Reduced MHD and gyrokinetic studies on auroral plasmas

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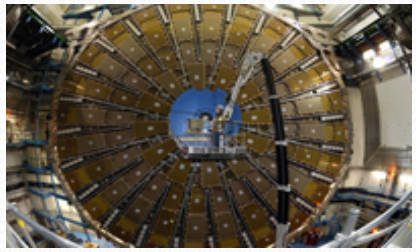
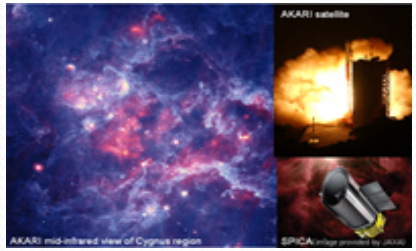
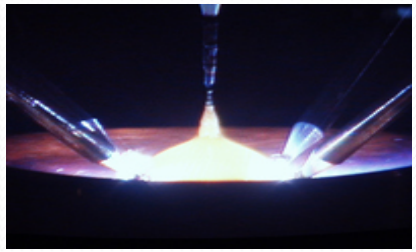
In collaborations with
S. Maeyama, GKV team, and Ph.D students at NU

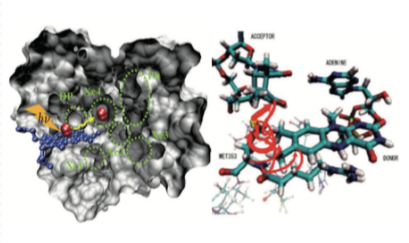
Department of Physics, Nagoya Univ.: An Overview

- Established in 1942, started from 5 groups
- Rapid growth with extension of frontiers in physics after 1960's
  - Particle physics, Astrophysics, Condensed matter physics, Biophysics, … , Plasma physics
  - Nobel Prize in Physics 2008
- Total 26 research groups (labs.)





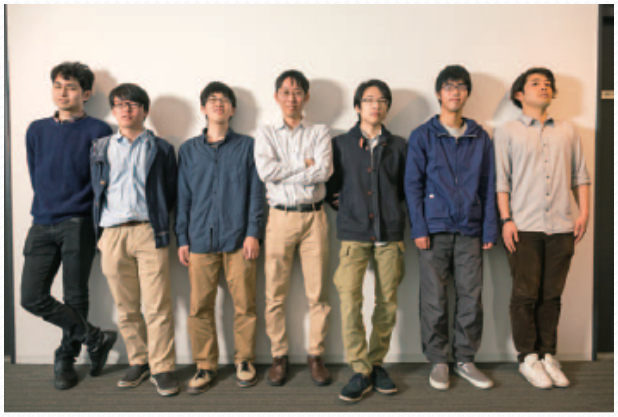




	Particle and Astrophysical Science	Material Science (Physics)
Theory	E, H, QG	R, S,
	C, Ta, Ω, P, Σ_T	TB, B
Experiments	F, N, Φ	L, M, I, V
	A, Uir, Ux, Σ_E	G, D, K

Plasma physics studies at P-Lab, Dept. Phys., NU

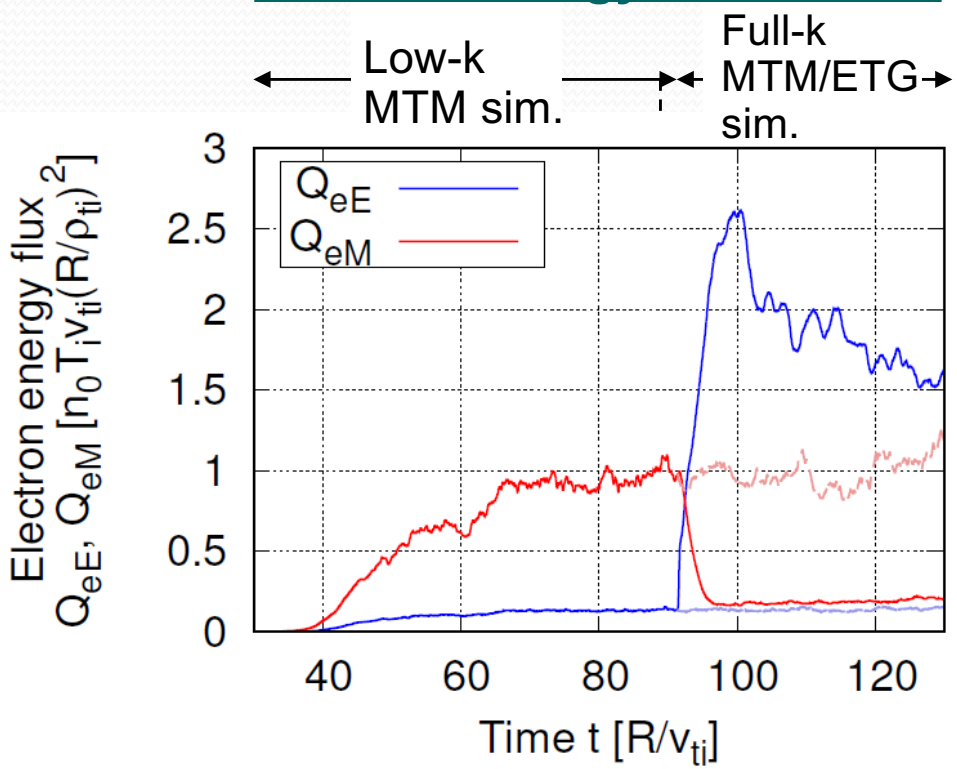
- GK simulations of turbulent transport
  - MTM-ETG, entropy transfer, kinetic ion effects on ETG turbulence, parallel correlation, …
  - GKV code extension – time-integrator, collision operator.
  - The Post-K priority issue
- Space plasma physics
  - Auroral physics, instabilities in the magnetosphere, etc
- Fundamental plasma physics
  - Kinetic turbulence cascade
  - Magnetic reconnection



