Effect of the penalized limiter-shaped heat sink for adiabatic electrons on particle transport in global gyro-kinetic simulations

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The forcing of a poloidally localized heat sink together with the poloidal $E \times B$ flows in the Scrape-Off Layer lead to poloidal asymmetries in the SOL density distribution. The dynamic of the initial transient is compared between two different penalizations: allowing or suppressing the transverse drifts within the immersed boundary. A quantification of the error on particle conservation is also provided.

In global gyrokinetic and flux-driven simulations for turbulent transport in Tokamak plasmas, the radial outer boundary condition acts as a heat sink [1]. The code GYSELA [2] has recently stepped to a penalized limiter boundary condition [3] that mimics the experimental Scrape-Off Layer (SOL) region. A radial outer heat sink of poloidally asymmetric limiter shape has been implemented within the adiabatic electron framework. This model considers the electrons in Boltzmann equilibrium along the magnetic field line and therefore do not resolve the perpendicular electron transport. Since the code evolves the 5-D distribution function for ion species only, particle conservation is a mandatory condition to satisfy the quasi-neutrality of the plasma system. GYSELA evolves the entire ion distribution function in the phase space without any separation between the equilibrium and the fluctuating scales. The initial phase of the simulations coincides with a reorganization of the distribution function towards the statistical equilibrium condition [4]. Due to computational memory limits of such big codes, the spatial step of GYSELA numerical grid is generally much larger than the plasma Debye length. All the phenomena happening at such small scales, such as the sheath layer characteristic of the plasma-wall interaction [5] are out of the range of these models. In the following we discuss the effect of the penalized radial outer heat sink of limiter shape implemented in GYSELA on the initial SOL density reorganization in two different penalization, that is allowing or suppressing the transverse drifts within the immersed boundary. Then we provide a preliminary quantification the error on particle conservation.

The limiter boundary condition for adiabatic electrons has been introduced in GYSELA with a penalization technique [6,7]. The geometry of a toroidally symmetric limiter and a first wall are modeled with a poloidally asymmetric immersed boundary maintained at low temperature by a Krook restoring force [3]. The Scrape-Off Layer of the simulations is identified in the plasma region where the magnetic field lines close inside the immersed boundary, that is in the limiter. The adiabatic electron response along the open field lines has been introduced by tying the flux surface averaged electric potential to the value ΛT_e within the SOL region, where $\Lambda = \sqrt{m_i/m_e}$ with $m_{i,e}$ the ion and electron mass respectively and T_e is the electron temperature. This results in a positive SOL electric field, which drive counterclockwise $E \times B$ poloidal flows. Finally, the immersed boundary has been electrically isolated by setting the electric potential equal to zero. Therefore an outward electric field is generated at the plasma-boundary interface, which drives $E \times B$ drift transport tangent to the boundary surface. This effect is specific of the implemented grounded boundary condition and does not model the sheath physics, which is out of the code resolution range. Also, the numerical resolution of the code introduces limits on the modeled boundary with respect to two main aspects: *(i)* the target temperature within the immersed boundary cannot be lower than the minimum value to well resolve the narrow Maxwellian in velocity space. Hence in principle particle transport is allowed within the immersed boundary. The target density towards which the restoring force acts cannot be fixed a priori but should instead be the local density before the Krook applies. *(ii)* the spatial transition between the plasma and the boundary regions is of finite extent. This creates a small layer at the plasma-boundary interface in the simulation domain where both plasma and wall physics acts simultaneously.

When a poloidally symmetric Maxwellian distribution function is initialized in GYSELA simulation with the penalized immersed boundary conditions described above, an initial transient leads to the accumulation of particle density inside the limiter via both parallel and transverse transport. Regarding the first, a transient phenomenon of condensation takes place along the field line intercepting the limiter: the density tends to accumulate in the low temperature region so to maintain a constant pressure [5]. The second concerns the competition between the vertical ∇B-drift and the reconnection current along the magnetic field line within the immersed boundary. Being τ_D the time taken by the vertical drift velocity $v_D$to push the ions of a vertical distance d, and $\tau_\parallel$the typical time to reconnect this charge separation along the field line at the thermal velocity and given that within the immersed boundary the temperature T_W is lower than in the plasma, the ratio $\tau_D/\tau_\parallel$ scales as $1/\sqrt{T_W}$. The colder the limiter, the fastest is the vertical motion with respect to the parallel one in the immersed boundary. Once inside the limiter, particles escape along the parallel direction on time scales longer then they arrive, which leads to a poloidally localized density accumulation within the immersed boundary. As a consequence, the plasma is polarized over the magnetic flux surfaces which cross the plasma-limiter interface. This polarization related to the initial transient can pollute the evolution of the SOL region. Furthermore, the accumulation of particles inside the limiter can lead to particle conservation issues: on one hand when a high density gathers locally where the temperature is very low, the numerical resolution in velocity space becomes determinant to correctly resolve the narrow distribution function and avoid the error propagation on the high density value; on the other hand, the vertical drift can push particles towards the bottom until they escape the numerical domain. To minimize the particle loss, the transverse drifts have been suppressed within the immersed boundary. In this case the boundary acts as a rigid impenetrable block with respect to perpendicular transport, keeping behaving as an electric resistance in the parallel direction. With this modification, the density within the immersed boundary stays constant and the particle transport induced by the limiter happens in the transition region at the plasma-boundary interface. The initial transient dynamic is modified as follows: the density that is pushed towards the bottom by the vertical drift and accumulates on the limiter surface, is the evacuated towards the high field side as a combined effect of both the $E \times B$ drift velocity tangent to the plasma-boundary interface and the poloidal SOL flows. In figure 1 is drawn the density radial profile at three different poloidal positions during the transient for a simulation with plasma size parameter $\rho_* = 1/150$, and aspect ratio $A = 6$: the density accumulation is clearly visible at the poloidal position close to the limiter in the high field side.

