Interaction between magnetic islands and turbulence in tokamaks

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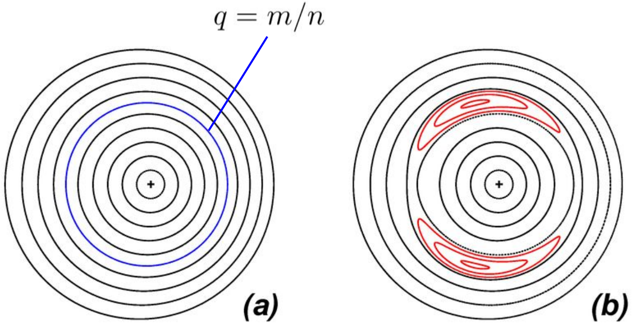
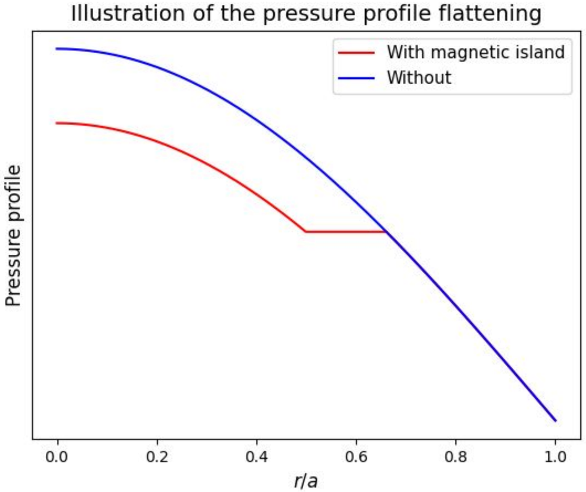
Magnetic islands in tokamaks

magnetic reconnection :
local merging of flux surfaces with ≠ T



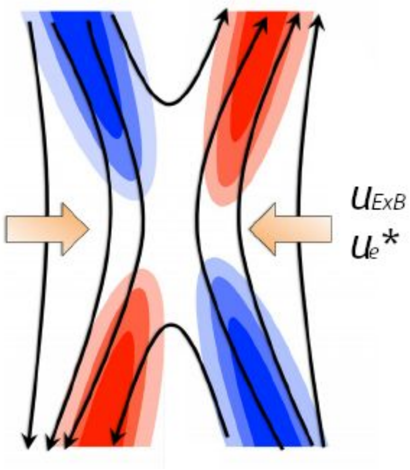


- modify turbulence
- NTM can cause disruptions

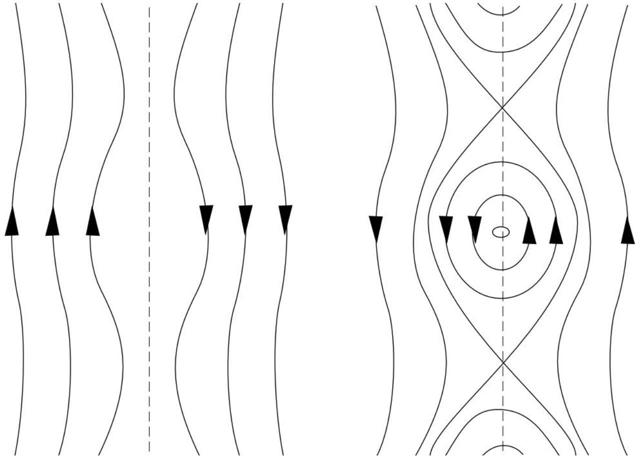
Impact of the interaction on confinement quality and transport ?

Origin of the magnetic island

Magnetic energy drives the tearing instability



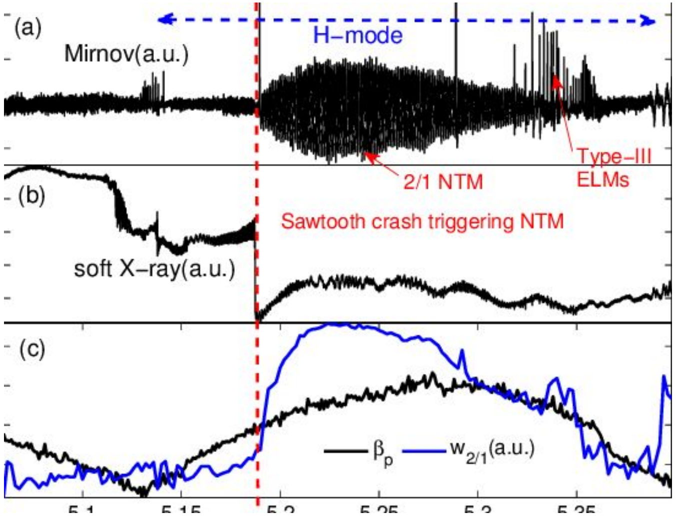
Large scales : ideal MHD => plasma and **B** are frozen-in
Small scales : non-ideal phenomena can break frozen-in law and lead to magnetic reconnection



Tokamaks are built tearing proof, what is creating magnetic islands ?

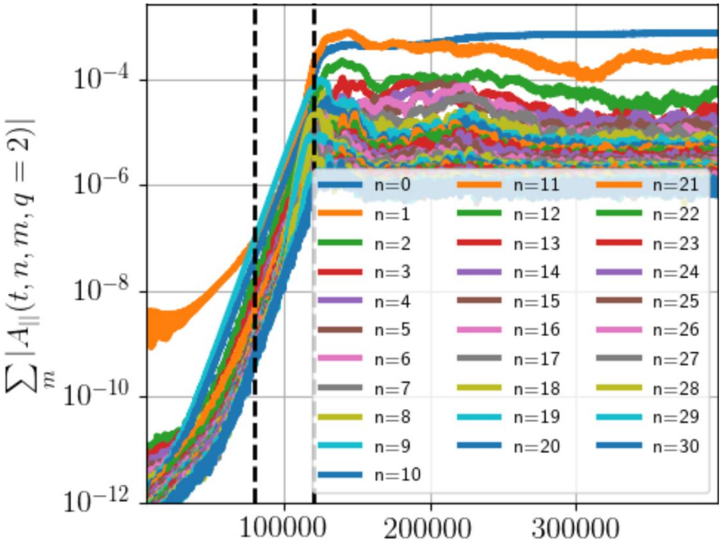
Effective drive of the magnetic island

Sawtooth crash triggering NTM



[Sauter 2002] [Xu Lq 2012]

Turbulence-driven magnetic island



[Agullo 2014] [Widmer 2023 ECMRP]

Mutual interaction between magnetic island and turbulence

Goals of the PhD

Study the interaction between magnetic island and turbulence using GYSELA

Compare the importance of inertial and collisional non-ideal phenomenon in magnetic island drive

