Effect of Anisotropic Fast Ions on Internal Kink Mode Stability in DIII-D Negative and Positive Triangularity Plasmas

By

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Plasma Shape and Fast Ions Affect Sawtooth Stability

- **Sawtooth**: periodic and abrupt collapses of the core plasma parameters; triggered by internal kink mode.

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- Sawteeth in negative triangularity (NegD) plasmas are much less studied.
  - TCV experiments (w/o NBI) show small sawteeth and shorter periods at low or negative triangularity plasmas. [H. Reimerdes PPCF 2000]
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- Sawteeth in negative triangularity (NegD) plasmas are much less studied.
  - TCV experiments (w/o NBI) show small sawteeth and shorter periods at low or negative triangularity plasmas. [H. Reimerdes PPCF 2000]
  - Trapped fast ion orbit and poloidal distribution are different in NegD plasmas compared to PosD

- The onset for a sawtooth is associated with the linear stability of internal kink mode. [F. Porcelli PPCF 1996]
Outline and Takeaways

- **Experimental observation**
  Fast ions from co-$I_p$ tangential NBI strongly stabilize sawteeth in both PosD and NegD plasmas; while fast ions from counter-$I_p$ NBI destabilize sawteeth.

- **Modeling of $n=1$ internal kink stability with MARS-K code**
  - MARS-K code: non-perturbative MHD-kinetic hybrid eigenvalue solver
  - Effect of adiabatic contribution
  - Effect of nonadiabatic contribution
  - Effect of rotation (and rotation shear)

  Takeaways: (1) Non-adiabatic (kinetic) contribution of transit motion of passing fast ions induces an asymmetry of mode stability around pitch=0.
  (2) Co-$I_p$ (counter-$I_p$) NBI stabilizes (destabilizes) internal kink mode. Qualitatively agrees with DIII-D experiments.
  (3) Anisotropic fast ions affect $n=1$ internal kink mode in a similar way in both negD and posD plasmas

- **Summary**

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**DIII-D**
National Fusion Facility
San Diego
Neutral Beam Injection (NBI) Direction Strongly Affects Sawtooth Stability in Negative Triangularity Plasmas

- Sawteeth are observed with co-$I_p$ or a combination of co- & counter-$I_p$ NBI, but become small amplitude and short periods with counter-$I_p$ beams.
Neutral Beam Injection (NBI) Direction Strongly Affects Sawtooth Stability in Negative Triangularity Plasmas

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Comparison Discharges with Negative Triangularity Shape have Similar $q$ Profile but Different Toroidal Rotation

- $q_0 \sim 0.85$ in co-$I_p$ NBI discharge, $q_0 \sim 0.90$ in counter-$I_p$ NBI case.
  - In fluid limit, $\gamma/\tau_A = 0.0047$ in co-$I_p$ NBI case, $\gamma/\tau_A = 0.0033$ in counter-$I_p$ NBI case.
    → $q$ profile difference cannot explain the sawtooth behavior difference

- Toroidal rotation direction is flipped due to NBI geometry change.

- Fast-ion distribution pitch ($v_{\parallel}/v$ relative to $I_p$) is different
  - Co-tan beam → pitch [0.6, 0.85]
  - Co-perp beam → pitch [0.5, 0.6]
In Positive Triangularity Plasma, \textit{Counter-}I_p \textit{NBI} has Destabilizing Effect on Sawtooth Stability but \textit{Co-}I_p \textit{NBI} has Stabilizing Effect.

