Princeton Plasma Physics Laboratory

PPPL-5315

A New Scaling for Divertor Detachment

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September 2016

Prepared for the U.S.Department of Energy under Contract DE-AC02-09CH11466.

A New Scaling for Divertor Detachment

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Abstract

The ITER design, and future reactor designs, depend on divertor "detachment," whether partial, pronounced or complete, to limit heat flux to plasma-facing components and to limit surface erosion due to sputtering. It would be valuable to have a measure of the difficulty of achieving detachment as a function of machine parameters, such as input power, magnetic field, major radius, etc. Frequently the parallel heat flux, estimated typically as proportional to P_{sep}/R_0 or $P_{sep}B_0/R_0$, is used as a proxy for this difficulty. Here we argue that impurity cooling is dependent on the upstream density, which itself must be limited by a Greenwald-like scaling. Taking this into account self-consistently, we find the impurity fraction $c_z \propto P_{sep} \Big/ \left[\langle B_p \rangle (1+\kappa^2)^{3/2} (n_{sep}/n_{GW})^2 \right]$.

The absence of any explicit scaling with machine size is concerning, as P_{sep} surely must increase greatly for an economic fusion system, while increases in the other parameters are limited. This result should be challenged by comparison with measurements on existing experiments. Nonetheless, it suggests that higher magnetic field, stronger shaping, double-null operation, "advanced" divertor configurations, as well as alternate means to handle heat flux such as metallic liquid and/or vapor targets merit greater attention.

1. Motivation and Outline

The parallel heat flux in future fusion experiments and fusion power systems will be substantially higher than in current experiments, but the steady-state power-handling capabilities of the plasma-facing components will be lower than the short-pulse capabilities of current systems. The plasma-facing components will operate in a much more challenging environment, and ultimately will be required to operate at high duty factor. Thus a high premium is placed on developing means to handle very high parallel heat fluxes within the plasma, at high duty factor, without unacceptable thermal damage or erosion due to sputtering. A leading approach is to "detach" the fusion plasma from the material surface of the divertor through volumetric power and ultimately pressure loss, whether partially, in a pronounced way, or completely[1]. This can dramatically reduce both heat flux and surface sputtering. These forms of detachment have been achieved in current experiments. At high $q_{||}$ in the scrape-off layer (SOL) however, substantial injection of impurities is required to sufficiently cool the plasma to facilitate pressure detachment through momentum exchange with neutral gas, with the result that there can be significant dilution of the hydrogenic species in the plasma and core radiation. Furthermore, the radiation zone tends to collapse to the x-point, resulting in degradation of the edge pedestal and reduced helium pumping capability. It is important to understand the impurity concentrations that will be required in future fusion power systems, including ITER, in order to make realistic projections and plans. In Section 2 of this paper we examine a simple model for impurity cooling, which should contain enough physics to obtain the basic scaling for plasma detachment. In Section 3 we develop the projected parallel heat flux in tokamak plasmas based on recent measurements and theory. Combining the results of Sections 2 and 3 we find reasonable agreement with more sophisticated calculations and measurements. In Section 4 we develop a simple scaling for the required impurity concentration to attain detachment, taking into account the likely Greenwald scaling of the separatrix density, and in Section 5 we discuss the implications of these results.

2. Impurity Cooling

A simple argument, due to Lengyl[2] and used by others[3,4,5], can be employed in an evaluation of the upstream parallel heat flux that can be dissipated by impurities, which we will assume leads to detachment of the plasma from the material surface of the divertor:

$$q_{\|} = \kappa_{e,\|}\frac{dT_e}{d\ell}; \qquad \frac{dq_{\|}}{d\ell} = n_e^2 c_z L_z$$

$$\frac{1}{2}\frac{dq_{\|}^2}{d\ell} = n_e^2 T_e^2 F_z \kappa_0 T_e^{1/2} L_z \frac{dT_e}{d\ell} \qquad eq.1$$