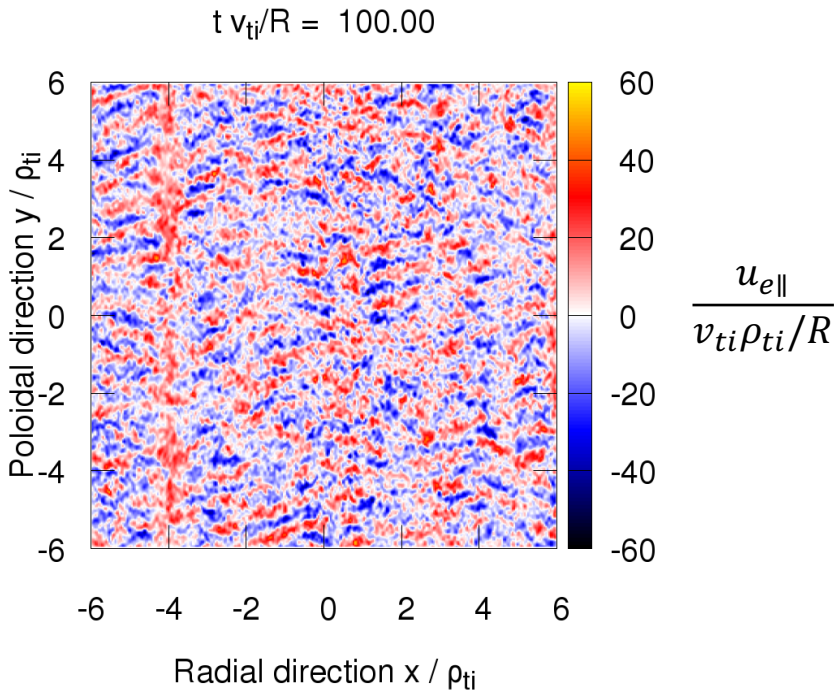
MTM turbulence suppressed by ETG mode growth

- MTM grows in the initial resolution, followed by the ETG dominant state in the finer resolution after $t > 90\, R/v_{ti}$
- The electron heat transport is finally governed by the ETG turbulence.

Electron energy flux Q_{eE},Q_{eM}



Electron parallel current on poloidal cross-section (at bad curvature region θ=0)



Outline

- Introduction
  - P-Lab, Dept. Phys., Nagoya Univ.
  - Recent highlights on GK turbulence studies at NU
- Motivation – auroral arc dynamics is a key issue in space physics
  - Magnetosphere-ionosphere (M-I) coupling and the feedback instability
- RMHD studies on nonlinear arc dynamics and transition to turbulence
- Gyrokinetic approach to the M-I coupling

M-I coupling and the feedback instability

Auroral arc growth as an instability in M-I coupling

- Separation of characteristic scales
  - Global geometry of M-I coupling system

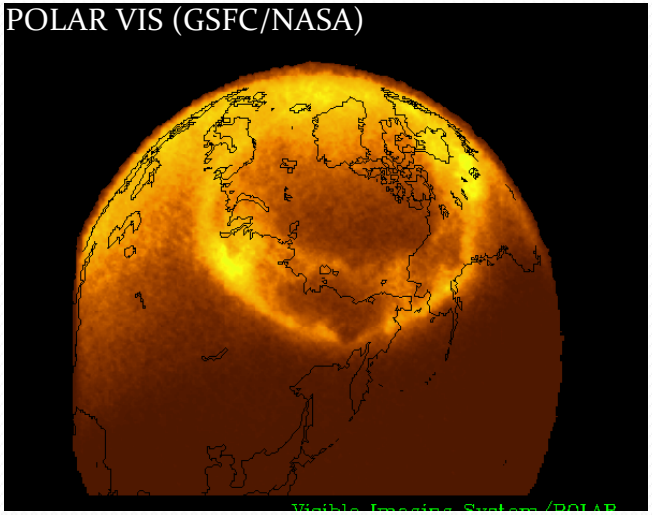
  => Field-line length ~ 100,000km

  => Auroral oval ~ a few 100's km in N-S

  - Spatio-temporal structres of auroral arcs

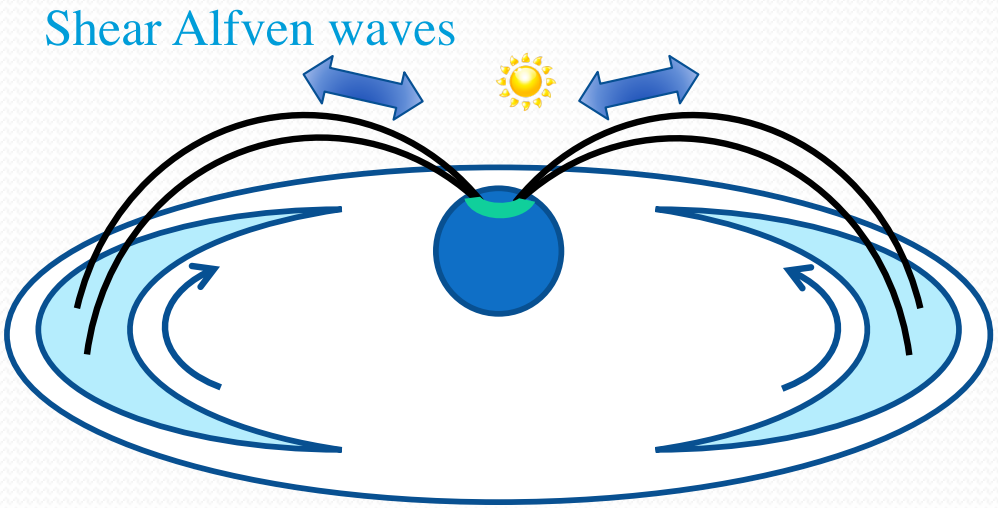
  => Distance of multiple arcs ~10 km

- What is a physical mechanism providing the arc structures and its dynamics (drift velocity, growth rate, ...) ?
  - Feedback instability (primary) for formation of arc structures
  - Nonlinear instability (secondary) for deformation of arc structures



