Up and downstream density scale asymmetries in Aditya tokamak scrape-off layer 3D simulations

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Abstract. In magnetically confined tokamak plasmas the width of plasma Scrape-off Layer (SOL) allows direct estimation of anomalous diffusivity in limited and diverted versions of plasma configurations. The diffusivity coupled to edge and SOL plasma fluctuations is to be a decisive factor in stability of fusion grade plasmas and can be characterized for its dependence on 3D effects in moderate size tokamaks like Aditya. For Aditya tokamak configuration, 3D effects in SOL plasma transport are studied using 3D Monte-Carlo transport code combination EMC3-EIRENE to complement the limited probe measurements during experimental operation of the device. As an important 3D effects, variation from 1D estimates of up and downstream density scale lengths are recovered to generate appropriate corrections for estimates of plasma diffusivity and other transport properties measured in Aditya tokamak plasma.

1. Introduction

The tokamaks are magnetic confinement devices to achieve improved plasma confinement and control in an ideally two dimensionally symmetric toroidal magnetic field configuration. Because of a toroidally localized, poloidal ring-like limiter, Strong 3-dimensional character of Scrape-off Layer plasma transport properties is expected in Aditya tokamak where the magnetized plasma experiments relevant to relatively larger fusion grade plasma device can be performed at moderate scales. In order to provide more sophisticated 3D global SOL plasma transport approximations, complementing the probe measurements, 3D Monte-Carlo coupled plasma-neutral transport code EMC3-EIRENE is implemented to the Aditya SOL plasma configuration as presented in this work [5-8]. As an important pointer to strength and character of edge and plasma turbulence that enable transition to high confinement regime, the SOL widths are strong indicator of plasma diffusivity and are readily available diagnostics to estimate its values. The SOL widths also decisive for intensity of heat fluxes incident on the targets and must be watched in to effectively optimizing the heat flux intensities in high power fusion grade plasma operations in large devices like ITER [3,4]. In rest of this paper we present, description of the model and application of the EMC3-EIRENE code to the Aditya SOL region followed by our results in terms of density gradient scale lengths of up and downstream SOL plasma as a function of anomalous plasma diffusivity. The comparison of the density scale lengths is done with simplistic expression of these lengths in a 2D symmetric SOL plasma and their discussion is followed by presenting important conclusions.
2. EMC3-EIRENE simulations of Aditya SOL plasma transport
Aditya is a moderate size tokamak having major and minor radii of 75 cm and 25 cm, respectively, with a maximum toroidal magnetic field of 0.72 T at the magnetic axis. In all discharges an outboard shift of plasma center from the magnetic axis and in outboard limited plasma discharges a slight shift of the plasma strike-point from the exact $\theta=0$ (mid plane) location is generally noted depending on the orientation of the toroidal magnetic field $B_t$. A complex distribution of connection lengths length ($L_c$) is already identified in the SOL region of Aditya in previous studies using EMC3-EIRNE [7,8]. The presently adopted version of the EMC3-EIRENE code works by executing Monte-Carlo plasma transport realizations along a 3D spatial mesh constructed following the equilibrium magnetic configuration of Aditya [11,12]. Originally applied to stellarators, helical devices [13,14] and recently to many tokamaks the underlying model model of the EMC3-EIRENE includes the balance equations for density, momentum, and energies of electrons and ions. Coupling of plasma transport code with neutral transport code EIRENE [6], provides their sources. An iterative procedure ensures a self-consistent solutions for both plasma and neutral particle parameters.

![Figure 1](image.png)

**Figure 1.** (a) The equilibrium magnetic flux surfaces for Aditya with a view of the poloidal ring limiter (thick circle centered at 75 cm) and the device vessel (thick square). (b) A schematic view describing the relative arrangement of the plasma core, LCFS, SOL and the experimentally explored ring limiter (located at $\Phi = 0^\circ$) in the device. The EMC3-EIRENE simulation grid. (c) for the ring limiter case.

As illustrated in figure 1(c), divided into 3 toroidal zones for optimum computation with zone-2 having higher resolution because of presence of ring limiter. Considering the relevant discharge conditions we use plasma current, $I_p = 25$ kA, plasma duration =25 ms, core electron temperature =100 eV, center chord averaged plasma density $5 \times 10^{18}$ m$^{-3}$, SOL plasma density $5 \times 10^{17}$ m$^{-3}$ where hydrogen is the working gas [6]. For the loop voltage $V_l = 2$ to 3 V with the plasma current $I_p = 25$ kA, an input power about 60 kW is used into the SOL from the core boundary surface. The converged output provides plasma density, temperature and flow velocity (Mach number). A good statistical accuracy ensures that their gradients can also be estimated.

