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

By
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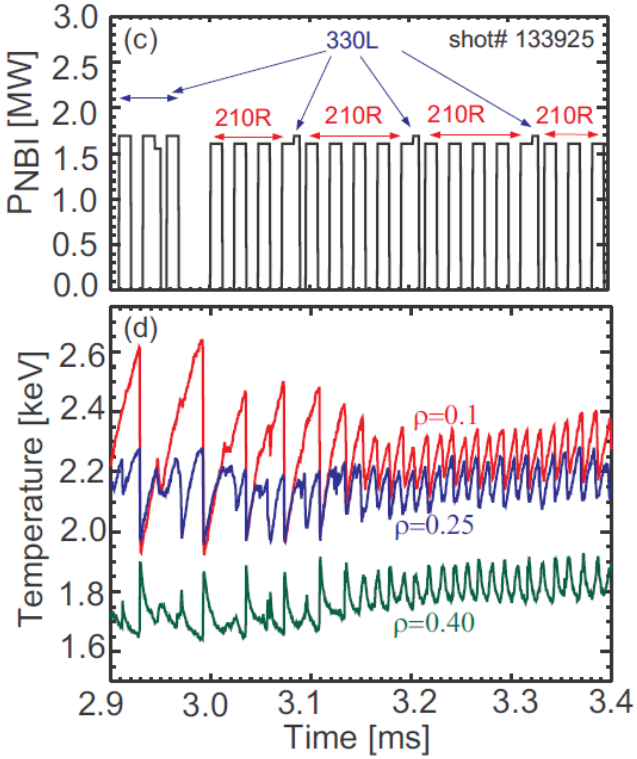

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Plasma Shape and Fast Ions Affect Sawtooth Stability

- **Sawtooth:** periodic and abrupt collapses of the core plasma parameters; triggered by internal kink mode.
- In positive triangularity (PosD) plasmas, fast ions from Neutral Beam Injection (NBI) generally have a stabilizing effect on sawteeth through kinetic and/or flow shear effects. [I. T. Chapman PPCF 2011]

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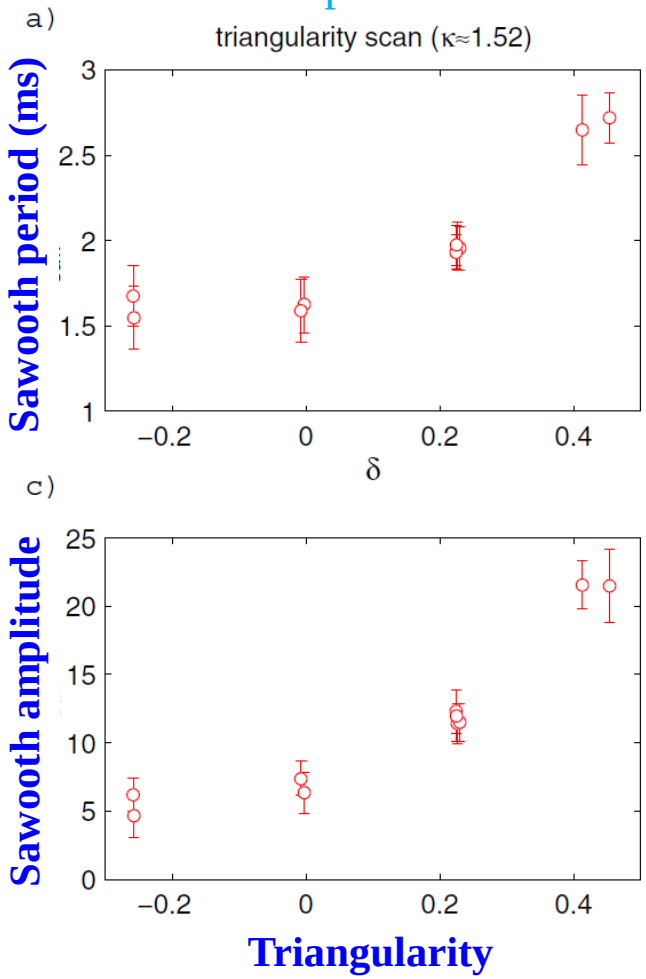
- Saweeth in negative triangularity (NegD) plasmas are much less studied.
- TCV experiments (w/o NBI) show small sawteeth and shorter periods at low or negative triangularity plasmas. [H. Reimerdes PPCF 2000]

TCV Experiments



H. Reimerdes PPCF 2000

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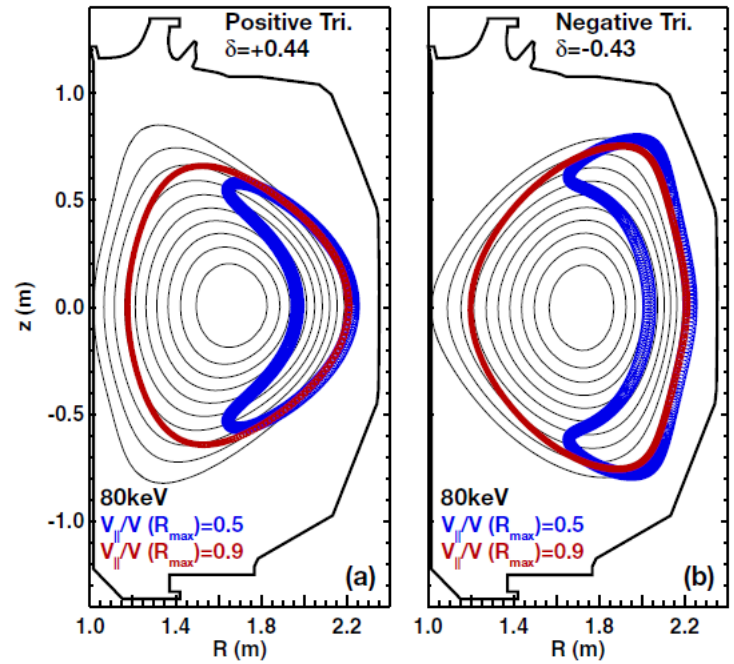
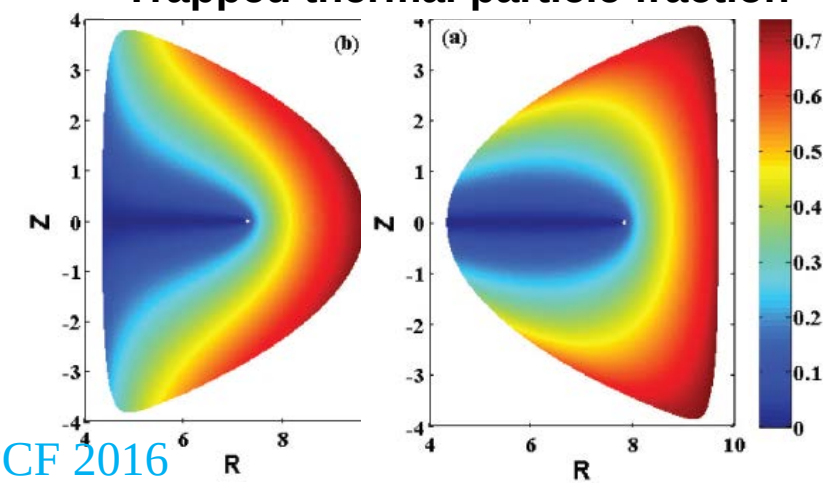
- Saweeth in negative triangularity (NegD) plasmas are much less studied.
  - TCV experiments (w/o NBI) show small sawteeth and shorter periods at low or negative triangularity plasmas. [H. Reimerdes PPCF 2000]
  - Trapped fast ion orbit and poloidal distribution are different in NegD plasmas compared to PosD
- The onset for a sawtooth is associated with the linear stability of internal kink mode.

