Effects of fast ion phase space modifications by instabilities on fast ion modeling

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How important are fast ion phase space modifications by instabilities for accurate integrated modeling?

• Fast ion driven instabilities (e.g. Alfvénic modes -AEs) tap energy from gradients of fast ion phase space
  – Phase space: energy, canonical toroidal momentum, magnetic moment \((E, P_\zeta, \mu)\)

• As a result, phase space is modified by instabilities

> What is the effect of those modifications on integrated modeling results?
  – Relevant for analysis of present, NB-heated plasmas
  – Relevant for improving predictions for ITER, Fusion Nuclear Science Facility (FNSF) and beyond
Outline

• Experimental scenarios and Modeling tools

• Simulation results from NSTX, DIII-D database
  – Fast ion distribution function
  – Profiles: NB driven current, fast ion density, NB power to thermal plasma
  – Global quantities: NB-CD efficiency

• Summary and outlook
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• Summary and outlook
Preliminary analysis of NSTX and DIII-D scenarios includes L/H-mode, ramp-up, steady-state, high-$q_{\text{min}}$ with substantial AE activity.

**Database:** 10ms samples; error bars indicate variance (systematic errors not included)
TRANSP code is used for time-dependent simulations including fast ion transport by instabilities

• TRANSP is a comprehensive code for integrated, time dependent simulations of tokamak discharges

• Its NUBEAM module is the work-horse for simulations including fast ions (NB injection, alphas)
  – “Classical” physics is assumed for fast ion evolution (e.g. scattering, slowing down)
  – Additional modules can be invoked to introduce non-classical fast ion transport
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> Here we compare results from two models for enhanced fast ion transport by instabilities:

> Simplest, ad-hoc diffusive model: $\Gamma_{fi} = -D_b \nabla n_b$
> New physics-driven, phase space resolved “kick” model

see talk by N. Gorelenkov for comparisons with “Critical Gradient Model”
New ‘kick model’ in NUBEM uses a *probability distribution function* to describe transport in phase space \((E, P_\zeta, \mu)\)

Kicks \(\Delta E, \Delta P_\zeta\) are described by

\[
p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu, A)
\]

- Each \(p(\Delta E, \Delta P_\zeta)\) can include the effects of multiple modes
- Up to 5 \(p(\Delta E, \Delta P_\zeta)\)’s can be used simultaneously
- Kicks assumed to be proportional to mode amplitude, \(A(t)\)
Mode properties, temporal evolution are inferred from experiments; use models if no experimental data available

• Mode structure, frequency, $n_{tor}$ from experiments + NOVA, or from simple models

• Plug modes in particle-following code ORBIT to compute $p(\Delta E, \Delta P_\zeta)$
  • Repeat for each mode, or set of modes

• Initial amplitude $A(t)$ from experiments
  • Can iterate to get better match with neutrons, $W_{MHD}$

• Use $p(\Delta E, \Delta P_\zeta), A(t)$ in NUBEAM/TRANSP for complete simulation
Transport “coefficients” are adjusted to match measured neutron rate, reconstructed $W_{\text{MHD}}$

black: “classical”, blue: ad-hoc $D_b$, red: kick model

- Combine preliminary results from NSTX & DIII-D database
- Ad-hoc model requires time-varying $0<D_b<2m^2/s$
- Kick model requires amplitudes $0<\delta B/B<10^{-3}$
  - Reasonable values compared to measurements
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Models result in considerably different fast ion distribution functions

- Ad-hoc $D_b$ model affects all ($E, P_\zeta, \mu$) regions indiscriminately
- Kick model includes ($E, P_\zeta, \mu$) selectivity:
  - AEs mainly affect higher-energy co-passing particles in this example
  - Lower energy, counter-passing particles (pitch<0) almost unaffected

> **Important when $F_{nb}$ is then used for AE stability calculations**
NB-driven current peaking is reduced; resulting $J_{nb}$ profile varies across models

Peaking is computed as ratio of central to average $J_{nb}$:

$$peaking = \frac{\sum_{r/a=0}^{r/a=0.2} J_{nb}}{<J_{nb}>_{0\leq r/a \leq 1}}$$

- Instabilities broaden NB-driven current
- Comparable broadening and reduction in peaking from both models

> But: $J_{nb}$ profiles can be substantially different
Fast ion density profile is also broadened by instabilities; differences observed for two models

- Results are *qualitatively* comparable
  - up to x2 reduction in central peaking
- Substantial differences arise from radial profiles
  - Transport in kick model depends on mode localization, resonances
Correlation between $J_{nb}$ and $n_b$ evolution emerges from kick model

e.g., focus on DIII-D #153072

- Ad-hoc diffusive model has purely radial transport
- Kick model takes into account correlation between $E$ and $P_\zeta$ variations
Correlation between $J_{nb}$ and $n_b$ evolution emerges from kick model

- Correlation observed when modes affect large portion of fast ion distribution function contributing to $J_{nb}$
- Resonances are dense in phase space
- Constraints on resonances in $E$ and $P_\zeta$ couple energy ($J_{nb} \sim E^{1/2}$) and radius: $\Delta P_\zeta / \Delta E = n / \omega$, with $P_\zeta = mRv_{par} - \Psi_{pol}$
NB power transferred to thermal plasma is reduced by similar amount for both models

- No substantial difference for volume-integral
- But: local power to thermal species can vary substantially

> *Important for local thermal transport analysis!*

[Heidbrink, PPCF 2014] [Holcomb, PoP 2015] [Podestà, NF 2015]
NB-CD efficiency, fast ion density are greatly reduced by strong AE activity

