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Abstract: Scrapeoff Layer (SOL) data from DIII-D and C-Mod have been acquired and analyzed for radial particle transport based on a particle balance model. This has allowed a detailed comparison for L-mode plasmas. The inferred radial particle flux, $\Gamma_\perp(r)$, is parameterized in terms of diffusive [$D_{eff}(r) \equiv \Gamma_\perp(r)/\nabla n(r)$] and convective particle transport [$v_{eff}(r) \equiv \Gamma_\perp(r)/n(r)$]. The magnitude of the inferred D_{eff} or v_{eff} increases across the SOL for both tokamaks. The inferred D_{eff} or v_{eff} in the 'far' SOL (one density e-folding length from the separatrix and beyond) are essentially unchanged by changes in core density by factors of 2-3. This corresponds to changes in the far SOL density, collisionality (ν^*), and radial fluxes of a factor of 10 or more. Thus ν^* does not appear to be an important parameter in determining the radial particle transport in that region.

The dimensionlessly-scaled SOL plasma profiles from the two tokamaks overlay for similar dimensionless plasma parameters. The SOL density profile near the separatrix is steeper than in the 'far' SOL. The scaled D_{eff} and v_{eff} are slightly larger on DIII-D than C-Mod. This difference appears to be within experimental uncertainties.

Neutral ionization in the SOL does not appear to affect radial transport but may be related to the observed flattening of the density profiles with increasing $\bar{n}_e$.

1. Introduction

There has been extensive work on Alcator C-Mod showing that cross-field ion transport can lead to significant plasma interaction with the walls of the main chamber and thus dominate the neutral pressures there. In particular those studies have included 2-D simulations of SOL transport [1], direct measurement of wall fluxes [2-4], and use of an interpretive transport analysis to determine cross-field transport coefficients directly from experimental measurements [2-4]. Modelling of ASDEX Upgrade [5], simple estimates of flows and equivalent transport coefficients [6], and DIII-D plasmas [7] have also indicated significant interactions with main chamber walls during steady state conditions (the effect of ELMs is also important but not the emphasis of this paper). Such interactions indicate that radial particle transport is stronger than expected, competing with parallel particle transport which, for an ideal divertor, should locate almost all plasma-surface interactions at divertor surfaces. The implications are multiple. Impurities which are the result of ion impact on main chamber surfaces have a much higher probability of reaching the core than those launched from the divertor [8-12]. Thus even a small first wall impurity source could strongly affect core impurity concentrations. The recycling that occurs in the main chamber leads to high neutral pressures there which can affect the near separatrix region (e.g. fueling, enhanced neutral-ion viscosity [13], cx energy losses [4]), as well as increase the probability of charge exchange sputtering of first-wall surfaces. If the radial transport is particularly strong then radial heat convection can become important [4,14], carrying power to the walls, cooling the core, and potentially playing a role in the density limit [4]. Such cooling of the core can of course lead to the thermal collapse of the core and a current disruption.

The balance of radial and parallel heat transport affects the heat load footprint on the divertor and other surfaces. Understanding the physics and scaling of the radial transport in the SOL would greatly enhance our ability to predict the performance of future experiments – both for the core and divertor. Lastly, it has been postulated that radial fluxes, both steady state and turbulent, lead to parallel flows in the SOL [15,16], having implications for core confinement mode [16] and impurity screening [9,10,17].

The direct measurement of ion fluxes to DIII-D main chamber surfaces, their dependence on confinement mode, ELMs and the resultant impurity sources is the subject of a companion paper [14]. The work presented here applies an interpretive analysis of cross-field transport to DIII-D and C-Mod SOL plasmas with the goal of using their similarities and differences to try and determine the important physics underlying the radial transport and how it scales. We find the effective transport coefficients derived for the two tokamaks to be very similar for the L-mode datasets examined: Their magnitudes are within a factor of two. The radial scaling is essentially the same. The lack of dependence on density is also the same. The datasets used cover the same range of SOL dimensionless parameters. We discuss the implications of these results in terms of plasma and atomic physics.

2. Experimental Arrangement

All results reported in this paper were obtained in ohmic deuterium discharges with a diverted, lower single-null magnetic equilibrium, and $B x \nabla B$ ion drift directed towards the lower X-point. Detailed information on Alcator C-Mod's and DIII-D's design, diagnostics, and operational characteristics can be found elsewhere [18,19]. The input power was in the range 1.1-1.6 MW increasing with density for C-Mod. Similar levels of power were used for the DIII-D discharge cases (0.9 MW Ohmic + 0.2 MW NB, rising to 0.8 MW NB at the highest densities). Neither tokamak had cryopumping for these discharges.

There are major differences between the two tokamaks. The first-wall material is carbon in DIII-D, molybdenum in C-Mod. Although both tokamaks periodically deposit a thin layer (100-150 nm) of boron on their vessel surfaces, in DIII-D the boron is quickly covered up with C in many areas, eroding in others. The boron is not covered in C-Mod and the only areas of B erosion are in the divertor [20,10]. The vessel and divertor geometries are significantly different as well. Figure 1 shows the cross-section of the two tokamaks for reference. The C-Mod divertor structure (see Fig. 1a) is a baffled, 'vertical plate' design which is optimized to spread the first power e-folding distance of the SOL (1-4 mm, mapped to outer midplane) over the vertical portions of the divertor plates. Primary limiter structures in the main chamber consist of a toroidally continuous inner-wall limiter, and principally two discrete outboard limiters far from the vessel wall. The DIII-D divertor has a horizontal plate design with less divertor structure – a more 'open' design. The inner limiter in DIII-D is also toroidally continuous. The divertor baffle structures at the entrance to both the upper and lower divertors serve as a toroidally-continuous limiters (marked 'A' and 'B' in Fig. 1b). Their location in the SOL is typically 5 cm from the separatrix, mapped to the midplane. Far out in the outer SOL are three, toroidally-spaced, small poloidal 'bumper' limiters protruding 1 cm from the wall.

There are additional, more obvious differences between these two experiments that need to be pointed out for completeness. The C-Mod tokamak is much smaller than DIII-D. The major radius of the plasma centers are 0.67 and 1.6 m respectively. The minor radii are in a similar ratio, 0.21 and 0.58 m respectively. The toroidal magnetic field in C-Mod is stronger than in DIII-D, 5.3 vs. 2.1 T.

Neutral pressures on both machines are measured near the outer midplane with ionization gauges. The density and temperature profiles across the outer SOL are measured using both Thomson scattering and Langmuir probes on DIII-D. For C-Mod Langmuir probes are the primary method.