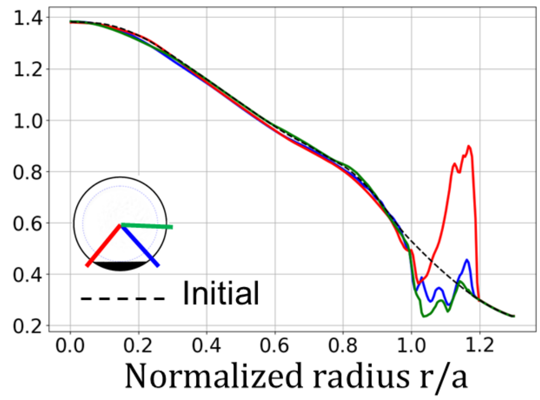

Figure 1 Radial density profile for the poloidal positions $\theta = 1.3\pi$ (red), $\theta = 1.7\,\pi$ (blue) and at midplane (green) during the initial transient

We finally quantify the level of particle conservation of GYSELA simulations with immersed limiter boundary. Two simulations are compared, the first at bigger $\rho_* = 1/150$, the second at smaller $\rho_* = 1/380$. Both simulations are run with the same aspect ratio $A = 6$ and the dimensionless wall temperature is equal to 0.3. The spatial grid (r, θ, φ) corresponds respectively to (255,512,32) and (512,1024,32) points and the velocity grid $(v_\parallel, \mu)$ of (256,64) points for both the simulations. The time evolution of the relative error is computed on the total number of particles N, i.e. the 5-D integral of the distribution function and is shown in figure 2. Therefore, being N_0 the total number of particle at the initial time, the error reads $(N - N_0)/N_0$. For the simulation $\rho_* = 1/150$ the error stabilizes at 0.5%. For the case $\rho_* = 1/380$ the error is always smaller, reaching at the end the value 0.2%. We interpret this improvement as an effect of the weaker vertical drift over other transport mechanisms.

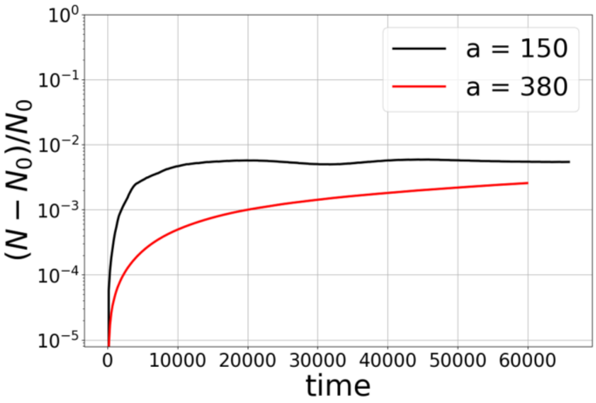

Figure 2 Relative error on the total number of particles

To summarize, the forcing of a cold spot within the plasma volume leads to an initial and transient reorganization of the SOL density which originates mainly from the vertical dynamics of the ∇B-drift. When drift velocities are active within the immersed boundary, the density accumulates inside the limiter under the effect of two different mechanisms: a condensation alike phenomenon on the cold spot along the magnetic field lines and, on the transverse direction, the vertical drift. When the transverse drifts are suppressed within the penalized region, the density that accumulated at the plasma-boundary interface at the bottom of the machine is moved along the poloidal direction on the high field side by a combined effect of the $E \times B$ poloidal SOL flows and the $E \times B$ drift at the plasma-boundary interface generated by the grounded boundary. The resulting relative error on the total particle conservation achieved when suppressing the transverse drifts from the immersed boundary stabilizes around a constant value lower than 1%. This work underlines one important property of the SOL physics: on the open field line region the charge separation created by the vertical drift cannot be balanced by the parallel reconnection currents. This task is instead carried out by the SOL poloidal $E \times B$ flows, which are less efficient and therefore create poloidal asymmetries in the SOL density distribution.

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