Ion-neutral interactions, MHD instabilities

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Partial ionization effects

- damping of waves
  Zaqarashvili et al. (2011a, 2011b, 2013), Soler el al. (2013a, 2013b), Popescu Braileanu et al. (2019a, 2019b)
- stabilization of the shock front in corrugation instabilities
  Snow & Hillier (2021)
- thinner current sheets in simulations of coalescence instability
  Murtas et al. (2021)
- misalignemit of spicules with the magnetic field
  de la Cruz Rodriguez & Socas-Navarro (2011), Martinez-Sykora et al. (2016)
- slippage of the neutrals in prominences
  Gilbert et al. (2002, 2007)
- direct observations of the decoupling
  Khomenko el al. (2016), Anan et al (2017), Wiehr at al. (2019), **poster S4_05**
- implementation: MHD+ambi, 2FL
  The difference in the two models increases with increasing $\tau_{\mathrm{coll}}/\tau_{\mathrm{hydro}}$ (*Zaqarashvili et al. 2011b*)

Two-fluid model

Two-fluid equations

Continuity:

$$\begin{cases} \dfrac{\partial \rho_\mathrm{n}}{\partial t} + \nabla \cdot (\rho_\mathrm{n} \mathbf{u}_\mathrm{n}) &= \boxed{S_\mathrm{n}} \\ \dfrac{\partial \rho_\mathrm{c}}{\partial t} + \nabla \cdot (\rho_\mathrm{c} \mathbf{u}_\mathrm{c}) &= \boxed{-S_\mathrm{n}} \end{cases}$$

Momentum:

$$\begin{cases} \dfrac{\partial (\rho_\mathrm{n} \mathbf{u}_\mathrm{n})}{\partial t} + \nabla \cdot (\rho_\mathrm{n} \mathbf{u}_\mathrm{n} \mathbf{u}_\mathrm{n} + p_\mathrm{n} \mathbb{I} - \hat{\tau}_\mathrm{n}) &= \rho_\mathrm{n} \mathbf{g} + \boxed{\mathbf{R}_\mathrm{n}} \\ \dfrac{\partial (\rho_\mathrm{c} \mathbf{u}_\mathrm{c})}{\partial t} + \nabla \cdot (\rho_\mathrm{c} \mathbf{u}_\mathrm{c} \mathbf{u}_\mathrm{c} + p_\mathrm{c} \mathbb{I} - \hat{\tau}_\mathrm{c}) &= \mathbf{J} \times \mathbf{B} + \rho_\mathrm{c} \mathbf{g} \boxed{-\mathbf{R}_\mathrm{n}} \end{cases}$$

Energy:

$$\begin{cases} \dfrac{\partial}{\partial t} \left(e_\mathrm{n} + \frac{1}{2} \rho_\mathrm{n} u_\mathrm{n}^2\right) + \nabla \cdot \left[\mathbf{u}_\mathrm{n} (e_\mathrm{n} + \frac{1}{2} \rho_\mathrm{n} u_\mathrm{n}^2) + (p_\mathrm{n} \mathbb{I} - \hat{\tau}_\mathrm{n}) \cdot \mathbf{u}_\mathrm{n} + \mathbf{q}_\mathrm{n}\right] \\ \qquad = \rho_\mathrm{n} \mathbf{u}_\mathrm{n} \cdot \mathbf{g} + \boxed{M_\mathrm{n}} \\ \dfrac{\partial}{\partial t} \left(e_\mathrm{c} + \frac{1}{2} \rho_\mathrm{c} u_\mathrm{c}^2\right) + \nabla \cdot \left[\mathbf{u}_\mathrm{c} (e_\mathrm{c} + \frac{1}{2} \rho_\mathrm{c} u_\mathrm{c}^2) + (p_\mathrm{c} \mathbb{I} - \hat{\tau}_\mathrm{c}) \cdot \mathbf{u}_\mathrm{c} + \mathbf{q}_\mathrm{c}\right] \\ \qquad = \rho_\mathrm{c} \mathbf{u}_\mathrm{c} \cdot \mathbf{g} + \mathbf{J} \cdot \mathbf{E} \boxed{-M_\mathrm{n}} \end{cases}$$