The ionization source profile in the SOL is used in the analysis contained herein. It is derived from the tangential measurement of the D_α profile in the SOL for DIII-D, Ly_α for C-Mod. Both toroidal measurements are made near the midplane in the outer, low-field, SOL. The local ionization source is determined from the product of the emissivity and the ionizations per photon ratio (S/XB) known from atomic physics [21]. It should be noted that while local n_e and T_e are used in this analysis, the ionization rate is not sensitive to their values. This is due to the weak dependence of S/XB on n_e and T_e for ionizing plasmas ($T_e >$ 10 eV).

The flux of ions to the wall is also of central importance to the radial flux analysis. The value is derived from SOL measurements and limiter geometry in the outer SOL based on a technique originally developed by LaBombard [2,3] and applied to C-Mod in several papers [2,3,22]. Herein, we will refer to this technique as the 'window-frame' technique. The rigorous explication of the technique, its particular application to DIII-D, and its generalization to more geometries, is described in the companion paper by Whyte [14].

3. Radial flux analysis

3.1 General description

We can use the particle balance equation not only to infer the radial flux density at the first-wall, but also at all points in the SOL, $\Gamma_{\perp}(r)$. Such *profiles* of cross-field fluxes are themselves a measure of cross-field transport. We will also present this information in two other ways. The first parameterizes the radial flux as driven by a diffusive mechanism, i.e. proportional to the local density gradient, $D_{eff}(r) = \Gamma_{\perp}(r)/\nabla n(r)$. The second way parameterizes the radial fluxes as driven by convection, $v_{eff}(r) = \Gamma_{\perp}(r)/n(r)$. These three ways to describe the radial transport will allow us to compare cross-field transport between DIII-D and C-Mod. The analysis is based on a model that requires measured n_e and T_e and the local ionization source (derived from the local emissivity of Ly_{α} or D_{α}) to solve the continuity equation as a function of radius in the outer SOL [3]. That analysis has been expanded in this paper to explicitly take into account neutral leakage from the divertor back into the SOL. A simpler, 0-D version of this analysis, has been used to estimate radial convective velocities in ASDEX_upgrade plasmas for a single point in the SOL [6].

Figure 2 illustrates the flows that are included in an average (poloidally over the SOL) sense. Loop 1 accounts for ions incident on the divertor plate that are recycled as neutrals, ionized and return to the divertor surface and hence is local to the divertor only. Loop 2 corresponds to ions flowing to the divertor plate which recycle there, but manage to pass through the divertor region and are ionized in the core. They then must radially transport out of the core and return to the divertor plate through the SOL. Loop 3 corresponds to radial transport of ions to first-wall surfaces *at any point outside the divertor* where they recycle as neutrals. They can be ionized in the SOL and/or the core plasmas but then must return to the first-wall again. The ions of Loop 4 recycle at the divertor but in contrast to loops 1 or 2, they escape the divertor through neutral leaks and return to the main SOL, and possibly the core, where they are ionized. They then must close the loop by flowing back to the divertor. These loops are used together in the following analysis assuming, for simplicity, poloidal and toroidal symmetry of the ionization sources and the radial ion fluxes. This means that even though loop 2 neutrals enter the core near the divertor, they leave the core as ions in a uniform way. Likewise, even though the leakage of neutrals from the divertor (loop 4) is poloidally localized, they are ionized uniformly around the outer SOL. This holds for loop 3 as well.

Several important points are noted here: 1) Only loops 3 and 4 can contribute to the measured ionization source (measured near the midplane for both DIII-D and C-Mod); 2) Loops 2 and 4 combine as ion flux back *into* the divertor, $\Gamma_{//,\mathrm{div}}$ (as opposed to the flux incident on the divertor plate); and 3) loop 2 contributes to the radial flux from the core, across the separatrix. We define the fraction of ion flux into the divertor that enters the core as neutrals (loop 2) to be $f_c \equiv \Gamma_2/\Gamma_{//,\mathrm{div}}$. $1\text{-}f_c \equiv \Gamma_4/\Gamma_{//,\mathrm{div}}$ is thus the fraction of ion flux into the divertor that escapes the divertor as neutrals through leaks (loop 4). The extremes of f_c correspond to loop 4 dominating $\Gamma_{//,\mathrm{div}}$ ($f_c = 0$) or loop 2 ($f_c = 1$).

3.2 Particle balance

We now turn to the basic continuity equation with $\Gamma_\perp$ and S_{ION} representing poloidally and toroidally averaged values. The direction '$\perp$ is thus perpendicular to the flux surface, in the radial direction. The continuity equation is then:

$$\nabla_\perp \cdot \Gamma_\perp + \nabla_{||} \cdot \Gamma_{||} = S_{ION} \tag{1}$$

Whereby we can solve for the radial flux at a given radial position r in the SOL:

$$\Gamma_\perp(r) = \int_{sep}^{r} \left[S_{ION} - \nabla_{||} \cdot \Gamma_{||} \right] \cdot dr + \Gamma_{\perp,sep} \tag{2}$$

If we further specify the Mach number of the parallel flow into the divertor, M, then the average divergence of the radial flux is $\nabla_{||} \cdot \Gamma_{||} = Mn(r)c_s(r)/L_{||}$. Eq. 1 becomes

$$\Gamma_\perp(r) = \int_{sep}^{r} \left[S_{ION}(r) - Mn(r)c_s(r)/L_{||} \right] \cdot dr + \Gamma_{\perp,sep}. \tag{3}$$

$c_s=(k(T_e+T_i)/m_i)^{1/2}$ is the sound speed, $L_{//}$ the field line length to the entrance of the divertor along the magnetic field, and S_{ION} is the volumetric ionization source rate. Note that r increases moving from the separatrix to the wall, r=0 denotes the center of the core plasma. The radial particle flux through the separatrix is determined by loop 2 and the measured ionization sources inside the core due to loops 3 and 4:

$$\Gamma_{\perp,sep} = \int_{0}^{sep} \left[S_{ION}(r) \right] \cdot dr + f_c \int_{sep}^{wall} \left[Mn(r)c_s(r)/L_{||} \right] \cdot dr \tag{4}$$

The flux to the wall, which is measured (and thus a boundary condition), is

$$\Gamma_{\perp,wall} = \int_{0}^{wall} \left[S_{ION}(r) \right] \cdot dr - (1-f_c) \int_{sep}^{wall} \left[Mn(r)c_s(r)/L_{||} \right] \cdot dr \tag{5}$$

Again, the core source of ions due to loop 2 (through f_c) is not directly accounted for by our measurement of the ionization source at the midplane. The flux to the divertor plate is not included in this model (nor loop 1) but is not important to this discussion of main-plasma SOL transport. At this point M and f_c are the two free variables in the analysis. We can directly impose one boundary condition, the measured flux to the wall (Eq 5), to determine the product (1-f_c) M.

