Toroidal modelling of interactions between internal kink instability and energetic ions in HL-2M

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Understanding the interaction between macroscopic magnetohydrodynamic (MHD) instabilities and energetic particles (EPs) remains a crucial issue for both present and future large tokamak experiments[1]. In order to maintain favorable conditions for fusion, energetic ions need to be confined inside the plasma for a sufficiently long time to deposit their energy onto the background thermal species. On the other hand, EPs are also known to strongly (either stabilization or destabilization) influence the MHD instabilities. The equilibrium distribution of EPs, in both the configuration and particle velocity spaces, plays an important role in this process. The present work investigates some of the aforementioned effects, specifically (i) targeting the internal kink instability and (ii) with application to the HL-2M device.

Besides the specific new application, this study also presents new physics aspects as compared to many of previous studies. Specifically, we consider the following.

- Non-perturbative MHD-kinetic hybrid computation of the IK instability in the presence of EPs.
- A systematic survey of kinetic contributions due to various EP drift resonances to the IK mode stability, assuming a reasonably realistic equilibrium distribution of EPs in the particle phase space (slowing down in energy and anisotropic in pitch, as shown in Fig.1) in HL-2M.
- Detailed guiding center drift orbits as traced by test EPs in the presence of magnetic perturbations due to the IK instability, with the overall perturbation amplitude being scanned.
- The EP loss fraction due to the unstable IK, as well as the strike point pattern on the limiting surface due to lost particles, is quantified for HL-2M.
- The loss study is performed, and the results contrasted, assuming either a static 3-D perturbation or a sawtooth like time-varying perturbation.

Compared to the fluid model, MHD-kinetic hybrid computations with MARS-K[2] show a stabilization effect on the IK in HL-2M. An exception is the strong fishbone-like drive to the mode by precessional drift resonances of trapped EPs, for a weakly unstable fluid IK in the presence of plasma flow. In addition, the transit resonance of co-current (counter-current) passing EPs destabilizes (stabilizes) the IK. While this resonance of co-NBI will introduce the infernal-like[3] mode structure. These results suggest that the sawtooth behavior can be controlled by the choosing the direction of NBI. REORBIT module[4] is utilized for the EP loss study. 3-D perturbations due to an unstable IK affect the EP drift orbit, confinement and loss in HL-2M, but the effect is generally moderate. The IK instability induced EP loss fraction is found to be typically less than 10%, without counting the prompt orbit loss associated with the 2-D equilibrium field for counter-current particles. The latter reaches about 16% in HL-2M. A sawteething-like time-varying perturbation field, produces about 30% loss for the co-current EPs in HL-2M. The majority of lost EPs tend to strike the lower divertor region, with only a small fraction of particles striking the low-field side mid-plane region of the limiting surface. These should thus be the regions of particular concern when operating HL-2M.

References

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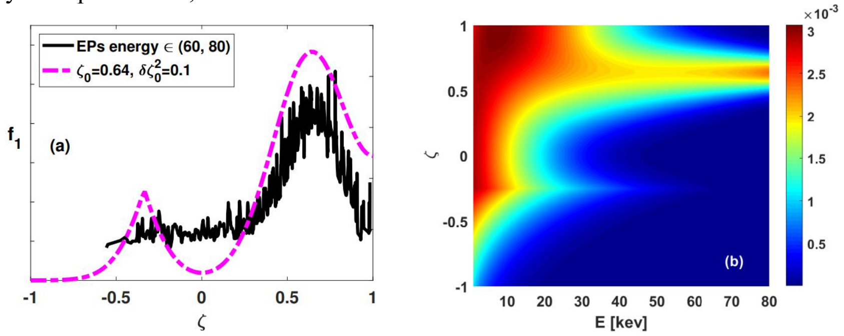

FIG. 1. (a) The EP distribution in the particle pitch angle space, calculated by TRANSP and averaged over the particle energy interval of 60-80 keV (solid line), versus that approximated by the analytic model and adopted in MARS-K simulations in this study (dash-dotted line). (b) The analytical EP distribution along the particle energy E and the particle pitch $\zeta \equiv v_{||}/v$.