Kinetic stability of negative-triangularity plasmas

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1. Introduction & Methods

Introduction

- **Negative triangularity (NT)** is an attractive plasma configuration along with its ELM-free nature while still retaining high confinement [1].
- Despite these advantages, NT plasmas uniquely lack second-stability access for edge ballooning modes and have lower global β_n limits than PT plasmas [2].
- **Kinetic MHD stability in NT** plasmas is expected to differ from PT due to magnetic geometry and trapped particle dynamics. Pressure anisotropy from **trapped particles** is expected to have a stabilizing influence on kink and ballooning modes—unlike in PT.

Methods

- Analysis is based on DIII-D shot #193802, which features a triangularity scan from positive to negative shaping (PT → NT).
- **Stability limits for n=1~5** were computed using **DCON** and its **kinetic DCON**, via pressure scan at fixed equilibrium.

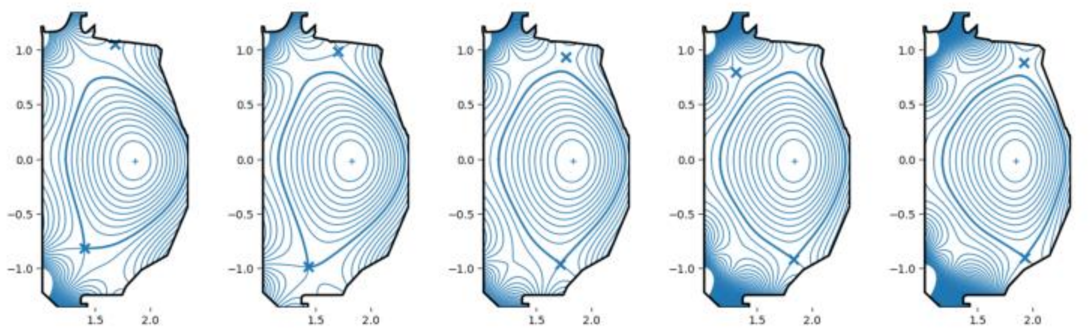


Fig 1. Equilibrium from DIII-D #193802, showing a shape scan from positive to negative triangularity.

The kinetic MHD($\delta W_{kinetic}$) perturbed potential energy is defined as [3][4]:

$$2\delta W_{kinetic} + i\,\frac{\tau_\varphi}{n} = 2\delta W_{Ideal} - \frac{2\pi\chi'}{M^2}\int d\psi d\varphi dE d\mu(\delta\mathcal{J}^*\delta f)$$

$$\delta f_{kls} = \sum_{\sigma\ell}\frac{1}{2\pi q}\frac{in\omega_{b,t}}{i[(\ell-\gamma nq)\omega_{b,t}-n\omega_p]-\nu}\frac{\partial f_M}{\partial\chi}\delta\mathcal{J}_{\sigma\ell}$$

Although dissipation breaks the energy principle, $\delta W_{kinetic}$ remains a useful stability proxy since the beta limit shifts little due to the steep gradient near 0.

$$\delta W_{kinetic} + \left(\frac{1-c}{c}\right)\frac{\tau_\varphi^2}{4n^2\delta W_L} < 0 \;\; (c : \text{plasma wall coupling})$$

The Kruskal–Oberman (KO) captures kinetic energy from particle motion along magnetic field lines on fast MHD time scales, neglecting drift and collisions [5].

$$\delta f_{ko} = -\frac{\omega_b}{2\pi T} f_M \delta\mathcal{J}$$

The Chew–Goldberger–Low (CGL) limit describes double-adiabatic pressure response that emerges as $\omega_E \to \infty$, suppressing orbit-resonant effects [6].

$$\delta f_{cgl} = \lim_{\omega_E\to\infty}\delta f_{kls}$$

2. n=1 kinetic stability

- Stability limits for the n=1 mode were computed across triangularities using Ideal MHD, KO, full kinetic, and CGL. Both ion and electron responses were included, with electrons playing a significant effect.
- The ordering $\delta W_{Ideal} \le \delta W_{kinetic} \le \delta W_{CGL}$ known as a general trend, is confirmed [6].
- In both PT and NT plasmas, the **full kinetic response provides comparable levels of passive RWM stabilization**, with NT additionally exhibiting **strong bounce-harmonic resonances** from deeply trapped particles.