Study the saturation of the inertial tearing

Outline

1. Magnetic island in tokamaks
2. **Collisional vs inertial drive**
3. Study of the collisionless tearing

Non-ideal phenomena inducing magnetic reconnection

ideal non-ideal

MHD simulations

$$\boldsymbol{E} = \boldsymbol{u} \times \boldsymbol{B} + \eta \boldsymbol{j} + \boldsymbol{E}_{\text{inertial}} + \ldots$$

induction resistivity $\propto m_e$

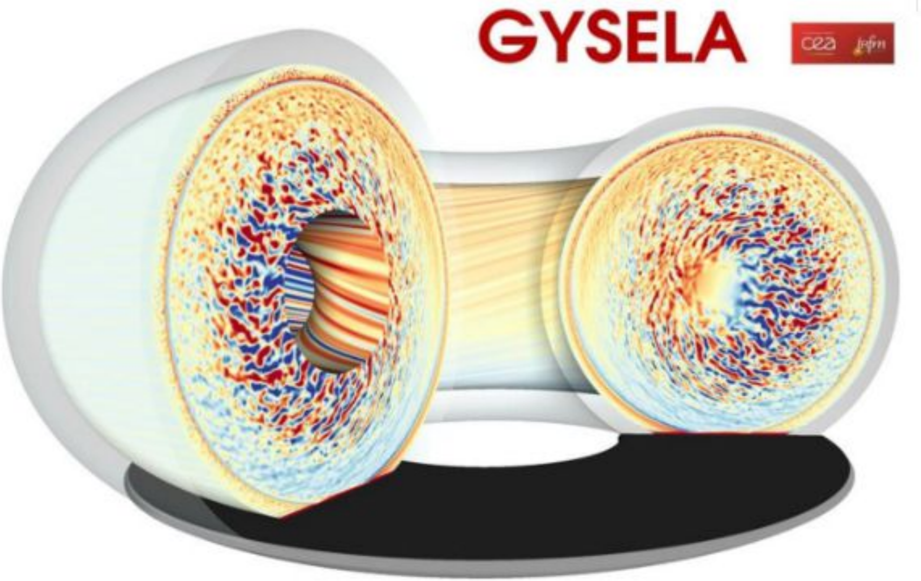
L (m) $\gg$ L_η (cm) $>$ d_e

How to correctly describe magnetic islands growth and saturation with inertial and resistive phenomena ?

Electromagnetic GYSELA

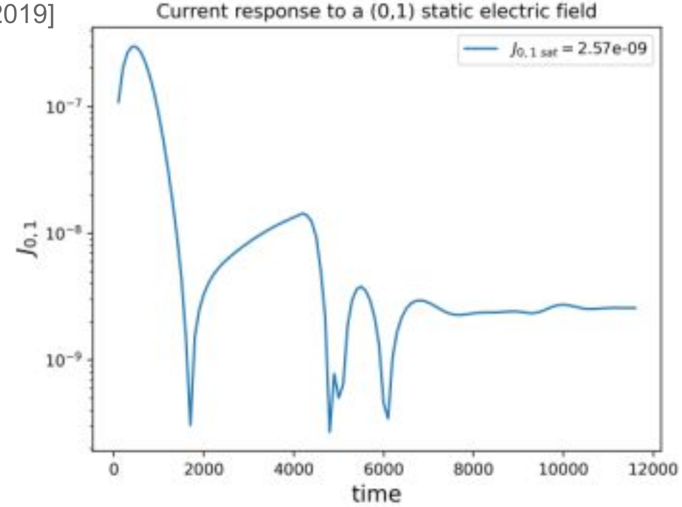
Gyrokinetic **se**mi-**la**grangian
global 5D full-f code

Solving ϕ and $A_{//}$ fluctuations [Gillot 2020]



Access the collisional regime in GYSELA

Examine GYSELA's ion-electron collision operator consistency with classical and neoclassical phenomena [Donnel 2019]



1st test : verify Spitzer's resistivity

We set a static electric field : $\phi = \phi_0 \cos(n\varphi)$

Comparison with current saturation

$$\frac{\hat{\phi}_0}{\hat{J}_{//}} = \frac{\epsilon_a^{3/2}}{q\hat{N}} \sqrt{\frac{m_e}{m_i}} \nu * \ \simeq \ 4.4\ 10^{-5}\ \nu *$$

2nd test : verify Bootstrap current

Saturation mechanism investigation

Island saturation size prediction critical for disruption prevention

Collisionless tearing using fluid simulations : inertia is non-dissipative [Porcelli, Grasso]

No gyrokinetic simulation of the collisionless saturation for now

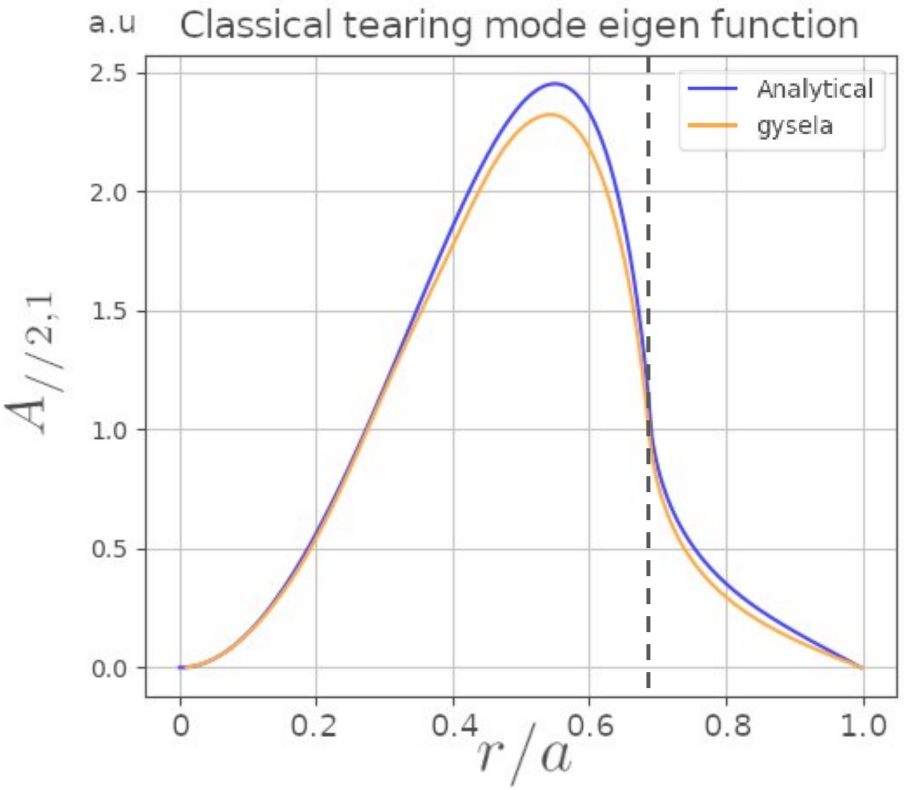
What kinetic effects could be responsible for the saturation ?

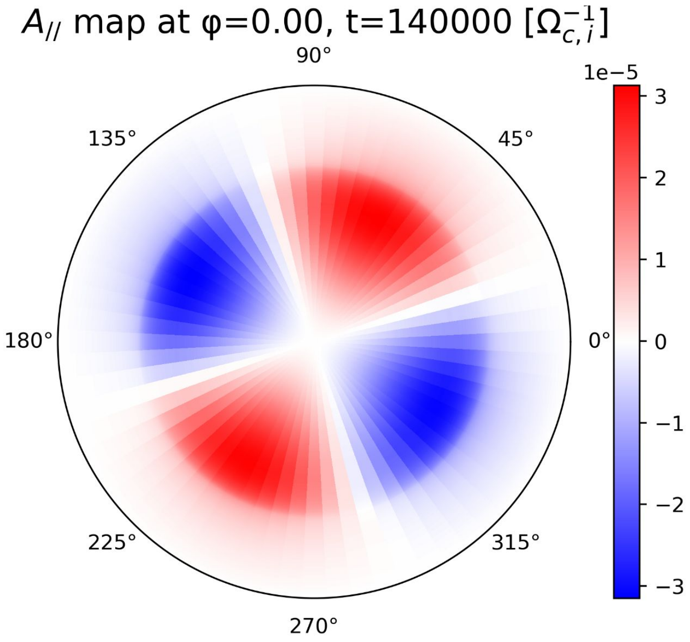
Does the saturation mechanism impact the saturation size ?

