IOP Publishing and International Atomic Energy Agency — Nuclear Fusion
Nucl. Fusion **52** (2012) 013009 (7pp) doi:10.1088/0029-5515/52/1/013009

Heuristic drift-based model of the power scrape-off width in low-gas-puff H-mode tokamaks

R.J. Goldston

Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA

E-mail: rgoldston@pppl.gov

Received 8 April 2011, accepted for publication 8 November 2011
Published 5 December 2011
Online at stacks.iop.org/NF/52/013009

Abstract
A heuristic model for the plasma scrape-off width in low-gas-puff tokamak H-mode plasmas is introduced. Grad B and curv B drifts into the scrape-off layer (SOL) are balanced against near-sonic parallel flows out of the SOL, to the divertor plates. The overall particle flow pattern posited is a modification for open field lines of Pfirsch–Schlüter flows to include order-unity sinks to the divertors. These assumptions result in an estimated SOL width of $\sim 2a\rho_p/R$. They also result in a first-principles calculation of the particle confinement time of H-mode plasmas, qualitatively consistent with experimental observations. It is next assumed that anomalous perpendicular electron thermal diffusivity is the dominant source of heat flux across the separatrix, investing the SOL width, derived above, with heat from the main plasma. The separatrix temperature is calculated based on a two-point model balancing power input to the SOL with Spitzer–Härm parallel thermal conduction losses to the divertor. This results in a heuristic closed-form prediction for the power scrape-off width that is in reasonable quantitative agreement both in absolute magnitude and in scaling with recent experimental data. Further work should include full numerical calculations, including all magnetic and electric drifts, as well as more thorough comparison with experimental data.

(Some figures may appear in colour only in the online journal)

1. Introduction

We now understand quantitatively many aspects of how heat is transferred to tokamak plasmas by energetic particles and radio waves. We also have a reasonable level of theoretical and empirical understanding of how heat is confined in the core of tokamak fusion plasmas, particularly in L-mode and ELMy H-mode regimes. Missing, however, is any validated understanding of how the heat escapes across the magnetic separatrix and is deposited onto plasma-facing components. Empirical scalings are highly inconsistent [1], and attempts to validate theoretical scalings against experimental data from individual experiments give contradictory results [2, 3].

In this paper we develop a heuristic model of the power scrape-off width outside of the separatrix in low-density H-mode tokamaks, based on assuming non-turbulent particle transport coupled with anomalous electron thermal transport. We compare the resulting magnitude and scaling of scrape-off-layer (SOL) widths with recently published experimental data from C-Mod, DIII-D, JET and NSTX, and find reasonable quantitative agreement. We then examine some of the simplifications of the model, and some implications of the model that can be examined experimentally. We conclude that while this heuristic model appears to be in reasonable agreement with experiment, more work is needed to make wider comparisons with carefully considered data bases, and calculations are needed with numerical codes that include the physics assumed here in order to provide quantitative, non-heuristic, predictions.

2. Drift-based SOL particle width

The model presented here is simple, but appears not to have been directly considered in the literature, although closely related issues have been examined [4–6]. It is well known that in the core of a collisional tokamak plasma the grad B and curv B drifts give rise to vertical motion of ion and electron gyro-centres. The divergence of this gyro-centre flow, resulting from pressure gradients, gives rise to an up–down asymmetric accumulation of ions. This asymmetric accumulation provides a parallel pressure gradient that drives balancing ion flows parallel to the magnetic field. Overall this flow pattern is referred to as Pfirsch–Schlüter flow. The gyro-centre picture of these flows is equivalent to the fluid picture, where the accumulation occurs due to the divergence of the diamagnetic flows in a torus. Here we use the gyro-centre picture, for its simplicity.

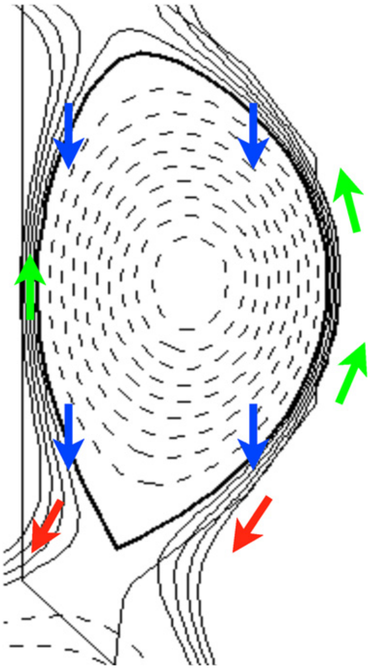

Figure 1. Pfirsch–Schlüter mass flows modified to include loss to divertor on open field lines. For toroidal magnetic field directed out of the page, and lower single-null divertor, magnetic drifts are vertically downwards, Pfirsch–Schlüter parallel flows are upwards near the midplane, and divertor parallel flows are downwards, towards divertors.