$$q_{\|,det} = n_{e,sep} T_{e,sep}\sqrt{2\int_{T_{e,det}}^{T_{e,sep}} F_z \kappa_0 T_e^{1/2} L_z \, dT_e}$$

where $q_{||}$ is the parallel electron heat flux and ℓ represents distance along a field line. $\kappa_{\|,e}$ is the parallel electron thermal conductivity, and κ_0 is $\kappa_{\|,e}$ divided by $T_e^{5/2}$ for the case of $Z = 1$. Taking $\ln(\Lambda) = 11.75$ as a compromise between upstream [$\ln(\Lambda) \sim 13.5$] and downstream [$\ln(\Lambda) \sim 10$] conditions, and further adjusting for T_e to be measured in eV, κ_0 is taken to be 2600 $Wm^{-1}eV^{-7/2}$. $F_z \equiv c_z \kappa_z$ is the ratio of impurity to electron density, $c_z = n_z/n_e$, multiplied by the finite-Z correction[6] to the $Z = 1$ electron thermal conductivity, called here κ_z. $n_{e,sep}$ and $T_{e,sep}$ are the electron density and temperature at the upstream separatrix. $T_{e,det}$ is an electron temperature at which it is assumed that detachment of the desired quality is achieved. In general we have taken this to be 1/2 of the first ionization potential of the impurity under consideration, but the result is insensitive to this assumption. L_z is the cooling rate coefficient due to impurities, where the volumetric plasma cooling power density is given by $p_{cool} = n_e n_z L_z = n_e^2 c_z L_z$. Here we include the energy invested in ionization as part of the cooling power (a modest effect for the parameters studied here). We evaluate the cooling power taking into account finite impurity lifetime in the plasma. The impurity charge-state distribution is evaluated in steady state, assuming a source of neutral atoms that undergo ionization and recombination as well as loss at a rate common to all charge states, $1/\tau_z$. This non-coronal effect on the charge-state distribution has a large impact on the c_z required for detachment.

Figures 1a, b, c and d show the $q_{||}$ that can be detached, according to equation 1, as a function of T_{sep} divided by $F_z^{1/2} n_{e,sep}$, for three values of τ_z. $n_{e,sep}$ is taken as 1 $10^{20}/m^3$ in all cases and F_z is expressed in percent. When three-body interactions are unimportant, these curves may be parameterized by $n_e \tau_z$. Except at very low T_{sep} (below any shown in Figure 1) this is very nearly the case here. Note that the detachable $q_{||}$ scales about as $T_{e,sep}^{3/2}$ over the relevant range of upstream separatrix temperature, T_{sep}, covering existing and future experiments, from about 70 to 300 eV. This implies that the integral in equation 1 scales about as T_{sep}.. It is interesting that the non-coronal effects are strongest on the lower-*Z* impurities, as shown in figure 1d, making lithium 50% as effective a radiator as nitrogen at moderate impurity lifetimes. This "finite life-time" collisional-radiative model is crude, as is the assumption that F_z is constant along a field line from the separatrix to the divertor target. Furthermore, c_z is difficult to measure in the scrape-off-layer, so is generally only available in the main plasma. Recognizing these limitations, we (and other authors[2,3,4,5]) nonetheless consider that this model may provide useful guidance.

