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A model is developed which constrains heat width, $\lambda_r$, based on global power balance, momentum conservation, pedestal stability and sheath heat transmission. The model relies on measurements of the ratio of separatrix to pedestal pressure; a ratio $\sim5\%$ is found to be expected for ITER. Applying this model indicates a constraint that the allowed $\lambda_r \sim 10-30$ mm for ITER if the divertor is in the high-recycling regime as expected ($T<20$ eV) while a $\lambda_r \sim 1-3$ mm requires a separatrix pressure approximately equal to the top pedestal pressure in violation of physical reasoning and the concept of a pedestal. A weaker constraint is applied in the model that upstream separatrix temperature simultaneously satisfies power balance. The constrained model cannot satisfy power balance with $\lambda_r < 3$ mm, and in order to obtain $\lambda_r \sim 5$ mm requires divertor plasma temperature $>100$ eV, a condition which would have very negative consequences for the divertor, but has never been observed experimentally.

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1. Introduction and Motivation

The issue of the scrape-off layer (SOL) integral radial power width, $\lambda_r$, remains a critical and unresolved issue [1, 2] for designing magnetic fusion boundary plasmas compatible with the limit of peak heat flux $< 10^{-15}$ MW m$^{-2}$ in actively-cooled plasma-facing components. For fixed total power ($P$) plasma exhaust requirements, the peak heat flux $\sim 1/\lambda_r$, so if $\lambda_r$ is too small the divertor components will fail. However first-principles explanations explaining $\lambda_r$ remain elusive. Empirical attempts at estimating $\lambda_r$ in large-scale devices like ITER have historically shown large amounts of scatter and poor self-consistency [3]. Recent activities have sought to improve $\lambda_r$ measurement fidelity in many present experiments (e.g. [4, 5]). Regression analysis of these data [5, 6] and a heuristic drift model [7] have suggested $\lambda_r \sim 1$-3 mm for ITER (depending on the precise definition of $\lambda_r$) a factor of up to five lower than previous estimates (e.g. [8]) raising serious concerns for ITER divertor viability.

Given these concerns and uncertainty it is desirable to develop methods of constraining $\lambda_r$ in ITER (and future fusion devices) independent of the $\lambda_r$ measurements themselves. We develop here such a method, constraining $\lambda_r$ based on SOL and pedestal pressure, sheath heat transmission and global power balance. This strategy is motivated by several observations. Recent developments in peeling-ballooning modeling and pedestal transport provide near-predictive capability for the H-mode pedestal pressure [9] while the SOL is adjacent to and essentially part of the pedestal. Simultaneously, recent measurements in Alcator C-Mod [10] confirm the standard sheath heat transmission coefficient [1]. Because the C-Mod divertor most closely matches the expected local conditions of the ITER divertor strikepoint (plasma density, ion flux, vertical, high-Z metal target) this provides confidence in using divertor density, n, and temperature, T, to calculate plasma heat exhaust $q_{div} \propto nT^{3/2} \propto pT^{1/2}$ which in turn is highly constrained to the divertor plasma pressure, p. Plasma pressure is the only quantity necessarily conserved along the separatrix from the divertor to the “upstream” midplane because the plasma can only exchange momentum to neutral species, which only exist in a small region of the SOL near the divertor plate in non-detached conditions. Taking these together, a relationship between the separatrix pressure and the known pedestal pressure will then provide a rigorous constraint on the allowed $\lambda_r$ and divertor T through the power exhaust requirement since $P_{div} \propto pT^{1/2} \lambda_r$. A further motivation for this methodology is that the divertor pressure and pedestal electron pressure are relatively well measured by probes and Thomson Scattering (TS) respectively.
In both regions it is expected that ions and electrons contribute roughly equal to total plasma pressure (due to collisional coupling) and therefore the unmeasured ion temperature is largely avoided as a diagnostic issue. The following labels are used for locations: “ped” is the top of the pedestal, “sep” is the separatrix, “U” is the upstream separatrix at the outer midplane and “div” is the separatrix at the divertor plate.