Consider now the separatrix at the edge of an H-mode tokamak plasma, shown in figure 1. Here the grad B and curv B drifts (downward-directed arrows crossing the separatrix, near top and bottom) carry ions across the last closed magnetic surface onto open field lines in the SOL, with Maxwellian-averaged velocity $\langle v_{\mathrm{grad}B+\mathrm{curv}B}\rangle = 2T/eZBR$. (We use here SI units, with T expressed in joules. Thus T/e is numerically equal to the temperature expressed in electron-volts.) In this region drift flows can be balanced not only by parallel flows that connect the bottom of the plasma to the top (upward-directed arrows in and along the SOL, near midplane), but also by parallel flows that leave the plasma region in the direction of the divertors (downward-directed arrows in and along the SOL, pointing into divertor region). *The first fundamental assumption of this heuristic model is that the parallel flow along B to the divertor competes at order unity with the usual Pfirsch–Schlüter parallel flow to the opposite side of the plasma.* This assumption is consistent with the measured parallel mass flow patterns [1, 7–11], where flows $\sim 0.5c_{\mathrm{s}}$ are found to be moving upwards at the midplane and downwards near the divertor throat, implying flow reversal in the lower outer quadrant of the SOL, for lower-single-null configurations with grad B drift downwards. Thus of order one half of the magnetic drift flux is entrained in the direction towards the divertor, and one half in the opposite direction. These data were only for L-mode plasmas. More recent flow measurements in ASDEX-Upgrade and TCV confirm these indications for ohmic, L-mode and H-mode plasmas [12–14], including measurement of $v_\parallel/c_{\mathrm{s}} \approx 0.5$ in the divertor entrance region of a low-power 'natural density' H-mode, $\sim$1 cm from the low-field-side separatrix in ASDEX-Upgrade.

We anticipate that our model is relevant only at zero or very low-gas-puff rates, with outgassed walls, where it can be assumed that volumetric sources in the near-plasma SOL are small, the plasma is well attached to the divertor, and the divertor acts as a significant sink of particles.

We can make a heuristic estimate of the drift-based SOL width that should result from this model by multiplying a typical residence time in the SOL, $L_\parallel/v_\parallel$, by the time-averaged positive grad B and curv B drift velocities perpendicular to the separatrix. We take an average parallel fluid velocity of $c_{\mathrm{s}}/2$, consistent with the experimental data discussed above, and $T_{\mathrm{i}} = T_{\mathrm{e}} = T_{\mathrm{sep}}$. Recognizing that the time-averaged radial drift velocity multiplied by the residence time is just the time-integrated radial displacement, and integrating from the midplane to the bottom of the plasma, we calculate

$$\Delta\psi_{\mathrm{p}} = \int_{MP}^{X-pt} (\vec{v}_{\mathrm{gc}}\cdot\vec{\nabla}\psi_{\mathrm{p}})\frac{\mathrm{d}l_\parallel}{c_{\mathrm{s}}/2}$$

$$= \frac{2}{c_{\mathrm{s}}}\int_{MP}^{X-pt} (\vec{v}_{\mathrm{gc}}\cdot\vec{\nabla}\psi_{\mathrm{p}})\frac{B}{B_{\mathrm{p}}}\,\mathrm{d}l_{\mathrm{p}}; \qquad B_{\mathrm{p}} = \frac{|\vec{\nabla}\psi_{\mathrm{p}}|}{R}$$

$$\Delta\psi_{\mathrm{p}} = \frac{2}{c_{\mathrm{s}}}\int_{MP}^{X-pt}\left(\vec{v}_{\mathrm{gc}}\cdot\frac{\vec{\nabla}\psi_{\mathrm{p}}}{|\vec{\nabla}\psi_{\mathrm{p}}|}\right)RB\,\mathrm{d}l_{\mathrm{p}}$$

$$= \frac{2}{c_{\mathrm{s}}}\int_{MP}^{X-pt}\frac{2T_{\mathrm{sep}}}{\bar{Z}eBr}RB\hat{z}\cdot\hat{\varphi}\times\mathrm{d}\vec{l}_{\mathrm{p}}$$

$$= \frac{4T_{\mathrm{sep}}}{\bar{Z}ec_{\mathrm{s}}}\int_{MP}^{X-pt}\hat{z}\times\hat{\varphi}\cdot\mathrm{d}\vec{l}_{\mathrm{p}} = \frac{4T_{\mathrm{sep}}a}{\bar{Z}ec_{\mathrm{s}}}$$

