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Abstract

Particle transport in the edge plasma and scrape-off layer will play a key role in the performance and operation of a tokamak fusion reactor: setting the width of the scrape-off layer density profile and its impurity screening characteristics, regulating the energetic particle fluxes onto first-wall components and associated impurity generation rates, and determining the effectiveness of the divertor in receiving particle exhaust and controlling neutral pressures in the main-chamber. The processes which govern particle transport involve plasma turbulence, phenomena which can not yet be reliably computed from a first-principles numerical simulation. Thus, in order to project to a reactor-scale experiment, such as ITER, one must first develop an understanding of particle transport phenomena based on experimental measurements in existing plasma fusion devices. Over the past few years of research, a number of fundamental advances in the understanding of the cross-field particle transport physics have occurred, replacing crude, incorrect, and often misleading transport models such as the "constant diffusion coefficient" model with a more appropriate description of the phenomenon. It should be noted that this description applies to transport processes in the absence of ELM phenomenon, i.e., physics underlying the "background" plasma state. In this letter, we first review the experimental support for this understanding which is based extensively on data from L-mode discharges and from H-mode discharges at time intervals without ELMs. We then comment on its implications for ITER.

Experimental Observations

Observations and analysis of profiles, plasma fluctuation phenomena, and scalings of particle transport within and across a number of experimental devices have pointed towards a new paradigm for SOL transport physics, replacing incorrect models such as the "Bohm-diffusion" model, with a more accurate description of the transport physics. This description involves a number of key elements which are illustrated in Fig. 1: (1) tendency for strong variation in the profile gradients and transport parameters (and physics) from the separatrix to the first-wall, dividing the SOL into *near* and *far* regions, (2) bursty transport dynamics in the far SOL (reminiscent of 'avalanches' in a self-organized critical system), carrying significant cross-field particle flux towards the first-wall, and (3) dependence of near SOL transport on the local collisionality. While a first-principles, quantitative description of the phenomena is not yet in hand, the experimental observations have pointed to underlying physics in the areas of main-chamber recycling and impurity sources, threshold conditions for divertor detachment, and the tokamak density limit.

Scrape-off layer profiles in many devices are often found to exhibit a two-zone structure: a steep gradient region in density and temperature near the separatrix (*near* SOL) and a flatter profile region (*far* SOL) extending from approximately one steep-gradient scale length outside the separatrix to the wall (e.g., ASDEX[1-3], ASDEX-Upgrade[4, 5], TEXT-U[6], DIII-D[7-10], C-Mod[11-13], JT-60U[14], JET[15], TEXTOR[16], TCV[17]). In order to explain the 'shoulder' profiles seen on ASDEX and ASDEX-Upgrade, a large outward drift or an effective diffusion coefficient much larger than Bohm transport in the far SOL was found necessary [2, 4, 5]. These results were early hints that cross-field particle transport in the far SOL could be of importance in a tokamak reactor, competing with or even dominating the parallel flow into the divertor. Subsequently, Alcator C-Mod focused attention on this behavior as it was reported to operate predominately in a 'main-chamber recycling regime' with most of the plasma efflux recycling on main-chamber surfaces rather than flowing into the divertor chamber [18-20]. The primary cause was linked to a strong increase in the effective cross-field particle diffusivity ($D_{eff} = -\Gamma/\nabla n$) with distance into the SOL, a result consistent with earlier heat diffusivity analyses [12, 15, 21, 22], and particle transport analysis [2, 4, 5, 23].

In related work it was shown that divertor neutral bypass leaks and/or open versus closed divertor structures showed little effect on the midplane pressure [12, 20, 24-26], an indication that rapid cross-field particle transport was the dominant source of main chamber neutrals. These observations paralleled and confirmed those made in ASDEX-Upgrade [27, 28] where the main-chamber neutral pressure was found to be insensitive to divertor geometry at medium and high densities. More recently, the level of main-chamber recycling and the density in the shoulder region of ASDEX-Upgrade has been found to be strongly connected [29]. In DIII-D, a recent analysis of a set of L and H-mode discharges has combined ion flux measurements at the wall, neutral pressures, and radial transport inferred from Dα fluctuations into a comprehensive picture [30]; the ion flux to the wall is typically of the order of the ion flux received at the divertor plate, increases with plasma density, and dominates in detached divertor regimes. Although some level of main-chamber recycling appears to exist in all devices, its contribution to midplane neutral pressures is not reported to be the same, suggesting a sensitivity to divertor geometry and/or operational regime [31]. For example, DIII-D [32], JET [33], and JT-60U [14] have reported a reduction in main chamber ionization sources and neutral pressures when the divertor was changed to a more closed geometry (adding outer baffle in the RDP-OB in DIII-D, going from Mk-I → Mk-IIA → Mk-IIAP in JET, and going from open to W-shaped divertor in JT-60U).