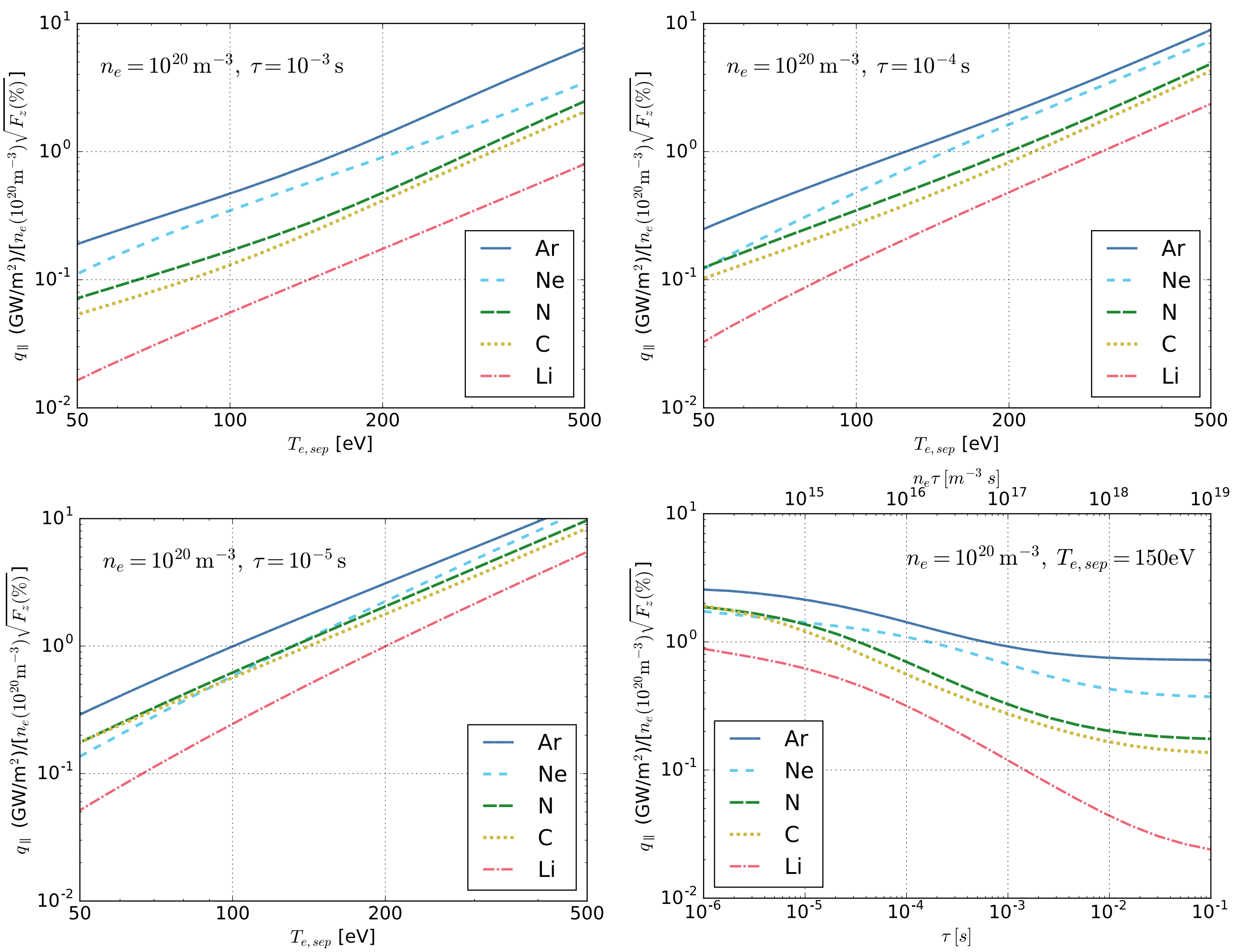

Figure 1. Detachable parallel heat flux divided by upstream density and square root of F_z in %. a-c) Varying values of $n_{e,sep}\tau_z$, evaluated at fixed $n_{e,sep}$ = $10^{20}/\mathrm{m}^3$. d) Varying $n_{e,sep}\tau_z$, at fixed $T_{e,sep}$ = 140 eV. Atomic physics from ADAS data base. For reference, sound-speed flow [c_s = $(2T/m)^{1/2}$] of deuterium at 100 eV, along a field-line length of 12 m at 150 eV, yields a transit time of 10^{-4} seconds.

