Investigating the double scale length of limited plasmas with nonlinear simulations of the TCV Scrape-Off Layer

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Introduction

Heat loads onto the limiter for inboard limited plasmas have been measured recently in TCV using infrared thermography [1]. The parallel heat flux profile in the Scrape-Off Layer (SOL) exhibits a double scale length, confirming previous results from other tokamaks [2]. A short scale length of the order of several millimeters is always present in the vicinity of the Last Closed Flux Surface (LCFS), while in the main SOL the heat flux decay length is typically ten times longer. Even though the ITER first wall design was recently changed to handle the extra heat flux associated with such a narrow feature [3], the underlying physics is not well understood yet.

Nonlinear simulations of the TCV SOL

To improve our understanding, numerical simulations of the TCV SOL are performed using the GBS code [4]. This code solves the drift-reduced Braginskii equations in a 3D geometry. The resulting plasma turbulence determines self-consistently both the equilibrium profiles and their fluctuations. The simulations include the effects of magnetic shear $\hat{s} = 1.5$, finite aspect ratio $\epsilon = 0.24$ and ion temperature $\tau = 1$. The reference case is based on experimental parameters from the TCV discharge #49170, the electron density $n_{e,0} = 5 \ 10^{18} m^{-3}$ and temperature $T_{e,0} = 25$ eV at the LCFS are estimated from flush mounted Langmuir probe (LP) data, located on the central column of TCV, acting as the limiter. These values determine $\rho^* = \rho_s/R_{ax}$, and therefore the size of the simulation, and the normalized Spitzer resistivity $\nu = e^2 n_e R_{ax}/(m_i \sigma_{||} c_s)$, where ρ_s is the ion Larmor radius computed with the sound speed c_s, and $R_{ax} = 0.84$ m is the position of the magnetic axis. The toroidal field on axis is $B_t = 1.45$ T. The value of $q_{edge} = 3.2$ is computed from the equilibrium reconstruction. The geometry of the toroidal limiter in the simulations is shown in Fig.1, together with the main simulation parameters and a snapshot of the resulting electron density. Also, in this first simulation the
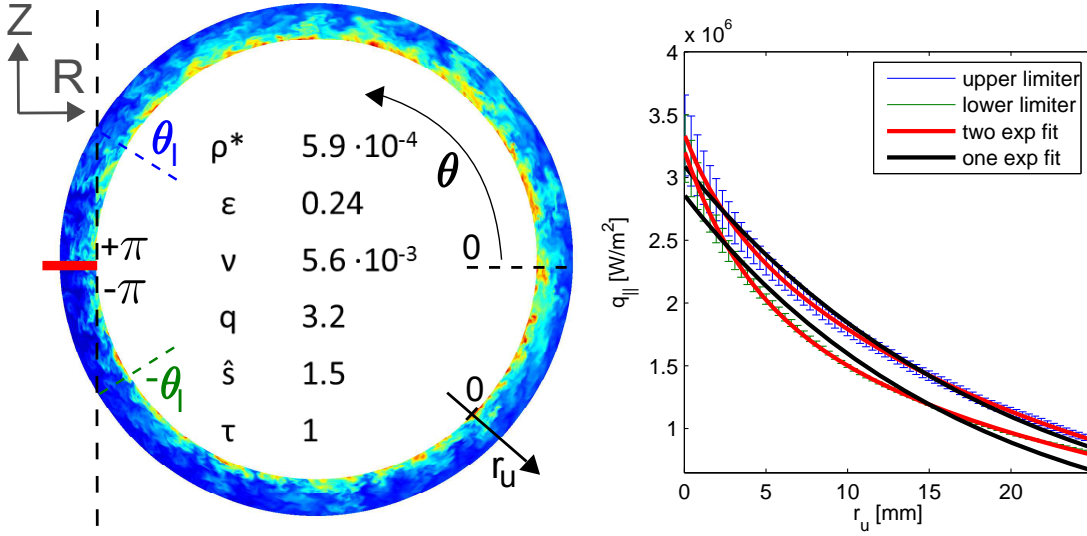
Figure 1: Left: snapshot of the electron density resulting from the GBS simulation, together with simulation (red) and TCV (black, dashed) limiter geometry. Right: fit of radial $q_{||}$ profiles taken along the limiters (blue, green) with a single exponential (black) and with a sum of two exponentials (red).

magnetic field and plasma current are antiparallel, contrary to the experiment.

