TH/7-1  Multi-phase Simulation of Alfvén Eigenmodes and Fast Ion Distribution Flattening in DIII-D Experiment

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Anomalous Flattening of the fast-ion profile during Alfvén-eigenmode activity

- A rich spectrum of TAEs and RSAEs with reversed q profile in current ramp-up phase
Theoretical studies related to the DIII-D experiments

- **Alfvén eigenmodes**
  - An excellent agreement in $\delta Te$ profile between NOVA prediction and ECE measurement [Van Zeeland (2009)]
  - Shearing of 2D AE profile was compared with TAEFL code [Tobias (2011)]
  - EP nonperturbative effects on TAE profile and freq. [Wang (2013)]
  - Validation of GK codes on transition from RSAE to TAE [Spong (2012)]

- **EP transport**
  - Multiple low amplitude modes ($dB/B\sim10^{-4}$) can account for significant modification of fast ion distributions [White (2010)]
  - Modeling of fast ion losses and stability of AE modes [Van Zeeland (2011, 2012)]

- **Nonlinear simulations** [Vlad (2009), Y. Chen (2013)]
We try a first comprehensive simulation of AE amplitude and EP transport!

• AE stability and amplitude depend on EP distribution
• EP transport depends on AE amplitude
• AEs and EP distribution should be solved in a self-consistent way. Difficulty arises from a gap between time scales:
  – slowing down time ~ 0.1-1 s, AE period ~ 10^-5 s
Life of an energetic particle: idea of multi-phase simulation

- in the slowing down process, energetic particle resonates with multiple AEs
- resonance regions have finite width ($\Delta v$) in velocity space
- interaction with AEs can be simulated at intervals shorter than $\tau_s^* \Delta v/v$
Multi-phase Simulation

[Y. Todo, Nucl. Fusion 54, 104012 (2014)]

• Hybrid simulation of energetic particles and an MHD fluid

• Multi-phase simulation =
  – classical simulation w/o MHD perturbations for 4ms  +
  – EP-MHD hybrid simulation for 1ms; performed alternately
  – reduce computational time to 1/5
Objectives

• Multi-phase simulation of a DIII-D experiment (#142111) and validation on
  – anomalous flattening of fast ion profile
  – electron temperature fluctuation: frequency, spatial profile, and amplitude

• Analysis of fast ion transport process in the simulation result
An extended MHD model coupled with energetic particles

\[ \frac{\partial \rho}{\partial t} = - \nabla \cdot (\rho \mathbf{v}) + \nu_n \Delta (\rho - \rho_{eq}) , \]  

(1)

\[ \rho \frac{\partial}{\partial t} \mathbf{v}_{\text{MHD}} = - \rho \mathbf{v} \cdot \nabla \mathbf{v}_{\text{MHD}} + \rho \mathbf{v}_{\text{pi}} \cdot \nabla (v_{||} \mathbf{b}) - \nabla p + (j - j'_h) \times \mathbf{B} \]

\[ + \frac{4}{3} \nabla (\nu \rho \nabla \cdot \mathbf{v}_{\text{MHD}}) - \nabla \times (\nu \rho \mathbf{\omega}) , \]  

(2)

\[ \frac{\partial \mathbf{B}}{\partial t} = - \nabla \times \mathbf{E} , \]  

(3)

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

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

(4)

\[ \mathbf{E} = - \mathbf{v}_E \times \mathbf{B} + \eta (j - j_{eq}) , \]  

(5)

\[ \mathbf{v} = \mathbf{v}_{\text{MHD}} + \mathbf{v}_{\text{pi}} + \mathbf{v}_{\text{tor}}, \quad \mathbf{v}_{\text{pi}} = - \frac{m_i}{2e_i \rho} \nabla \times \left( \frac{p \mathbf{b}}{B} \right) , \]  

(6)

\[ \mathbf{v}_{||} = \mathbf{v}_{\text{MHD}} \cdot \mathbf{b}, \quad \mathbf{v}_E = \mathbf{v}_{\text{MHD}} - \mathbf{v}_{||} \mathbf{b} , \]  