$$\lambda = \frac{\Delta\psi_{\mathrm{p}}}{|\nabla\psi_{\mathrm{p}}|} = \frac{4T_{\mathrm{sep}}a}{\bar{Z}eB_{\mathrm{p}}Rc_{\mathrm{s}}}; \qquad c_{\mathrm{s}} = \left[\frac{(1+\bar{Z})T_{\mathrm{sep}}}{\bar{A}m_{\mathrm{p}}}\right]^{1/2};$$

$$\bar{Z} \equiv \frac{n_{\mathrm{e}}}{\sum_i n_i}; \qquad \bar{A} \equiv \frac{\sum_i n_i A_i}{\sum_i n_i}$$

$$\lambda = \underbrace{\frac{4a}{\bar{Z}eB_{\mathrm{p}}R}\left(\frac{\bar{A}m_{\mathrm{p}}T_{\mathrm{sep}}}{(1+\bar{Z})}\right)^{1/2}}_{\text{ion drift}} \quad \text{or}$$

$$\underbrace{\frac{4a}{eB_{\mathrm{p}}R}\left(\frac{\bar{A}m_{\mathrm{p}}T_{\mathrm{sep}}}{(1+\bar{Z})}\right)^{1/2}}_{\text{electron drift}} \approx \frac{2a}{R}\rho_{\mathrm{p}} \qquad (1)$$

where in the first case we consider the ion magnetic drift speed, weighted by the ion charge, so in effect the average ambipolar speed, assuming that radial particle transport is determined by the ion drift motion. In the second case the radial transport is assumed to be set by the electron magnetic drift speed. As discussed in section 5, the self-consistent electric fields in the SOL need to be calculated to select between these two options, and to provide an accurate numerical coefficient for the result.

As an initial 'sanity check', evaluating equation (1) for typical JET and C-Mod parameters, e.g. $a = 0.95$, 0.22 m, $R = 2.95$, 0.69 m, $I_{\mathrm{p}} = 2$, 1 MA, $T_{\mathrm{sep}} = 100$, 75 eV and $B_{\mathrm{p}} = \mu_0 I_{\mathrm{p}}/\{\pi[2(1+\kappa^2)]^{1/2}\}$ with $\kappa = 1.7$, we do find results that are reasonably consistent with experimental measurements of the power scrape-off width projected to the outer midplane [15, 16]: $\lambda = 4.4$, 1.7 mm. Evidently the power scrape-off width in low-gas-puff H-mode tokamaks cannot be assumed to exceed the ion poloidal gyro-radius by a large factor.

It is interesting to note that the derivation of equation (1) parallels the derivation of the orbit shift of a passing ion. Conservation of canonical angular momentum underlies the mathematically convenient cancellation of terms. Perhaps even more interesting is that this calculation parallels the standard neoclassical calculation of the gradient scale length that is required to generate sonic-level Pfirsch–Schlüter flows. In this sense, independent of the assumption of losses to the divertor, it may be that this calculation provides a lower limit on the SOL width, due to changing Pfirsch–Schlüter physics at high parallel flow rates approaching the sound speed. Sonic-level Pfirsch–Schlüter flows imply order-unity variations in pressure around a flux surface, as does net transport across a flux surface of the same order as the magnetic drifts. Radial and poloidal electric fields can be expected to play an important role, as well, as discussed below. Determination of numerically accurate poloidal variations of pressure and flows in this regime await an analytic or numerical neoclassical calculation that does not assume $\lambda \gg \rho_p$, extending, for example, the work of [17] to high flow rates and order-unity pressure variation.

Implicit in this derivation is the assumption that cross-field particle motion at the separatrix is dominated by classical drifts. This is consistent with the observation in ASDEX-U [18] and DIII-D [19], that *ion thermal transport* is near neoclassical at the plasma boundary in deuterium H-mode plasmas, and with the general result of substantially improved particle confinement in deuterium H-modes. It is also consistent with SOL analyses discussed in [3, 20]. However, one can ask if it is reasonable to assume that classical drifts dominate the *particle flux* across the separatrix, even if ion thermal transport is neoclassical.