To complete the evaluation of equation 1, we will require a formula for the finite-*Z* correction to electron parallel thermal conductivity. Braginskii[6] gives this correction for discrete values of *Z*, displayed in Table 1. A fit to these results accurate to within 1% is also shown: $\kappa_z \approx \left(0.672+0.076Z_{eff}^{1/2}+0.252Z_{eff}\right)^{-1}$. Braginskii's values themselves are only given to 1% precision.

Z_{eff}	Braginskii κ_z	Fit κ_z
1	1.000	1.000
2	0.775	0.779
3	0.643	0.641
4	0.546	0.546
Infinity	3.96/Z_{eff}	3.97/Z_{eff}

Table 1: Finite Z_{eff} correction to $Z = 1$ thermal conductivity from Braginskii, and fit presented here.

We now have the correction factor for thermal conductivity, κ_z, and so can evaluate $F_z \equiv c_z\kappa_z$. In the case where there is a single dominant impurity, we also have $Z_{eff} = 1 + c_z\left(Z^2 - Z\right)$. In figure 2 we plot F_z vs. c_z for Z = 3, 7, 10 & 18. These values correspond to fully ionized lithium, nitrogen, neon and argon – clearly an overestimate for a realistic situation. However, as shown in Section 3, κ_z cancels in the final result.

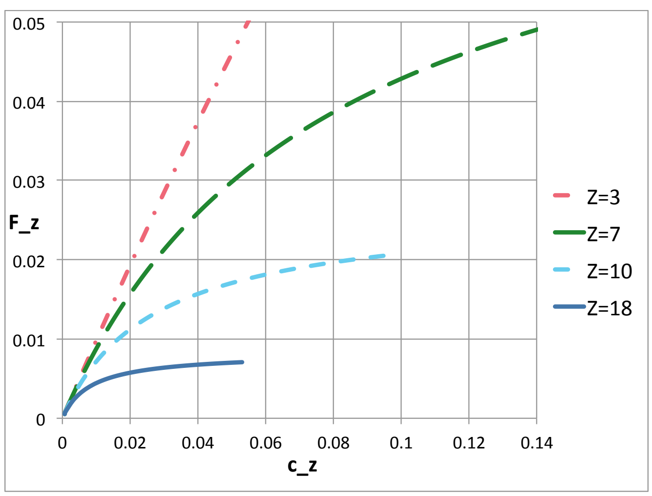

Figure 2: $F_z \equiv c_z\kappa_z$ vs. c_z, where κ_z is the finite-Z correction to the parallel electron thermal conductivity and $c_z \equiv n_z/n_e$.

The last term required for the R.H.S. of equation 1 is $T_{e,sep}$. If we use Stangeby's two-point model[7] with 100% power loss near the divertor target, we have

$$T_{e,sep} = \left(\frac{7}{2}\frac{q_{\parallel}\pi q_{cyl}R}{\kappa_z\kappa_0}\right)^{2/7} \qquad eq.2$$

Where the factor $\pi q_{cyl}R$ is chosen to represent an estimate of the divertor connection length in conventional magnetic configurations. While the integral dT_e in equation 1 weights L_z by $T_e^{1/2}$, it is more directly applicable to note that $dq_{\|}/d\ell \propto L_z/T_e^2$, indicating that the loss power density is highly concentrated near the low temperature end of a field line, just before detachment. We have also evaluated $T_{e,sep}$ explicitly, by integrating the one-dimensional heat equation using the calculated radiation as a function of T_e. For a wide range of parameters and impurities we find that for 100% cooling power the approximation in equation 2 is about 5% high, showing no apparent scaling with $q_{||}$ or impurity species.

