ACCESSING STABLE OPERATIONAL WINDOWS IN K-DEMO
Testing stability assessment workflow for conceptual pilot plan design

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An improved workflow for stability assessment has been developed and successfully applied to conceptual K-DEMO plasmas. The process begins with extracting information from the 0D system code to generate a series of free-boundary equilibria consistent with poloidal field (PF) coils using TOKAMAKER[1]. These equilibria are then analysed using a suite of stability codes—DCON[2], RDCON[3], and STRIDE[4]—to evaluate kink-ballooning and linear tearing mode stabilities. A total of 500 different plasma profiles in a range of plasma current I_P and pressure represented by β_N. DCON applications show the Kink-ballooning β_N limit is mainly determined by $n = 1$ as expected, but surprisingly $n = 3$ limit is lower than that for $n = 2$. This indicates the potential importance of $n = 3$ instability in the presence of wall, given that wall stabilizing effects decrease rapidly as the toroidal mode n increases. Further RDCON and STRIDE codes have been employed to estimate the toroidal tearing mode index Δ', for the first time extensively for conceptual plasmas. Although tearing-stable cases can be found in high-I_P scenarios when β_N is sufficiently low, the results show that most tested plasmas are unstable against $(m = 2, n = 1)$ mode. Overall, this study highlights the necessity of incorporating stability assessment into the system design loop to ensure that proposed design points maintain stable operational windows. The workflow presented in this paper is both fast and reliable, making it well-suited for integration into system design tools.

During the preliminary design phase of nuclear fusion reactors, engineers traditionally prioritize quantitative 0D parameters—such as q_0 and β_N—to facilitate rapid optimization and performance evaluation of stability and confinement [5,6]. Yet, MHD analysis is essential for unravelling the intricacies of plasma dynamics, including critical instabilities and the complex interplay between magnetic fields and plasma, which are pivotal to a reactor's operational success. Acknowledging the shortcomings of relying solely on simplified approaches, we conducted a comprehensive MHD stability analysis for the new tokamak device K-DEMO, aiming to elevate its design reliability and performance beyond the limitations of conventional 0D frameworks.

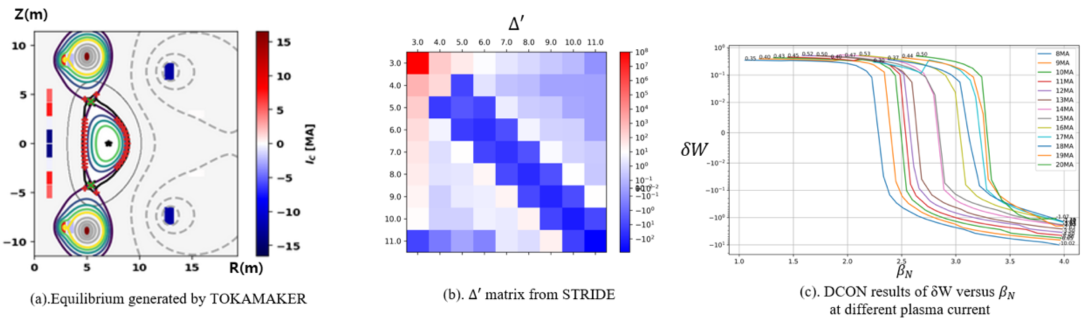
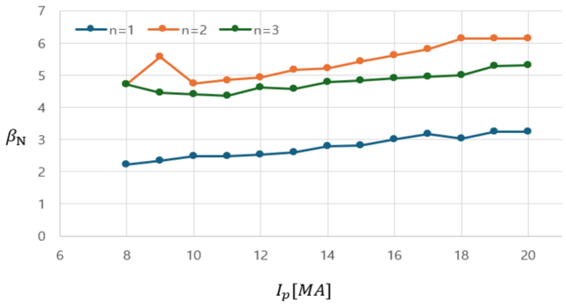


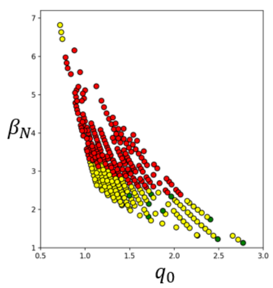
Fig. 1 (a) Equilibrium generated by TOKAMAKER, showing flux surfaces and poloidal field coil currents (blue to red). (b) Δ' matrix from STRIDE, where red denotes regions prone to tearing-mode instability and blue indicates stability. (c) DCON results for δW as a function of β_N, evaluated at various plasma currents, illustrating the kink stability limit.

For K-DEMO, we utilized the TOKAMAKER code to generate a diverse set of plasma profiles, specifically emphasizing flat-top profiles to reflect realistic operational conditions and adopted a free-boundary approach to produce equilibria tailored for stability assessments. These target equilibria are then tested against ideal MHD instability up to $n = 5$ using DCON and resistive tearing instability using RDCON and STRIDE. Both RDCON and STRIDE are based on toroidal Newcomb equation to construct resistive outer-layer solutions and tearing mode index Δ', but with different numerical schemes. Due to the influence of multiple singular surfaces and characteristics of toroidal geometry, Δ' is represented as a matrix rather than a vector, unlike in cylindrical geometry. Nevertheless, since tearing mode formation is primarily influenced by individual surfaces and to reduce computation time, instability was determined based on the sign of the diagonal components of Δ'. These calculations can be highly sensitive to errors in equilibrium force balance. Running both RDCON and STRIDE in parallel and ensuring agreement between their results serves as a crucial validation step for the stability assessment.

The integrated workflow along with free-boundary equilibrium, ideal and resistive stability calculations is then applied to a large set of K-DEMO profiles. Figure 1(a) shows profile generation with TOKAMAKER, followed by β_N and current scans (500 per profile). Figure 1(b) presents a Δ' matrix from STRIDE, where red indicates instability and blue indicates stability. Instabilities at q = 3, 4 suggest island formation. Figure 1(c) shows δW scans for n=1, revealing a sharp β_N drop and an increasing β_N limit with current. Figure 2(a) summarizes β_N limits for n=1–3, with n=2 exceeding n=3 and increasing with current. Figure 2(b) plots analyzed profiles, with red, yellow, and green points indicating different stability conditions. Green points were further confirmed as stable up to n=5. This approach identified K-DEMO profiles stable in both ideal MHD and tearing modes.



(a). β_N limits on the plasma current



(b). Scatter plot of β_N versus q_0

Fig. 2 (a) ideal MHD β_N limit with plasma current I_p for n=1, n=2, and n=3. The n=1 limit is consistently lower, while n=2 and n=3 tend to allow higher β_N values at increased current. (b) Scatter plot of β_N versus q_0, colored to indicate stability margins as derived from tearing-mode or kink-ballooning assessments. The red points indicate instability in all cases for n=1 to n=3, while the yellow points are unstable only for the tearing mode. The green points are stable for n=1 to n=5 as well as the tearing mode.

The efforts presented in this paper are being extended to a comprehensive dataset of plasma profiles and equilibrium configurations, with the goal of determining the critical thresholds for achieving intrinsic MHD stability without reliance on external stabilization. By synthesizing these findings, this work overcomes the low-fidelity constraints of traditional stability assessments, establishing a seamless connection to medium-fidelity MHD analysis. This refined approach bridges the gap between simplified early-stage modelling and the detailed plasma physics necessary for designing a high-performance tokamak like K-DEMO, providing a robust and predictive framework for its development.

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