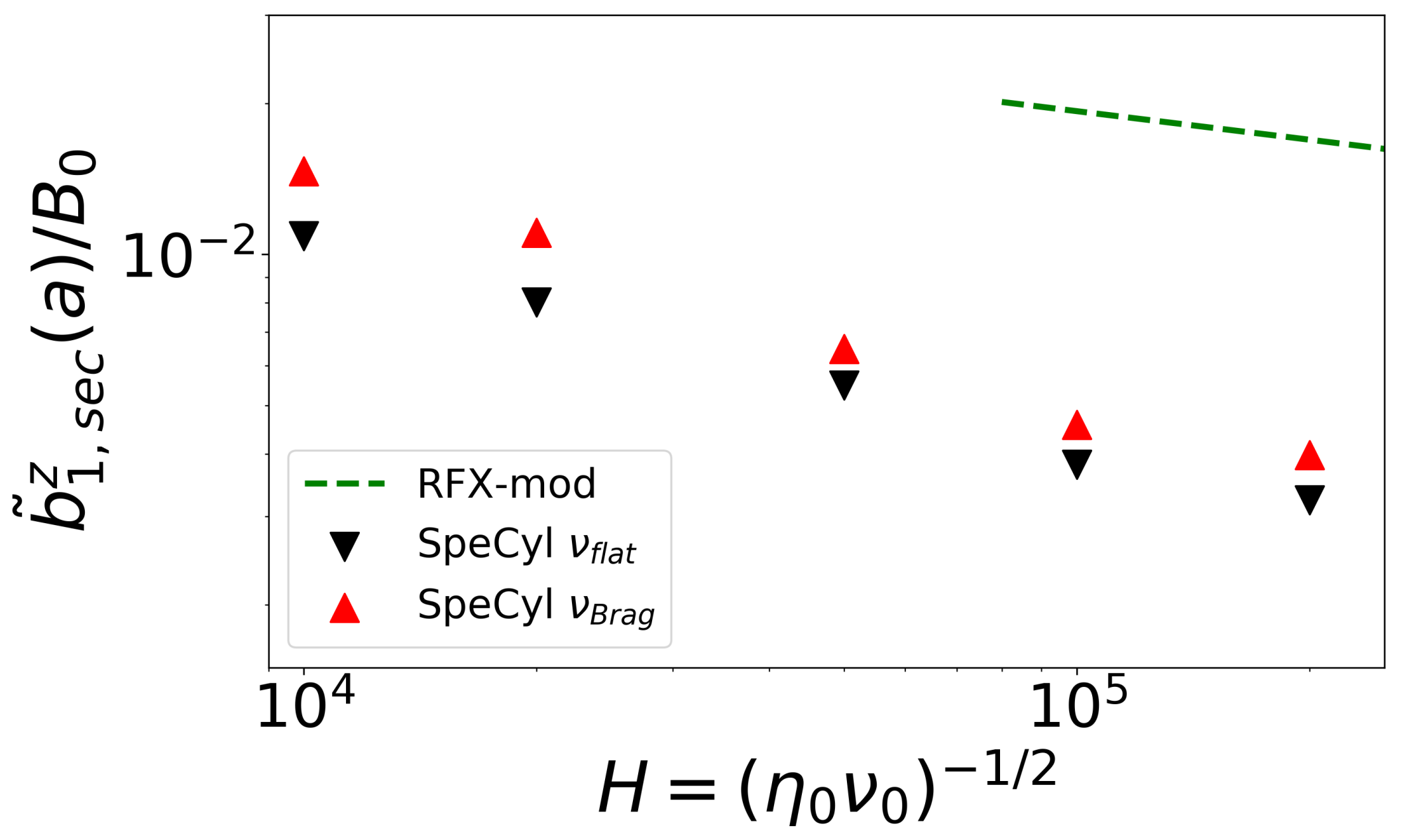
Local effects of Brag.-prof visc



"Order 1" effect. Core res: W_k enhancement and W_M damp (low $\nu_\perp$). Inter res: W_k damp and W_M enhancement (high $\nu_\perp$).

$\Rightarrow$ Basic picture of interplay: the velocity field counteracts the development magnetic instabilities [11].

Effects on the viscosity anomaly



- Shift between SpeCyl simulations (with ν_{flat}) and the experimental scaling for the relation: $\tilde{b}^{m=1}/B_0 \propto H^\alpha$
- Interpreted as the viscosity anomaly factor ($\delta := \nu_{sim}/\nu_{exp} \sim 250$) [12]

If a $\nu_{Brag,\perp}$ profile is considered in SpeCyl:

- the $m = 1$ secondary modes are enhanced
- the 'difference' with the experimental data is slightly reduced → anomaly reduction: $\delta \sim 70$

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