Outline

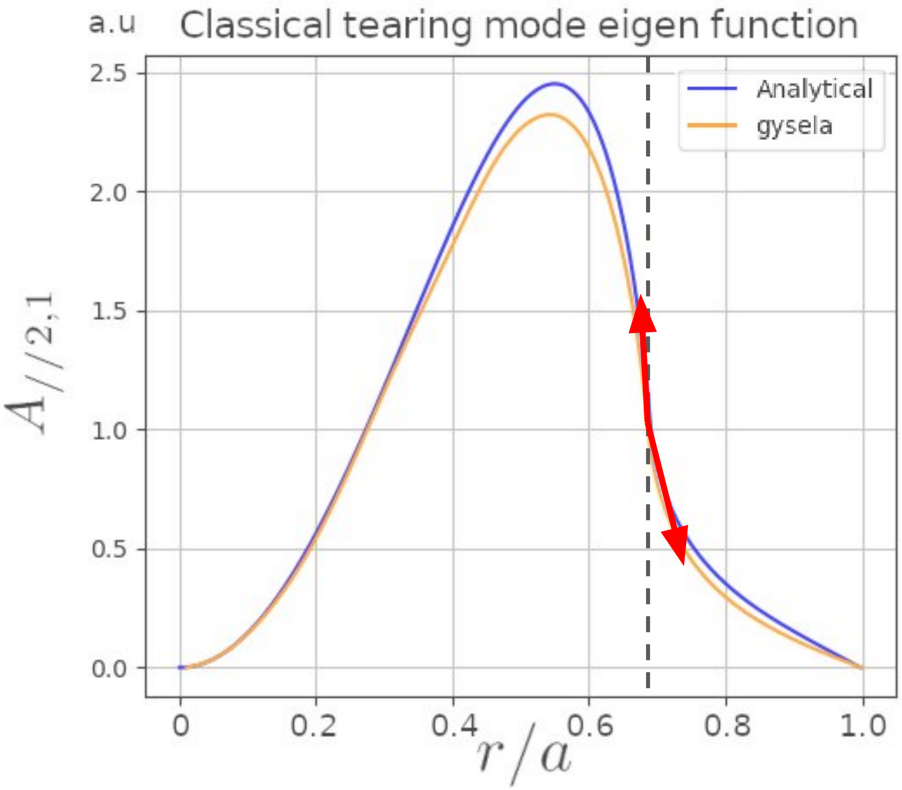
1. Magnetic island in tokamaks
2. Collisional vs inertial drive
3. **Study of the collisionless tearing**