3. Parallel Heat Flux and Agreement with Other Models and Experiment

Next we evaluate the unmitigated $q_{||}$ that needs to be detached, on the basis of the Heuristic Drift (HD) model[8], which matches the international database for low-gas-puff H-mode data very well both in magnitude and in its specific scalings[9], albeit with an offset (upwards compared with the data) of 1.25. Unlike available empirical fits, the model obeys the constraints of plasma physics. We take the spreading factor S in the Eich fit[10] used in the associated data interpretation at 0.5 λ_q based on measurements[6] and note that this causes the conventional λ_{int} to be 1.79 λ_q. $\lambda_{int} \equiv \int q\, dR / \hat{q}$ and thus relates the peak heat flux to the total. Here we are using the numerically determined ratio rather than the simple fit[11] $\lambda_{int} \sim \lambda_q + 1.64$ S, which deviates from the precise result by up to 4% in regions of interest. A fit accurate to within 0.1%, and correct in both asymptotic limits, is given by

$$\frac{\lambda_{int}}{\lambda_q} \approx \left\{ \left[1 + \left(\frac{\pi S}{\lambda_q} \right)^{2.0038} \right]^{1/2.0038} + 0.5185 \left\{ 1 + 0.1038 \left[\ln\left(\frac{S}{\lambda_q} \right) \right]^2 \right\}^{-2.6181} \right\} \qquad eq.3$$

If we assume, as is conventional, that 2/3 of the plasma transport power crossing the separatrix, P_{sep}, travels to the outer divertor, we have for the peak value of $q_{||}$ at the location where $B = B_0$, the toroidal field at the plasma center, along the outer separatrix field line from the x-point:

$$q_{\|} = \frac{1.25 P_{sep} B_0}{3\pi \cdot 1.79 \left\langle \lambda_{q,HD} \right\rangle R_0 \left\langle B_p \right\rangle} \qquad eq.4$$

where $\left\langle B_p \right\rangle \equiv \mu_0 I_p \Big/ \left[2\pi a \sqrt{\left(1+\kappa^2\right)/2} \right]$.

$\left\langle \lambda_{q,HD} \right\rangle$ is the poloidally averaged value, given by

$$\left\langle \lambda_{q,HD} \right\rangle = 5671 \cdot P_{sep}^{1/8} \frac{\left(1+\kappa^2\right)^{5/8} a^{17/8} B_0^{1/4}}{I_p^{9/8} R_0} \left(\frac{2\bar{A}}{1+\bar{Z}} \right)^{7/16} \left(\frac{Z_{eff}+4}{5} \right)^{1/8} \qquad eq.5$$

$$\bar{A} \equiv \sum_i n_i A_i \Big/ \sum_i n_i \qquad \bar{Z} \equiv n_e \Big/ \sum_i n_i$$

The simple model used here amounts to assuming a flat distribution of $q_{||}$ with width λ_{int}. However we know from theory and experiment[12] that the electron temperature profile is 7/2 wider than the heat flux channel. The SOL density profile measured on ASDEX-Upgrade[12] is about 3/2 wider than the electron temperature profile, constituting $\eta_e = 1.5$. Together these cause the radiation loss, which scales as $n_{e,sep} T_{e,sep}^{3/2}$, to form an effective channel 1.62 times wider than the heat-flux channel. To capture this effect, L_z can be multiplied by this factor, and so the curves in figure 1 by 1.27. Furthermore, Kallenbach et al.[13] indicate that the measured parallel heat flux conducted to the outer divertor, in the absence of radiative cooling, equals $P_{sep}/2.3$, rather than the conventionally assumed value of $P_{sep}/1.5$, a factor of 1.53. This is likely due to some combination of the heat flux in the far SOL region[14], where the scrape-off length is much greater than predicted in the HD model, "blob" transport, and ELM losses.

When we compare our simplified model with that of Kallenbach et al.[13], which has been successfully calibrated against experimental data on ASDEX-Upgrade, we find good agreement. The case shown in figure 4 of reference 13 has P_{sep} = 10.8 MW, $n_{e,sep}$ = 7 10^{19} /m^3, L_{div} = 20m and c_N = 4%. Assuming a plasma current of 1.2 MA, we get n_{GW} = 1.44 10^{20} / m^3, $<\lambda_{q,HD}>$ = 4.0mm and $q_{||}$ = 900 MW/m^2, giving $T_{e,sep}$ = 144 eV. To evaluate the $q_{||}$ *t*hat will be dissipated, the nitrogen curve shown in figure 1 should be multiplied by 0.7 for $n_{e,sep}$, by $(4 \times 0.68)^{1/2}$ for F_z, and by 1.27 for the radiative channel width, giving an upward adjustment of 1.47. Following the procedure of reference 13, $q_{||}$ should be adjusted downwards for non-radiative losses by a factor of 1.53, to 590 MW/m^2, resulting in very good agreement with Kallenbach's assumed $n\tau_z$ = 5 10^{16} sec/m^3.

