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On the influence of environmental parameters on mixing and reconnection caused by the Kelvin-Helmholtz instability at the magnetopause

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Outline

- Motivation
- Introduction
- Parameters exploration
  - Initial density jump
  - Shear layer width
  - Hall-term
  - Resolution
- Simulated spacecrafts
- Conclusion

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Motivation

Understanding the mechanisms underlying the solar wind entering Earth's magnetosphere is one of the biggest goals of magnetospheric physics as it forms the basis of space weather phenomena such as magnetic storms and auroras (Hasegawa, Fujimoto et al., Nature, 2004)

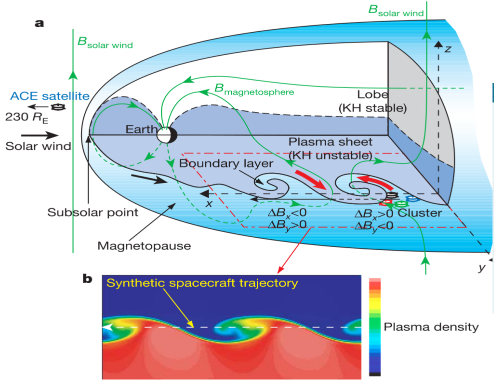
Observations

- Solar wind matter regularly enters the magnetosphere
  - during southward IMF, solar and geomagnetic fields are anti-parallel
    $\rightarrow$ reconnection at low-latitude
  - during northward IMF, fields are parallel
    $\rightarrow$ reconnection should not be efficient
- Nonetheless plasma boundary layer gets thicker during northward IMF
  $\rightarrow$ solar wind is still penetrating the magnetopause.

Motivation

Several hypothesis

- Simultaneous northern and southern cusps reconnections
- KH instability in non-linear stage enhancing mixing
- Double reconnection at mid-latitude



The in-situ data by various spacecrafts (Cluster, THEMIS) support the KHI hypothesis (Hasegawa, Fujimoto et al., Nature, 2004).
But how does it works, and is it sufficient ?

Previous studies and state of the art : 2D simulations

Settings

Most studies until now focused on 2D simulations of KHI in (Hall-)MHD frame

- Initial v $\parallel$ B, both sheared $\rightarrow$ KHI stabilized
- Initial v $\perp$ B, both sheared $\rightarrow$ KHI enhanced
- Homogeneous density, single KHI vortex

Conclusions

- KHI can cause reconnection on KH time scale (Nykyri & Otto, 2001)
- Possible fast anomalous ion mixing, efficiency mitigated by inhomogeneity (Terasawa, 1992 & 1994)
- Hall-MHD has various effects depending on initial configuration, but usually enhance instability, reconnection and transport
- Matsumoto and Seki (2007) showed existence of secondary 3D KHI
- 2.5D simulations exhibited important z-component development
- Structure of Hall term and nature of the situation studied points to 3D

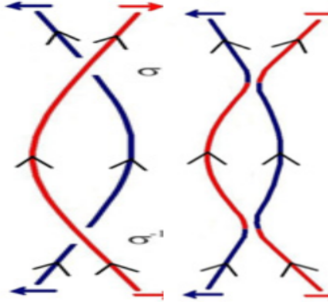
Previous studies and state of the art : 3D simulations

Settings

- Angle between v and B not only $\parallel$ or $\perp$
- Initial density jump
- Large slab encompassing high to low latitudes

Conclusions

- Various orientation influence growth of KHI and thickness of boundary layer
- Density jump add competition with Rayleigh-Taylor instability
- Large simulation to encompass field lines as far as possible $\rightarrow$ due to 'frozen-in' properties, local phenomenon can reflect at a distance along field lines : double mid-latitude magnetic reconnection (Faganello et al. 2012)



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Initial and boundary conditions

Box size : $L_x = 70, L_y = 188, L_z = 377$ (ion inertial lengths), resolution $N^3 = 200^3$, periodic in y and z-directions, x-direction continuous extrapolation.
Solution of Grad-Shafranov equation with ignorable y-direction:

$$A_y(x,z) = 0.5\left(\frac{4x}{3} + \frac{L_x}{2\pi}\sinh\left(\frac{2\pi x}{L_z}\right)\cos\left(\frac{2\pi z}{L_z}\right)\right).$$

$$B_x = -\frac{\partial A_y}{\partial z}, B_y = 0, B_z = -\frac{\partial A_y}{\partial x}, V_x = 0, V_y = \frac{M_A}{2}\tanh\left(\frac{A_y}{L_u}\right), V_z = 0.$$

$$\rho = 0.5(\rho_c + 1) + 0.5(\rho_c - 1)\tanh\left(\frac{A_y}{L_u}\right).$$

$$\delta A_y = \epsilon \sum_{m=1}^{6} \cos\left(\frac{2\pi m x/L_y + \phi(m)}{m}\right) \times \exp - \left(\frac{x}{2L_u}\right)^2 \times \exp - \left(\frac{z}{2L_u}\right)^2$$

