Effects of MHD instabilities on Neutral Beam current drive


and the NSTX-U Research Team

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Reliable, quantitative predictions of Energetic Particle (EP) dynamics are crucial for burning plasmas

- EPs from Neutral Beam (NB) injection, alphas, RF tails drive instabilities,
  - e.g. Alfvénic modes – AEs

- With instabilities, ‘classical’ EP predictions (e.g. for NB heating, current drive) can fail

> Predictive tools are being developed, validated for integrated modeling of these effects in present and future devices (ITER, Fusion Nuclear Science Facility – FNSF)
Outline

• NSTX discharges with strong MHD are used to test and validate EP transport models

• Modeling methods beyond ‘classical’ EP physics are developed to account for MHD effects

• New model captures MHD modifications of EP phase space leading to Neutral Beam current redistribution
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Alfvénic modes (AEs) and kink–like modes degrade fast ion confinement, plasma performance

NSTX

Major radius 0.85 m
Aspect ratio 1.3
Plasma current \( \sim 1 \) MA
Toroidal field <0.55 T
Pulse length <2 s
Neutral Beam sources:
\[ P_{\text{NBI}} \leq 6 \text{ MW} \]
\[ E_{\text{injection}} \leq 95 \text{ keV} \]
\[ 1 < v_{\text{fast}} / v_{\text{Alfvén}} < 5 \]

Super–alfvénic ions, high \( \beta_{fi} \): plethora of fast ion driven instabilities

[Fredrickson, NF 2013]
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Transport code TRANSP includes NUBEAM module for classical fast ion physics

- Additionally, \textit{ad-hoc} diffusivity $D_{fi}$ is used to mimic enhanced fast ion transport
  - Assumed uniform in radius, pitch, energy in this work

- Metric to set $D_{fi}$: match neutron rate, $W_{mhd}$

\[ D_{fi} = \begin{cases} 0.0 \text{ m}^2/\text{s} \\ 1.0 \text{ m}^2/\text{s} \\ 2.0 \text{ m}^2/\text{s} \\ 5.0 \text{ m}^2/\text{s} \end{cases} \]

measured

simulated with $D_{fi}(t)$
However: instabilities introduce fundamental constraints on particle dynamics

From Hamiltonian formulation – single resonance:

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

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

\( \Delta P_\zeta \) vs \( \Delta E \)

\( P_\zeta \sim mRv_{\text{par}} - \Psi \), canonical angular momentum

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

where \( \Psi \) : poloidal flux

\( R \) : major radius

\( m \) : mass
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\( \omega = 2\pi f \), mode frequency
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These effects are not accounted for by ad-hoc \( D_{fi} \). A new method is needed to include them in integrated modeling.
Constants of motion \((E, P_\zeta, \mu)\) are the natural variables to describe wave–particle interaction.

Effects of multiple TAE modes

\[ \mu \frac{B_0}{E} \]

\[ P_\zeta \]

\[ R. B. White, \text{Theory of toroidally confined plasmas, Imperial College Press (2014)} \]
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:
  \[
  \frac{1}{T_{\text{wave}}} < \frac{1}{\tau_{\text{resonance}}} < \frac{1}{\tau_{\text{collisions}}}
  \]
  neglected \hspace{1cm} \text{relevant time scale} \hspace{1cm} \text{classical}
- Re-bin for each $(E,P_\zeta,\mu)$ region

Phase space, $E_0=80.0\text{keV}$

Effects of multiple TAE modes

$\Delta E_1$, $\Delta E_2$, $\Delta E_3$, $\Delta E_N$

$\Delta P_{\zeta 1}$, $\Delta P_{\zeta 3}$, $\Delta P_{\zeta 2}$, $\Delta P_{\zeta N}$

$	ext{neglected}$ \hspace{1cm} \text{relevant time scale} \hspace{1cm} \text{classical}$
New ‘kick model’ uses a **probability distribution function** for particle transport in \((E, P_\zeta, \mu)\) space.

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

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

which includes the effects of multiple modes, resonances.

