A new magnetohydrodynamic hybrid simulation model with thermal and energetic ions

Y. Todo, H. Wang, and M. Sato (NIFS)

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PLASMA SIMULATOR

Post-K Priority Issue 6

K computer

Outline

- Energetic particle and MHD hybrid simulation
- Extension with kinetic thermal ions
- Application to Alfvén eigenmode (AE)
  - Lower saturation level for higher β_{bulk}
  - Energy transfer to thermal ions from energetic particles through AE
  - Distribution function analysis of thermal ions
- Application to energetic particle driven geodesic acoustic mode (EGAM)

Energetic particles and MHD hybrid simulation

- energetic particles (fast ions, alphas): Particle-in-cell (PIC) simulations
- bulk plasma = MHD fluid
- the coupling between EP and MHD is taken into account through the EP current in the MHD momentum equation
- neutral beam injection (NBI), collisions, and losses are considered

An extended MHD model coupled with energetic particles

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \nu_{\mathrm{n}} \Delta(\rho - \rho_{\mathrm{eq}}) \,, \tag{1}$$

$$\rho \frac{\partial}{\partial t} \mathbf{v}_{\mathrm{MHD}} = -\rho \mathbf{v} \cdot \nabla \mathbf{v}_{\mathrm{MHD}} + \rho \mathbf{v}_{\mathrm{pi}} \cdot \nabla \left(\mathrm{v}_{\|} \mathbf{b} \right) - \nabla p + \underline{(\mathbf{j} - \mathbf{j}_h') \times \mathbf{B}}$$

$$+ \frac{4}{3} \nabla (\nu \rho \nabla \cdot \mathbf{v}_{\mathrm{MHD}}) - \nabla \times (\nu \rho \vec{\omega}) \,, \tag{2}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \,, \tag{3}$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot \left[p (\mathbf{v}_{\mathrm{MHD}} + \mathbf{v}_{\mathrm{tor}}) \right] - (\gamma - 1) p \nabla \cdot \left[(\mathbf{v}_{\mathrm{MHD}} + \mathbf{v}_{\mathrm{tor}}) \right]$$

$$+ (\gamma - 1) [\nu \rho \omega^2 + \frac{4}{3} \nu \rho (\nabla \cdot \mathbf{v}_{\mathrm{MHD}})^2 + \eta \mathbf{j} \cdot (\mathbf{j} - \mathbf{j}_{\mathrm{eq}})] + \chi \Delta (p - p_{\mathrm{eq}}) \,, \tag{4}$$

$$\mathbf{E} = -\mathbf{v}_E \times \mathbf{B} - \mathbf{v}_{\mathrm{tor}} \times (\mathbf{B} - \mathbf{B}_{\mathrm{eq}}) + \eta (\mathbf{j} - \mathbf{j}_{\mathrm{eq}}) \,, \tag{5}$$

$$\underline{\mathbf{v} = \mathbf{v}_{\mathrm{MHD}} + \mathbf{v}_{\mathrm{pi}} + \mathbf{v}_{\mathrm{tor}}}, \quad \mathbf{v}_{\mathrm{pi}} = -\frac{m_i}{2 e_i \rho} \nabla \times \left(\frac{p \mathbf{b}}{B} \right) , \tag{6}$$

$$\mathrm{v}_{\|} = \mathbf{v}_{\mathrm{MHD}} \cdot \mathbf{b} \,, \; \mathbf{v}_E = \mathbf{v}_{\mathrm{MHD}} - \mathrm{v}_{\|} \mathbf{b} \,, \tag{7}$$

$$\mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B} \,, \; \vec{\omega} = \nabla \times \mathbf{v}_{\mathrm{MHD}} \,, \; \mathbf{b} = \mathbf{B}/B \,, \tag{8}$$

based on an extended MHD model given by Hazeltine and Meiss

EP effect

thermal ion diamagnetic drift

+

(equilibrium toroidal rotation =0)

$\nu = \eta/\mu_0 = \nu_n = \chi = 10^{-6} v_A R_0$

EP current density

Energetic ion current density without ExB drift:

$$\mathbf{j}_h' = \int q_h (\mathbf{v}_{//}^* + \mathbf{v}_B) f d^3 v - \nabla \times \int \mu f \mathbf{b} d^3 v$$

parallel + curvature drift + grad-B drift   magnetization current

When we neglect $B^* = B(1 + r_{//} \mathbf{b} \cdot \nabla \times \mathbf{b})$ in the drift kinetic equations,

$$\mathbf{j}_h' = \mathbf{j}_{h//} + \frac{1}{B}\left(P_{h//} \nabla \times \mathbf{b} - P_{h\wedge} \nabla \ln B \times \mathbf{b}\right) - \nabla \times \left(\frac{P_{h\wedge}}{B} \mathbf{b}\right).$$