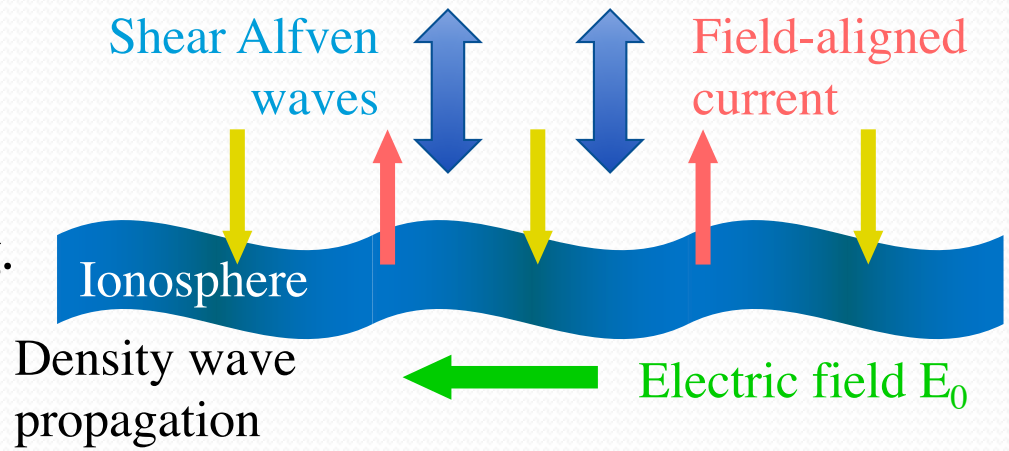
Feedback instability in M-I coupling

- Feedback instability: a possible mechanism to explain spontaneous growth and formtion of auroral arc structures in M-I coupling
  (Atkinson, Sato, in 1970's)



- When the convection ***E*** field exceeds a critical value, auroral arcs can grow though resonance of the shear Alfven wave and the density wave in the M-I coupling.

- => 3-D MHD simulation of feedback instability

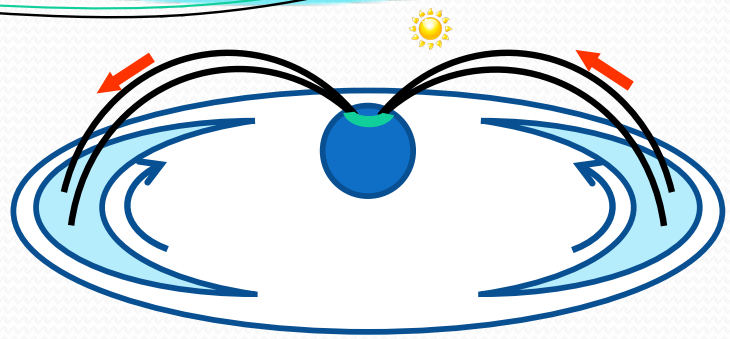


Recent progress of the feedback instability studies

- Competition of the feedback and ballooning instabilities
  - A possible scenario of auroral beading
- Influence of the large-scale field aligned current
  - Magnetic shear enhancing the feedback instability growth
- Secondary instability growth induced by arc formation
  - Structural deformation due to nonlinear K-H instability
- Nonlinear evolution of the feedback instability [Watanabe+ 2016]
  - Auroral vortex formatoin and transition to Alfven turbulence
- Gyrokinetic description of the M-I coupling [Watanabe, GRL2014]
  - Unified theory of auroral growth and particle acceleration.

Reduced MHD model of the magnetosphere-ionosphere couplig

Reduced MHD model for the magnetosphere



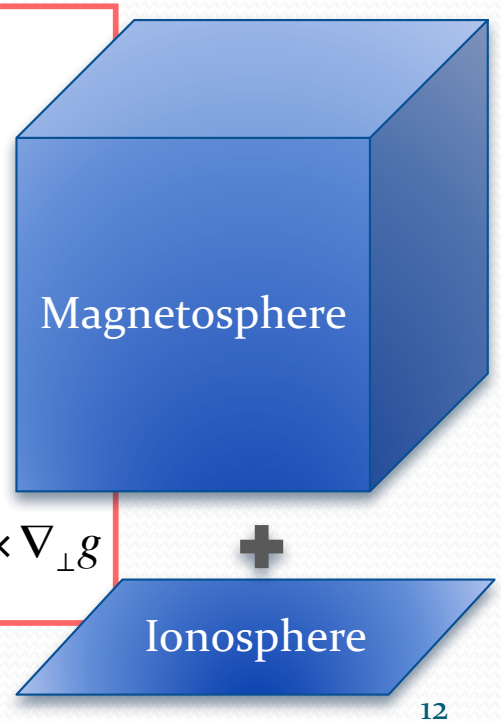
- δB << Earth's B field, and low-β
- Perpendicular wave length (x_f)
  << parallel wave length (x_s), equilibrium scales (x_s)
- Local flux tube model (periodic in the perpendicular direction)
- Impose the rigid E_0xB rotation driving the convection flow

