Kinematic viscosity estimates in reversed-field pinch fusion plasmas

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THEORY OF FUSION PLASMAS
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Aim of this work

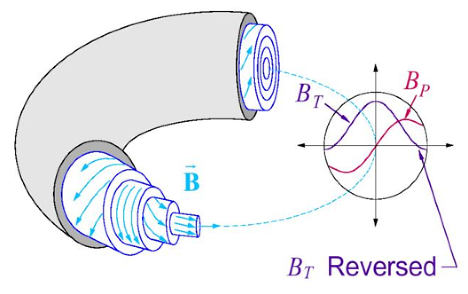
Framework: Visco-resistive magneto-hydrodynamics (MHD) of reversed-field pinch (RFP) fusion plasmas.
Aim of this poster:

- to study the effects of a non-uniform scalar viscosity in visco-resistive MHD simulations
- to estimate the kinematic viscosity on the basis of RFX-mod experimental data.

Reversed-field pinch configuration

Reversed-Field Pinch (RFP) configuration [1] 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)
- ⇒ high self-organization level
- same order of magnitude for magnetic fields: $B_\phi \approx B_\theta$.



Visco-resistive MHD model

SpeCyl [2] solves the visco-resistive MHD model. Hypothesis:

- constant mass density
- negligible pressure ($\beta << 1$)
- cylindrical geometry

Input parameters: dimensionless resistivity η and viscosity ν:

SpeCyl equations

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} = \mathbf{j}\times\mathbf{B} + \nu\nabla^2\mathbf{v}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}) - \nabla\times(\eta\mathbf{j})$$

$$\nabla\cdot\mathbf{B} = 0 \qquad \nabla\times\mathbf{B} = \mathbf{j}$$

By means of a proper change of coordinates [3] η and ν can be replaced by the magnetic Prandtl number $P = \nu/\eta$ and the Hartmann number $H = 1/\sqrt{\eta\nu}$:

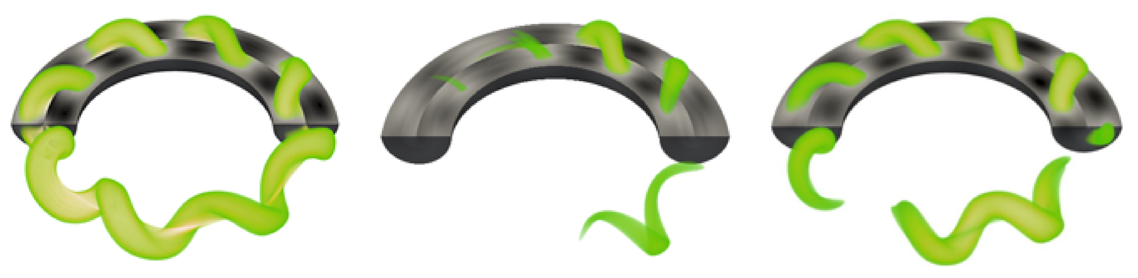
'Rescaled' SpeCyl equations

$$P^{-1}\left(\frac{\partial \mathbf{v}}{\partial t} + \cancel{\mathbf{v}\cdot\nabla\mathbf{v}}\right) = \mathbf{j}\times\mathbf{B} + H^{-1}\nabla^2\mathbf{v}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}) - \nabla\times(H^{-1}\mathbf{j})$$

⇒ η and ν jointly rule the plasma dynamics through H
⇒ H together with Magnetic Perturbation (finite $b_r(a)$, [4]) determines the plasma helical regime.