Domain large enough for two pairs of KH vortices.
'high-latitude' conditions 'relaxed' → not KHI unstable.
Alfvén Mach number M_A=1,the sonic Mach number M_c=1, $\beta = 0.7$, $L_u = 3$, $\eta = 1e-3$, ρ_c=4.7

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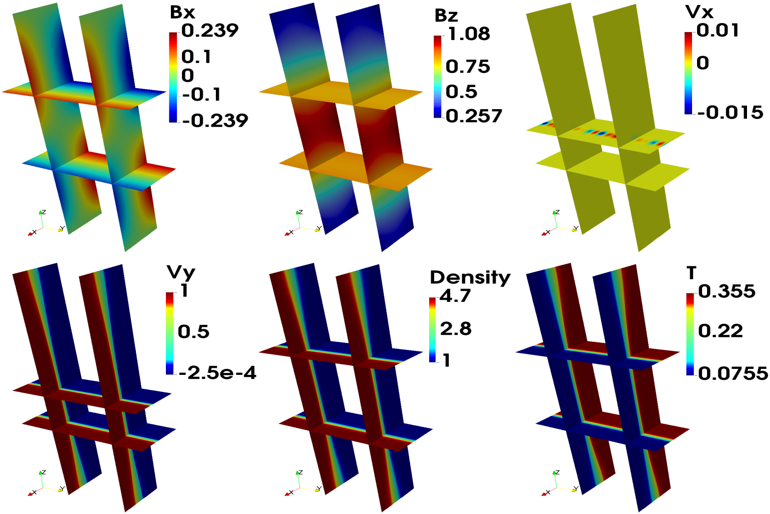
Initial and boundary conditions



Reproduction of Faganello et al.

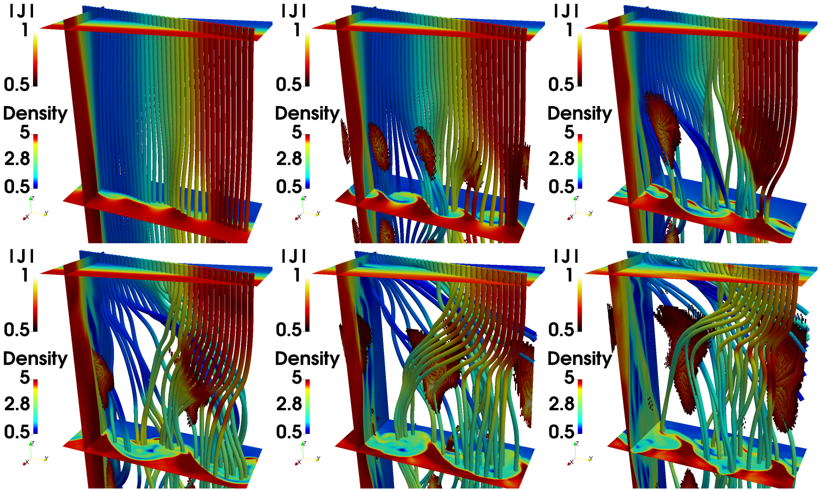


Figure : Snapshots of the time evolution of the reference run

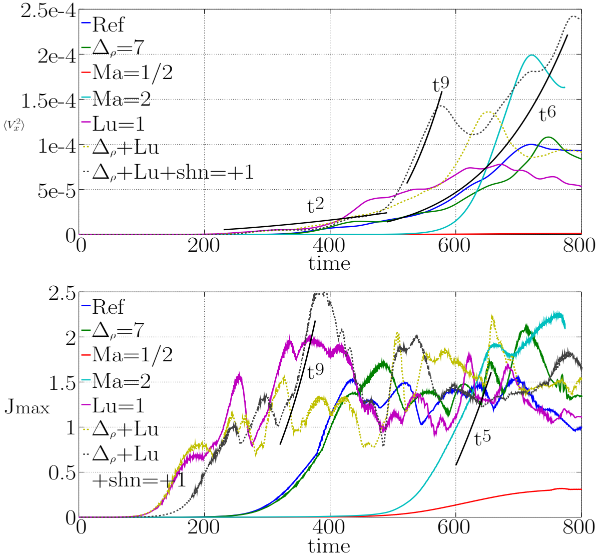
Parameters exploration

Aim of the study

Value of several initial physical quantities modified to assert their influence on growth rate and topological development of the KHI.

