A gyrofluid model to investigate collisionless reconnection with finite β_e effects

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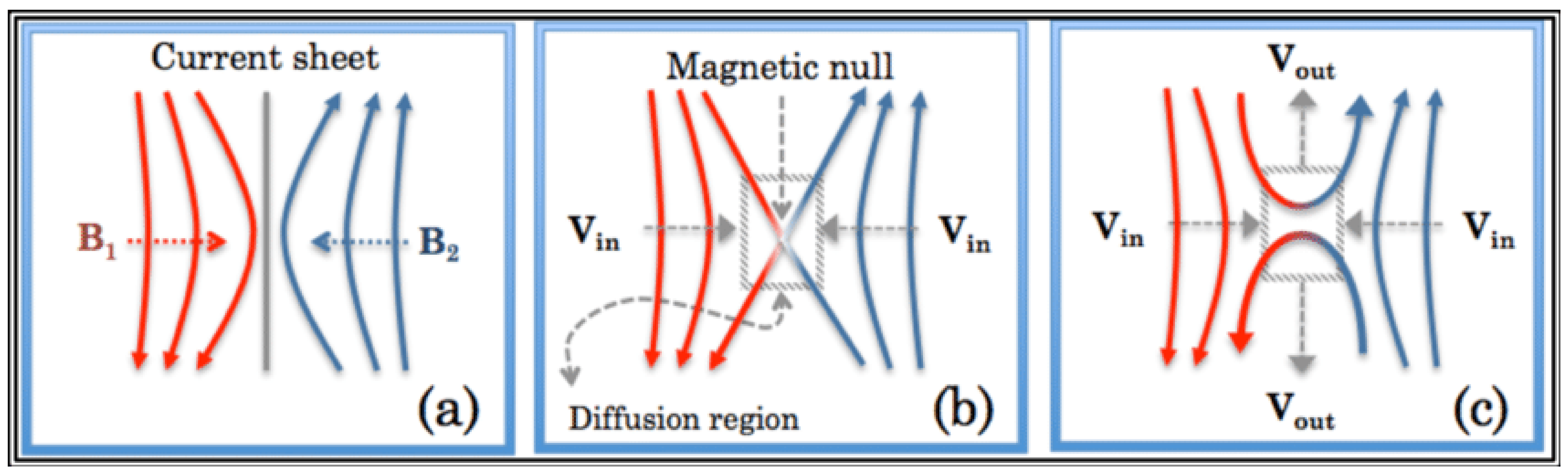
- We provide a gyrofluid extension of previous studies based on the $\beta_e \to 0$ limit (e.g. Porcelli F., Borgogno D., Califano F., Grasso D., Ottaviani M., Pegoraro F., Plasma Phys. Control. Fusion, 44, B389-B405 (2002)).
- Finite β_e effects can be relevant for reconnection in some collionless plasmas such as the solar wind.
- Finite $\beta_e \to$ **finite parallel magnetic perturbations and electron FLR effects**.
- Gyrofluid models provide an effective tool, complementary to kinetic models, for studying such effects.

1. Magnetic reconnection



2. The gyrofluid Model

Ions are assumed to be immobile and cold, $T_i/T_e = 0$ ($\rho_i \to 0$).
Slab geometry with strong guide field,

$$\mathbf{B}(x,y,t) \approx \mathbf{z} + B_\parallel(x,y,t)\mathbf{z} + \nabla A_\parallel(x,y,t) \times \mathbf{z}.$$

Two evolution equations and three static relations from *Tassi et al. 2020*

Continuity: $$\frac{\partial N_e}{\partial t} + [G_{10e}\phi - \rho_s^2 2G_{20e}B_\parallel, N_e] - [G_{10e}A_\parallel, U_e] = 0,$$

Ohm's law: $$\frac{\partial(G_{10e}A_\parallel - d_e^2 U_e)}{\partial t} + \rho_s^2[G_{10e}A_\parallel, N_e] + [G_{10e}\phi - \rho_s^2 2G_{20e}B_\parallel, G_{10e}A_\parallel - d_e^2 U_e] = 0,$$

Quasi-neut.: $$\left(\frac{G_{10e}^2 - 1}{\rho_s^2} + \nabla_\perp^2\right)\phi - (G_{10e}2G_{20e} - 1)\,B_\parallel = G_{10e}N_e,$$

$\parallel$Ampère's law: $$\nabla_\perp^2 A_\parallel = G_{10e}U_e,$$

$\perp$Ampère's law: $$(G_{10e}2G_{20e} - 1)\frac{\phi}{\rho_s^2} - \left(\frac{2}{\beta_e} + 4G_{20e}^2\right)B_\parallel = 2G_{20e}N_e.$$

Gyro-averaged operators: $G_{10e} = 2G_{20e} \to e^{-k_\perp^2 \frac{\rho_e^2}{2}}$.