One concern we have about this analysis model is that while the ionization source, wall flux, n_e, and T_e measurements are localized, the analysis assumes they are indicative of a poloidal/toroidal average. N_e and T_e are fairly constant in the SOL on a given flux surface outside the divertor and so localized measurements are an appropriate approximation of the poloidal/toroidal average. The wall flux measurements for DIII-D approximate the required averaging process over the low-field SOL due to the fact that the limiting structures, and thus the window-frame, cover the entire outer SOL (details provided in the companion paper by Whyte [14]). The C-Mod measurements of wall fluxes are localized to a much smaller 'window frame' in the low-field SOL (details provided in [2,3,22, Whyte, submitted to PPCF #49]. Those measurements are thus a more localized average over the SOL

It is almost assured that there are poloidal/toroidal variations in the ionization source. Again, given that n_e and T_e are roughly constant on a flux surface in the low-field SOL (outside the divertor) the variation in recycling and accompanying neutral sources will lead to variations in the magnitude of the ionization source, as opposed to the profile shape. We can then use this assumption about the profile shape by further assuming that the poloidally-averaged radial profile of S_{ION} can be approximated by a constant factor times the localized profile measurement - $S_{ION} = \alpha \cdot S_{ION,m}$ where $S_{ION,m}$ is the measured radial profile. We can return to equation 5 and rewrite it in the form:

$$\Gamma_{\perp,wall} = \alpha A - (1-f_c) \cdot \mathrm{B}$$
$$\text{where A} = \int_0^{wall} \left[S_{ION,m}(r)\right] \cdot dr \text{ and B} = \int_{sep}^{wall} M \cdot \left[n(r) c_s(r)/L_{||}\right] \cdot dr \qquad (6)$$

Then, for any value of f_c and M we can solve for α required to match the measured $\Gamma_{\perp,\mathrm{wall}}$ (we have thus added a third free variable besides f_c and M). In a sense this allows us to extract the radial information from the ionization profile useful to transport analysis, without having to make any assumptions that the measured absolute magnitude is correct. As will be seen later, the range of α that is consistent with the data do not affect the transport results.

3.3 Experimental input into the selection of *M*

In the following analysis we select values of f_c and M that reflect our present understanding of SOL flows. We digress in order to review some of the relevant measurements and modeling found in the literature. We are particularly interested in measurements of Mach flow at the *entrance* to the divertor in the sense that this is the limiting ‘drainage’ out of the SOL which is competing with radial transport. Such measurements are made in C-Mod at the entrance to the outer divertor with a scanning probe with multiple tips [23]. Figure 1a shows the location of the probe and its travel. The results of such Mach measurements for a density scan from the experiments included in the current study are shown in Figure 3a. At low densities the flow is away from the divertor near the separatrix (negative M, reversed flow) and rises towards 0.3 in the far SOL. As density is increased the reversed flow near the separatrix disappears. Note that measurements of ExB flows by the same probe [24] tend to increase flow towards the divertor at all radii at the outer divertor. ExB flows would have the opposite effect at the inner divertor. For the purposes of this study we assume that the ExB effect on flow into or out of the divertor averages out between the two divertors.

Measurements of Mach flows have been made by Asakura [25] at multiple points around the JT-60U SOL including in the divertor. The measurements at the entrance to the inner divertor are the most relevant to this analysis and are reproduced in Figure 3b. The flows are away from the divertor near the separatrix similar to what is seen at the outer divertor entrance on C-Mod. Asakura also notes that the reversed flows near the separatrix become less strong (essentially stagnant) as the density is increased.

There are also measurements of SOL flows at the entrance to the JET divertor. During a period when JET was operated with upper single-null plasmas ($B\times\nabla B$ towards the x-point as in C-Mod and JT-60U), a series of measurements were made. Those by deKock [26] and Loarte [27] are reproduced in Figure 3c. These include a range in densities with Ohmic, L- and H-mode plasmas. The measurements made by Loarte also indicate a decrease in reversed flow near the separatrix as plasma density is increased. The uncertainty in the location of the separatrix for the JET measurements are fairly large - ± 25 mm. More recent measurements on JET with a scanning Langmuir probe have been made midway between the inner and outer divertor entrances yielding Mach numbers as high as M=0.6 and flows towards the inner divertor across the entire SOL[28].

The Mach number at the entrance to the divertor in DIII-D is, unfortunately, not as well documented. A scanning probe has been inserted from below with lower single-null L-mode plasmas very similar to those used in this study. The probe passes much closer to the x-point than in the other studies of Figure 3. Mach measurements are restricted to regions near the separatrix (ρ<10 mm, mapped to the outer midplane). We find $-.1 \le M_{SEP} \le 0.1$ at low densities with attached divertor. As density increases prior to detachment, M increases to ~0.3-0.4 toward the lower divertor. The data is not available at higher densities. These data are consistent with that of Figure 3.

There appears to be several consistent characteristics to the SOL flows at the entrance to the divertor on the above experiments: 1) There is often flow away from the divertor near the separatrix; 2) That reversed flow becomes stagnant or positive as the density is increased; and 3) The flow in the far SOL is towards the divertors with values of order 0.4.

3.4 Experimental input to the value of f_c

The experimental data informing our specification of f_c is sparse. In order to infer the value of f_c (from eq. 6) one needs to know the flux into the divertor (part 'B' of eq. 6) *and* the leakage flux that makes it back to the midplane [$(1\text{-}f_c)$B] which then contributes to the measured ionization source (loop 4). There are some C-Mod and DIII-D results relevant to this issue. For Alcator C-Mod [22] it was found that the integrated divertor neutral leakage current, I_{loop4}, contributes a small amount to the midplane pressure relative to total ion current to the wall, I_{loop3}. Since the ionization is proportional to the neutral density, we can describe this contribution with the parameter

$$R_{leak} = \frac{I_{loop4}}{I_{loop3} + I_{loop4}} \propto \frac{(1 - f_c) \cdot B}{\alpha \cdot A} \qquad (7)$$

with A and B as defined in Eq. 6. The value of R_{leak} from Alcator C-Mod data was ~ 10-20%[22]. ASDEX Upgrade estimates of divertor neutral leakage, based on different methods, yield R_{leak} ~ 0.4 [29]. We note that R_{leak} does not reflect the actual leakage, just what makes it to the midplane region. Most of the neutrals that escape from the divertor through leaks are ionized locally in the near divertor SOL and return as ions to the divertor. Such localized loops would not affect our analysis other than potentially enhancing M near the divertor. As we will see later the C-Mod R_{leak} measurements imply a high value of f_c.