In Section 2 we use pressure measurements on present experiments to provide an expectation of the ratio of separatrix to pedestal pressure in ITER. In Section 3 the pressure/power balance model is developed and applied to the ITER Q=10 H-mode scenario. Section 4 discusses the sensitivity of the model results to its assumptions and Section 5 contains the conclusions.

2. Assessing the ratio of separatrix to pedestal pressure

The ratio of separatrix pressure to pedestal pressure has been measured over a variety of conditions in Alcator C-Mod and DIII-D (Fig. 1). The discharges used for the analysis are a subset of those used for cross-device comparisons of heat flux width [4]. All discharges are H-mode (ELMy H-mode on DIII-D, EDA H-mode on C-Mod) with auxiliary heating from both neutral beams and RF heating. Separatrix pressure is obtained from the maximum electron pressure at the outer divertor as measured by embedded Langmuir probes. The outer divertor is used because in all cases these plasma were not detached, and therefore total pressure will be constant along the separatrix. The total separatrix pressure is defined here as four times the electron pressure at the sheath entrance: a factor of two arising from the Bohm sound-speed criterion which forces the static pressure (nT) to decrease a factor of two, and the other factor of two from the assumption that ions and electrons equally contribute to pressure \((T_i\approx T_e)\) in the collisional divertor plasma. The pedestal electron pressure, defined as the pressure at the “top” of the pedestal, is measured by upstream Thomson Scattering (TS). The pedestal “top” typically resides at 4-5% of the minor radius inside the separatrix (insert, Fig. 1, [11]). The total pressure at the pedestal’s top is taken to be twice the electron pressure, i.e. \(T_i\approx T_e\) based on C-Mod and DIII-D ion measurements. We also include a single data point as published from JET (Fig. 2 of [11]) which uses TS for both the separatrix and pedestal pressure, therefore relying on magnetic reconstructions for the separatrix value.

The separatrix-to-pedestal ratio ranges from \(\sim1\text{-}10\%\) and the most likely value for ITER is \(\sim5\%\) (Fig. 1). The ratio best organizes to global power density (P/S, heating power per surface area) with a
roughly linear dependence among the different devices and within data from each device as well (although there is considerable scatter). Conversely there is no apparent organization of the ratio to $q_{95}$. The experimental P/S and $q_{95}$ cover the range expected for the ITER 500 MW fusion power Q=10 scenario (P/S~150MW/700m²~ 0.22 MW/m², $q_{95}$~3) and therefore we use the experimental trends to interpolate an expected separatrix-to-pedestal ratio of 0.05 with 50% uncertainty based on the data scatter (shaded region of Fig. 1).

3. Model and Results

A simple model satisfying global power exhaust is developed for the ITER ($R_0$=6.2 m, $B_0$=5.3 T) Q=10, 500 MW fusion power case. Total heating power is 150 MW, power into the SOL is $P_{SOL}$=100 MW and the power exhausted to the divertor plate $P_{div}$=50 MW. The SOL parallel area available to exhaust heat to the two divertors is

$$A_{q//} \equiv 4\pi R \lambda_r \left(\frac{B_0}{B_\phi}\right)_{U} \approx 17 \lambda_r [m^2]$$

where the average major radius R~5 m of the divertors, and the upstream (“U”) outer midplane field pitch ($B_0 / B_\phi$)$_U$~ 0.27 with $B_\phi(R) = B_0R_0 / R$, $B_{\phi,U} \approx 4 T$ and $I_p$=15 MA. Note $\lambda_r(B_0 / B_\phi)$ is a constant on a flux surface which is why it is used to conventionally define the radial power width as its equivalence at the outer midplane even though it is physically evaluated at the divertor plate [12]. The parallel heat exhaust at the separatrix location of the divertor plate (“div”) is set by sheath heat transmission

$$q_{//} = \gamma \left(10^{20} n_{20,div}\right) c_s kT_{div} \approx 1.1 n_{20,div} T_{div}^{3/2} [MW \ m^{-2}]$$

