Far-reaching Impact of Intermittent Transport across the Scrape-off Layer: Latest Results from ASDEX Upgrade

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Abstract. We report the latest results of turbulence and transport studies in the ASDEX Upgrade scrape-off layer (SOL). These results cover the following research topics: SOL fluctuations, ion energies in the SOL, and the influence of magnetic perturbations (MPs) on the SOL transport. A relation between the plasma and floating potential fluctuations, \( V_p \) and \( \tilde{V}_f \), has been studied experimentally and by gyrofluid simulations. The results indicate that near the separatrix, the ‘standard’ assumption \( \tilde{V}_p = \tilde{V}_f \) can yield erroneous measurements of the turbulence-induced particle flux. These studies emphasize the importance and feasibility of direct plasma potential measurements. Measurements by a retarding field analyzer (RFA) reveal that both, ELM and turbulent filaments convey hot ions over large radial distances in the SOL. The measured far SOL ELM ion temperature increases with the ELM energy and can reach up to 50% of the pedestal top temperature. This indicates that large ELMs deposit a large fraction of their energy outside the divertor. RFA measurements, combined with the predictions from a fluid model of the parallel filament transport provide evidence that more intense filaments propagate faster radially. Large filaments of ion saturation current observed in the SOL in type I ELMs are replaced by more continuous bursts in mitigated ELMs. Additionally, the ions in the far SOL in mitigated ELMs are colder compared with those measured in type I ELMs at the same separatrix distance. Observing that extreme energy transport events in the SOL fade away as type I ELMs undergo transition to mitigated ELMs goes along with earlier findings in AUG that e.g. plasma energy loss and the excursions of the divertor power load decrease after the transition to mitigated ELMs. Splitting of the divertor strike zones observed by the infrared imaging in H-mode with magnetic perturbations agree with predictions from the EMC3-Eirene simulations. This suggests that the ‘lobe’ structures due to perturbation fields observed near the X-point are not significantly affected by plasma screening, and can be described by a vacuum approach, as in the EMC3-Eirene.

1. Introduction

Convective transport of hot and dense plasma filaments¹ in the scrape-off layer (SOL) due to ELMs and turbulence will place wear on plasma facing components (PFCs) and affect erosion, dust production and the tritium inventory in burning plasma reactors. Getting as much information as possible from today’s tokamaks is essential for understanding of the heat and particle transport in the SOL, which is critical for predicting the plasma-wall interactions in ITER and beyond. This contribution highlights the latest research of intermittent transport in the SOL of the ASDEX Upgrade (AUG) tokamak. Emphasis is given to electric probe measurements. The key diagnostic systems for turbulence and transport studies in the AUG SOL are briefly described in section 2. Individual research topics are covered in the following sections: 3 – L-mode and inter-ELM turbulence, 4 – Far SOL ELM ion energies, 5 – Influence of magnetic perturbations on SOL transport.

¹ The term ‘filament’ is typically used for field-aligned structures observed during ELMs, while the turbulent coherently propagating objects are more often called ‘blobs’, referring of their cross-field appearance. Since both, blobs and ELM filaments, are field-aligned objects evolving in the SOL in the same manner, in this paper we refer to both ELM and turbulence structures simply as filaments.
FIG. 1. Poloidal cross section of AUG, showing a typical lower single-null plasma equilibrium and the location of the reciprocating probes. Inset panel illustrates the infrared camera view.

FIG. 2. From top to bottom: fluctuations of ion saturation current, electron density, electron temperature, plasma potential and floating potential measured from conditionally-sampled I-V characteristics.

2. Diagnostic set up

In AUG, as in most tokamaks, turbulence and transport in the SOL is studied mainly by electric probes. The probe system in AUG is depicted in Fig 1. The workhorse diagnostic is a horizontal reciprocating probe manipulator (RPM) located 31 cm above the outboard midplane. The RPM is used to immerse various advanced electric probes into the plasma [1]. Two other probe heads – a Langmuir probe (LP) with radially separated pins for filament transport studies (dubbed the filament probe, FP) [2] and a new retarding field analyzer (another identical RFA can be mounted on RPM) – are installed inside the torus on magnetically-driven reciprocating manipulators. Probe data are measured at an acquisition frequency of 2 MHz with 14-bit ADC resolution. During the reciprocation, the probes can be maintained for a programmed time interval at fixed outboard midplane separatrix distance, Δrsep. As illustrated in Fig. 1, the power fluxes estimated from probe measurements can be compared with observations from an infrared (IR) camera (framing frequency up to 25 kHz) viewing the RPM and the FP. The measurements by probes in the main SOL are complemented with data from other pertinent diagnostics such as e.g. flush-mounted Langmuir probes [3], X-point reciprocating probe [4], divertor thermography, visible light imaging and the multi-channel Doppler reflectometers [5].