Smaller amplitude & more frequent sawteeth with counter-\(I_p\) NBI \(\rightarrow\) destabilizing effect
In Positive Triangularity Plasma, **Counter-\( I_p \)** NBI has Destabilizing Effect on Sawtooth Stability but **Co-\( I_p \)** NBI has Stabilizing Effect

Smaller amplitude & more frequent sawteeth with counter-\( I_p \) NBI $\rightarrow$ destabilizing effect

Larger amplitude & less frequent sawteeth w/ NBI $\rightarrow$ stabilizing effect
Outline and Takeaways

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  Fast ions from co-$I_p$ tangential NBI strongly **stabilize sawteeth** in both PosD and NegD plasmas; while fast ions from counter-$I_p$ NBI **destabilize sawteeth**

- **Modeling of $n$=1 internal kink stability with MARS-K code**
  
  - MARS-K code: non-perturbative MHD-kinetic hybrid eigenvalue solver
  - Effect of adiabatic contribution
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  Takeaways: (1) **Non-adiabatic** (kinetic) contribution of **transit motion of passing** fast ions **induces an asymmetry** of mode stability around pitch=0.
  
  (2) co-$I_p$ (counter-$I_p$) NBI stabilizes (destabilizes) internal kink mode. **Qualitatively agrees with DIII-D experiments.**
  
  (3) Anisotropic fast ions affect $n$=1 internal kink mode in a similar way in both negD and posD plasmas

- **Summary**
MARS-K is Utilized for Linear Stability Analysis of \( n=1 \) Internal Kink Mode

MARS-K: non-perturbative MHD-kinetic hybrid eigenvalue solver
- Thermal ions and electrons are treated as a single fluid  
  Y.Q. Liu POP 2014
- Drift kinetic resonances of fast ions are self-consistently included via the perturbed kinetic pressure tensor in the momentum equation, which allows self-consistent modification of the mode eigenfunction by kinetic effects

Resonant operator in \( f_L^1 \):

\[
\lambda_{ml} = \frac{n[\omega_{*N} + (\dot{\varepsilon}_k - 3/2)\omega_{*T} + \omega_E] - \omega}{n\omega_d + [\alpha(m + nq) + l]\omega_b + n\omega_E - \omega - iv_{eff}}
\]

- 1st order correction of Finite Obit Width (FOW) correction can be included

- \( \alpha = 0 \): trapped
- \( \alpha = 1 \): passing
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- Anisotropic slowing-down model is assumed for NBI-generated Fast Ions (FI)

\[
f^0(\psi, \epsilon_k, \zeta) = \frac{C(\psi)}{\epsilon_k^2 + \epsilon_c^2} f_1(\psi, \epsilon_k, \zeta)
\]

\[
f_1(\psi, \epsilon_k, \zeta) = \sum C_i(\psi, \epsilon_k) f_2(\zeta | \zeta_i)
\]

\[
f_2(\zeta | \zeta_i) = f_2(\epsilon_k, \zeta | \zeta_i) = \frac{e^{-(\zeta-\zeta_i)^2/\delta \zeta^2}}{2\sqrt{\pi} \delta \zeta}
\]

- Central pitch $\zeta_0$ of FI distribution is scanned while fixing the spatial distribution, energy distribution and FI pressure.
- Integration over pitch is a constant for all scans. → Pitch distribution is the same for all flux surfaces.
MARS-K is Utilized for Linear Stability Analysis of n=1 Internal Kink Mode

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- Drift kinetic resonances of fast ions are self-consistently included via the perturbed kinetic pressure tensor in the momentum equation, which allows self-consistent modification of the mode eigenfunction by kinetic effects
- Anisotropic slowing-down model is assumed for NBI-generated Fast Ions (FI)
- Perturbed kinetic pressure has adiabatic and non-adiabatic parts

\[ p = p_{th}I + p_{\parallel} \hat{b}\hat{b} + p_{\perp}(I - \hat{b}\hat{b}) \]
\[ = p_{th}I + (p_{\parallel}^a + p_{\parallel}^{na})\hat{b}\hat{b} + (p_{\perp}^a + p_{\perp}^{na})(I - \hat{b}\hat{b}) \]

Adiabatic \[ p_{g}^a = \sum_j \int d\Gamma E_g (-\xi_{\perp} \nabla f_j^0) \]
Non-adiabatic \[ p_{g}^{na} = \sum_j \int d\Gamma E_g f_j^1 \]
(FI slowing-down distribution function) (kinetic)  
(Perturbed FI distribution function)
Kinetic Equilibrium and Experimental Profiles are Used for Modeling Input

NegD equilibrium: DIII-D 170660@1775ms
- B=2.0 T, I_p=0.88 MA, q_0=0.88
- Pressures scaled up by 2.0 from exp.
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NegD equilibrium: DIII-D 170660@1775ms
- \( B = 2.0 \, \text{T} \), \( I_p = 0.88 \, \text{MA} \), \( q_0 = 0.88 \)
- Pressures scaled up by 2.0 from exp.