This agreement might come as a surprise, since the present model does not include a calculation of ion-neutral collisions, a key feature of Kallenbach's model. However in that model neutral interactions only dissipate about 10% of the parallel heat flux in ASDEX-Upgrade, and less in devices with higher $q_{||}$. Neutral effects are important for assessing the divertor gas pressure required for detachment, but here we are primarily interested in the upstream density requirement. Note that for fixed magnetic field, consistent with the fixed λ_q assumed in figure 4, $n_{e,sep}/n_{GW}$ rises by a factor of about three at fixed $q_{||}$ and c_N in traversing a factor of five increase in linear dimension from ASDEX-Upgrade to Demo1, illustrating the limitation of $q_{||}$ as a figure of merit for the difficulty of detachment. At fixed $n_{e,sep}/n_{GW}$ a much greater c_N would be required.

3. Scaling

The rough agreement found above suggests that it could be valuable to consider the scaling of this result from existing to future devices. We will solve for the impurity concentration required as a function of global parameters. We start from equation 1, noting that the term on the RHS scales about as $T_e^{3/2}$. Multiplying both sides by R_0 and normalizing the separatrix density to the Greenwald limit for the bulk plasma, we have:

$$q_{\|}R_0 \propto \left(\frac{q_{cyl}q_{\|}R_0}{\kappa_z}\right)^{3/7} F_z^{1/2} f_{GW,sep} \frac{R_0}{a}\left\langle B_p\right\rangle\left(1+\kappa^2\right)^{1/2}$$

$$F_z f_{GW,sep}^2 \propto \frac{\left(q_{\|}R_0\right)^{8/7}}{\left(\frac{q_{cyl}}{\kappa_z}\right)^{6/7}\left(\frac{R_0}{a}\right)^2\left\langle B_p\right\rangle^2\left(1+\kappa^2\right)} \qquad eq.6$$

Already there is something revealing about this result. $q_{||}$ only appears in the combination $q_{||}R_0$ and no variable with dimension of length appears elsewhere. Since $q_{||}R_0$ scales as $P_{sep}B_0/(<B_p>\lambda_{int})$, and our experimental data indicate that λ_{int} itself carries no explicit scaling with machine size, we can see already that there is no explicit size scaling to mitigate the effects of increasing P_{sep} with size on the requirement for increasing impurity concentration.

We proceed to evaluate the scaling of $q_{||}R_0$ from equations 3 and 4. The final term in equation 5 is the result of a less accurate form for κ_z, so we use the form developed here instead.

$$q_{\|}R_0 \propto P_{sep}^{7/8} B_{t,0}^{3/4}\left\langle B_p\right\rangle^{1/8}\frac{R_0}{a}\left(1+\kappa^2\right)^{-1/16}\left(\frac{\bar{A}}{1+\bar{Z}}\right)^{-7/16}\kappa_z^{1/8} \qquad eq.7$$

Now we have

$$F_z f_{GW,sep}^2 \propto \frac{P_{sep}B_{t,0}^{6/7}\left(\frac{\bar{A}}{1+\bar{Z}}\right)^{-1/2}\kappa_z^{1/7}}{\left(\frac{R_0 q}{a\kappa_z}\right)^{6/7}\left\langle B_p\right\rangle^{13/7}\left(1+\kappa^2\right)^{15/14}} \qquad eq.8$$

leading to the final result, in which κ_z cancels out:

$$c_z \propto \frac{P_{sep}}{\left\langle B_p\right\rangle\left(1+\kappa^2\right)^{3/2} f_{GW,sep}^2}\left(\frac{1+\bar{Z}}{\bar{A}}\right)^{1/2} \qquad eq.\ 9$$