The D_α measurements from DIII-D, described in more detail in the companion paper by Whyte [14], also indicate R_{leak} is small for DIII-D. As previously stated, it is not possible to discriminate between the SOL ionizations caused by loops 3 and 4. However a dominant loop 4 would have two primary effects: 1) The D_α emission in the main chamber would correspond to a much larger ionization source than the window frame-based inference of ion flux to main chamber surfaces (leakage neutrals would lead to D_α in the main chamber but the resulting ions must return to the divertor rather than the wall); and 2) the localized leakage out of the lower, dominant, divertor would lead to a poloidal asymmetry in D_α emission. In other words the peak in SOL ionizations (evidenced by D_α light emission) would occur close to the active divertor due to neutral attenuation/plasma pumping. Both of the effects cited above are contraindicated in DIII-D. The D_α measurements of neutral influx from the upper baffle (labeled 'A' in Fig. 1) closely match the ion fluxes incident on that same baffle [14]. In addition, near up-down symmetry is found between the brightness of D_α chords viewing the upper and lower baffles (which intersect the same flux surface). The clear lack of this asymmetry in the D_α data implies that leakage cannot be dominating the contributions to SOL ionizations. Like C-Mod this would imply that the loop 4 magnitude is small compared to loop 3 and R_{leak} is again small. This would be consistent with the DIII-D lower divertor design and modeling which indicates that divertor leakage is small [30,31].

Given that the divertor leakage is relatively weak compared to the wall current (R_{leak} small) we can argue that f_c is large. The total integrated wall current, I_{loop3}, is of similar magnitude to the ion flux into the divertor, I_{loop2} for the two experiments [3,14] (For C-Mod I_{loop3} is often greater than I_{loop2}). If $I_{loop4} << I_{loop3}$ then

$$(1-f_c) \propto \frac{I_{loop4}}{I_{loop2}} \approx \frac{I_{loop4}}{I_{loop3}} << 1 \qquad (8)$$

leading one to the conclusion that f_c is close to 1. On the basis of the above arguments and the sensitivity study (section 3.6) we have chosen $f_c = 0.9$ for the figures in this paper. We also perform an analysis of the dependence of the result on the selection of f_c and M (Section 3.6).

There is an additional piece of indirect evidence that is consistent with a large f_c. The neutral influx towards the core can be written as the random neutral flux – $n_0\bar{c}/4$ where n_0 is the local molecular neutral density, proportional to the local neutral pressure, and $\bar{c}$ is the random thermal velocity for room temperature molecules. If loop 4 was the dominant source of neutrals at the midplane then one would expect that the measured ion flux to the wall to be much smaller than the equivalent neutral influx there (determined through local pressure or D_α measurements). Again, the C-Mod [2,3] and DIII-D [14] data indicate the opposite. The effective neutral influx is approximately the same as the measured wall flux indicating Loop 3 is dominant in determining the midplane pressure and neutral influx. This is consistent with the other evidence cited above.

3.5 SOL radial transport in C-Mod and DIII-D

Utilizing the experimental techniques discussed above, we have compared lower single-null L-mode discharges from the two tokamaks over a range in core line-averaged density. The results are shown in Figure 4. The first column of data corresponds to C-Mod measurements for three different line-averaged densities (density information given in figure caption). The second column of data are the same profiles from the DIII-D SOL for four different line-averaged densities. There are several similar characteristics. For example, the n_e profiles (a, g) all show a steeper density gradient near the separatrix than farther out in the SOL. The steeper and flatter sections of the density profile will be referred to here as the ‘near’ and ‘far’ SOL. We also see that the far SOL density profile becomes flatter as the core density is raised. The temperature profile (b, h) is relatively unaffected by these changes in $\bar{n}_e$. This is not surprising at the separatrix where the balance of heat crossing the separatrix with parallel heat conduction should determine T_e. The far SOL temperature profile can be fairly flat. The ionization source profile (c, i) both increases and broadens as a function of density. This indicates that more of the incoming neutrals are being ionized farther from the separatrix, consistent with the increasing n_e in the far SOL.

The radial ion flux (d, j), determined by the methods described earlier, often decreases in the near SOL, flattening out or increasing in the far SOL. The assumptions for this particular analysis are M=0.04 at the separatrix rising linearly to 0.4 in the far SOL (4mm from the separatrix on C-Mod, 10mm for DIII-D) and constant at a value of 0.4 further out in the SOL. Examples of the general shape of such a Mach profile used for this analysis are shown in Figure 5a. We have also assumed $f_c = 0.9$. The $\Gamma_\perp$ profile reflects the differences in profile shapes of S_{ION} and parallel losses (proportional to $nT^{0.5}$). The latter is strongest near the separatrix and falls off more rapidly than S_{ION} as a function of distance from the separatrix. The corresponding local D_{eff} (e,k) and v_{eff} (f,l) are shown in Figure 4 as well. We see that these profiles are also similar on the two experiments, lower in the near SOL than in the far SOL. The D_{eff} and v_{eff} are both slightly larger on DIII-D than for C-Mod. v_{eff} provides a more attractive basic description of the radial transport, particularly in the far SOL, for several reasons. First, D_{eff} can become un-physically large (i.e. $D_{eff} >> D_{Bohm}$), especially where the density gradient essentially goes to zero. Second, the far SOL v_{eff} is quite invariant to changing density, and is therefore an indication of a constant transport mechanism that is an underlying cause of the SOL behavior. We note that the fairly flat T_e profile in the far SOL would indicate that heat convection [$Q = 5T_e\Gamma_\perp = 5T_e(D\nabla n + nv)$] is dominant over conduction ($Q = \chi\nabla T$) there [3].