3. L-mode and inter-ELM turbulence

Cross-field turbulent transport during inter-ELM periods will be one of the major causes of erosion of the beryllium first wall in ITER [6]. An insight into turbulent processes is traditionally gained by studying L-mode SOL which bears a lot of resemblance to inter-ELM SOL but the absence of ELMs makes it less harsh for probe measurements.
3.1. The importance and feasibility of direct plasma potential measurements

The fluctuation-induced radial particle flux, $\Gamma_r$, is among the most important parameters characterizing turbulent transport. Ideally, $\Gamma_r$ should be evaluated from the fluctuations of the plasma density and the plasma potential as $\Gamma_r \propto \langle \tilde{n}_e \tilde{V}_p \rangle$. Since the measurements of $\tilde{n}_e$ and $\tilde{V}_p$ are beyond the capability of a simple Langmuir probe, $\Gamma_r$ is almost never derived in this way. Instead, $\Gamma_r$ is estimated from the most easily measurable fluctuations of ion saturation current ($\tilde{I}_{\text{sat}}$) and floating potential ($\tilde{V}_f$) by assuming $\tilde{n}_e \propto \tilde{I}_{\text{sat}}$ and $\tilde{V}_p \approx \tilde{V}_f$. In AUG, the legitimacy of this assumption was tested in an experiment in which $\tilde{n}_e$, $\tilde{V}_p$, $\tilde{I}_{\text{sat}}$, $\tilde{V}_f$ and $\tilde{T}_e$ (with $\tilde{T}_e$ the electron temperature fluctuations) were measured simultaneously near the separatrix from conditionally-sampled LP current-voltage (I-V) characteristics and from an emissive probe (EP) [7]. The main result of this experiment is illustrated in Fig. 2. It shows that $\tilde{V}_f$ and $\tilde{V}_p$ are anti-correlated due to $\tilde{T}_e$ (a strong influence of electron temperature on plasma potential measurements was observed earlier in other tokamaks – see references in Ref. [7]). This observation indicates that at least near the separatrix, the assumption $\tilde{V}_p \approx \tilde{V}_f$ is inconsistent with experimental observations and cannot yield correct estimates of $\Gamma_r$ other than by coincidence. It is also worth noticing that this observation is consistent with accompanying simulations of probe measurements in a turbulent SOL [7, 8] using the three-dimensional electromagnetic gyrofluid code GEMR [9, 10]. As an illustrative example, $\Gamma_r$, derived from synthetic LP measurements of $\tilde{I}_e$ and $\tilde{V}_f$ is compared in Fig. 3 with $\Gamma_r$ obtained directly from $\tilde{n}_e$ and $\tilde{V}_p$. The former yields erroneously large $\Gamma_r$, which could be avoided in experiment by measuring the plasma potential. A recent experiment in AUG, in which $\tilde{V}_p$ was assessed by two independent techniques, demonstrates the feasibility of such measurements. In this experiment, which will be described in detail elsewhere [11], the RPM was equipped with a probe head consisting of a ball pen probe (BPP) [12] which measures a potential close to $V_p$, and an electrically floating LP. As shown in Fig. 4, at the turning point of the reciprocation, the LP reaches the temperature at which it undergoes a transition to an EP, providing additional measurements of $V_{EP} \approx V_p$ during the probe outward motion. Observing
that two techniques measure similar values of $V_p$ is encouraging (we also recall a good comparison of $E_r \approx -\nabla V_p$ from the BPP with $E_r$ from Doppler reflectometry in AUG [1]).

Now, when the diagnostics for $V_p$ measurements are becoming mature enough, it will be important to verify if the strong difference in amplitude and fluctuation phase of $V_p$ and $V_f$, observed in Ref. [7] for particular plasma conditions, generally applies to a SOL plasma.