3. Up and downstream plasma parameter characteristics
For the case of $D_\perp = 1$ m$^2$s$^{-1}$, in Fig. 2(a) and (b) the simulated plasma density profiles (2D surfaces) describing the effects of presence of ring limiter at the downstream toroidal location ($\Phi = 0^\circ$) is compared with that at the upstream location ($\Phi = -180^\circ$) where the sharp gradients of the profiles are largely smeared off. The radial profiles of density extracted from these results at various poloidal angles representing inboard and outboard radial extension across the SOL are plotted in figure 2(c) and (d), corresponding to upstream and downstream locations, respectively. A characteristic drop of a factor of about two in the density value from upstream location to downstream locations in the SOL region ($r - r_0 > 0$) is recovered in each case validating the essential accuracy of the simulation results. With availability of 3D spatial distributions of plasma parameters on the mesh their gradients are
obtainable for a range of $D_\perp$ values such that the density gradient scale lengths and their dependence on the plasma diffusivity can be characterized. In order to extract the effects introduced purely by 3D attributes of the SOL due to the toroidally localized ring limiter and poloidally localized plasma strike-zone, these lengths can now be compared with simpler one or two dimensional versions of these characteristics. As a preliminary effort the comparison of radial density gradient length, recovered here as function of effective plasma diffusivity is made with the most essential model that approximates diffusivity and SOL width relationship given as follows [1,2],

$$\lambda_n = L D_\perp / c_s$$  \hspace{1cm} (1)

where $L$ is the magnetic connection length and $c_s$ is the ion acoustic velocity. Below we calculate SOL widths for a range of diffusivity values from Model equation (1) at the upstream ($\Phi = -180^\circ$) and downstream ($\Phi = 0^\circ$) locations to compare them with the numerically obtained diffusive SOL width extracted from the EMC3-EIRENE data.

### 3.1. SOL width and gradient scales at upstream and downstream locations

The radial density profiles from up and downstream location at various poloidal angle values are used to characterize the relationship (1), between diffusivity and SOL width. The procedure adopted here involves determination of the plasma density ($n$) and its radial gradient in the SOL region from the simulation data and obtaining $\lambda_n = n / (dn/dr)$ for a range of $D_\perp$ values. For a selected radial location, $r = 25.5$ cm in the SOL (where $r = 25$ cm corresponds to the LCFS location), the $\lambda_n$ values are obtained for the complete range of diffusivity value used for the simulations. For the upstream location these values of $\lambda_n$ are presented in figure (3) (b), (d) and (f) corresponding to poloidal locations $\theta = 0^\circ$, $\theta = 90^\circ$ and $\theta = -90^\circ$, respectively. The local connection length value on the respective flux tubes and average sound velocity along the flux tube are used on the other hand with the value of diffusivity in each case to obtain the alternate value of $\lambda_n$ by substituting them in expression (1).

For very small diffusivities, e.g., $D_\perp = 0.25$ m$^2$s$^{-1}$, the $\lambda_n$ values estimated by (1) shows good agreement with the simulated data as presented in figure 3(b), (d) and (f). However, the radial density decay length $\lambda_n = n / (dn/dr)$ obtained from a local gradient shows a finite fluctuation with variation in $D_\perp$. The similar analysis is made using the density data at an upstream toroidal location $\Phi = -180^\circ$ presented in figure 3 (b), (d) and (f). The upstream profiles are free from any non-monotonic variation

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**Figure 2.** Simulated density profiles (a) upstream ($\Phi = -180^\circ$) and (b) downstream ($\Phi = 0^\circ$) and their radial variation at (c) upstream and (d) downstream at poloidal angles ($\theta = -90^\circ$), ($\theta = 0^\circ$) and ($\theta = 90^\circ$).

**Figure 3.** Dependence of SOL width $\lambda_n$ on $D_\perp$ from analytic model (1) (circles) compared to computed value of (stars).
with respect to $D_\perp$. This simplification at upstream is attributed to smearing of the structures present in the plasma parameters due to stronger diffusive effect over larger distance at upstream. Note that the limiter is about a length $m(R + a)$ away from this toroidal location towards the downstream location $\Phi = 0^\circ$ where it intersects the LCFS at $r = 25$ cm at the mid plane. At the downstream location large density jump across the LCFS is present and gradients, as visible from figure 2(d) downstream profiles, change sharply along the radial direction. This variation is however relaxed at poloidal angles away from the outboard mid plane. On the other hand, very smooth change in gradient is present in the upstream profiles throughout the poloidal extent as seen from figure 2(c).

4. Summary and conclusions

The 3D simulations of plasma transport in the SOL of non axisymmetric toroidally discontinuous poloidal ring-limiter configuration of Aditya tokamak plasma are done. The simulations are optimized to capture 3D effects in the transport properties of the SOL plasma and generate a substitute for largely 2D simplistic models in use for interpretation of the limited probe measurements. The validation of the simulation results in terms of conventional up and downstream characteristics of the plasma owing along the individual flux tubes is done. With availability of complete 3D spatial plasma parameter distributions, the computation of local gradients allows numerical estimation of the density gradient scale length and corresponding correction in them arising from the 3D effects. The density gradient scale lengths are analysed and compared with respect to simplistic estimates of the SOL widths applicable to one or two dimensional plasma flow along the open field lines. The contrast between the SOL widths recovered at upstream and downstream locations could be characterized showing that the SOL widths at the downstream locations have a rather complex dependence on the diffusivity. In addition to deviation in the SOL widths derived from the radial plasma from the simplistic estimates because of presence of 3D effects, in presence of stronger fluctuations, or correspondingly at larger diffusivity values used in the simulation, the complexity of 3D effects observed enhancing. The origin of this enhancement is expect to be in the increased possibility of mutual interaction between spatially wider 3D helical plasma structures at larger diffusivities.

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