INFERNAL-KINK INSTABILITY IN NEGATIVE-TRIANGULARITY PLASAMAS WITH NEGATIVE CENTRAL SHEAR

Li Li[1], Xiumin Zhang[1], Yueqiang Liu[2], Zhiyao Dong[1], Jingwei Li[1], Yunfeng Liang[3] and Fangchuan Zhong[1]

[1] College of Physics, Donghua University, Shanghai, China.
[2] General Atomics, San Diego, California, United States of America
[3] Forschungszentrum Jülich GmbH, Jülich, Germany.

Email: lili8068@dhu.edu.cn

The edge transport barrier (ETB) enhances core plasma performance, increases non-inductive bootstrap current, and reduces external heating power, improving fusion economy. Therefore, H-mode is the preferred operating mode for most tokamaks due to its superior confinement and higher operating parameters [1]. However, H-mode faces several challenges: strong plasma-PFC interactions due to ETB, conflicts between PFC damage limits and L-H transition thresholds, complexities in controlling detached regimes, and type-I ELMs causing exhaust issues. Recent experimental results obtained from DIII-D [2] and TCV [3], featuring negative triangularity shapes (neg-D), present a promising approach to address the aforementioned challenges associated with edge transport barrier in plasma. The absence of a strong ETB in neg-D plasma allows access to an ELM-free regime but still with good confinement. However, further careful investigation is required to comprehend the MHD instability in these neg-D configuration plasmas.

Negative central shear (NCS) is associated with the formation of internal transport barriers (ITBs), which are crucial for the advanced tokamak (AT) concept in conventional (positive-triangularity) plasmas [4-7]. Developing a similar NCS scenario with ITB for negative-triangularity plasmas is important, as ETB formation near the edge is often not feasible in these plasmas. NCS can be realized in neg-D discharges in the plasma core, where triangularity differences between positive and negative configurations are minor [8, 9].

However, NCS equilibria are prone to infernal (or quasi-interchange) instability, frequently observed in positive triangularity plasmas. This instability occurs when the minimum q-value (q_{min}) is near a rational number and there is sufficient pressure drive at q_{min}. It can complicate plasma operation during current ramp-up or produce long-lived modes (LLMs). Additionally, this instability can couple with external kink modes in high-pressure plasmas, forming the infernal-kink mode.

This work systematically investigate the stability of the n=1 ideal infernal-kink instability in neg-D plasmas with negative central shear for the equilibrium safety factor [10]. The latter is motivated by the desire to form the internal transport barrier in the neg-D configuration, which is known to have difficulty to form the edge transport barrier. We also contrast the MHD stability results with that from the pos-D configuration, with otherwise similar equilibrium profiles (the plasma pressure, toroidal current density as well as the safety factor). All stability computations are carried out utilizing the MARS-F code, based on a series of semi-analytically designed equilibria with varying plasma boundary shape.

As a key conclusion, we find that infernal-kink mode is generally more unstable in neg-D plasmas as compared to the pos-D counterpart, as shown in Fig. 1. This poses certain MHD limitations on achieving stable operational regime with ITB and with the neg-D concept. Based on our numerical findings, we propose a recipe for resolving this issue, by (i) forming the ITB not too close to the magnetic axis in neg-D plasmas to avoid strong kink-drive, and (ii) by allowing q_{min} further away from rational numbers (integer numbers for the n=1 instability) to avoid the infernal drive.

For comparison, we find that the infernal-kink mode is more stable in pos-D plasmas with the same safety factor profile and the same β_N value. In fact, a stable window opens up near δ~0.2 for the n=1 infernal mode (with sufficient large s_{qmin} and without wall stabilization), as we scan triangularity of the plasma boundary shape. Imposing an ideal-wall boundary condition suppresses the external kink drive, leading to wider stable windows extending to the neg-D regime (δ>-0.25).

Physics-wise, we find that the more unstable behavior of the infernal-kink mode with the neg-D configuration is mainly due to less favorable (or even unfavorable) average magnetic curvature near the q_{min} location, as compared to the pos-D counterpart. The larger Shafranov shift associated with the neg-D shape helps the mode stabilization, but is not sufficient to overcome the destabilizing effect due to bad curvature. On the other hand, the aforementioned two competing effects can be employed to explain the non-monotonic dependence of the computed mode growth rate versus δ and the appearance of the stable window at intermediate (positive) delta values. As another interesting physics point, we identify a strong poloidal mode coupling due to plasma shaping (toroidicity, elongation, triangularity, etc.), which helps explain the slight shift (with respect to that predicted by the analytic theory) of the peak location of the mode growth versus $q_{\min}$.

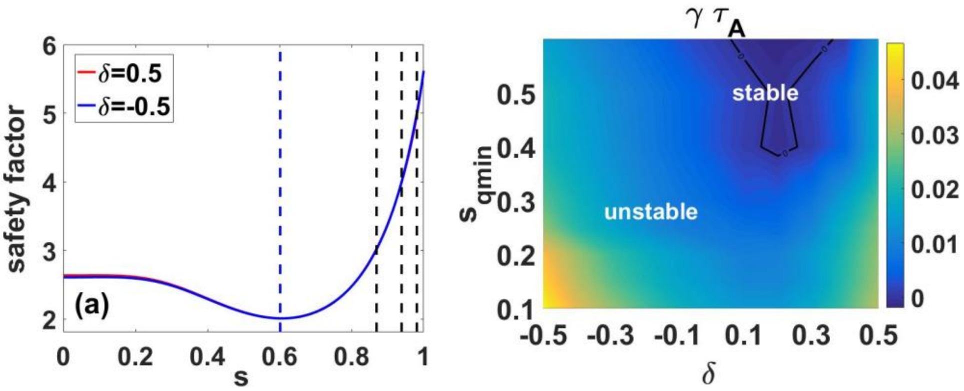

Figure. 1. A series of equilibria with varying triangularity δ of the plasma boundary shape from $\delta = -0.5$ to 0.5 while fixing the safety factor profile, showing (a) radial profiles of the safety factor. Here $s = (\psi_p)^{1/2}$ with ψ_p being the normalized equilibrium poloidal magnetic flux. Vertical dashed lines in (a) indicate the radial locations of the *n*=1 rational surfaces. The vertical dashed line in blue shows the $q_{\min}$-location. (b) plots the MARS-F computed growth/damping rate of the *n*=1 no-wall infernal-kink instability while varying both the plasma triangularity δ and the radial location (s_{qmin}) of $q_{\min}$, with the safety factor profiles shown in Fig. 1(a). The black curve indicates marginal stability. The normalized plasma pressure is fixed at $\beta_{\mathrm{N}} = 2$.

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