3.2. Ion energies in turbulent plasma filaments

The ion temperature in turbulent plasma filaments, $T_{i,\text{fil}}$, affects the filament dynamics in several ways [13]. However, because of the lack of $T_{i,\text{fil}}$ measurements and the complexity of modeling finite ion temperature effects, most turbulent models assume cold ions, i.e. $T_{i,\text{fil}} = 0$ (even though this assumption is unrealistic in the tokamak SOL where less mobile ions are naturally hotter than electrons [14]). New measurements of $T_{i,\text{fil}}$ were recently obtained in AUG by an RFA mounted on the RPM, showing that turbulent filaments convey hot ions over large radial distances in the SOL. An RFA uses a series of grids shielded behind a narrow slit. The slit plate monitors the ion current density, $j_{\text{sat}}$. One of the grids is swept positively to remove ions with energy below the grid potential, $V_{g1}$. Another electrode, a collector, measures the current of ions ($I_c$) with energy above $eV_{g1}$. The conditional sampling technique from Ref. [15] was used to extract $T_{i,\text{fil}}$. Filaments characterized by a similar ion current density, $j_{\text{sat,fil}}$, were selected from the measured time trace. As illustrated in Fig. 5, $T_{i,\text{fil}}$ was obtained from the e-folding voltage of the corresponding $I_c$ plotted against $V_{g1}$. The filament ion temperature from Fig. 5 seems to decrease radially with the decay length of $\lambda_{Ti} \approx (\Delta r_{\text{sep}}^{(2)} -\Delta r_{\text{sep}}^{(1)})/\log(T_{i,\text{fil}}^{(1)}/T_{i,\text{fil}}^{(2)}) \approx 2\log(47/16) \approx 2$ cm. Additionally, Fig. 6 indicates that more intense filaments are characterized by somewhat higher $T_{i,\text{fil}}$. At the midplane separatrix distance $\Delta r_{\text{sep}} = 21$ mm, $T_{i,\text{fil}}$ is up to 70% of the ion temperature at the separatrix, $T_{i,\text{sep}}$ obtained from spectroscopic measurements. A factor of 2 larger $T_{i,\text{fil}}$ at $\Delta r_{\text{sep}} = 21$ mm from Fig. 6 compared to $T_{i,\text{fil}}$ at $\Delta r_{\text{sep}} = 25$ mm from Fig. 5 can be partly explained by ~30% longer parallel magnetic connection length, $L_{//}$, in the plasma pulses from Fig. 6, and thus weaker parallel loss ($\propto c_s/L_{//}$, with $c_s$ the ion sound speed). Assuming that turbulent filaments

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**FIG. 5.** Conditionally-sampled filament ion I-V characteristics measured by an RFA in AUG ohmic discharge. Dashed: exponential fit to the decaying part of the ion I-V characteristic which yields (a) $T_{i,\text{fil}} \approx 47$ eV at $\Delta r_{\text{sep}} = 25$ mm versus (b) $T_{i,\text{fil}} \approx 16$ eV at $\Delta r_{\text{sep}} = 45$ mm.

**FIG. 6.** The filament ion temperature (circles) measured at $\Delta r_{\text{sep}} = 21$ mm, plotted against the filament ion current density. The values of $j_{\text{sat,fil}}$ correspond to $(1-4.5)\sigma$ above the time averaged mean. Squares denote the radial filament propagation speed required in the parallel loss model to match $T_{i,\text{fil}}$. 

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originates near the separatrix [16] (i.e. $T_{i,fil} = T_{i,sep}$ at the filament birth location), $\lambda_{Ti} \approx \Delta r_{sep}/\log(T_{i,sep}/T_{i,fil}) \approx 3-7$ cm, estimated from the data from Fig. 6. This value of $\lambda_{Ti}$ can be compared with $\lambda_{Ti} \approx 2$ cm obtained from the data from Fig. 5, measured at $\Delta r_{sep} = 25-45$ mm. The observation that $T_{i,fil}$ drops faster radially further away from the separatrix suggests that the filament radial propagation velocity, $v_{rad}$, decreases as the filaments rarify due to parallel loss. The reliability of the conditional-sampling technique used to obtain $T_{i,fil}$ was tested on artificial RFA measurements generated by the GEMR simulations [17, 18]. These simulations have also addressed various aspects of ion temperature measurements in turbulent SOL by an RFA. Such instrumental study can be particularly important now, when RFAs are being installed in a number of tokamaks.

