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

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Abstract
An heuristic model for the plasma scrape-off width in H-mode plasmas is introduced. Grad *B* and curv *B* drifts into the SOL are balanced against 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-Shlüter flows to include 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, defined 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 from deuterium plasmas. Further work should include full numerical calculations, including all magnetic and electric drifts, as well as more thorough comparison with experimental data.

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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 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. Even published empirical scalings are highly inconsistent (Loarte *et al.*, 2007).

In this paper we develop a heuristic model of the power scrape-off width outside of the separatrix in 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 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 (Stangeby, 2000, p. 561, Chankin *et al.,* 2007). 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-centers. The divergence of this gyro-center 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-center picture of these flows is equivalent to the fluid picture, where the accumulation occurs due to the divergence of the ion and electron diamagnetic flows in a torus. Here we use the gyro-center picture, for its simplicity.

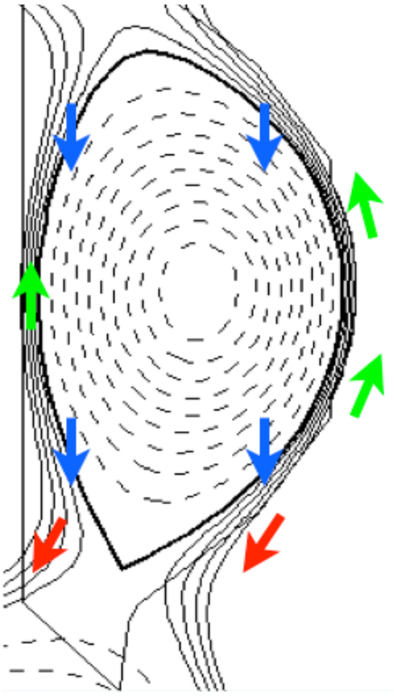

Figure 1. Pfirsch-Schlüter mass flows modified to include loss to divertor on open field lines.

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 (downwards 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 $<v_{gradB+curvB}> = 2T/eZBR$. In this region drift flows can be balanced not only by parallel flows that connect the bottom of the plasma to the top (upwards directed arrows in and along SOL, near midplane), but also by parallel flows that leave the plasma region in the direction of the divertors (downwards directed arrows in and along SOL, pointing into divertor region). Using this heuristic picture, which is generally consistent with measured mass flow patterns (Loarte *et al.*, 2007) including the reversal of flow in the lower region of the LFS SOL for ion grad *B* drift down with lower single-null divertor (albeit in L-mode), we can estimate the drift-based particle width that should result from this process by multiplying a typical residence time in the SOL ($\propto L_{//}/c_s$) times the poloidally averaged positive grad *B* and curv *B* drift velocities perpendicular to the separatrix. Using a simple model of nested concentric ellipses, taking the connection length to be along *B* from the mid-plane to the bottom of the plasma and assuming an average parallel speed based on experimental data (Loarte *et al.*, 2007) of $c_s/2$, with $T_i = T_e = T_{sep}$, we find:

$$\begin{aligned}\Delta &= L_{\|}\frac{2}{c_s}\left\langle v_{gradB+curvB}\right\rangle_r = \left[\frac{\pi a}{2}\,\frac{\left(1+\kappa^2\right)^{1/2}B}{2\left\langle B_p\right\rangle}\right]\left[\frac{4\bar{A}m_p}{\left(1+\bar{Z}\right)T_{sep}}\right]^{1/2}\left[\left(\frac{2T_{sep}}{\bar{Z}eBR}\right)\left(\frac{2}{\pi\left(1+\kappa^2\right)^{1/2}}\right)\right] \\ &= \frac{2a\left(\bar{A}m_pT_{sep}\right)^{1/2}}{\left(1+\bar{Z}\right)^{1/2}\bar{Z}eR\left\langle B_p\right\rangle} \sim \frac{2a}{R}\rho_p\end{aligned} \qquad (1)$$

where $\bar{Z} \equiv n_e \Big/ \sum_i n_i$ and $\bar{A} \equiv \sum_i n_i A_i \Big/ \sum_i n_i$. Here we are using the ion magnetic drift speed, weighted by the ion charge, so in effect the average ambipolar speed, assuming that radial particle transport is limited by the ion motion. If instead we were to consider the radial motion to be set by the electron magnetic drift speed, then a factor of $1/\bar{Z}$ would be eliminated. Further theoretical analysis and comparison with experiment are required to select between these alternatives.