  [F. Porcelli PPCF 1996]

M. Van Zeeland NF 2019



Trapped thermal particle fraction



J. Ren PPCF 2016

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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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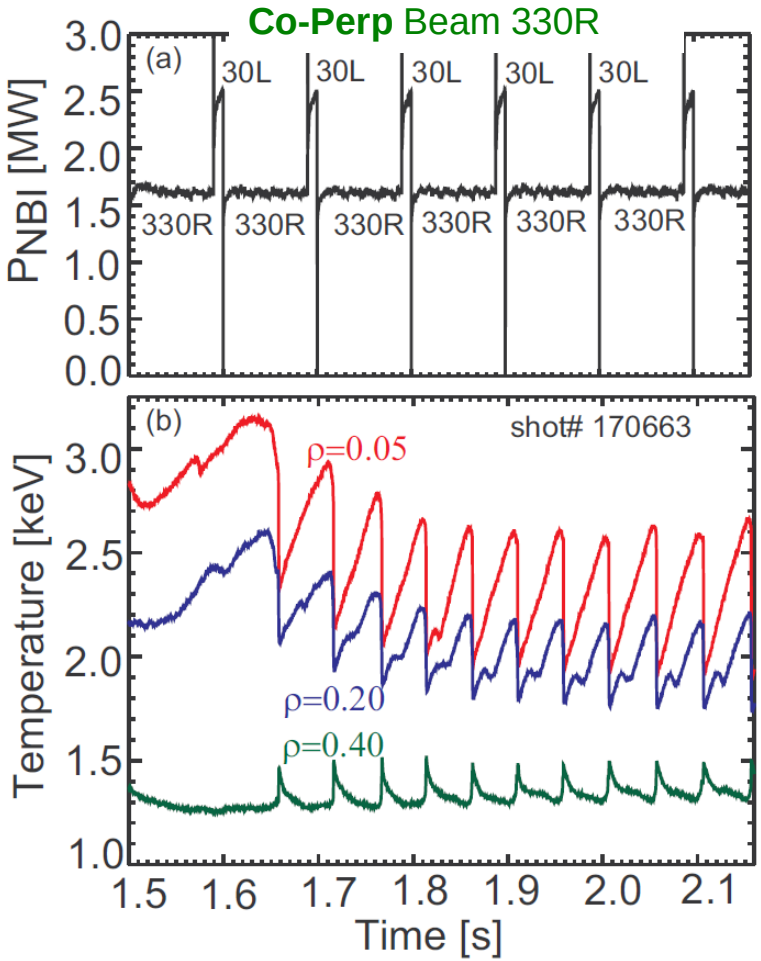
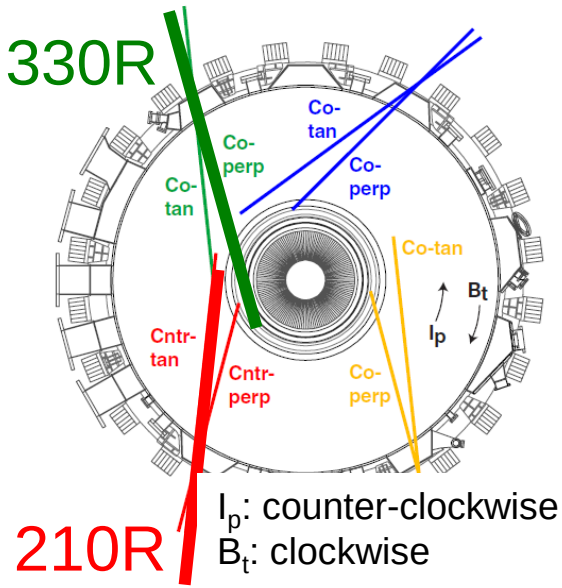
Neutral Beam Injection (NBI) Direction Strongly Affects Sawtooth Stability in Negative Triangularity Plasmas





- **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.**

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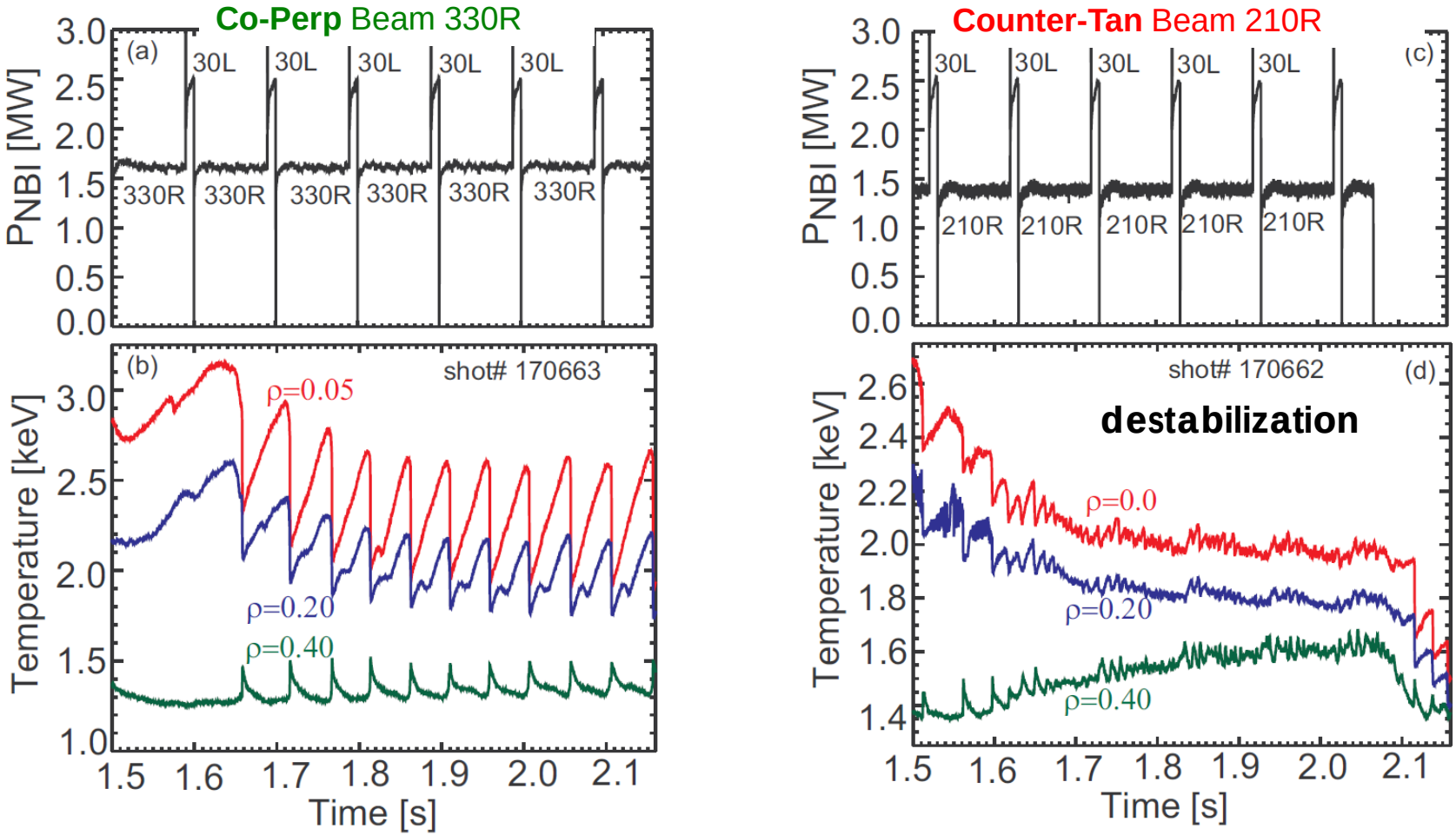