Ideal induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u}_\mathrm{c} \times \mathbf{B}) \, .$$

Collisional terms

We define α so that : $\rho_e \nu_{en} + \rho_i \nu_{in} = \rho_{\mathrm{n}} \rho_{\mathrm{c}} \alpha^{\mathrm{el}}$; $\alpha = \alpha^{\mathrm{el}} + \alpha^{\mathrm{cx}}$

$$S_{\mathrm{n}} = \rho_{\mathrm{c}} \Gamma^{\mathrm{rec}} - \rho_{\mathrm{n}} \Gamma^{\mathrm{ion}}$$

$$\mathbf{R}_{\mathrm{n}} = \rho_{\mathrm{c}} \mathbf{u}_{\mathrm{c}} \Gamma^{\mathrm{rec}} - \rho_{\mathrm{n}} \mathbf{u}_{\mathrm{n}} \Gamma^{\mathrm{ion}} + \rho_{\mathrm{n}} \rho_{\mathrm{c}} \alpha (\mathbf{u}_{\mathrm{c}} - \mathbf{u}_{\mathrm{n}})$$

$$M_{\mathrm{n}} = \frac{1}{2} \Gamma^{\mathrm{rec}} \rho_{\mathrm{c}} u_{\mathrm{c}}^2 - \frac{1}{2} \rho_{\mathrm{n}} u_{\mathrm{n}}^2 \Gamma^{\mathrm{ion}} + \frac{1}{\gamma - 1} \frac{k_{\mathrm{B}}}{m_{\mathrm{n}}} \left(\rho_{\mathrm{c}} T_{\mathrm{c}} \Gamma^{\mathrm{rec}} - \rho_{\mathrm{n}} T_{\mathrm{n}} \Gamma^{\mathrm{ion}} \right) + \frac{1}{2} ({u_{\mathrm{c}}}^2 - {u_{\mathrm{n}}}^2) \rho_{\mathrm{n}} \rho_{\mathrm{c}} \alpha + \frac{1}{\gamma - 1} \frac{k_{\mathrm{B}}}{m_{\mathrm{n}}} (T_{\mathrm{c}} - T_{\mathrm{n}}) \rho_{\mathrm{n}} \rho_{\mathrm{c}} \alpha$$

$\alpha = f(T_n, T_c)$, $\Gamma^{\mathrm{ion}} = f(T_c, \rho_c)$, $\Gamma^{\mathrm{rec}} = f(T_c, \rho_c)$.

Popescu Braileanu et al. (2019a)

RTI

Previous work

Previous studies of PI effects on RTI:

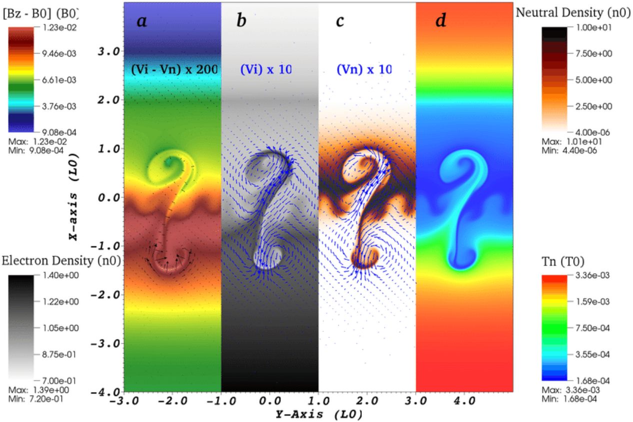
- enhance the growth at the scales where the magnetic field imposes a cutoff or indirectly

  Khomenko et al. (2014), Arber et al (2007)