If the energetic particle distribution is isotropic ($P_{h//} = P_{h\wedge} \equiv P_h$),

$-\mathbf{j}_h' \times \mathbf{B}$ term in the MHD momentum equation is reduced to

the pressure gradient, i.e., $-\mathbf{j}_h' \times \mathbf{B} = -\nabla P_h$

an extended MHD model with kinetic thermal ion and energetic particle

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}_E=-\nabla_\perp p_e+(\mathbf{j}-\mathbf{j}_i'-\mathbf{j}_h')\times\mathbf{B}$$

$$\frac{\partial\mathbf{B}}{\partial t}=-\nabla\times\mathbf{E},\quad \mathbf{j}=\frac{1}{\mu_0}\nabla\times\mathbf{B}$$

$$\mathbf{E}=-\mathbf{v}_E\times\mathbf{B}+\frac{\nabla_{||}p_e}{(-e)n_e}+\eta(\mathbf{j}-\mathbf{j}_{\mathrm{eq}})$$

$$n_e=n_iZ_i+n_hZ_h,\ p_e=n_eT_{e0}$$

$$\rho=n_im_i+n_hm_h,\ \rho\mathbf{v}=n_im_i\mathbf{v}_i+n_hm_h\mathbf{v}_h$$

$$\text{PIC: } n_i,\ n_h,\ \mathbf{v}_i(\mathrm{v}_{i||},p_{i||},p_{i\perp}),\ \mathbf{v}_h(\mathrm{v}_{h||},p_{h||},p_{h\perp}),$$

$$\mathbf{j}_i'(p_{i||},p_{i\perp}),\ \mathbf{j}_h'(p_{h||},p_{h\perp})$$

$$\mathbf{v}=\mathrm{v}_{||}\mathbf{b}+\mathbf{v}_E+(\text{grad-B+curvature+magnetization})$$

Drift kinetic

δf PIC

cf. XHMGC
[X. Wang (2011)]

Application to an Alfvén eigenmode

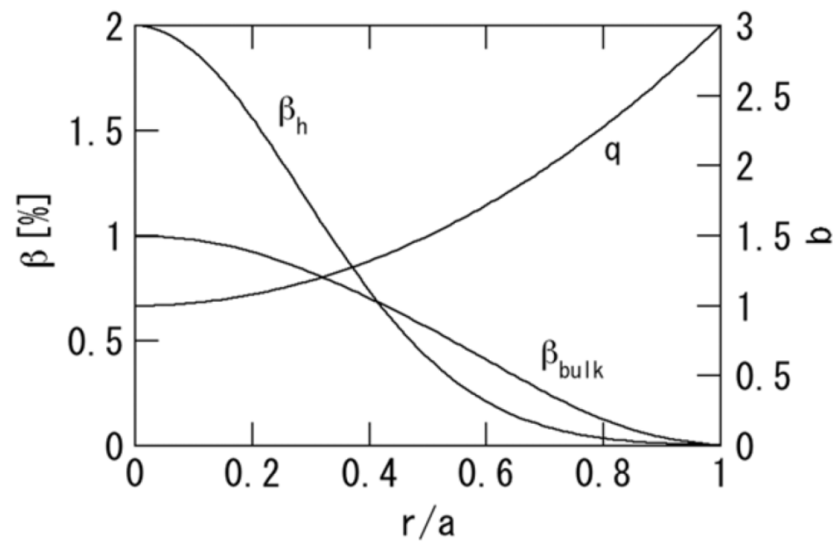
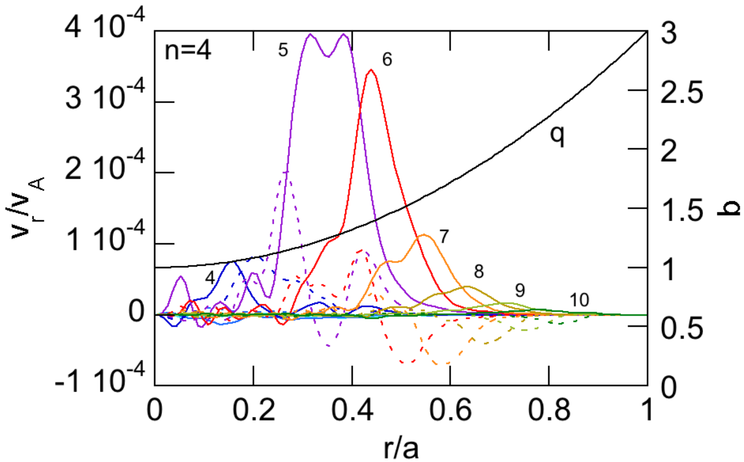
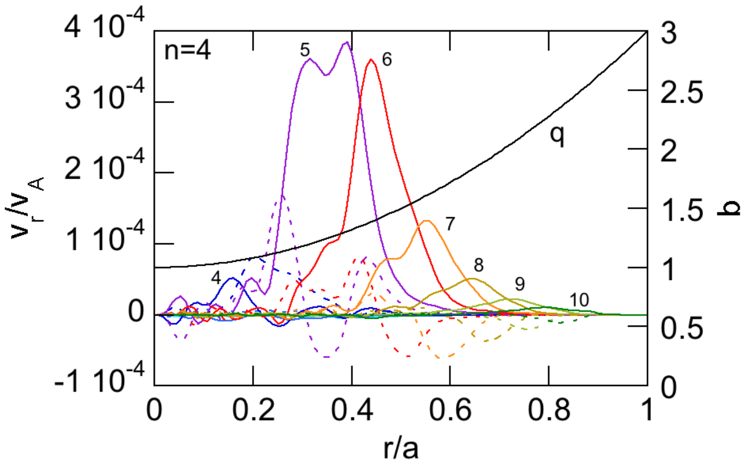