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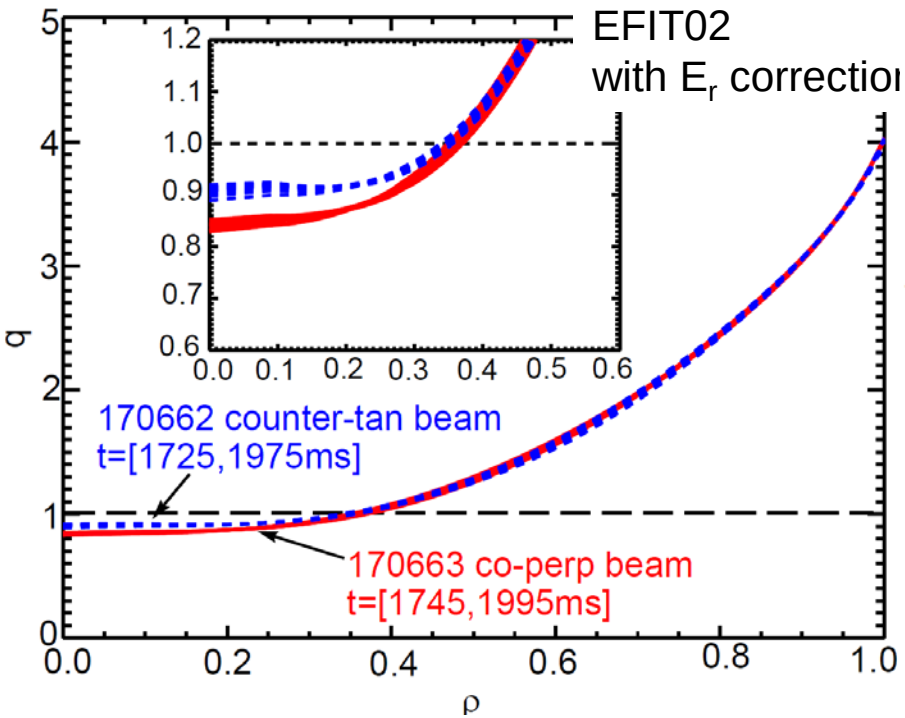
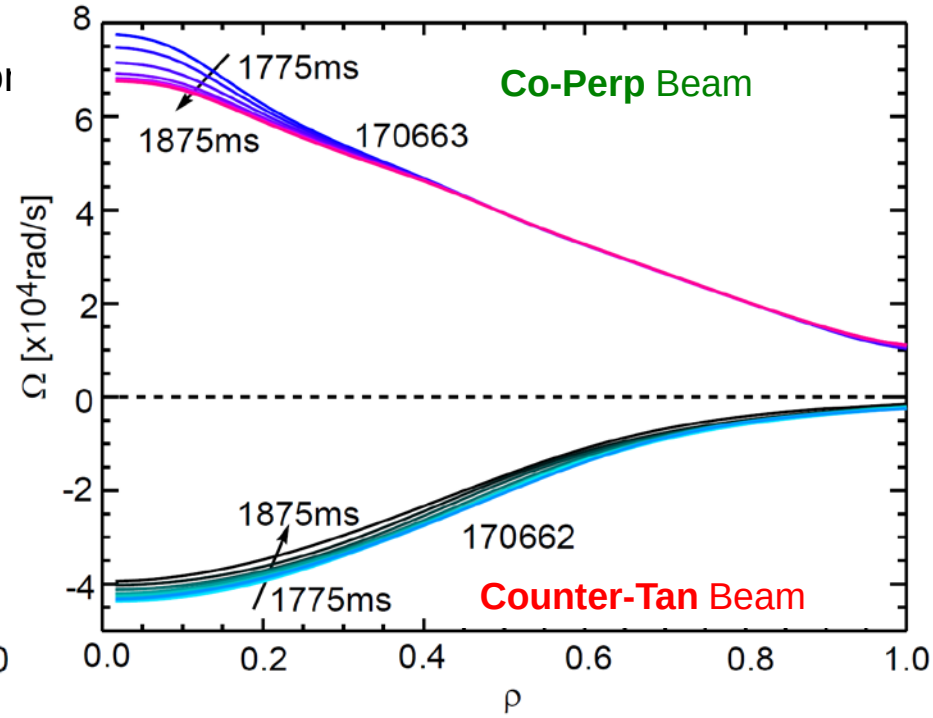
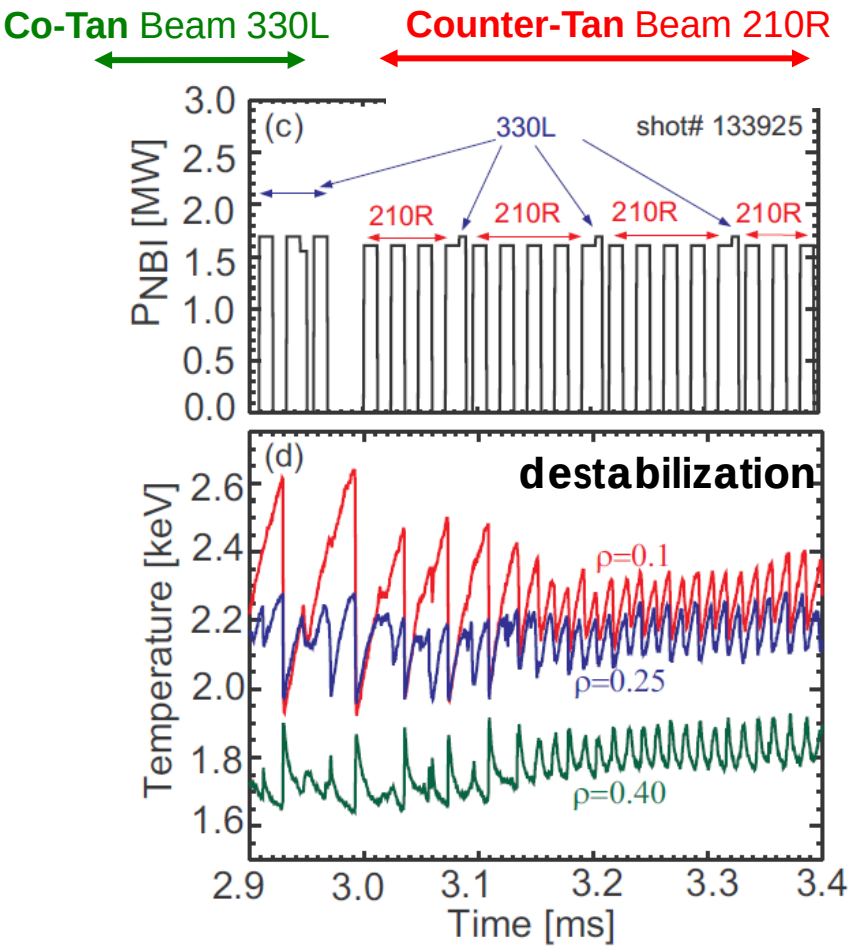
Comparison Discharges with Negative Triangularity Shape have Similar q Profile but Different Toroidal Rotation

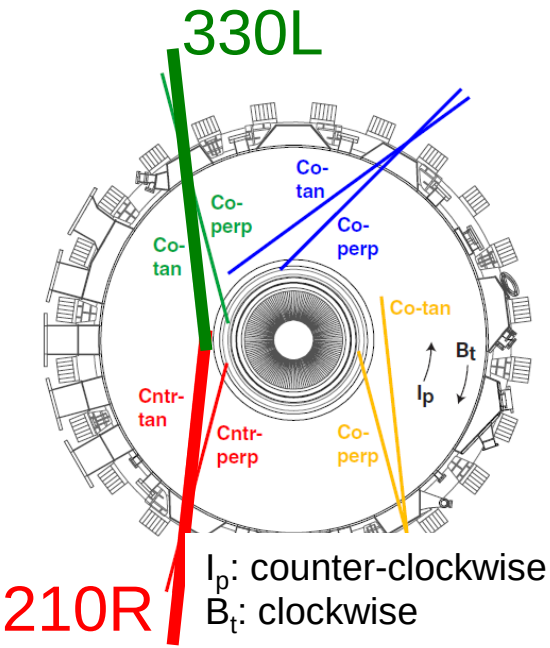




- q_0~0.85 in co-I_p NBI discharge, q_0~0.90 in counter-I_p NBI case.
- In fluid limit, γ/τ_A=0.0047 in co-I_p NBI case, γ/τ_A=0.0033 in counter-I_p NBI case.
  → q profile difference cannot explain the sawtooth behavior difference
- Toroidal rotation direction is flipped due to NBI geometry change.
- Fast-ion distribution pitch ($v_{//}/v$ relative to I_p) is different
  - Co-tan beam → pitch [0.6,0.85]
  - Co-perp beam → pitch [0.5,0.6]
  - Counter-tan beam → pitch [-0.85,-0.6]
  - Counter-perp beam → pitch [-0.6,-0.5]