**correlated random walk in** \(E, P_\zeta\)

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**Phase space,** \(E_0=80.0\text{keV}\)

Effects of multiple TAE modes

- lost ctr-passing
- lost trapped
- potato
- stagnation
- co-passing

**ORBIT code modeling,** random initialization of particles in phase-space

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[Podestà, PPCF 2014]
\( p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu) \) 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 \( \Delta E, \text{large } \Delta P_\zeta \)
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Two NSTX cases are analyzed in detail: TAE avalanche and avalanche + kink–like mode (multi–mode scenario)

TAE avalanches + kink-like mode
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TAE avalanches cause an abrupt drop in fast ions and up to \(~40\%\) reduction in local NB–driven current density

- Results from ‘kick model’
- Fast ions redistributed outward, lose energy
  - Consistent with constraints from resonant interaction:
    \[ \frac{\Delta P_\zeta}{\Delta E} = n/\omega \]

- NB–driven current \(J_{nb}\) is also redistributed out
- \(J_{nb}(r)\) modification largely unpredicted by \textit{ad–hoc} \(D_{fi}\) in this case
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TAE avalanches

+ kink-like mode

\( n=1 \)

\( n=2 \)

\( n=3 \)

\( n=2-6 \)
Synergy between different classes of instabilities modifies MHD effects on $J_{nb}(r)$ – not captured by ad-hoc $D_i$.

- Kinks have broad radial structure, connect core to boundary.

> Synergy arises from mode overlap in phase space.
Synergy between different classes of instabilities modifies MHD effects on $J_{nb}(r)$ – not captured by ad-hoc $D_f$

- Kinks have broad radial structure, connect core to boundary

> Synergy arises from mode overlap in phase space
Phase-space is *selectively* modified by instabilities: TAEs $\rightarrow \Delta P_\zeta/\Delta E = n/\omega$, kinks $\rightarrow$ mostly $\Delta P_\zeta$
Simulated neutron rate agrees with experiments for both TAE avalanches & multi-mode cases

Use ‘kick model’ coupled to stand-alone NUBEAM

![Graphs showing neutron rate and mode amplitude for TAEs and kink-like modes](image-url)
Summary

• NB–driven current profile can be strongly affected by MHD instabilities
  – Not all effects properly captured by classical EP physics

• A new model is implemented in TRANSP for EP simulations including phase–space details
  – Validation within TRANSP framework is in progress

• New tools will improve scenario development on NSTX Upgrade & future devices
  – NB current drive optimization
  – NB–driven current profile control for high–q_{min} steady state operations
‘Kick’ model exploits separation of typical time scales between instabilities and collisional processes

- 3 time scales characterize particle motion in the presence of instabilities:
  - $1/f_{\text{wave}} \sim 10\text{'s } \mu s$
  - $\tau_{\text{resonance}} > 10\times\tau_{\text{transit}} > 100\text{'s } \mu s$
  - $\tau_{\text{collisions}}, \tau_{\text{slowdown}} \gg \gg 1 \text{ ms}$

- Relevant time scale for *secular* $\Delta E, \Delta P_\zeta$ by waves is $\tau_{\text{resonance}}$

- Classical mechanisms already included in IM codes (TRANSP)
  - E.g. collisions, slowing down, atomic physics
Reduced models offer advantages for Integrated Modeling (IM), plasma control over \textit{first-principles} codes

- \textit{First-principles} codes not (yet) suitable for extensive ‘scans’ with multiple shots, long time-scale simulations
  - Inclusion in real-time control schemes also unpractical

- IM codes (e.g. TRANSP) have accurate treatment of atomic physics, ‘classical’ mechanisms
  - Reduced models for EP transport are good complement

- IM codes have much broader scope than just EP physics
  - Physics-based reduced models improve accuracy of simulations, retaining ‘generality’ of IM codes
## Summary comparison of some reduced models used for EP transport

<table>
<thead>
<tr>
<th></th>
<th>ad-hoc $D_{fi}$</th>
<th>CGM model (*)</th>
<th>kick' model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>physics-based</strong></td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>required input</strong></td>
<td>$D_{fi}(\rho,t)$</td>
<td>growth/damping rates</td>
<td>probability, mode amplitude</td>
</tr>
<tr>
<td><strong>applicability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>multi-mode</td>
<td>indirectly</td>
<td>multiple AEs</td>
<td>AEs, kinks, NTMs. Fishbones/EPMs?</td>
</tr>
<tr>
<td>steady-state</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>transients</td>
<td>yes</td>
<td>only for $\tau &gt; \tau_{relax}$</td>
<td>yes</td>
</tr>
<tr>
<td><strong>phase-space selectivity</strong></td>
<td>modest</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>predictive runs</td>
<td>requires guess $D_{fi}$</td>
<td>requires mode spectrum: growth/damping</td>
<td>requires mode spectrum, amplitude</td>
</tr>
<tr>
<td>improvements</td>
<td>none planned</td>
<td>extend to 2D in velocity space</td>
<td>remove $\mu$ conservation</td>
</tr>
</tbody>
</table>

(*) CGM – Critical Gradient Model
see Gorelenkov TH/P1-2, Heidbrink EX/10-1
Simulations with *ad-hoc* $D_{fi}$ show similar fast ion drops, but largely underestimate $J_{nb}(r)$ modification.