(7)

\[ \mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B}, \quad \mathbf{\omega} = \nabla \times \mathbf{v}_{\text{MHD}}, \quad \mathbf{b} = \mathbf{B} / B , \]  

(8)

Based on an extended MHD model given by Hazeltine and Meiss

EP effect

thermal ion diamagnetic drift

+ equilibrium toroidal rotation

\[ \nu = \eta / \mu_0 = \nu_n = \chi = 5 \times 10^{-7} \nu_A R_0 \]
Frequency spectrum evolution in the experiment at $t \sim 525\text{ms}$ #142111

- AEs with $n=1-5$ are observed.
- In the simulation, energetic particle drive is restricted to $n=1-5$ to reduce numerical noise.

[M. A. Van Zeeland, NF 52, 094023 (2012)]
Setup of simulation

• DIII-D discharge #142111 at t=525ms is investigated using an equilibrium data reconstructed with EFIT code.
• Realistic beam ion deposition profile (full, half, and third energy components) is given by TRANSP code.
• Collisions (slowing down, pitch angle scattering, energy diffusion) with realistic parameters are taken into account.
• Particle losses take place at the plasma boundary (r/a=1).
• 8 million particles are injected with constant time intervals in 150ms.
• Beam injection power is 6.25MW.
Time evolution of stored fast ion energy and MHD kinetic energy

- Multi phase simulation: classical phase is run w/o MHD for 4ms and then hybrid phase is run with MHD for 1ms. This combination is repeated until stored fast ion energy is saturated at t=70ms.
- After t=70ms, the MHD fluctuation reaches to a steady level.
Comparison of fast ion pressure profiles (classical, multi-phase, exp.)

• Fast ion pressure profile flattening takes place in the multi phase simulation.
• The fast pressure profile in the multi-phase simulation is close to that in the experiment.
Fast ion distribution in velocity space

Classical

Multi-phase
Comparison among classical phase durations

- two classical phase durations (4ms and 9ms) are compared
- very good agreement in fast ion pressure profile (top right)
- similar MHD fluctuation level (bottom)
Bulk temperature fluctuation spectra at $r/a=0.49$ at $t \geq 70$ms

- Comparison in frequency (sim., exp.): $n=1$ (62kHz, 68kHz), $n=3$ (69kHz, 74kHz), $n=4$ (73kHz, 79kHz), $n=5$ (77kHz, 84kHz)
- $n=2$ mode is missing at the simulated moment in experiment
δTe Spatial Profiles in multi-phase simulation

\begin{align*}
n &= 3, \quad f = 69\text{kHz} \\
n &= 4, \quad f = 73\text{kHz} \\
n &= 5, \quad f = 77\text{kHz}
\end{align*}
Comparison of temperature fluctuation profile with ECE measurement for n=3

- good agreement in spatial profile (left)
- good agreement in **amplitude** within a factor of 2 (left)
- good agreement in phase profile (right)
Comparison of temperature fluctuation profiles with ECE measurement for n=4 and 5

- good agreement in spatial profile (left)
- good agreement in amplitude within 20% (left)
- good agreement (n=4) and reasonable agreement (n=5) in phase profile (right)
Evolution of fast ion energy flux brought about by AEs

- steady and intermittent flux
- avalanches with multiple modes
- consistent with resonance overlap
  (Berk & Breizman 1995)
Summary

• First comprehensive simulation that predicts
  – nonlinear saturated amplitude of AEs
  – and fast ion pressure profile consistent with measured values in experiment

• Temperature fluctuation profiles brought about by three of TAEs in the simulation are compared with experiment.
  – good agreement in radial profiles of amplitude and phase
  – good agreement in absolute amplitude within a factor of 2

• Steady and intermittent fast ion energy flux with avalanches

• The multi-phase simulation is useful for the prediction of AE activity and EP transport in burning plasmas