The measured $T_{i,fil}$ was used to estimate $v_{rad}$ from a fluid model of the parallel filament transport in the SOL, described in Ref. [19]. Despite of its relative simplicity, the model was previously successful in reproducing a variety of experimental observations in AUG and JET [17, 19-23]. Additionally, in Ref. [22] the results obtained from the fluid model were consistent with the Monte Carlo simulations of ELM filaments [24]. In the present simulations, $v_{rad}$ was adjusted to match the measured $T_{i,fil}$. As shown in Fig. 6, the required $v_{rad}$ is in the range of 400-1000 m s$^{-1}$, which conforms with earlier measurements of $v_{rad}$ [13]. A tendency for $v_{rad}$ to increase with the filament particle density, observed in Fig. 6, is consistent with the models of the filament dynamics in the SOL (see references in [25]) which predict that denser filaments are subject to faster radial advection. RFA measurements also revealed some similarities of L-mode and inter-ELM turbulent transport in the SOL. These new measurements of inter-ELM transport in the AUG far SOL were reported in Ref. [26].

Furthermore, two new electric probes were being developed for AUG in the collaboration with the Institute of Plasma Physics in Prague, charting separate paths in SOL $T_i$ measurements. The first probe – a ball pen probe – measures $T_i$ by virtue of a positively swept collector recessed below the probe leading edge [27]. In AUG, the ball pen probe was...
operated with fast voltage sweeping frequencies, aiming to measure $T_i$ fluctuations [27]. The second probe – an ExB analyzer which is currently being fabricated – is similar to an analyzer used in the DITE tokamak [28] and is dedicated for fast SOL $T_i$ measurements in the COMPASS and AUG tokamaks.

4. Far SOL ELM ion energies

Experiments in the past few years have shown that ELMs can reach non-divertor PFCs with a large fraction of their initial energy [14, 19-23, 29, 30]. In ITER, the ELM-wall interactions can produce impurities, which are more likely to contaminate the confined plasma compared with those originating from the divertor. For fuel ions and low-Z impurities, the intensity of ELM-wall interactions is determined by ELM ion energies in the far SOL. However, with exception of earlier measurements on JET [20] and AUG [22, 30], far SOL ELM ion energies were practically unknown, making predictions towards ITER uncertain.

Systematic measurements of the far SOL ELM ion energies have been performed in AUG using the RFA mounted on the RPM (fast-ion losses during ELMs are covered in an accompanying contribution [31]). Illustrative results discussed here appear in more detail in Ref. [23]. Figure 7 shows typical time traces of $j_{sat}$ and $I_e$ measured by the RFA in two similar type I ELMs at $\Delta r_{sep} = 35$ mm. Note that both, $j_{sat}$ and $I_e$, feature a rich filamentary structure observed from earlier LP and IR measurements (see references in Ref. [23]). It is worth mentioning that the ELM filamentary structure measured by the RFA was found to be well correlated with that observed simultaneously by the visible light imaging of the probe head [23]. Figure 7 shows that $I_e$ drops with increasing $V_{sl1}$ due to reflection of low energy ELM ions by the RFA grid. The characteristic far SOL ELM ion energy can be estimated from the collector current e-folding voltage. This is a principle of the conditional sampling method used in [23], which yields the ELM-averaged ion temperature, $T_{i,ELM}$, shown in Fig. 7. $T_{i,ELM}$ is plotted against the ELM energy, $W_{ELM}$, and is in the range of 20-200 eV, corresponding to 5-50% of the ion temperature at the pedestal top. $T_{i,ELM}$ decreases with the separatrix distance and increases with $W_{ELM}$. The former can be explained by the parallel energy loss to the divertor as the filaments propagate outwards. The latter suggests that on average the filaments in large ELMs propagate faster radially and have less time to cool due to parallel loss before reaching the far SOL (as was shown in [23], the variation of the initial ELM filament ion temperature results in small changes of the far SOL $T_{i,ELM}$). This would be consistent with a larger fraction of $W_{ELM}$ deposited outside the divertor in large ELMs, observed in DIII-D [32] and JET [33, 34]. The ELM filament $v_{rad}$ estimated from the measured $j_{sat}$ and $T_{i,ELM}$ is in the range of 500-2000 m s$^{-1}$ [23]. The same range of $v_{rad}$ was previously measured in the AUG far SOL by the FP [2, 35]. Given the dependence of $v_{rad}$ on the filament density predicted by some models [25], it is perhaps not surprising that ELM filaments which carry larger $j_{sat}$ compared with less intense turbulent filaments are also characterized by somewhat larger $v_{rad}$. The same observation was reported from the MAST tokamak [36].