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 → destabilizing effect

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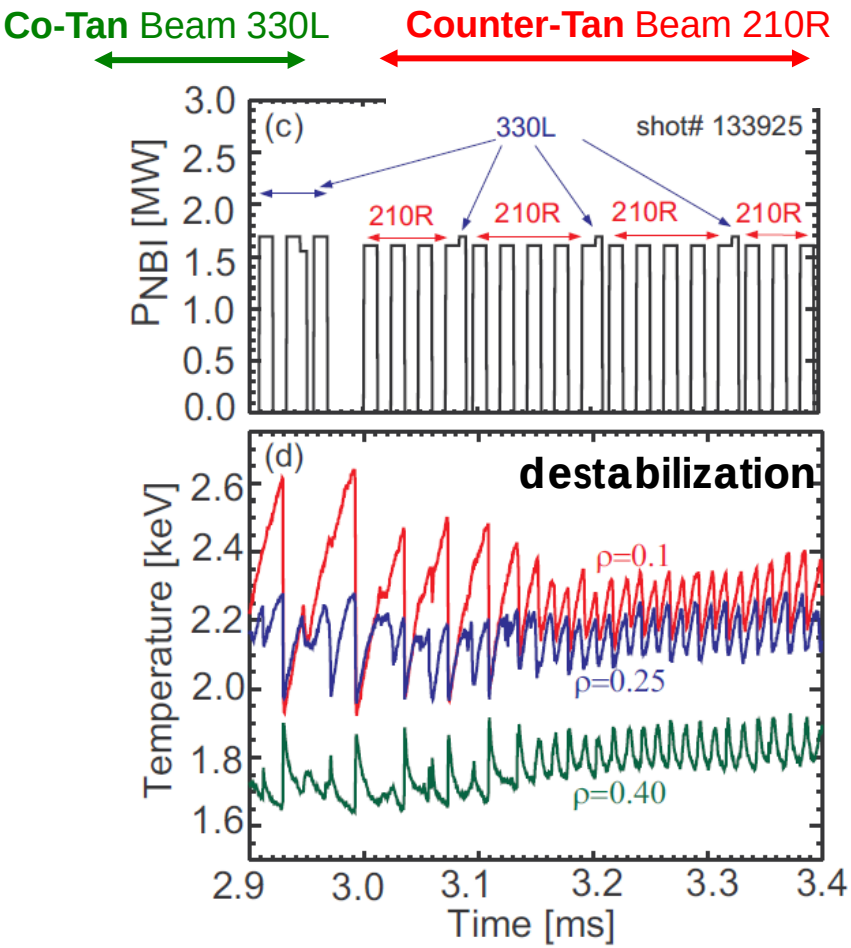

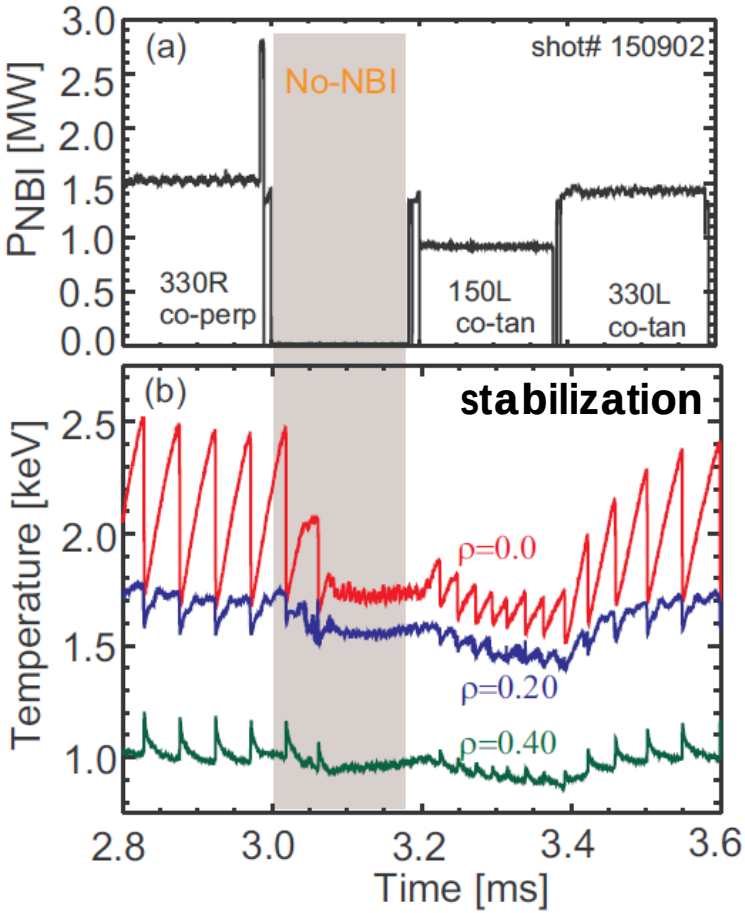

Smaller amplitude & more frequent sawteeth with counter-I_p NBI → destabilizing effect

Larger amplitude & less frequent sawteeth w/ NBI →stabilizing effect

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- **Summary**

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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:

Diamagnetic drift Mode eigenvalue

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

Precession drift

α=0: trapped
α =1: passing

Bounce/Transit

EXB

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

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- Anisotropic slowing-down model is assumed for NBI-generated Fast Ions (FI)

$$f^0(\psi, \epsilon_k, \varsigma) = \frac{C(\psi)}{\epsilon_k^2 + \epsilon_c^2} f_1(\psi, \epsilon_k, \varsigma)$$

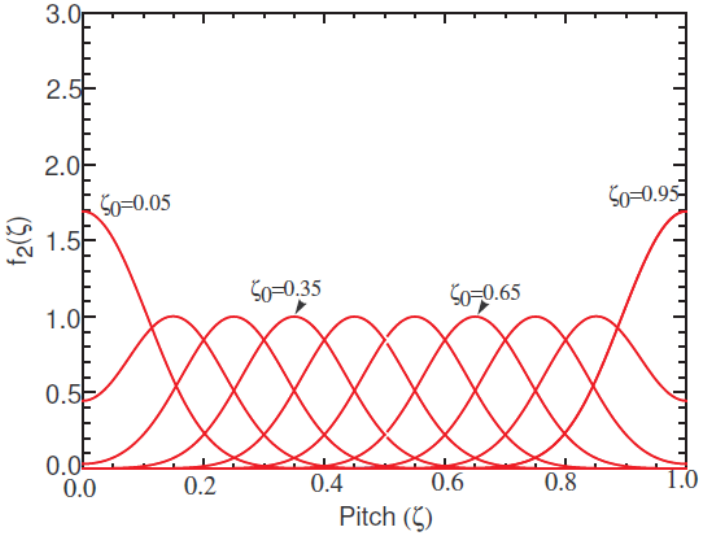
Y.Q. Liu POP 2014
Gorelenkov NF 2005

$$f_1(\psi, \epsilon_k, \varsigma) = \sum C_i(\psi, \epsilon_k) f_2(\varsigma|\varsigma_i)$$

Anisotropy in pitch

$$f_2(\varsigma|\varsigma_i) = f_2(\epsilon_k, \varsigma|\varsigma_i) = \frac{e^{-(\varsigma-\varsigma_i)^2/\delta\varsigma^2}}{2\sqrt{\pi}\delta\varsigma}$$

- Central pitch ζ_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.



