Gyro-kinetic simulations of magnetic Island induced ITG mode

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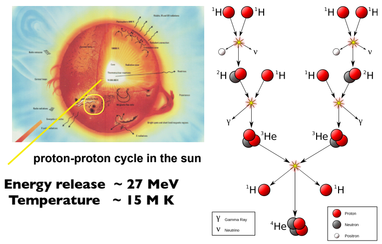
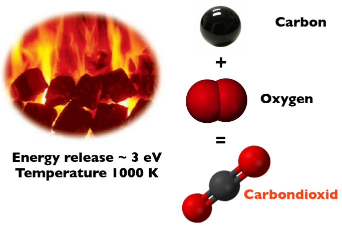
1. Why study nuclear fusion ?

Nuclear Fusion in the sun's center



Energy release ~ 27 MeV
Temperature ~ 15 M K

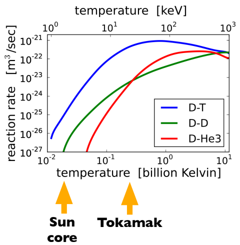
Energy from coal burning



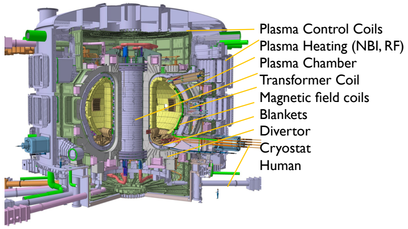
Energy release ~ 3 eV
Temperature 1000 K

Nuclear Fusion of hydrogen releases 5000000x times the energy of burning coal and without C02 emission or no long living nuclear waste !

Reaction rate for fusion



Sketch of ITER Tokamak (starting from 2019)



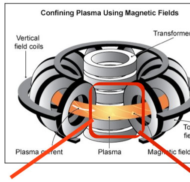
2. Abstract

Magnetic fusion plasmas are subject to a variety of instabilities, such as MHD modes and micro-instabilities. Micro-instabilities, such as drift-waves, which are scaled by the finite Larmor radius (FLR) of ions or electrons are of great importance in order to understand the transport mechanisms and to improve plasma confinement performance of fusion plasmas.
The drift wave is one of the typical micro-instabilities in tokamak plasmas. It has been extensively studied that ion temperature gradient (ITG) driven turbulence may dominate the ion transport with the regulation of the self-generated zonal flows. Here, we numerically investigate the ion temperature gradient mode (ITG) instability in the presence of a magnetic island using a gyro-kinetic simulation code.

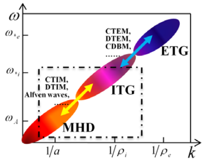
We perform reduced gyro-kinetic simulation (2d sheared slab) with kinetic ion and electron species by keeping all gyro-kinetics effects. We found out that the poloidal coupling induced by the magnetic island enables unstable modes to dissipate energy by stable modes. However, in contrast to gyro-fluid simulations, the short-wavelength modes, which appears in full gyro-kinetic. treatment, substantially reduces the dissipation channel and the stabilizing effect due to coupling is strongly reduced, indeed the destabilizing effect due to the formation of new rational surfaces dominates.

3. Multi scale interaction in Tokamaks

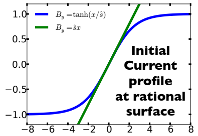
Sketch of Tokamak



Scales of instabilities inside the core Plasma and their interaction



MHD Instabilities (Magnetic Islands)

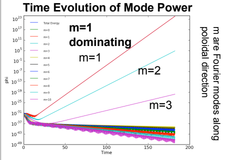


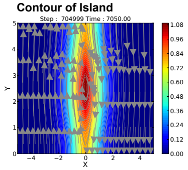
Reduced MHD Equation System

$$\frac{\partial \psi}{\partial t} = [\phi, \psi] - \frac{1}{S}\nabla_\perp^2 \psi$$

$$\frac{\partial}{\partial t}\left(\nabla_\perp^2 \phi\right) = [\phi, \nabla_\perp^2 \phi] - [\psi, \nabla_\perp^2 \psi] \quad ,$$

