Development of a hybrid fluid-kinetic particle-based model for simulating plasma heating and fueling by neutral beam injection

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Numerical models for simulating neutral beam injection (NBI) using the hybrid fluid-kinetic code Hybrid-VPIC [1] are described and used to investigate fueling and heating of a classical magnetic mirror. High-energy neutral beams provide heating, momentum transfer, and fuel to magnetically confined plasmas. Integrated modeling of fusion plasma systems including NBI is challenging due to varying length scales and time scales of the system; for example, the size of a magnetic mirror is typically several meters, and global stability evolves over microseconds, whereas electrons in the high-field magnetic throat have gyro orbits of order microns and gyrofrequencies of order picoseconds. Hybrid fluid-kinetic models with kinetic ions and fluid electrons exploit this scale separation by eliminating the fastest and smallest electron dynamics while retaining kinetic ion effects (i.e., non-Maxwellian distributions and finite Larmor radius). In Hybrid-VPIC, a generalized Ohm's law governs mass-less fluid electrons and ion dynamics are evolved with the fully-kinetic particle-in-cell method with Monte Carlo collisions. In this study, we discuss new particle collision models developed within Hybrid-VPIC for simulating inelastic collisions between charged and neutral particles including charge exchange and ionization. We explore the transition from a charge-exchange dominated regime for low beam energies (~25 keV) to an ionization dominated regime for high beam energies (~100 keV) in a case study of NBI fueling of a magnetic mirror.

[1] Le, A., Stanier, A., Yin, L., Wetherton, B., Keenan, B., & Albright, B. (2023). Hybrid-VPIC: An open-source kinetic/fluid hybrid particle-in-cell code. *Physics of plasmas*, *30*(6).