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- Anisotropic slowing-down model is assumed for NBI-generated Fast Ions (FI)
- Perturbed kinetic pressure has **adiabatic** and **non-adiabatic** parts

$$\mathbf{p} = p_{th}\mathbf{I} + p_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}} + p_{\perp}(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}})$$

$$= p_{th}\mathbf{I} + (\mathbf{p}_{\parallel}^{\mathbf{a}} + \mathbf{p}_{\parallel}{}^{na})\hat{\mathbf{b}}\hat{\mathbf{b}} + (\mathbf{p}_{\perp}^{\mathbf{a}} + \mathbf{p}_{\perp}{}^{na})(\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}})$$

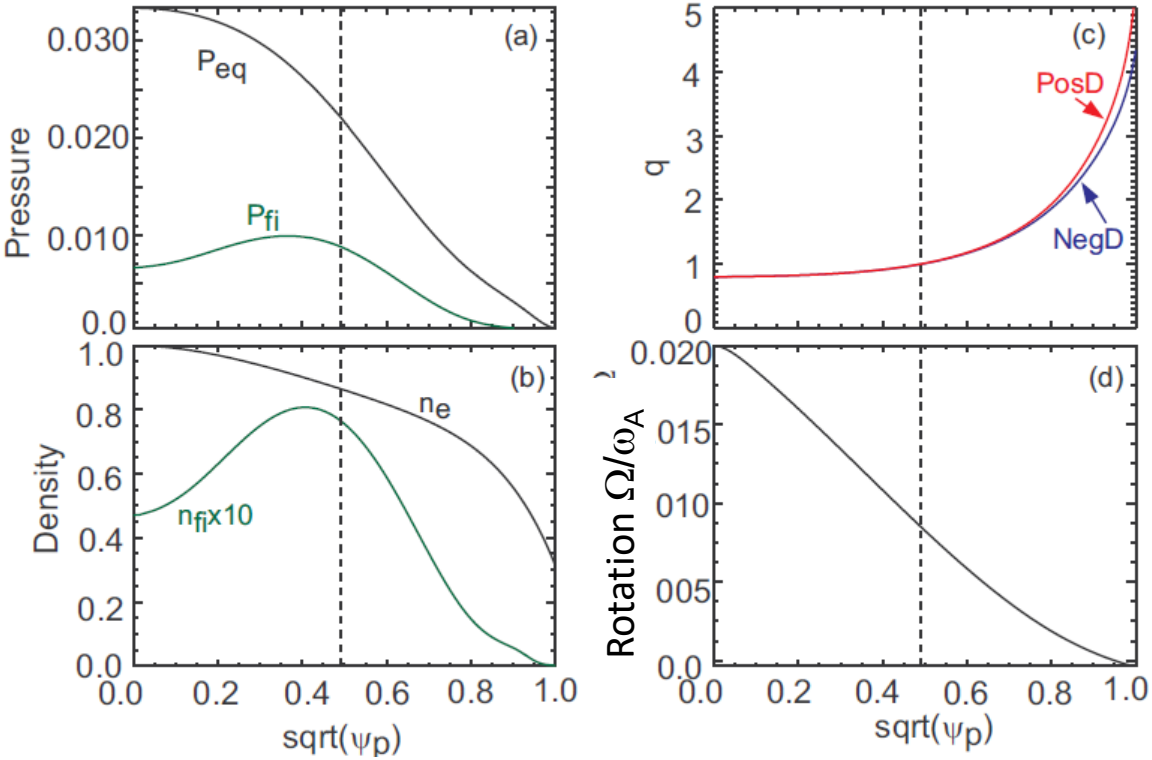
Adiabatic $p_g^a = \sum_j \int d\Gamma E_g(-\xi_\perp \nabla f_j^0)$

FI slowing-down distribution function

Non-adiabatic (kinetic) $p_g^{na} = \sum_j \int d\Gamma E_g f_L^1$

Perturbed FI distribution function

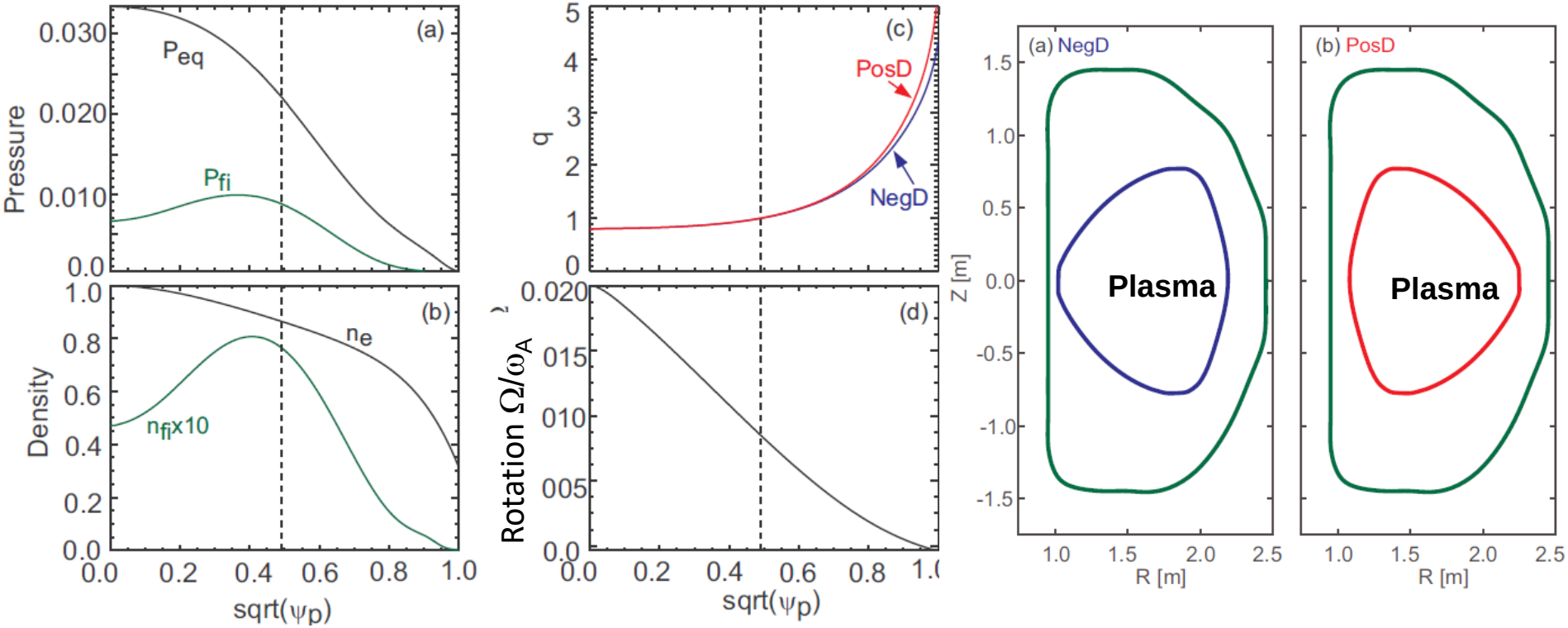
Kinetic Equilibrium and Experimental Profiles are Used for Modeling Input



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.

Kinetic Equilibrium and Experimental Profiles are Used for Modeling Input



NegD equilibrium: DIII-D 170660@1775ms

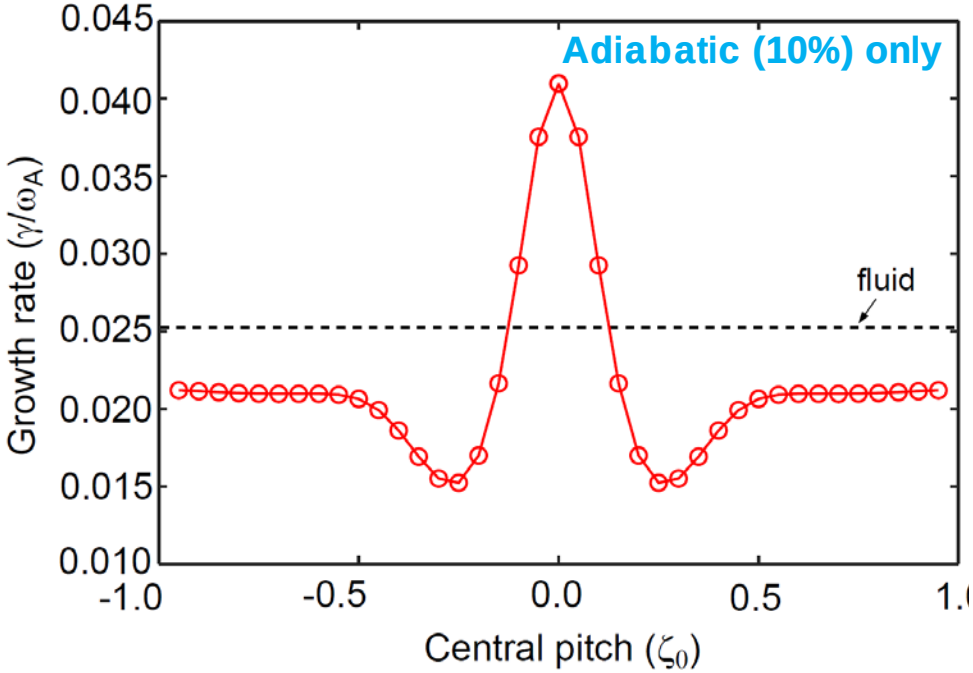
- B=2.0 T, I_p=0.88 MA, q_0=0.88
- Pressures scaled up by 2.0 from exp.

