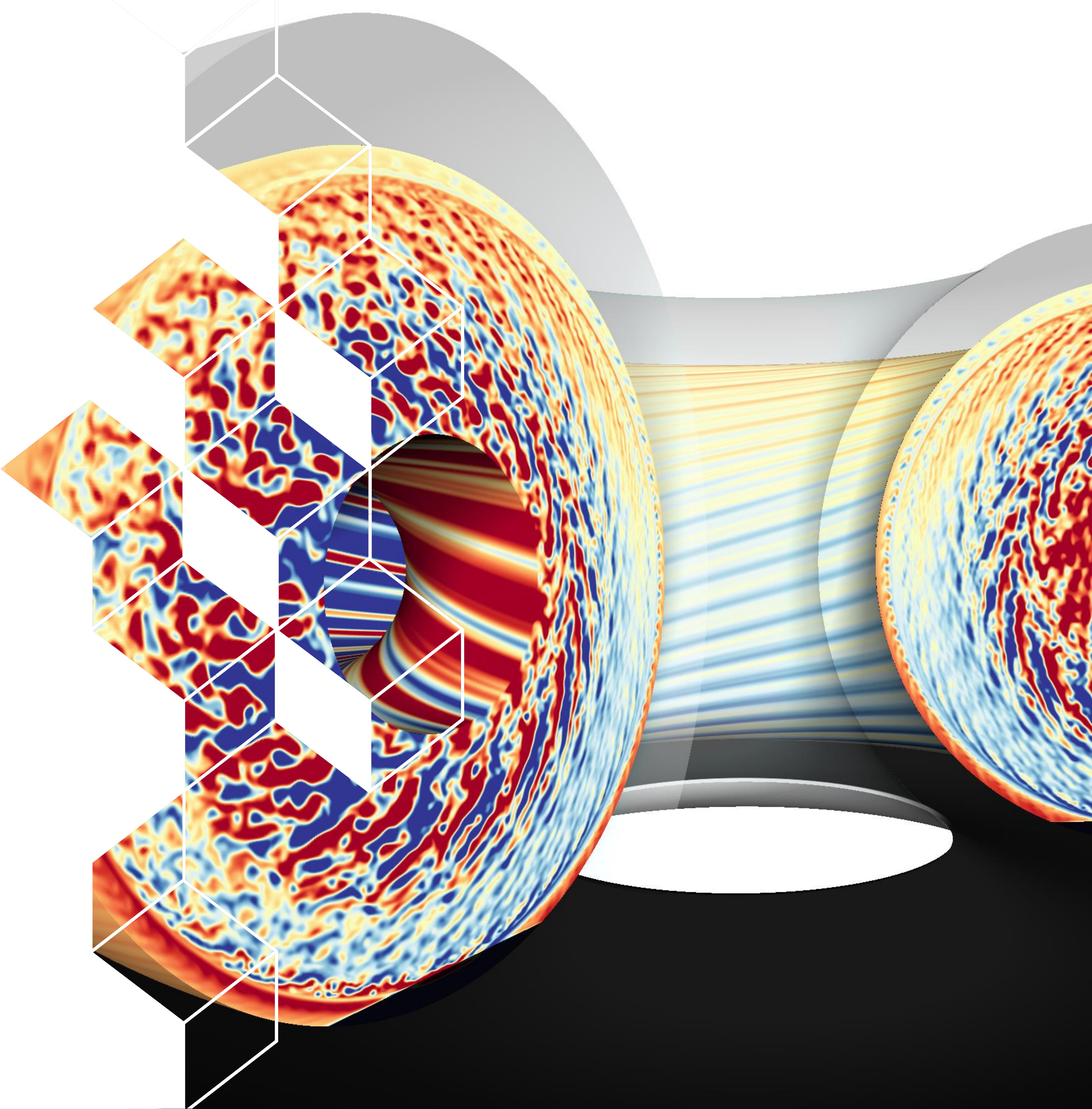
Electromagnetic version of GYSELA: current status and perspectives



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GYSELA features

- Global, flux-driven gyrokinetic (GK) code
- Backward semi-Lagrangian scheme for the Vlasov part
- Multiple ion species is possible
- Three kind of electron models: adiabatic, hybrid, kinetic
- Limiter condition (for adiabatic electrons, in development with electrons)
- Shaping taken into account. In this work, circular cross-sections
- Historically, the code was electrostatic. But an electromagnetic version ($A_{||}$ only) has been included during the PhD of Camille Gillot (2020).
- The numerical scheme implemented is based on the pull back scheme [A. Mishchenko 2014] to treat the problem of magnetic cancellation.

