Simulations of Alfven eigenmodes in an ITER-like plasma

Y. Todo (NIFS, Japan)

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Introduction

- For more realistic simulation of Alfven eigenmodes, we implemented the drift model and an extended Ohm's law in the simulation code MEGA [MHD and energetic alpha particles, Y. Todo et al., Phys. Plasmas 12, 012503 (2005)].

- An ITER plasma with weakly reversed magnetic shear was investigated with the extended MEGA code.

Outline

- Simulation model (Drift model)
- An Ohm's law extended with the electron Landau fluid model
- Initial condition
- Results I: ITER plasma with $\beta_{\alpha 0}$=2% and weakly reversed shear
- Results II: ITER plasma with $\beta_{\alpha 0}$=1% and weakly reversed shear
- Summary

Drift model[1] + current coupling model of energetic particles

$$\frac{dn}{dt} + n\nabla\cdot\mathbf{v} = 0$$

$$\left.\frac{d}{dt}\right|_{MHD} P + \frac{5}{3}P\nabla\cdot\mathbf{v}_{MHD} = 0$$

$$\mathbf{E} + \mathbf{v}\times\mathbf{B} + \frac{1}{en}\left(\frac{1}{2}\nabla P - \mathbf{j}\times\mathbf{B}\right) = \eta\left[\mathbf{j} - \frac{3n}{4B}\mathbf{b}\times\nabla\frac{P}{n}\right]$$

$$m_i n\left[\frac{d\mathbf{v}_E}{dt} + \left.\frac{d}{dt}\right|_{MHD}(\mathbf{b}v_{//})\right] + \nabla P = (\mathbf{j} - \mathbf{j}_h')\times\mathbf{B}$$

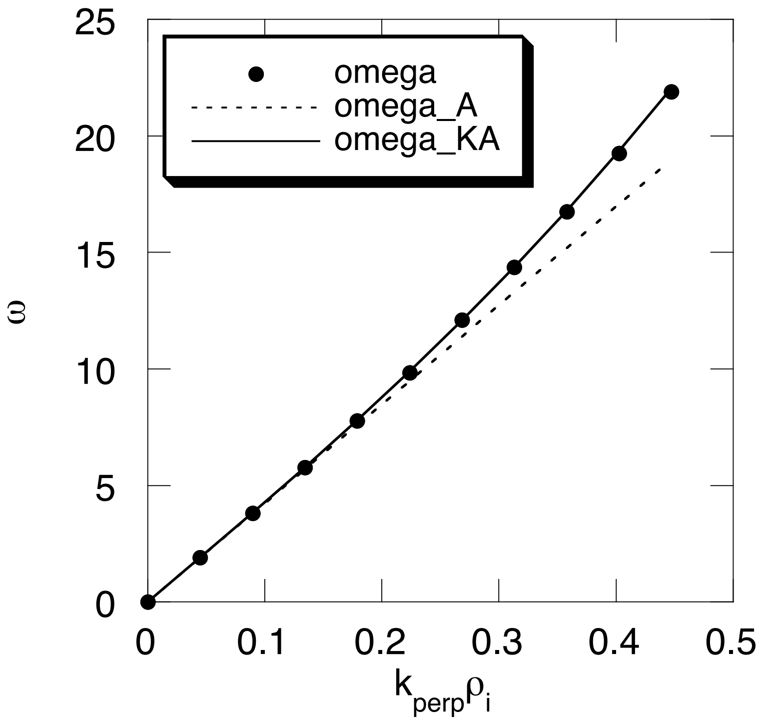
$$\left.\frac{d}{dt}\right|_{MHD} \equiv \frac{\partial}{\partial t} + (\mathbf{v}_E + v_{//}\mathbf{b})\cdot\nabla$$

$$\mathbf{v}_{pi} = \frac{1}{2enB}\mathbf{b}\times\nabla P$$

$$\mathbf{E}_\perp + \mathbf{v}_E\times\mathbf{B} = 0$$

1) R. D. Hazeltine and and J. D. Meiss, "Plasma Confinement" (Addison-Wesley Publishing Company, 1992).

Dispersion relation of the kinetic Alfven wave: comparison of the simulation results with theory



$$\omega^2 = k_{//}^2 v_A^2 \left[1 + k_\perp^2 \rho_i^2 \left(\frac{3}{4} + \frac{T_e}{T_i} \right) \right]$$

$$k_\perp / k_{//} = 1/3$$

The dispersion relation of the kinetic Alfven wave is well reproduced with the drift model simulation.

