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Theory-based Scaling of the SOL Width in Circular Limited Tokamak Plasmas

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ABSTRACT

A theory-based scaling for the characteristic length of a circular, limited tokamak scrape-off layer (SOL) is obtained by considering the balance between parallel losses and non-linearly saturated resistive ballooning mode turbulence driving anomalous perpendicular transport. The SOL size increases with plasma size, resistivity, and safety factor q . The scaling is verified against flux-driven nonlinear turbulence simulations, which reveal good agreement within a wide range of dimensionless parameters, including parameters closely matching the TCV tokamak. An initial comparison of the theory against experimental data from several tokamaks also yields good agreement.

INTRODUCTION

The peak heat load onto the plasma facing components of tokamak devices depends on the scrape-off layer (SOL) width [1–10], which results from a balance between plasma injection from the core region, turbulent transport, and losses to the divertor or limiter. While determining the SOL width and understanding the transport mechanism involved are critical issues for ITER and all future tokamak devices, so far there are no first-principle methods from the theory to predict the SOL width even for the simplest circular, limited plasmas.

The present letter reports on a theory-based scaling of the SOL characteristic pressure radial scale length $L_p = -p/\nabla p$ at the outboard mid-plane of an inboard limited plasma. The SOL width results from a power balance between parallel losses and anomalous transport due to low frequency interchange turbulence. Our work concentrates on a relatively simple, circular, inner-wall limited configuration. Understanding a circular configuration is a departure point for studying more complicated geometries or regimes, and is important for the start-up phase of ITER. The scaling derived in the present letter is verified against global, flux driven, 3D turbulence simulations of the SOL and agrees reasonably well with experimental data from inner wall limited tokamak discharges. We note that, in the past, there have been attempts to explain the SOL width using 2D models (see e.g., [11, 12]).

Recent studies using an electromagnetic drift-reduced Braginskii fluid model [13] have shown that the magnitude of the turbulent fluxes in the SOL can be predicted using the non-linear local flattening of the pressure profile caused by the linear modes [14, 15], the so-called gradient removal mechanism. Here, we summarize the results of this saturation model, which is fully derived in [14]. In non-linear, flux-driven simulations, it is observed that turbulent saturation occurs when the pressure nonlinearity exhausts the linear drive from the background gradient, i.e. $p_1 = p_0 \sim \sigma_r/L_p$. The subscripts 0 and 1 indicate background and perturbed quantities, respectively. The radial extension of the mode, $\sigma_r \approx \sqrt{L_p/k_0}$, is obtained from a non-local linear theory [16, 17] (k_0 is the poloidal wavenumber). Then, using the leading order contribution of a continuity equation, the radial E×B turbulent flux can be expressed as $\Gamma = p_0\gamma/k_0$, where γ is the linear growth rate of the instability that dominates the non-linear dynamics. The balance between perpendicular turbulent transport, $\partial_r\Gamma \sim \Gamma/L_p \sim p_0 \gamma/(k_0L_p)$, and the parallel losses at the sheath, $\nabla_{\parallel}(pv_{\parallel}e) \sim p_0c_s/(qR)$, leads to an

estimate of the profile length

$$L_p \sim (qR/c_s) (\gamma/k_\theta)_{max} \quad (1)$$

where R is the tokamak major radius, $q \approx (r/R)B_\phi/B_\theta$ is the cylindrical tokamak safety factor, and $c_s = \sqrt{2T_e/m_i}$ is the sound speed assuming $T_e = T_i$. (Note that the assumption $T_i = T_e$ is only expected to hold at high collisionality, as discussed in Ref. [3]. The detailed analysis of ion temperature effects is left for future work.) In deriving equation (1), it is assumed that the flux is driven by a single mode that maximizes $\gamma = k_\theta$.