3.6 Sensitivity analysis

The profiles shown in figure 4 are for selected M and f_c but are characteristic of what we have found from our transport analysis, even as those two "free" parameters are varied. To illustrate this we show the results from a sensitivity study of the dependence of the v_{eff} profile on f_c and M for one of the medium density DIII-D cases shown in Figure 4g-i. v_{eff} at the wall is held fixed at the experimental values ($= \Gamma_{\perp,wall}/n_{e,wall}$) as for all analyses. The various M profiles used are based on the data shown in Figure 3 and are shown in Figure 5a. M is assumed to rise linearly from a variable separatrix value to M = 0.4 at a distance of 10 mm from the separatrix. The 10 mm location is based on scaling to the same normalized radius in the C-Mod data of Figure 3a where the variation of M with changing plasma density is no longer present ($r-r_{sep}$ = 4 mm). The choice of M = 0.4 from 10 mm to points further out in the DIII-D SOL is based on an average of the far SOL data in Figures 3a-c. We feel this is a fairly strong test of radial transport in that the flow to the divertor is quite strong over most of the SOL. An M = 0.4, constant across the SOL, profile is included in the study as well (solid line, Fig. 5a).

We find that the variation of M in the near SOL has little effect on the resultant transport analysis. In Figure 5b-d the v_{eff} profiles for 3 values of f_c and the three Mach profiles of Fig. 5a are shown. The $v_{eff}(r)$ profile flattens ($v_{eff,sep}$ increases relative to the fixed experimental wall value) as M is increased. This is expected because more SOL ionization source (i.e. increased α) is needed to offset the increase of 'drainage' to the divertor brought about by higher M while still matching the experimental wall flux. As f_c is decreased $\Gamma_{\perp,sep}$ (and thus $v_{\perp,sep}$) decreases because less of the divertor parallel flux goes directly to the core (loop2, equation 4). The value of R_{leak} rises as f_c is decreased or M is increased by definition. Given the experimental evidence for small R_{leak} then values of f_c of order 0.8 – 0.9 are the most appropriate choice. The value of α ranges from 2-4, being close to 2 for f_c = 0.9 (Fig. 5d). This is consistent with the DIII-D chordal D_α brightness data discussed in Section 3.4. Those data showed that the midplane measurement of D_α (used to determine the ionization source profile) was lower than the dominant recycling locations (upper and lower baffles) in the outer SOL by a factor of order 2-2.5.

The above sensitivity analysis has been applied to the C-Mod data with the same results. We have also explored the effect of even larger variations in Mach number where we have varied it across the entire SOL, as opposed to just the near SOL. In all cases, for both C-Mod and DIII-D, v_{eff} increases as a function of distance from the separatrix. This appears to be a robust result independent of tokamak or assumptions.

On the basis of the above sensitivity analyses and experimental measurements we have chosen an M profile, and resulting v_{eff} analysis, for the case of M(sep) = 0.04 at the separatrix, of the general form shown in Figure 5a, for all comparisons between C-Mod and DIII-D. This includes the analysis shown in Figure 4.

4. Dimensionless analysis

The profile data for the two tokamaks shown in Figure 4 are similar in appearance. Can we be more quantitative about their similarity? Are the similarities driven by plasma or atomic physics? The dimensionless scaling approach [32,33] gives us a way to determine whether the plasma physics of different discharges is 'similar'. We start with a comparison of the *global* discharge parameters and then concentrate on the SOL. Table 1 outlines the core plasma characteristics, both dimensional and dimensionless, of the C-Mod and DIII-D discharges used in this study. While the discharges were not designed to have identical dimensionless constants, nonetheless the normalized values for magnetic field and plasma current are within 30% and the normalized separatrix densities span about the same range.

The dimensionless *SOL* parameters of the compared discharges included in this study cover a similar range for both sets of experimental data. Shown in Figure 6 are the profiles of ν^* (6a), ρ^* (6b) and β (6c) in the SOL (for normalized minor radius) for the discharge data shown in Figure 4. The range in density for the two tokamaks represented by the various profiles lead to a similar range in normalized plasma parameters. Note also that the main effect of varying the discharge density is to vary ν^*. The values of ρ^* for the two tokamaks do differ in the far SOL.

Utilizing the same dimensionless scaling methodology we can also scale the transport analysis results of Figure 4 in order to more directly compare the two experiments. The scaling used for each of the parameters is described in Table 2. Density and temperature scaling are the usual [32]. We have used the sound speed as the scaling parameter for velocity, v. The rest of the parameters are based on n_e, T_e, and v with the scaling based on the particle balance equation (Eq. 1) and the equivalency between the parameter in question and parameters with known scaling. For example the scaling of S_{ION} is equivalent to $\nabla \cdot \Gamma = nv/a$.

Figure 7 shows the results of this effort where the DIII-D data have been scaled to C-Mod. The SOL densities (Figure 7a) for the two machines are very similar in magnitude. The location of the 'breakpoint' between the region of short e-folding length near the separatrix ('near' SOL) and longer e-folding length ('far' SOL) is of order r/a = 1.025 – 1.03 for both experiments. C-Mod has a shorter equivalent e-folding length in the near SOL. Both experimental profiles evidence a flattening of the profile in the far SOL with increasing density as discussed earlier.

The scaled DIII-D temperatures (Figure 7b) near the separatrix are slightly higher than those for C-Mod. The effective diffusion coefficients (Figure 7c) and convective velocities (Figure 7d) all increase as a function of distance from the separatrix. The DIII-D values of both D_{eff} and v_{eff} are slightly higher than that of C-Mod, roughly a factor of 2, similar to the ratio of minor radii (~ 2.8) as well as the difference in ρ^* noted earlier. The most striking feature is that the derived far SOL v_{eff} do not vary significantly with large changes in density, both core and SOL. The implication of this is that whatever is driving the observed radial fluxes is similar on the two machines and is not strongly dependent on changing SOL density profile or ν^* or divertor/tokamak geometry. The small increase in the near SOL v_{eff} with increasing density is consistent with an analysis of C-Mod data restricted to this region [4]. The basic SOL plasma physics on the two experiments appears to be very similar for the plasma discharges chosen.