- inhibit the instability

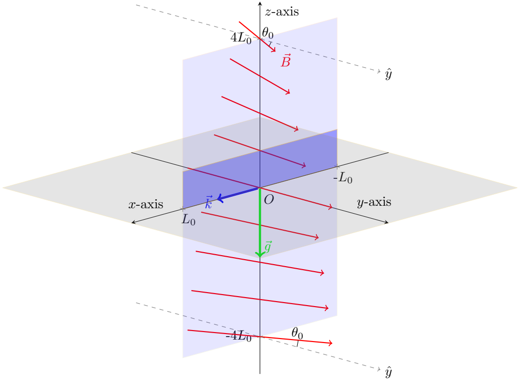
  Diaz et al. (2012)

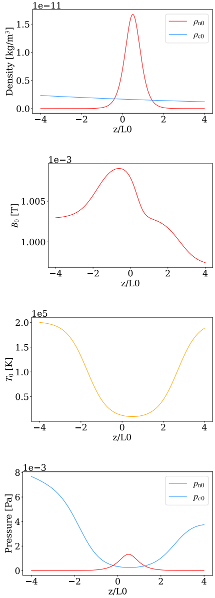
Previous work



smooth density profile, neutral visc. and th. cond., perpendicular mag. field
Leake et al. 2014

Setup

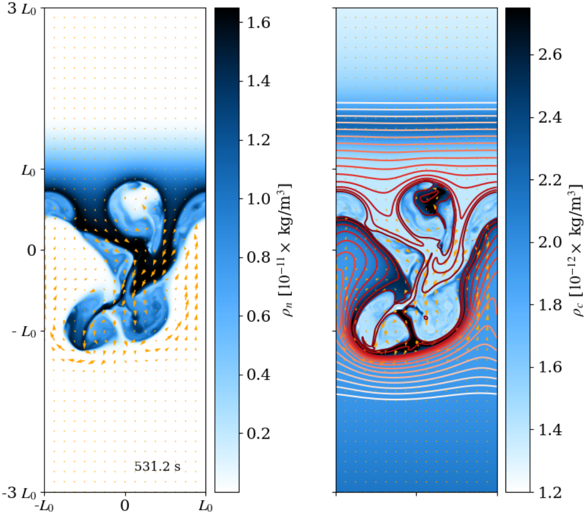




$L_0 = 1$ Mm

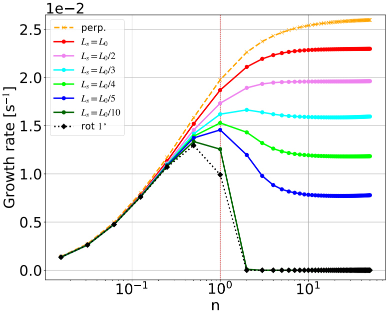
Popescu Braileanu et al. 2021a, 2021b, 2022 (in rev.)

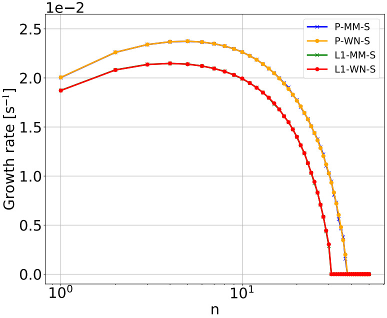
RTI


3 L_0
L_0
0
- L_0
-3 L_0
-L_0
0
L_0
531.2 s
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
ρ_n [$10^{-11} \times$ kg/m^3]
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
ρ_c [$10^{-12} \times$ kg/m^3]