PosD equilibrium:
- Flip negD equilibrium around the magnetic axis
- Similar \( q \) in core but higher \( q_{\text{edge}} \) compared with negD

Baseline in negD and posD: resistivity=0, rotation=0, no wall
Adiabatic Contribution Affects Mode Stability and Mode Structure

- Symmetric about pitch=0
- Growth rate varies with pitch because anisotropic fast-ion distribution affects adiabatic contribution to $P_{\text{par}}, P_{\text{perp}}$
- Eigenmode structure also changes with pitch $\xi_0$

![Diagram showing perturbed radial displacement with Fluid or with isotropic FI and with anisotropic FI due to adiabatic contribution.](image)
Asymmetry about pitch=0 is caused by non-adiabatic contribution of transit motion of passing fast ions.

- In order to check the pure kinetic effects, adiabatic contribution is temporarily replaced with isotropic slowing-down FI distribution.
- Kinetic resonance effect induces finite mode frequency.

MARS-K *non-perturbative* runs w/ partial (10%) kinetic effects included.
Both adiabatic and nonadiabatic contributions are self-consistently included.

In both negD and posD plasmas, co-$I_p$ tangential NBI has a strong stabilizing effect, while counter-$I_p$ tangential NBI has a destabilizing effect.

With the same equilibrium profiles, anisotropic fast ions affect $n=1$ internal kink mode in a similar way in both negD and posD plasmas, albeit with a larger growth rate in negD plasma.
Similar Mode Structure of $n=1$ Internal Kink Mode In NegD and PosD Plasmas

MARS-K non-perturbative runs w/ full kinetic effects

- Other poloidal Fourier harmonics of eigenfunction (radial displacement) are also similar in negD and posD plasmas.
Similarity in NegD and PosD is mainly because of Mode Eigenfunction being Localized in Plasma Core

MARS-K non-perturbative runs w/ full kinetic effects

- Similarity in NegD and PosD configurations are also found in the internal kink mode stability in EU DEMO with isotropic alpha particles. [Zhou PPCF 2021]
- Mainly because triangularity vanishes towards the magnetic axis.
Plasma Rotation (and Shear) has Relatively Weak Effect on $n=1$ Internal Kink Mode Stability

- Plasma rotation mainly induces a frequency doppler shift.
- Plasma resistivity, kinetic effects of thermal particles, or the presence of ideal/resistive wall weakly affects the mode stability.
- Finite Orbit Width (FOW) correction decreases the asymmetry.
Summary

- DIII-D experiments show that the fast ions from co-$I_p$ NBI strongly stabilize sawteeth in both posD and negD plasmas, while fast ions from counter-$I_p$ NBI destabilize sawteeth.

- Non-perturbative MARS-modeling suggests that
  - Due to the drift kinetic resonance effects, co-$I_p$ (counter-$I_p$) NBI stabilizes (destabilizes) internal kink. Qualitatively agrees with DIII-D experiments.
  - The asymmetry about pitch=0 is mainly due to the non-adiabatic (kinetic) contribution of transit motion of passing fast ions. FOW correction of the adiabatic part partially cancels the asymmetry.
  - Anisotropic fast ions affect n=1 internal kink mode in a similar way in both negD and posD plasmas, albeit with a larger growth rate in negD plasma.
  - Plasma toroidal rotation (and shear), kinetic effects of thermal particles, plasma resistivity, or the presence of ideal/resistive wall weakly affects the mode stability.