Generalization of the Heuristic Drift Model of the Scrape Off Layer for Finite Collisionality

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Overview: The "Heuristic Drift" (HD) model for the scrape off layer power flux width [1] was explicitly formulated for low-gas-puff H-Mode conditions. Experimental results in these conditions have shown good agreement with the model. In 2015, however, ASDEX-Upgrade (AUG) data showed that the scrape-off width broadens as the collisionality increases [2], which is inconsistent with the HD model as formulated. We hypothesize that this broadening is due to enhanced residence time of heat in the scrape-off-layer (SOL) at higher collisionality, due to higher classical parallel thermal resistance. This allows more time for cross-field drifts to broaden the SOL. We find reasonable agreement with more extensive recent AUG data [3] for SOL broadening at high collisionality. This broadening may play a synergistic role with turbulence in degrading global energy confinement.

Parallel Confinement Time: If we assume that the electric potential, ϕ, is proportional to T, then both magnetic and electric cross-field drift flows are proportional to the pressure, nT. Thus it is interesting to use the parallel energy confinement time, $\tau_{E\|}$, to represent the parallel confinement time during which cross-field drifts serve to broaden the SOL. This is in contrast to the parallel particle confinement time, $\tau_{p\|}$, used in the derivation of the low-gas-puff model of [1]. We use Stangeby's two-point model [4] to calculate the parallel energy confinement time including collisions, allowing thereby a generalization of the HD model to finite collisionality. We assume total pressure balance along a field line, neglecting any region of momentum loss near the divertor target, and $n_iT_i \approx n_eT_e$, so that we can write

$$\tau_{E\|} \approx \frac{3n_uT_uL_\|}{q_{\|,u}} \tag{1}$$

We use Stangeby's equation 4.94 [4]

$$T_{u,eV}^{7/2} - T_{t,eV}^{7/2} = \frac{7}{2}\frac{q_{\|,u}L_\|}{\kappa_0} \tag{2}$$

as well as his generalization of the heat flux to the target including downstream power loss, equation 5.19 [4]

$$q_{\|,0} = \frac{\gamma n_t T_t c_{s,t}}{1 - f_{power}} \tag{3}$$

The term f_{power} is the fraction of the power crossing the separatrix that is lost volumetrically from the SOL, near the divertor, by atomic processes.

Combining equations 2 and 3 with equation 1, along with parallel pressure balance and the assumption of Mach 1 flow at the target, we find after some algebra to eliminate target parameters:

$$\tau'_{E\|}\left[1-\left(\frac{1-f_{power}}{\tau'_{E\|}}\right)^7\right]=7.39\cdot10^{-2}f(Z_{eff})\nu^*_{SOL}(Z=1) \tag{4}$$

where $\tau'_{E\|}\equiv\tau_{E\|}/\tau_{E\|0}$ and $\tau_{E\|0}=6L_{\|}/(\gamma c_{s,u})$. $\nu^*_{SOL}(Z=1)$ is the collisionality evaluated using upstream parameters, as in Stangeby. However, we adopted here the fit to the classical electron thermal conductivity in [5].

$$\begin{gathered}\kappa_0=2600/f(Z_{eff})\\ f(Z_{eff})=0.672+0.076Z_{eff}^{1/2}+0.252Z_{eff}\end{gathered} \tag{5}$$

Equation 4 has interesting limits. At low collisionality and f_{power} we find $\tau_{E\|}=\tau_{E\|0}$, which scales as in the low-gas-puff HD model, so the earlier HD result holds under the current analysis in the region of its applicability. On the other hand, at high SOL collisionality $\tau_{E\|}\propto\tau_{E\|0}\nu^*_{SOL}$. Equation 4 requires numerical solution to solve for $\tau'_{E\|}$, but it is easily plotted by varying $\tau'_{E\|}$ and computing $f(Z_{eff})\nu^*_{SOL}(Z=1)$, as shown in figure 1.