5. Effects of neutrals

We do not expect the atomic physics (e.g. ionization profile, transparency of the SOL to neutrals) to scale with dimensionless plasma parameters. For example, one can define the neutral mean free path, λ_{mfp}, in the following way:

$$\lambda_{mfp} = \frac{v_{FC}}{n_e\left[2\langle\sigma v\rangle_{CX,H0} + \langle\sigma v\rangle_{IONIZ}\right]} \tag{9}$$

For the purposes of this discussion we use v_{FC} , the velocity resulting from Franck-Condon dissociation of the D_2 molecule, instead of the local ion thermal velocity (T_i not measured). The cross-sections for charge-exchange, elastic collisions (approximated as equal to the CX rate), and ionization are included. The way to compare the two experiments would be to compare λ_{mfp}/a. Since λ_{mfp} is dominated by the density ($n_e \propto a^{-2}$ from Table 1), then one expects the following:

$$\frac{\lambda_{mfp,D}}{a_D} \propto \frac{1}{n_D a_D} = \frac{1}{n_C}\frac{a_D^2}{a_C^2}\frac{1}{a_D} = \frac{1}{n_C a_C}\frac{a_D}{a_C} \propto \frac{\lambda_{mfp,C}}{a_C}\frac{a_D}{a_C} \tag{10}$$

where the subscripts '*C*' and '*D*' correspond to C-Mod and DIII-D respectively. Thus the normalized neutral mean free path should be larger in DIII-D than C-Mod by the ratio of the machine size for a fixed aspect ratio. In Figure 8 we have plotted the normalized neutral mean free path (Eq. 9-10) of a 2 eV Franck-Condon neutral for both sets of experimental profiles of n_e and T_e shown earlier in Figure 4. It would appear that the DIII-D SOL is slightly more transparent to neutrals than C-Mod when comparing plasmas of similar ν^*. This is as expected. The difference between the two experiments is particularly pronounced in the near SOL. For the far SOL most of the DIII-D and C-Mod discharges are fairly similar – the normalized mean free path there is of order the distance to the separatrix. For example at r/a = 1.1 $\lambda_{mfp}/a \sim 0.12$.

6. Discussion

The use of localized measurements to derive global transport with a scaling factor appears reasonable given the consistency among the various measurements. For example we know that the measured midplane S_{ION} measurement is a poloidal minimum. The inference of midplane radial flux based on the midplane D_α brightness is ~ 2.5x lower than the window-frame-derived flux to the wall or outer edge pressure measurements [14], both being poloidal averages. The midplane D_α brightness is also much lower than D_α brightnesses measured at the upper and lower baffle ([14], points 'A' and 'B' in Fig. 1). In C-Mod the midplane pressure measurement is similarly lower than other pressure measurements above and below the midplane [22]. Such poloidal variation is consistent with the value of α required in the transport model to enhance the measured midplane ionization source by a factor of 2-3 for DIII-D in order to match the measured wall fluxes. This is particularly significant for DIII-D in that the wall flux measurement is an average over the entire outer half of the machine.

The D_{eff} and v_{eff} derived for these two experiments are meant only as a guide to the general transport rather than a definitive statement about the underlying transport drive (flux proportional to the density gradient or density itself). However it is our opinion that convection is the dominant process in the far SOL. Turbulence studies indicate that the radial transport can be quite bursty and dominated by long wavelength (along B), poloidally localized enhancements in the local plasma density which travel radially outward with a high velocity (e.g. { #49;Zweben, 2002 #69;Terry, 2003 #68}). Such bursty transport is clearly convective. The velocity of such radially traveling filaments can be of order 100-500 m/sec, not inconsistent with the v_{eff} derived from the data in this paper. We expect the v_{eff} derived in the current analysis to be lower than the velocity of the filaments because we are analyzing the time-averaged background density profile which includes the effect of such short-lived filamentary transport as well as any background diffusive transport.

A convective model for heat transport is supported by T_e measurements. T_e profiles in the far SOL tend to have very small gradients and still the plasma is fully ionized (T_e ~ 5-10 eV). So some source of radial heat flow must be supporting the ionization of neutrals, the accompanying radiation, and parallel losses to the divertor. The level of radial heat flow must be of order 100-200 kW at the highest densities in this study. Conduction cannot supply such power in the presence of such small T_e gradients without extremely large $\chi_\perp$. The convective velocities derived herein easily provide substantial radial heat flows. Another alternative is the heat flow driven by particle diffusion ($Q = 5T_eD\nabla\square$). However, as discussed earlier, our feeling is that the D_{eff} derived can be unphysical as the density gradients become extremely small.

There already exists a body of work indicating that radial transport increases as a function of distance into the SOL. Bosch showed that the flattened region of the far SOL in ASDEX-Upgrade was consistent with enhanced diffusion or convection there [5]. The convection velocity used for the single plasma condition shown was constant over the SOL at 70 m/sec. Umansky [1] and LaBombard [3] showed that a constant $D_\perp$ (and no convection) was inconsistent with density profiles with positive second derivatives (e.g. exponentially decreasing). Umansky [1] used UEDGE to determine that C-Mod plasmas required a $D_\perp$ profile remarkably similar to that derived in this analysis both in magnitude and shape to match measured plasma profile characteristics, midplane D_α and pressure measurements. Pigarov has expanded such analysis with his 2D fluid modelling of DIII-D plasmas [7]. He postulates a poloidal variation in transport characteristics, maximizing radial transport at the outer midplane. In allowing for a radially constant $D_\perp$ he finds that a radially increasing $v_\perp$ is required to match the experimental measurements of midplane D_α and pressure. The $v_\perp$ required is again similar in magnitude and shape to that derived in this work directly from experimental data. Simple arguments paralleling the philosophy of the radial transport analysis of this paper have been used to estimate transport coefficients at a point in the SOL for ASDEX-Upgrade for typical conditions [6]. The authors of that paper assumed negligible flow to the divertor and flux balance (ions flowing radially outwards and neutrals flowing radially inward) at a point in the SOL a few cm from the separatrix, the resulting radial velocities and diffusion coefficients are similar to that obtained here. Those authors also argued that the effective radial velocity should decrease closer to the separatrix as the sources went to zero.

The radial dependence of v_{eff} is a robust result. Large variations in $\Gamma_\perp$ and S_{ION} do not appear to affect the radial dependence. In fact, the data essentially overlay over a wide range in $\overline{n}_e$ for a given machine in the far SOL. This is all the more surprising in that we have taken the ratio of two strongly varying (as a function of $\overline{n}_e$) experimental measurements to determine v_{eff}! We note that the boundary condition of the wall flux imposed, and thus v_{eff} (wall), is determined by a separate measurement. It is also essentially invariant with changing density.

