Particle simulation of energetic particle driven Alfvén modes

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Outline

• Introduction
• Hybrid MHD-Gyrokinetic code (HMGC)
• Simulation of NNB heated JT-60U discharge
• Simulation of NB heated DIII-D discharge:
  – single-\(n\) simulations ...
  – vs. multi-\(n\) simulation
• Conclusions
Introduction

- Transport of fast ions (alphas and/or ions produced by aux. heating) can be enhanced by their resonant interaction with Alfvén modes
- Alfvén modes: TAEs, ..., Energetic Particle driven Modes (EPMs)
- EPMs can produce “avalanches” (ballistic fast-ion transport and radially moving unstable front)
- Burning plasma scenarios should avoid strongly driven Alfvén modes in order to prevent performance degradation and first wall damage
- Hybrid MHD-particle codes address these issues: particle-wave interactions retained in a self-consistent way
- ITER reversed shear scenario predicted to be close or above EPMs threshold
- Comparison between simulation and present day tokamak discharges
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• Hybrid MHD-Gyrokinetic Code (HMGC):
  – thermal plasma described by MHD equations
  – energetic particles (EP) described by nonlinear guiding-center Vlasov equation (Particle-in-cell technique)
  – self-consistent simulations (particles treated non perturbatively)
  – mode-mode coupling neglected in single-\(n\) simulations (but particle nonlinearities fully retained)
  – multi-\(n\) simulations retain also MHD nonlinearities
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Simulation of JT-60U discharge

Experiment

Weak shear, NNB heated discharge: Abrupt Large amplitude Events (ALEs) and fast Frequency Sweeping (FS) modes

- strong $n=1$ mode;
- $\beta_{H0}=8\pi P_{H0}/B^2 \approx 3\%$;
- $\Delta t_{ALE-exp} \approx 50 \div 200$ µs

Simulation

\( n=1 \) mode

**Simulation of JT-60U discharge-cont’d**

Energetic particle density profile

- **before ALE**
- **after ALE (experimental)**
- **relaxed (simulation)**

\[ \frac{n_i}{n_{i0}} \]

\( r/a \)
Simulation of JT-60U discharge-cont’d

Simulation

\[ n=1 \text{ mode} \]

Energetic particle density profile

- before ALE
- after ALE (experimental)
- relaxed (simulation)

linear growth rate \[ \gamma \approx 0.106 \tau_{A0}^{-1} \]
burst time scale \[ \Delta t_{EPM} \approx 150 \mu s \]
(S. Briguglio et al., PoP 14 (2007) 1-10)

\[ \delta B_\theta(t) \text{ and power spectrum of } \delta B_\theta(t, \omega) \text{ close to the plasma edge} \]
Simulation of JT-60U discharge-cont’d

Simulation

\( n=1 \) mode

Energetic particle density profile

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\( \delta B_\theta (t) \) and power spectrum of \( \delta B_\theta (t, \omega) \) close to the plasma edge

fast Frequency Sweeping (FS) mode:
reproduced only if distortion of EP distribution function in velocity space after ALE is retained
Simulation of JT-60U discharge-cont’d

Simulation

$n=1$ mode

Frequency spectra of fluctuating scalar potential in $[r, \omega]$ plane from simulation:

ALE  EPM
Simulation of JT-60U discharge—cont’d

Simulation

\( n=1 \) mode

Frequency spectra of fluctuating scalar potential in \([r, \omega]\) plane from simulation:

\[
\text{ALE} \leftrightarrow \text{EPM}
\]

Energetic particle distribution function from simulation (\([E, \alpha]\) plane, \(r/a \approx 0.5\)):

Detailed diagnostics on wave-particle power exchange and \(\delta F\) show that radial displacement mainly involves resonant ions

\[
\delta F = F_{\text{sat}}(\alpha, E) - F_{\text{SD}}(\alpha, E)
\]

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Simulation of DIII-D discharge

- A rich spectrum of oscillations in the Alfvénic range has been observed in DIII-D tokamak reversed-shear discharges heated by neutral beams
- Excellent radial resolution of the experimental spectrograms permits qualitative and quantitative comparison with numerical simulations
- DIII-D discharge #122117:
  - neutral beam heated ($\beta_{H0} \approx 0.8\%$), reversed shear discharge
  - discrepancy between experimentally measured (EFIT, FIDA) and TRANSP (classical deposition) computed energetic particles density profile
- Comparison between HMGC nonlinear simulations and experimental results
Simulation of DIII-D discharge-cont’d