Although a quantitative prescription for cross-field particle transport (theory-based or empirically-based) remains to be formulated, scaling studies of gradient lengths, effective diffusivities and/or time-averaged particle transport velocities have revealed important dependencies which serve to constrain physics-based descriptions. For example, a number of experiments have identified a steepening of gradients (inferred as a reduction in diffusivity) as the local electron temperature increased [12, 14, 22, 34, 35] as well as little sensitivity to the value of the magnetic field strength [12, 22, 36, 37]. These observations are clearly incompatible with a Bohm-like diffusion model and more in-line with a critical-beta model combined with a collisionality dependence [38], perhaps further constrained by a relationship between density and temperature gradients, η_e = d(Log T_e)/d(Log n) ~ 2 [29, 39]. Recently, C-Mod has correlated particle diffusion coefficients and cross-field transport velocities ($v_{eff} = \Gamma/n$) in the near SOL with parallel collisionality which also tracks with discharge density normalized to Greenwald density (n/n_G) [13, 40]. As collisionality increases, fluctuation amplitudes, particle transport and associated heat convection increases dramatically across the SOL, impacting the SOL/divertor power balance at moderate n/n_G (promoting divertor detachment) and impacting discharge power balance at high n/n_G (promoting thermal collapse and density-limit disruption). A strong dependence of cross-field heat diffusivity with n/n_G has also been noted on ASDEX-Upgrade[41]. At a basic plasma physics level, the latter observations suggests that SOL turbulence and resultant cross-field transport may set a fundamental density limit for tokamaks even in the absence of impurity radiation [42]. While in practice, the operational density limit for a reactor will involve impurity accumulation and radiation as well as requirements to remain in an H-mode regime (elements which define operational limits in existing experiments), these observations reveal aspects of the physics upon which the overall behavior may be understood.

The underlying physics of cross-field transport involves plasma turbulence. Data from a number of experiments have demonstrated a clear correspondence between the character of edge plasma fluctuation phenomena in the near and far SOL regions and particle transport levels [10, 13, 30, 39, 43, 44]. Fluctuations in the far SOL are found to exhibit a 'bursty' character, with intermittent 'transport events' carrying plasma towards the main-chamber wall with velocities well exceeding 100 m s^{-1}. Turbulence imaging systems record 'blobs' or plasma 'filaments' aligned with respect to the local B-field and propagating poloidally and radially-outward [45-47]. In this case, the statistics of the fluctuations (probe signals and visible light), as characterized in the probability distribution functions (PDFs), exhibit a non-Gaussian tail, such that large-amplitude but rare outward-going transport events account for a large fraction of the total particle flux. A statistical link between bursty transport behavior and the departure from the most probable gradient has been recently identified [48]. Transport events that result in a large departure from the average gradient propagate across field lines with large velocities (~ 500 m s^{-1}). These characteristics appear to be independent of confinement mode (L- vs. H-mode) [30, 46, 47], although the time-averaged fluxes tend to be lower in H-mode discharges, consistent with a global increase in particle confinement. It should be noted that while non-Gaussian PDFs, intermittency, and motion of coherent structures has been well documented over a number of years [49-58], clear connections to a rapid cross-field transport mechanism in the far SOL and the potential impact on tokamak reactor operation have only recently been widely recognized.

In contrast to the far SOL, fluctuations in the near SOL region are found to exhibit a near-Gaussian PDF. Moreover, at locations inside the separatrix there is evidence of reversed skewness or the formation of plasma ‘holes’ [47]. Folded into this picture are the observations that transport and fluctuation levels on the high-field side SOL are significantly reduced relative to the low-field side [46, 50, 59, 60], consistent with the expectation of higher turbulence and transport levels in regions of ‘bad’ field-line curvature. In summary, fluctuation statistics combined with data from turbulence imaging ‘movies’ indicate that plasma structures intermittently ‘peel away’ from the edge of the steep-gradient near SOL region and freely propagate towards the wall. This result appears independent of L- or H-mode confinement and separate from ELM phenomena. Magnetic curvature and/or variation in $|B|$ appears to play a role. These observations have provided a framework for developing/testing theory-based plasma transport descriptions and suggest that the overall level of cross-field particle transport in the SOL may ultimately be set by conditions near the separatrix.