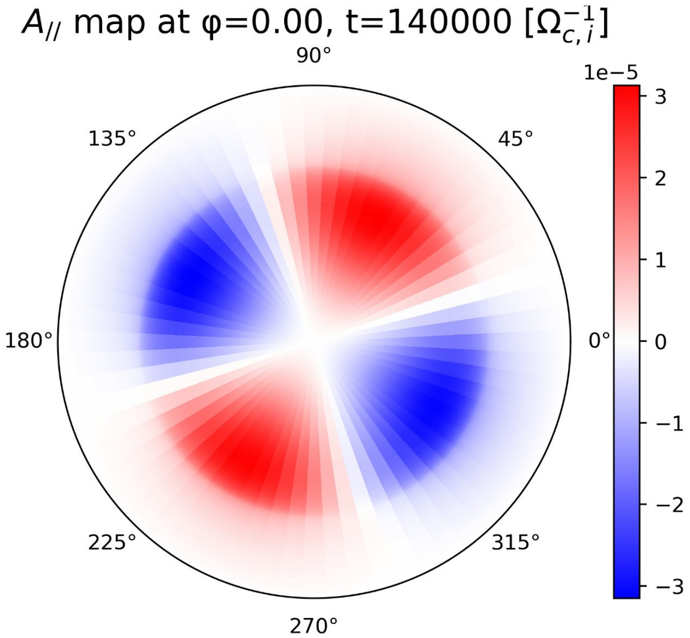
Tearing mode structure



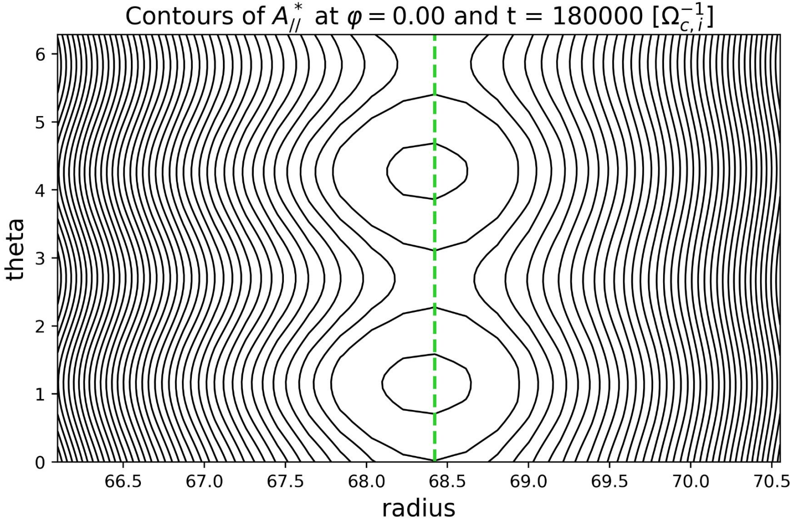


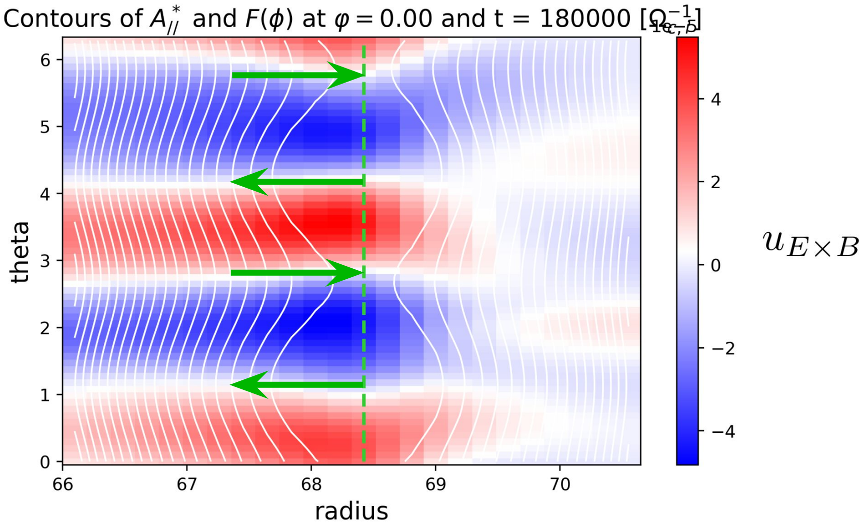
Tearing mode structure





Magnetic islands in GYSELA



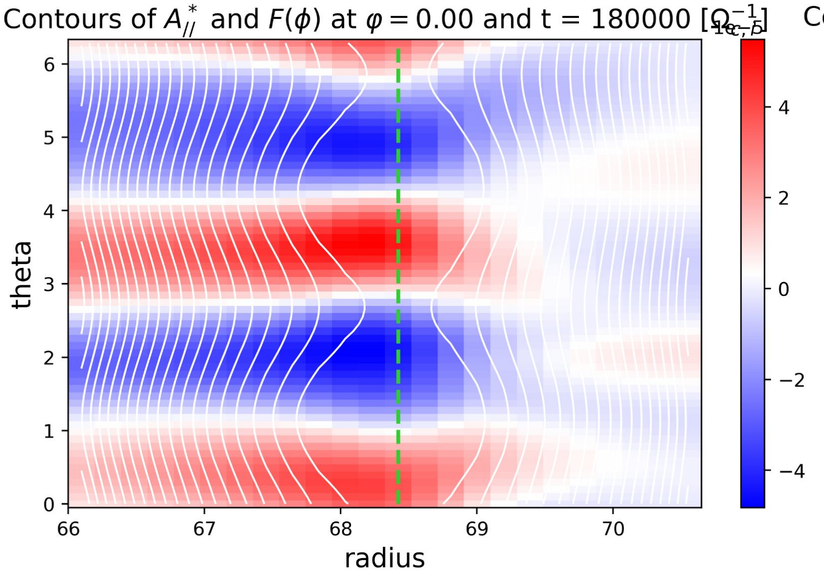


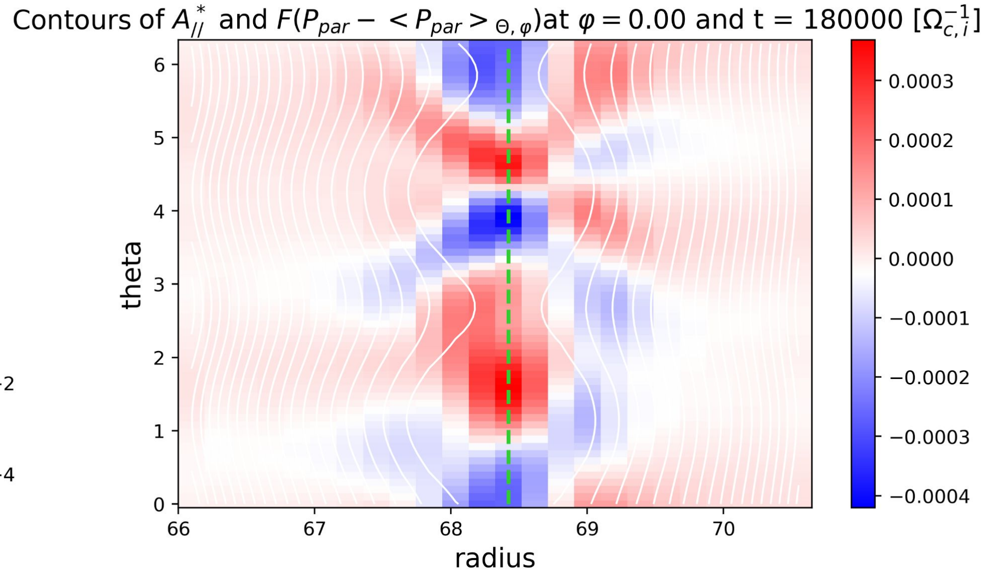
Simulations consistent with the classical picture

Diamagnetic vs ExB drift

$$u_{E\times B} = \frac{-\nabla\phi \times B}{B^2}$$

$$u_e* = \frac{\nabla P_e \times B}{e n_e B^2}$$





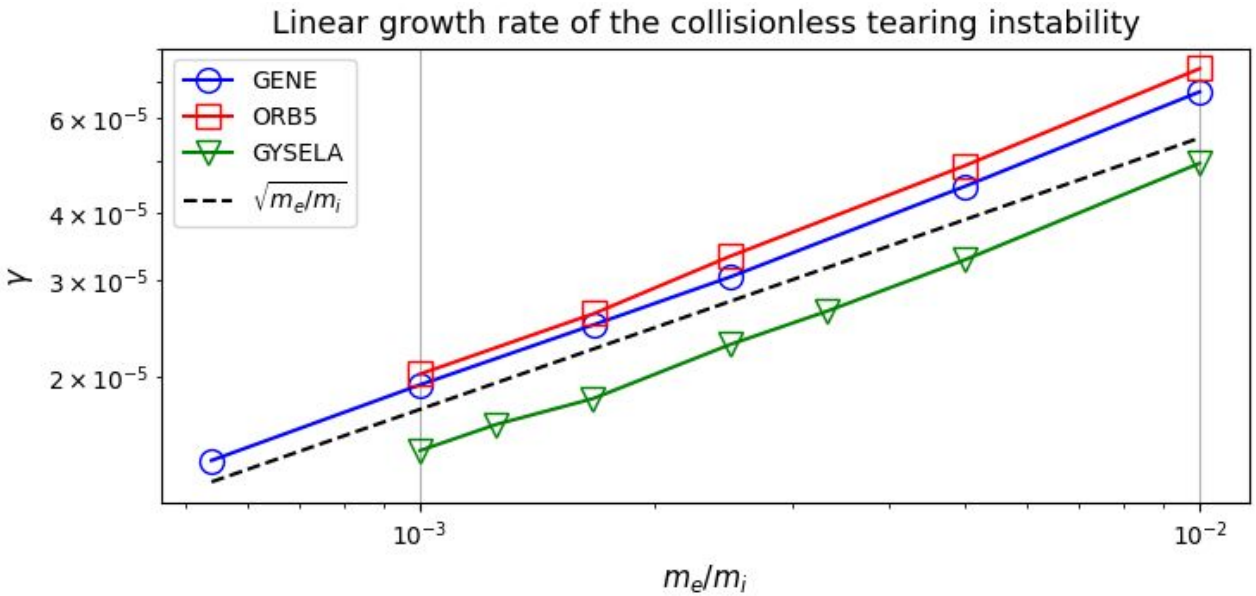
Benchmark with ORB5 and GENE

Lack of an extensive kinetic description of the collisionless classical tearing mode

Selected parameters [Jitsuk 2024]