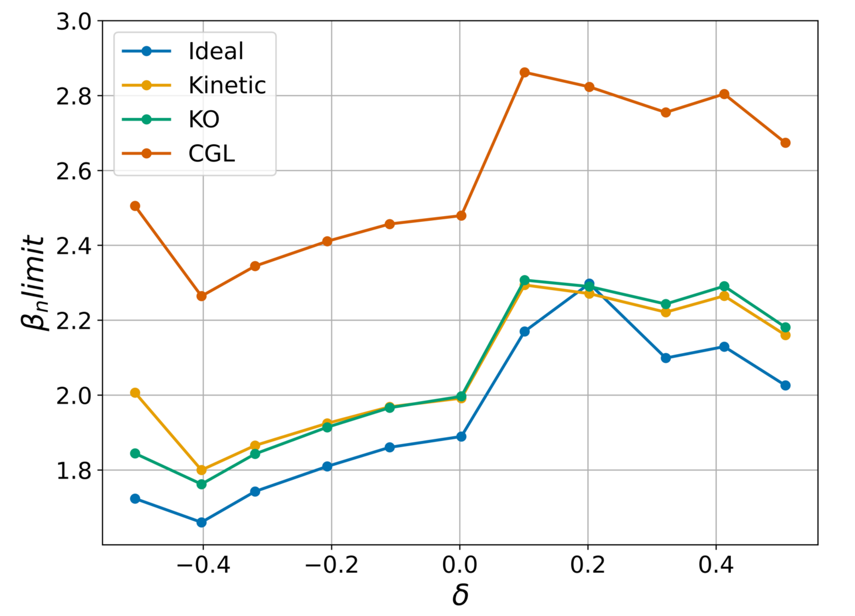


Fig 2. Stability limit β_n^{limit} versus δ, obtained from Ideal, Kinetic, Kruskal-Oberman, and CGL models.

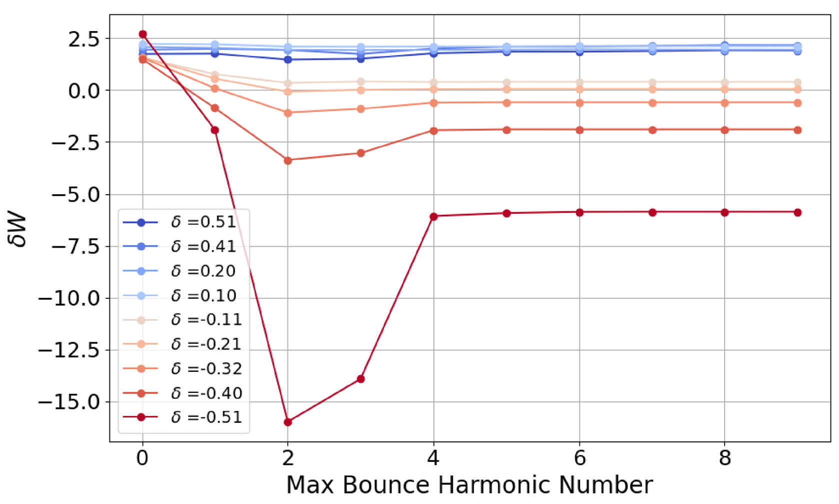


Fig 3. δW convergence with bounce harmonics for various triangularities, showing strong trapped-particle effects at high negative δ.

- A bounce harmonic scan was performed, varying the maximum included harmonic number from 0 to 9 for different triangularities δ.
- It reveals that in NT the perturbed potential energy δW converges later then PT, indicating a significant contribution from **higher-order bounce harmonics**.
- This behavior suggests that stronger coupling to **deeply trapped particles** are more influential in NT.