$\rho_e = \sqrt{\frac{m_e}{m_i}}\rho_s = d_e\sqrt{\frac{\beta_e}{2}}$: **electron Larmor radius**.
$\beta_e = 8\pi\frac{n_0 T_e}{B_0^2}$: ratio between the electron pressure and the magnetic pressure,
$d_e = \frac{c}{L}\sqrt{\frac{m_e}{4\pi e^2 n_0}}$: electron skin depth. ρ_s: sonic Larmor radius,

Using $A_e = G_{10e}A_\parallel - d_e^2 U_e$, the Hamiltonian and the Poisson bracket read,

$$H(N_e, A_e) = \int \frac{d^2x}{2}\left(\rho_s^2 N_e^2 - A_e U_e - N_e(G_{10e}\phi - \rho_s^2 G_{10e}B_\parallel)\right),$$

$$\{F,G\} = \int d^2x\left(N_e([F_{N_e}, G_{N_e}] + d_e^2\rho_s^2[F_{A_e}, G_{A_e}]) + A_e([F_{A_e}, G_{N_e}] + [F_{N_e}, G_{A_e}])\right).$$

3. Set up

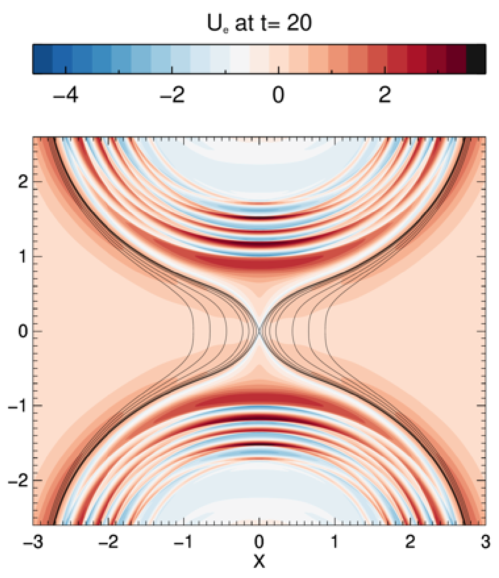
Equil.: $A_\parallel^{(0)}(x) = \sum_{-30}^{30} a_n e^{inx}$, $\phi^{(0)}(x) = 0$,

a_n are the Fourier coefficients of $1/\cosh(x)^2$.

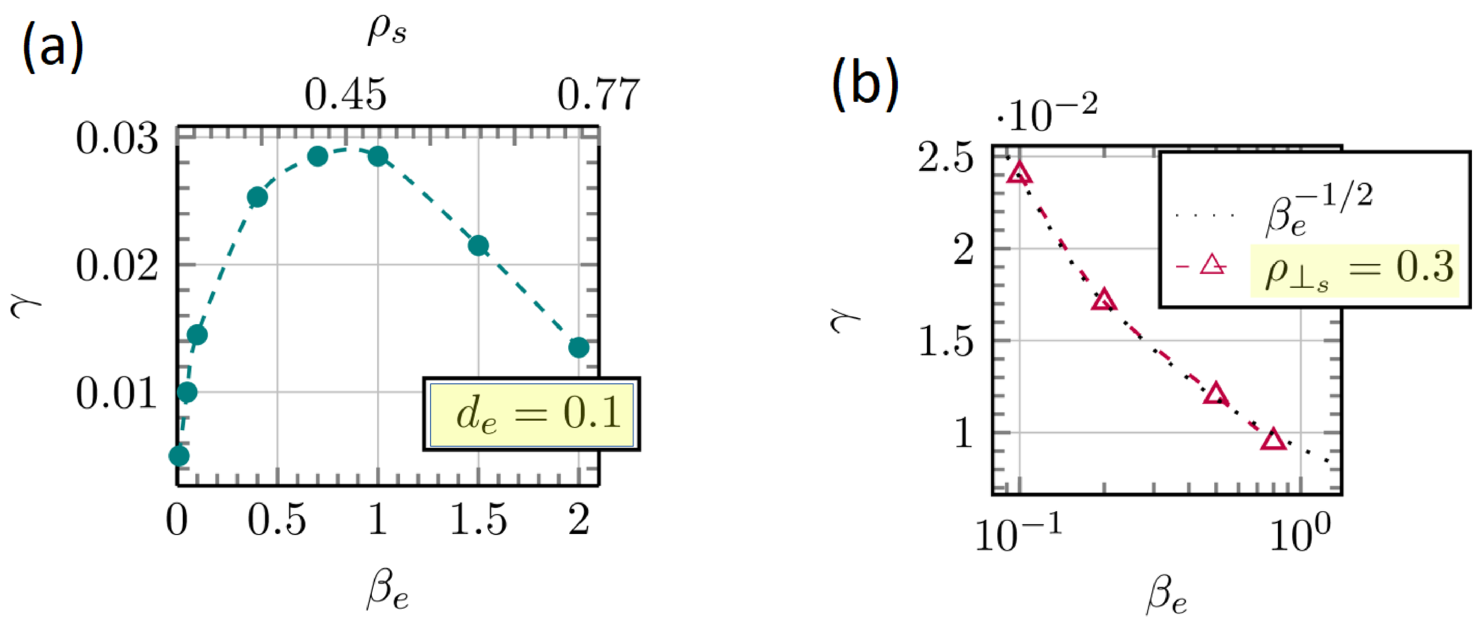
We keep $m_e/m_i = 0.01$.