The pressure gradient length can now be computed assuming that SOL turbulence is driven by resistive ballooning modes (RBMs). Non-linear, 3D electromagnetic simulations have addressed the nature of SOL turbulence in limited circular plasmas, finding that RBMs dominate the plasma dynamics [15, 18]. The SOL is very collisional compared to the plasma core, and, in the absence of magnetic field line periodicity, RBMs are dominant over non-linearly driven drift waves [18]; at the same time linearly unstable drift-waves are efficiently damped by the magnetic shear [19]. Electromagnetic induction has a destabilizing effect on RBMs near the ideal ballooning threshold [15]. Ion temperature effects could introduce the ion temperature gradient mode (ITG), but ITGs are important at much lower collisionalities than in the regime of interest ($v_* \sim 20-50$) [20]. It is also possible to estimate the non-linear regime instability using linear calculations and an estimate of the radial flux driven by each instability [21]. This calculation, when carried out for experimentally relevant parameters (connection length, collisionality, plasma size, positive magnetic shear, etc.), confirms the importance of RBMs in the SOL.

In order to obtain L_p through equation (1), we now seek for the typical growth rate and poloidal wave length of RBMs. A simple dispersion relation for RBMs, valid in the low β limit and considering only the low-field side midplane region (where the curvature drive for the modes is strong), can be obtained from the reduced resistive MHD equations:

$$(\gamma^2 - \gamma_b^2) k_\theta^2 = -\gamma \frac{\mu_0 \sigma_\parallel v_a^2}{q^2 R^2} (1 - \alpha) - \gamma^3 \mu_0 \sigma_\parallel. \quad (2)$$

Here $\gamma_b = c_s \sqrt{2/(RL_p)}$ is the typical RBM growth rate, σ_\parallel is the parallel Spitzer conductivity (neoclassical corrections to the Spitzer formula are neglected, since the large v_* in the SOL prevents trapping), $v_a = B/\sqrt{\mu_0 m_i n}$ is the Alfvén speed, $\alpha = q^2 \beta R/L_p$ is the ideal ballooning stability parameter, and we have approximated $\nabla_\parallel \sim 1/(qR)$.

The term on the right hand side of equation (2) results from the parallel dynamics in the Ohm's law. Parallel streaming is mediated by an effective conductivity $\sigma_\parallel (1 - \alpha)$ that allows RBMs to grow at lower k_θ provided that (a) the conductivity decreases, (b) β increases or (c) the connection length $L_c \sim qR$ increases [15]. The poloidal wavelength of the mode is a key component of the saturation rule given by equation (1), and therefore the strength of the parallel damping effect must

be estimated. Equation (2) leads to $k_\theta = (\mu_0 \sigma_{\parallel} v_a^2)(1 - \alpha)/(q^2 R^2 \gamma_b) = k_b^2$.

The SOL pressure gradient length L_p can now be obtained from equation (1) together with the RBM estimates $k_\theta = k_b$ and $\gamma = \gamma_b$. In order to normalize equation (1), we introduce a characteristic length $L_\perp = \rho_s = c_s/\omega_{ci} = \sqrt{2T_e m_i}/(eB)$ and the adimensionalized Spitzer resistivity $\nu = (e^2 n R)/(m_i \sigma_{\parallel} c_s)$. The scaling obtained is

$$\tilde{L}_p \tilde{R}^{-1/2} = \left[2\pi \alpha_d (1 - \alpha)^{1/2} / q \right]^{-1/2}, \quad (3)$$

where L_p and R are normalized to ρ_s (denoted by a tilde) and $\alpha_d = 2^{-3/4} \nu^{-1/2} (R/L_p)^{1/4} / (2\pi q)$ is a dimensionless variable that measures the strength of the parallel damping term in equation (2) [22, 23].

Equation (3) is particularly amenable for comparisons with flux-driven non-linear turbulence simulations. To that effect, we have carried out a verification of the scaling using global, non-linear simulations of the SOL dynamics using the GBS turbulence code, a numerical implementation of a global drift-reduced Braginskii model. The physical model and the code are fully described in [13]. Starting from the Braginskii fluid equations [24], we adopt the orderings $d/dt \ll \omega_{ci}$, $k_\perp \gg k_\parallel$, and $T_i \ll T_e$, which result in drift-reduced electromagnetic equations describing the nonlinear evolution of the plasma density, vorticity, electron and ion parallel velocity, perturbed poloidal magnetic flux, and electron temperature. The generalized Ohm's law includes plasma conductivity, electron inertia, electromagnetic fluctuations, and diamagnetic stabilizations. The equations are a two-fluid superset of the reduced MHD equations and they can describe the resistive and inertial branches of drift waves and ballooning modes, and, in addition, the ideal ballooning mode. Simulations including finite ion temperature effects, which can increase the drive for RBMs [20], will be carried out in future work.