Although there are strong similarities in the SOL transport inferred from DIII-D and C-Mod data our study is inconclusive regarding the relative roles of plasma and neutral transport. The plasma characteristics of the two sets of data from DIII-D and C-Mod cover similar large ranges in ν^*. β and ρ^* hardly vary. The derived v_{eff} are similar in magnitude and profile shape. We thus feel that it is unlikely that ν^* is very important in determining transport in the *far SOL*. We note that in a previous C-Mod study aimed very specifically at the *near SOL*, the local gradients did scale with ν^* [4]. That result is consistent with the results of the current analysis for C-Mod in the region near the separatrix (Figures 4f & 7d).

This data provides no real basis for determining the dependence of transport coefficients on β and ρ^*. One question is whether the difference in v_{eff} between the two tokamaks by about a factor of 2 is significant. This difference is probably within experimental errors given the assumptions of the measurements being a poloidal average, the difference in window frame geometry/size used, and the uncertainties in the measurement of Γ_{wall}. It is also possible that this difference is due to the small differences in ρ^* or some additional parameter not yet thought of. Clearly new experiments are needed to examine the potential role of ρ^* and β which were not strongly varied in this study.

Neutrals do not seem to be important in determining transport coefficients. Changing the neutral pressure and mean free path in the SOL by ~ factor of 10 does not have significant effect on the derived v_{eff} and D_{eff}. But, there is a correlation between increased neutral pressure and flattening of the density profile in the far SOL. It is likely that although the transport (v_{eff}) is not changing in the far SOL, changes in neutral mean free path, λ_{mfp}/a, still have a significant effect on the profile shape. This argument is supported by the modeling study of gas-puffing into a SOL plasma completely opaque to neutrals [34]. Such opacity leads to a density 'hill' in the far SOL such that density increases with distance from the separatrix in that region. That same 'hill' is removed when the neutral influx is lowered in changing the fueling from gas to pellets. The idea of large neutral influxes leading to a flattening of the far SOL profile has been discussed in earlier modeling [35-37]. There the neutral influx was artificial, being rerouted from the divertor. Another source of large neutral influxes can be the result of radial ion fluxes recycling on the main chamber. In a study of main chamber recycling [3] simple particle balance considerations connected the SOL neutral density to the level of radial ion fluxes, leading to a critical neutral density above which ionization can flatten the profile.

Further experimental support for the effect of neutrals on the SOL profile comes from a radial transport study for JET [38]. The JET SOL is much more transparent to neutrals than

C-Mod or DIII-D in terms of λ_{mfp}/a while the transport appears to be the same. As expected, the JET n_e profiles in the SOL are much less flat than for C-Mod.

The role of neutrals in affecting the SOL n_e profiles can be likened to the onset of a radial 'recycling condition', similar in some ways to the 'high recycling condition' that occurs in a divertor. A divertor high-recycling condition is essentially 1D in nature and arises when the mean free path for ionization and the parallel collision length become short compared to the divertor dimensions; there is a positive feedback loop between ionization, local density and fluxes. Although the 2-D SOL is more complicated, having parallel as well as radial loss terms, the overall response can be similar; as λ_{mfp}/a in the SOL becomes smaller the probability of a neutral reaching the core (and fueling through the separatrix) is reduced. Assuming that main chamber fluxes are significant, if not dominant, in fueling the core, then, to maintain the same core density (neutral flux reaching the core), the inward neutral flux must increase. The increase in neutral influx leads to more ionization in the SOL, increases in density (and radially outward ion fluxes), and further decreases in λ_{mfp}/a. The above positive feedback is a plausible explanation of the nonlinear increase in the far SOL density (flattening of the profile) and radial fluxes with increasing $\overline{n}_e$. An alternative explanation to the flattening of the density profile in the far SOL as the density is increased is that transport itself is changing, namely that the ratio of cross-field to parallel transport is increasing [37]. Our results indicate that radial transport is not changing with increasing density, just the fluxes. Further experimental comparisons of different tokamak SOLs with more significantly different λ_{mfp}/a would be helpful.

While the primary emphasis of this paper is on radial transport in the SOL the question of the magnitude of main chamber particle fluxes is of course, of interest. The companion paper addresses this for DIII-D [14]; the result being that the ratio of inferred total flux to main chamber surfaces to that reaching the divertor plates varies from 0.1 for low-density DIII-D attached plasmas to of order 1 for detached divertor plasmas. The situation is similar for C-Mod (see Table 3). Multiplying the limiter radius flux densities of Figure 4 by the plasma surface area (7 m^2), the ratio of main chamber to divertor plate particle fluxes varies from 0.1 to 0.7 as the density is increased for the cases shown. At the highest densities the outer divertor is detached and thus the total flux in the divertor (ions + neutrals from recombination) is typically a factor of 3-5 higher . The ratio of main chamber fluxes to the flux *into* the divertor is higher, of order 1 for all cases. The gas puff rates are ~ 2 orders of magnitude less than the integrated flux to the wall at all densities.

7. Summary

We have made similar measurements of plasma parameters in the SOL of DIII-D and Alcator C-Mod for the purpose of comparing the radial particle transport in these two tokamaks. The two sets of data have been subjected to the same transport analysis model thus allowing a detailed comparison for L-mode plasmas.

The dimensionlessly-scaled SOL plasma profiles essentially overlay for similar dimensionless plasma parameters. The SOL density profile near the separatrix is steeper than in the ‘far’ SOL. The breakpoint, in normalized radius, between these two regions is approximately the same for the two tokamaks. The far SOL density profile becomes flatter with increasing n_e (core or edge). The near SOL density gradient is more pronounced in C-Mod.

An analysis based on particle balance has been used to infer radial fluxes. Assumptions of parallel Mach number and the circulation of neutrals in the divertor are required as well. Data from several tokamaks on Mach flows have been assembled in order to specify the level of parallel flow into the divertor (based on Mach number) and neutral flows. The principal boundary condition is the radial flux at the limiter/wall radius. This is measured similarly on the two different experiments using the window frame technique, albeit with different window frame geometries. The inferred radial flux can be portrayed as due to diffusive ($D_{eff}(r) = \Gamma_{\perp}(r)/\nabla n(r)$) or convective particle transport ($v_{eff}(r) = \Gamma_{\perp}(r)/n(r)$). The magnitude of the inferred D_{eff} or v_{eff} increases across the SOL and is not particularly sensitive to the assumptions of parallel flow. More importantly, the inferred D_{eff} or v_{eff} in the far SOL are essentially unchanged by the change in core density by factors of 2-3. This corresponds to changes in the far SOL density (and $\nu*$) and radial fluxes of ~ a factor of 10! The implication is that at least $\nu*$ is not a important parameter in determining the radial particle flux in the far SOL. The dependence of radial particle transport on $\rho*$ □□ β remains to be addressed.