Multi-tip probe measurements have been made of the net turbulent electrostatic radial particle flux, Γ_t, at the separatrix of DIII-D H-mode plasmas, near the midplane [21]. This includes, of course, both inward and outward turbulent motion. For ohmic H-modes and ELM-free H-modes where measurements are available within a SOL width of the separatrix, the reported local values of Γ_t are $(1 \pm 0.5) \times 10^{20}\,\mathrm{m^{-2}}$ and $(4 \pm 1.5) \times 10^{20}\,\mathrm{m^{-2}}$. For these cases multiplying the locally measured density 2 mm inside the separatrix by the magnetic drift velocity based on the measured electron temperature at this location, one obtains $\Gamma_{\mathrm{grad}B+\mathrm{curv}B} = 1.4 \times 10^{20}\,\mathrm{m^{-2}}$ and $6 \times 10^{20}\,\mathrm{m^{-2}}$. Based on theoretical considerations, the turbulent transport is likely to be localized to the outer midplane, as is assumed in the analyses in the references, while the drift flux varies smoothly along the lower half of the torus. Furthermore, recent measurements [22] give an extremely low value of $\Gamma_t \sim 8 \times 10^{18}\,\mathrm{m^{-2}}$. (The authors estimate that this corresponds to a turbulent loss current of about 30 A.) Thus it appears likely that, under the assumption of order-unity drift flux loss to the divertor (and order-unity Pfirsch–Schlüter return flux to the main plasma), the net particle loss due to drifts exceeds the loss due to turbulent flux in these cases of low-gas-puff H-mode. While other measurements of Γ_t are available in ohmic or L-mode plasmas, or far from the separatrix of H-mode plasmas [23–26], no other published measurements appear to be available close to the separatrix in H-mode, except at the highest densities ($n/n_{\mathrm{GW}} > 0.85$) [27], where the present analysis is not expected to apply.

There is a surprising consequence of this heuristic picture that can provide a consistency check on the assumption of dominant losses due to classical cross-field drifts. Let us assume that all of the particle flux crossing the separatrix is due to the grad B and curv B drifts, and we further assume that one half of that flux returns to the plasma via Pfirsch–Schlüter flows, while one half leaves to the divertor plate, because a particle leaving the bottom half of the torus is roughly equally likely to flow to the divertor as to the top half, simply based on the connection length. Furthermore, experimentally there are comparable midplane and divertor Mach flows [1, 7]. Thus we can immediately estimate the net flux of particles across the separatrix (using the electron drift speed):

$$I_{\mathrm{loss}} = \frac{4\pi a n_{\mathrm{sep}} T_{\mathrm{sep}}}{B}. \qquad (2)$$

For the DIII-D parameters in the H-mode phase at 2.6 s in figure 3 of [28], $n_{\mathrm{sep}} = 2.5 \times 10^{19}\,\mathrm{m^{-3}}$ and $T_{\mathrm{sep}} = 80\,\mathrm{eV}$, equation (2) gives a loss current of 1.2 kA, in agreement with the experimental result shown in this figure. Note that in the L-mode at 2.3 s, the edge density and temperature are much lower, giving a drift loss current of 0.18 kA, much less than the measured value of 3 kA. This is consistent with the conventional understanding that turbulent losses dominate over drift losses in the L-mode.

From the loss current we can next calculate the particle confinement time:

$$\tau_p = \frac{\pi B R a \kappa n_{\mathrm{core}}}{2(T_{\mathrm{sep}}/e) n_{\mathrm{sep}}}. \qquad (3)$$

Using the parameters quoted above for JET and C-Mod, taking $B = 2$ and 5 T respectively, assuming $n_{\mathrm{core}}/n_{\mathrm{sep}} = 2$ for both, one finds for the particle confinement times, 375 ms and 67 ms, respectively, qualitatively reasonable H-mode values.

While recognizing the presence of turbulence in the SOL as analysed, for example, in [29], on the basis of the above it appears that it is not excluded to consider the hypothesis that anomalous particle transport is sub-dominant in driving particle flux across the separatrix in low-density H-mode plasmas, when compared with net losses of order one half of the drift flux.

3. Heat transport

While our heuristic derivation at this point addresses particle transport at the plasma edge, yielding the intriguing result that the SOL width in H-mode tokamaks with non-turbulent particle transport should be of the order of the poloidal ion gyro-radius, apparently consistent with recent measurements, it does not explicitly address heat transport. It also does not provide a means to predict T_{sep}, on which the drift speed depends.

Based on the previously noted ASDEX-U and DIII-D results, it is reasonable to assume that in H-mode plasmas the dominant heat transport across the separatrix is due to anomalous electron thermal diffusion. Furthermore, it is straightforward to calculate that the local heat flux associated with the grad B and curv B drifts, averaged over an isotropic Maxwellian particle distribution, is simply $q = (5/2)nT\langle v_{\mathrm{grad}B+\mathrm{curv}B}\rangle$. For the JET parameters noted above, if one assumes that one half of this heat flux goes to the divertor and one half returns to the plasma via Pfirsch–Schlüter type flows, consistent with the measured parallel flows, this amounts to only 1 MW summed over both the ions and the electrons, much less than the experimentally measured loss power. However, if we assume a modest electron thermal diffusivity of $1\,\mathrm{m^2\,s^{-1}}$, consistent with the ASDEX-U and DIII-D results, and take ~ 4 mm to be the gradient scale length, the resulting heat flux is 10 MW, consistent with experiment. Of course this analysis simply shows consistency between JET H-mode results and those of ASDEX-U and DIII-D, so should not be surprising.