The plasma dynamics is evolved within an annulus in the open magnetic field line region of the plasma vessel. Entire flux surfaces, up to the limiter, are included in the simulation domain. We use a simple circular geometry with a toroidal limiter on the high field side mid-plane, with constant q and constant magnetic shear $\hat{s} = rq'/q$. Boundary conditions at the magnetic pre-sheath entrance, where the plasma interfaces with the limiter plates and the ion drift approximation breaks down, are computed following the model by Loizu et al [25].

The drift-reduced Braginskii model used for the simulations does not separate fluctuations from the background profiles, and no separation between equilibrium and turbulent length scales is imposed a priori. The plasma density, temperature, potential, and parallel velocities are initialized using smooth profiles with a small perturbation superimposed. Plasma sources, which mimic the plasma outflow from the core, are then introduced. The pressure gradient increases until linearly unstable modes appear, driving turbulence that leads to perpendicular transport. Over a longer period, the modes saturate and a non-linear turbulent steady state is achieved. Since interchange turbulence and sheared flows occur in the simulated plasma, blob dynamics are also present in the simulations. The plasma gradients are naturally reached as a balance between plasma injection,

turbulent transport, and parallel losses at the plasma sheaths. Therefore, the GBS code is especially suited for verifying the dimensionless scaling given by equation (3).

An extensive simulation campaign, the details of which will be published in a longer paper, was carried out to investigate the inner-wall limited SOL parameter space. In essence, we are interested in simulating limited plasmas where RBMs dominate transport and to maximize the range of the dimensionless parameter space probed. The resistivity and q are varied to investigate the effect of the parallel dynamics of the turbulent modes. The plasma β is increased by several orders of magnitude to test the strength of electromagnetic effects predicted by equation (2). Crucially, the normalized major radius \tilde{R} is increased by a factor of 4 in order to test the effects of the plasma size predicted by the scaling. The simulations lie within the following range of parameters: $q = 3, 4, 6$; $\beta = 0$ to 10^{-3} ; $= 0.01, 0.1, 1$, $\tilde{R} = 500, 1000, 2000$, $\hat{s} = 0, 1, 2$. The poloidal resolution of the simulations is such that turbulent structures with $k_\theta \rho_s$ up to 2 are included. Taking TCV as an example ($R = 0.88\text{m}$, $B = 1.4\text{T}$, $T_{e,\text{SOL}} \approx 15\text{eV}$, $n_{e,\text{SOL}} \approx 3 \times 10^{18}\text{m}^{-3}$) we obtain $\tilde{R} \approx 2000$, $v \approx 0.01$, $\alpha_d \approx 0.5$, $\beta \approx 10^{-5}$, $v^* \approx 40$, while $q = 3-6$ and $\hat{s} \approx 2$. The SOL pressure gradient length typically has a width of a few centimeters, $\tilde{L}_p \sim 100$, $\tilde{R}/\tilde{L}_p \approx 20$. Our simulations are able to match this regime closely – a set of simulations with parameters equivalent to the TCV SOL were carried out.

We now verify the dimensionless scaling. The equilibrium pressure profiles observed in the turbulent steady-state typically have the form $p \sim \exp(-\tilde{r}/\tilde{L}_p)$ with L_p ranging from 25 to 150. The ideal stability parameter ranges from 0 to 0.25, while d (which only depends weakly on R/L_p) ranges between 0.01 and 0.6. From L_p , α , and α_d we obtain the left and right hand sides of equation (3), which are shown as a scatter plot in figure 1. Note that, by splitting the left and right hand sides, the plasma size dependence and the dependence on q and v can be observed separately. It is concluded that the dependence on plasma size (through R) and the dependence on the connection length $\sim q^{-1}$ are both well described. Overall, good agreement is found between the non-linear simulation results and the prediction of the analytical theory over the entire parameter range. This is due to the fact that the non-linear turbulent spectra observed in GBS simulations are typically dominated by a few resonant long wavelength modes with $k_\theta \rho_s \sim 0.1$. Furthermore, secondary instabilities, such as the Kelvin-Helmholtz mode, do not play a significant role saturating SOL turbulence in the regime of interest here [14].