RTI

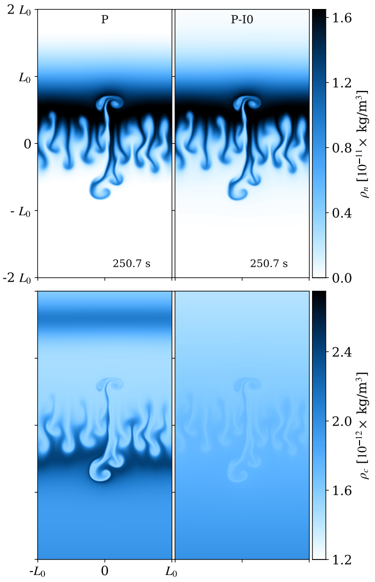
Growth rates

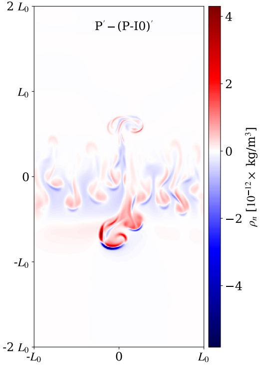




RTI

Ionization/recombination

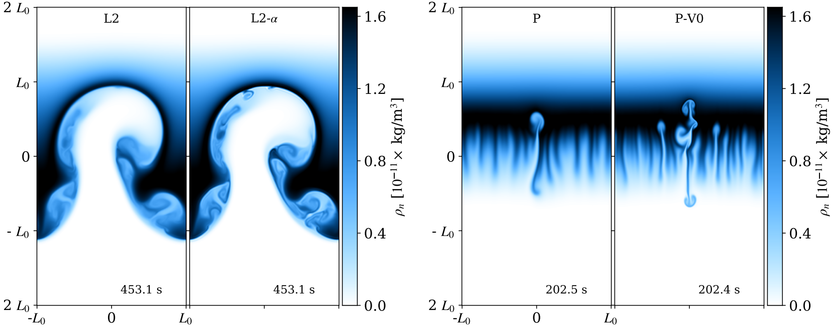


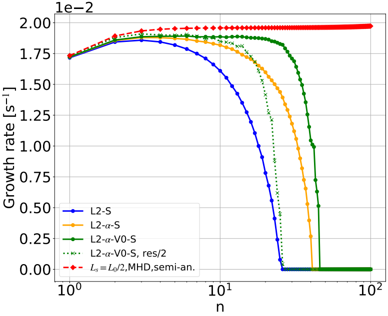


- Linear growth rates are the same
- Nonlinear phase: prominence material falls faster in the simulation without ion./rec.

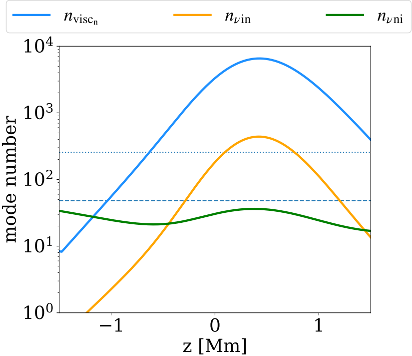
RTI

Elastic collisions





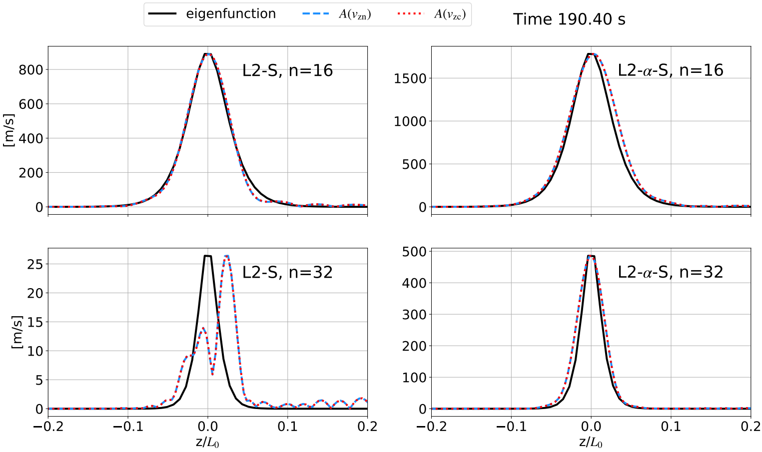
1e−2
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Growth rate [s⁻¹]
10^0
10^1
10^2
n
L2-S
L2-α-S
L2-α-V0-S
L2-α-V0-S, res/2
$L_s = L_0/2$,MHD,semi-an.