Figure 1. Spatial profiles of energetic-ion beta, bulk plasma beta and safety factor.

- Plasma profile used in Todo+ (2010) [Nucl. Fusion 50, 084016]
- Focus on n=4 toroidal Alfvén eigenmode (TAE)
- Isotropic slowing down distribution with $v_h=1.2v_A$
- $\beta_{bulk0}=1\%$
- $\beta_{h0}=1.5\%$

Comparison in TAE spatial profile





MHD

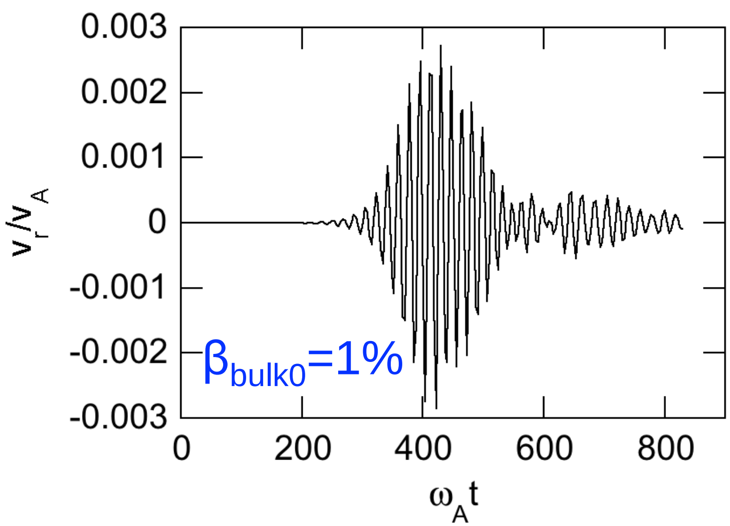
$\omega=0.328\omega_A$
$\gamma=0.031\omega_A$

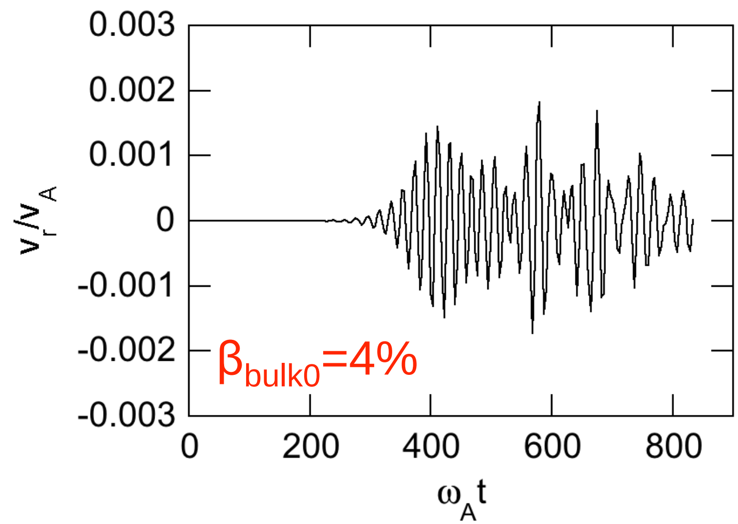
kinetic thermal ion
$(p_e=n_e{*}T_{e0})$