If the edge electron thermal diffusivity of $1\,\mathrm{m^2\,s^{-1}}$ continues into the SOL, the characteristic time for filling a 4 mm SOL at this thermal diffusivity is 8 μs, comparable to the parallel loss time of about 10 μs due to Spitzer–Härm thermal diffusivity at 100 eV. *Our second fundamental assumption in this heuristic model, therefore, is that anomalous electron thermal diffusivity is adequate to 'fill' with electron heat the plasma channel defined by the flows discussed above.* We assume that electron heat does not flow significantly beyond this channel. In the very simplest heuristic picture, where we take a density of n_{sep} within the channel, and zero density outside of the channel, this is evident. Plasma heat cannot be transferred by plasma to the vacuum. In a more realistic situation with profiles, at the low densities outside of the main channel parallel losses are found to become sheath limited, which reduces the heat flux compared with the $T^{7/2}$ scaling associated with Spitzer–Härm thermal conductivity. Furthermore, radial turbulent heat flux is limited by falling density, even at constant T, through the relation $q_\perp \propto \langle \tilde{p}\tilde{v}_\perp \rangle$.

We now develop the implications of the assumption that anomalous electron thermal diffusivity fills the particle channel defined by the flows discussed above, and that the channel is emptied of heat by Spitzer–Härm electron thermal conductivity. Along the field lines this corresponds to the usual two-point model. Here we assume that the heat flux crossing the separatrix into the SOL is constant along the separatrix surface. This gives

$$P_{\mathrm{SOL}} = \frac{4\pi R \lambda B_{\mathrm{p}} \chi_{0,S} T_{\mathrm{sep}}^{7/2}}{(7/4) B L_\parallel}. \quad (4)$$

Combining equations (4) and (1) to eliminate T_{sep}, and evaluating the constants, we arrive at

$$\lambda = 5671 \cdot P_{\mathrm{SOL}}^{1/8} \frac{(1+\kappa^2)^{5/8} a^{17/8} B^{1/4}}{I_{\mathrm{p}}^{9/8} R} \left(\frac{2\bar{A}}{\bar{Z}^2(1+\bar{Z})} \right)^{7/16} \times \left(\frac{Z_{\mathrm{eff}}+4}{5} \right)^{1/8} \quad \text{all units SI} \quad (5)$$

if we assume that the ion magnetic drift determines the net particle transport, and

$$\lambda = 5671 \cdot P_{\mathrm{SOL}}^{1/8} \frac{(1+\kappa^2)^{5/8} a^{17/8} B^{1/4}}{I_{\mathrm{p}}^{9/8} R} \left(\frac{2\bar{A}}{(1+\bar{Z})} \right)^{7/16} \times \left(\frac{Z_{\mathrm{eff}}+4}{5} \right)^{1/8} \quad \text{all units SI} \quad (6)$$

if we assume that the electron magnetic drift determines the net transport. The dimensional variables are expressed in SI units: metres, watts, teslas and amperes.

What is perhaps most striking about equations (5) and (6) is the strong inverse dependence on I_{p}. Furthermore, since plasma current scales with the linear dimension of a device at fixed R/a, q, κ, and B, all of the size scaling in this expression is implicit, coming in through the weak power scaling.

We can also solve equations (4) and (1) for T_{sep}, giving

$$\frac{T_{\mathrm{sep}}}{e} = 30.81 \cdot P_{\mathrm{SOL}}^{1/4} \left[\frac{(1+\bar{Z})}{2\bar{A}} \right]^{1/8} \frac{a^{1/4}(1+\kappa^2)^{1/4} B^{1/2}}{I_{\mathrm{p}}^{1/4}} \times \left(\frac{Z_{\mathrm{eff}}+4}{5} \right)^{1/4} \quad (7)$$

again assuming the electron drift velocity is determinant, and with all units SI. (Note that T_{sep}/e is expressed in volts.) The resulting T_{sep} is close to 100 and 75 eV for assumed JET and C-Mod parameters.