3. Low-n>1 kinetic stability

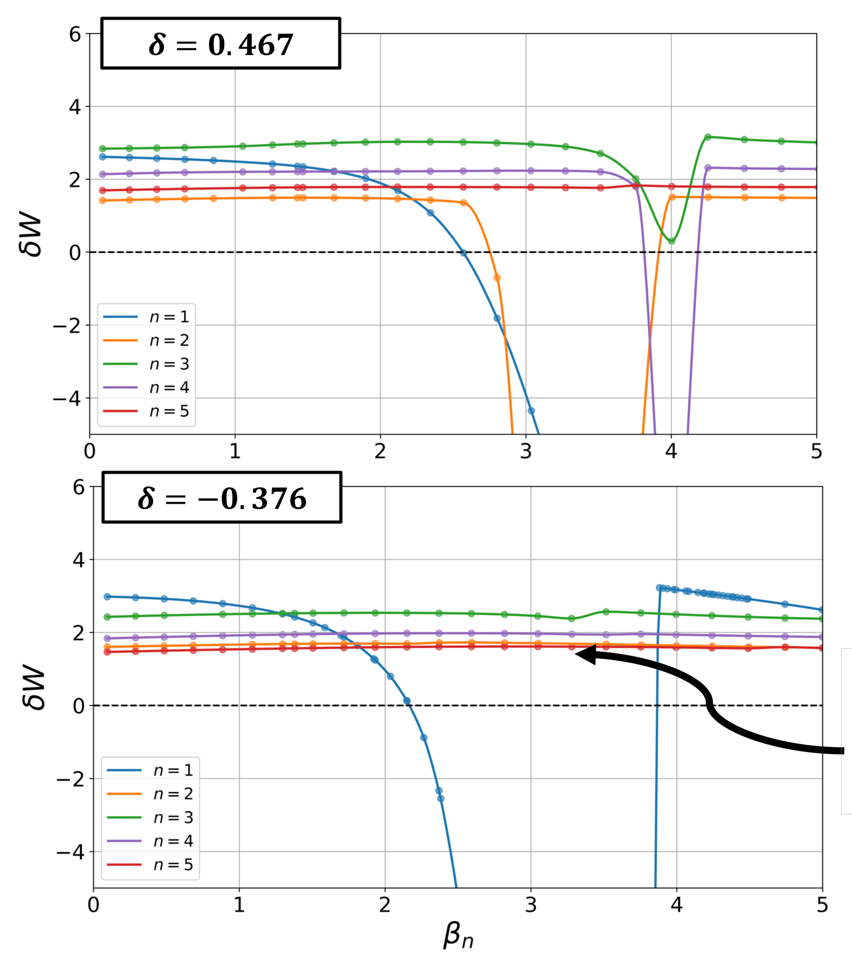


Fig 4. Perturbed potential energy δW for toroidal modes n=1–5 from full kinetic MHD analysis across β_n scan.

- Full kinetic MHD analysis including both ion and electron responses was also performed for $n > 1$ modes.
- For $n = 1,2$, a direct-type equilibrium was used; for $n > 2$, inverse-type equilibrium was applied for more precise computation
- In the positive triangularity (PT) case, modes $n = 1 \sim 3$ all show instability in certain β_n regions (i.e., $\delta W < 0$).
- However, **the NT case demonstrates that kinetic effects fully suppress instabilities for all modes with $n > 1$ across the β_n range.**
- Ideal MHD, KO, and CGL approximations yield unstable δW for all $n = 1\text{–}4$ modes, even with strong NT shaping. As triangularity decreases, the gap between the first and second stability regions narrows.