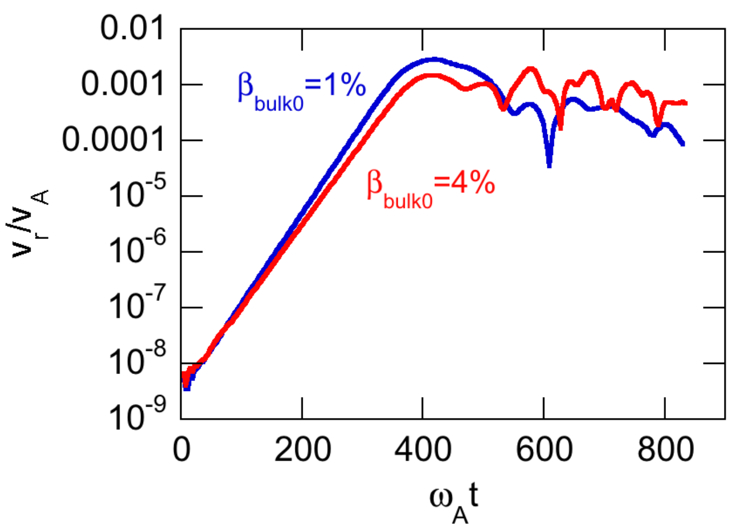
$\omega=0.333\omega_A$
$\gamma=0.035\omega_A$

Comparison between β_{bulk0}=1% and 4%.

Comparison for saturation amplitude

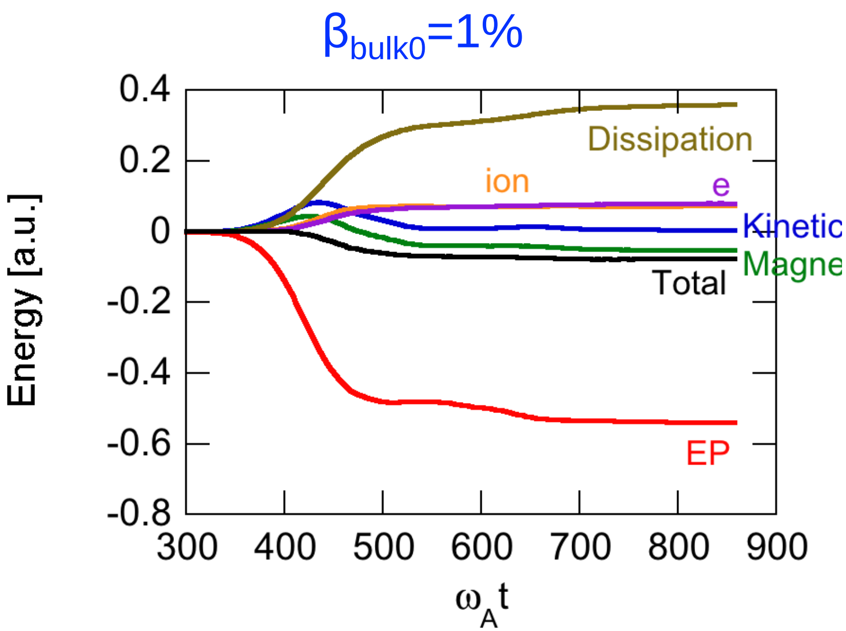


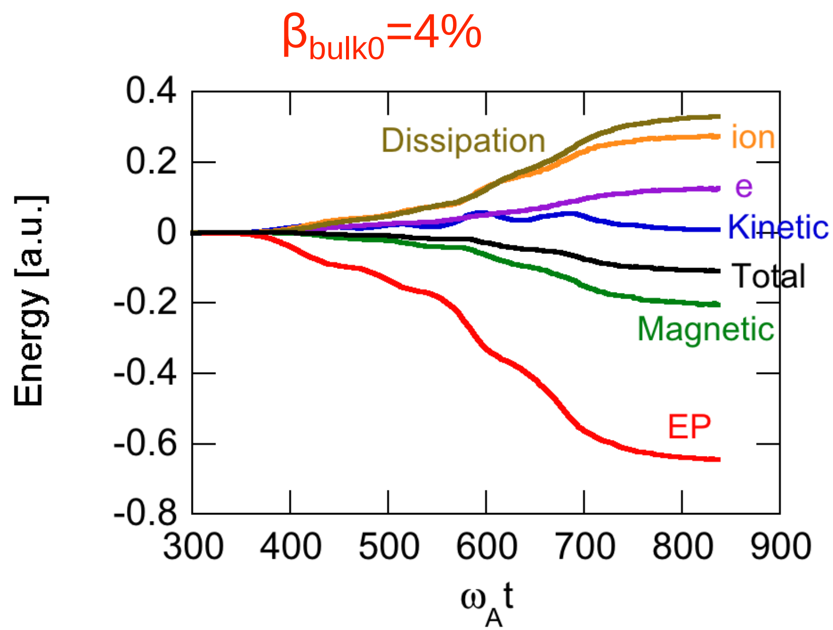




- The saturation amplitude is lower for β_{bulk0}=4% than for β_{bulk0}=1%.
- Another TAE with lower frequency appears at $\omega_A t$~600 after the saturation.