Implicit in this derivation is the assumption that cross-field particle motion is dominated by classical drifts. This is consistent with the observation in ASDEX-U (Chankin *et al.*, 2006) and DIII-D (Callen *et al.*, 2010) 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.

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. Evaluating equation 1 for typical JET and C-Mod parameters, e.g., $a = 0.95, 0.22$m, $R = 2.95, 0.69$m, $I_p = 2, 1$ MA, $T_{sep} = 100, 75$ eV, $\kappa = 1.7$, one does find reasonable results: $\Delta = 4.4, 1.7$ mm.

There is another surprising consequence of this simple picture that should provide a direct check on the assumption of dominant classical cross-field drifts. If we 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 type flows, while one half leaves to the divertor plate, we can immediately calculate the ion confinement time within the separatrix:

$$\tau_p = \frac{\pi \bar{Z} e B R a \kappa n_{core}}{2 T_{sep} n_{sep}} \qquad (2)$$

Using the parameters quoted above for JET and C-Mod, taking $B = 2$ and 5T respectively, and assuming $\bar{Z} = 1$ and $n_{core}/n_{sep} = 2.5$ for both, one finds for the particle confinement times, 375 and 67 msec respectively, qualitatively reasonable values.

Furthermore, multi-tip probe measurements have been made of the turbulent electrostatic radial particle flux, Γ_t, at the separatrix of DIII-D plasmas, near the midplane (Moyer *et al.*, 1997). 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 $1 \pm 0.5\ 10^{20}/\mathrm{m}^2$ and $4 \pm 1.5\ 10^{20}/\mathrm{m}^2$. For these cases multiplying the locally measured density 2mm inside the separatrix by the magnetic drift velocity based on the measured electron temperature at this location, one obtains $\Gamma_{\mathrm{gradB+curvB}} = 1.4\ 10^{20}/\mathrm{m}^2$ and $6\ 10^{20}/\mathrm{m}^2$. The turbulent transport is likely to be localized to the outer midplane, while the drift flux varies smoothly along the lower half of the torus. Thus it appears likely that the average drift flux exceeds the turbulent flux in these cases.

Perhaps it is not unreasonable, therefore, to examine the hypothesis that anomalous particle transport is sub-dominant in driving particle flux across the separatrix in H-mode plasmas.

3. Heat Transport

While the above heuristic derivation addresses *particle* transport at the plasma edge, yielding some intriguing results, it does not address heat transport. It also does not provide a means to predict T_{sep}, on which D 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 show that the local heat flux associated with the grad B and curv B drifts, averaged over an isotropic Maxwellian particle distribution, is simply $q = (5/2)nT\langle v_{gradB+curvB}\rangle$. 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 Pfirsh-Shlüter type flows, this amounts to only 1 MW summed over both the ions and the electrons, much less than experimentally measured. However if we assume a modest electron thermal diffusivity of 1 m^2/sec, consistent with the ASDEX-U and DIII-D results, and take $\Delta \sim 4$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 m^2/sec continues into the SOL, the characteristic time for filling a 4mm SOL at this thermal diffusivity is 8 μsec, comparable to the parallel loss time of about 10 μsec due to Spitzer-Härm thermal diffusivity at 100 eV. We *assume* in this model, therefore, that anomalous electron thermal diffusivity is adequate to "fill" with electron heat the particle channel defined by the flows discussed above. We also *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 to the vacuum. In a more realistic situation with profiles, at the low densities outside of the main density 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 $q_\perp \propto \langle \tilde{p}, \tilde{v} \rangle$.

We now develop the implications of the assumptions 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 line 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

$$P_{SOL} = \frac{4\pi R \Delta \langle B_p \rangle \chi_{0,S} T_{sep}^{7/2}}{(7/4) B L_{\parallel}} \tag{3}$$

Combining equation 3 with equation 1 to eliminate T_{sep}, and evaluating the constants, we arrive at:

$$\Delta = 5671 \cdot P_{SOL}^{1/8} \frac{\left(1+\kappa^2\right)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left[\frac{2\bar{A}}{\bar{Z}^2 \left(1+\bar{Z}\right)} \right]^{7/16} \left(\frac{Z_{eff}+4}{5} \right)^{1/8} \tag{4}$$

where the dimensional variables are expressed in S.I. units: meters, Watts, Teslas and Amperes. If we were to have used the electron magnetic drift velocity in equation 1, then a factor of $1/\bar{Z}^{7/8}$ would drop out of equation 4. Let us denote this variation equation $4'$:

$$\Delta = 5671 \cdot P_{SOL}^{1/8} \frac{\left(1+\kappa^2\right)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left[\frac{2\bar{A}}{\left(1+\bar{Z}\right)} \right]^{7/16} \left(\frac{Z_{eff}+4}{5} \right)^{1/8} \tag{$4'$}$$