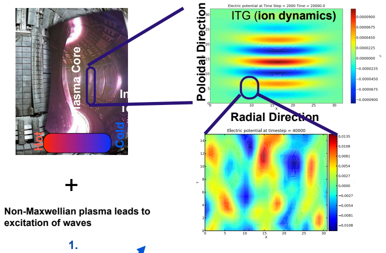
Reconnection phenomenon destabilization and formation of an magnetic Island





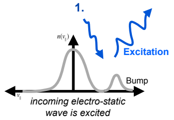
Study the interaction between MHD+ITG (+ETG)

Micro-Instabilities due to Temperature gradient



+

Non-Maxwellian plasma leads to excitation of waves



A large temperature gradient, leads to a destabilization of the ion sound wave by inverse Landau damping. The resulting ITG wave is responsible for anomalous heat and particle transport in Tokamaks.

4. Methods

We use highly parallelized simulation code (gkc [1]) to study gyro-kinetic drift turbulence in sheared-slab (2D) geometry.

Gyro-kinetic Vlasov-Poisson Equation System :

$$f_{M\sigma} = n_\sigma\left(\frac{m_\sigma}{2\pi T_\sigma}\right)^{3/2} e^{-\left(\frac{m_\sigma v_\parallel^2}{2T_\sigma}+\frac{\mu B_0}{T_\sigma}\right)} \qquad F_1(x,k_y;v_\parallel,\mu;\sigma=\{i,e\})$$

$$\lambda_D^2 k_\perp^2 \phi + \sum_{\sigma=\{i,e\}} \frac{q}{T}\left(1-\Gamma_0(\rho_{t\sigma}k_\perp^2)\right)\frac{e_j\phi_1}{T_{j0}} = \sum_{\sigma=\{i,e\}} q_\sigma \int_{\mu=0}^{\infty} J_0(\sqrt{2\mu\rho_{t\sigma}^2 k_\perp^2})\int_{v_\parallel=-\infty}^{\infty} f_{1\sigma}\, dv_\parallel\, d\mu$$

$$\frac{\partial f_{1\sigma}}{\partial t} = \left(\omega_n + \omega_{T\sigma}\left[\frac{mv_\parallel^2}{2T}+\frac{\mu B}{T}-\frac{3}{2}\right]\right) ik_y f_{0\sigma}\langle\phi\rangle + \frac{q_\sigma}{T} ik_y \hat{s} x v_\parallel\left(f_1+\langle\phi\rangle f_0\right) + v_\parallel\left[A_{1\parallel}, f_1 + q_\sigma \phi f_0\right] + \mathcal{C}_{\text{Coll}}$$

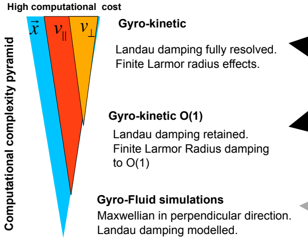
Add static m=1 magnetic Island (analytical solution)

$$\psi = \frac{\hat{s}x^2}{2} + \frac{w^2\hat{s}}{16}\sin(\zeta x)\left(e^{iky}+e^{-iy}\right)$$

We use direct mode-coupling to avoid transformation from Fourier to real space

$$\left[A_{1\parallel}, f_1 + q_\sigma f_0\right] = -\psi_x\left(k_y^{m+1} f_1^{m+1} + k_y^{m-1} f_1^{m-1}\right) + \psi_x\left(k_y^{m+1}\phi^{m+1} + k_y^{m-1}\phi^{m-1}\right) q_\sigma f_0 + \psi k_y^1\left(f_{1,x}^{m+1} - f_{1,x}^{m-1}\right) - \psi k_y^1\left(\phi_x^{m+1} - \phi_x^{m-1}\right) q_\sigma f_0$$

Simulation models to be compared :



Gyro-kinetic
Landau damping fully resolved.
Finite Larmor radius effects.