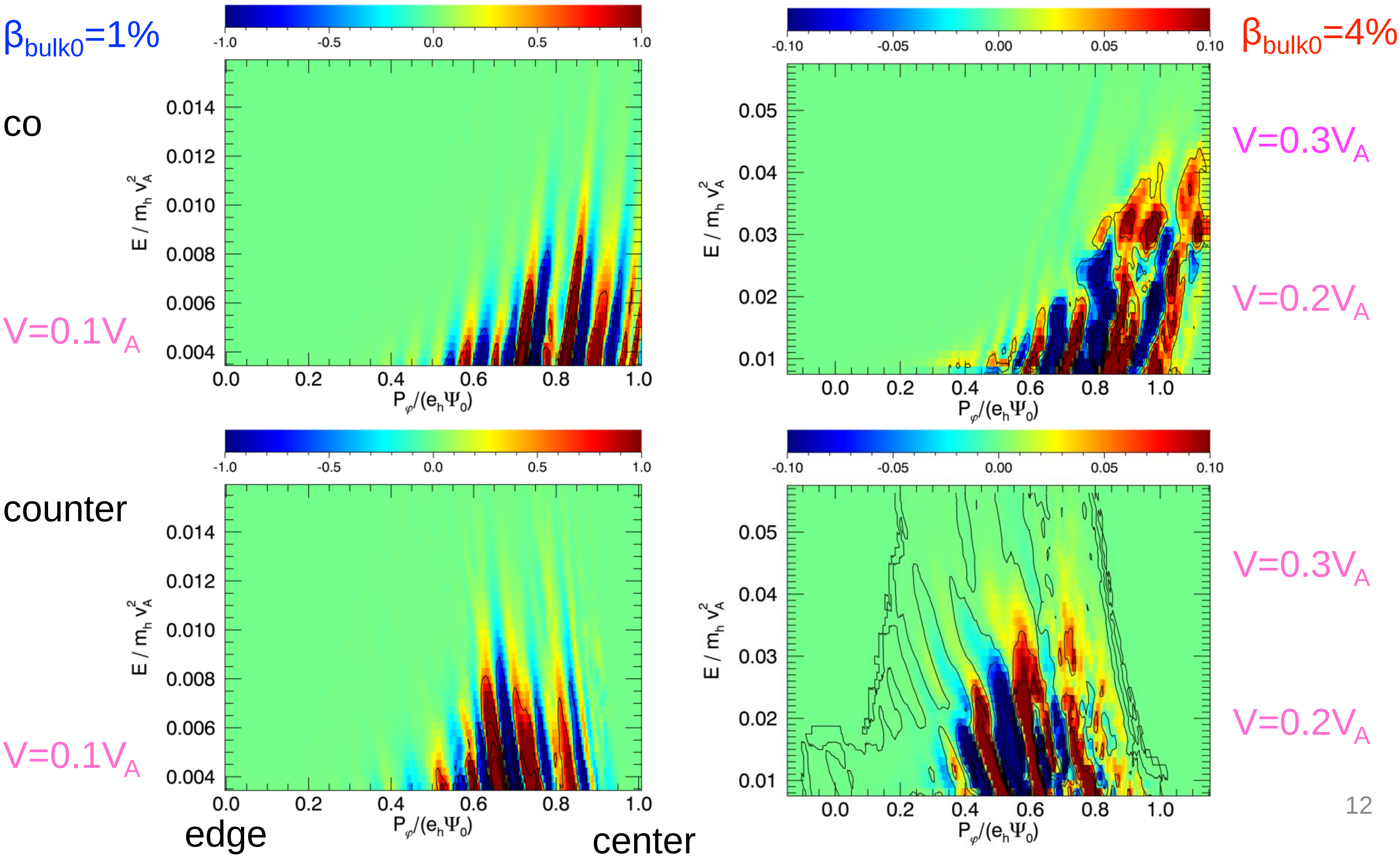
Comparison for energy evolution





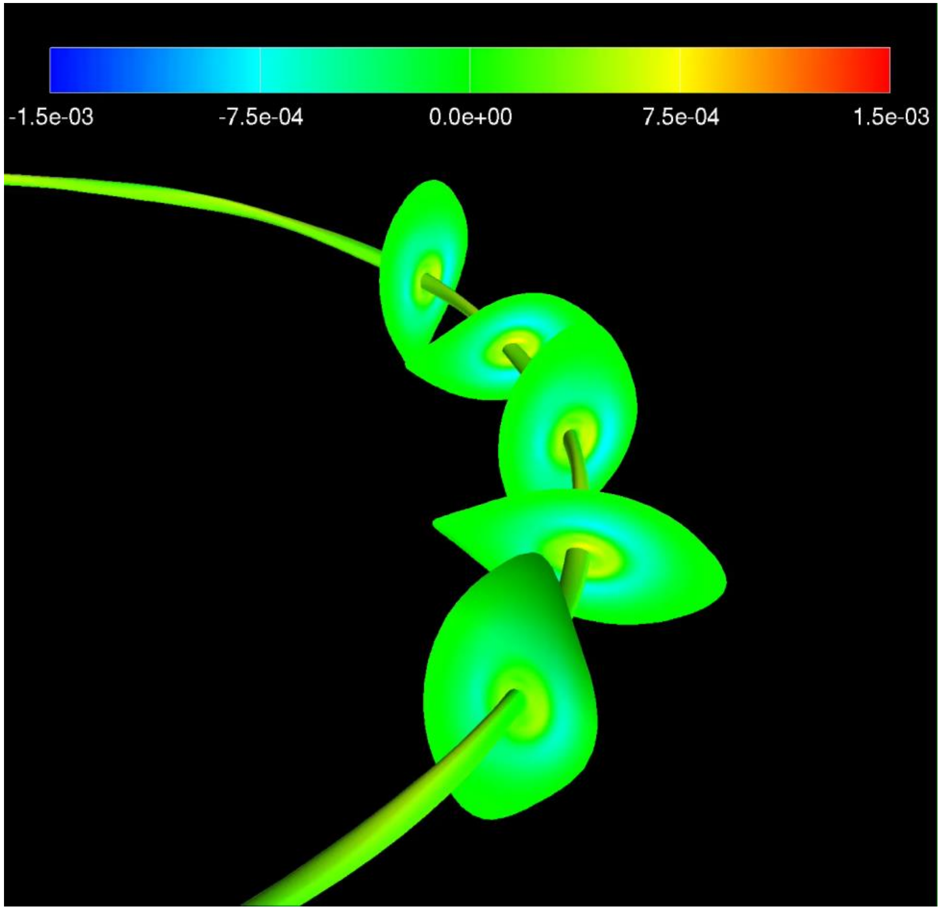
- Decrease in energetic particle (EP) energy indicates that EP drives the instabilities.
- Increase in thermal ion (ion) energy indicates that thermal ions stabilize the instabilities (Landau damping).