Another piece of evidence that ELMs carry hot ions into the far SOL is obtained from the comparison of the total power flux, $q_i$, estimated from the RFA measurements and from an IR camera viewing the probe. An example of such a comparison is shown in Fig. 8. RFA-inferred $q_i$ is obtained from the measured $j_{sat}$ and $T_{i,ELM} = 71$ eV (for $W_{ELM} \approx 28$ kJ) using the standard sheath-transmission theory [37]. Additionally, we assume the ELM-averaged electron temperature, $T_{e,ELM} = 15$ eV on average from earlier LP measurements in AUG [1]. As can be seen from Fig. 8, RFA and thermographic measurements of $q_i$ are in a fairly good agreement given the number of uncertainties in a probe-thermography comparison [38] and in calculating $q_i$ from probe data [39]. This agreement provides further evidence that the RFA-inferred $T_{i,ELM}$ can be trusted. Moreover, $T_{i,ELM}$ from Fig. 8 agrees with earlier estimates of $T_{i,ELM}$ in the AUG SOL, obtained from the RFA and 2-d IR thermography [22, 30].
5. The influence of magnetic perturbations on the SOL transport

The achievement of ELM mitigation is critical in order to avoid damage to in-vessel components in ITER. Studies of the SOL transport in AUG have entered a scarcely explored territory with the newly installed in-vessel magnetic perturbation (MP) coils and the subsequent ELM mitigation achieved [40, 41]. The mitigation was found to be associated e.g. with smaller plasma energy loss and reduced excursions the total divertor power load when type I ELMs were replaced by a stream of smaller, more frequent ELM-like events [40, 41]. Probe measurements at the outboard midplane are to some extend consistent with these observations. As illustrated in Fig. 9, in some plasma pulses with MPs, large $j_{\text{sat}}$ filaments associated with type I ELMs are replaced by more continuous and somewhat smaller bursts in mitigated ELMs. However, there are cases where bursts of $j_{\text{sat}}$ remain similar (or become even more pronounced) when type I ELMs undergo transition to mitigated ELMs [42, 43]. Detailed investigation of $j_{\text{sat}}$ dynamics in type I versus mitigated ELMs is a subject of ongoing research. Additionally, Fig. 7 shows that the far SOL $T_{\text{i,ELM}}$ measured in mitigated ELMs with reduced $j_{\text{sat}}$ excursions is lower compared with $T_{\text{i,ELM}}$ in type I ELMs. This observation goes along with the idea that the decrease in the filament density results into more sluggish radial filament advection [25], and thus faster radial cooling of the filaments.

In an L-mode discharge with the plasma density $n_e \approx 0.13 n_G$ (with $n_G$ the Greenwald density), the MPs lead to flattening of $V_f$ and $j_{\text{sat}}$ profiles near the outboard midplane separatrix and a factor 2 increase of the far SOL $j_{\text{sat}}$ [42, 43]. The flattening of $V_f$ in the SOL is qualitatively consistent with the drop of $E_r$ during MPs observed by the Doppler reflectometry. The statistical moments and the gradient of the far SOL $j_{\text{sat}}$ are not affected by MPs. At $n_e \approx 0.25 n_G$ there is a little, if any, effect of MPs on the SOL.

Another effect of MPs on the SOL near the X-point observed in AUG is illustrated in Fig. 10. The inset panel shows an R-z plot of the minimum normalized poloidal flux radius, $\Psi_{\text{min}}$, touched by the magnetic field lines passing between the divertor targets. $\Psi_{\text{min}}$ is obtained from equilibrium plus vacuum perturbation fields and is a measure of the field line penetration depth into the plasma. Finger-like structure due to MPs, first introduced in Ref. [44] and observed experimentally on DIII-D [45] and MAST [46], is seen near the X-point. Some lobes intersect the divertor target and channel relatively large power flux to the divertor. This leads to several maxima in divertor power load profile in Fig. 10. It is worth highlighting that the measured splitting of the divertor strike zones (observed also in L-mode at low $n_e$ [43]) is
consistent with the EMC3-Eirene simulation of the same discharge [47] (radiated power to the divertor, neglected in the simulation, can explain a factor 2 larger divertor power load from IR measurements in Fig. 10). The agreement indicates that the lobe structure can be described accurately enough by the vacuum approach as used in EMC3-Eirene.

References
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