What is perhaps most striking about equations 4 and $4'$ is the strong inverse dependence on I_p. Furthermore, since plasma current scales with the linear dimension of a device at fixed R/a, κ, q, and B, *all* of the size scaling in this expression is implicit, coming in through the weak power scaling. For fixed R/a, κ, $\bar{A}$, $\bar{Z}$, q and Z_{eff} the scaling of equation 4 is $\Delta \propto P_{SOL}^{1/8} / B^{7/8}$.

We can also solve equations 3 and 1 for T_{sep}, giving:

$$\frac{T_{sep}}{e} = 30.81 \cdot P_{SOL}^{1/4} \left(\frac{\bar{Z}^2 (1+\bar{Z})}{2\bar{A}} \right)^{1/8} \frac{a^{1/4} \left(1+\kappa^2\right)^{1/4} B^{1/2}}{I_p^{1/4}} \left(\frac{Z_{eff}+4}{5} \right)^{1/4} \tag{5}$$

again with all units S.I. Note that T/e is expressed in Volts. The resulting T_{sep} is close to 100 and 75 eV for assumed JET and C-Mod parameters. The factor of $\bar{Z}^{1/4}$ would fall out if the electron magnetic drift velocity were used.

4. Comparison with Recent Experimental Results

Recently heat flux width measurements have been published for C-Mod (LaBombard *et al.*, in press), DIII-D (Lasnier *et al.,* 2010), JET (Fundamenski *et al.*, 2010), and NSTX (Gray *et al.*, 2010). Experimental methods have been improved, and these widths are believed to be more accurate than those reported previously. 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 (Loarte *et al.*, 1999), $\lambda_q \equiv \int p\,dl / \hat{p}$, 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 dependencies on other variables, similar to equation 4. Table 1 evaluates equation 4 for deuterium plasma cases reported in the references, 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 a range of parameters is provided, and overall the number of data points addressed is modest, so these results should be viewed not so much as definitive, but reasonable, and strongly encouraging of further comparisons with experimental data bases.

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
Δ (model)	2.83E-03	7.18E-03	9.15E-03	5.08E-03	1.75E-03
λ_q (exp't)	4.00E-03	6.10E-03	8.00E-03	6.30E-03	3.50E-03

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. A long tail of heat flux in the outer SOL of C-Mod may increase the value of λ_q compared with other experiments, and FWHM estimates of λ_q 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. The effect of wall recycling is reported to be large in C-Mod (LaBombard *et al.*, 2000), which would violate the assumptions of the present model. 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 would be associated with recycling particle flux in this model.

The heuristic derivation presented here 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 should be viewed with some skepticism, motivating not only further comparison with data but also future quantitative modeling efforts based on the physical ideas presented here. Extrapolation to future devices is sobering, giving a width for standard parameters in ITER ~ 2mm. This extrapolation, while cautionary, should itself be viewed with caution.

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 (Goldston, 2010, Stangeby *et al.*, 2010, Hill *et al.*, in press, Goldston, in press), however, indicates that while the divertor target heat flux can be spread out compared with $T^{7/2}$ 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} in ASDEX-U conditions (Coster *et al.,* 2004), and T_{sep} only enters to the 1/2 power in our calculation.

Another concern with this heuristic model is that poloidal *ExB* drifts can affect the residence time of plasma in the SOL, and that radial *ExB* drifts can affect the cross-field drift velocity within the SOL. If we assume along with Stangeby and Chankin, 1996, and Stangeby, 2000, p. 542 that $\phi \sim T/e$ in the SOL, then we can estimate the magnitude of the poloidal and radial drifts, respectively,

$$v_p = \frac{E_r}{B_T} \sim \frac{T_{sep}}{eB_T\Delta} \sim \frac{T_{sep}}{eB_T}\frac{\left(1+\bar{Z}\right)^{1/2} R\bar{Z}e\left\langle B_p\right\rangle}{2a\left(\bar{A}m_pT_{sep}\right)^{1/2}} \sim \frac{c_s}{2}\frac{\left\langle B_p\right\rangle}{B_T}\frac{R\bar{Z}}{a} \tag{6}$$

$$v_r = \frac{E_p}{B_T} \sim \frac{T_{sep}}{eBa\sqrt{\left(1+\kappa^2\right)/2}} = \left\langle v_{gradB} + v_{curvB}\right\rangle_r \frac{\pi R\bar{Z}}{4a} \tag{7}$$