Single Helicity | Multiple Helicity | Quasi-Single Helicity

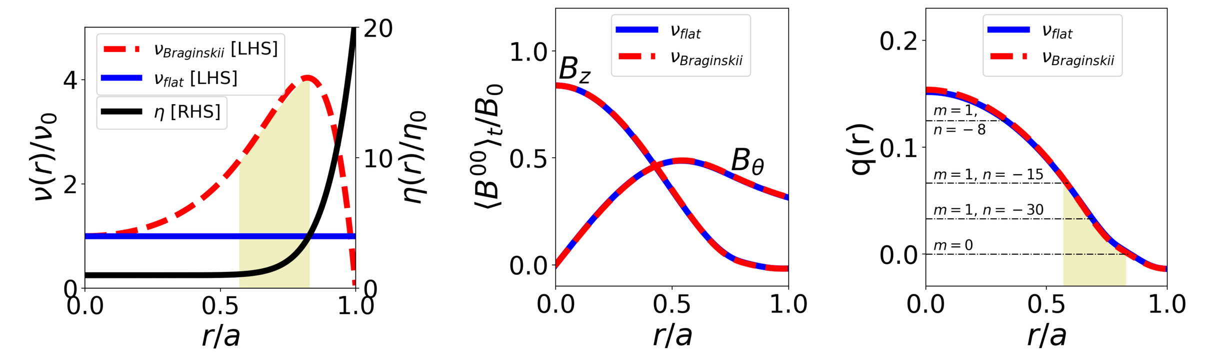


$H < 2000$ | $H > 2000$ | $H > 2000$ + MP

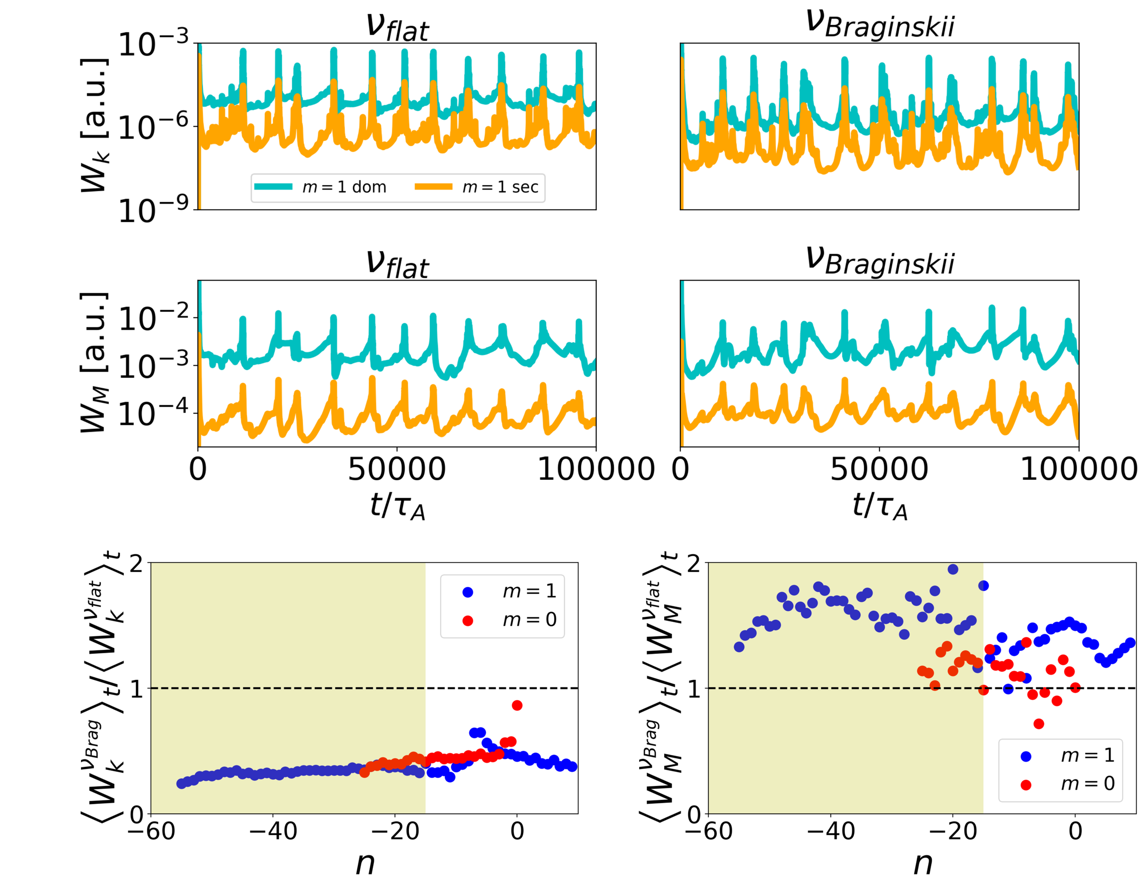
- Resistivity η profile: Spitzer-like $\eta \propto T_e^{-3/2}$, according to typical experimental temperature profiles.
- Viscosity ν profile: uniform in the majority of the simulations. ν represents the major uncertainty parameter among the transport coefficients [5]: different estimates exist according to classical [6] and turbulent theories [7].

MHD simulations: non-uniform viscosity

1) SpeCyl simulations settings: $\eta_0 = 10^{-6}$ $\nu_0 = 10^{-4}$ $b_r(a) = 0$.