One interesting consequence of equation 4 is that f_{power} can compensate for collisionality, such that for $f_{power}=1$ a SOL with collisionality of 13.5 has the same $\tau'_{E\|}$, and so presumably SOL width, as in the low-gas-puff HD model. At this point, the increase in parallel confinement time due to collisionality is compensated by the reduction in parallel confinement time due to radiation. In this model radiative losses are strictly in series with parallel thermal conduction, so for high enough collisionality radiative losses no longer have a significant effect on $\tau_{E\|}$.

Comparison with ASDEX-Upgrade data: Figure 2 shows the SOL pressure gradient scale length normalized to the poloidal gyro-radius vs. collisionality in recent AUG Thomson scattering data [3]. For this analysis the collisionality was evaluating using plasma parameters at a distance $\lambda_T/2$ outside of the separatrix, and the calculated magnetic connection length from the midplane to the divertor target was employed. These discharges had a range of gas puffing and modest impurity seeding in a few cases, but generally a low fraction of SOL radiated power. The orange line is equation 4 with $f_{power}=0$.

Discussion: These results suggest that the broadened pressure profile in the SOL seen at higher collisionalities in AUG could be caused by the increased parallel energy confinement time in the SOL at higher collisionality, which allows more time for drifts to cause broadening.

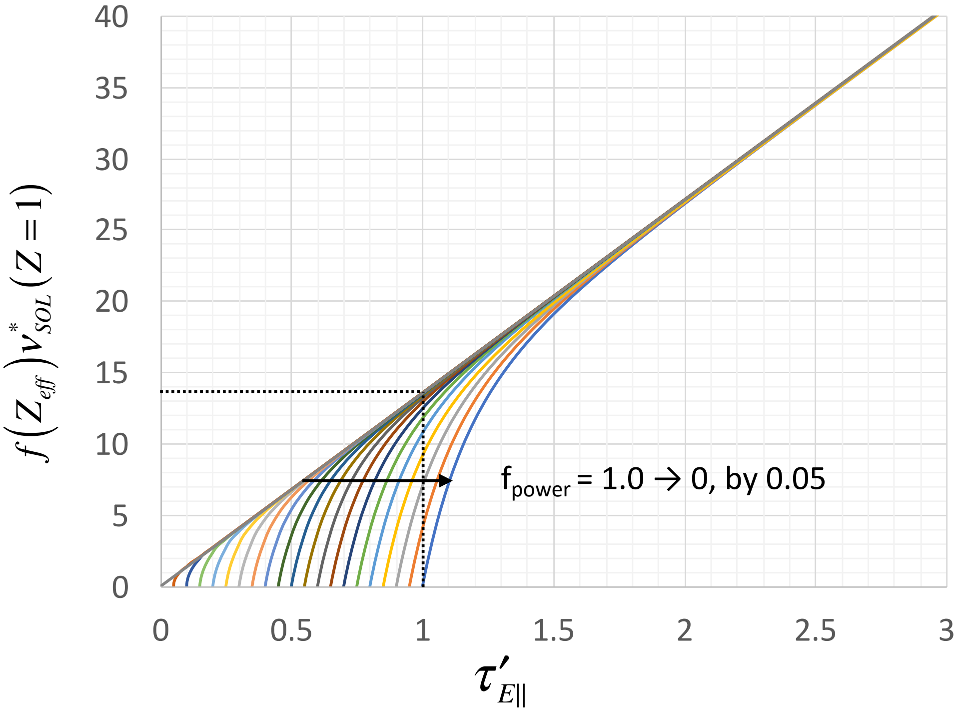

Figure 1: Collisionality vs. normalized confinement time, eq. 4. f_{power} falls from 1 to 0 by steps of 0.05 from left to right. $\tau'_{E\|} = 1$ at $f_{power} = 1$ and $f(Z_{eff})\nu^*_{SOL}(Z=1) = 13.5$.

It seems unlikely, however, that the much greater broadening of the density observed in the SOL [3] could be neoclassical in origin. Most likely this is due to turbulence.

