Investigate the effect of energetic particles on MHD modes using NOVA-K code

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2012-06-29 Experiment Seminar

Background

- In addition to thermal ions and electrons, tokamak plasmas often contain super-thermal species, which are called fast or energetic particles
- Energetic particles (EPs) can be created from various sources:
  - $\rightarrow$ Externally: ion/electron cyclotron heating, LHW heating, NBI
  - $\rightarrow$ Internally: runaway electrons associated with disruptions, fusion reaction
- The EPs can destabilize some global MHD modes.
- The destabilizing effects (drive effects) of EPs can be calculated by the NOVA-K code

NOVA-K code

NOVA-K is a 2D Kinetic-MHD linear stability code for tokamaks with energetic particles.

- MHD description for thermal plasma and Kinetic for EP
- Can calculate the frequency and mode structure of MHD Alfven waves
- The destabilizing effects (drive effects) of EP on MHD modes

$\rightarrow$ Authors: C. Z. Cheng, N. Gorelenkov, G. Y. Fu (PPPL)

$\rightarrow$ NOVA-K is written in Fortran Language

$\rightarrow$ Approximate number of code lines: 10,000 lines

$\rightarrow$ Code was first used in 1988 after the discovery of TAE

NOVA-K code

- NOVA-K first calculates the ideal MHD modes without the EP: mode frequency, mode structure, and polarization
- Then NOVA-K uses the calculated MHD modes structure to calculate the destabilizing effects of EP (contribution of EP to the growth rate of the modes)
- Besides the EP drive effects, NOVA-K also includes various damping effects:
  - $\rightarrow$ Thermal electron/ion Landau damping
  - $\rightarrow$ Continuum damping
  - $\rightarrow$ Collisional damping of trapped electrons
  - $\rightarrow$ Radiative damping
- Threshold is determined by the balance of EP drive and damping rate.

Physical model of NOVA-K code

- Thermal plasma is described by the Ideal MHD equations

Momentum equation

$$\rho_m\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)=-\nabla p+(\nabla\times\boldsymbol{B})/\mu_0\times\boldsymbol{B}$$

Faraday's Law

$$\frac{\partial \boldsymbol{B}}{\partial t}=\nabla\times(\boldsymbol{u}\times\boldsymbol{B})$$

Equation of state

$$\frac{\partial p}{\partial t}+\boldsymbol{u}\cdot\nabla p=-\gamma p\nabla\cdot\boldsymbol{u}$$

Expression of perturbation

- Due to toroidal symmetry, perturbation can be represented by a single toroidal mode, $\exp(-in\zeta)$.
- However, due to the poloidal nonuniform, different poloidal harmonics are coupled, perturbation should include all Fourier series in θ

$$\boldsymbol{\xi}(\psi,\theta,\zeta,t)=\sum_{m=-\infty}^{m=+\infty}\boldsymbol{\xi}_m(\psi)\exp[i(m\theta-n\zeta-\omega t)]$$

- Mode structure (ψ dependence of the perturbation) is treated in NOVA-K using finite-element expansion

Perturbed EP distribution is solved from drift kinetic equation

- Equilibrium distribution: $F = F(P_{\varphi 0}, \varepsilon_0, \mu_0)$
- Ideal MHD perturbation: $\boldsymbol{B}^{(1)} = \nabla \times (\boldsymbol{\xi} \times \boldsymbol{B}_0)$
- Perturbed EP distribution due to ideal MHD perturbation is solved from the drift kinetic equation:

$$\delta f = -\frac{Ze}{c}\boldsymbol{\xi}_\perp \nabla\psi \frac{\partial F}{\partial P_{\varphi 0}} - \mu_0 \frac{B_\parallel^{(1)}}{B_0}\frac{\partial F}{\partial \mu_0} - \delta g,$$

where

$$\delta g = -i(\omega - n\omega_\star)\frac{\partial F}{\partial \varepsilon_0}\int_0^t \mathcal{L}^{(1)} d\tau,$$

$$\mathcal{L}^{(1)} = -\left(m v_\parallel^2 - \mu_0 B_0\right)\boldsymbol{\xi}\cdot\boldsymbol{\kappa} + \mu_0 B_0 \nabla\cdot\boldsymbol{\xi}_\perp,$$

$$\omega_\star = \frac{\partial F}{\partial P_{\varphi 0}} \Big/ \frac{\partial F}{\partial \varepsilon_0}.$$

NOVA-K input

- MHD equilibrium
- Energetic particles distribution

$\rightarrow$ The MHD equilibrium is easy to obtain.