where $\gamma \sim 8$ [1] is the heat transfer coefficient as recently validated [10], $n_{20} [10^{20} \ m^{-3}]$ and T [eV] are divertor density and temperature respectively and $c_s = 8.7 \times 10^3 T_{div}^{1/2} \ [m/s]$ is the sound speed set by the Bohm criterion. In order to satisfy power exhaust $P_{div} = q_{//} A_{q//} =50$ MW. Note that by our model definition $\lambda_r$ is the “integral” radial width evaluated at the divertor so that it is readily used to determine global divertor power exhaust; a definition previously used (e.g. Eq. 1 of [12]). Note because the $\lambda_r$ is defined by the power exhaust requirement it requires no explicit model for the shape of the heat footprint yet can be used to determine the peak heat flux. The stated SOL widths in other studies may be somewhat smaller since they use multiple parameters to characterize the divertor heat width [5]. Furthermore it is noted that some regression fits [5,6] and the drift model [7] suggest the width is solely set by poloidal B. Since this is matched for ITER by Alcator C-Mod, one would
expect an integral $\lambda_r \sim 3$ mm taken directly from C-Mod H-mode measurements [4]. Therefore we estimate that these studies predict or extrapolate a range of $\lambda_r \sim 1$ - 3 mm to compare to our simple model.

To satisfy divertor power exhaust Eqs. 1 and 2 can be combined to find a requirement for the divertor static pressure

$$p_{20, div} = 2 n_{20, div} T_{div} \frac{5.4}{T_{div}^{1/2} \lambda_r} [10^{20} \text{ m}^{-3} \text{ eV}]$$

Eq. 3

assuming $T_e = T_i$ in the definition of $p_{20}$.

Invoking total pressure conservation at the separatrix and noting that static pressure decreases a factor of two from the upstream plasma to the sheath entrance we constrain separatrix total pressure based on heat exhaust requirement by

$$p_{20, sep} = 10.8 \frac{T_{sep}^{1/2} \lambda_r}{T_{div}^{1/2} \lambda_r} [10^{20} \text{ m}^{-3} \text{ eV}]$$

Eq. 4

However the separatrix pressure is also constrained by the pedestal. Based on extensive modeling and comparison to experiments the ITER Q=10 pedestal pressure [9] is expected to be 92 kPa or $p_{20, ped} \sim 3000$. Note that this is not a large extrapolation from present experiments with present experiments straddling the ITER beta values and the absolute ITER pressure only 2.5x that found in C-Mod ELMy H-mode (see Fig. 8 of [9]). Based on Section 2 we expect the ITER separatrix pressure to be 5% of the pedestal pressure or $p_{20, sep} = 150 \pm/50\%$. Using Eq. 4 and $p_{20, sep} = 150$, Fig. 3 shows the allowed combinations of $T_{div}$ and $\lambda_r$ that satisfy power balance. For the standard assumption that the divertor will be in the high-recycling regime so that $T_{div} \sim 10$ eV we find that the expected value of $\lambda_r \sim 22$ mm with a range of $\lambda_r \sim 15$ - 40 mm between $75 < p_{20, sep} < 225$. For $T_{div} \sim 10$ eV, a $\lambda_r \sim 1$-3 mm would require a separatrix pressure $\sim 3000$, i.e. near-to or in excess of the pedestal pressure, clearly in violation of physical reasoning and/or the definition of a pedestal.