$$\left(\frac{\partial}{\partial t}+\frac{\mathbf{E}_0\times\mathbf{B}_0}{B_0^2}\cdot\nabla_\perp\right)\omega=\frac{B_0^2}{\rho_0}\nabla_\parallel\left(\frac{j_\parallel}{B_0}\right)-\{\phi,\omega\}+\frac{2}{\rho_0}\mathbf{b}_0\times\kappa\cdot\nabla_\perp p+\nu\nabla_\perp^2\omega$$

$$\left(\frac{\partial}{\partial t}+\frac{\mathbf{E}_0\times\mathbf{B}_0}{B_0^2}\cdot\nabla_\perp\right)\psi=\frac{1}{B_0}\nabla_\parallel(B_0\phi)+\frac{\eta}{\mu_0}\nabla_\perp^2\psi$$

$$\left(\frac{\partial}{\partial t}+\frac{\mathbf{E}_0\times\mathbf{B}_0}{B_0^2}\cdot\nabla_\perp\right)p=-\{\phi,p\}-(\mathbf{b}_0\times\nabla_\perp\phi)\cdot\nabla_s P_0$$

$$j_\parallel=\frac{B_0}{\mu_0}\nabla_\perp^2\psi\quad,\quad\omega=\nabla_\perp^2\phi\quad,\quad\nabla_\parallel=\mathbf{b}_0\cdot\nabla+\{\psi,\quad\}\quad,\quad\{f,g\}\equiv\mathbf{b}_0\cdot\nabla_\perp f\times\nabla_\perp g$$



Two-fluid equations for the ionosphere

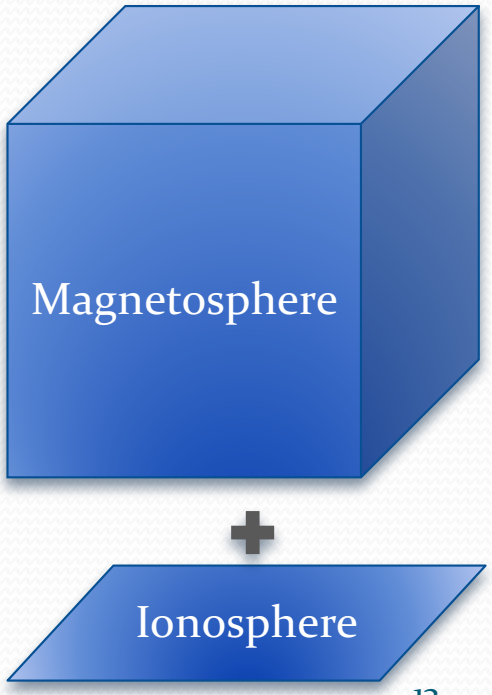
- Continuity of electron and ion density (height-integrated)

$$\frac{\partial n_e}{\partial t} + \frac{\mathbf{E}\times\mathbf{B}_0}{B_0^2}\cdot\nabla_\perp n_e = \frac{j_\parallel}{eh} - \alpha n_i n_e \qquad \frac{\partial n_i}{\partial t} + \nabla_\perp\cdot\left(\mu_P n_i \mathbf{E} + D\nabla_\perp n_i\right) = -\alpha n_i n_e$$

coupled with the quasi-neutrality equation (n_i=n_e)

=> Continuity of the ionospheric density and current

$$\boxed{\begin{aligned} &\frac{\partial n}{\partial t} + \frac{\mathbf{E}\times\mathbf{B}_0}{B_0^2}\cdot\nabla_\perp n = \frac{j_\parallel}{eh} - \alpha n^2 \\ &\nabla_\perp\cdot\left(\mu_P n\mathbf{E}\right) - \frac{\mathbf{E}\times\mathbf{B}_0}{B_0^2}\cdot\nabla_\perp n = D\nabla_\perp^2 n - \frac{j_\parallel}{eh} \quad , \qquad \mathbf{E} = -\nabla_\perp\phi \end{aligned}}$$



- Closure relations

=> Continuity of ϕ and $j_{||}$ => M-I coupling

M-I coupling allows the Alfven wave growth

- Conjugacy of auroras in the two hemispheres leads to symmetric or anti-symmetric condition on the equator
  $\Psi=0$ or $d\Psi/dz=0$ at $z=l$

- Condition of the M-I coupling (at z=0)
  - Continuity of $\boldsymbol{E}$ and $j_{||}$ demands non-vanishing Ψ and $d\Psi/dz$
  - Poynting flux input and Joule heating