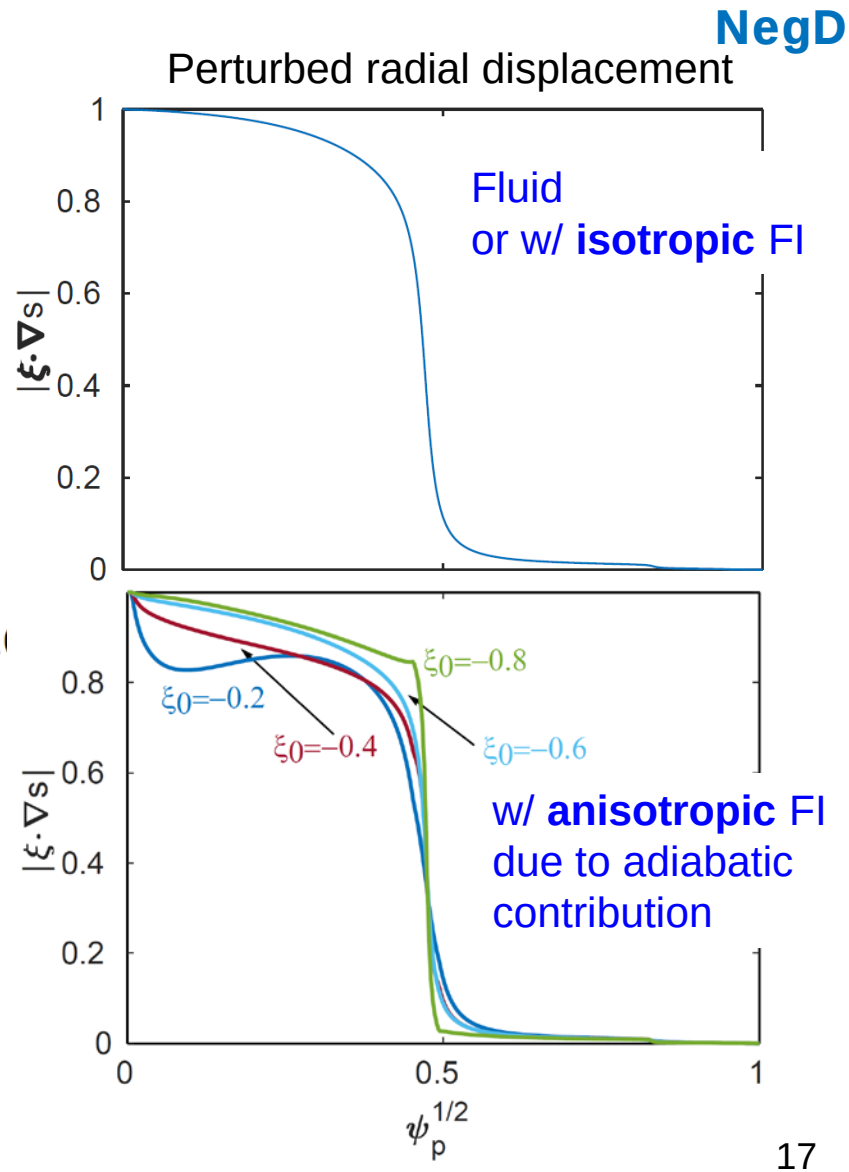
PosD equilibrium:

- flip negD equilibrium around the magnetic axis
- Similar q in core but higher q_{edge} compared with negD

Baseline in negD and posD: resistivity=0, rotation=0, no wall

Adiabatic Contribution Affects Mode Stability and Mode Structure



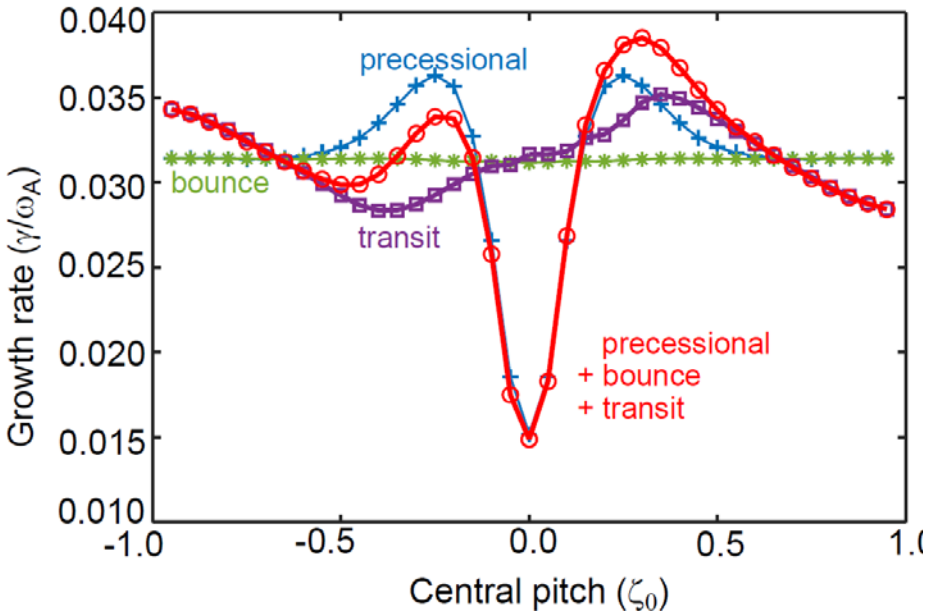


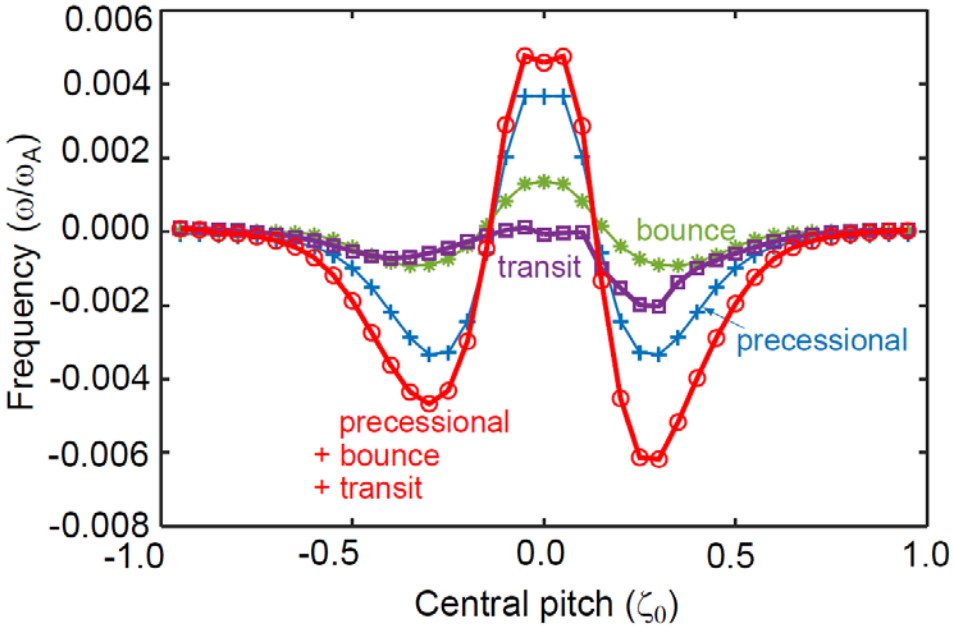
- Symmetric about pitch=0
- Growth rate varies with pitch because anisotropic fast-ion distribution affects adiabatic contribution to P_{par} ,P_{perp}
- Eigenmode structure also changes with pitch ξ_0