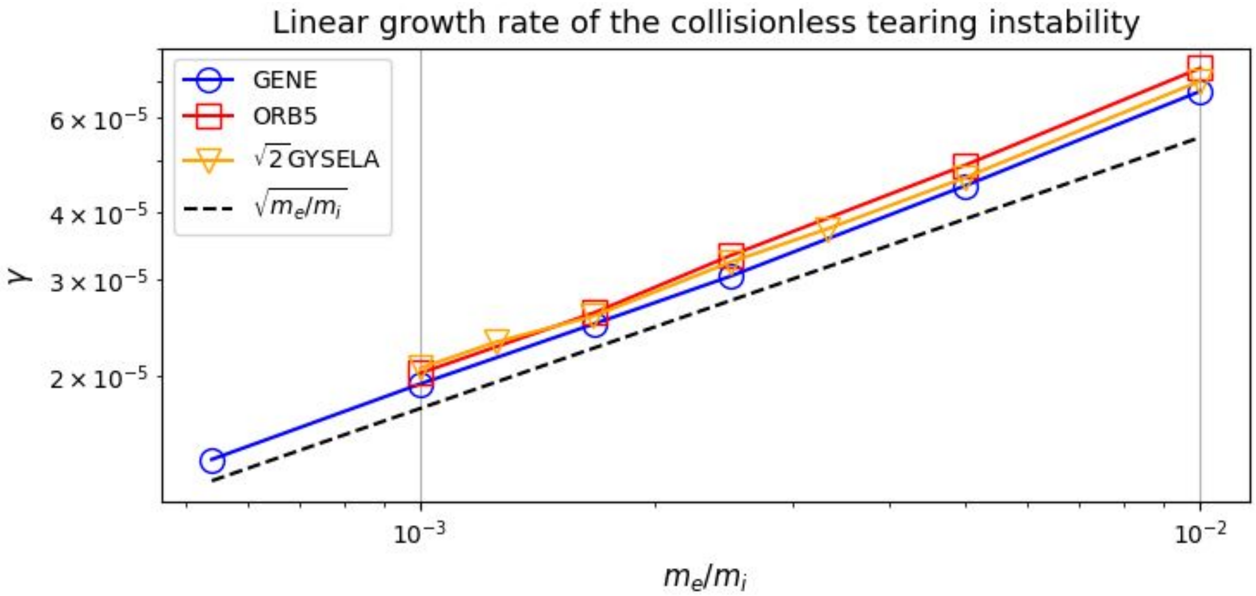
$q(x_a)$	$\sum_{i=0}^{8} c_i x_a^i$
$T_{0\mathrm{i}} = T_{0\mathrm{e}} = T_{\mathrm{eq}}(x_a)$	1
$n_{0\mathrm{i}} = n_{0\mathrm{e}} = n_{\mathrm{eq}}(x_a)$	1
$\beta_\mathrm{e} = 8\pi n_{0\mathrm{e}} T_{0\mathrm{e}} / B_0^2$	0.2%
$\rho_\mathrm{i}^* = \rho_\mathrm{i}/a$	0.01
$\varepsilon_a = a/R_0$	0.1
ν_{coll}	0

Benchmark with GENE and ORB 5



[Jitsuk 2024]

Benchmark with GENE and ORB 5



Normalization issue ?
Review all parameters

[Jitsuk 2024]

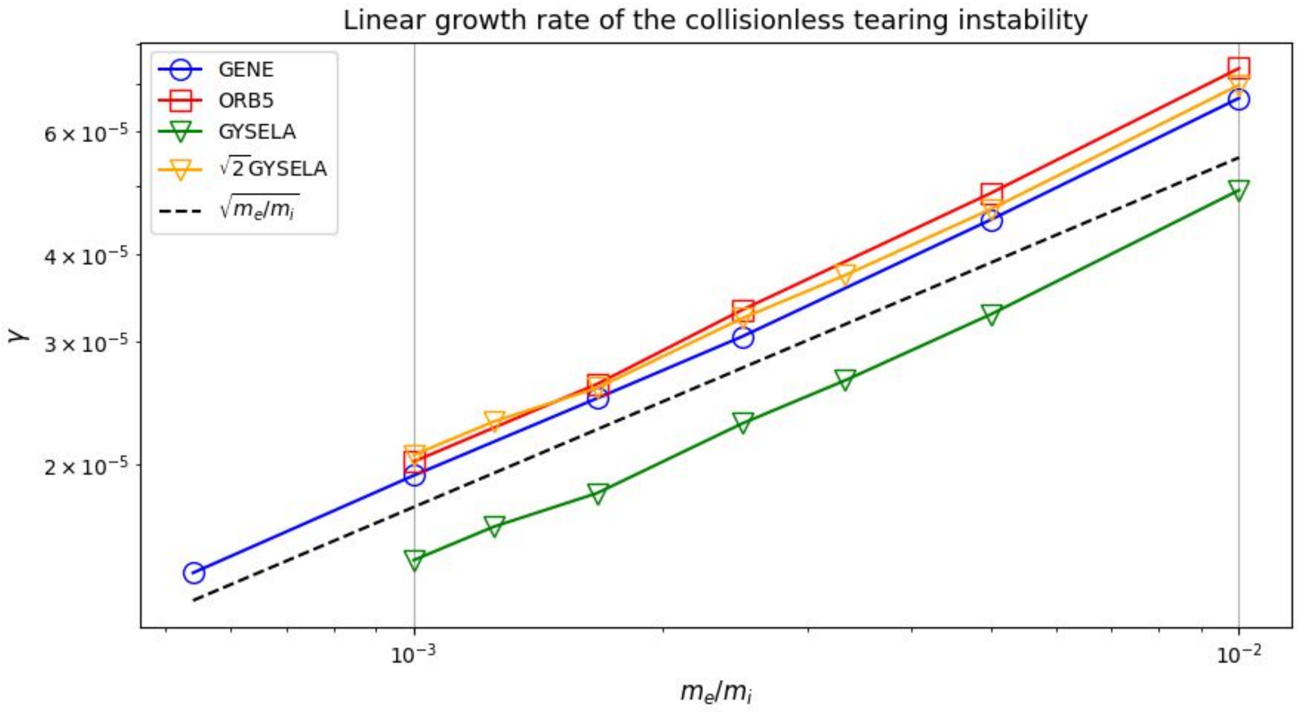
Conclusions

- Accessing the collisional regime in GYSELA
- Collisionless tearing benchmark
- Kinetic saturation mechanisms

Perspectives (EnR T-ReCS 2024-2025)

- Study the impact of an island on turbulent transport in turbulent simulations
- Confront simulation results to experimental data from TCV