- For the shear Alfven wave solution of u, v

$$v(du/dz)|_{z=0} \neq u(dv/dz)|_{z=l}$$

=> Symmetry breaking of the boundary condition

=> Non-Hermitian system: $\int_0^l u\, Lv^* dz \neq \int_0^l v^*\, Lu dz$

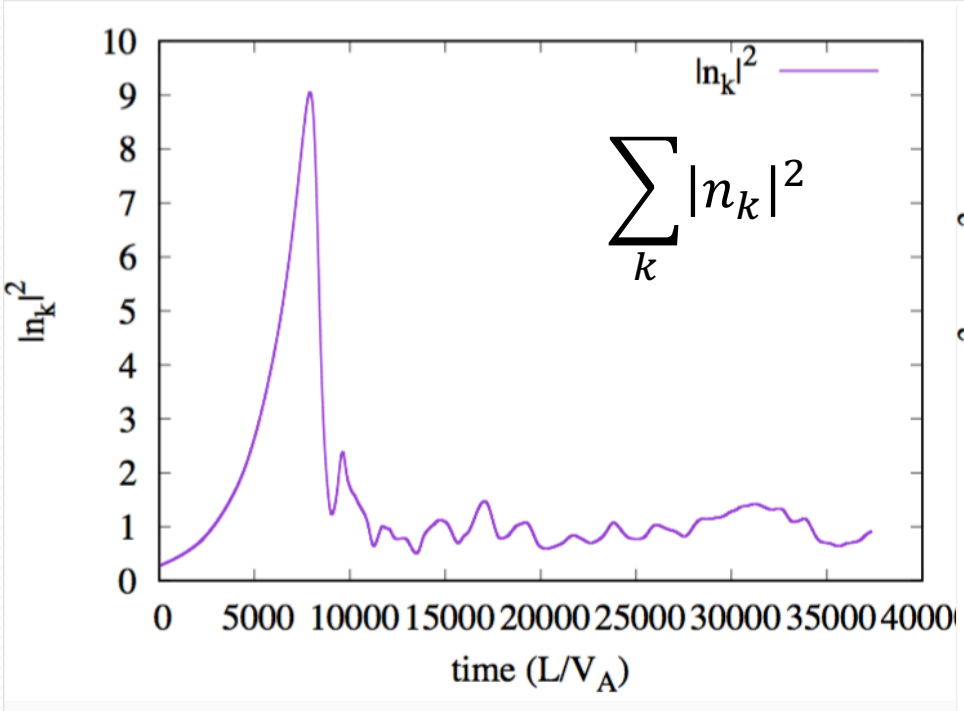
=> Complex eigenvalues are allowed with energy source

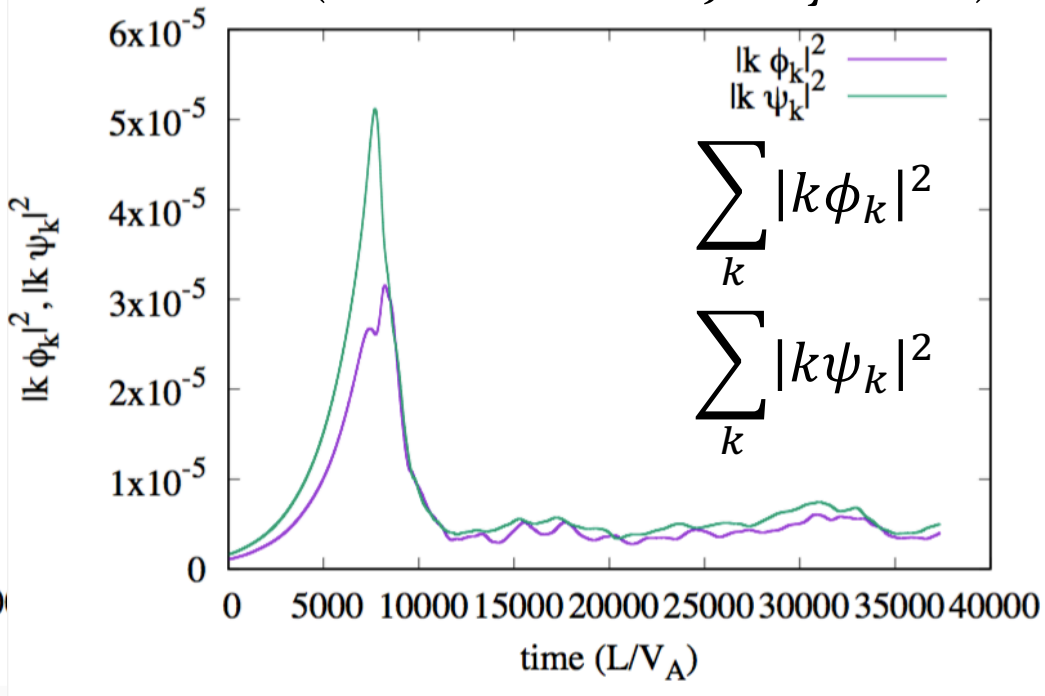
Turbulence transition in the M-I coupling system

Nonlinear stage of the feedback instability with constant drive

- Time history of density (left) and electromagnetic field energy (right)

(Watanabe+ New J. Phys. 2016)