The fixed parameter is highlighted in yellow.

Out of plane current density for $\rho_s = 0.63$, $d_e = 0.1$, $\beta_e = 0.9$.



4. Linear phase



(a): ρ_s and β_e are increasing $\to$ we observe a competition between the **destabilizing effect of** ρ_s and the **stabilizing effect of** β_e. This can also be interpreted as fixing the background density, n_0, the ion mass (so that d_e is fixed) and the guide field amplitude B_0, while increasing the electron temperature T_{0e}.

(b): d_e decreases as β_e increases, keeping a constant $\rho_e = 0.03$. We observe the same scaling as in the gyrokinetic study of *Numata et al. 2011*.

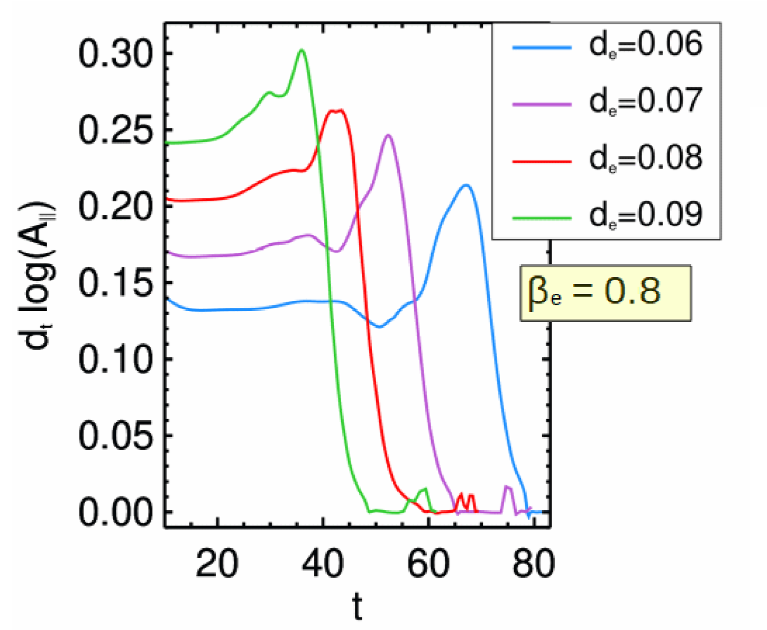
Only increasing β_e (considering a varying mass ratio) results in stabilizing the tearing mode as in *Numata et al. 2015*.

Good capability of the gyrofluid model to reproduce gyrokinetic results and the fluid theory of *Fitzpatrick et al. 2007*, in a quantitative way.

This study can be also relevant for astrophysical plasmas with large temperatures, such as in the Earth magnetosheath, where some $\beta > 1$ values are observed, in the presence of a guide field, during reconnection events (*Man et al. 2020*).

5. Non-linear phase

Strongly unstable case ($\Delta' = 14.3$). Here d_e increases together with ρ_s.



For $d_e = 0.09 \to$ double faster-than-exponential phase. Nonlinear growth acceleration was numerically predicted for the $m = 1$ mode in tokamaks, corresponding to large-Δ' regimes in slab model (*Aydemir et al. 1992*).
For $d_e \ll 0.07$, $\to$ growth of the magnetic island slows down.
Growth of the island seems to be delayed. Maximum width of the magnetic structures before saturation are identical.