sqrt(2) discrepancy

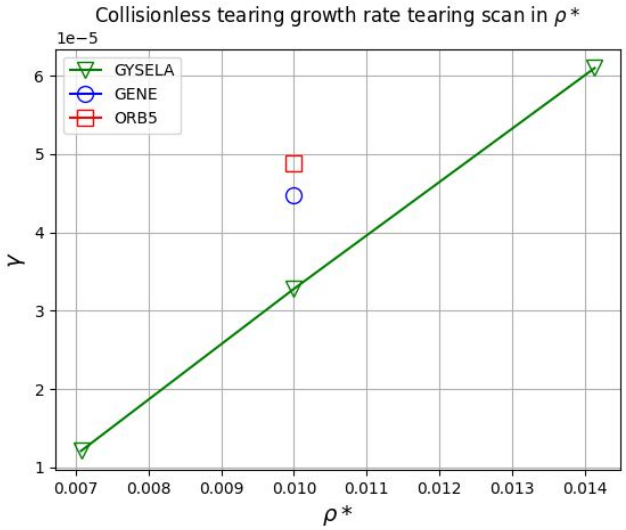


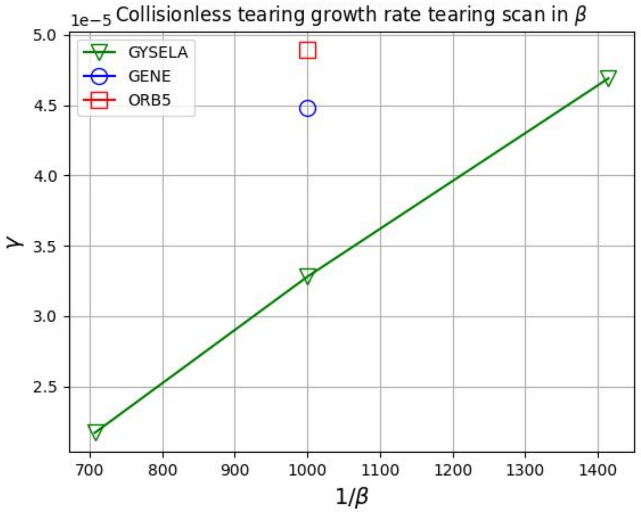
sqrt(2) discrepancy

discrepancy unlikely

in amplitude

$$\gamma \propto \frac{\rho*^2}{\beta}\sqrt{\frac{m_e}{m_i}}$$





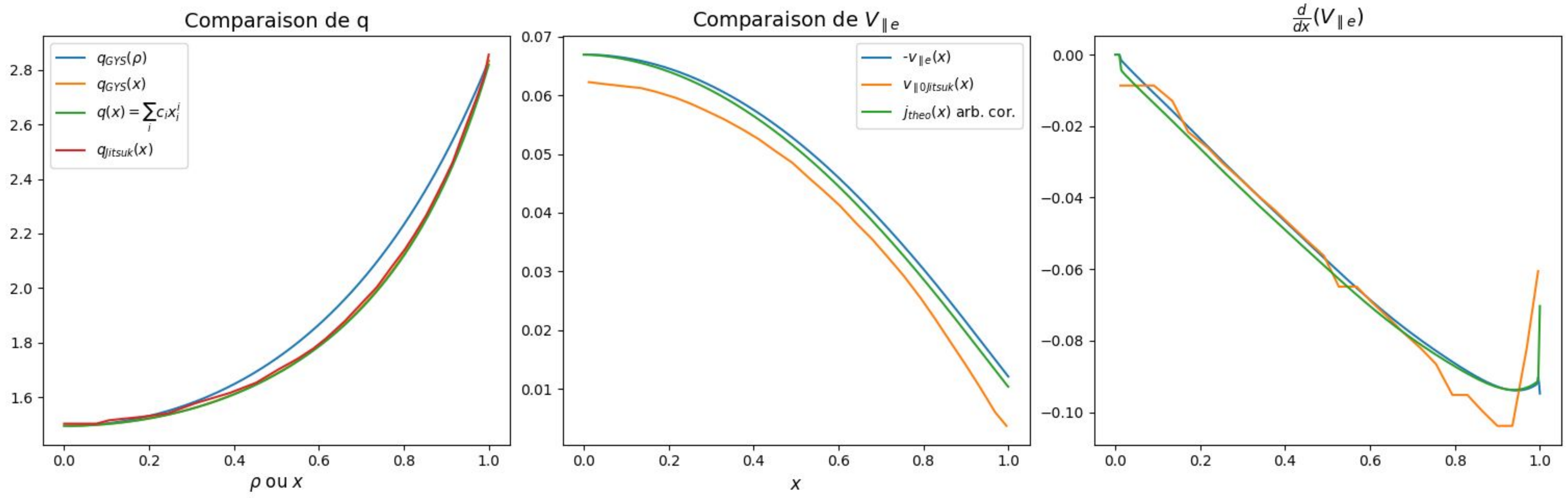
factor $2^{\frac{1}{4}}$ unlikely

incompatible with factor $\beta = \frac{P}{\frac{B^2}{2\mu_0}}$

Conversion script

$$x = \sqrt{\frac{\psi}{\psi_{edge}}} \longrightarrow \rho = \frac{r}{a}$$

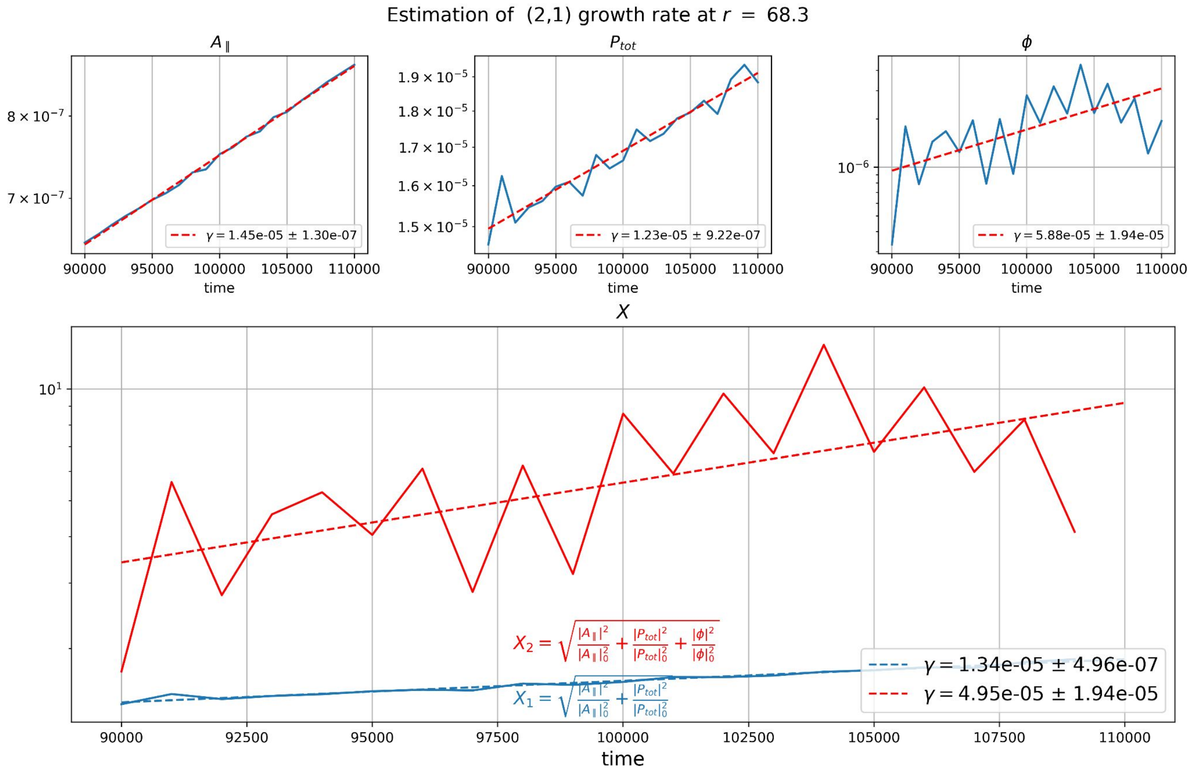
$$\rho^2 = \frac{\int_0^{x(\rho)} x q_{cyl}(x) dx}{\int_0^1 x q_{cyl}(x) dx}$$