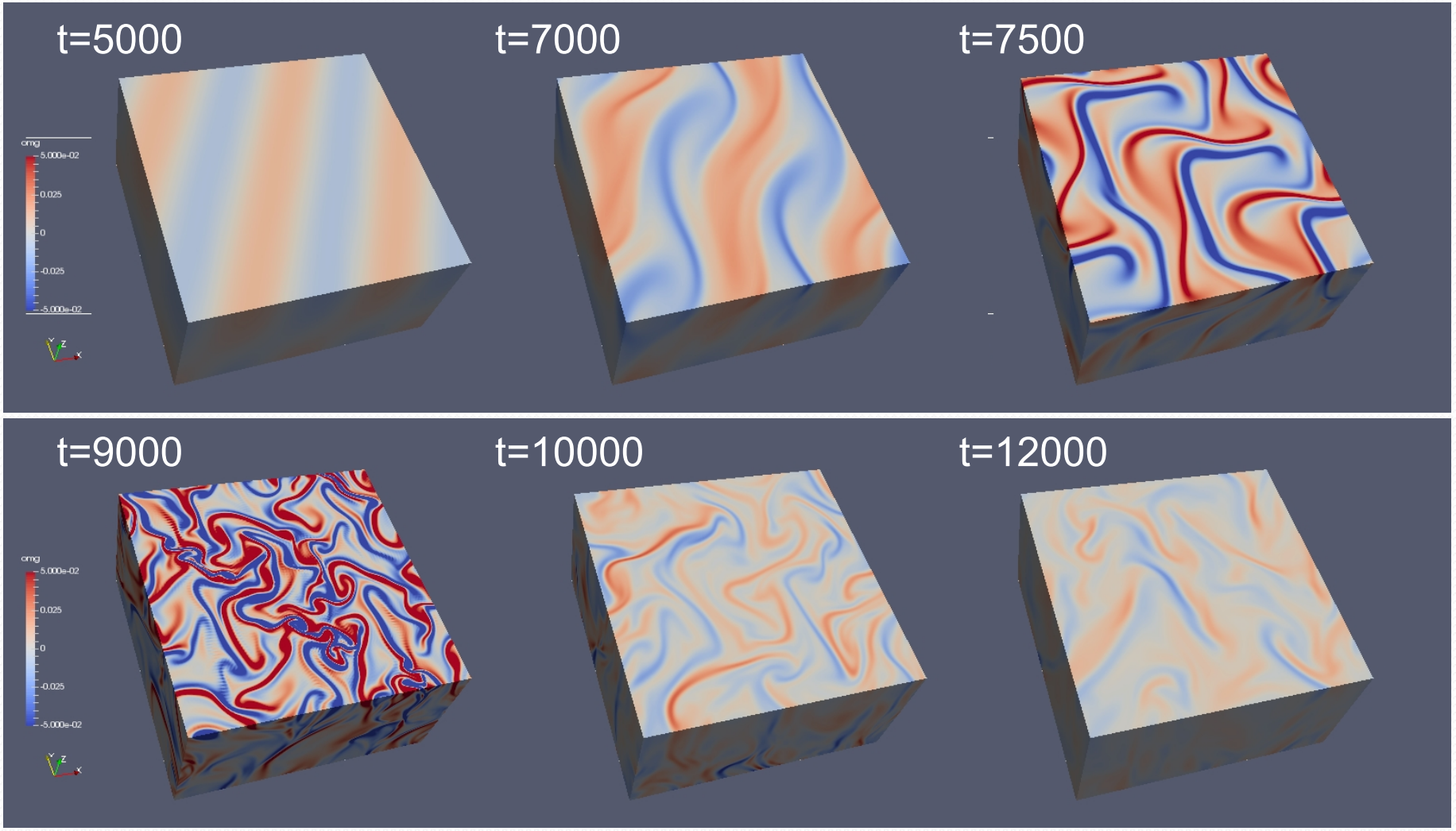


- Transition to the Alfvenic turbulence ($\delta E^2 \sim \delta B^2$) after saturation of the feedback instability growth

Vorticity distributions

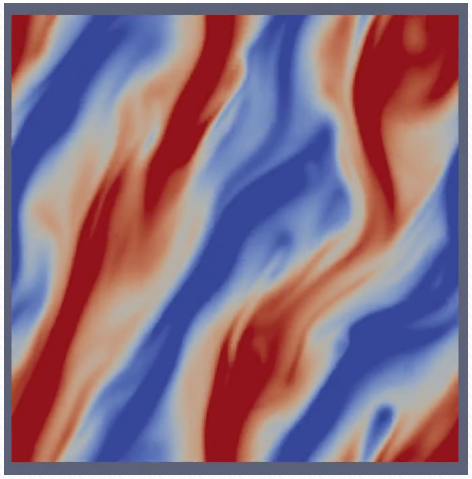
(Watanabe+ New J. Phys. 2016)

- Turbulence transition through the secondary instability

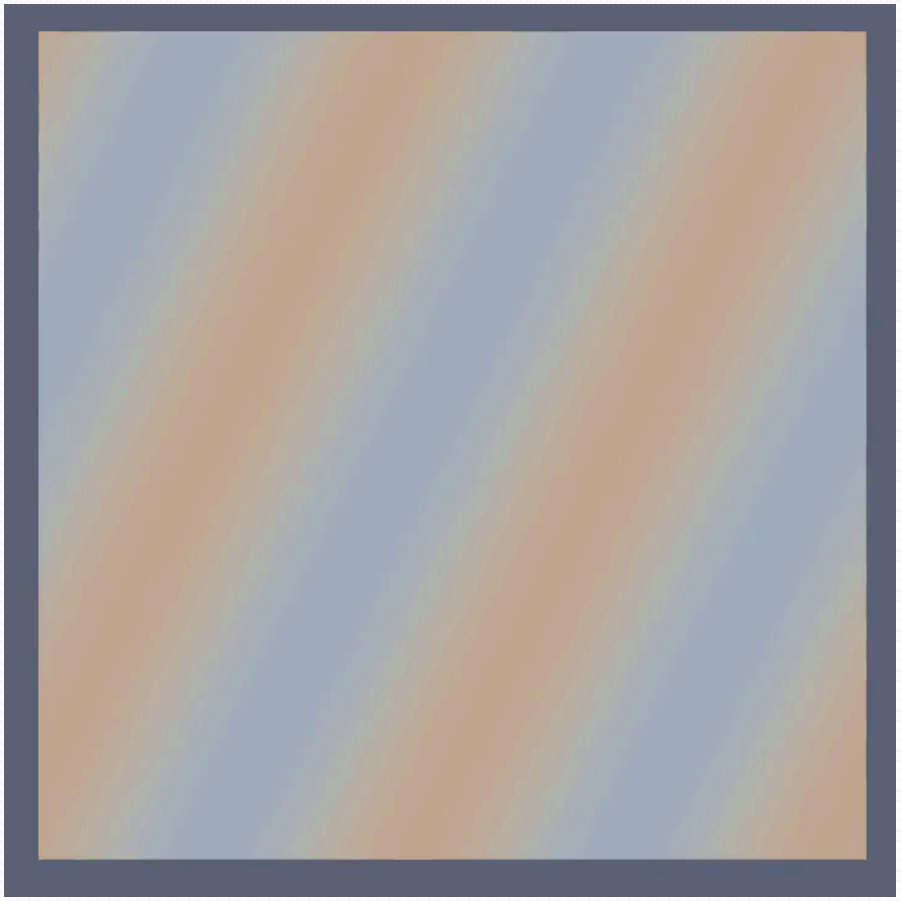


Simulation with higher resolution: Ionospheric density fluctuations

- Initial sinusoidal mode structure is deformed by vortex motions.