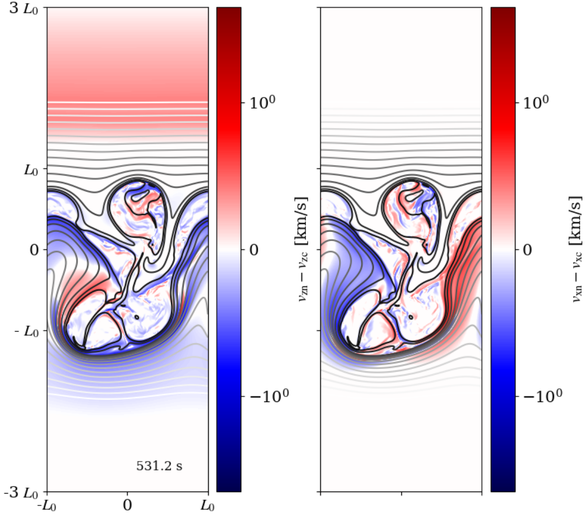
$n_{\mathrm{visc_n}}$
$n_{\nu \mathrm{in}}$
$n_{\nu \mathrm{ni}}$
10^4
10^3
10^2
10^1
10^0
mode number
−1
0
1
z [Mm]

RTI

Elastic collisions

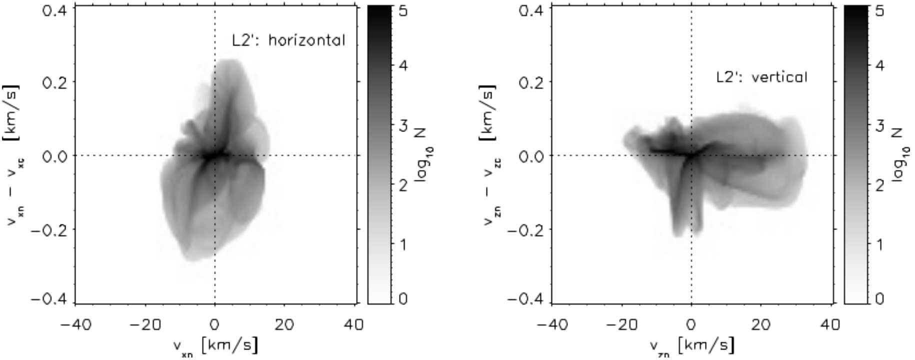


Decoupling in velocity



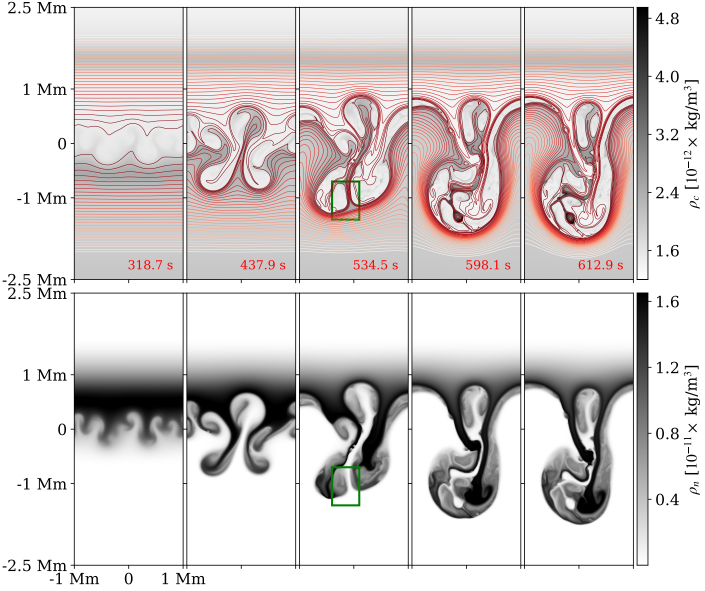
- Decoupling highly localized, up to 10% of the flow velocity