An Ohm's law extended with the electron Landau fluid model

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} + \frac{1}{en}\left(\frac{1}{2}\nabla P - \mathbf{j} \times \mathbf{B}\right) = \eta_{LF}\mathbf{j}_{//}$$

$$\eta_{LF} = \frac{m_e}{n_e e^2}\sqrt{\frac{\pi}{2}}v_{te}\left|k_{//}\right|$$

$$\left|k_{//}\right| \approx \frac{1}{2qR_0}$$

The effective resistivity is given by the Landau fluid model [G. W. Hammet et al. Phys. Fluids B 4, 2052 (1992).]

The parallel wave number is a reasonable approximation for Alfven eigenmodes.

The damping rate of the n=4 TAE in the TFTR D-T plasma investigated with this code is $5\times10^{-3}\omega$, which is a half of the NOVA-K results [G. Y. Fu et al., Phys. Plasmas 5, 4284 (1998)]. This suggests that a more careful modeling is needed for a quantitative prediction.

Guiding center approximation for energetic particles

$$\mathbf{u} = \mathbf{v}_{//}^{*} + \mathbf{v}_{E} + \mathbf{v}_{B}$$

$$\mathbf{v}_{//}^{*} = \frac{v_{//}}{B^{*}}[\mathbf{B} + \rho_{//} B \nabla \times \mathbf{b}]$$

$$\mathbf{v}_{E} = \frac{1}{B^{*}}[\mathbf{E} \times \mathbf{b}]$$

$$\mathbf{v}_{B} = \frac{1}{q_{h} B^{*}}[-\mu \nabla B \times \mathbf{b}]$$

$$\rho_{//} = \frac{m_{h} v_{//}}{q_{h} B}$$

$$\mathbf{b} = \mathbf{B} / B$$

$$B^{*} = B(1 + \rho_{//} \mathbf{b} \cdot \nabla \times \mathbf{b})$$

$$m_{h} v_{//} \frac{d v_{//}}{dt} = \mathbf{v}_{//}^{*} \cdot [q_{h} \mathbf{E} - \mu \nabla B]$$

An extended Grad-Shafranov Equation

[E. V. Belova et al. Phys. Plasmas 10, 3240 (2003)]

Fast ion current density without ExB drift:

$$\mathbf{j}'_h = \int q_h(\mathbf{v}^*_{//} + \mathbf{v}_B) f_0(P_\varphi, \varepsilon, \mu) d^3 v - \nabla \times \int \mu f_0(P_\varphi, \varepsilon, \mu) \mathbf{b} d^3 v$$

parallel + curvature drift + grad-B drift   magnetization current

Find the stream function the fast ion current:

$$j'_{h,R} = -\frac{1}{R}\frac{\partial K}{\partial z} \qquad j'_{h,z} = \frac{1}{R}\frac{\partial K}{\partial R}$$

An extended Grad-Shafranov equation:

$$R\frac{\partial}{\partial R}\frac{1}{R}\frac{\partial \psi}{\partial R} + \frac{\partial^2 \psi}{\partial z^2} = -\mu_0 R^2 \frac{d}{d\psi} p - \mu_0 R j'_{h,\varphi} - \frac{I}{(2\pi)^2}\frac{dM}{d\psi}$$

$$I \equiv 2\pi R B_\varphi$$

$$M \equiv I - 2\pi K$$

Initial distribution of alpha particles

$$f(P_\varphi, v) = h(P_\varphi)g(v)$$

$$h(P_\varphi) = \sum_{n=0} a_n \left(\frac{P_{\varphi,\max} - P_\varphi}{P_{\varphi,\max} - P_{\varphi,\min}} \right)^n$$

$$g(v) = \frac{1}{v^3 + v_c^3} \qquad (v \le v_\alpha)$$

$$= 0 \qquad (v > v_\alpha)$$

Here, a_n is chosen using the least square method so that the alpha particle pressure is close to the one specified.