GYSELA scheme for electromagnetic perturbations

Vlasov

[Gillot PhD 2020]

$$B_{||}^* \dot{\vec{X}} = \left(w - \frac{e}{m} J[\psi_h]\right) \vec{B}^* + \frac{\vec{b}}{e} \times \vec{\nabla}\mathcal{H}$$

$$m B_{||}^* \dot{w} = -\vec{B}^* \cdot \vec{\nabla}\mathcal{H} - e B_{||}^* J[\partial_t \psi_s]$$

$$\vec{B}^* = \vec{B} + \frac{mw}{e} \nabla \times \vec{b} + \frac{m}{e} \nabla \times (J[\psi_s]\vec{b})$$

$$\psi = \psi_s + \psi_h$$

Ampère

$$-\mu_0^{-1} \nabla_\perp^2 (\psi_h + \psi_s) + \sum_{\text{species}} \frac{n_0 e^2}{m} \psi_h = \sum_{\text{species}} e \int w J^\dagger [F B_{||}^*] \mathrm{d}w \mathrm{d}\mu - J_{||,\mathrm{eq}}$$

Basic idea: to control the cancellation problem, ψ_s is used as an accumulator of ψ_h

It leads to a change of coordinates for Vlasov $w^{\mathrm{old}} = v + \frac{e}{m} J[\psi_h^{\mathrm{old}}]$

$$w^{\mathrm{new}} = v + \frac{e}{m} J[\psi_h^{\mathrm{new}}] = v$$

Outlook

- Electromagnetic version with GYSELA

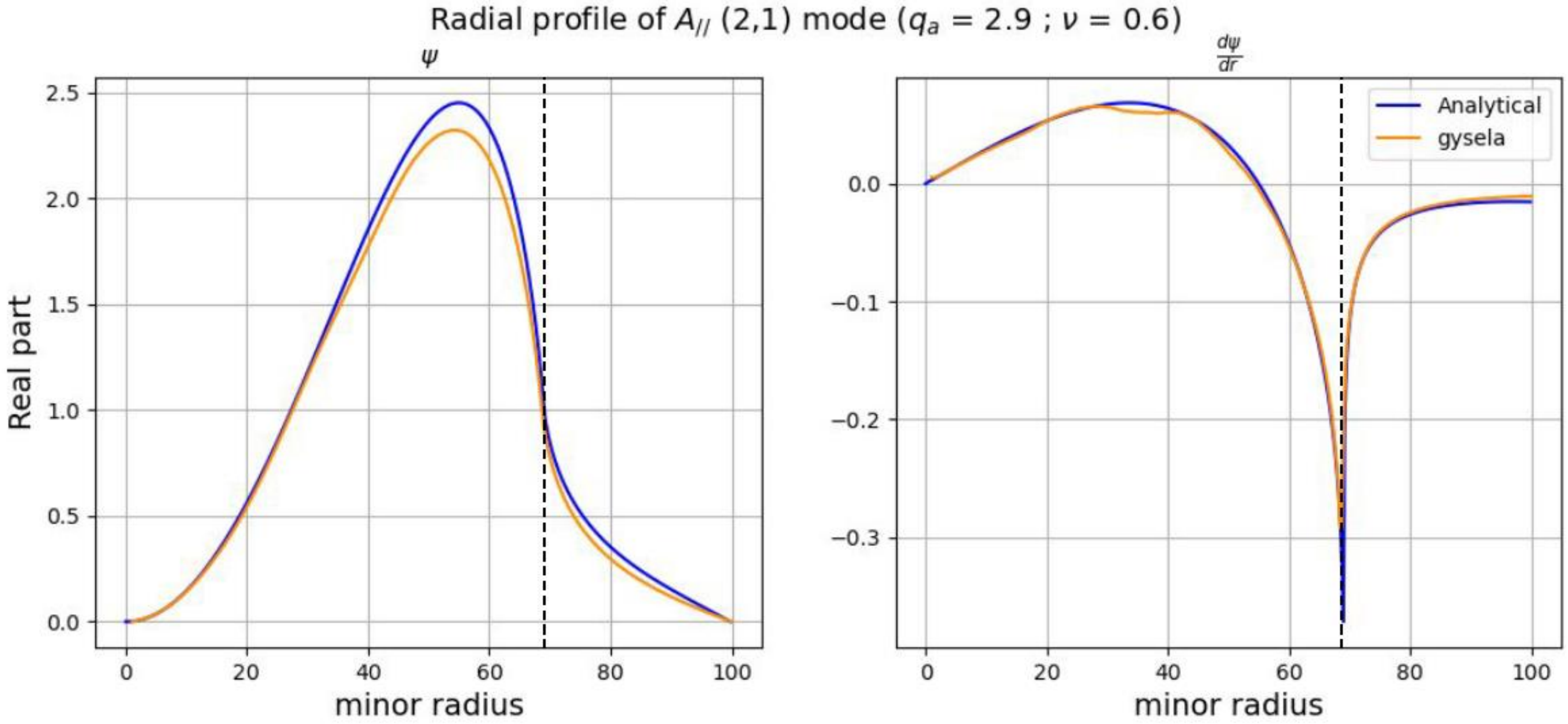
- Tearing without electric potential nor collisions

- Tearing with electric potential but no collisions

- Perspectives:
  - ❖ Tearing with electric potential & collisions
  - ❖ Interaction between the tearing instability and turbulence
  - ❖ Change Ampère solver: from circular to shaped plasmas

