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Stochastic and spectral methods as complimentary approaches to modelling neutral-plasma interaction

G. J. Wilkie[1], F. Laggner[1], A. Maan[1], T. Kessler[2], R. Hager[1], S.-H. Ku[1], R. M. Churchill[1], C.S. Chang[1], A. Bortolon[1], S. Rjasanow[2], D. Stotler[1]
[1] Princeton Plasma Physics Laboratory
[2] Saarland University
e-mail (speaker): gwilkie@pppl.gov

In plasmas with a high neutral density, the details of neutral transport and collisions become increasingly important for first-principles predictions. Atomic and molecular transport also plays an important role in diagnosing plasma via line radiation.

Monte Carlo methods used in tools like DEGAS2[1] are particularly robust and efficient in the limit where collisions between neutral species are negligible. Novel results from this regime will be presented that employ synthetic diagnostics both to validate kinetic plasma simulations and infer the recycling behavior of liquid metal plasma-facing components.

Stochastic methods, however, suffer a significant performance penalty in treating nonlinear interactions. Because of this, state-of-the-art fusion-relevant neutral solvers employ a simplified BGK collision operator. This simplified collision operator is tuned only to the fluid viscosity and cannot be expected to provide accurate kinetic results when neutral-neutral interactions are important. This is the case in detachment-relevant regimes, wherein a very low plasma temperature allows a high neutral density. A similar approximation is also commonly used for neutral-ion charge exchange[2], and this approximation is inconsistent with the physical charge-exchange cross section.[3]

The difficulties associated with these types of nonlinear interactions motivated the development of a conservative spectral solver of the nonlinear Boltzmann transport equation.[4] This tool, tentatively called LightningBoltz, builds upon the recent Galerkin-Petrov treatment of Gamba & Rjasanow.[5] LightningBoltz, even when run at low velocity-space resolution, is successfully benchmarked against several analytic results and other software including DEGAS2 (see Figure 1).

This capability enables the behavior of dense neutrals in divertor-like conditions to be predicted strictly from first principles without an approximate nonlinear collision operator. Results from a 1D comparison between the nonlinear Boltzmann operator and the BGK simplification will be presented with implications for divertor detachment. A reduced model has been developed to predict under what conditions this difference is likely to be significant. In addition, an acceptance-rejection technique will be presented that allows a rigorous Monte Carlo treatment of charge exchange with non-Maxwellian plasma.

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References
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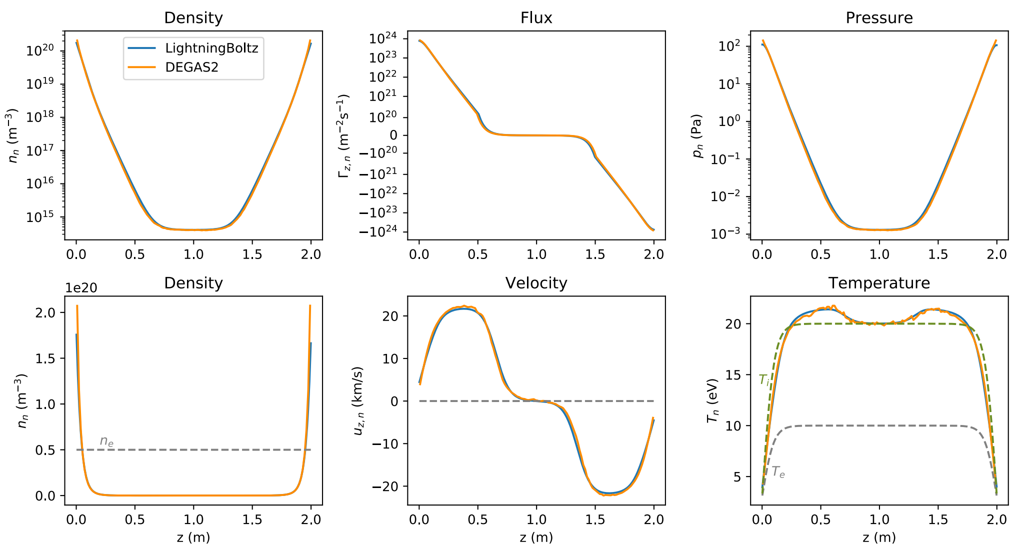

Figure 1: Results of a 1D+3V steady-state benchmark between a conservative spectral Boltzmann solver (LightningBoltz) with a Monte Carlo neutral solver (DEGAS2).