Stability and transport in high-beta stellarators: the role of kinetic ballooning modes

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Kinetic ballooning modes (KBMs) [1, 2] play a central role in determining the stability and transport properties of high-beta plasmas, particularly in non-axisymmetric magnetic confinement devices such as stellarators. In Wendelstein 7-X (W7-X), KBMs are of particular interest due to their potential to limit performance even in configurations that are stable against ideal magnetohydrodynamic (MHD) instabilities. Unlike ideal MHD ballooning modes, which are constrained by global stability boundaries, KBMs can be influenced by finite Larmor radius effects and kinetic responses, which become particularly important at low pressure gradients where fluid drive is weaker. While FLR effects are generally stabilizing, their role near marginality remains nontrivial and may influence KBM thresholds.

During recent high-performance operational phases at W7-X, moderate but systematic energy losses were observed in certain discharges, despite the absence of large-scale MHD activity. These losses have been increasingly associated with the onset of KBMs, pointing to a kinetic stability boundary that may constrain future performance unless properly understood and controlled. As part of the most recent experimental campaign, substantial progress has been achieved in identifying the conditions under which KBMs are triggered and in mapping their behavior across different magnetic configurations. This has included a combination of different diagnostics, alongside gyrokinetic simulations to interpret the observed turbulence signatures.

This talk will provide a comprehensive overview of both theoretical and experimental progress in the study of KBMs, with a particular focus on recent results from W7-X. We will examine how key magnetic geometry parameters, especially the vacuum rotational transform, local magnetic shear, and mirror ratio, affect KBM growth rates and thresholds. Comparative studies across multiple magnetic configurations reveal that those with higher local iotas and mirror ratios tend to exhibit increased susceptibility to KBM onset [3]. These results underscore the importance of targeted configuration optimization, not only to suppress KBM activity but also to balance against other forms of turbulence. In addition to the core findings, we will discuss how W7-X's enhanced heating and fueling capabilities, particularly the integration of pellet injection and neutral beam injection, affect pressure profiles and drive conditions for KBMs.

As W7-X continues to demonstrate high-power, long-pulse discharges, insights into KBM behavior are proving increasingly vital. Understanding the interplay between magnetic geometry, pressure-driven instabilities, and turbulence will be critical for sustaining high-confinement regimes over extended durations. Ultimately, this research contributes not only to the optimization of W7-X operation but also to the broader goal of designing next-generation stellarators capable of achieving reactor-relevant performance. This work highlights ongoing efforts to mitigate KBM-driven transport and improve plasma confinement, offering valuable guidance for the design and operation of future fusion energy devices.

References
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