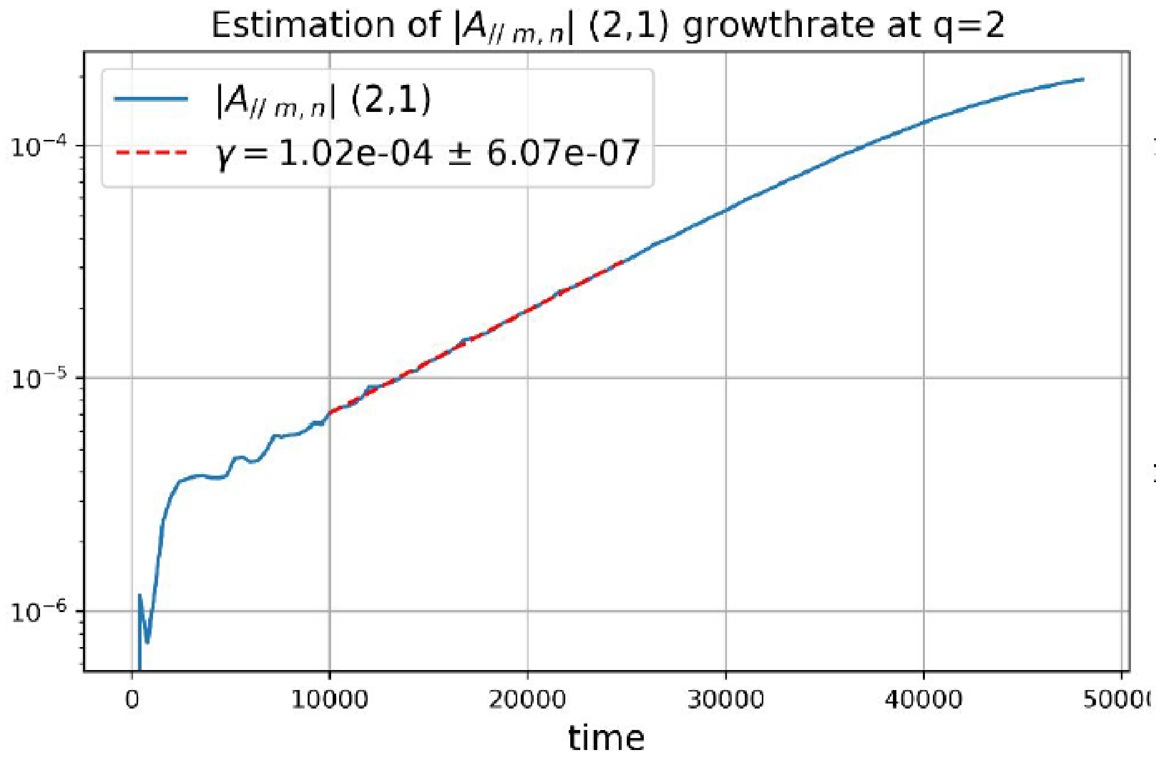
Tearing w/o Φ & collisions: radial shape of A// in agreement with prediction

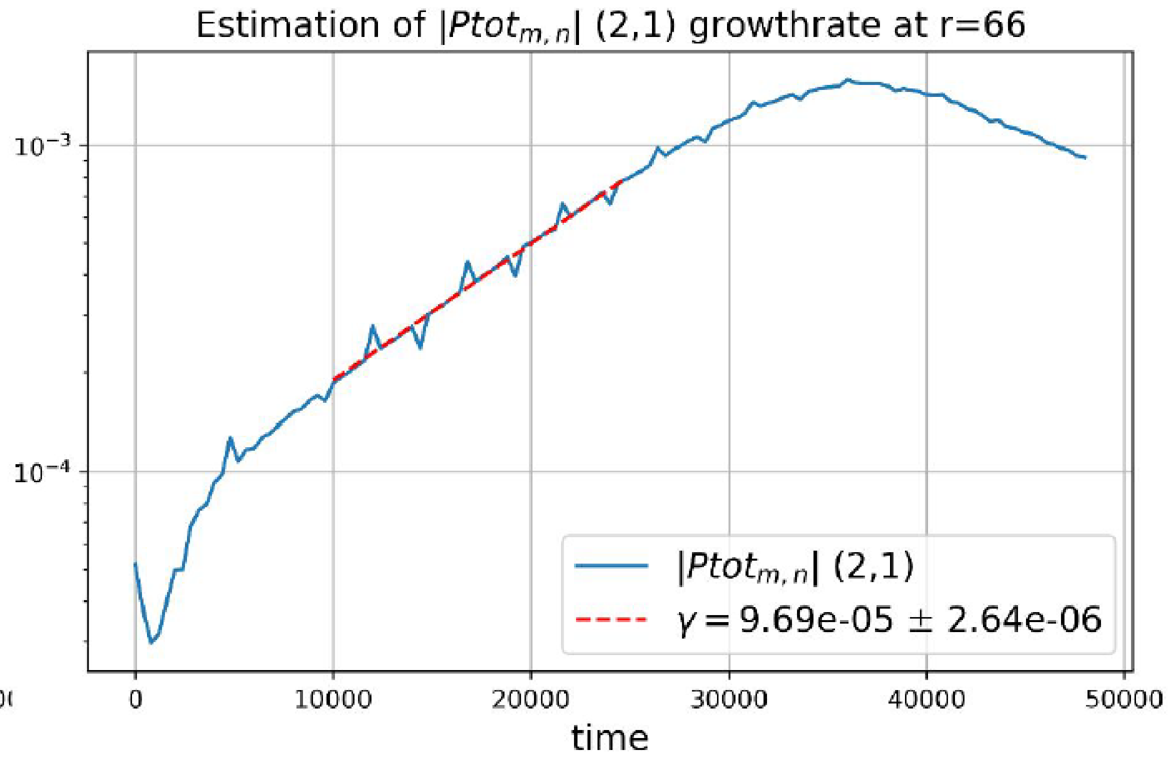
- Vlasov & Ampère equations are solved. No electrostatic potential, no collisions
- Only the toroidal mode number n=1 is kept (numerical filter on other modes)