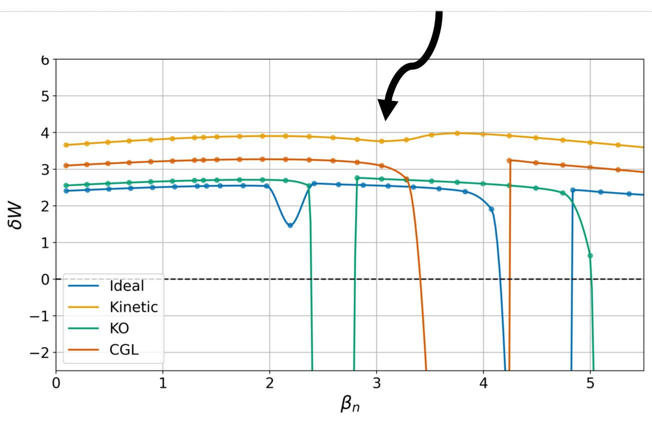
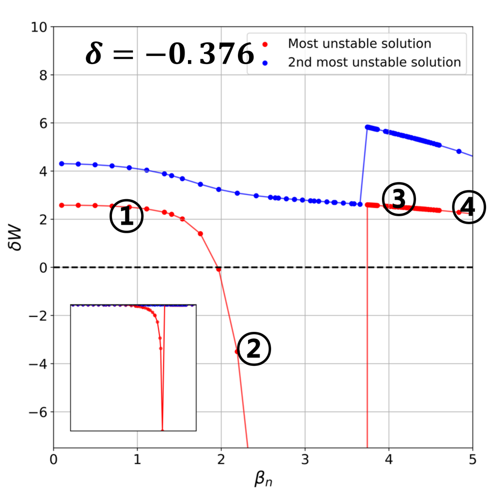


Fig 5. Perturbed potential energy δW from pressure scan at $\delta = -0.376$ in different models for $n = 2$.

4. Second stability regime



- In PT, the n=1,m=2mode grows and becomes unstable with increasing pressure.
- In NT, the same mode becomes unstable at lower β_n, consistent with NT's reduced stability limit. Beyond a certain point, however, only in NT does the m=2 kink-like structure disappear, marking the onset of a second stability regime.

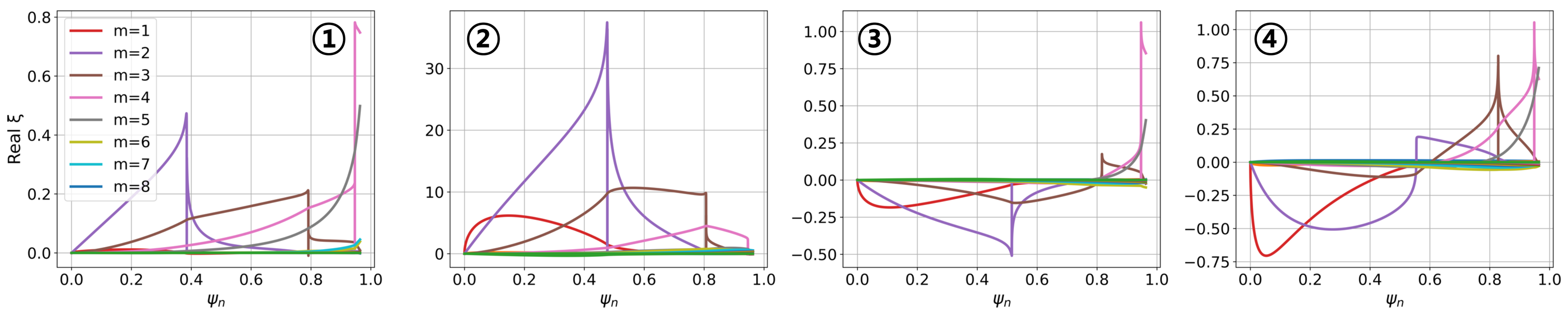
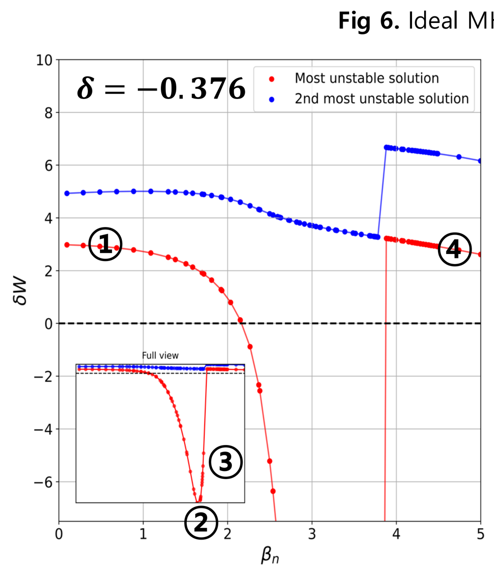


