Advanced Numerical Methods for the Steady-State Plasma Transport Problem

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(Dated: July 15, 2011)

Solving the problem of steady-state plasma transport is as important for magnetic fusion as it is challenging. In a steady-state fusion reactor, energy and particle sources exactly balance naturally driven sinks. The sources can be external, such as fueling injections, or internal, such as thermonuclear reactions. The sinks can come from collisional (neoclassical) processes, or, more strongly, from profile-gradient-driven turbulence. Predicting the performance of future fusion experiments depends largely on accurately modeling the interaction of turbulence and transport. However, solving this problem is extremely challenging, in large part due to the highly disparate temporal and spatial scales involved. While turbulence, being dominated by gyrokinetic particle motion, can occur over a few centimeters at frequencies of megahertz, it may take several seconds for that turbulence-induced flux to transport energy radially across the meter-sized plasma.

TGYRO [1] solves the transport problem by calculating neoclassical and gyrokinetic fluxes at several discrete radial locations, balancing these fluxes with plasma sources, and using a Newton solver to iterate to a global solution. However, the steady-state transport problem is too complex for a traditional Newton algorithm: the global residual terrain can be difficult to navigate, with narrow valleys, broad planes and multiple local minima. An additional challenge is that turbulence calculations can be very expensive, potentially costing several thousand CPU-hours each, so the efficiency of the root-finding algorithm directly impacts the feasibility of the problem.

Using intuition gained by a simple test problem, we develop advanced algorithms for the TGYRO transport solver that improve the efficiency and reliability of the root-finder. These include a Levenberg-Marquardt problem formulation and line residual backtracking. As a test, we compare the performance of these methods on a series of discharges from the DIII-D and NSTX machines, using TGLF [2] as the transport driver. Finally, we predict the results of an upcoming experiment on NSTX and show how adding impurities to RF-heated plasmas can improve electron plasma confinement.

This work is supported by the SciDAC Center for the Study of Plasma Microturbulence and DOE Contract DE-AC02-09CH11466.

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