While the appearance of shoulders in the far SOL aided in the discovery of a rapid transport phenomena in this zone, particle balance analysis suggests that the same underlying transport physics is active in discharges without a shoulder. For example, although only a weak shoulder is normally observed in JET, the cross-field convection velocity profiles inferred from particle balance are found to be remarkably similar to that inferred in discharges from C-Mod [61] where the dimensionless plasma physics parameters were similar. Comparisions between DIII-D and C-Mod yield the same trends [62]. The opacity of the far SOL to neutral penetration may offer part of the explanation for the appearance of a shoulder [61]; if wall-recycled neutrals ionize in the far SOL, they are rapidly transported back to the wall as ions. Thus, depending on the opacity to neutrals and the underlying cross-field plasma transport, the far SOL can exhibit a ‘perpendicular high-recycling’ regime with flattened density profiles [20, 63, 64]. In tokamak plasmas with the same dimensionless plasma physics parameters, the SOL would tend to be less opaque to neutrals as the machine gets larger and, by inference, exhibit less of a shoulder. This trend is consistent with present observations. However, it is important to note that conditions in the ITER SOL are expected to be dimensionlessly dissimilar to any current tokamak. Modeling indicates that the ITER SOL is opaque to neutrals [65], leading to a shoulder in the far SOL for gas-fuelled discharges.

In light of the transport physics in the far SOL, the level of plasma interaction with main chamber surfaces is a concern. Main chamber impurities are poorly screened by the SOL, can impact the core plasma, and may be a dominant source for co-deposition of carbon and tritium in the divertor. Indeed, evidence for main-chamber wall impurities contributing significantly to the overall impurity source [66, 67] and affecting erosion/deposition patterns [68] has been seen in existing experiments. Moreover, the rapid transport mechanism sets a minimum level of recycling and neutral pressure surrounding the confined plasma, which is independent of divertor geometry and neutral bypass leakage.

Clearly, more research is required to develop quantitatively accurate models for particle transport in the tokamak edge. The development and testing of physics-based descriptions is particularly important since we need to understand how the behavior seen in present devices scales to reactor-size machines. Since the edge plasma state involves strong turbulence, this will require close contact between experiments and the development of 3-D turbulence theory/simulation tools. Cross-machine comparisons are particularly valuable to explore the universality of the transport phenomena and the dependence on dimensionless parameters (in terms of fluctuation statistics and transport fluxes), and to allow a projection to reactor-machines (in the absence of a detailed physics model). Along these lines, the recent comparisons between C-Mod, DIII-D, and JET shows SOL profiles (including D_{eff} and v_{eff}) that are similar in shape and magnitude when scaled according to dimensionless plasma physics parameters [61, 62]. In particular, the magnitude of v_{eff} in the far SOL is roughly the same while at the same time v_{eff} is found to have a weak dependence on those dimensionless parameters. These results give an initial guide and suggest that the total plasma flux onto main-chamber surfaces may be roughly independent of machine size in dimensionlessly identical discharges. However, the scaling of these results to ITER is complicated by the lack of a complete set of matching dimensionless parameters in present tokamaks plus lack of surety regarding the importance of SOL opacity to neutrals.

Implications for ITER

Based on data from present experiments, it is likely that a mechanism of rapid cross-field transport will be present in the far SOL of ITER, even in the absence of ELMS, with time-averaged outward convection velocities in the range of 20 to 100 m s^{-1}. The current predictions for the ITER SOL parameters [65] indicate that the opacity of the SOL to neutrals is similar to much smaller machines (due to high field, high density, high SOL temperatures, large size). This indicates that one cannot rule out shoulder profiles nor significant main chamber interactions. In the near term, the potential impact of this physics on impurity production from the main-chamber wall, resultant core plasma Z_{eff}, main-chamber ion recycling and neutral pressures could be crudely assessed with 2-D plasma/neutral transport codes by inputting the cross-field plasma convection profiles seen in present experiments and specifying a unity hydrogenic recycling coefficient at the main-chamber wall. In the longer term, a physics-based transport prescription (which is experimentally-tested!) is needed for accurate modeling. The material selection for the main-chamber wall could be influenced, owing to ionic and charge-exchange neutral fluxes which would be elevated relative to presently modeled scenarios. The optimization of the divertor geometry, with regard to neutral leakage, may be relaxed in view of an irreducible contribution to neutral pressure in the main-chamber from wall recycling, and/or modified to accommodate fluxes arriving from the far SOL. The separation distance between the last closed flux surface and the main-chamber first-wall surface may be a key parameter in regulating the main-chamber recycling level, particularly in discharges where a ‘perpendicular recycling’ regime can be avoided. At an absolute minimum, the distance should be sufficient to accommodate the sharp density fall-off associated with the near SOL transport physics; crudely scaling from existing experiments, this distance should exceed about 2% of the plasma minor radius.

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This short paper is the result of a charge from Guy Matthews and Nobu Asakura (July 29, 2003) to review the area of “particle transport in the SOL – including main chamber recycling” as part of a general review of progress since the ITER physics basis was published in 1999. Since there was no treatment of SOL particle transport physics in that document, the present review ended up covering a larger time span, explicitly referencing work as far back as 1984. The reader should be aware that the references are not meant to be exhaustive, but to provide a representative cross-section of developments in the field. We apologize for any omissions. In addition to Guy Matthews and Nobu Asakura, we would like to thank Ralph Schneider, Kent McCormick, Dennis Whyte, Jose Boedo, Richard Pitts, Peter Stangeby, Kevin Erents, Wojtek Fundamenski and Carlos Hidalgo for valuable comments.