$\rightarrow$ The energetic particles distribution generated by rf wave is usually difficult to get from experiments.

$\rightarrow$ The EP distriubtion due to rf wave can be calculated from Fokker-Planck code + rf code

NOVA-K output

- Shear Alfvén continuum.
- Frequency and mode structure of ideal MHD modes
  - $\rightarrow$ External/Internal kink modes
  - $\rightarrow$ Toroidal Alfvén Eigenmodes(TAE)
- Drive/damping rate
  - $\rightarrow$ Energetic particles drive/damping
  - $\rightarrow$ Thermal electron/ion Landau damping
  - $\rightarrow$ Continuum damping
  - $\rightarrow$ Collisional damping of trapped electrons
  - $\rightarrow$ Radiative damping

Toroidicity-Induced Alfvén Eigen-mode (TAE)

- TAE is a type of global shear Alfvén eigenmode.
- Exists only in toroidal geometry: created due to toroidal coupling
- Usually has only two dominant poloidal mode numbers
- Frequency is discrete, lies within the “gaps” in the shear Alfvén continuum.
- Can be strongly destabilized by α-particles in burning tokamak plasmas.
- Mode identification is easy: frequency, mode structure, polarization

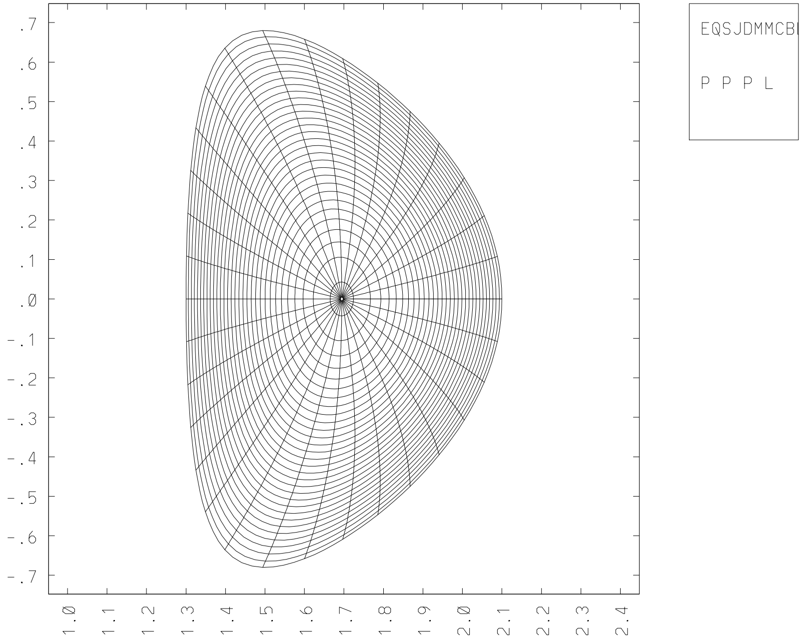

Figure 1. EAST equilibrium. The shape parameters of LCFS are $R_0 = 1.7m$, $a = 0.4m$, elongation $\kappa = 1.7$, and triangularity $\delta = 0.5$.