Tearing w/o Φ & collisions: Numerical estimation of the growth rate

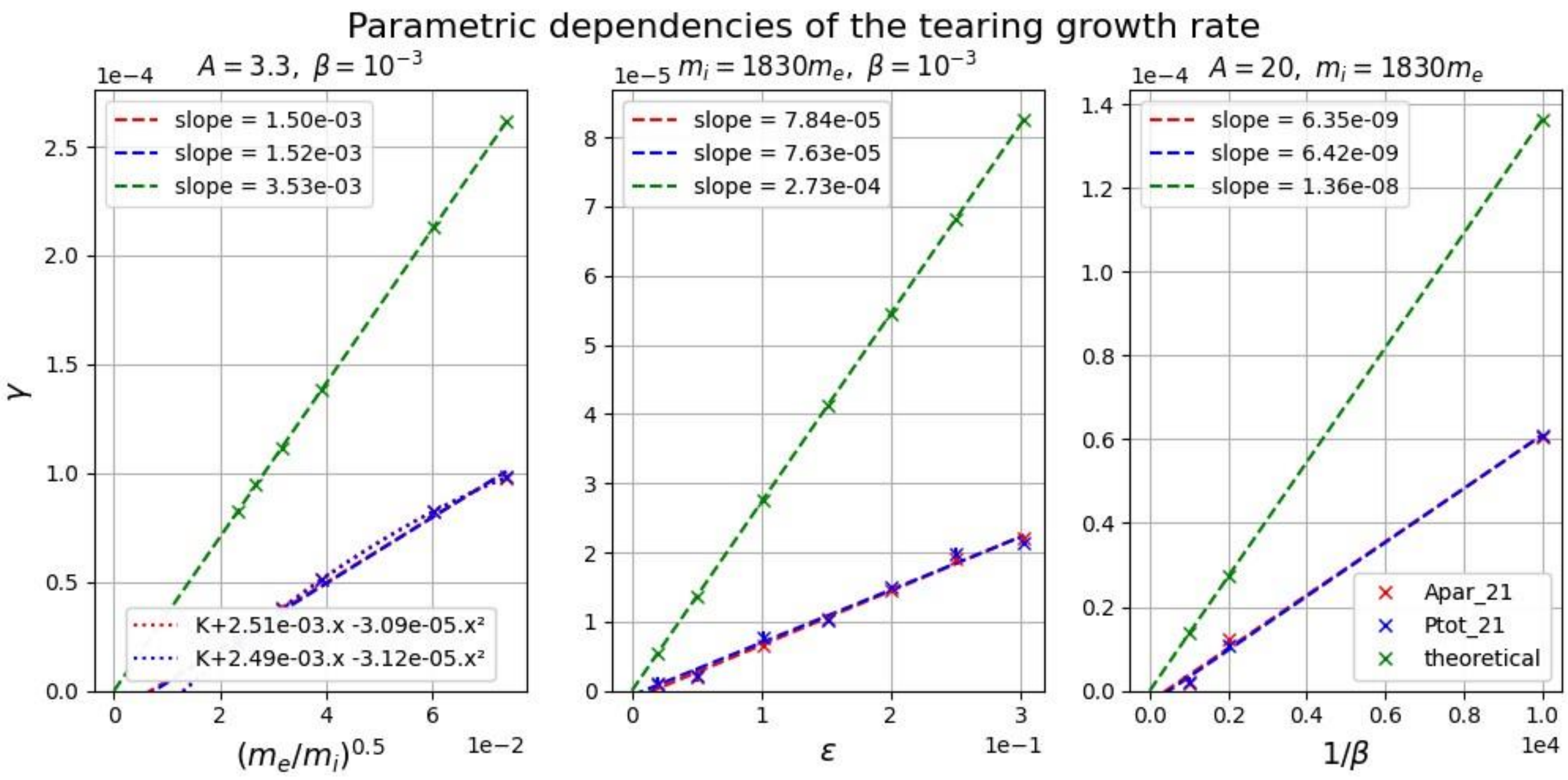
- Linear phase = when both $A_{\parallel m,n}$ and $P_{tot,m,n}$ are growing with the same growth rate