- Turbulent fluctuations with drift motions



(movie created by M. Kaneyama)

Application of the gyrokinetics to the M-I coupling

Gyrokinetic description of magnetospheric plasma

- Take the gyrophase average of the Vlasov equation with the gyrokinetic ordering

$$\frac{\omega}{\Omega} \sim \frac{\rho}{L} \sim \frac{\delta f}{F_0} \sim \frac{e\phi}{T} \sim \frac{k_\parallel}{k_\perp} \sim O(\varepsilon) \qquad k_\perp \rho \sim O(1)$$

- Gyrokinetic equaiton for perturbed gyrocenter distribution function $\delta f_s^{(g)}$ (s: ions or electrons; with FLR, electron inertia etc.)

$$\left[\frac{\partial}{\partial t} + v_\parallel \mathbf{b}\cdot\nabla + \mathbf{v}_{ds}\cdot\nabla - \frac{\mu_s}{m_s}\mathbf{b}\cdot\nabla B\frac{\partial}{\partial v_\parallel}\right]\delta f_s^{(g)} + \frac{c}{B_0}\left\{\Phi - \frac{v_\parallel}{c}\Psi, \delta f_s^{(g)} + \frac{e_s\varphi}{T_s}\right\}$$
$$= -v_\parallel F_{0s}\frac{e_s}{T_s}\left(\mathbf{b}\cdot\nabla\Phi + \frac{1}{c}\frac{\partial\Psi}{\partial t}\right) + F_{0s}\frac{e_s}{T_s}\left[\mathbf{v}_{*s}\cdot\nabla\left(\Phi - \frac{v_\parallel}{c}\Psi\right) - \mathbf{v}_{ds}\cdot\nabla\Phi\right]$$

- Quasi-neutrality and Ampere's law for electromagnetic fields

$$\sum_s e_s \int J_0(k_\perp\rho_s)\delta f_{s\mathbf{k}_\perp}^{(g)} d^3v - n_0\sum_s \frac{e_s^2\phi_{\mathbf{k}_\perp}}{T_s}\left[1 - e^{-k_\perp^2\rho_{ts}^2} I_0\left(k_\perp^2\rho_{ts}^2\right)\right] = 0$$

$$\begin{cases} \Phi_{\boldsymbol{k}_\perp} = J_0(k_\perp v_\perp/\Omega_s)\phi_{\boldsymbol{k}_\perp} \\ \Psi_{\boldsymbol{k}_\perp} = J_0(k_\perp v_\perp/\Omega_s)\psi_{\boldsymbol{k}_\perp} \end{cases}$$

$$k_\perp^2\psi = \frac{4\pi}{c}\sum_s e_s \int v_\parallel \delta f_{s\mathbf{k}_\perp}^{(g)} d^3v$$

A simplified model case with slab geometry with a uniform background

- The gyrokinetic equation leads to the linear dispersion relation of a kinetic Alfven wave with $\exp(ik_{\parallel}z - i\omega t)$

$\varepsilon_M(\omega, \mathbf{k}) = 0 \Leftrightarrow$

$$\boxed{\sum_s \frac{1-\Gamma_0(b_s)}{k_\perp^2 \lambda_{Ds}^2} = \left[\frac{\omega^2}{ck_\parallel^2}\sum_s \frac{1-\Gamma_0(b_s)}{k_\perp^2\lambda_{Ds}^2} - 1\right]\cdot\left[\sum_s \frac{\Gamma_0(b_s)}{k_\perp^2\lambda_{Ds}^2}\left(1+\zeta_s Z(\zeta_s)\right)\right]}$$

$$\Gamma_0(b_s) = e^{-b_s} I_0(b_s), \quad b_s = k_\perp^2 \rho_{ts}^2, \quad Z(\zeta_s) = \frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty} \frac{e^{-t^2}}{t-\zeta_s}dt, \quad \zeta_s = \omega/\sqrt{2}\,k_\parallel v_{ts}$$

- For a magnetospheric plasma bounded with the ionosphere, one finds an eigenfunction given by a superposition of up- and down-going waves

$$\psi_{\boldsymbol{k}_\perp}(z) = \psi_{\boldsymbol{k}_\perp, k_\parallel} \sinh[ik_\parallel(z-l)]$$

$$\phi_{\boldsymbol{k}_\perp}(z) = \frac{V_A}{c}\chi_{k_\parallel}\psi_{\boldsymbol{k}_\perp, k_\parallel}\cosh[ik_\parallel(z-l)]$$

$$\boxed{\chi_{k_\parallel} = \frac{k_\perp^2\rho_{ti}^2}{1-\Gamma_{0i}}\frac{k_\parallel V_A}{\omega}}$$

Ionospheric equations and the M-I coupling condition

- Quasi-neutrality and continuity equations for the density and current lead

$$\frac{\partial n}{\partial t} + \frac{\boldsymbol{E} \times \boldsymbol{B}_0}{B_0^2} \cdot \nabla_\perp n = \frac{j_\parallel}{eh} - \alpha n^2$$

$$\nabla_\perp \cdot \left(\mu_P n \boldsymbol{E}\right) - \frac{\boldsymbol{E} \times \boldsymbol{B}_0}{B_0^2} \cdot \nabla_\perp n = D \nabla_\perp^2 n - \frac{j_\parallel}{eh} \quad , \quad \boldsymbol{E} = -\nabla_\perp \phi$$