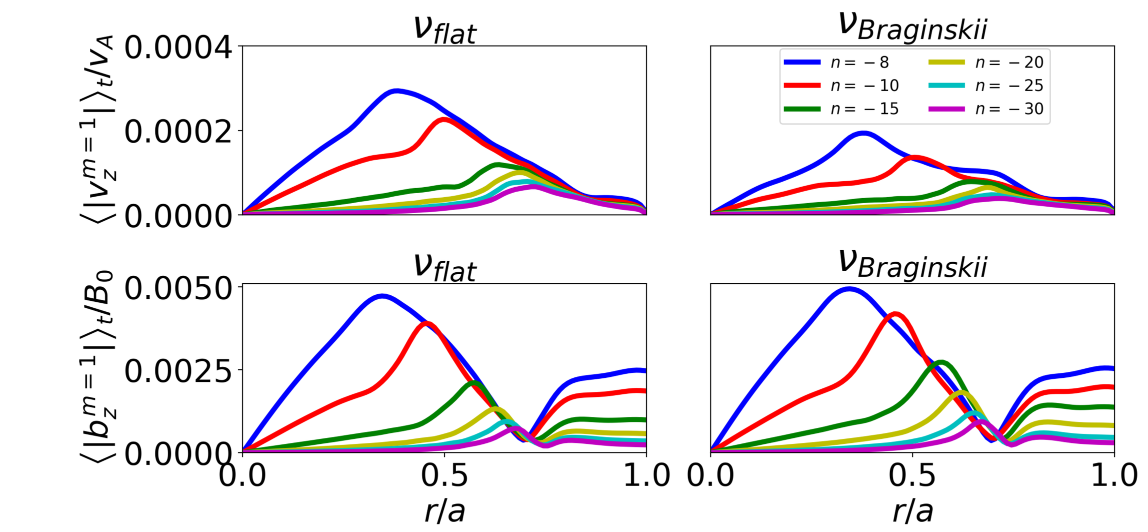


2) Effects on the kinetic and the magnetic energy:



⇒ ν_{Brag} profile causes a damp of the kinetic energy W_k and a slight enhancement of the magnetic energy W_M.

3) Effects on the flow and magnetic field eigenfunctions:

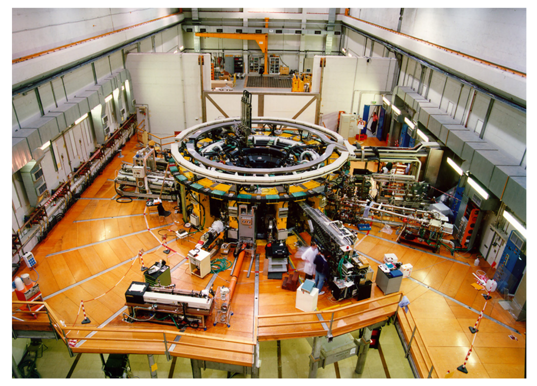


⇒ ν_{Brag} profile causes a damp of velocity eigenfunctions and a slight enhancement of magnetic field eigenfunctions.

RFX-mod 243 shots database [8]

RFP config. parameters

R_0	2 m
a	0.459 m
I_p	130 kA – 2.0 MA
B_0	0.15 T – 2.0 T
n_e	$3.5\cdot10^{18} - 2.2\cdot10^{20}\,\mathrm{m}^{-3}$
T_e	60 eV – 1.1 keV



Viscosity estimates on RFX-mod data

- Classical Braginskii viscosity [6]: momentum transport originated by Coulomb collisions, depending on the direction with respect to the magnetic field (∥, ⊥). The presence of $\mathbf{B}$ and ∇T gives rise to $\nu_\times$