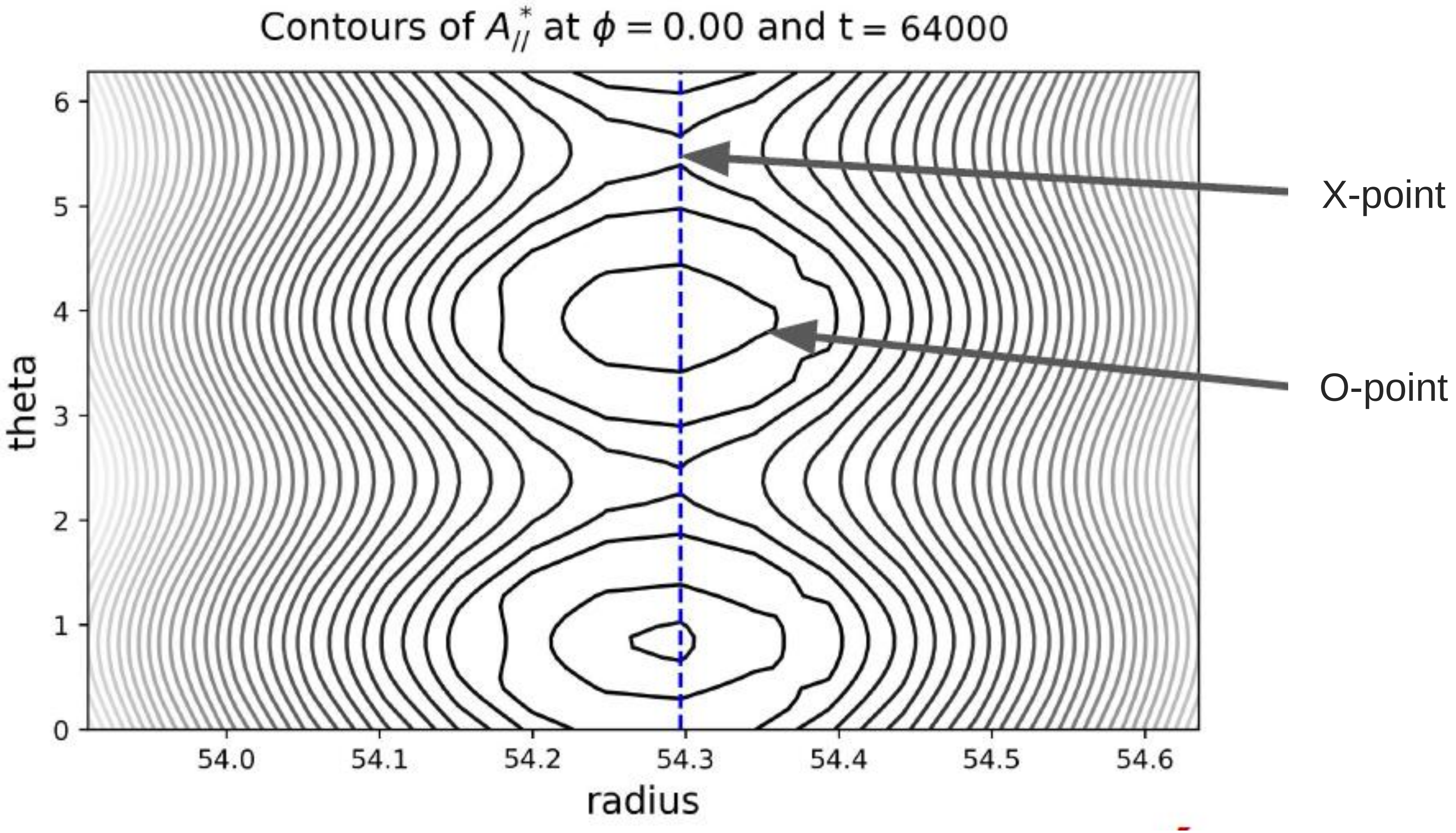
Tearing w/o Φ & collisions: Parameter dependence of the growth rate

- An analytical prediction has been derived: $\gamma \propto \Delta' \sqrt{\frac{m_e}{m_i}} \frac{\varepsilon}{\beta}$ Dependencies retrieved



Tearing w/o Φ & collisions: Magnetic island retrieved

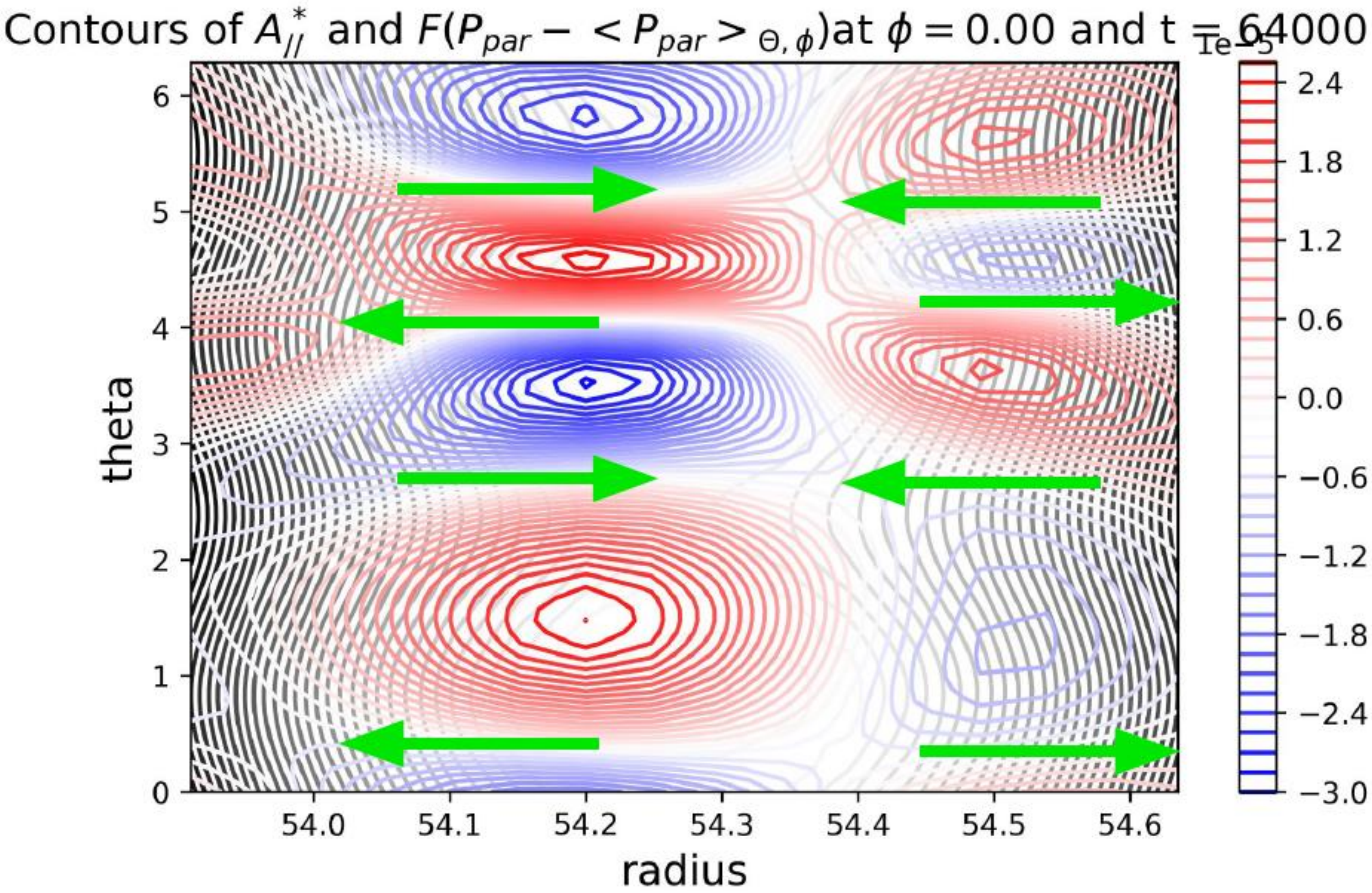
- Change of coordinates to be in the referential q=-m/n [A, Poyé (2012)]