4. Comparison with recent experimental results

Recently heat flux width measurements have been published for C-Mod [16], DIII-D [30], JET [31] and NSTX [32]. Experimental methods have improved, and these widths are believed to be more accurate than those reported previously, although measurement uncertainties remain. The quoted results are for outer strike point measurements in deuterium H-mode plasmas with low or zero gas puffing, and avoiding the effects of large ELMs. The experimental widths quoted below are 'integral' widths [33], $\lambda \equiv \int p\, \mathrm{d}l/\hat{p}$ mapped magnetically to the plasma midplane. A striking general pattern in the new experimental results is a strong inverse dependence on I_{p}, with relatively weak dependences on other variables, similar to equations (5) and (6). Table 1 evaluates equation (5) for deuterium plasma cases reported in [16, 32], assuming $\bar{Z} = 1$ and $\bar{A} = 2$.

No account has been taken for the difference between the reported heating power and the SOL power. Some of the input parameters are educated guesses, particularly in the case of JET, where only ranges of parameters have been provided, whose extent is roughly represented by the 'JET low λ' and 'JET high λ' columns. Overall the number of data points addressed is modest. Thus these results should be viewed not so much as definitive, but reasonable, and strongly encouraging of further comparisons with experimental data bases.

The worst fit is to the data from C-Mod, which is in EDA H-mode, unlike the ELMy H-modes of the other cases. The EDA H-mode has enhanced particle flux compared with conventional H-modes, likely violating the assumptions of this model. A long tail of heat flux in the outer SOL of C-Mod may increase the value of λ compared with other experiments, and FWHM estimates of λ in C-Mod are in much closer agreement with the model result shown in table 1. Measurements excluding the heat flux tail also show a clear inverse dependence on plasma current, more closely resembling the other experimental results. This highlights the need for experimentalists to work with their data to provide a carefully considered data set for comparison with models, and to find a way to exclude the effect of 'tails', which could be associated with recycling particle flux in this model.

Most recently [34], the heuristic model presented here has been compared with the estimated projected exponential

Table 1. Comparison with recent experimental data in deuterium.

	JET low λ	JET high λ	NSTX, 1 MA	DIII-D, 1 MA	C-Mod, 1 MA
P_{SOL} (W)	1.05E + 07	1.05E + 07	5.50E + 06	4.30E + 06	2.00E + 06
B_t (T)	3.00E + 00	2.00E + 00	4.40E − 01	2.00E + 00	5.40E + 00
κ	1.68E + 00	1.68E + 00	2.25E + 00	1.75E + 00	1.65E + 00
a (m)	9.50E − 01	9.50E − 01	5.90E − 01	5.95E − 01	2.20E − 01
I_p (A)	3.00E + 06	1.20E + 06	1.00E + 06	1.00E + 06	1.00E + 06
R (m)	2.95E + 00	2.95E + 00	8.70E − 01	1.76E + 00	6.80E − 01
Z_{eff}	2.00E + 00	2.00E + 00	2.00E + 00	2.00E + 00	2.00E + 00
λ (exp't)	4.00E − 03	6.10E − 03	8.00E − 03	6.30E − 03	3.50E − 03
λ (model)	2.83E − 03	7.18E − 03	9.15E − 03	5.08E − 03	1.75E − 03

scrape-off width at the outer midplane, for deuterium data from JET and ASDEX-Upgrade. The experimental heat flux measured at the divertor plate was fit to the convolution of an assumed exponential profile of heat flux emerging from the SOL near the plasma surface with an assumed Gaussian profile of spreading along the divertor leg to the strike point. The exponential width was compared with the heuristic model. For this purpose equations (5) and (6) were multiplied by a factor of $R\langle B_p\rangle/(RB_p)_{OMP}$. The agreement in absolute magnitude and in scalings with plasma current, magnetic field, power and size are each within the 1σ measurement error bars. When hydrogen and helium data from JET are included, equation (6) (electron drift constrained) provides a better fit than equation (5) (ion drift constrained).

The heuristic derivation presented here, and the means of comparing with experimental measurements, cannot claim accuracy better than (possibly multiple) factors of order unity, so the level of agreement in absolute magnitude of the results in table 1, and even [34] should be viewed with some skepticism, motivating not only further comparison with data but also future quantitative modelling efforts based on the physical ideas presented here. Extrapolation to future devices is sobering, giving a width for standard parameters in ITER ∼2 mm. This extrapolation, while cautionary, should itself be viewed with caution. In particular ITER is not planned to operate in the low-gas-puff regime analysed here, but rather in a partially detached regime. Analysis should be undertaken to examine the difficulty of achieving partial detachment using the model presented here for plasma behaviour in the SOL close the plasma. However, this should be done self-consistently, because as discussed below, enhanced ionization in the SOL would, even without detachment, result in a widened power scrape-off width.