Starting from equations (1) and using $\gamma = \gamma_b$ and $k_\theta = k_b$, it is also possible to obtain a scaling in terms of engineering parameters. This is a more practical approach for comparing against experimental data and to extrapolate L_p to future devices. Since β is very small in the SOL of circular limited plasmas, we take the electrostatic limit $\alpha \ll 1$, which leads to the following scaling:

$$L_p \approx 7.97 \times 10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_e^{-2/7} n_e^{2/7}. \quad (4)$$

Here q , n , and T_e must be provided at the last closed flux surface, while R and B_ϕ must be provided at the magnetic axis. All quantities are expressed using SI units except for T_e , which is given in eV.

The constant factor arises from the Spitzer conductivity, and we have approximated the Coulomb logarithm $\ln \Lambda \approx 15$. The factor of $q^{8/7} \sim I_p^{-8/7} p$ results in a strong dependence of L_p on the plasma current, while the explicit dependence on T_e and n is rather weak.

Equation (4) has been compared against experimental data from inner wall limited discharges in five devices, as shown in figure 2. The abscissa provides experimental measurements while the ordinate provides theoretical predictions given by equation (4). The data involve inner wall limited discharges from Alcator C-MOD [1], COMPASS [10], JET [8, 9], TCV [10], and Tore Supra [2, 7]. The data used in figure 2 is shown in table 1. The profile data were measured using reciprocating Langmuir probes, except for Tore Supra, where a retarding field analyzer was used to measure T_i and a tunnel probe was used to measure n and T_e . L_p has been obtained by determining the characteristic length of an exponentially decaying pressure profile. The horizontal bars indicates the 95% confidence interval obtained from the fitting of L_p . Ion temperature measurements were available only in Tore Supra discharges, thus when T_i is not available we approximate $L_p \approx L_{pe}$ (a correlation between L_{Te} and L_{Ti} has been demonstrated in [3]). We have also applied our scaling to the ITER start-up phase, using as indicative parameters $R = 6.2\text{m}$, $B = 5.2\text{T}$, $T_{e,\text{SOL}} = 50\text{eV}$, $n_{e,\text{SOL}} = 10^{19}\text{m}^{-3}$, and $q = 5-8$, obtaining $L_p = 6-10\text{cm}$.

Finally, it is noted that recent analysis of reciprocating probe measurements show that sometimes very steep pressure gradients are found just outside the last closed flux surface. This effect results in a very narrow (a few mm) feature where most of the heat flux can be dissipated [8, 9], and it might lead to enhanced power loads near the apex of the ITER inner first wall. This phenomenon could involve plasma transport across the separatrix and neoclassical transport effects may be important [26]. In our current approach, we have found that only one length scale was needed to describe the SOL profiles. The steepening of the SOL profiles near the LCFS will be addressed in the future by including a closed flux surface region within the non-linear simulations.

In conclusion, we have obtained a theory-based scaling for the SOL pressure gradient length in inner wall limited discharges. The scaling, provided by equations (3) and (4), arises as a natural consequence of the balance between parallel losses at the plasma sheath and perpendicular turbulent transport driven by a resistive instability, with the gradient removal model used as a saturation mechanism. The scaling has a clear physical interpretation that clarifies the role of plasma current, machine size, and collisionality in determining the SOL width.

The predictions of our model have been compared in figure 1 against fluxdriven non-linear turbulence simulations and in figure 2 against tokamak experimental data. The non-linear simulations match the analytical model within a wide range of parameters, including a case where the dimensionless parameters match very closely the SOL of the TCV tokamak. An initial comparison with experimental data is also very encouraging.

It is remarked that the physical model used for k_b and γ_b was chosen for simplicity, as it is meant to capture the parallel dynamics of long wavelength RBMs in an analytically tractable way. A reduced model including all geometry effects, compressible flows, electron inertial effects, diamagnetic

stabilizations, ion temperature, etc, could be developed using a linear stability code to compute $\omega = k\theta$. We anticipate, however, that the physical mechanism responsible for setting L_p should be robust and, moreover, it provides a framework that could be extended to more sophisticated configurations where the instability driving turbulent transport could be different.