A further constraint on the upstream conditions in ITER is that the scenario operates near the Greenwald density limit ($n_{20} \leq I_{p[MA]} / \pi a_{in}^2 \approx 1.2$) [13] so that the pedestal density is < $10^{20}$ m$^{-3}$. From a multi-device database [8] it was found that the separatrix density was 40-50% of the pedestal density and therefore a reasonable estimate to the upstream density is $n_{20, U} \sim n/n_{Gr} \sim f_{Gr} \sim 0.4$-0.5, i.e. increasing the upstream density significantly from these values would violate the global Greenwald density $n_{Gr} \sim 10^{20}$ m$^{-3}$ on ITER. Therefore we can estimate the upstream electron temperature
\[ T_{e,U} = \frac{P_{20,up}}{(1 + \alpha)n_{20}} = \frac{10.8}{(1 + \alpha)T_{div}^{1/2} \lambda_r f_{Gr,20}} [eV] \]  
\text{Eq. 5}

where \( \alpha \equiv T_i / T_e \) at the upstream separatrix. The expected \( T_{e,U} \) values consistent with divertor power exhaust are shown in Fig. 2b for the case of \( \alpha = 2 \) and \( n_{20,U} \sim f_{Gr} = 0.4 \) showing that at fixed \( T_{div} \sim 10 \) eV the upstream \( T_{sep} \) increases from \( \sim 200 \) eV at \( \lambda_r \sim 10 \) mm to \( \sim 2000 \) eV at \( \lambda_r \sim 1 \) mm.

This upstream \( T \) can be further used to estimate local parallel heat exhaust out of the upstream / midplane SOL towards the divertors via either Spitzer-Harm electron heat conduction [1]

\[ q_{\parallel,SH} \equiv \frac{2}{7} \pi R d_{gy} \left( T_{e,U}^{7/2} - T_{e,div}^{7/2} \right) = 10^{-5} \left( T_{e,U}^{7/2} - T_{e,div}^{7/2} \right) [MW \ m^{-2}] \]  
\text{Eq. 6}

with \( \kappa_{0,e} = 2000 \), or in the case the heat is “Flux-Limited”

\[ q_{\parallel,FL} \equiv 0.3 n v_{th,e} k T_e \simeq 2 f_{Gr} T_{e,U}^{3/2} [MW \ m^{-2}] \]  
\text{Eq. 7}

where \( v_{th,e} \) is the electron thermal velocity. Following standard practice the resulting parallel heat flux is determined by the limiting of these two and

\[ \frac{1}{q_{\parallel,U}} = \frac{1}{q_{\parallel,SH}} + \frac{1}{q_{\parallel,FL}} \]  
\text{Eq. 8}

with the result shown in Fig. 2c for the case described above. It is immediately observed that a portion of the \( T_{div}, \lambda_r \) space is disallowed because the upstream (heat source) \( T \) is less than the divertor (heat sink) \( T \), in violation of basic thermodynamics. For \( T_{div} = 10 \) at the pressure constrained value \( \lambda_r \sim 22 \) mm the upstream heat flux is several 100’s MW/m², while for \( \lambda_r \sim 1 \) mm the heat flux exceeds 10 GW/m² even in the flux-limited regime.

The results of Fig. 2 are combined into Fig. 3 to examine reasonable ranges of \( T_{div}, \lambda_r \) space where power and pressure balance can be satisfied. The case is with the same parameters as Fig. 2. A significant region of the space (blue shading) is disallowed due to \( T_{div} > T_U \) indicating that even without further constraints the minimum allowed width is \( \sim 4 \) mm. The SOL power exhaust \( P_{SOL} \equiv q_{\parallel,U} A_{\parallel,U} \), where the parallel exhaust width is evaluated using upstream \( \lambda_{r,U} \) (Eq. 1), is shown by the dotted line contours overlaid with the separatrix pressure requirements. It is possible that the upstream width \( \lambda_{r,U} \) is smaller than the divertor width \( \lambda_r \) since this quantity is not necessarily conserved from upstream to downstream, just pressure. Therefore we estimate that a reasonable “modeled” range for \( P_{SOL} = 100 \) is obtained in the range \( \lambda_r / 3 \leq \lambda_{r,U} \leq \lambda_r \) reflecting the possibility that the upstream heat width might be as small as 1/3 of the divertor width if it follows for
instance from ~2/7 of the temperature gradient scale-length [8]. The intersection of possible \( P_{\text{SOL}} \)
=100 MW and \( P_{\text{div}} \) (via the \( p_{20,\text{ped}} \) constraint) indicate the allowed range of \( T_{\text{div}}, \lambda_r \) that simultaneously satisfy divertor and SOL power exhaust requirements (red shaded region of Fig. 3). In this case, the most likely value at \( p_{20,\text{ped}}=150 \) and \( P_{\text{SOL}}=100 \) MW is with \( T_{\text{div}} \sim 12 \) eV and \( \lambda_r \sim 20 \) mm, suggesting this very simple model predicts that the high-recycling divertor is a self-consistent response of the SOL/divertor. The possible ranges are \( T_{\text{div}} \sim 3-50 \) eV and \( \lambda_r \sim 8 \) to 40 mm.

