Challenges for Predictive Simulations of Alpha Particle-Driven Modes in Burning Plasmas

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Outline

1. Key Issues of Alpha Collective Effects in Burning Plasmas:

   (a) Effects of alpha particles on stability of MHD modes;

   (b) Stability of alpha particle-driven Alfven modes;

   (c) Nonlinear dynamics of alpha-driven Alfven modes and related alpha particle transport.

2. Physics Ingredients for Predictive Simulations

3. Computational Challenges

4. Tokamaks versus Stellarators

Key Questions

- Stability Threshold of Energetic Particle Modes
- EPM instability in internal transport barrier
- Condition for resonance overlap and related alpha particle transport due to multiple modes at $k_\theta \rho_\alpha \sim 1$ ("Alfven sea" at $\gamma/\omega > 1/(4n)$?).

Physics Ingredients for Predictive Simulations

- Equilibrium:

  Realistic finite aspect ratio finite beta equilibrium solutions required to describe Alfven spectrum accurately.

- Linear Stability:

  Non-perturbative energetic particle drive with finite orbit width;

  thermal ion kinetic effects for radiative damping and drift wave effects.

- Nonlinear Dynamics:

  Fluid and particle nonlinearity;

  Particle collisional effects on wave-particle trapping;

  Self-consistent evolution of multiple modes.

Computational Challenges for Simulating High-n TAE/EPM in Burning Plasmas

- We are developing a massive parallel 3D hybrid code PARM3D which can be used to simulate energetic particle-driven MHD modes;
- PARM3D evolves particle/MHD hybrid equations on 3D unstructured grid. The energetic particle effects are coupled to the MHD equations through pressure tensor or current.
- Massive parallel computations are needed for simulating high-n TAE/EPM in burning plasmas:

  CPU time scales as $N_r N_\theta N_\phi N_{time}$. Since $N \propto 1/n$ and $k_\theta \rho_\alpha \sim 1$, we have:

  $CPU time \propto (a/\rho_\alpha)^4$

  This translates into about 10 days per nonlinear run for $n \sim 10$ using whole T3E (644 processors) at NERSC. This scale of simulations will be possible in next few years with improved numerical algorithm.

Energetic Particle-driven Alfvens Modes: Tokamak versus Stellarators

- Many Alfven modes have been observed in stellarators with features similar to those in tokamaks:

  GAE and TAE in W7-AS, fishbones and TAE in CHS and LHD etc.

- Theoretically, we expect physics of TAE/AE in stellarators are same to that in tokamaks.

- However, there are significant differences:

  Aspect ratio of stellarators tend to be much larger, except compact QAS and QOS;

  Wider range of q profile: monotonic reversed q profile, flat q profile;

  3D geometry induces new AE (MAE, HAE etc) and new wave particle resonances.