The poloidal velocity estimated here can be greater than the poloidal projection of parallel flows estimated at $c_s/2$ (Chankin, 1997, Krasheninnikov, 1995). 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 Δ). Interestingly, the radial *ExB* velocity in the SOL itself is also potentially larger than that due to the gradient and curvature drifts, also including a factor of $R\bar{Z}/a$ (relative to equation 1, but a factor of R/a relative to the electron magnetic drift velocity). These effects tend to cancel, since in essence $\Delta \sim v_r \ell_p / v_p$. However it is worth noting that using this relation equations 6 and 7, in the absence of the earlier derivation, do not constrain the value of Δ. The role of the radial *ExB* drift has been examined for the case of a straight, cylindrical, limited plasma (Petrov, 1984) 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 (Rozhansky *et al.,* 2003), reducing its effect on these results.

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 $\bar{Z}$ scalings of equations 4 and 4′. Comparisons of measured flows with such theoretical calculations are also critical.

A final concern is that the model assumes $T_i = T_e = T_{sep}$. This approach, although perhaps appropriate for a heuristic model, hides some issues. If collisionless ions emerging from deeper within the plasma are important (Chang *et al.,* 2002), 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. 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 equation 4.

6. Exceptions that Prove (*i.e.,* Test) the Rule

It is clear that there are exceptions to equation 4. 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 turbulence is a key element of this model.

High gas puffing is observed to cause spreading of the heat flux on divertors, apparently more readily than predicted in fluid models based on fixed anomalous cross-field particle transport (Wischmeier *et al.,* 2009). 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 (Fundamenski *et al.,* 2010) 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. In a very simple interpretation the present model would predict that the ratio of the outer to the inner SOL width would scale as $(1 + \delta) / (1 - \delta)$.

It has been noted on C-Mod (LaBombard *et al.,* in press) that λ_q 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 upwards-directed particle flow is intercepted by the inwards-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 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.

More work is also needed to compare this model, both in its heuristic form and in the form of detailed modeling, with experimental data. The widest possible data base, analyzed on as common a basis as possible, would be most valuable. Predictions and measurements of heat flux “tails” need to be compared. The effects of $T_i \neq T_e$ 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 *vs.* outer SOL width, as a function of triangularity. In general quantitative measurements and 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 (Ryutov, 2007) and greatly extended divertor field lines (Valanju *et al*., 2009) should be examined numerically and compared with experiment.

Scaling with atomic charge and mass should be examined, but with caution. Initial JET results (Fundamenski *et al*., 2010) for H and He *vs*. D plasmas, appear more consistent with equation $4'$ than with equation 4, 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 behavior at the separatrix. One would expect, in contrast, a larger enhancement of confinement in H-mode in H *vs*. 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, possibly giving rise to a wider SOL density channel than derived here, perhaps leading to an extended tail as observed on C-Mod. Finally, one must be careful to use the appropriately averaged $\bar{Z}$ and $\bar{A}$ at the plasma edge in evaluating equation 4 or $4'$. These presumably do not vary as strongly as the Z and A of the externally fueled species. Furthermore, as discussed above, the effect of *ExB* drifts may modify the predicted $\bar{Z}$ scaling.

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.

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References

Callen, J D, Groebner, R J, Osborne, T H, Canik, J M, Owen, L W, Pankin, A Y, Rafiq, T, Rognlien, T D and Stacey, W M 2010 Analysis of pedestal plasma transport *Nucl Fusion* **50** 064004

Chang, C, Kue, S and Weitzner, H 2002 X-transport: A baseline nonambipolar transport in a diverted tokamak plasma edge *Phys Plasmas* **9** 3884-3892

Chankin, A 1997 Classical drifts in the tokamak SOL and divertor: Models and experiment *Journal of Nuclear Materials* **241** 199-213

Chankin, A V*, et al.* 2006 SOLPS modelling of ASDEX Upgrade H-mode plasma *Plasma Phys Contr F* **48** 839-868

