DIRECT COMPARISON OF GYROKINETIC AND FLUID SCRAPE-OFF LAYER SIMULATIONS

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Typically, fluid simulations are used to study the dynamics of the Scrape-Off Layer (SOL) and for divertor design in tokamaks. However, fluid models are only valid if the SOL is highly collisional, an assumption that is valid in many present day experiments but could break down in high-power scenarios envisioned for burning plasmas and fusion pilot plants depending on the divertor solution used. In high-recycling regimes with high separatrix density and low separatrix temperatures, fluid calculations may still be valid, although it is important to verify this. However, in low-recycling regimes with higher temperatures and lower density, the SOL dynamics will likely be kinetic. Fusion pilot plants could exist in a much less collisional parameter regime, and it is critical to understand the implications.

We will report on the investigation of SOL scenarios for the proposed Spherical Tokamak for Energy Production (STEP) [1] shown in Fig. 1, systematically comparing fluid and gyrokinetic treatments of the parallel SOL physics in order to identify important kinetic effects. We show that even in the nominal high recycling STEP scenario, the mean free path is long compared to the parallel temperature gradient length scale and kinetic effects have a large impact. The simulations consist of 2D axisymmetric SOL simulations of a deuterium plasma with argon as the radiating impurity using a fluid code, the B2.5 portion of the SOLPS-ITER [2] package, and a gyrokinetic code, Gkeyll [3].

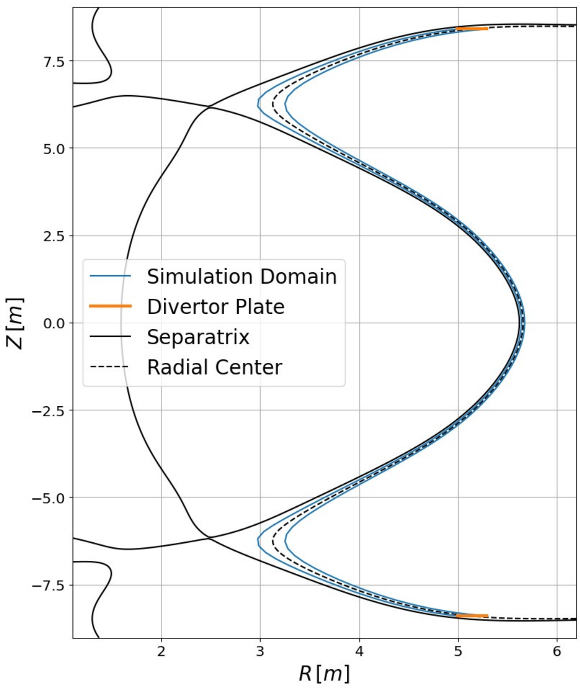

Figure 1: Simulation domain used for STEP SOL simulations. The solid black lines marks the separatrix and the dashed black line marks the flux surface at the radial center of the simulation domain. The blue lines indicate the inner and outer radial boundaries of the simulation domain and the orange lines indicate the divertor plates which are the parallel boundaries.

We ran SOL simulations with 80 MW of power flowing into the outboard SOL and an upstream density of $2.5\text{x}10^{19}$ m^{-3}. We find that the dynamics of the upstream SOL are kinetic—the velocity distributions are not Maxwellian and there is significant mirror trapping of the ions as shown in Fig. 2. This reduces the parallel ion heat conduction and drastically raises the upstream ion temperature in kinetic simulations relative to fluid simulations. Our simulations resulted in upstream electron and ion temperatures of 290 eV and 1.2 keV respectively in kinetic simulations and 240 eV and 530 eV respectively in fluid simulations. Even parameters from the fluid simulations indicate that kinetic effects could be important - upstream, the ratio of the ion mean free path to the connection length is 2.3 in fluid simulations (12 in kinetic simulations). When drifts are included, kinetic simulations show that the heat flux width is broadened to the ion banana width while fluid simulations do not capture this effect.

We also find that, in a magnetic configuration with a Super-X like divertor, the mirror force accelerates particles along the divertor leg resulting in an enhanced potential drop along the field line [4]. We demonstrate that the assumption of equal ion and impurity temperatures often made in fluid codes is invalidated by kinetic simulations; impurities are expelled by the potential before they have time to thermally equilibrate with the deuterium. The combination of the enhanced potential drop and low impurity temperature results in superior confinement of impurities to the divertor region in kinetic simulations; when the potential drop from midplane to divertor plate is large relative to the impurity temperature, the fraction of impurities able to travel upstream is small. In simulations with low radiation fractions, kinetic simulations display an upstream impurity density several orders of magnitude lower than fluid simulations. At higher radiation fractions, the difference is reduced, but the upstream impurity density is still approximately two orders of magnitude lower in kinetic simulations as shown in Fig. 3.

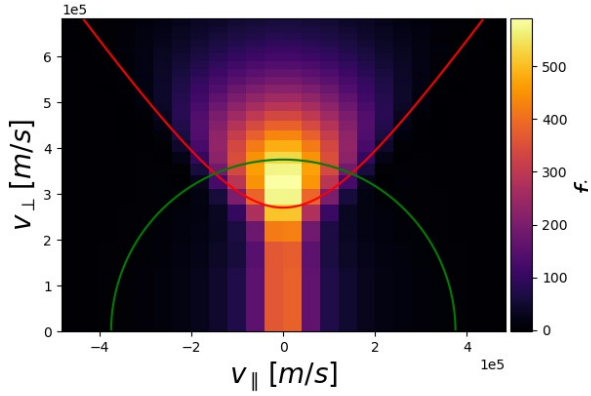

Figure 2: Ion distribution function 2 mm away from the radial center upstream at the midplane. The red line indicates the trapped-passing boundary including the effect of the potential and the green line is a contour of a Maxwellian with the same temperature as the distribution function.

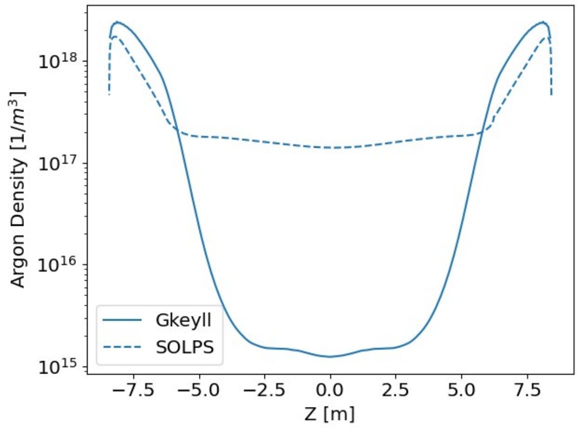

Figure 3: Total charged argon density (summed over charge states) plotted along the field line at the radial center of the domain in SOLPS and Gkeyll. The two codes have approximately the same radiated power (25 MW), but the upstream impurity density in Gkeyll is a factor of 100 lower than in SOLPS.

These findings have important implications for both high and low recycling regimes–the kinetic regimes characteristic of future devices may have wider heat flux widths and be able to support larger downstream impurity densities (and hence more radiated power) than would be suggested by SOLPS. Larger heat flux widths ameliorate the issues associated with a high heat load at the divertor plates and higher confinement of impurities to the divertor region would entail at least two benefits: (1) avoidance of impurity contamination of the core plasma, and (2) avoidance of high upstream densities, which can degrade confinement according to Ref. [4].

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