5. Possible concerns with the heuristic model

One possible concern with this model is shared with any approach that uses the 2-point model to relate upstream parameters to downstream heat fluxes. The presence of cross-field transport violates the assumptions of the simplified 2-point model. Recent research [35–38], however, indicates that while the divertor target heat flux profile can be spread out compared with the profile of $T^{7/2}$ at the midplane, the 2-point model remains accurate for relating T_{sep} to P_{SOL}. One can also be concerned that the collisionality is low enough, even in the heat flux channel, that non-local flux-limiting effects could play an important role. However, even rather extreme flux limiters were shown to have a weak effect on T_{sep} for given P_{SOL} under ASDEX-U conditions [39], and T_{sep} only enters to the 1/2 power in our calculation. However, it should be recognized that simple flux limiters do not reflect the full range of physical effects that occur in plasmas with finite mean-free-path compared with parallel gradient scale length.

Another concern with this heuristic model is that poloidal $E \times B$ drifts can affect the residence time of plasma in the SOL, and that radial $E \times B$ drifts can affect the cross-field drift velocity within the SOL. If we assume along with [4, 40] that $\phi \sim T/e$ in the SOL, then we can estimate the magnitude of the poloidal and radial drifts, respectively,

$$\frac{E_r}{B_T} \sim \frac{T}{eB_T\lambda} = \frac{T}{eB_T}\frac{ZeR\langle B_p\rangle}{a(mT)^{1/2}} = v_{t,i}\frac{R}{a}\frac{\langle B_p\rangle}{B_T} \qquad (8)$$

$$\frac{E_p}{B_T} \sim \frac{T}{eBa\sqrt{(1+\kappa^2)/2}}. \qquad (9)$$

The poloidal velocity estimated here can be greater than the poloidal projection of parallel flows estimated at $c_s/2$ [41, 42]. However, the overall scaling is the same, with the exception of a factor of $R\bar{Z}/a$, (R/a if one uses the electron magnetic drift velocity to calculate λ). Interestingly, the radial $E \times B$ velocity in the SOL itself is also potentially larger than that due to the gradient and curvature drifts, by the same factor. These effects tend to cancel, since in essence $\lambda \approx v_r \ell_p / v_p$. However, it is worth noting that using this relation equations (8) and (9), in the absence of our earlier derivation, do not determine λ. The role of the radial $E \times B$ drift has been examined for the case of a straight, cylindrical, limited plasma [43] giving a scrape-off width of order a poloidal gyro-radius. However, in a divertor plasma the poloidal gradient in ϕ may be concentrated in the private flux region [44] reducing its effect.

These observations are somewhat sobering, since the effects of these drifts may come in at order unity, and may affect the aspect ratio and $\bar{Z}$ scaling. High spatial resolution, low numerical dissipation calculations are required to determine the effects of electric field drifts both on the magnitude of the projected SOL width and its scaling with R/a and $\bar{Z}$ in this model, and in particular to select, on a theoretical basis, between the scalings of equations (5) and (6). Comparisons of measured flows with such theoretical calculations are also critical.

An interesting aspect of this discussion is that it is well known that the radial currents across closed field lines in neoclassical theory are ambipolar only in the presence of a specific poloidal rotation speed. Under the extreme conditions here, where the scrape-off width is of order the ion poloidal gyro-radius, this rotation can be expected to be large, and could be associated self-consistently with turbulence suppression and the H-mode transition.

A final concern is that the model assumes $T_i = T_e = T_{sep}$. This approach, although appropriate for a heuristic model, hides some issues. If collisionless ions emerging from deeper within the plasma are important [45], their effect is lost here. Furthermore, the ion–electron coupling time at the midplane is relatively long (although the coupling time ($\propto T^{3/2}/n$) falls with distance from the midplane), so it is also conceivable that ion parallel thermal transport could play a role, for high enough T_i/T_e. As the plasma density varies, the coupling between the ions and electrons becomes stronger, so these effects could depend on density, perhaps providing some density scaling not evident in equations (5) and (6).

6. Exceptions that prove (i.e. test) the rule

It is clear that there are exceptions to equations (5) and (6). Generally speaking the SOL widths of L-mode plasmas are wider than those of H-modes. This can be viewed as confirming the idea that low ion turbulent transport is a key element of this model. Intense gas puffing is also observed to cause spreading of the heat flux at divertors, more readily than predicted in fluid models based on fixed anomalous cross-field particle transport [46]. This model would predict that if the particle channel is widened by gas puffing, then the heat flux should in general widen as well.