Asymmetry about pitch=0 is Caused by Non-adiabatic Contribution of Transit Motion of Passing Fast Ions

MARS-K **non-perturbative** runs w/ **partial (10%) kinetic effects** included

NegD





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

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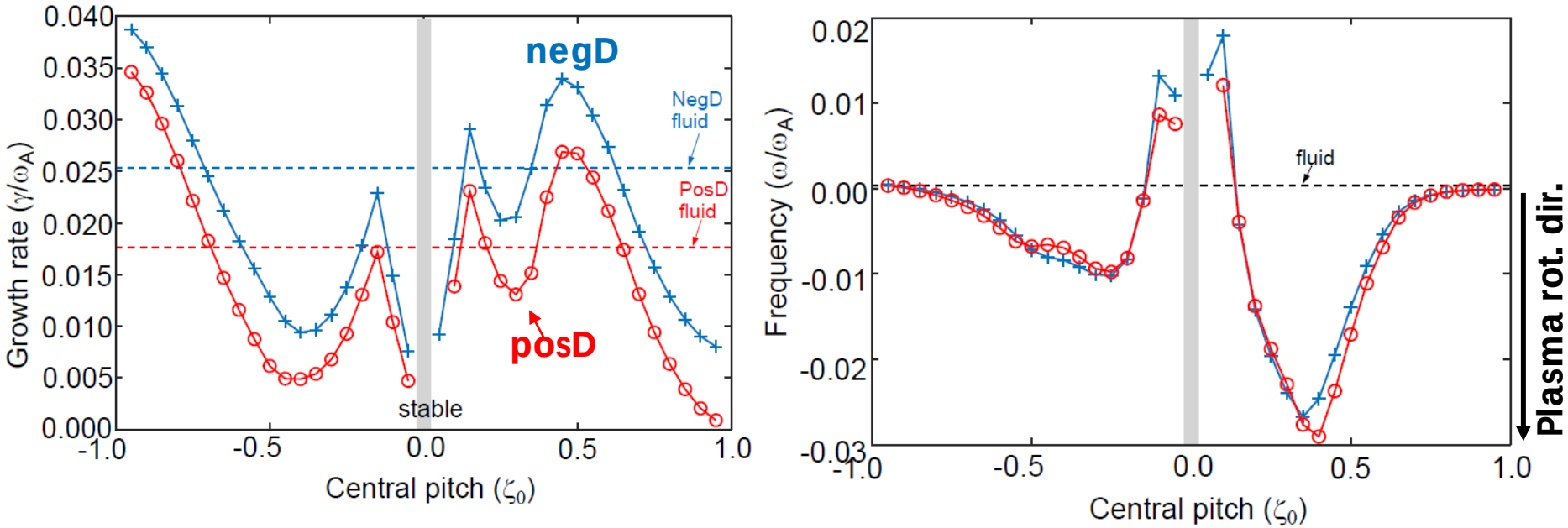
NBI Geometry has Similar Effect on n=1 Internal Kink Mode Stability in both NegD and PosD

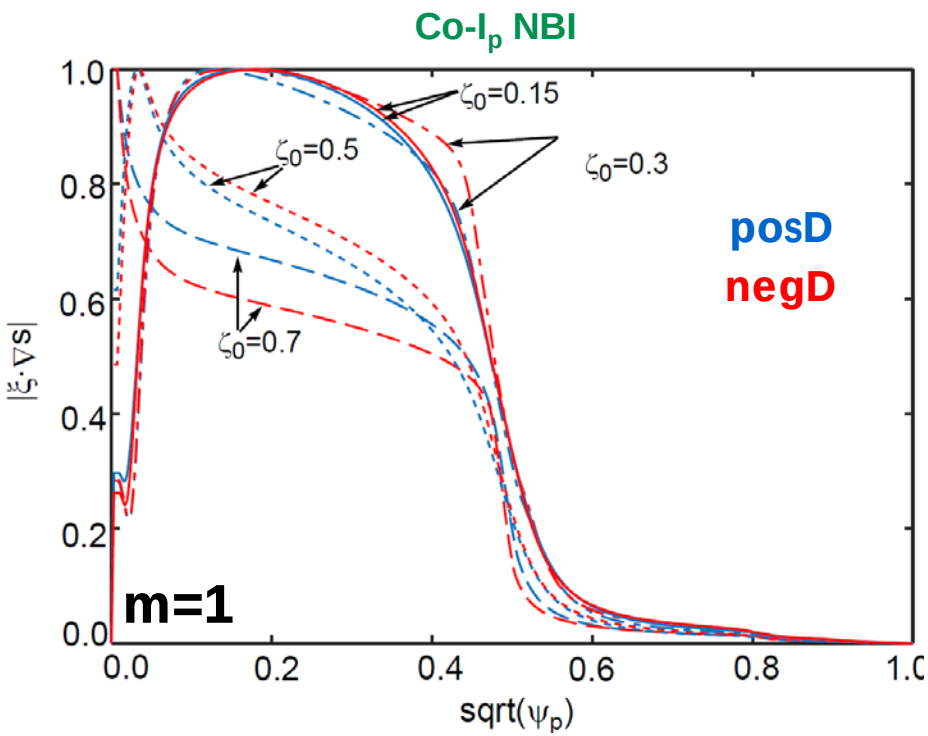
MARS-K **non-perturbative runs w/ full kinetic effects**

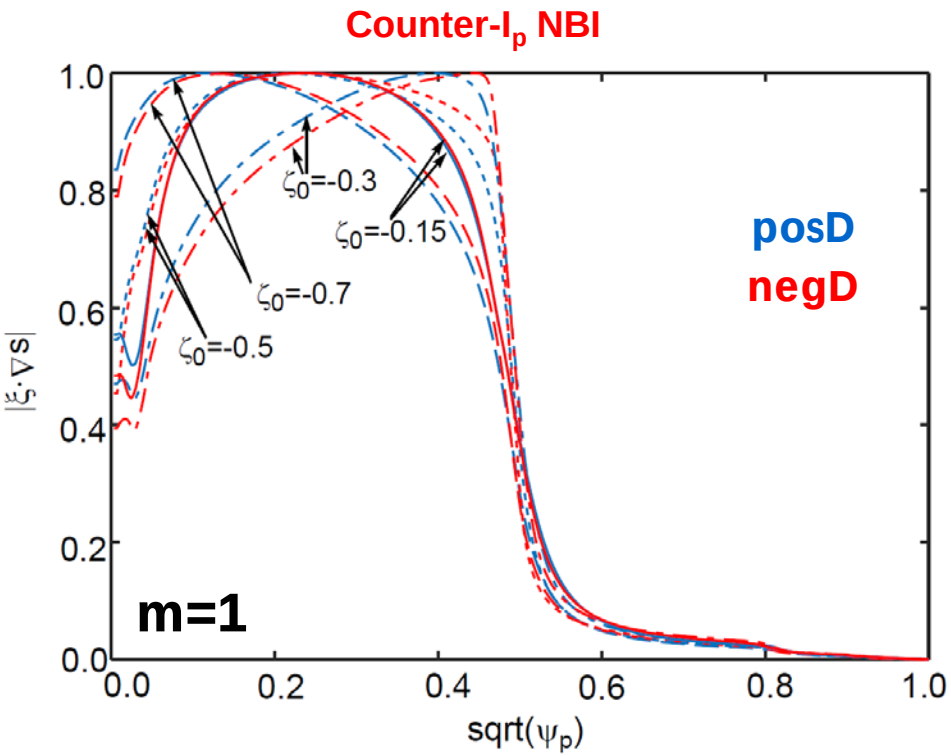


- Both adiabatic and nonadiabatic contributions are self-consistently included.
- In both negD and posD plasmas, co-I_p tangential NBI has a strong stabilizing effect, while counter-I_p tangential NBI has a destabilizing effect.
- With the same equilibrium profiles, anisotropic fast ions affect n=1 internal 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**