- Uniform $D_{fi}$ acts in the same way on *all* particles at *all* radii.
- No constraints from wave–particle interaction.
 Scaling factor $A_{\text{mode}}(t)$ is obtained from measurements, or from other observables such as neutron rate + modeling

- 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
Mode amplitude can evolve on time-scales shorter than typical TRANSP/NUBEAM steps of \( \sim 5–10 \) ms.

\( F_{nb} \) evolution must be computed as a sequence of sub-steps:

- Duration \( \delta t_{\text{step}} \) sufficiently shorter than time-scale of mode evolution.
- Examples here have \( \delta t_{\text{step}} \sim 25–50 \) µs.

Energy and \( P_\zeta \) steps assumed to scale linearly with mode amplitude:

- Roughly consistent with ORBIT simulations.

\[ A_{\text{mode}}[\text{a.u.}] \]

\[ n_{\text{tor}}=2 \quad n_{\text{tor}}=4 \quad n_{\text{tor}}=6 \quad \text{total} \]

\[ t-t_0 \text{ [ms]} \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \quad 1.4 \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \quad 1.4 \]

\[ \Delta E \text{ [keV/ms]} \]

\[ -1.0 \quad -0.5 \quad 0.0 \quad 0.5 \quad 1.0 \]

\[ \Delta P_\zeta \text{[a.u.]} \]

\[ A_{\text{rel}}=0.50 \]

\[ A_{\text{rel}}=1.00 \]

\[ A_{\text{rel}}=1.50 \]

\[ \sigma_E \text{[a.u.]} \]

\[ 10 \times \sigma_{P_\zeta} \]

\[ 0.0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \]

\[ 0.0 \quad 0.5 \quad 1.0 \]

\[ \Delta E \text{ [keV/ms]} \]

\[ \Delta P_\zeta \text{[a.u.]} \]

\[ A_{\text{mode}} \text{[a.u.]} \]

\[ 0.0 \quad 0.5 \quad 1.0 \quad 1.5 \]
Each type of mode is characterized by its own amplitude vs time (e.g. from experiments)

For each type of mode, energy and $P_\zeta$ steps assumed to scale linearly with mode amplitude
  - Consistent with ORBIT simulations
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 $A_{mode}$, $p(\Delta E, \Delta P_\zeta|E, P_\zeta, \mu)$
- convert $F_{nb}(E, p, R, Z)$ to $F_{nb}(E, P_\zeta, \mu)$

NUBEAM step $k+1$

- re-compute sources, scattering, slowing down, $E, P_\zeta$ “kicks”
- 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
Spherical torus NSTX is well suited for NB physics studies, model validation

<table>
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<tr>
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<th>NSTX–U</th>
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<tr>
<td>Major radius</td>
<td>0.85 m</td>
<td>0.9 m</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Plasma current</td>
<td>~1 MA</td>
<td>&lt;2 MA</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>&lt;0.55 T</td>
<td>&lt;1 T</td>
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<td>Pulse length</td>
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Neutral Beam sources:

- \( P_{\text{NBI}} \leq 6 \, \text{MW} \)
- \( E_{\text{injection}} \leq 95 \, \text{keV} \)

New NBI set on NSTX-U will enable more flexible NB current drive

[Menard, NF 2012]
Predicted NSTX-U scenario with strongly peaked fast ion pressure has unstable TAEs

- Fast ion pressure is >2 times larger than in reference NSTX discharge

- NOVA-K finds spectrum of (linearly!) unstable TAEs with $n=3-6$

- Predicted mode structure is narrower on NSTX-U than for typical NSTX
‘Kick’ and ad–hoc $D_{fi}$ models predict comparable reduction of total $J_{nb}$ – but profiles are very different

- Reduction in total $J_{nb}$ is modest, <20%
- Local $J_{nb}(r)$ changes are much larger
- ‘Kick model’ predicts localized reduction of $J_{nb}(r)$ because of narrow mode structures
- Non-linear physics may result in broader modes, though