The δf method

The energetic ion pressures are calculated using the particle weight:

$$P_{h//}(\mathbf{x}) = P_{h//0}(\mathbf{x}) + \sum_{i}^{N} m_h v_{//i}^2 w_i S(\mathbf{x} - \mathbf{x}_i) \ ,$$

$$P_{h\perp}(\mathbf{x}) = P_{h\perp 0}(\mathbf{x}) \frac{B(\mathbf{x})}{B_0(\mathbf{x})} + B(\mathbf{x}) \sum_{i}^{N} \mu_i w_i S(\mathbf{x} - \mathbf{x}_i) \ .$$

The evolution of the particle weight is given by,

$$\frac{d}{dt} w_i = -\alpha V_i \frac{d}{dt} f_0(\varepsilon, \mu, P_\varphi) = -\alpha V_i \left[\frac{d\varepsilon}{dt} \frac{\partial f_0}{\partial \varepsilon} + \frac{dP_\varphi}{dt} \frac{\partial f_0}{\partial P_\varphi} \right]$$

[α : normalization factor,

V_i : phase space volume which the i-th particle occupies]

An ITER plasma with weakly reversed shear (based on ITER technical basis)

$$\beta_\alpha = \beta_{\alpha 0} \exp[-(r/0.45a)^2]$$

$$q(r/a=0) = 3.5$$

$$q(r/a=0.7) = 2.2 = q_{min}$$

$$q(r/a=1.0) = 5.3$$

$$R = 6.35\mathrm{m},\ a = 1.85\mathrm{m}$$

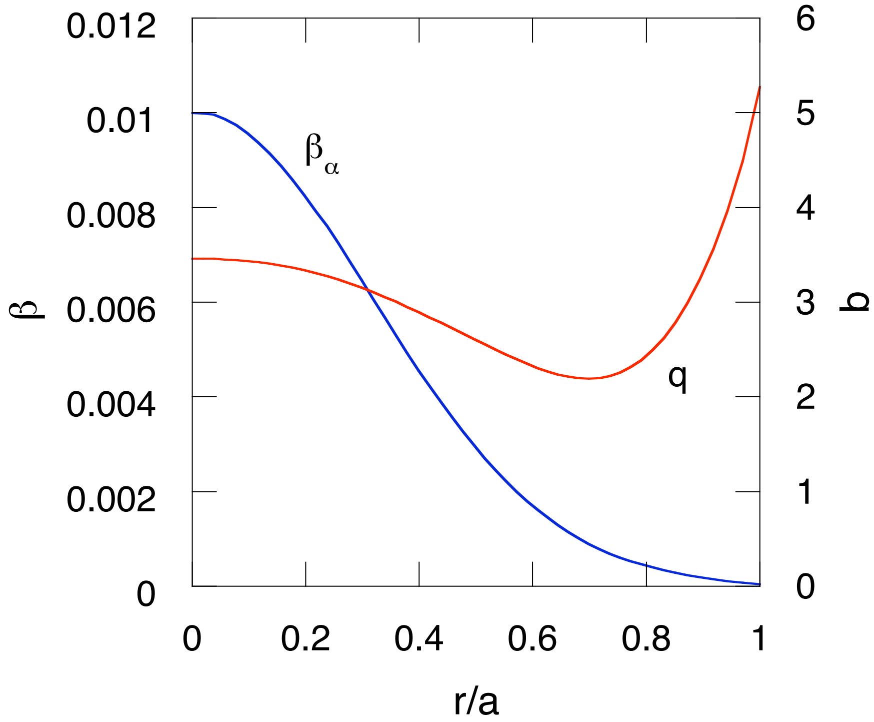
$$\kappa = 1.85,\ \delta = 0.4$$

$$B = 5.18\mathrm{T},\ n_e = 6.7 \times 10^{19}\,\mathrm{m}^{-3}$$

$$\beta_{thermal} = 2.5\%$$

$$T_e = 12.3\mathrm{keV}$$

$$v_\alpha = 1.48 v_A \quad \text{(corresponds to 3.5MeV)}$$

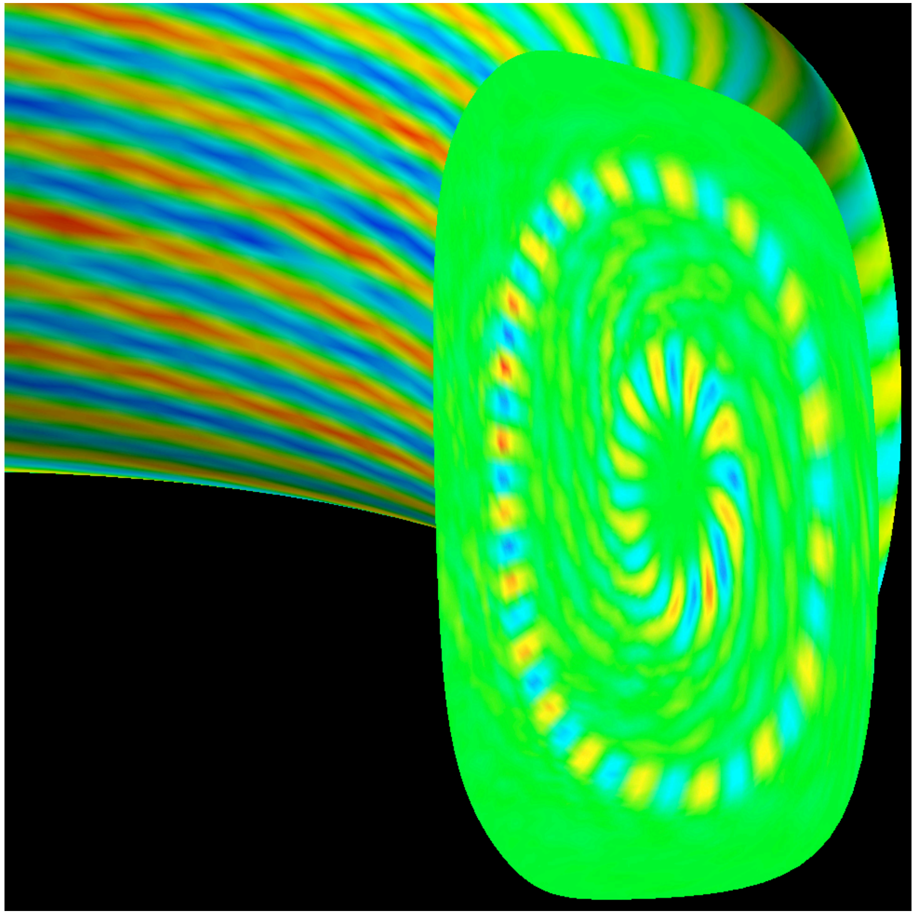


Two cases were investigated.

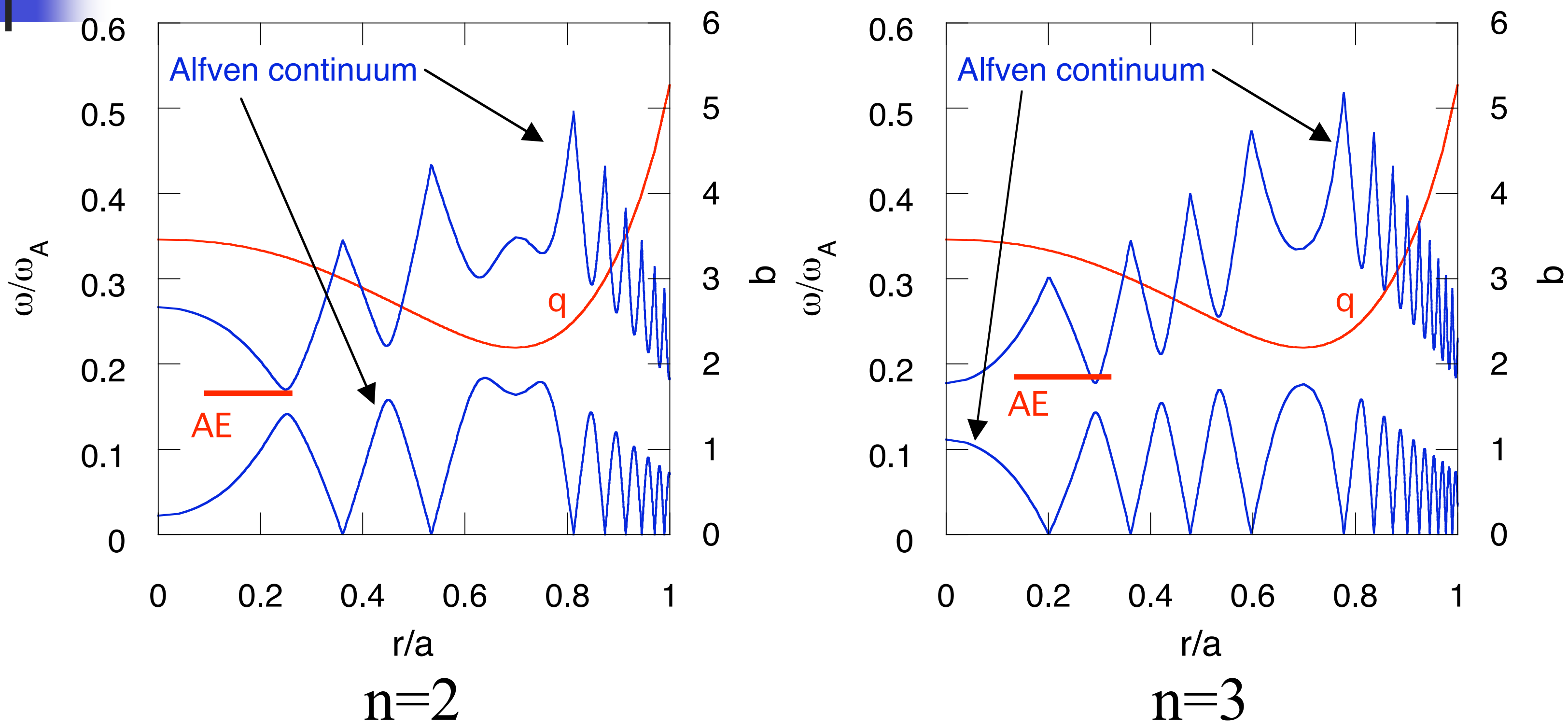
- $\beta_{\alpha 0}$=2%
- $\beta_{\alpha 0}$=1%