- Experimental evidences (discharge #122117):

**The Upgraded ECE Diagnostic Measures the Radial Eigenfunction**

- RSAEs: Reversed Shear Alfvén Modes
- TAEs: Toroidal Alfvén Modes (gap modes)

Simulation of DIII-D discharge-cont’d

- Experimental evidences (discharge #122117):
  - RSAEs: Reversed Shear Alfvén Modes
  - TAEs: Toroidal Alfvén Modes (gap modes)

- Fast-ion profile:
  - Classical: from TRANSP;
  - FIDA: Fast Ion $D_\alpha$ (FIDA) diagnostic measures the spectrum of fast ions with 5 cm radial resolution;
  - Equilibrium: kinetic EFIT (from MSE and magnetics), with subtraction of thermal pressure
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Single-\(n\) HMGC simulation for discharge \#122117, energetic particle density profile from \textsc{TRANSP}:

- \textsc{TRANSP} profile is strongly unstable, modes localized at \(q_{\text{min}}\)
- collective mode dynamics (Energetic Particle Modes, EPMs, here \(n=2\)) cause a relevant flattening of the EP density radial profile
- in good agreement with the experimental one
- similar results for \(n=3\) and \(n=4\) simulations
Single-\(n\) simulation of DIII-D discharge-cont’d

Single-\(n\) simulations, power spectra of scalar potential in the plane \([r, \omega]\): dominant modes localized at \(q_{\text{min}}\) radius

linear growth phase, \(\gamma \tau A_0 \approx 0.1\)
Single-\(n\) simulation of DIII-D discharge-cont’d

Single-\(n\) simulations, power spectra of scalar potential in the plane \([r,\omega]\): dominant modes localized at \(q_{\text{min}}\) radius

Linear growth phase, \(\gamma \tau_{A0} \approx 0.1\)

Saturated phase

100 kHz

60 kHz

Simulations with nominal \(q_{\text{min}} = 3.99\) give too low absolute values of the frequencies (\(\approx 0.5 f_{\text{exp}}\)
Single-\(n\) simulation of DIII-D discharge-cont’d

- Possible explanations for frequency mismatching:
  - coupling with acoustic waves neglected (no BAE gap in our MHD model);
  - frequencies of the modes very sensitive to \(q_{\text{min}}\) values (main feature of RSAE/AC modes), within exp. uncertainty
Single-\(n\) simulation of DIII-D discharge-cont’d

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  - coupling with acoustic waves neglected (no BAE gap in our MHD model);
  - frequencies of the modes very sensitive to \(q_{\text{min}}\) values (main feature of RSAE/AC modes), within exp. uncertainty

Power spectra of scalar potential ([\(r, \omega\] plane) for \(n=2\) cases:
- linear growth phase: frequency weakly affected by \(q_{\text{min}}\) variation (strongly driven mode)
Single-\( n \) simulation of DIII-D discharge-cont’d

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Power spectra of scalar potential ([\( r, \omega \) plane]) for \( n=2 \) cases:

- linear growth phase: frequency weakly affected by \( q_{\text{min}} \) variation (strongly driven mode)

Tip of the lower Alfvén continuum at \( q_{\text{min}} \) very sensitive to \( q_{\text{min}} \) value
Single-\( n \) simulation of DIII-D discharge-cont’d

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  - coupling with acoustic waves neglected (no BAE gap in our MHD model);
  - frequencies of the modes very sensitive to \( q_{\text{min}} \) values (main feature of RSAE/AC modes), within exp. uncertainty

Power spectra of scalar potential ([\( r, \omega \) plane]) for \( n=2 \) cases:

linear growth phase:
  - frequency weakly affected by \( q_{\text{min}} \) variation (strongly driven mode)

saturated phase:
  - sensitivity to \( q_{\text{min}} \) recovered

Tip of the lower Alfvén continuum at \( q_{\text{min}} \) very sensitive to \( q_{\text{min}} \) value
Fair agreement between single-$n$ simulations and experiment (considering both radial extension and frequency) is obtained for $q_{\text{min}} = 3.89$, slightly smaller than the nominal value.
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Multi-$n$ simulation of DIII-D discharge