Label	Δ_ρ	M_A	L_u	shn
Ref	4.7	1	3	0
Δ_ρ	7	1	3	0
M_A=1/2	4.7	0.5	3	0
M_A=2	4.7	2	3	0
L_u	4.7	1	1	0
Δ_ρ+L_u	7	1	1	0
Δ_ρ+L_u+shn= 1	7	1	1	1

Parameters exploration



Δ_ρ=7 similar values of $< V_x^2 >$, higher values of J_{max}.

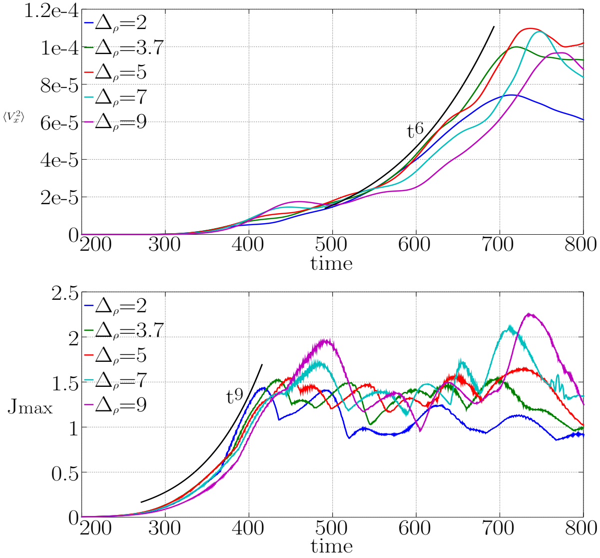
Ma=1/2 does not develop KHI.

Ma=2 starts later, but higher $< V_x^2 >$.

L_u=1 lower $< V_x^2 >$, higher J_{max}.

$\Delta_\rho+L_u$ starts faster, highest values of $< V_x^2 >$ and J_{max}.

Parameters exploration : Initial density jump



All Δ_ρ similar values of $< V_x^2 >$, but highest for Δ_ρ=5.

Highest values of J_{max} for largest values of Δ_ρ.

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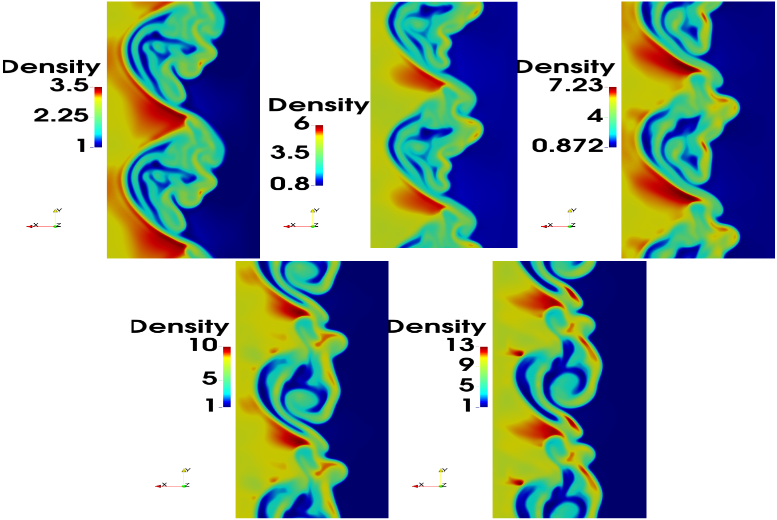
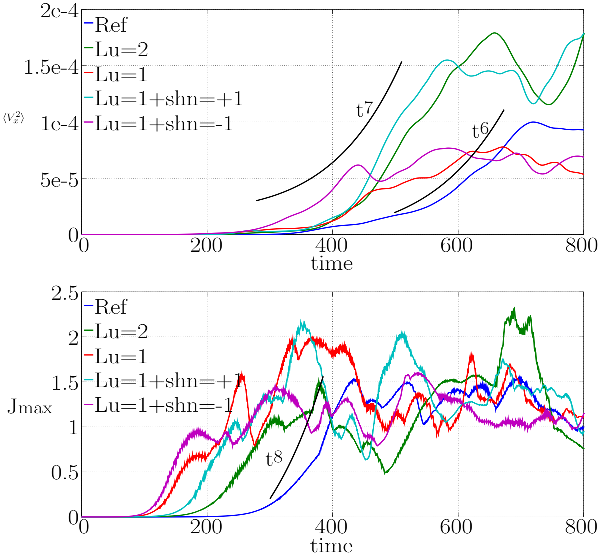
Parameters exploration : Initial density jump