Two types of unstable modes are observed ($\beta_{\alpha 0}$=2%)

1. Low n (n=2,3) Alfven eigenmodes at r/a~0.3. The frequency is $\omega_{n=3}$=0.19 ω_A and $\omega_{n=2}$=0.17ω_A.
2. A middle n (m/n=20/9) and low frequency mode (pressure driven MHD mode) at $q=q_{min}$=2.2, r/a~0.7. The frequency is $\omega = 6\times10^{-3}\ \omega_A$.



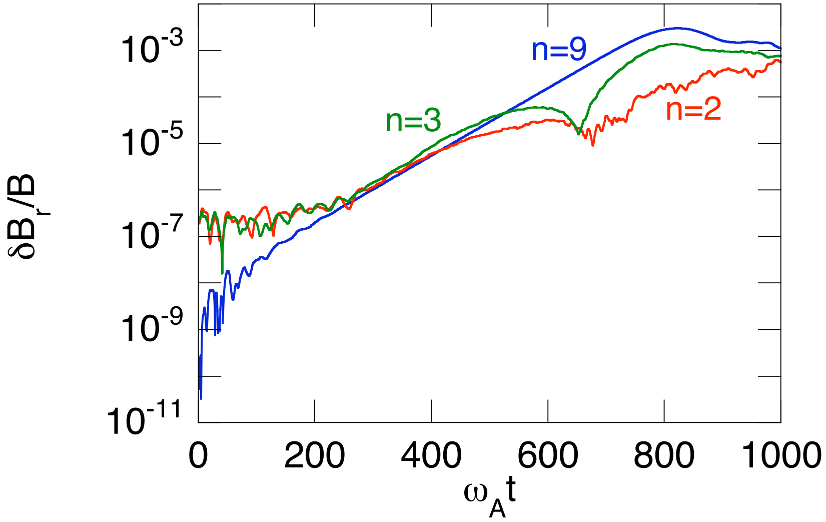
Alfven continua and Alfven eigenmodes



1. The frequency of each eigenmode is close to the upper continuum.

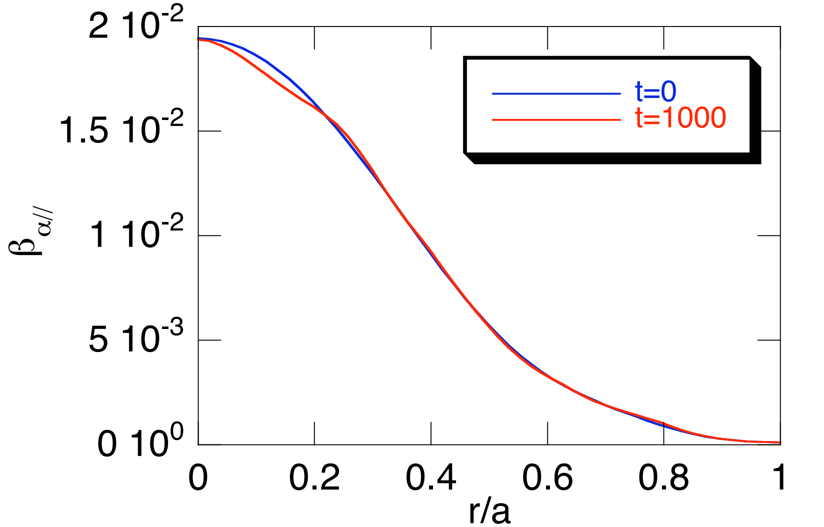
2. The eigenmodes are spatially localized in one side of the respective gaps.