$n=1,...,5$ - TRANSP energetic particle density profile, nominal $q$ profile

- all MHD nonlinearities included but:
  - $(m=0,n=0)$ not evolved (MHD model not adequate)
  - $(m=1,n=0)$ energetic particle drive neglected
Multi-$n$ simulation of DIII-D discharge

$n=1,\ldots,5$ - TRANSP energetic particle density profile, nominal $q$ profile

- Pick-up only the dominant poloidal component for each toroidal mode number $n$
- Dominant mode: $n=2$
Multi-$n$ simulation of DIII-D discharge

$n=1,...,5$ - TRANSP energetic particle density profile, nominal $q$ profile

- Pick-up only the dominant poloidal component for each toroidal mode number $n$
- Dominant mode: $n=2$
- Nonlinear coupling on $n=1$
Multi-$n$ simulation of DIII-D discharge

$n=1,\ldots,5$ - TRANSP energetic particle density profile, nominal $q$ profile

- Pick-up only the dominant poloidal component for each toroidal mode number $n$
- Dominant mode: $n=2$
- Nonlinear coupling on $n=1$ and $n=5$ clearly observed during linear phase of dominant mode
Multi-\(n\) simulation of DIII-D discharge

\(n=1,\ldots,5\) - TRANSP energetic particle density profile, nominal \(q\) profile

- Pick-up only the dominant poloidal component for each toroidal mode number \(n\)
- Dominant mode: \(n=2\)
- Nonlinear coupling on \(n=1\) and \(n=5\) clearly observed during linear phase of dominant mode
- At saturation, \(n=1\) dominates
Multi-$n$ simulation of DIII-D discharge-cont’d

$n=1,...,5$ - TRANSP energetic particle density profile, nominal $q$ profile

power spectra of scalar potential in the plane $[r,\omega]$ for:

- **linear phase**
  - ($n=2$ mode dominates)
Multi-$n$ simulation of DIII-D discharge-cont’d

$n=1,\ldots,5$ - TRANSP energetic particle density profile, nominal $q$ profile

Power spectra of scalar potential in the plane $[r,\omega]$ for:

- **linear phase** 
  ($n=2$ mode dominates)

- **nonlinear phase** 
  ($n=1$ mode dominates)
Multi-\( n \) simulation of DIII-D discharge-cont’d

\( n=1,...,5 \) - TRANSP energetic particle density profile, nominal \( q \) profile

The overall effect of the \textit{multi-\( n \) simulation} on the \textit{fast ion density profile} is of the same order of that obtained in the \textit{single-\( n \) simulations} (e.g., \( n=1,\ n=2 \))
Multi-$n$ simulation of DIII-D discharge-cont’d

$n=1,...,5$ - TRANSP energetic particle density profile, nominal $q$ profile

The overall effect of the multi-$n$ simulation on the fast ion density profile is of the same order of that obtained in the single-$n$ simulations (e.g., $n=1$, $n=2$)

*Furthermore ...*
Multi-$n$ simulation of DIII-D discharge-cont’d

$n=1,...,5$ - TRANSP energetic particle density profile, nominal $q$ profile

The overall effect of the multi-$n$ simulation on the fast ion density profile is of the same order of that obtained in the single-$n$ simulations (e.g., $n=1$, $n=2$)

Furthermore ...

Comparison between max $E_{\theta,m,n}$ of single-$n$ simulations and of multi-$n$ one (energetic particle radial velocity $v_r \sim E_\theta$) shows that both
1) competition of different-$n$ modes in extracting energy from resonant particles (as expected for EPMs), thereby flattening the fast ion profile, and
2) the energy transfer from fast to slower growing modes by mode-mode coupling cause each toroidal mode to saturate at a lower level than that reached in the corresponding single-$n$ simulation
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Conclusions

• Hybrid MHD-Gyrokinetic code (HMGC) has been used to compare simulation results with strongly beam heated discharges in present-day tokamaks

• Evidence of strongly unstable EPMs has been observed in simulations, resulting in macroscopic broadening of energetic particle density profile on very fast time scale (~100 µs)

• Fair agreement with the experimentally observed profiles have been obtained (JT-60U, DIII-D)

• First multi-\(n\) simulation shows that saturation amplitudes are reduced w.r.t. single-\(n\) ones (effect on fast ions is not altered)