Annexes

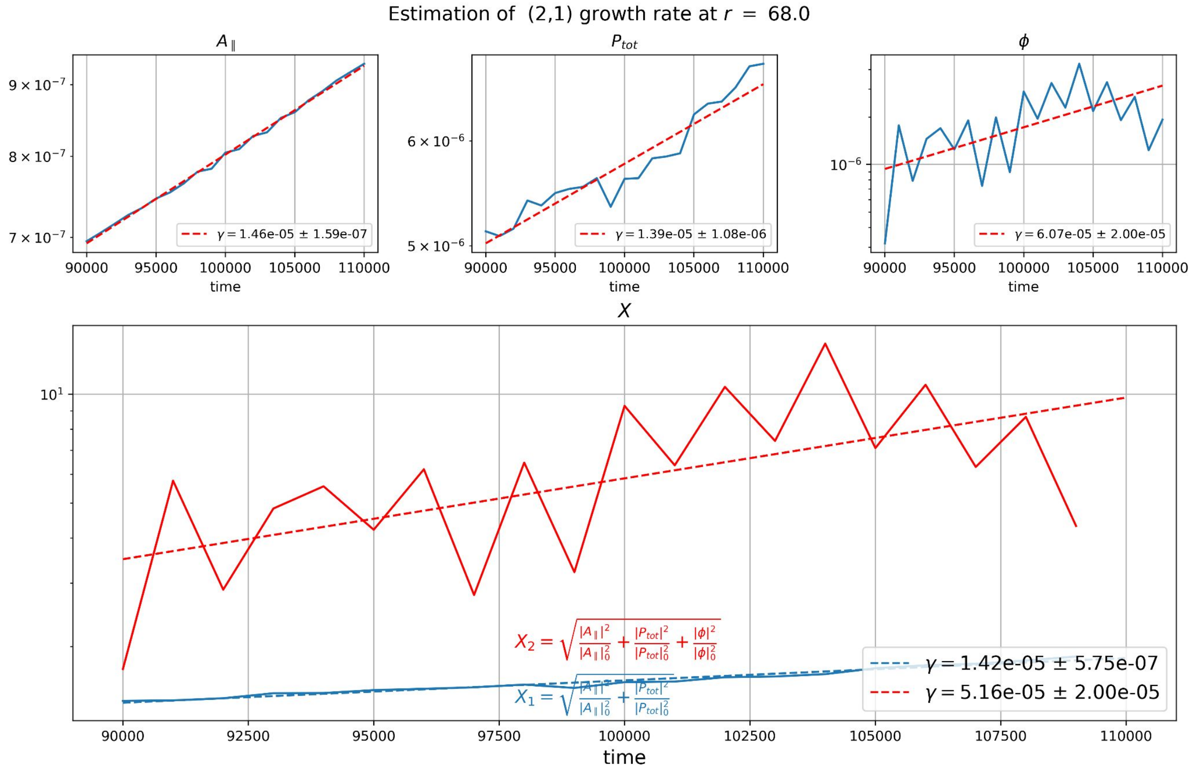
Radial resolution impact on instability

Nr = 512

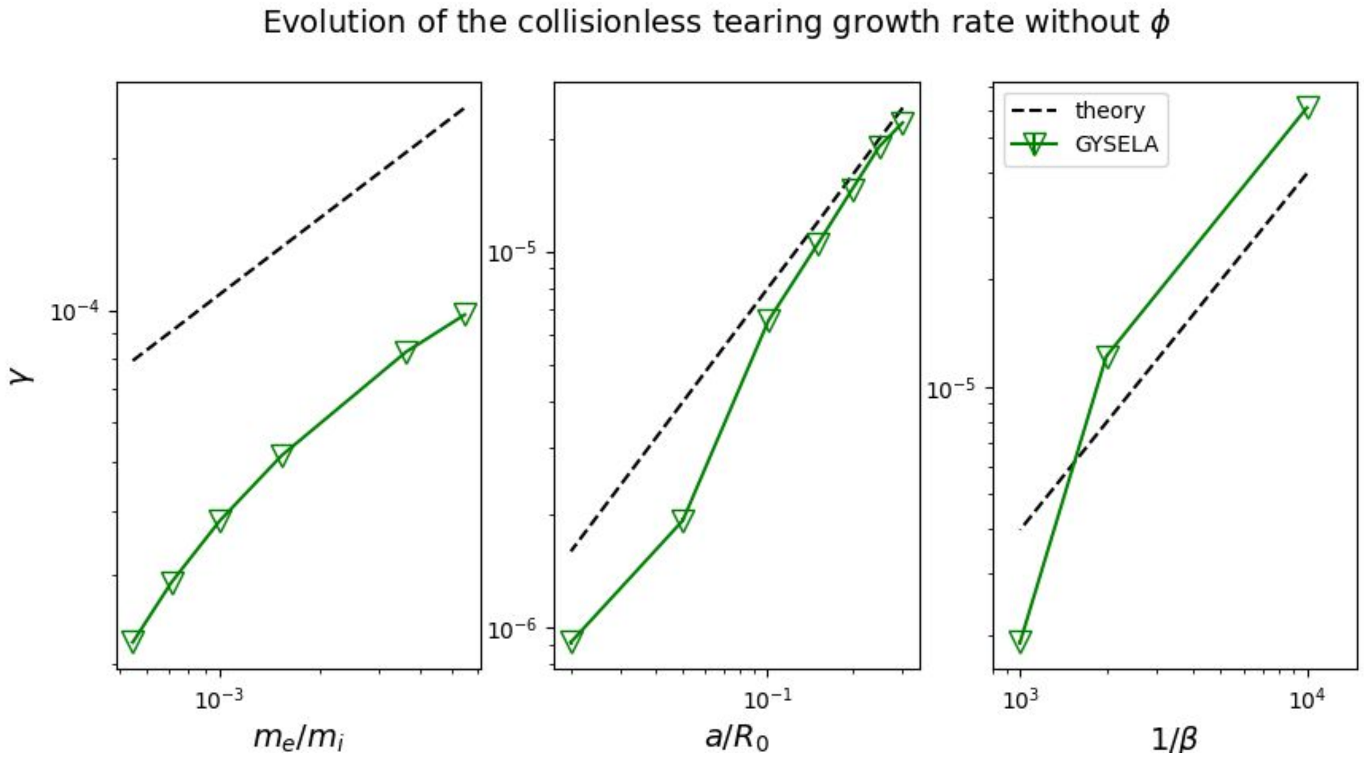


Radial resolution impact on instability

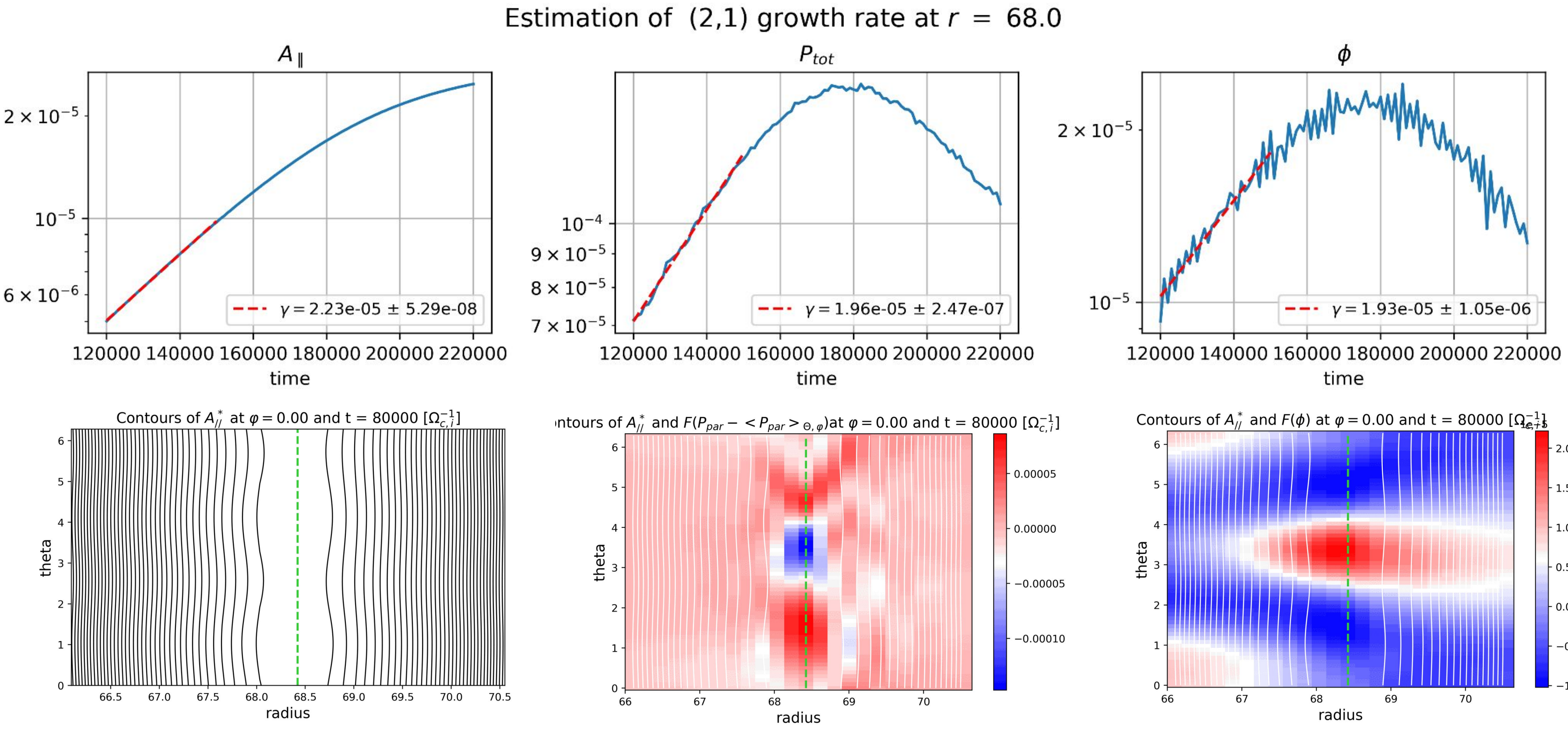
Nr = 1024



Collisionless study without ϕ



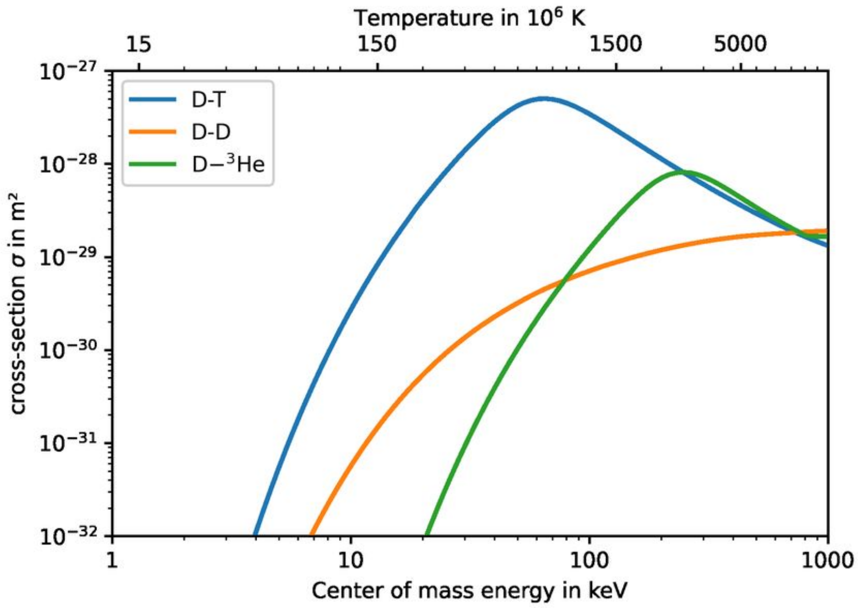
Early study of saturation using GYSELA