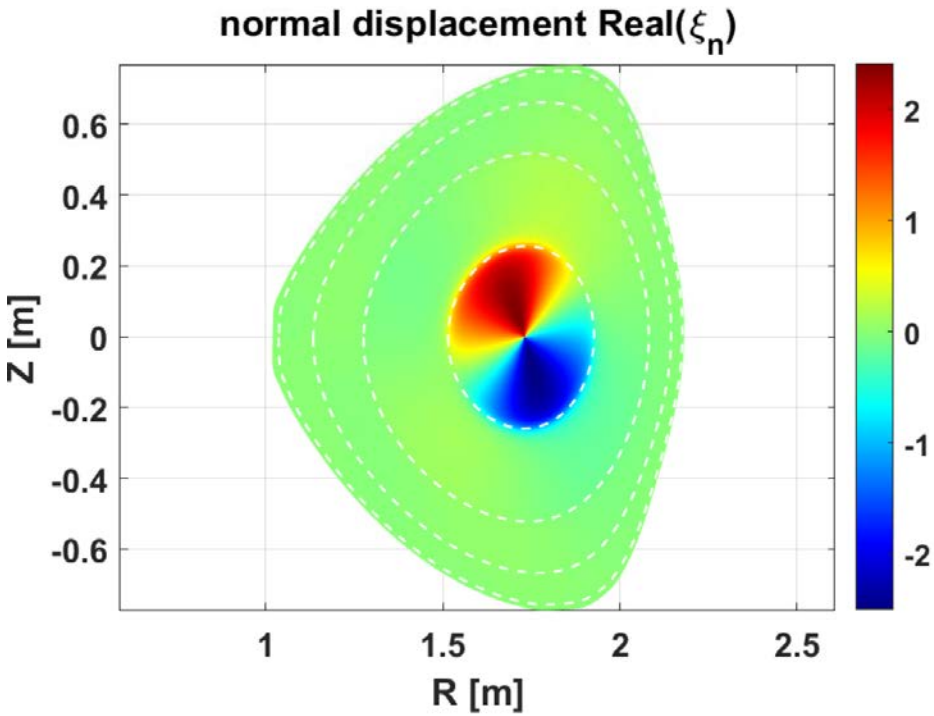


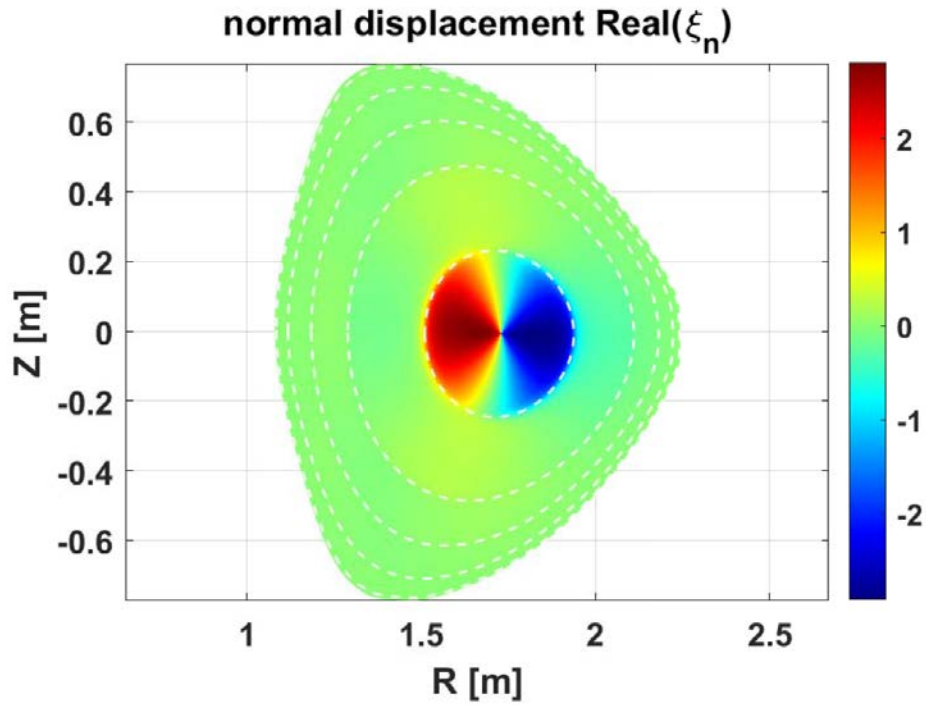


- Other poloidal Fourier harmonics of eigenfunction (radial displacement) are also similar in negD and posD plasmas.

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.

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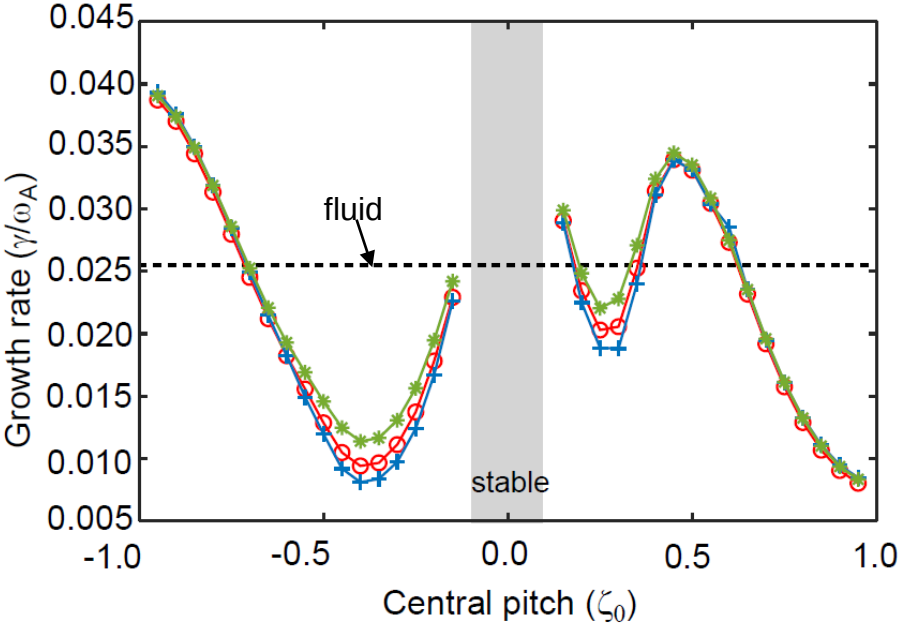
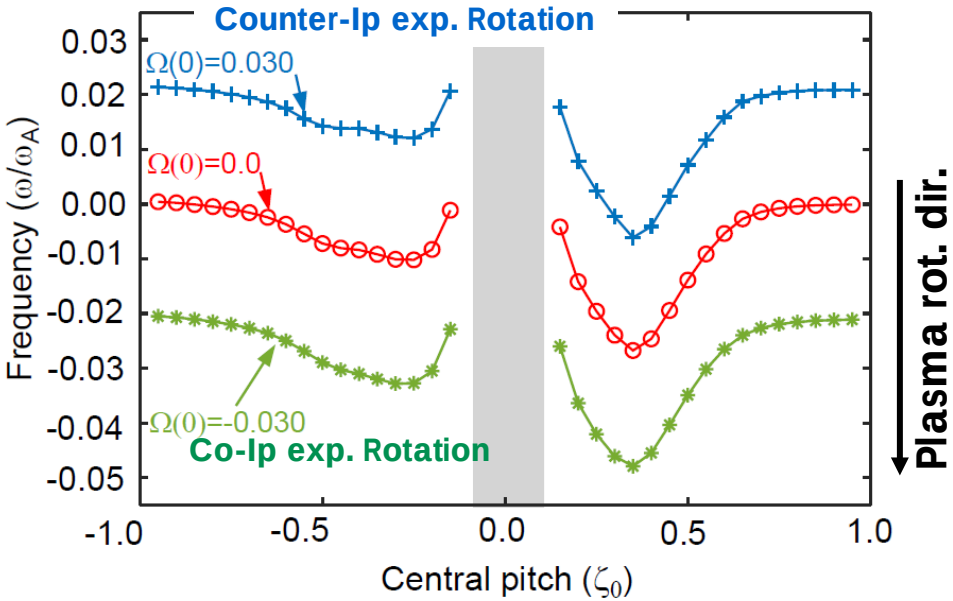
Plasma Rotation (and Shear) has Relatively Weak Effect on n=1 Internal Kink Mode Stability

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

NegD





- 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.

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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.

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