Gyro-kinetic O(1)
Landau damping retained.
Finite Larmor Radius damping to O(1)

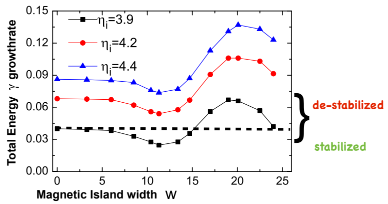
Gyro-Fluid simulations
Maxwellian in perpendicular direction.
Landau damping modelled.

Our simulation code handles both types. Compare results.

Compare to gyro-fluid

5. Results

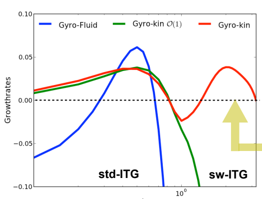
Gyro-fluid results from Wang et al. [2]



Stabilization effect due to mode coupling and dissipation of energy by stable modes

Destabilization due to formation of new rational surfaces which triggers ITG growth

Poloidal growthrates without magnetic Islands between different gyro-models



Short-wavelength modes
Smolyakov et al (2002, PRL)
Gao et. al (2003, PoP)
Hirose et. al (2002, PoP)

Simple quasi-linear estimate :

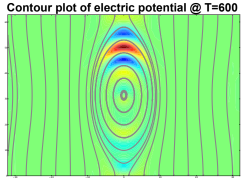
$$Q_{sw-ITG} = \frac{\gamma}{k_\perp^2} \ll Q_{std-ITG}$$

thus *normally* not important

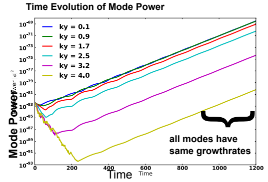
Example Simulation with Island width of w=13

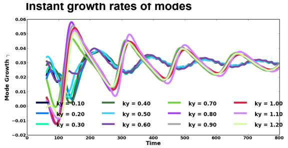
$L_x = 80,\ L_y = 64,\ N_x = 256,\ Nk_y = 65,\ \hat{s} = 0.4,\ \eta_i = 4.2$

Contour plot of electric potential @ T=600

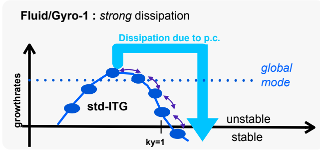


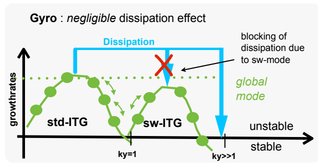
Poloidal coupling leads to the formation of a global mode (all modes have same frequency and growthrate). Energy can be transfered from unstable modes to stable modes and dissipated by away.





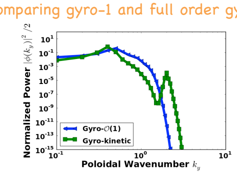
Dissipation mechanism w/o sw-ITG

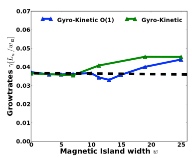




We conclude that the appearance of the sw-ITG mode blocks the dissipation of std-ITG mode thus the stabilization effect of a magnetic island on ITG waves is reduced.

Comparing gyro-1 and full order gyro-kinetic simulations





(The sw-ITG mode can be clearly seen in the turbulence spectra (picture left). The dependence of total energy growth vs. Island size w with sw-ITG mode shows very weak stabilization effects. Destabilization dominates with island size bigger than w=8 (picture right)

6. References

[1] GKC : https://github.com/philscher/gkc

[2] Wang et al., http://dx.doi.org/10.1063/1.3166600

[3] P.P. Hilscher et al., ISBN-13: 978-4431540663