Decoupling in velocity



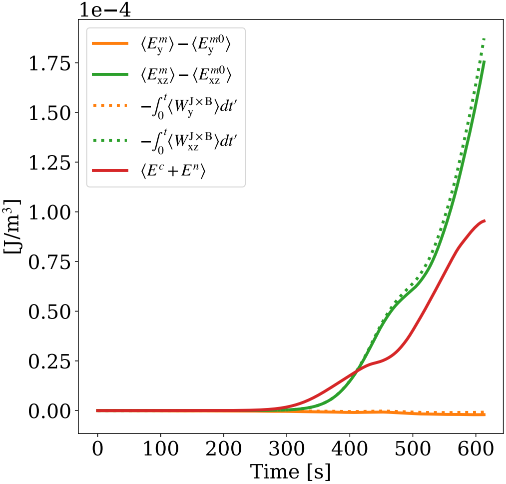
- Larger decoupling in horizontal direction
- Vertical decoupling asymmetry in downflow as neutrals fall faster

RTI 4x

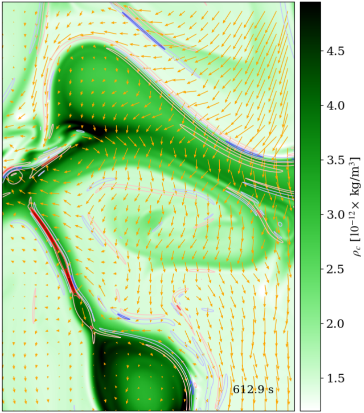


2.5 Mm
1 Mm
0
-1 Mm
-2.5 Mm
318.7 s
437.9 s
534.5 s
598.1 s
612.9 s
4.8
4.0
3.2
2.4
1.6
ρ_c [$10^{-12}\times$ kg/m^3]
1.6
1.2
0.8
0.4
ρ_n [$10^{-11}\times$ kg/m^3]
-1 Mm
0
1 Mm

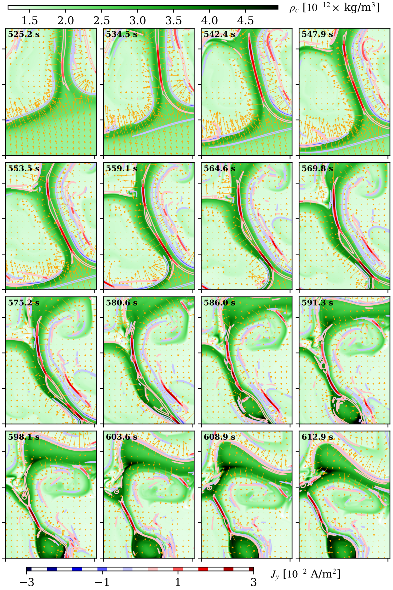
RTI 4x


1e−4
$\langle E^m_{\mathrm{y}}\rangle - \langle E^{m0}_{\mathrm{y}}\rangle$
$\langle E^m_{\mathrm{xz}}\rangle - \langle E^{m0}_{\mathrm{xz}}\rangle$
$-\int_0^t \langle W^{\mathrm{J\times B}}_{\mathrm{y}}\rangle dt'$
$-\int_0^t \langle W^{\mathrm{J\times B}}_{\mathrm{xz}}\rangle dt'$
$\langle E^c + E^n\rangle$
[J/m^3]
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
100
200
300
400
500
600
Time [s]