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Case	q	R [m]	B_ϕ [T]	T_e [eV]	n_e [10^{19} m^{-3}]	$L_{p,exp}$ [cm]	$L_{p,th}$ [cm]
Alcator C-MOD	2.7	0.67	2.7	21.1	1.66	1.7	1.4
	2.7	0.67	2.7	29.4	3.74	3.2	1.6
	2.7	0.67	3.8	36.8	4.75	1.2	1.3
	2.7	0.67	3.8	26.6	6.67	3.7	1.6
	2.7	0.67	5.4	21.6	2.78	1.9	1.1
	2.7	0.67	5.4	23.2	4.77	2.3	1.2
Compass	2.6	0.56	1.15	26.9	1.04	2.2	1.5
	4.2	0.56	1.15	20.2	0.68	2.0	2.5
JET	3.0	2.96	2.53	29.6	0.26	3.9	2.5
TCV	5.0	0.87	1.2	20.8	0.35	3.8	3.4
	5.0	0.87	1.2	31.5	0.39	3.8	3.1
Tore Supra	5.4	2.23	3.2	10	0.22	4.6	4.5
	9.4	2.23	3.85	14.0	0.14	5.9	6.1
	4.9	2.23	3.85	18.0	0.40	3.5	3.6

Table 1: Plasma parameters used to obtain figure 2.

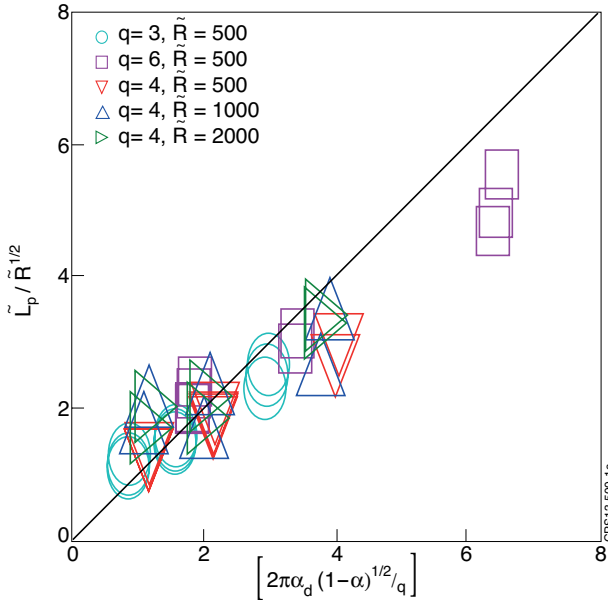


Figure 1: Dimensionless pressure gradient length \tilde{L}_p normalized by $\tilde{R}^{1/2}$ is shown as a function of the dimensionless parameters α , α_d , and q . All the parameters (except for q , which is imposed) are self consistently obtained in the GBS simulations. The solid line represents equation (3).

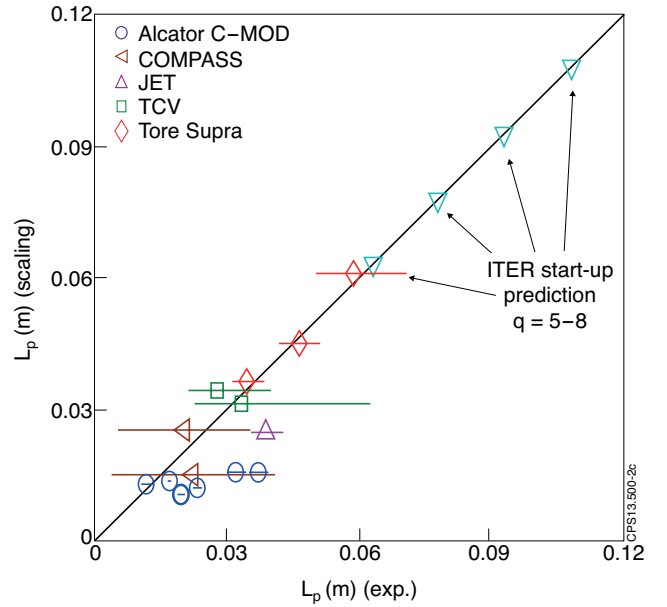


Figure 2. Scaling given by equation (4) is compared against experimental data from inner wall limited discharges. The abscissa and ordinate provide, respectively, the experimental data and the prediction of the theoretical scaling. The horizontal bars indicates the 95% confidence interval obtained from the fitting of L_p . ITER start-up predictions are displayed as "down-triangles".