- The increase in thermal ion energy is larger for β_{bulk0}=4% than for β_{bulk0}=1%.

thermal ion δf in (P_φ, E) space at $\omega_A t$=756



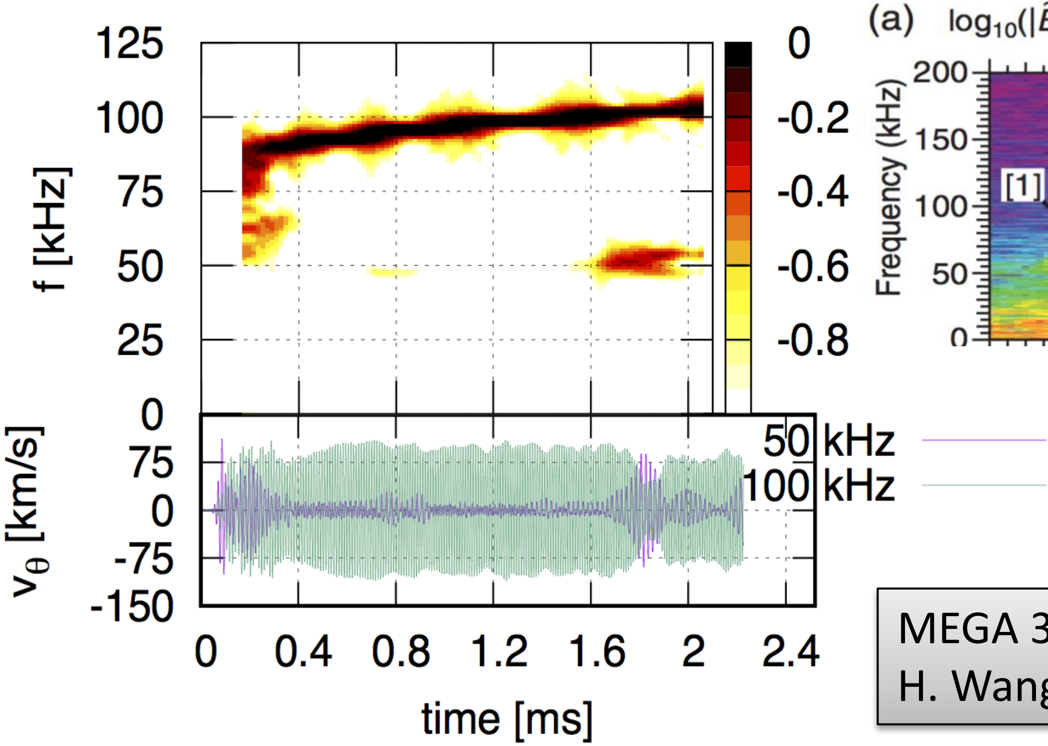
APPLICATION TO ENERGETIC PARTICLE DRIVEN GEODESIC ACOUSTIC MODE (H. WANG)