Fig 6. Ideal MHD analysis in NT plasma showing δW evolution and mode structure across β_n



- After this certain point, the $m = 1$ and $m = 2$ harmonics exhibit negative amplitudes, and their corresponding δW becomes positive in both **ideal and kinetic run**.
- One difference is that the full kinetic response produces a smooth trend, clearly showing that the $m = 2$ harmonic stops growing and decreases.

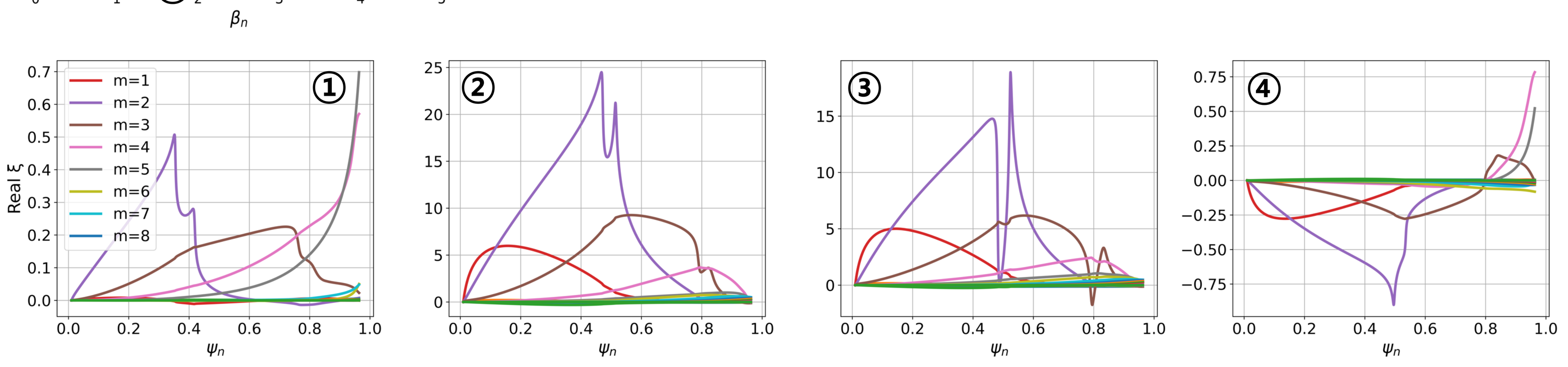


Fig 7. Kinetic MHD analysis in NT plasma showing δW evolution and mode structure across β_n