If we assume that the midplane potential in the SOL is given by $\phi = 3T/e$, the E_rB_t/B^2 shearing rate suggested by figure 2 is $u'_{pol} = 3T/(\tau'^2_{E\|}eB\rho^2_{pol}) = 3c_sB_{pol}/(\tau'_{E\|}\lambda_pB_{tor})$. The generic gyro-Bohm growth rate is of order c_s/λ_p, so the SOL shearing rate can be competitive with gyro-Bohm growth rates. In an HD-like model one would expect the same pressure gradient scale length, over about one such scale length, within the separatrix as outside, due to their communication via drifts. Thus it is also interesting to note that the diamagnetic shearing rate under these circumstances is 1/3 of the SOL shearing rate, so still not insignificant. In both cases, high $\tau'_{E\|}$ reduces the shearing rate compared with the gyro-Bohm growth rate, and may thus contribute to enhancing turbulence near the separatix, suggesting a synergy between neoclassical and turbulence effects. Enhanced edge turbulence with resulting degraded pedestal performance are consistent with the AUG observation of degraded global energy confinement at high SOL collisionality [3]. Equation 4 may also explain why confinement can be enhanced by modest amounts of impurity radiation, since for lower collisionalities radiated power loss can narrow the SOL significantly, and $f(Z_{eff})$ depends rather weakly on Z_{eff} at low values of Z_{eff}. By the same token radiative detachment with f_{power} near unity, at moderate collisionality,

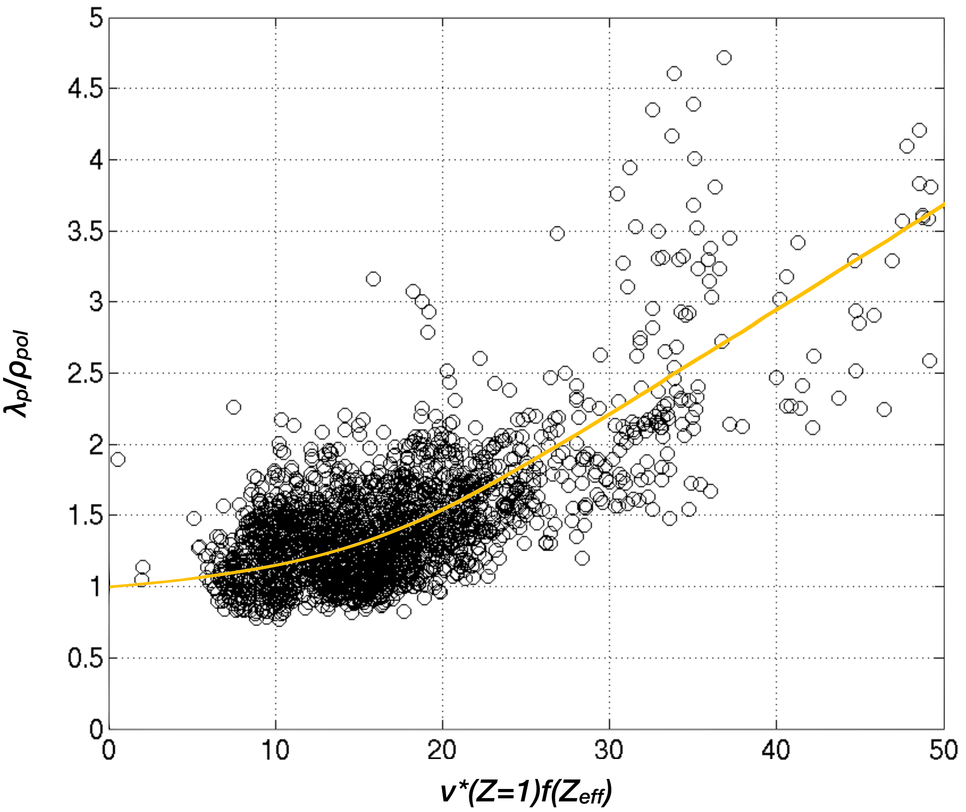

Figure 2: Pressure gradient scale length in near SOL divided by ion poloidal gyro-radius, λ_p/ρ_{pol}, vs. collisionality, AUG experiment and equation 4, with $f_{power} = 0$.

does not necessarily result in a broadening of the SOL pressure profile with associated core confinement degradation.

Clearly a very important step in further elucidating this physics is to perform similar measurements on larger and smaller tokamaks than AUG, and on those with differing aspect ratios.

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