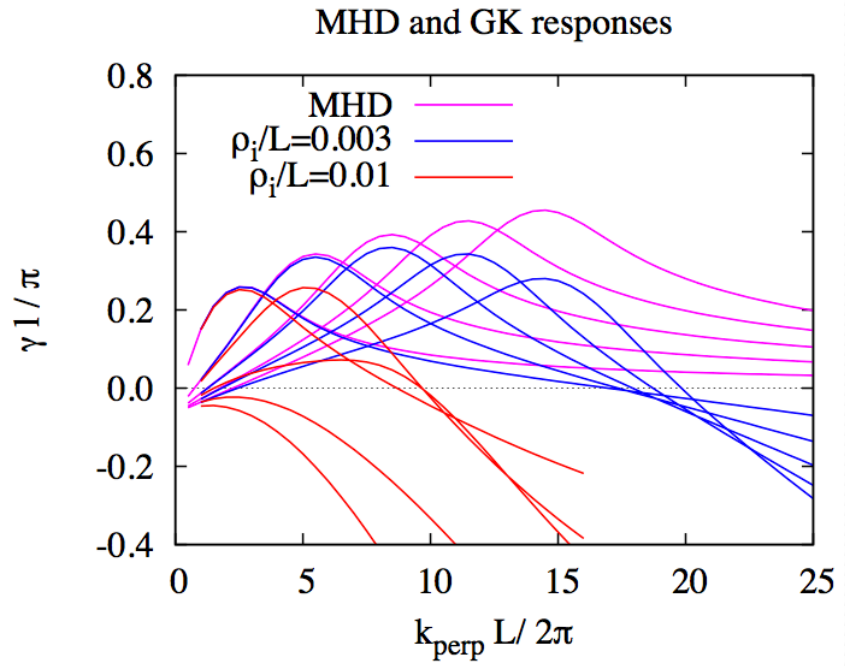
- The linear dispersion relation reduces to

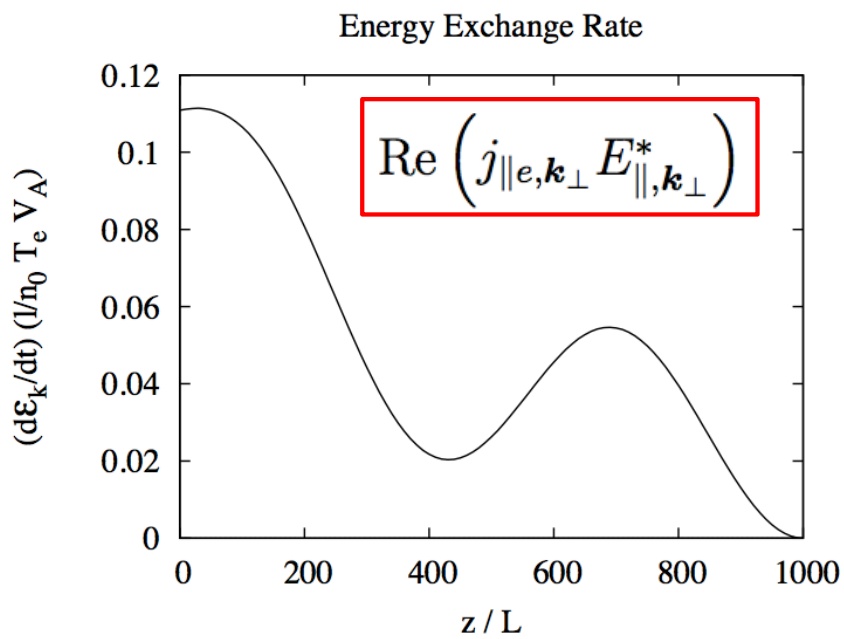
$$\varepsilon_I(\omega, \mathbf{k}; \phi / j_{||}) = 0 \quad \Leftrightarrow \quad \omega = \frac{\boldsymbol{k}_\perp \cdot \left[\mu_P \boldsymbol{E}_0 - (\boldsymbol{E}_0 \times \hat{z}) / B_0\right] - i k_\perp^2 D}{1 + \Sigma_P \left. \frac{k_\perp^2 \phi}{j_\parallel} \right|_{z=0}} - 2 i \alpha n_0$$

- Current closure and continuity of the perpendicular electric field provide the M-I coupling condition, that is, the magnetospheric impedance

Feedback instability analysis with the gyrokinetic equations

- Gyrokinetic equations are applied to the magnetosphere, including electron accelerations in auroral regions
- Unstable solutions, the stabilizing FLR effects
- Electron acceleration by KAWs during auroral growth





[T.-H. Watanabe, GRL 2014]

$$\left(\begin{array}{l} l = 1000L, \mu E_0 = 0.001, \Sigma_P = 5, D = \alpha = 0 \\ v_{te} = V_A, T_i = T_e, m_i = 1836 m_e, \rho_e = 0 \end{array}\right)$$

Summary

- We discussed linear and nonlinear analyses of the feedback instability in the M-I coupling system.
  - Competition of the feedback and ballooning instabilities in the M-I coupling.
  - Transition to the Alfven turbulence in fully nonlinear simulation of the feedback instability, in case with the constant instability drive (uniform E-field)
  - A spiral structure of the ionospheric density spontaneously generated during the transition phase to auroral turbulence.
  - Gyrokinetic equations are applied to M-I coupling, that is, a self-consistent model of auroral arc growth and auroral electron acceleration.