RTI 4x

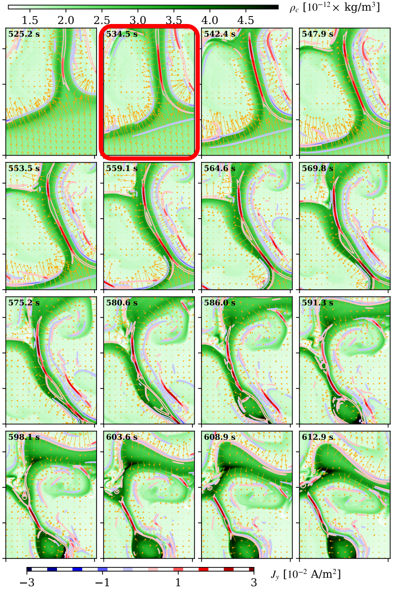

612.9 s
4.5
4.0
3.5
3.0
2.5
2.0
1.5
ρ_c [$10^{-12}\times$ kg/m^3]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
ρ_n [$10^{-11}\times$ kg/m^3]

RTI 4x



- Neutral spikes approach, current sheets form dynamically
- Plasmoids break up the current sheets which reform and elongate, aspect ratio ≈20

RTI 4x



- Neutral spikes approach, current sheets form dynamically
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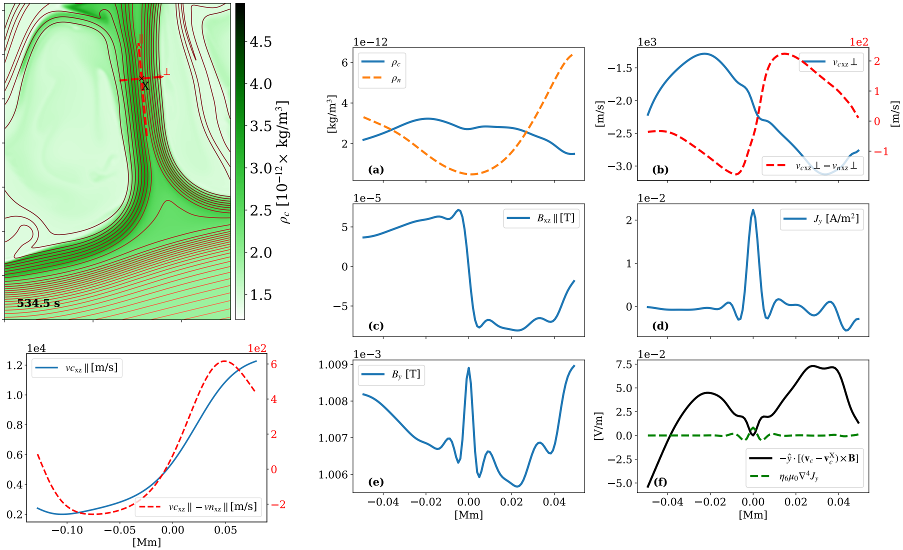
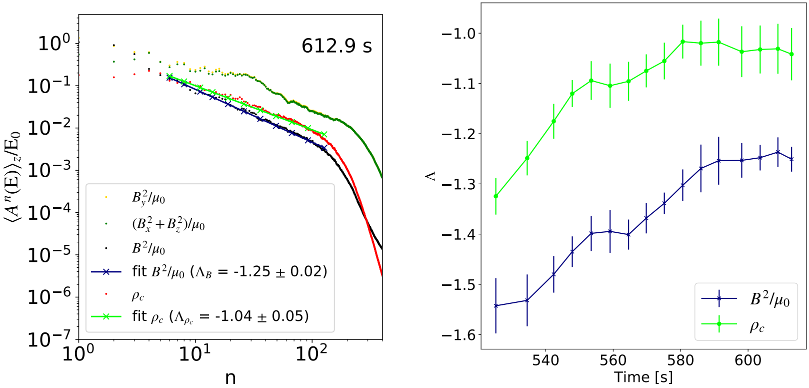
RTI 4x