For a single dominant impurity, and hydrogenic species with average atomic mass A_H, we find equation 10, illustrated in figure 3.

$$\left(\frac{1+\bar{Z}}{\bar{A}}\right)^{1/2} = \left[\frac{2-c_z\left(Z-1\right)}{A_H\left(1-Zc_z\right)+A_z c_z}\right]^{1/2} \qquad eq.\ 10$$

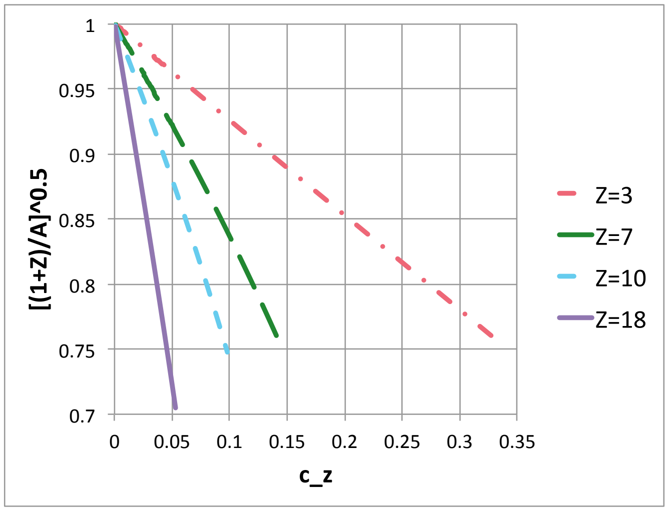

Figure 3: $\left(\frac{1+\bar{Z}}{\bar{A}}\right)^{1/2}$ $vs.\ c_z$ for Z = 3, 7, 10 and 18, A = 7, 14, 20 and 40 in deuterium (A_H = 2) plasmas.

This is the term that scales the sound speed in a hydrogen plasma for fixed $T_e = T_i$ to an impure and/or deuterium or deuterium-tritium plasma. One could neglect this factor as unproven by experimental results. However recent experiments on JET[15] may have shown its effect in comparing the H-mode density limit for *H* and *D* plasmas. For a 50% replacement of deuterons with fully stripped nitrogen ions, it has only an 11% effect, reducing the required c_z. Note, however, that a population of heavy, partially stripped impurities could have a larger effect, as can be evaluated using equation 10.

4. Discussion

This result suggests that the difficulty of detachment, as measured by the necessary impurity concentration, c_z scales as $P_{sep}/[\langle B_p\rangle(1+\kappa^2)^{3/2}(n_{sep}/n_{GW})^2]$, with no explicit size scaling, rather than with the more conventionally assumed P_{sep}/R_0 or $P_{sep}B_0/R_0$. This implies increasing difficulty as fusion systems move to separatrix powers an order of magnitude greater than presently employed, while increasing magnetic fields by a factor of ~ 2 – 3, since there may not a be a factor of three headroom above present impurity seeding levels for an economic fusion system. (See Table 2.)

