Coupling plasma and neutral kinetic models: Considerations and solutions

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In the edge and divertor regions of magnetic confinement devices, the plasma and neutral species are both highly non-Maxwellian. First principles simulation of this environment therefore requires self-consistent kinetic theory. To this end, the gyrokinetics edge simulation suite XGC [1] is coupled to DEGAS2 [2], a Monte Carlo transport solver for the neutral species. Earlier iterations of this coupling identified a lack of energy and momentum conservation. This unphysical behavior was due to the simplified treatment of the charge-exchange interaction: effective Maxwellian distributions were used to represent the field particle distributions in each of the respective collision operators that couple the plasma to the neutral gas [3]. A rigorous treatment recognizes charge-exchange as a nonlinear interaction between (unknown \textit{a priori}) non-Maxwellian populations.

The lack of conservation is one manifestation of the equivalent Maxwellian approximation whenever nontrivial cross sections are used. One way of mitigating this complication is by approximating the charge-exchange cross section as uniform in energy. This has been previously implemented in XGC1 [4], and sacrifices accuracy to a tolerable extent for the low-recycling regime. However, this approximation does not generalize well to regimes where other neutral interactions become important.

We propose and implement a conservative spectral method [5] in DEGAS2 to facilitate kinetic plasma coupling and nonlinear collisions. This is a manifestly conservative and highly efficient method for solving the nonlinear Boltzmann equation without approximation (beyond numerical discretization). The efficiency is enabled by precomputation of the discrete collision operators, which can be saved between simulations and shared among the spatial cells. The collision operator for ions is found by projecting the orthogonal Burnett basis onto the velocity mesh, as enabled by the “total-f” framework of XGC1 [6]. In addition to mitigating the lack of conservation in charge-exchange interactions, the spectral method also admits the powerful ability to rigorously handle nonlinear neutral-neutral scattering, a unique capability among practical kinetic edge simulation models.


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