GYROKINETIC STUDIES ON THE STABILIZATION OF HIGH FIELD AXISYMMETRIC MAGNETIC MIRRORS

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Magnetic mirrors are an exciting and active field of fusion research and pose interesting computational challenges for gyrokinetic turbulence and stability codes. Mirrors are an attractive fusion device because their simple cylindrical geometry has numerous advantages for reliability, availability, maintainability, and inspectability. They are inherently steady state, with no plasma current to inject energy to cause a disruption. The Wisconsin High-Field Axisymmetric Mirror (WHAM) is an experiment which aims to test the viability of today's technology to create a tandem mirror fusion reactor [1]. They aim to demonstrate the performance of one end plug, advanced using today's capabilities of high-temperature superconducting magnets, sloshing ion neutral beam injection, high-power electron-cyclotron heating, high-harmonic fast wave ion heating, and shear flow stabilization.

Using computational tools for physics modelling and benchmarking them against experimental results is central to the mission of WHAM [2]. Their present models are time-independent, bounce averaged along the field line, and assume axisymmetry in the dynamics, leading to only the radial spatial dimension being considered (1x2v) and neglecting the expander regions. There are critical phenomena that can only be shown when considering full 2x or 3x dynamics. Furthermore, kinetic codes are needed to study the effects of heating mechanisms and shear rotation on the MHD interchange instability.

Gkeyll is a suite of discontinuous Galerkin (DG) continuum solvers for kinetic plasma problems [3]. The generalizable methods in Gkeyll have strong potential to answer these outstanding questions. Gkeyll simulations of magnetic mirrors present several difficult computational challenges [4]. High resolution is needed to resolve the compression of phase space due to the strong magnetic gradient forces. These high resolutions lead to a small time-step, but we aim to solve for time scales above collision times. Fast electron dynamics are fundamental, but long-time-scale phenomena are what we are interested in. This code is developed with a uniform velocity grid along a field line, but the grid necessary in the expander is not necessarily appropriate in the center. Although these simulations are challenging, our group has pioneered novel DG algorithms to address the challenges.

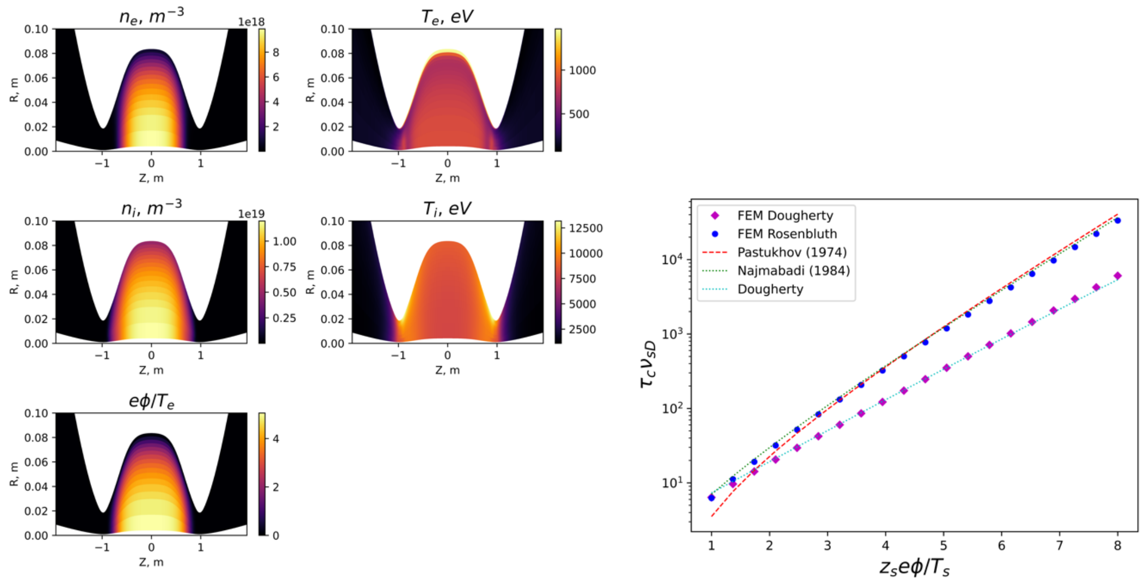

Fig 1. *Left: Density, temperature, and electrostatic potential of a deuterium and electron 2x2v simulation of WHAM run for 126 microseconds. Appropriate detail is resolved, with temperature peaking near the mirror throat and a dramatic density decrease in the expander. The potential reproduces appropriate estimates given by prior analytical work given modifications to the collision frequency. Right: parallel confinement time for electrostatically confined electrons in a mirror trap, showing how the Dougherty collision operator underestimates the confinement time due to scaling differences compared to the more accurate Coulomb collision operator.*

Recent developments have resulted in a ~200x speedup compared to a few years ago, enabling deeper and more extensive studies. Figure 1 showcases the developments our group has pushed forward in 2x2v studies for the steady-state equilibrium of WHAM. The most rigorous collision operator in Gkeyll is the Dougherty collision operator, which is attractive due to its relatively simple form, but assumes a velocity-independent collision frequency and an isotropic diffusion coefficient. Advances have been made in improving the Dougherty collision operator to produce the appropriate ambipolar potential compared to the more accurate Coulomb collision operator from an analytical calculation for the confinement time of electrostatically trapped species. Furthermore, novel conservative schemes for non-uniform velocity and position space grids have reduced the required resolution by 20x compared to uniform resolution simulations.

This work will present additional simulations with enhanced computational improvements and include beam heating effects for more accurate distribution functions. Novel techniques will be shown for non-uniform spatial grids that pack cells near the mirror throat. Analytic representations of electrons in the expander regions of mirrors will be shown to preserve physics fidelity and improve the computational efficiency. These contributions are essential in 5D gyrokinetic turbulence and stability studies, as well as informing others studying mirrors about the structure of the distribution function.

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