Chankin, A V, Coster D P, Asakura N, Corrigan G, Erents S K, Fundamenski W, Müller H W, Pitts R A, Stangeby P C, Wishmeier M 2007 A possible role of radial electric field in driving parallel ion flow in scrape-off layer of divertor tokamaks, *Nucl. Fusion* **47** 762 – 772, Appendix A

Coster, D P, Bonnin, X, Braams, B, Reiter, D and Schneider, R 2004 Simulation of the edge plasma in tokamaks *Phys Scripta* **T108** 7-13

Fundamenski, W*, et al.* 2010 Effect of ion mass and charge on divertor heat load profiles on JET *IAEA FEC 2010* EXD/P3-11

Goldston, R J 2010 Downstream heat flux profile versus midplane T profile in tokamaks, *Physics of Plasmas*, **17**, 012503

Goldston, R J 2011 When is it Valid to Assume that Heat Flux is Parallel to *B*?, *Journal of Nuclear Materials* in press

Hill, D N, Porter, G D, Rognlien, T D 2011 Two dimensional transport effects in the the tokamak scrape-off layer plasma, *Journal of Nuclear Materials*, in press

Gray, T, Maingi, R, Mclean, A, Soukhanovskii, V and Ahn, J-W 2010 Dependencies of the divertor and miplane heat flux widths in NSTX *IAEA Fusion Energy Conference, 2010* EXD/P3-13

Krasheninnikov, S, Sigmar, D and Yushmanov, P 1995 Effect of ExB drift on divertor plasma flows *Phys Plasmas* **2** 1972-1975

Labombard, B, Terry, J L, Hughes, J W, Brunner, D, Payne, J, Reinke, M L, Lin, Y and Wukitch, S 2010 Divertor heat flux footprints in EDA H-mode discharges on Alcator C-Mod *Journal of Nuclear Materials* 1-4

Labombard, B, Umansky, M, Boivin, R, Goetz, J, Hughes, J, Lipschultz, B, Mossessian, D, Pitcher, C and Terry, J 2000 Cross-field plasma transport and main-chamber recycling in diverted plasmas on Alcator C-Mod *Nucl. Fusion* **40** 2041-2060

Lasnier, C, Makowski, M, Boedo, J, Brooks, N, Hill, D, Leonard, A and Watkins, J 2010 Scaling of divertor heat flux profile widths in DIII-D *IAEA FEC 2010* EXD/P3-20

Loarte, A*, et al.* 1999 Multi-machine scaling of the divertor peak heat flux and width for L-mode and H-mode discharges *Journal of Nuclear Materials* **266** 587-592

Loarte, A*, et al*. 2007 Chapter 4: Power and particle control *Nucl Fusion* **47** S203-S263

Moyer, R A, Cuthbertson, J, Evans, T, Porter, G and Watkins, J 1997 The role of turbulent transport in DIII-D edge and divertor plasmas *Journal of Nuclear Materials* **241** 633-638

Petrov, V 1984 Characteristics of steady-state plasma-flow in the tokamak limiter scrape-off layer *Nucl Fusion* **24** 259-266

Rozhansky, V, Kaveeva, E, Voskoboynikov, S, Coster, D, Bonnin, X and Schneider, R 2003 Potentials and currents in the edge tokamak plasma: Simplified approach and comparison with two-dimensional modelling *Nucl Fusion* **43** 614-621

Ryutov, D D 2007 Geometrical properties of a "snowflake" divertor *Phys Plasmas* **14** 064502

Stangeby P C and Chankin A V, (1996) Simple models for the radial and poloidal ExB drifts in the scrape-off layer of a divertor tokamak: Effects on in/out asymmetries *Nucl Fusion* **36** 839-852

Stangeby P C 2000 *The Plasma Boundary of Magnetic Devices* New York Taylor & Francis

Stangeby P C, Canik J M, Whyte, D G 2010 The relation between upstream density and temperature widths in the scrape-off layer and the power width in an attached divertor, *Nuclear Fusion* **50** 125003

Valanju, P M, Kotschenreuther, M, Mahajan, S M and Canik, J 2009 Super-x divertors and high power density fusion devices *Phys Plasmas* **16** 056110

Wischmeier, M, Groth, M, Kallenbach, A, Chankin, A, Coster, D, Dux, R, Herrmann, A, Müller, H, Pugno, R and Reiter, D 2009 Current understanding of divertor detachment: Experiments and modelling *Journal of Nuclear Materials* **390** 250-254

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