Visualization of Fast Ion Phase-space Flow in Plasmas Well-below, Near and Well-above Alfven eigenmode Stability Threshold in Tokamak

X.D. Du[1], W.W. Heidbrink[2], M.A. Van Zeeland[1], J. Gonzalez-Martin[1], M.E. Austin[3], Z. Yan[4], G.R. Mckee[4]

[1] General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
[2]University of California, Irvine, California 92697, USA
[3]University of Texas-Austin, Austin, Texas 78712, USA
[4]Univeristy of Wisconsin-Madson, Madison, Wisconsin 53706-1687, USA
e-mail (speaker): duxiaodi@fusion.gat.com

Transport of fast ions along certain local phase space paths, referred to as fast ion phase-space flow, has been systematically measured by an imaging neutral particle analyzer (INPA) [1, 2] in three plasma regimes, which are well-below, near, and well-above the Alfvén eigenmode stability threshold [3, 4].

(1) In plasmas well-below the AE stability threshold, fast ions are well-confined on passing particle orbits without noticeable transport over the phase space. The observed INPA images agree well with the synthetic INPA images, using the fast ion distribution predicted by neoclassical theory.

(2) In plasmas near the AE stability threshold, INPA images in the presence of AE activity moderately deviate from those without AE activity. The image difference can be well interpreted by AE-driven, phase-space fast ion flow. As seen in Figs. 1 (a) and (b), paths of this flow over the velocity space (or streamlines) is reconstructed by the intersection lines of curved E' and μ surfaces, referred to as E'&μ line (where $E' = E-\omega/n*P_\zeta$; E, P_ζ and μ are the energy, canonical toroidal momentum and magnetic moment of ions; ω and n are the angular frequency and toroidal mode number of AEs, respectively). Resonant fast ions move radially inward by gaining energy and move radially outward by losing energy and the trajectory well aligns with the E'&μ lines that pass through the mode resonances near the injection energy of neutral beams.

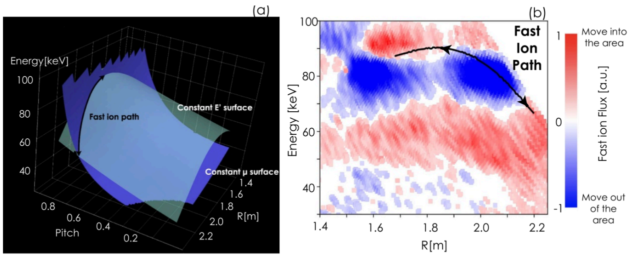

Figure 1. (a) Reconstructed constant μ = 18 keV T−1 surface and constant E′ surface. The intersection lines of two curved surfaces are the fast ion phase space flow path, indicated by the black arrow. (b) The averaged flow image from 0.37 s to 0.4 s, along with the projection of the E′ and μ line from (a).

(3) In plasmas well-above the AE stability threshold, fast ion phase-space dynamics show additional features. Fast ions are transported out of the birth positions so promptly along the streamlines that the slowing-down process from the injection energy is not observable, exhibiting strong critical gradient behavior at local phase space. As a result, the increase of electron temperature is very small, in spite of an increase of beam power by ~45%. It should be emphasized that the directions of phase-space transport, induced by AEs with different frequencies, structures and mode numbers, do not largely differ.

One of the interesting findings from this study is that, even though multiple small-amplitude AEs with a broad range of frequencies and toroidal mode numbers are destabilized in plasmas with very different safety factors q and bulk plasma parameters, the direction of phase space flow does not largely alter for fast ions on passing orbits. This strongly indicates the possibility to develop a computationally-efficient fast ion phase-space transport model, which flattens local fast ion density profiles at resonances along E'&μ lines. The radial widths of flattening are determined by AE amplitudes, which could be obtained empirically from experiments.

This work was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award Numbers DE-SC0020337, DE-AC05-00OR22725, DE-FC02-04ER54698, DE-AC02-09CH11466, and DE-SC0015878.

References

[1] Du X.D., Van Zeeland M.A., Heidbrink W.W. and Su D. Nucl. Fusion 58 082006 (2018)
[2] Van Zeeland M.A., Du X.D., Heidbrink W.W., Stagner L. and Su D. J. Instrum. 14 C09027 (2019)
[3] Du X.D. et al Phys. Rev. Lett. 127 235002 (2021)
[4] Du X.D. et al., Nucl. Fusion 63, 046020 (2023)