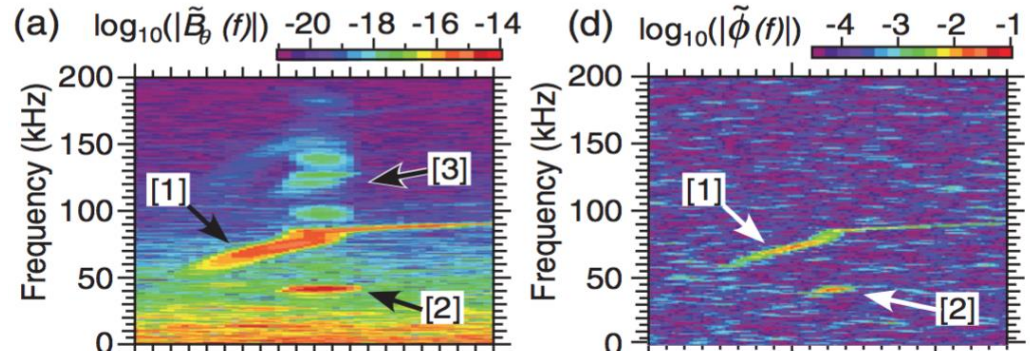
Oscillation of EGAM (v_θ)



- The v_θ oscillation is a combination of m/n=0/0 (strong), 1/0 (medium) and 2/10 (weak) components.

Validation with LHD experiment



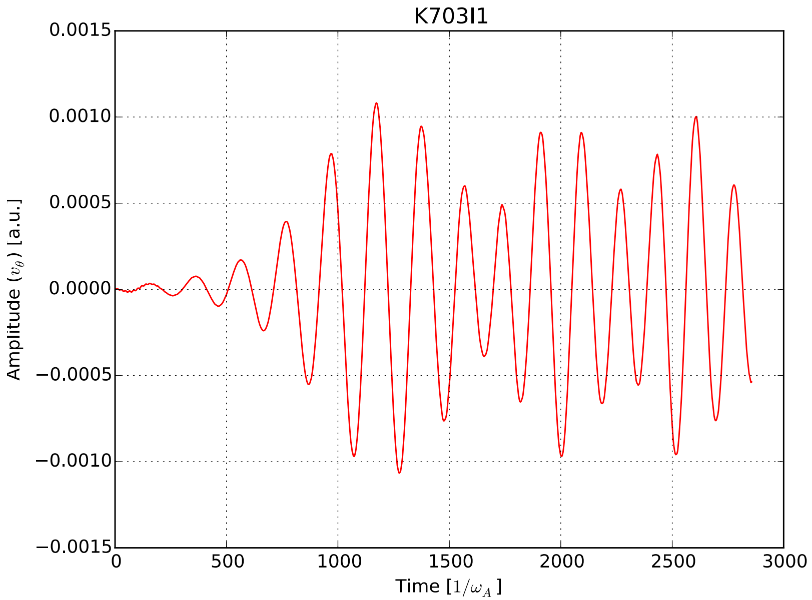


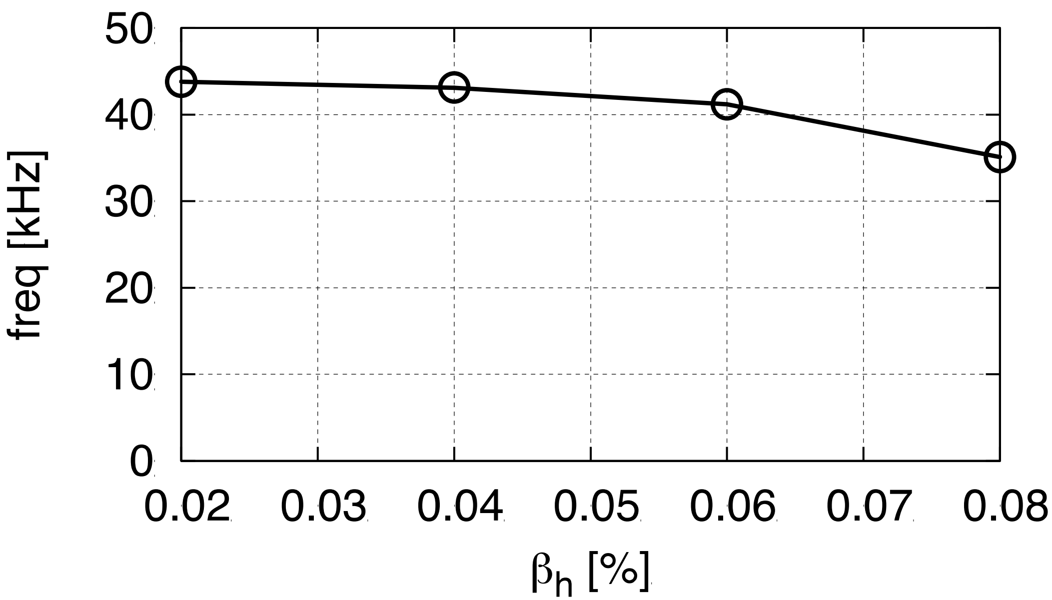
LHD Experiment
T. Ido et al, PRL **116**, 015002 (2016)