Comparison with experimental data

The parallel heat flux is computed from the plasma density n_e, the electron and ion temperature T_e, T_i as $q_{||} = \gamma n_e \sqrt{\dfrac{T_e + T_i}{m_i}} T_e$, where all the quantities are averaged in time and in the toroidal direction, and $\gamma = 7$ is the sheath power transmission factor. In order to compare with experimental data, $q_{||}(r_u, \theta)$ has been averaged for $\theta_l < \theta < \pi$ and $-\pi < \theta < -\theta_l$, where θ_l is the angle where the whole GBS profile crosses the TCV-like limiter, resulting in two radial profiles, for the upper and lower parts of the limiter respectively. The narrow feature observed in the experiments is also seen in the simulations. Indeed, the limiter profiles are well fitted by the sum of two exponentials

$$q_{||}(r_u) = q_s \exp(-r_u/\lambda_s) + q_l \exp(-r_u/\lambda_l) \tag{1}$$

while the fit with a single exponential is unsatisfactory as shown in Fig.1. The fitted values of $\lambda_s = 2.7, 3.7$ mm and $\lambda_l = 22.3, 25.3$ mm for the upper and lower limiters respectively are similar with the experimental ones $\lambda_{s,exp} = 2.9$ mm , $\lambda_{l,exp} = 36.7$ mm. Furthermore, $q_{||}(r_u)$ has been analyzed at every fixed θ, revealing a strong poloidal variation of the fitted parameters (Fig.2). Above the midplane ($\theta \geq 0$), the narrow feature is relatively less
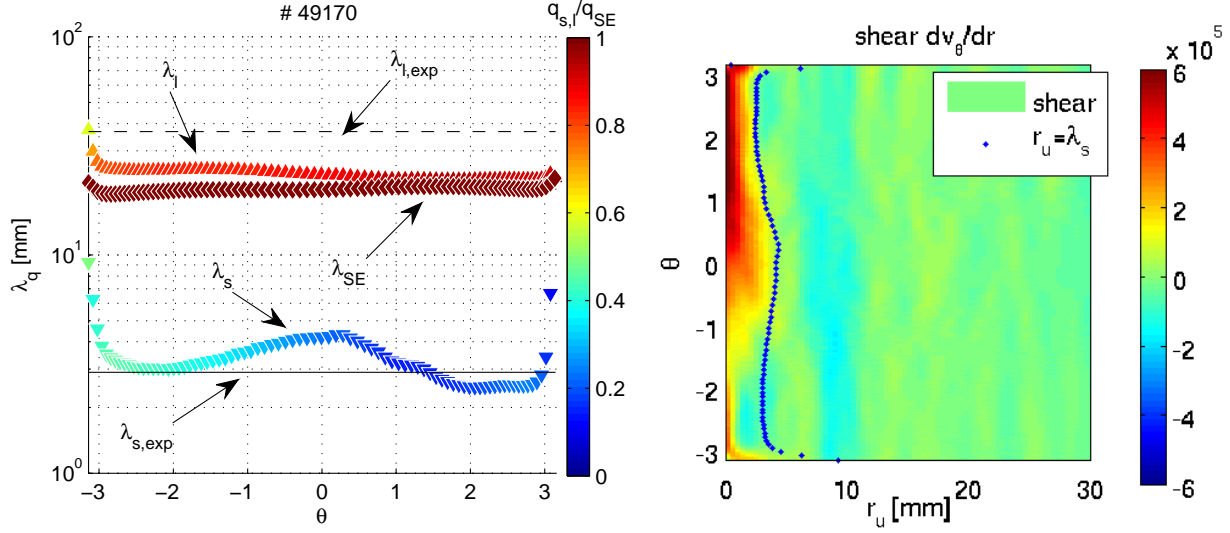
Figure 2: Left: poloidal variation of the fitted decay lengths of the heat flux, color-coded with their relative magnitude. The value resulting from a single exponential fit is shown, together with the experimental values. Right: velocity shear in the polidal plane, displayed with the short scale length of the heat flux profile.