534.5 s
ρc [10^-12 × kg/m^3]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1e4
1e2
vcxz ∥ [m/s]
vcxz ∥ − vnxz ∥ [m/s]
[Mm]
1e−12
ρc
ρn
[kg/m^3]
(a)
1e3
1e2
vcxz ⊥
vcxz ⊥ − vnxz ⊥
[m/s]
(b)
1e−5
Bxz ∥ [T]
(c)
1e−2
Jy [A/m^2]
(d)
1e−3
By [T]
(e)
1e−2
[V/m]
−ŷ · [(vc − vc^X) × B]
η6μ0∇^4Jy
(f)
[Mm]

RTI 4x


612.9 s
$\langle A^n(\mathrm{E})\rangle_z/\mathrm{E}_0$
n
B_y^2/μ_0
$(B_x^2+B_z^2)/\mu_0$
B^2/μ_0
fit B^2/μ_0 (Λ_B = -1.25 ± 0.02)
ρ_c
fit ρ_c (Λ_{ρ_c} = -1.04 ± 0.05)
Λ
Time [s]
B^2/μ_0
ρ_c

RTI 4x

Analytical estimation of the numerical diffusivity coefficient.

$$\mathscr{F}[u'](k) = \mathscr{F}[u](k) - \mathscr{F}[u](k) \cdot h(k)\,,$$

$$u'(x) = u(x) - u(x) * \mathscr{F}^{-1}[h](x)\,,$$

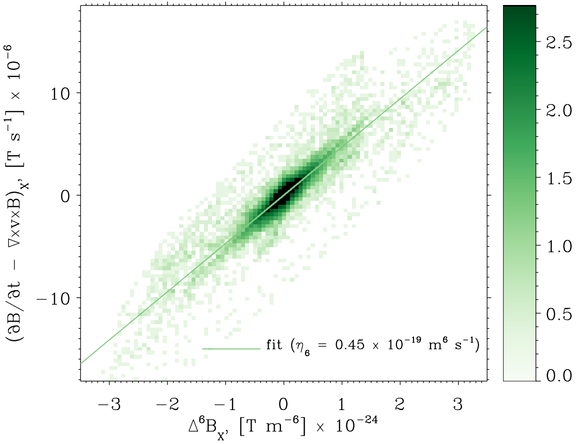
For the filtering function: $h(k) = \sin^6\left(k\dfrac{\Delta x}{2}\right)$,

$$\mathscr{F}^{-1}[h](x) = -\frac{1}{64}\delta(x+3\Delta x) + \frac{3}{32}\delta(x+2\Delta x) - \frac{15}{64}\delta(x+\Delta x) + \frac{5}{16}\delta(x) - \frac{15}{64}\delta(x-\Delta x) + \frac{3}{32}\delta(x-2\Delta x) - \frac{1}{64}\delta(x-3\Delta x)$$

$$\frac{\partial u}{\partial t} = \eta_6^F \frac{\partial^6 u}{\partial x^6}, \quad \eta_6^F = \frac{\Delta x^6}{64\Delta t}\,, \eta_6^F = 4.714 \times 10^{18}\mathrm{m}^6\mathrm{s}^{-1}\,.$$

RTI 4x

Estimation of the numerical diffusivity coefficient from simulations.



more than one order of magnitude larger than Spitzer resistivity

Conclusions

- Two-fluid effects are mostly relevant at the PCTR, smooth transition is necessary to capture two-fluid effects.
- No cutoff due to the magnetic field for large enough shear length.
- Ion-neutral collisions and viscosity supress the growth in the linear phase and produce cutoff.
- Large decoupling up to 10%. The decoupling across the current sheet is much larger than the decoupling along the current sheet.
- Two fluids effects are important (width of the current sheet comparable to MFP, ambi coef. three orders of magnitude larger than mag. dif. coef.).
- Almost stationary density and magnetic field spectra that could be compared to observations.
- Estimating the numerical diffusivity is important.