Conversely, if deuterium recycling is significantly reduced, resulting in more rapid depletion of particles from the SOL, then the heat flux channel should be narrower than predicted here on the basis of a flow pattern characteristic of normal recycling conditions. This may be occurring in NSTX plasmas with strong lithium conditioning [32] that show narrower power scrape-off widths than normally observed at similar global parameters in that device.

Experimentally it is observed that in double-null plasmas the inner SOL width is quite narrow. A simple interpretation of the present model would predict that the ratio of the outer to the inner SOL width in a double-null H-mode plasma would scale as $(1 + \delta)/(1 - \delta)$. It would be especially interesting to test this hypothesis in a double-null plasma with negative triangularity, where the expected effect of turbulence would be the usually observed wider outer SOL, while the present model, simply interpreted, appears to predict the opposite.

It has been noted on C-Mod [16] that λ does not change when a single-null plasma with the ion grad B drift in the direction of the divertor is shifted to a double-null. Since in this picture the upward-directed particle flow is intercepted by the inward-going grad B drift before it reaches the upper divertor, this result appears to be qualitatively consistent with the model.

7. Future research

More work is needed to develop a fully quantitative, rather than just heuristic, model of the physics described here. All electric and magnetic drifts need to be included, based on realistic calculations of the potential distribution in the SOL, as well as parallel flows, preferably validated by experimental measurements in H-mode plasmas. It will be especially interesting to see the amplitude of E_r shear that results, and its possible self-consistent role in turbulence suppression.

It is particularly challenging that no role is assumed in this model for cross-field anomalous particle transport or viscosity. This means that high-resolution calculations will be needed with low numerical dissipation. Certainly much can be gained from fluid codes, but since the gradient scale lengths are not much larger than the ion gyro-radius and parallel connection lengths are not much larger than mean free paths, PIC codes that can take into account the effects of strong spatial gradients of electric fields on $E \times B$ drifts and non-Maxwellian velocity distributions on parallel heat flux may be required.

More work is also needed to compare this model, both in its heuristic form and in the form of detailed modelling, with experimental data. The widest possible data base, analysed on as common a basis as possible, would be most valuable. Perhaps the convolved form used by Eich *et al* [34] should be applied generally. The effects of T_i–T_e need to be assessed.

Some of the ancillary predictions of this picture, such as the magnitude and scaling of τ_p in H-mode plasmas, should be compared with experiment, although care should be taken to include the effect of impurity ionization within the separatrix, and to exclude the effects of ELMs. Also interesting would be studies of the inner versus outer SOL width, as a function of triangularity. In general quantitative measurements and numerical predictions of inboard and outboard SOL properties for double-null and single-null plasmas with ion drift both towards and away from the divertor would provide valuable tests of this model. The effects of high flux expansion [47] and considerably extended divertor field lines [48] should be examined numerically and compared with experiment.

Scaling with atomic charge and mass should be examined, but with caution. JET results [31, 34] for H and He versus D plasmas are more consistent with equation (6) than with equation (5), motivating consideration of the assumption that electron, rather than ion, magnetic drifts determine the SOL width. One needs to exercise some caution, however, since H plasmas have poorer H-mode performance, so may not achieve near-neoclassical behaviour at the separatrix. One would expect, in contrast, a larger enhancement of confinement in H-mode in H versus D, due to the lower ion neoclassical transport of H and higher L-mode transport rate. Edge thermal transport coefficients have not been measured in hydrogen H-mode plasmas. In the case of He plasmas, in addition to the lack of confirmation of neoclassical ion thermal transport at the separatrix, there is likely to be higher wall recycling compared with D plasmas, due to less efficient pumping even on well-conditioned surfaces, possibly giving rise to a wider SOL density channel than derived here. Finally, one must be careful to use the appropriate values of $\bar{Z}$ and $\bar{A}$. These presumably do not vary as strongly as the Z and A of the externally fuelled species. Furthermore, as discussed above, the effect of $E \times B$ drifts may modify the predicted scaling with respect to Z.

Most importantly, this model may suggest ways to increase the power scrape-off width in future devices. For example a source of plasma in the SOL would allow electron heat to diffuse further. On the other hand, since the overall projection is that the power scrape-off width only increases weakly with device size, this result suggests the need to consider more radical solutions for power handling in future devices.

Acknowledgments

The author thanks Thomas Eich, Wojtek Fundamenski, Sergei Krasheninnikov, Brian LaBombard, Bruce Lipschultz, Vladimir Rozhansky, Peter Stangeby, the TCV Group, Dennis Whyte and Michael Zarnstorff for helpful discussions. This research is supported by the US Department of Energy, under contract DE-AC02-09CH11466.

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