The profile of the inferred radial transport coefficients, D_{eff} or v_{eff}, is essentially the same on the two experiments, rising steadily across the SOL. The absolute magnitude of D_{eff} or v_{eff} differs by a factor of ~ 2 between the two experiments. This difference is within the uncertainties of the measurements so we cannot say whether it is significant.

The transparency of the far SOL to neutrals for the two tokamaks varies similarly for the discharges and tokamaks studied. The normalized neutral atom mean free path, λ_{mfp}/a, is of order the distance to the separatrix in the far SOL. In contrast, near the separatrix, the DIII-D λ_{mfp}/a is longer by approximately a_{DIII-D}/a_{C-Mod} as expected. The decrease in λ_{mfp}/a with increasing local density does not appear to affect radial transport but may be related to the observed flattening of the density profiles.

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Parameter	C-Mod	DIII-D
Minor radius (m)	0.21	0.58
Aspect ratio	3.19	3.04
q_{95}	3.7	3.8
Elongation	1.67	1.72
δ_{upper}, δ_{lower}	0.19, 0.5	0.22, 0.49
$B R^{5/4}$	3.2	4.08
$I_p R^{1/4}$	0.9	1.2
$n_e R^2$	5, 7.3, 11.5	7.8 , 10.4, 12.5, 16
$n_{sep} R^2$	3.1, 5.8, 8.5	2.9, 4.0, 5.2, 6.6
β_T (%)	0.3, 0.3, 0.35	0.25, .32, .34, .43

Table 1 Core plasma discharge characteristics and dimensionless constants for global parameters on C-Mod and DIII-D for this study. Different n_e, n_{sep} indicate line-averaged and separatrix density (in 10^{19} m^{-3}) values from density scan. Other units: R[m], B[T], I_p[MA]

Parameter	Scaling basis	scaling
n_e		a^{-2}
T_e		$a^{-1/2}$
v (or v_{eff})	$\sqrt{T_e}$	$a^{-1/4}$
$\Gamma_\perp$	nv	$a^{-9/4}$
S_{ION}	$\nabla\cdot\Gamma$ -> nv/a	$a^{-13/4}$
D_{eff}	$\Gamma/\nabla n$ -> nv/(n/a)	$a^{3/4}$

Table 2 Dimensionless scaling used for SOL parameters on C-Mod and DIII-D.

a) $\bar{n}_e$ (10^{20} /m^3)	b) Wall flux density (10^{20}/m^3/s)	c) Total flux to wall (10^{22}/s)	d) Total flux to outer div. (10^{22}/s)	e) Total flux into outer div. (10^{22}/s)	f) Ratio 1	g) Ratio 2
1.1	2.2	0.15	1.3	0.3	0.1	.0.5
1.8	6.8	0.45	2.2	0.54	0.2	0.85
2.6	20.0	1.4	2.0	1.4	0.7	1.0

Table 3: Comparison of wall and divertor fluxes for the three C-Mod cases. a) line-averaged density; b) Wall flux density from Figure 4; c) Total wall flux based on a plasma surface area of 7 m^2; d) Integral of particle flux to the outer divertor plate; e) integral of the flux into the divertor; f) ratio of c to d; g) ratio of c to e.

Figure captions

Figure 1: C-Mod (a) and DIII-D (b) cross-sections. The locations of a number of diagnostics are shown as well. The SOL n_e and T_e profile measurements are made using the midplane Langmuir probe on C-Mod and the Thomson system in DIII-D. The ionization source, S_{ION}, is determined through the measurement of the SOL emissivity profile of Ly_α (C-Mod) and D_α (DIII-D). Limiter surfaces in the SOL include the toroidally continuous inner wall and 2 toroidally-discrete (~ 20 cm wide) poloidal limiters on C-Mod. The baffles at the entrance to upper and lower divertor (labeled 'A' and 'B' in 1b) in DIII-D are toroidally continuous as is the inner wall.

Figure 2: The recycling flows of ions and neutrals through the SOL, divertor and core plasmas. Loop 1 accounts for ions incident on the divertor plate. Loop 2 indicates neutrals that recycle from the divertor, enter the core and travel back to the divertor plate as ions. Loop 3 indicates neutrals created outside the divertor that circulate through the SOL and core and return to the vessel surfaces. Loop 4 accounts for the fraction of divertor recycling that escapes the divertor as neutrals and is ionized in the SOL and core, returning to the divertor as ions.

Figure 3: Experimental measurements of the Mach flow profile in the SOL at the entrance to the divertor for a) C-Mod (outer divertor), b) JT-60U (inner divertor), and c) JET (outer divertor). The diamonds and triangle data in (c) are reproduced from Loarte [27]. The JET squares and circle data are from a paper by deKock [26]. The C-Mod data correspond to the cases shown later in this paper. The JT-60U data are reproduced from a paper by Asakura [25].

Figure 4: Measured profiles from C-Mod and DIII-D for n_e (a,g), T_e (b,h), S_{ION} (c,i). Also shown are the results of the transport analysis for $\Gamma_\perp$ (d,j), D_{eff} (e,k) and v_{eff} (f,l). All are L-mode cases but with varying $\bar{n}_e$. The C-Mod data correspond to $\bar{n}_e$=1.1, 1.6, & 2.6x10^{20} m^{-3}. The DIII-D data correspond to $\bar{n}_e$ = 2.5, 3.5, 4.5, & 5.5x10^{19} m^{-3}.

Figure 5: Sensitivity of the derived v_{eff} on f_c and M profile. A) profiles of M used in this sensitivity study. B-d) The effect of variations in f_c. The resultant α and R_{leak} are shown as well. Note that the measured flux to the wall determines v_{eff} there.

Figure 6: ν*, ρ* and β profiles in the SOL for the two machines as a function of the normalized outer midplane radius, r/a, where r/a = 0,1 are the plasma center and separatrix respectively. The different profiles shown correspond to the different $\overline{n}_e$ shown in Figure 4.

Figure 7: The results of the transport analysis shown in Figure 4 for DIII-D are scaled (based on Table 2) and replotted with the C-Mod data. Shown are a) n_e, b) T_e, c) D_{eff}, d) v_{eff}. The 'near' SOL region is shaded.

Figure 8: Normalized neutral mean free path for the two experiments and the cases shown in Figures 4 and 7.

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