Parameters exploration : Shear layer width



More complex situation.

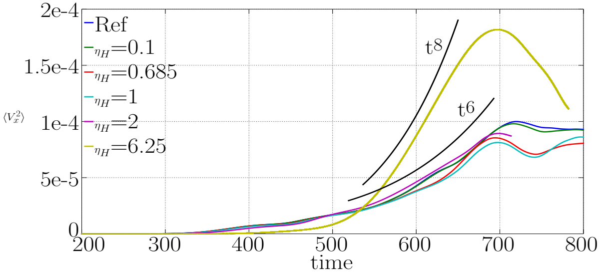
For $< V_x^2 >$:
L_u=1 < L_u=3 < L_u=2.

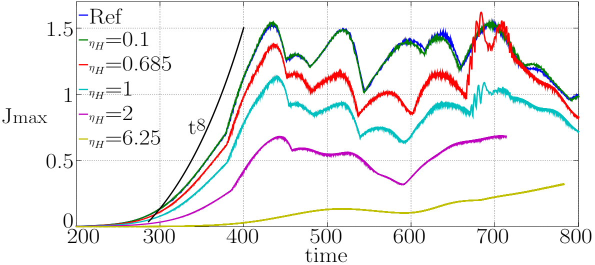
For J_{max} :
L_u=3 < L_u=1 < L_u=2.

shn=+1 yields highest $< V_x^2 >$ and J_{max}.

shn=-1 yields lowest $< V_x^2 >$ and J_{max}.

Parameters exploration : Influence of the Hall-term



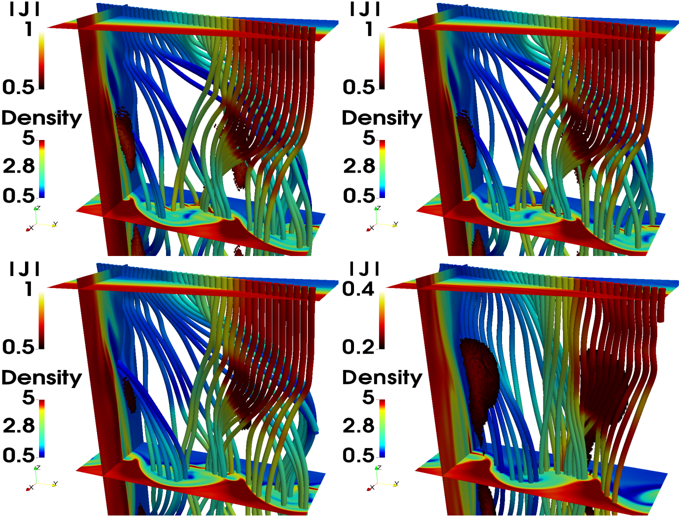


More complex situation.

Similar $< V_x^2 >$ for all η_H except $\eta_H = 6.25$ (realistic values)
$\rightarrow$ recover usual results from literature.

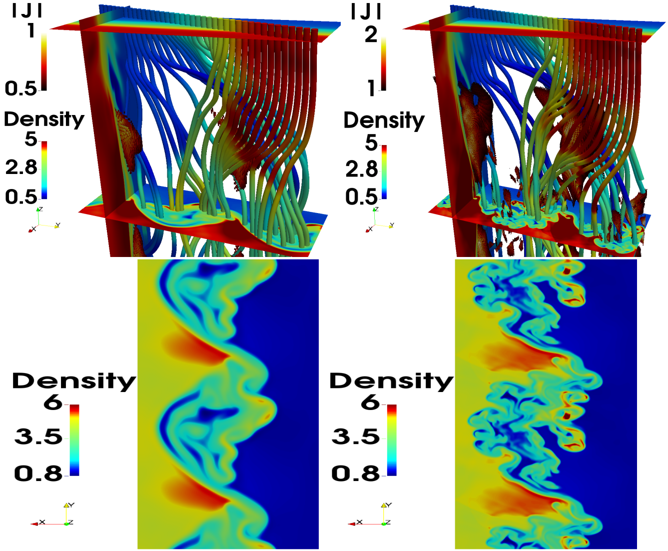
J_{max} decreases regularly as η_H increases.