Tearing w/o Φ & collisions: Magnetic island standard picture

$$\boldsymbol{u}_e^* = \frac{\nabla P_e \times \boldsymbol{B}}{e n_e B^2}$$

Pressure quadrupole retrieved



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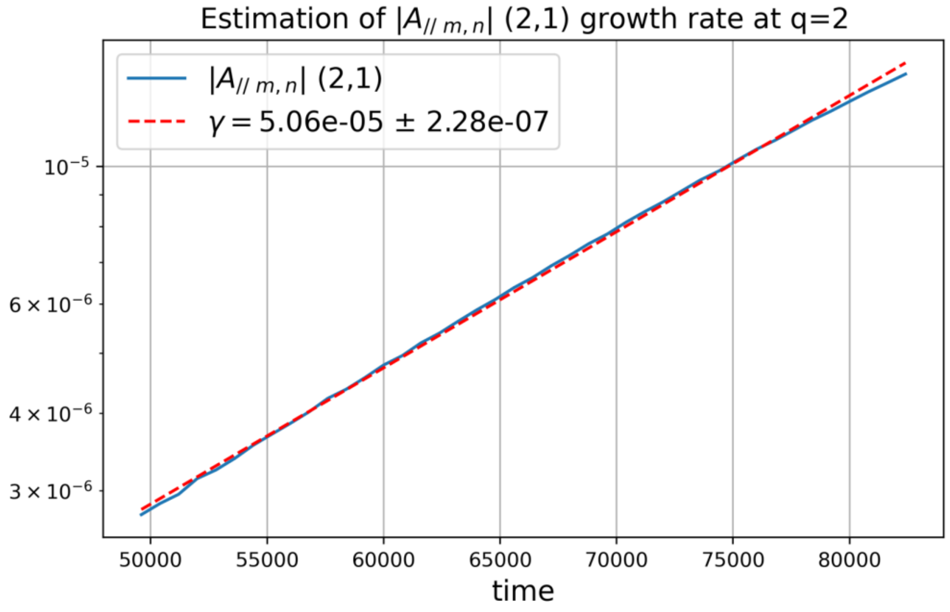
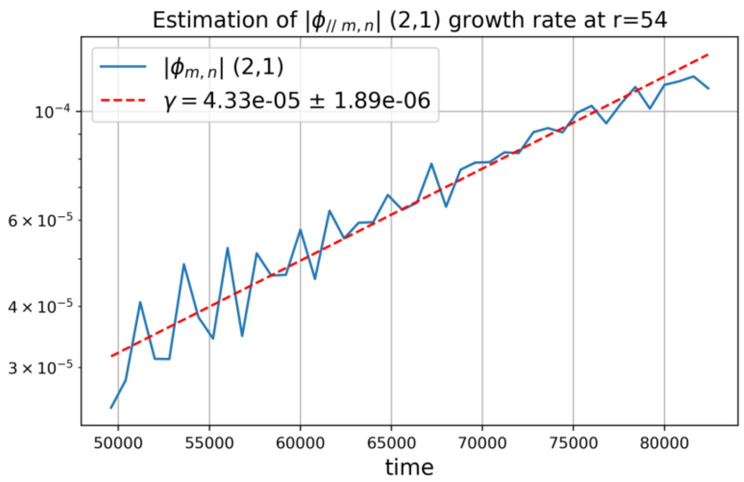
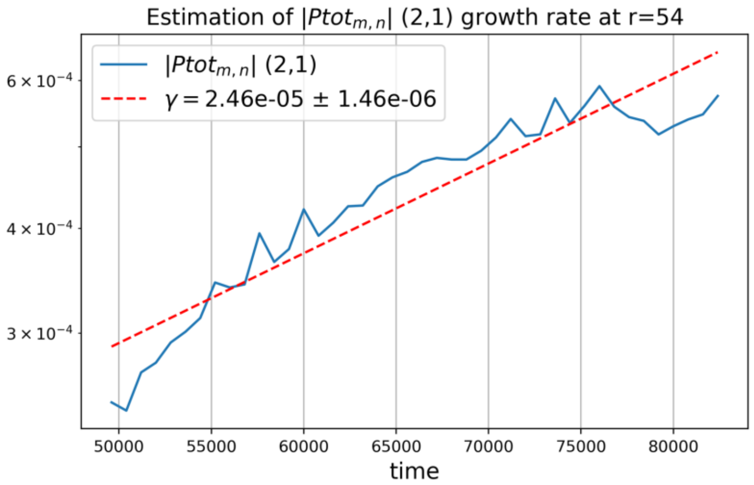
Tearing with Φ but no collisions: Numerical estimation of the growth rate