- Neutron deficit scales with AE virulence
  - Neutron deficit roughly proportional to AE activity
- Up to 50% overall reduction in $\eta_{Jnb}$ is computed

$\eta_{Jnb} = \frac{\sum_{r/a} J_{nb}}{\sum_{r/a} J_{tot}} \frac{1}{P_{NB}}$

Slight differences between two transport models
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Summary & outlook

• Two models tested for fast ion transport in integrated simulations:
  – Simple, ad-hoc diffusion model
  – Phase space resolved “kick” model
  – See talk by N. Gorelenkov for additional comparison with physics-based “Critical Gradient Model” (CGM)

• Ad-hoc model OK for global quantities (e.g. neutrons, $W_{\text{MHD}}$)
• But: substantial differences observed for profiles, fast ion distribution function & their temporal evolution

• Future work:
  – Further validate kick model vs. phase space resolved measurements
    ▪ e.g. from FIDA, ssNPA
  – Investigate models performance for predictive simulations:
    ▪ q-profile evolution
    ▪ $J_{\text{nb}}$ efficiency and radial profiles (important for control)
    ▪ Implications for thermal transport & power balance analysis
Backup
Instabilities introduce fundamental constraints on particle dynamics.

From Hamiltonian formulation – single resonance:

\[ \omega P_\zeta - nE = \text{const.} \quad \Longrightarrow \quad \Delta P_\zeta / \Delta E = n / \omega \]

\( \omega = 2 \pi f \), mode frequency \( n \), toroidal mode number

These effects are not accounted for by ad-hoc diffusive models. “Kick” model used to include them in integrated modeling.

\[ P_\zeta \sim mRv_{\text{par}} - \Psi, \text{ canonical angular momentum} \]

\[ \mu \sim v_{\text{perp}}^2 / (2B), \text{ magnetic moment} \]

where \( \Psi \): poloidal flux

\( R \): major radius

\( m \): mass
Particle-following codes are used to extract distribution of ‘kicks’ $\Delta E, \Delta P_\zeta$ for each bin $(E,P_\zeta,\mu)$

- ORBIT code: record $E,P_\zeta,\mu$ vs. time for each particle
- Compute average kicks over multiple wave periods
- Re-bin for each $(E,P_\zeta,\mu)$ region
\( p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu) \) and a time-dependent ‘mode amplitude scaling factor’ enable multi-mode simulations

- Example: toroidal AEs (TAEs) and low-frequency kink
- \( p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu) \) from particle-following code ORBIT
- Each type of mode has separate \( p(\Delta E, \Delta P_\zeta) \), \( A_{\text{mode}}(t) \)
- TAEs and kinks act on different portions of phase space
- Amplitude vs. time can differ, too
- Effects on EPs differ
  > TAEs: large \( \Delta E, \Delta P_\zeta \)
  > kinks: small \( \Delta E, \) large \( \Delta P_\zeta \)
Scaling factor $A_{\text{mode}}(t)$ is obtained from measurements, or from other observables such as neutron rate + modeling.

- Best option: use experimental data (e.g. reflectometers, ECE)
- If no mode data directly available, $A_{\text{mode}}$ can be estimated based on other measured quantities.

**Example: use measured neutron rate**

- Compute ideal modes through NOVA
- Rescale relative amplitudes from NOVA according to reflectometers
- Rescale total amplitude based on computed neutron drop from ORBIT
- Scan mode amplitude w.r.t. experimental one, $A_{\text{mode}}=1$: get table
- Build $A_{\text{mode}}(t)$ from neutrons vs. time, table look-up
Original scheme to advance fast ion variables according to transport probability in NUBEAM module of TRANSP

- **NUBEAM step k**
  - read Plasma State, $F_{nb}$ info
  - read $A_{mode}$, $p(\Delta E, \Delta P_\xi | E, P_\xi, \mu)$
  - convert $F_{nb}(E, p, R, Z)$ to $F_{nb}(E, P_\xi, \mu)$

- **Re-compute sources, scattering, slowing down**

- **NUBEAM step k+1**
  - convert $F_{nb}(E, P_\xi, \mu)$ to $F_{nb}(E, p, R, Z)$

**Loop – MC mini-steps**
- **Sample** $\Delta E_j, \Delta P_\xi_j$
- **Evolve** $E_j, P_\xi_j$
- **Diagnostics** (e.g. classify orbit)

**Loop – $F_{nb}$ particles**

**Add “kicks” to $F_{nb}$ variables**
Improved scheme to advance fast ion variables according to transport probability in NUBEAM module of TRANSP

NUBEAM step $k$:
- Read Plasma State, $F_{nb}$ info
- Read $A_{mode}$, $p(\Delta E, \Delta P_{\zeta} | E, P_{\zeta}, \mu)$

Re-compute sources, scattering, slowing down, $E, P_{\zeta}$ “kicks”:
- Convert $F_{nb}(E, p, R, Z)$ to $F_{nb}(E, P_{\zeta}, \mu)$
- Convert $F_{nb}(E, P_{\zeta}, \mu)$ to $F_{nb}(E, p, R, Z)$

Loop – MC mini-steps:
- Sample $\Delta E_j, \Delta P_{\zeta,j}$
- Evolve $E_j, P_{\zeta,j}$
- Diagnostics (e.g. classify orbit)

Loop – $F_{nb}$ particles:
- Add “kicks” to $F_{nb}$ variables during orbiting

NUBEAM step $k+1$