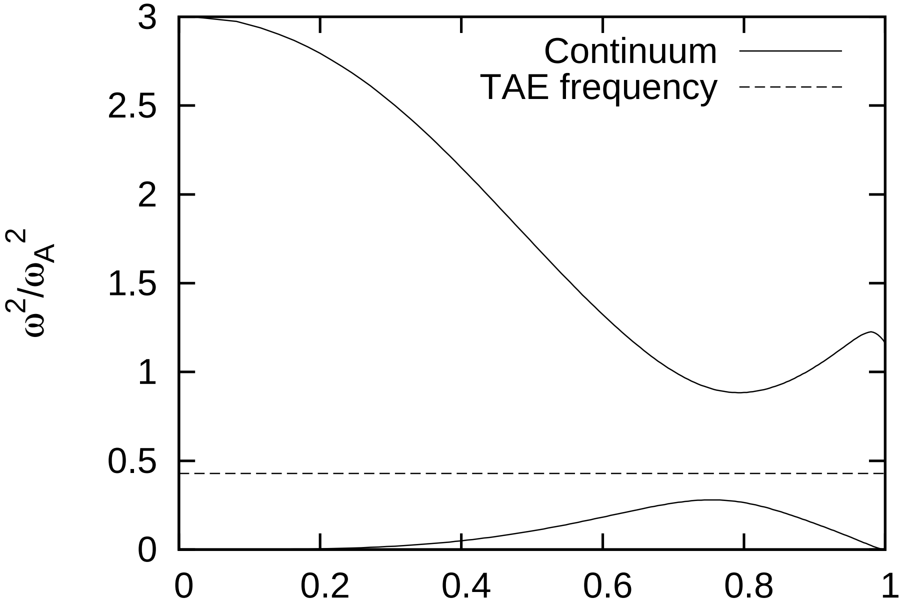

Figure 2. n=1 continuum spectrum and TAE frequency $\omega^2/\omega_A^2 = 0.429$, where $\omega_A = B(0)/\left[q(1)R_0\sqrt{\mu_0 n(0) m_i} \right]$. The TAE frequency $\omega = 916\mathrm{kHz}$ for the case of $B(0) = 1T$, $n(0) = 4 \times 10^{19} m^{-3}$, and $q(1) = 2$.

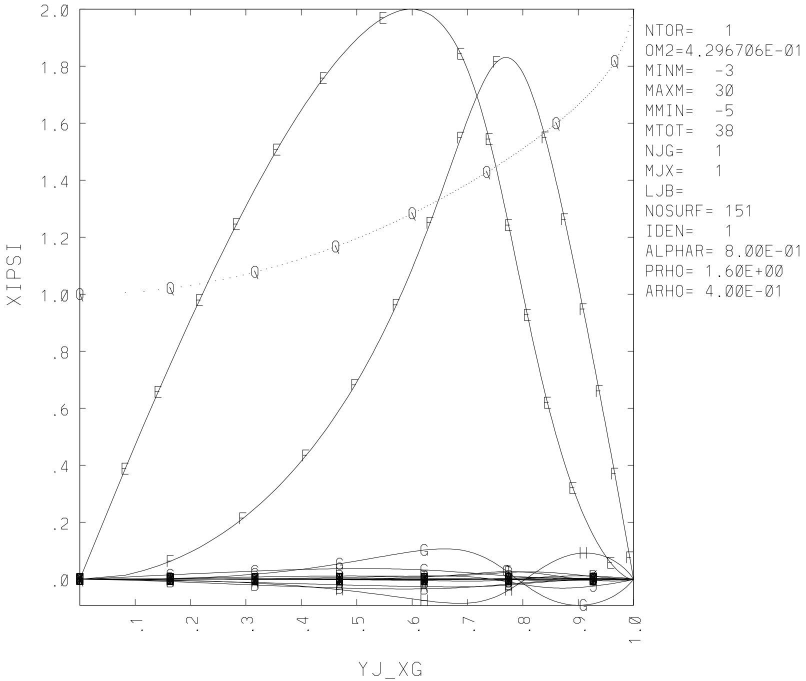

Figure 3. Mode structure of n=1 TAE. Dominant poloidal modes are $m = 1$ and $m = 2$. Mode frequency $\omega^2/\omega_A^2 = 0.429$.

NOVA-K can estimate the beta threshold for instabilities

Threshold is determined by balance of:

- EP drive growth rate (reliably calculated)
- Damping rate (calculation is very sensitive to parameters)
  - → Theon/ion Landau damping
  - → Continuum damping
  - → Collisional damping of trapped electrons
  - → Radiative damping

Formula to estimate the EP beta threshold for instabilities:

$$\beta_{h\,\mathrm{crit}} = \beta_h \frac{\mathrm{all\ dampings}}{\mathrm{EP\ drive\ growth\ rate}}$$

Summary

- NOVA-K can calculate various ideal MHD Alfven modes and the influence of EPs on these modes.
- The prediction of NOVA-K can be readily compared with experiments.

Thank You!