4. Discussion on sensitivity to separatrix density

Given the simplicity of the model in Section 3 it is worthwhile to examine the sensitivity of the allowed \( \lambda_r \) and \( T_{\text{div}} \) to model assumptions. The results in Fig. 3 already account for the expected ~factor of 2-3 uncertainty in model parameters (pressure ratios, sheath heat transmission factor or upstream power width) indicating that the basic result of the model regarding divertor heat width are robust. The remaining important assumption is the upstream density. Based on present experiments [8] it is most likely that \( n_{20,\text{U}} \sim 0.4 \) however it will not violate the density limit to allow this parameter to decrease.

The results of relaxing \( n_{20,\text{U}} \) to lower values is shown in Fig. 4. Lowering \( n_{20,\text{U}} \) increases upstream T at constant pressure and therefore the disallowed \( T_{\text{div}} > T_{\text{U}} \) space (Fig. 3) decreases in size. Simultaneously the higher upstream T affects \( P_{\text{SOL}} \) predictions through Eqs. 6, 7. Fig. 4 shows the results of evaluating the maximum possible values that satisfy power balance via the methodology demonstrated in Fig. 3. It is seen that at the “most expected” \( (p_{20,\text{ped}}=150 \) and \( P_{\text{SOL}}=100 \) MW) equilibrium point that \( \lambda_r \) decreases to ~4-5 mm as \( n_{20,\text{U}} \) approaches 0.2, while the maximum allowed \( \lambda_r \) tends to stay quite large ~40 mm. However it is seen that in order for the “most expected” equilibrium \( \lambda_r \) to decrease below ~8 mm a simultaneous divertor temperature in excess of 100 eV is required. Such a high plasma temperature has never been observed in a divertor (but would be problematic for a divertor due to very high sputtering) even in the low-recycling or “sheath-limited” regimes which find maximum \( T_{\text{div}} < 100 \) eV. It is beyond the scope of this paper to fully discuss this in detail, but it would seem likely that very high divertor temperatures (well in excess of 100’s of eV up to 1 keV) are disallowed due to thermal and ionization stability arguments for the SOL. Or stated another way there is a good reason one uses closed flux-surfaces to attain high T plasmas.

In summary of the discussion, even allowing for very large uncertainties/ranges in the model
assumption it appears that the ITER heat width is robustly > 10 mm based on pressure/power balance and 1-3 mm widths do not appear possible if the ITER divertor temperature is < 100 eV. It is unclear at this point why this result is so inconsistent with some present empirical extrapolations [5,6]. It is suggested that considerations of pressure/power balance along the lines of the presented work be applied to the present database and analysis to determine issues of self-consistency.

5. Conclusions

A model independent of measuring power widths $\lambda_r$ is developed which constrains ITER $\lambda_r$ based on global power balance, momentum conservation and recent improvements in understanding pedestal stability and sheath heat transmission. Experimental measurements suggest a separatrix to pedestal pressure ratio ~5% for ITER. Applying the simple model indicates a constraint that the allowed $\lambda_r$ ~ 10-30 mm for ITER if the divertor is in the high-recycling regime as expected (divertor T~5-20 eV). With a high-recycling divertor, a $\lambda_r$ ~1 mm would require a separatrix pressure approximately equal to the pressure at the top of the pedestal clearly in violation of the concept of a pedestal. A weaker constraint is also applied in the model that upstream separatrix pressure and T must simultaneously satisfy power balance. Even assuming large uncertainties in the model, it is not possible to satisfy power balance with a $\lambda_r$ < 4 mm even in the extreme case of divertor T > 100 eV.