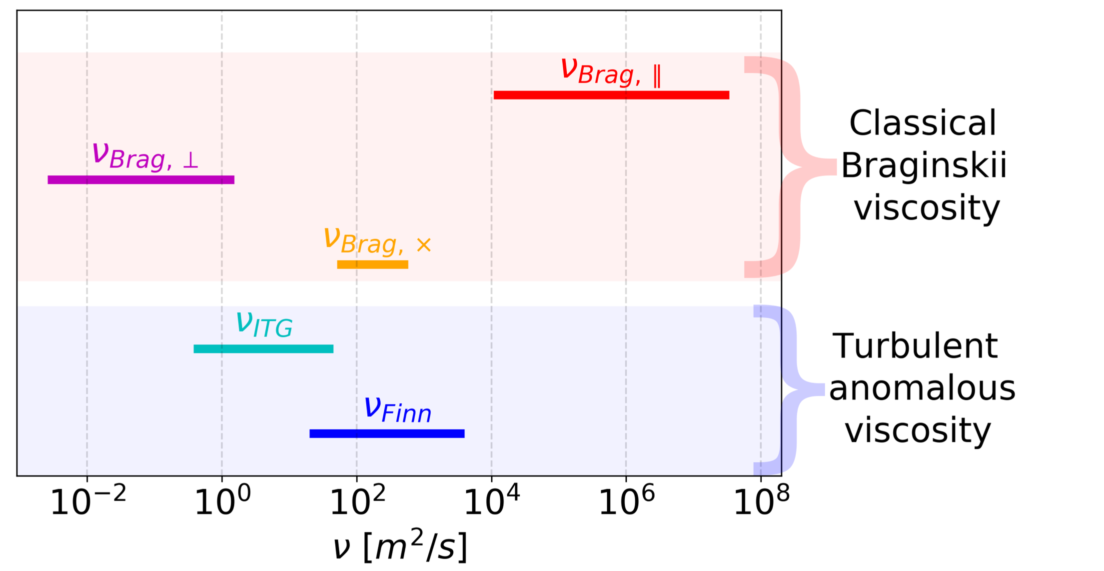
$$\nu_\parallel \propto \frac{T_i^{5/2}}{Z_{eff}^4 \ln\Lambda \gamma^{1/2} n_i} \qquad \nu_\perp \propto \frac{\gamma^{1/2} n_e \ln\Lambda}{T_i^{1/2} B^2} \qquad \nu_\times \propto \frac{T_i}{Z_{eff} B}$$

- ITG viscosity [9]: ITG mode that damps velocity fluctuations, generating viscous heating

$$\nu_{ITG} \propto \frac{\gamma^{1/2} T_e T_i^{1/2}}{Z_{eff} a_T^{3/4} a_B^{1/4} B^2}$$

- Finn viscosity [10, 11]: momentum transport in a stochastic magnetic field by sound waves propagation

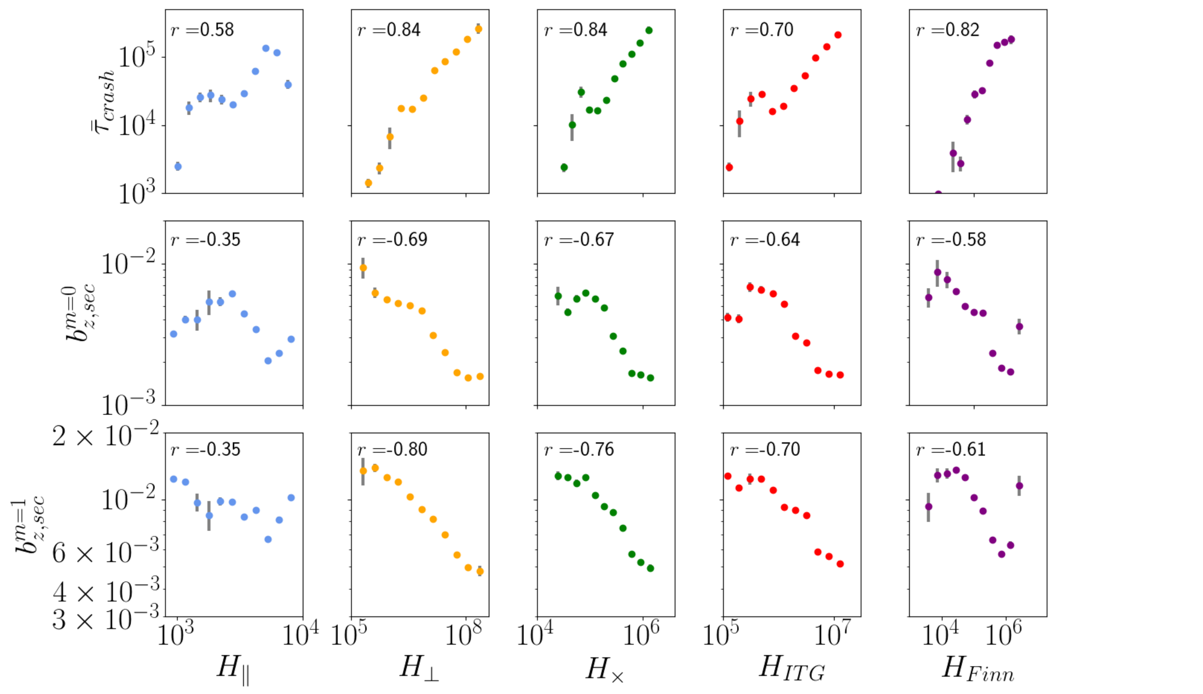
$$\nu_{Finn} = c_s L_C \sum_{m,n} \left(\frac{b^r_{m,n}}{B}\right)^2$$