strong since q_s/q_{SE} decreases, where q_{SE} is the heat flux magnitude resulting from a single exponential fit. Such an asymmetry might be due to the $\mathbf{E} \times \mathbf{B}$ drift velocity, whose main component is in the positive θ direction. Also, a strong correlation is found between the velocity shear $\mathrm{d}v_\theta/\mathrm{d}r$ of the $\mathbf{E} \times \mathbf{B}$ velocity and the steeper part of the profile, as shown in Fig. 2. The current in the SOL flowing to the limiter is computed from the simulation as $j_{||} = q_e n_e(v_{i,||} - v_{e,||})$, where $v_{i,||}, v_{e,||}$ are the ion and electron parallel velocities. Two profiles are obtained for the limiter with the same procedure used for $q_{||}$. The result is compared in Fig. 3 with the current measured by the LPs biased at the limiter potential. The presence of electronic currents in the region $r_u \leq \lambda_s$ is found in both experiments and simulations, suggesting a correlation between the narrow feature and such non-ambipolar currents, as already observed in COMPASS [5].

The role of resistivity

Experimentally, it has been shown that the excess heat load in the SOL scales with $\Delta P_{SOL} \equiv 4\pi R_{LCFS} B_\theta / B_\phi \int_0^\infty [q_{||}(r_u) - q_{||,l}(r_u)] dr_u \propto T_e^{1.43} n_e^{-1.01}$ [1], i.e. approximately with $1/\nu$. Three more simulations have been performed, in which the resistivity is increased by a factor 10, 20, 40 respectively. Due to time constraints, these simulations are not fully converged yet.
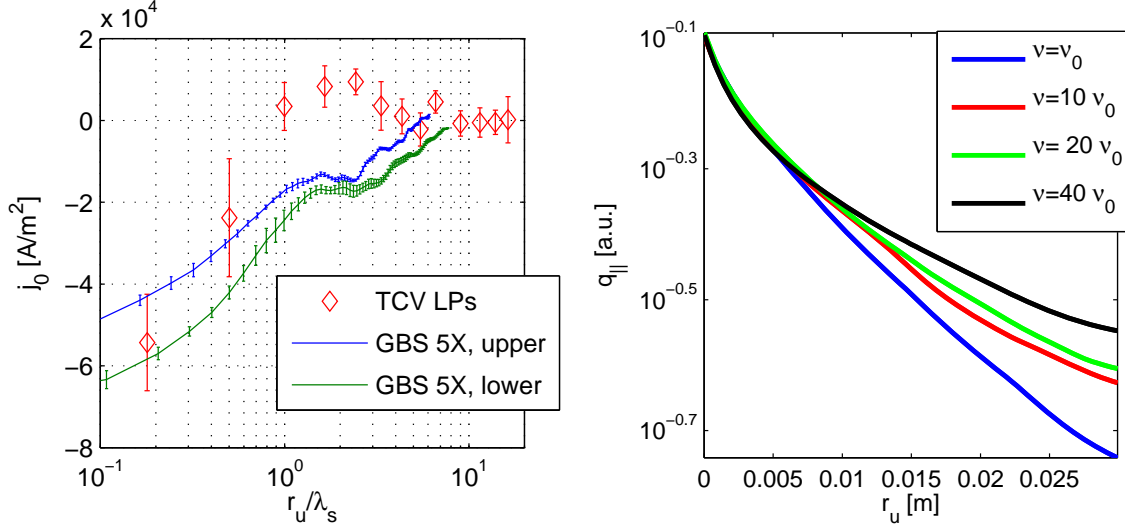
Figure 3: Left: density current flowing to the grounded limiter measured by LP in TCV discharge #49170 (red diamonds), and average profiles from the GBS simulation (5X magnification) for the upper (blue) and lower (green) limiter. Rigth: change in the (poloidally averaged) $q_{||}$ profiles increasing the resistivity.

Preliminary results are shown in Fig.3, where the poloidally averaged profiles of $q_{||}$ are displayed. Qualitatively, increasing ν flattens the profiles in the main SOL, while the narrow feature is still present. A quantitative analysis is foreseen, once an increased statistics will be available, together with a more detailed analysis of the statistical properties of plasma density and potential fluctuations. Moreover, another simulation with a different safety factor ($q_{edge} = 5.2$) is being performed and experiments in TCV are planned for the MST-1 campaign at the end of 2015. In particular, experiments in helium plasmas are foreseen.

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