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References

Figure Captions

Fig. 1

Measured ratios of divertor separatrix pressure to pressure at the top of the H-mode pedestal. C-Mod and DIII-D use divertor probes for divertor pressure and upstream Thomson Scattering for the pedestal pressure. The JET data point [10] from upstream data only. (Top) Ratio organized to $q_{95}$ (Bottom) Ratio organized to global heating power density $P/S$. The star indicates expected value for ITER $Q=10$ H-mode scenario: $q_{95} \sim 3$, $P/S \sim 0.22$ MW m$^{-2}$. (Top Insert) Example pedestal pressure profile and fit from C-Mod.

Fig. 2

Contours of model results versus assumed $T_{\text{div}}$ and $\lambda_r$ for ITER $Q=10$ case of $P_{\text{div}} = 50$ MW, upstream density $n_{20,U} = 0.5$, $p_{20,\text{ped}} \sim 3000$ (a) Separatrix pressure required to satisfy divertor heat exhaust. Red line: expected ITER value for $p_{20,\text{sep}} \sim 5\%$ (Fig. 1) of $p_{20,\text{ped}}$ denoted by orange line (b) Upstream electron temperature assuming $T_{i,U} = 2T_{e,U}$. (c) Upstream parallel heat flux. Regions where Spitzer-Harm conductivity or flux limiters dominant are noted as well as disallowed regions due to divertor $T$ exceeding upstream $T$. Star indicates most expected value if ITER divertor $T = 10$ eV.

Fig. 3

Integrated contour plot of model for ITER $Q=10$, $P_{\text{div}} = 50$ MW, upstream density $n_{20,U} = 0.5$, $p_{20,\text{ped}} \sim 3000$. Solid line contours: separatrix pressure required to satisfy divertor heat exhaust (Fig. 2). Dashed line contours: upstream $P_{\text{SOL}} = 100$ SOL power exhaust from product of upstream $q_{\parallel,U}$ (Fig. 2) and $A_{q_{\parallel,U}} \propto \lambda_{r,U}$ for two different limiting assumptions of the upstream width compared to the divertor width. Shaded blue region is disallowed due to divertor $T$ exceeding upstream $T$. Star indicates where $P_{\text{div}}$ and $P_{\text{SOL}}$ are simultaneously satisfied. The red shaded region indicates expected range of allowed $T_{\text{div}}$ and $\lambda_r$ to satisfy power balance within model uncertainty.
Fig. 4

Sensitivity of model results for allowed $T_{\text{div}}$ (bottom) and $\lambda_r$ (top) to assumed upstream density $n_{20,U}$ for case: $P_{\text{div}} = 50$ MW, $P_{\text{SOL}} = 100$ MW, $T_{i,U} = 2T_{e,U}$. Diamonds: $P_{\text{div}} = 50$ MW and $P_{\text{SOL}} = 100$ MW are exactly satisfied. Squared and triangles denote allowed range for minimum and maximum $\lambda_r$ respectively. The shaded red region of Fig. 3 shows an example of how the range is determined.
Fig. 1
Fig. 2
Fig. 3
Fig. 4

Heat width $\lambda_r$ (mm)

Divertor $T$ (eV)

Evaluation criterion
- $P_{20,\text{div}} = 150$
- $P_{\text{SOL}} = 100$ MW
- min. allowed $\lambda_r$
- max. allowed $\lambda_r$

upstream separatrix: density $n_{20}$ or Greenwald fraction

$P_{20,\text{div}} = 150$
$P_{\text{SOL}} = 100$ MW
min. allowed $\lambda_r$
max. allowed $\lambda_r$