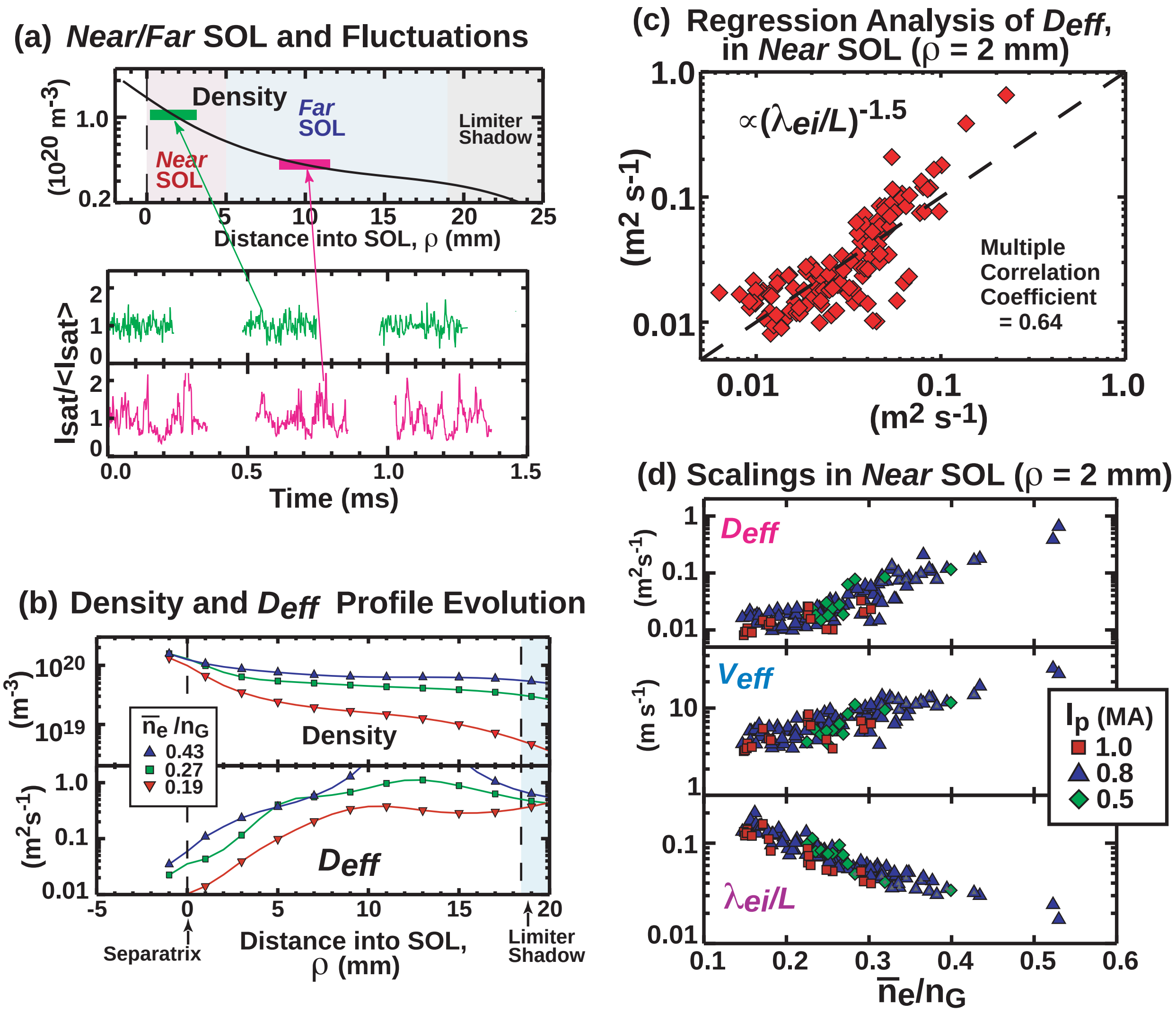

Fig. 1 SOL profiles and plasma transport characteristics in ohmic L-Mode discharges on Alcator C-Mod (from Refs. [13, 40]) which illustrates key features seen in many devices: (a) *near* and *far* SOL zones with change in fluctuation character, (b) strong variation in D_{eff} across the SOL and flattening of the SOL with increasing core density, (c) correlation of *near* SOL D_{eff} with parallel collisionality, (d) trend of increased particle transport coefficients with increased discharge density (collisionality).

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