Saturation levels and alpha particle transport ($\beta_{\alpha 0}$=2%)



The saturation levels are

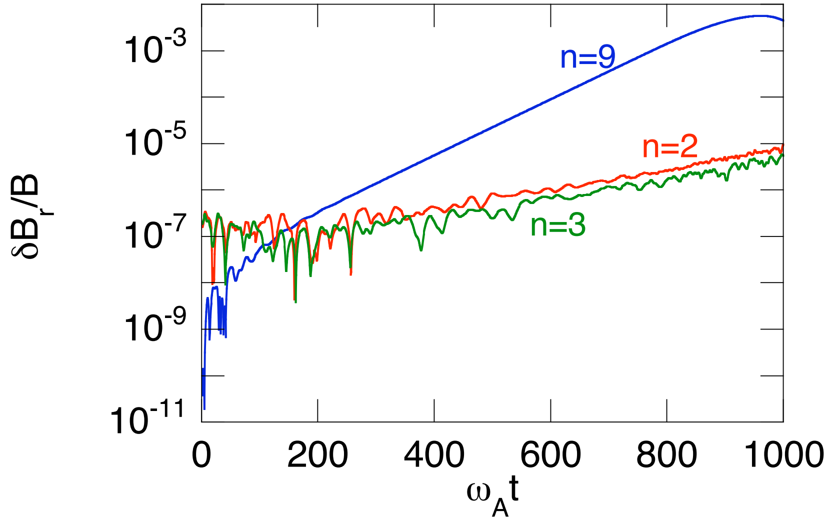
$\delta B_r/B \sim 10^{-3}$.



The reduction in alpha particle beta value is

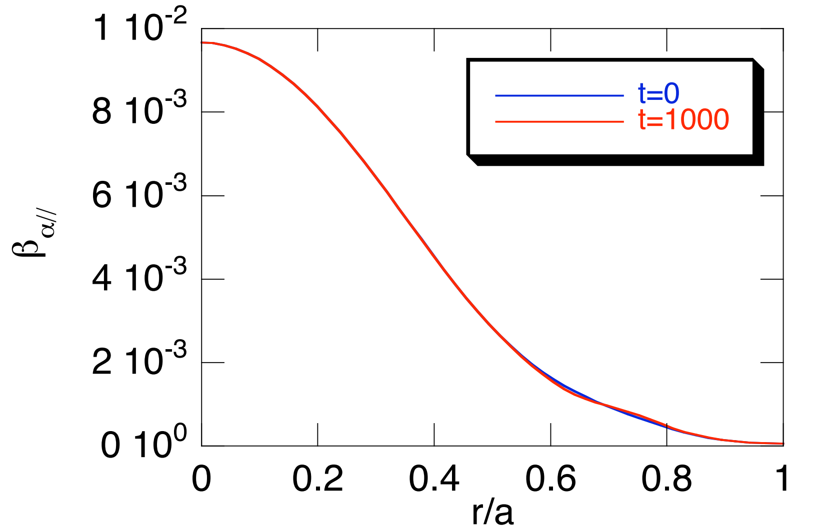
$|\delta\beta_\alpha| \sim 6\times10^{-4}$.

Saturation levels and alpha particle transport ($\beta_{\alpha 0}$=1%)



The saturation level of the n=9 mode is

$\delta B_r/B \sim 5\times10^{-3}$.



The reduction in alpha particle beta value is

$|\delta\beta_\alpha| \sim 10^{-4}$.

Summary

- The simulation code for MHD and energetic alpha particles (MEGA) has been extended with the drift model. The electron Landau fluid model is also employed to extend the Ohm's law.
- An ITER plasma with weakly reversed magnetic shear was investigated.
- Alfven eigenmodes with n=2 and 3 are unstable near the plasma center. An MHD instability with n=9 takes place at $q=q_{min}=2.2$.
- The reduction in alpha particle beta value is $|\delta\beta_\alpha|\sim 6\times 10^{-4}$ for $\beta_{\alpha 0}=2\%$ and $|\delta\beta_\alpha|\sim 10^{-4}$ for $\beta_{\alpha 0}=1\%$.