Parameters exploration : Influence of the Hall-term



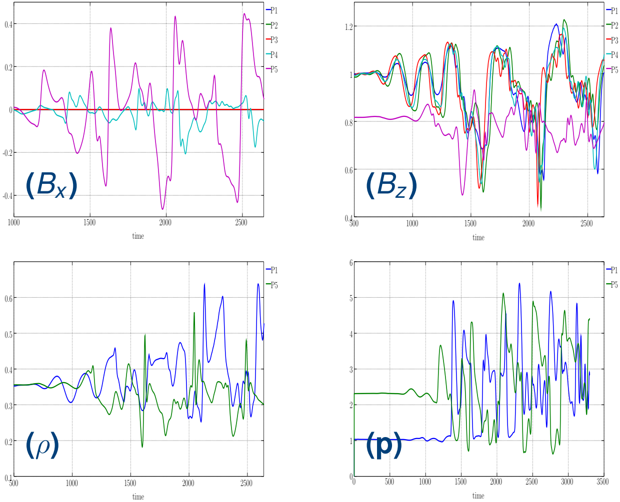
Magnitude and spatial extension of the current sheets decreases as η_H increases.

Parameters exploration : Influence of the resolution



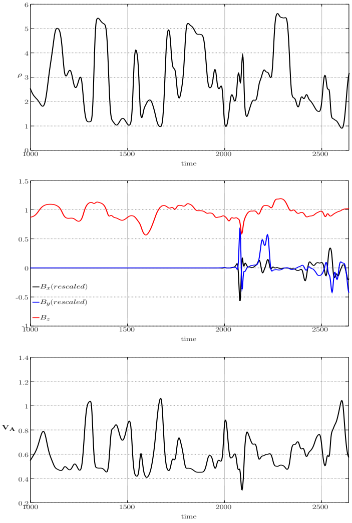
Magnitude of the current increases as resolution increases. Magnetic gradients and secondary instabilities better resolved.

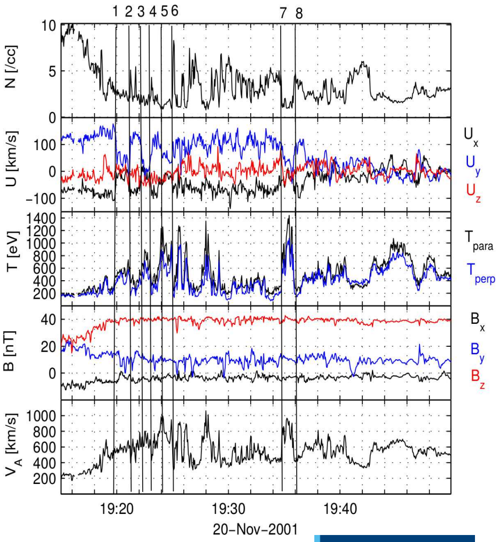
Simulated spacecrafts



First set reproduces Cluster around the interface (P1 to P4). Other located close to the current sheets coordinates.

Simulated spacecrafts





Conclusion

- Double reconnection at mid-latitude recovered.
- Density jump influence the boundary layer $\rightarrow$ non-mixed blob important for DMLR.
- Shear layer width influence KHI evolution. Combined with Δ_ρ and shn $\rightarrow$ even more complex.
- Hall-MHD does not modify the phenomenon, but changes the magnitude of current (here inhibition).
- Higher resolution $\rightarrow$ resolves a lot more secondary instabilities + current magnitude at least 2 times larger.
- Article to be submitted

Conclusion

- Q-maps and diagnostics for reconnection characterization $+$ evaluation of mass entry.
- Improve simulation of spacecrafts to actually compare with in-situ data.
- Use parameters value derived from experimental measures $\rightarrow$ correct shear length and magnitude, density jump, Mach and β
- Implement a more efficient scheme (MHD : 200^3 in 3.5 days (32 proc), Hall-MHD 4 to 8 times longer).

Thank you for your attention