- The numerical time step needs to be reduced: $\Delta t\Omega_{ci} = 5$ without Φ; $\Delta t\Omega_{ci}$ =1 with Φ
- Linear phase = when $A_{\parallel m,n}$, $\Phi_{\parallel m,n}$ and $P_{tot,m,n}$ are growing with the same growth rate







Ongoing work. More simulations to come

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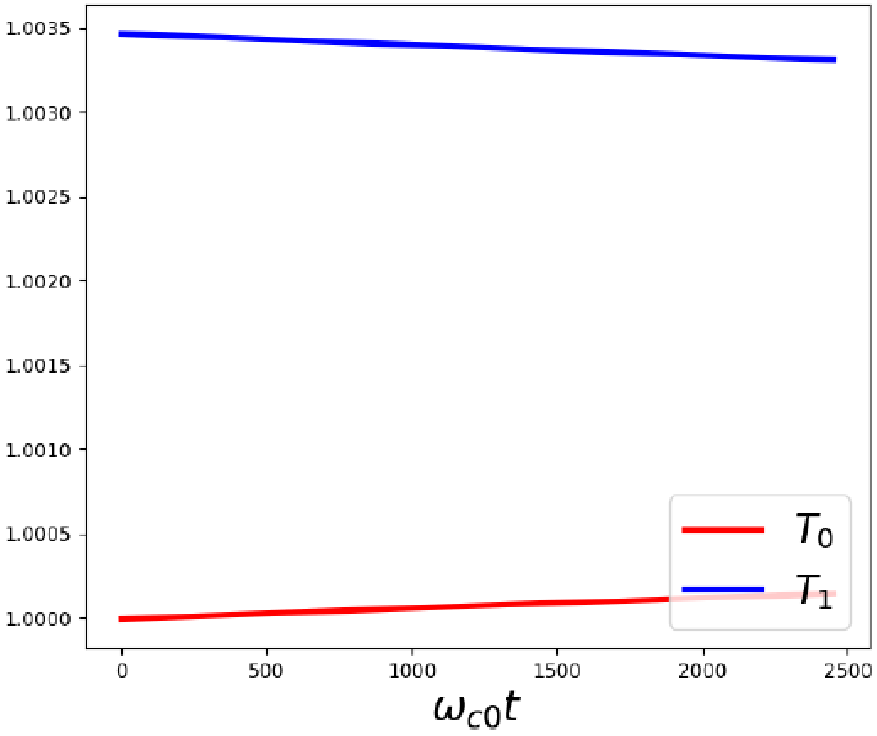
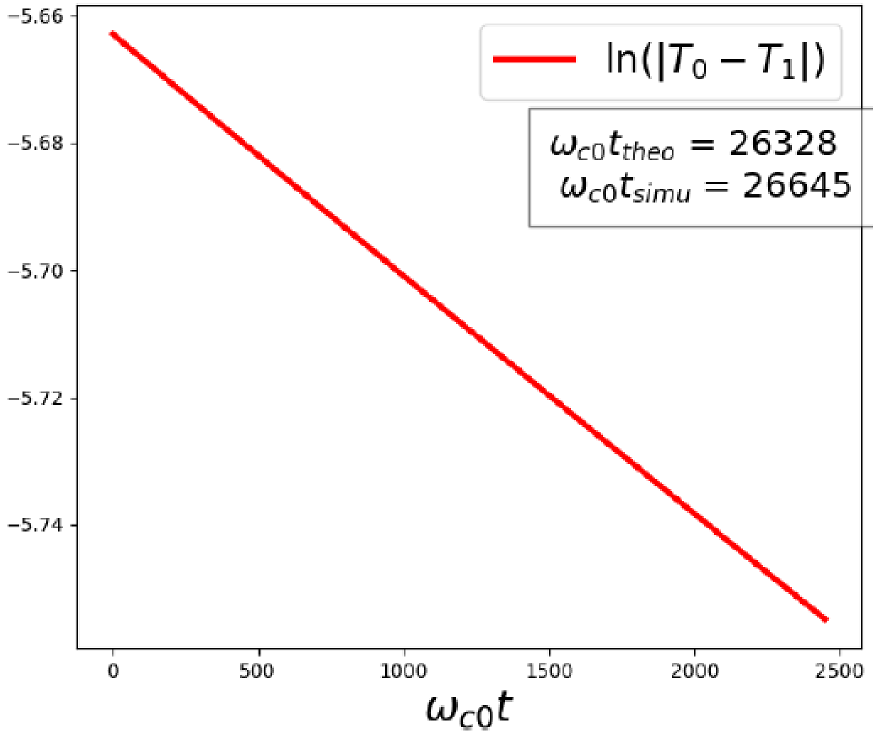
Ongoing test: collisions with realistic mass ratio