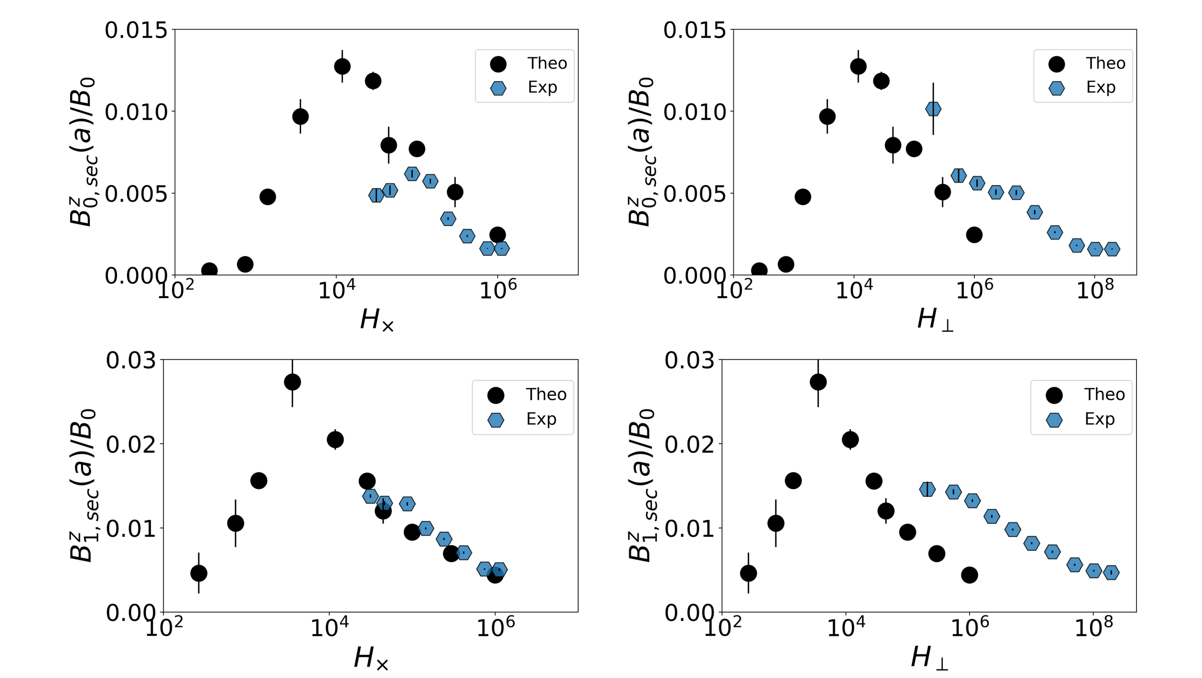
⇒ Test of the numerical simulations - experimental data adherence to compare the viscosity estimates.

Simulations and data comparison

The normalized time scale of reconnection events $\bar{\tau}_{crash}$, the secondary $m = 0$ and $m = 1$ modes are ruled by the Hartmann number in SpeCyl simulations [12]. For the experimental data:



- $\nu_\parallel$ produces small correlation
- ν_{ITG}, ν_{Finn} produce lower correlations than the other estimates
- the $\nu_\perp$ and $\nu_\times$ produce the highest correlation levels.



A non monotonous trend of the secondary $m = 0$ modes for $\nu_\times$ and an anomaly factor $\delta \sim 250$ for $\nu_\perp$ are highlighted by the quantitative comparison.

Conclusions

- Visco-resistive MHD simulations: "Braginskii-like" viscosity profiles produce a moderate damp of the plasma flow and an increased MHD magnetic activity of spectral components resonating in spatial regions where the viscosity profile is higher, confirming a simple picture of the interplay between plasma flow and magnetic field – i.e. $v\downarrow \;\Rightarrow\; b^{m,n}\uparrow$.
- RFX-mod experimental data: ν estimates according to the main theories of transport. Braginskii $\nu_\perp$ maximizes the SpeCyl simulations - exp data adherence, followed by $\nu_\times$. An anomaly in the quantitative comparison with simulations still persists, to which the viscosity profile, the axysimmetric flow effect, a $\nu_\perp$ - $\nu_\times$ interaction and a resistivity anomaly can possibly contribute.

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