Not enough modes in the simulation to conclude

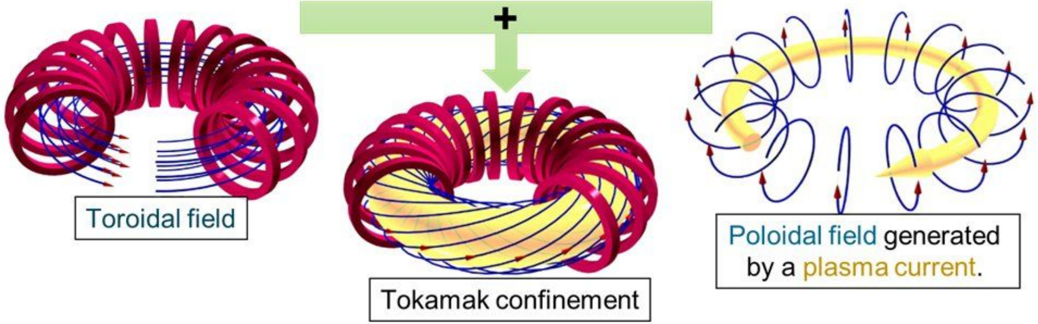
Taming the fusion energy

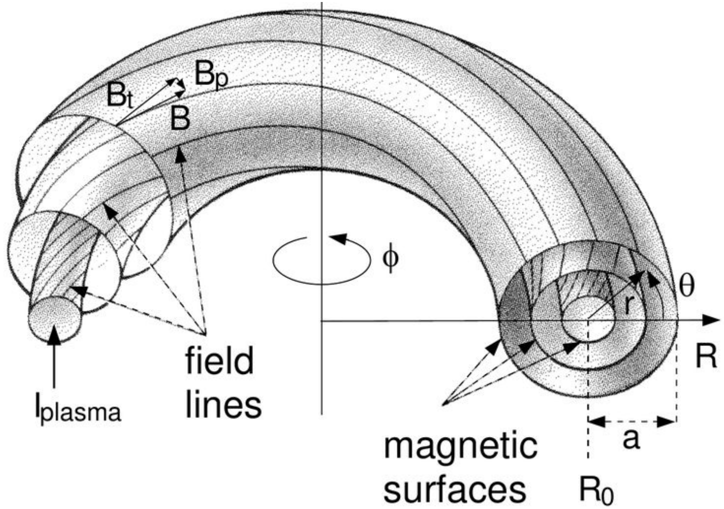
- D-T fusion require high density and energy



Need to control hot and dense plasma

Tokamak configuration





- Ideally and at 1st order : particles are confined on nested flux surfaces