$m_i/m_e = 200$

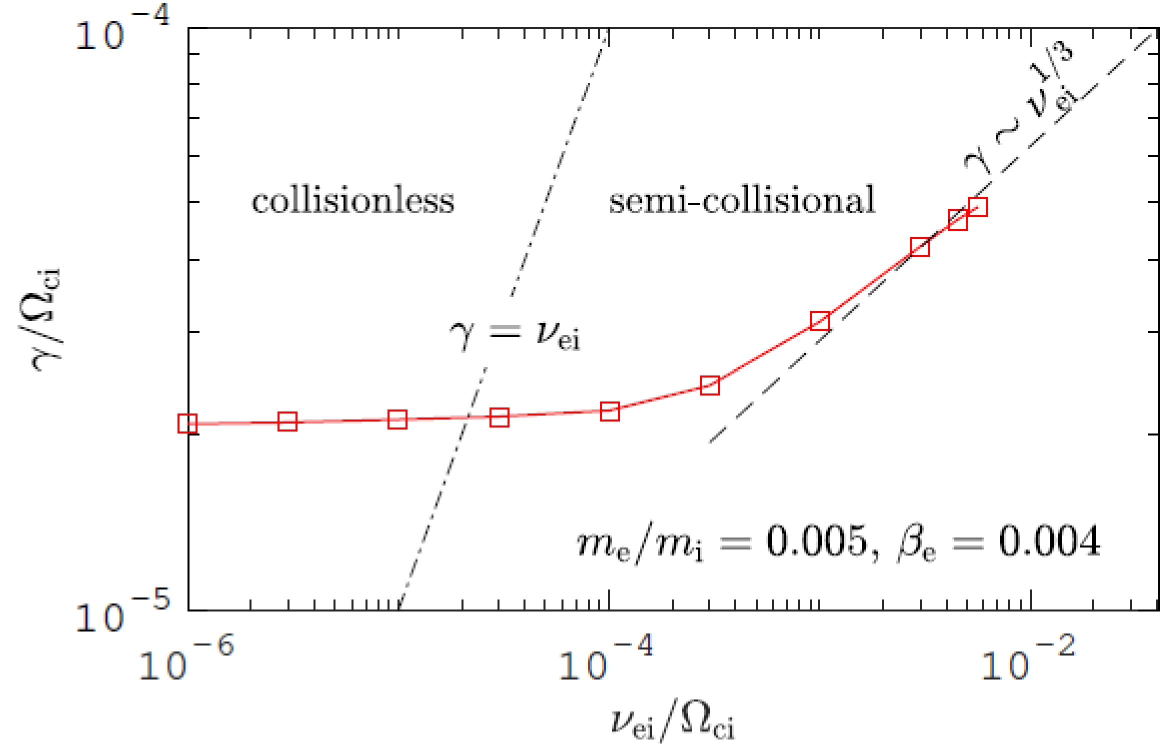




Ok up to mi/me = 200. Problem for mi/me = 400. Needs to be solved before being used for the tearing study

Next steps:

- Try to include GYSELA in a benchmark performed between GENE, ORB5, GKW and a two fluid code [Jitsuk 2023]
- In particular, a collisionality scan will be performed to retrieve the transition between the collisionless and semi-collisional regimes



Interaction between the tearing instability and turbulence

- PhD work of Roméo Bigué (2023-2026). PhD director: M. Muraglia, supervisors: Y. Sarazin and P. Donnel

- PhD included in the ENR project « Magnetic reconnection in tokamaks: from theoretical foundations to solutions for fusion energy » PI: M. Muraglia

- A three steps approach:
  - ❖ Impact of turbulence on the linear growth rate and saturation of the tearing instability:
    Comparison between simulations with or without turbulence (numerical filter applied on potentials with $n > n_{threshold}$)

  - ❖ Impact of a static magnetic island on turbulence: profile modification, turbulence spreading… To do so, electrostatic simulations will be perfomed. Maybe with adiabatic electrons. Can be discussed,

  - ❖ Fully consistent simulations: transport accross magnetic island, saturation of the magnetic island width

Change of Ampère's solver

$$-\mu_0^{-1}\nabla_\perp^2(\psi_h+\psi_s)+\sum_{\text{species}}\frac{n_0e^2}{m}\psi_h \;=\; \sum_{\text{species}} e\int wJ^\dagger[FB_{||}^*]\mathrm{d}w\mathrm{d}\mu - J_{||,\mathrm{eq}}$$

For now, FFT is used in the Ampère (assuming circular cross sections).

But a new solver has been developed for the quasi-neutrality equation in shaped plasmas

This solver needs to be used also for Ampère to allow electromagnetic simulations in shaped plasmas

Conclusion

- Electromagnetic version with GYSELA is a priori working. Need to be tested with collisions
- A PhD will use this new version to study the interaction between the tearing and turbulence
- There is also an ongoing internship (CEA) and a postdoc (Singapour) starting to use this version to study TAEs
- An improvement to be able to run electromagnetic simulations in shaped plasmas is foreseen