5. Application and future work

Application

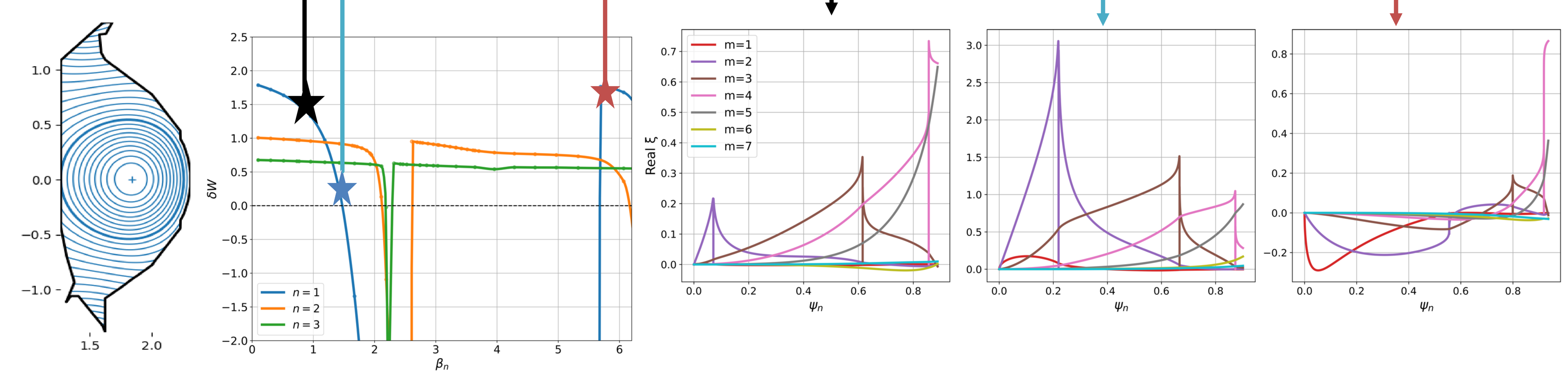


Fig 8. KSTAR #36167 (t = 5000 ms, Ip=313.9 kA, δ=−0.102) with radial eigenfunctions at three locations overlaid.

- Ideal MHD stability analysis was performed for a KSTAR NT discharge.
- A second stability regime at $n = 1$ was found, with negative $m = 1,2$ harmonics and $\delta W > 0$, consistent with DIII-D.

Future works

- Investigate the mechanism behind the second stability region in NT plasmas, which remains theoretically unclear.
- Observed in Fig. 10, where torque modification appears to enable access, further investigate how kinetic effects may facilitate entry into the second stability region.
- Extend the current upper-boundary PT–NT shaping scan in KSTAR to a full-boundary scan, enabled by the broader shaping access expected after the KSTAR-II upgrade (see Fig. 9), which would allow comprehensive kinetic stability studies across the PT–NT space.

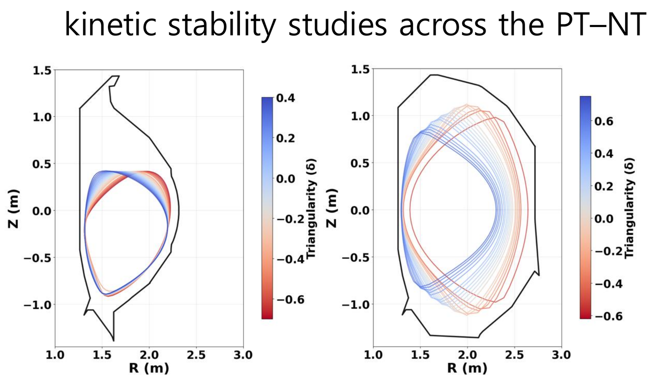


Fig 9 Proposed PT–NT shaping scan equilibria for upcoming KSTAR experiments before and after the KSTAR-II upgrade. (Contributed by Jaebaem Cho)

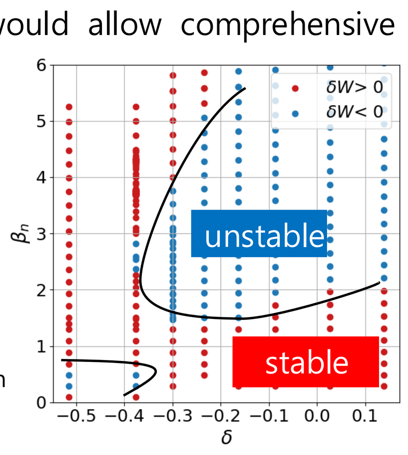


Fig 10. β_n–δ stability structure with torque-modified second stability access.

6. References

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