This result highlights the strong role of the Greenwald fraction at the separatrix both in the future and for data interpretation. It is sometimes assumed, tacitly or otherwise, that this will be a free parameter in future devices with SOLs that are opaque to neutrals, since it is believed that the core can be fueled by pellets while the SOL is fueled by gas puffing, decoupling their two densities. However results from C-Mod[16,17] and ASDEX-Upgrade[18] indicate that high temperature pedestals and good H-Mode confinement are correlated with $n_{e,sep} < \bar{n}_e/2$. NSTX achieves high confinement with lithium conditioning, which may reduce the separatrix density due to reduced recyling[19]. Results from JET[15] and DIII-D[20] support the hypothesis[9] that it is the pressure in the SOL that sets the upper density limit of the H-Mode near the Greenwald limit. Finally, and very interestingly, results from ASDEX-Upgrade[12], as noted above, indicate that over a range of powers and plasma currents, $\eta_e \equiv \mathrm{dln}T_e/\mathrm{dln}n_e$ is approximately constant, suggesting a role for ETG modes, as calculated at the edge of NSTX[21]. These results together imply that a high-temperature pedestal, such as required in ITER and Demo, may require a low separatrix density. It should be recognized, however, that the low collisionality, high f_{GW} regime will only become available for scientific study with ITER operation. Equally, or perhaps more importantly, ITER will provide the definitive test for the size scaling of λ_{int} at reactor dimensions.

	ASDEX-U	JET	ITER	FNSF (A=4)	EU Demo1
P_{sep}	10.7	14	100	107	150
B_t	2.5	2.5	5.3	7.5	5.7
R_0	1.6	2.9	6.2	4.8	9.0
P_{sep}/R	6.7	4.8	16.1	22.3	16.7
$P_{sep}B_t/R$	16.7	12.1	85.5	167.2	95.0
I_p	1.2	2.5	15	7.9	20
a	0.52	0.90	2.00	1.20	3.00
κ_{95}	1.63	1.73	1.80	2.10	1.70
$<B_p>$	0.34	0.39	1.03	0.80	0.96
q*	3.16	2.79	2.42	3.85	2.77
n_{GW}	1.44E+20	9.82E+19	1.19E+20	1.75E+20	7.07E+19
$c_N \propto P_{sep}/(<B_p>(1+\kappa^2)^{3/2})$	4.0%	4.1%	10.1%	9.7%	18.6%

Table 2: Some comparisons with recent operating points on existing devices, and future projections. c_N is normalized to the ASDEX-Upgrade case from reference 13, discussed in Section 2. Note that c_N is evaluated in the divertor, so the nitrogen is not fully ionized, and c_N in the core of ASDEX-Upgrade is observed to be significantly lower. P_{sep} is reduced by 40% for the double-null divertor in the Fusion Nuclear Science Facility (FNSF). EU Demo1 employs core radiation to limit P_{sep} to just above what is required to sustain H-mode confinement.

Despite the uncertainties, the present result suggests that there may be considerable advantage to higher magnetic fields. Strong shaping, which both directly reduces the needed c_z and also allows higher poloidal magnetic field strength at fixed q_{cyl}, reduces c_z further, possibly in conjunction with lower aspect ratio. Future designs should explore options for higher magnetic field, strong shaping including varying aspect ratio, double-null operation, and advanced divertor configurations that may encourage detachment through larger $L_{||}$ and/or reduced B as the divertor target is approached.

Importantly, this work indicates the strong need for new experimental methods[22] to measure c_z in the SOL, and determine if, indeed, the c_z *in the SOL* required for detachment scales as predicted here. These measurements also need to be compared with more sophisticated models that include plasma transport in evaluating the spatial dependence of c_z, as well as in determining the non-coronal deviation from charge-state balance.

Finally, given the warning implicit here, this work should motivate further research and development on alternative strategies for power handling, such as the use of fast-flowing liquid metal divertor targets[23] and/or lithium metal vapor localized in the divertor chamber[24]. The results shown in figure 1 indicate that lithium is only a factor of 2 less efficient at dissipating $q_{||}$ than nitrogen for given c_z, and in principle lithium vapor can be very effectively localized in the divertor region through differential pumping via condensation, making it unlikely that the radiative zone will move to the x-point location as detachment is achieved.

Acknowledgments:
Authors R.G. and M.R. would like to thank the University of Leiden Lorentz Center "Taming the Flame" workshop for providing the atmosphere in which these ideas could most easily be fleshed out. This work was supported by DOE Contracts Numbers: DE-AC02-09CH11466 and DE-AC05-00OR22725.

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