6. Comparison Fluid ($\beta_e = 0$) /Gyrofluid ($\beta_e \neq 0$)

When $\beta_e \sim m_e/m_i \sim 0$ the model can be reduced to (*Schep et al. 1994*)

$$\frac{\partial \nabla_\perp^2\phi}{\partial t} + [\phi, \nabla_\perp^2\phi] - [A_\parallel, \nabla_\perp^2 A_\parallel] = 0,$$

$$\frac{\partial}{\partial t}\left(A_\parallel - d_e^2\nabla_\perp^2 A_\parallel\right) - \rho_s^2[\nabla_\perp^2\phi, A_\parallel] + \left[\phi, A_\parallel - d_e^2\nabla_\perp^2 A_\parallel\right] = 0.$$

A dispersion relation, valid for, $\frac{\gamma d_e}{k_y \rho_s}\Delta' \ll 1$, that brings a corrective term to the formula of *Porcelli et al. 1991*,

$$\gamma = 2k_y\frac{d_e\rho_s}{\pi\lambda}\Delta' + \frac{\gamma^2 d_e \pi\lambda}{4k_y\rho_s^2}.$$

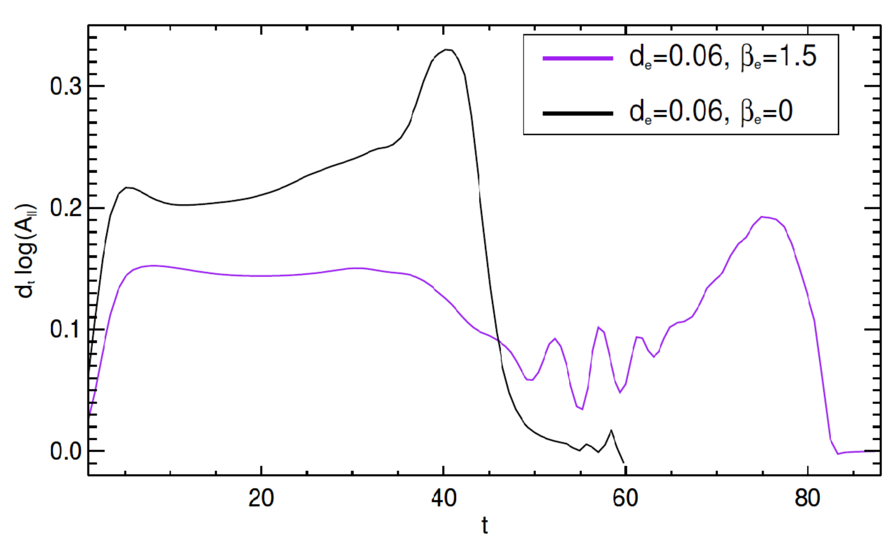


Figure: Fluid simulation with $\beta_e = 0$ (black curve) and gyrofluid simulation $\beta_e = 1.5$ (purple curve), for $\rho_s = 0.519$ and $d_e = 0.06$. For $\beta_e = 1.5$, appearance of a slow down phase preceding the explosive growth.

7. Brief investigation of the hot ion regime

If we take the parent model in the limit $T_i/T_e \to +\infty$, the static relations are

$$\phi = \frac{\rho_s^2 N_e}{\left(1 - \frac{\beta_e}{2}\right)G_{10e} - G_{10e}^{-1}},$$

$$B_\parallel = \frac{\beta_e}{2\rho_s^2}\phi.$$

For $\beta_e > 0.5$, the growth rate is very insensitive to ion temperature.

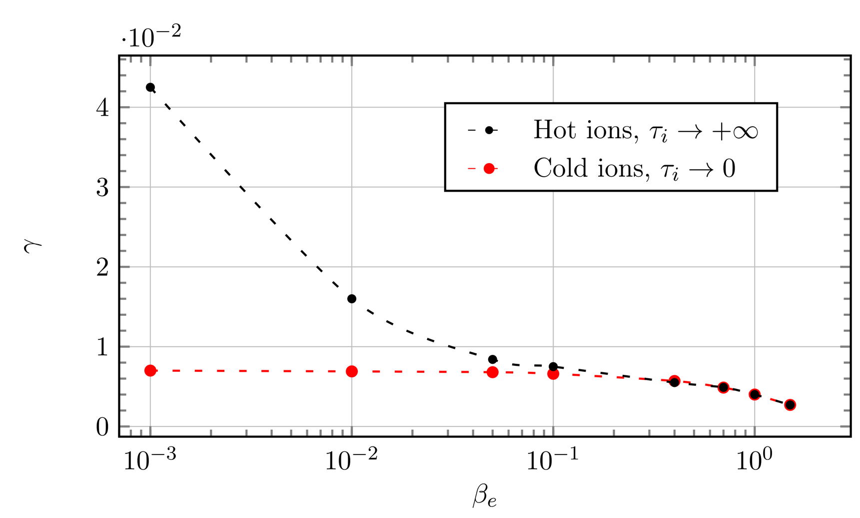


Figure: $d_e = 0.1$, $\rho_s = 0.1$, $\Delta' = 0.59$.

8. Reference

Granier et al. 2021: https://arxiv.org/abs/2110.03052