MEGA 3D Simulation
H. Wang et al., PRL **120**, 175001 (2018)

- The primary mode chirps up from 70 kHz to 100 kHz.
- The secondary mode frequency is 50kHz, about half of the primary mode frequency.
- The secondary mode is excited in the nonlinear phase.
- This is the first simulation of EGAM and the associated secondary mode in the realistic 3-dimensional LHD configuration.

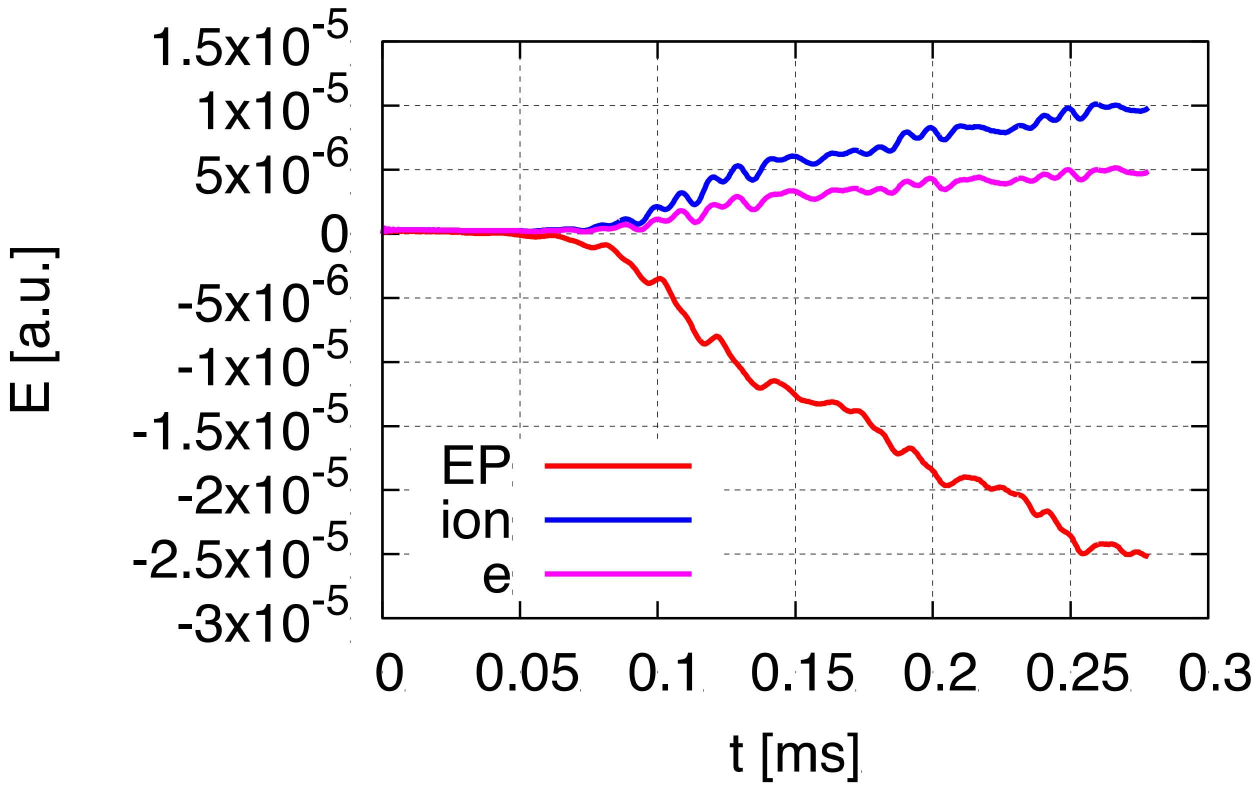
Simulation of EGAM with the new model





- The theoretical GAM frequency should be 54kHz.
- The oscillated mode frequency is lower than GAM frequency.
- The frequency decreases with β_h increases. This is consistent with the theoretical prediction and previous simulation.

Energy transfer from EP to thermal ions



- Energetic particle energy is transferred to thermal ions through the interaction with the EGAM.

Summary

- Energetic particle and MHD hybrid simulation
- Extension with kinetic thermal ions
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  - Lower saturation level for higher β_{bulk}
  - Energy transfer to thermal ions from energetic particles through the interaction with AE
  - Distribution function analysis of thermal ions
- Application to energetic particle driven geodesic acoustic mode (EGAM)
- Work in progress: AE (Todo), EGAM (Wang), and MHD instabilities in LHD (Sato)