Significant widening of divertor power flux distribution with increasing SOL power due to enhanced anomalous transport at Wendelstein 7-X

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Power exhaust remains an important issue for future fusion reactors. For instance, ITER, featuring the typical poloidal divertor where the width of the scrape-off layer (SOL) is of order of 1 mm, may be damaged due to overheating if not properly mitigated [1]. Here stellarators with an island divertor [2] offer an attractive alternative concept of the heat exhaust. The island divertor utilizes large magnetic islands at the plasma boundary, which are intersected by the divertor target plates. In the standard configuration there are 5/5 magnetic islands, each of the island connects two out of ten divertor units: one upper and one lower divertor. The heat, which crosses the separatrix is transported inside those islands towards the divertor target plates. As the connection lengths of field lines in the SOL islands are much longer than in tokamaks and the temperature gradients in the SOL are not very high, it is expected that ExB drifts may contribute equally to the transport in the SOL as the convective or conductive transport channels, which leads to rather complex heat and particle transport mechanisms in the 3D geometry of an island divertor.

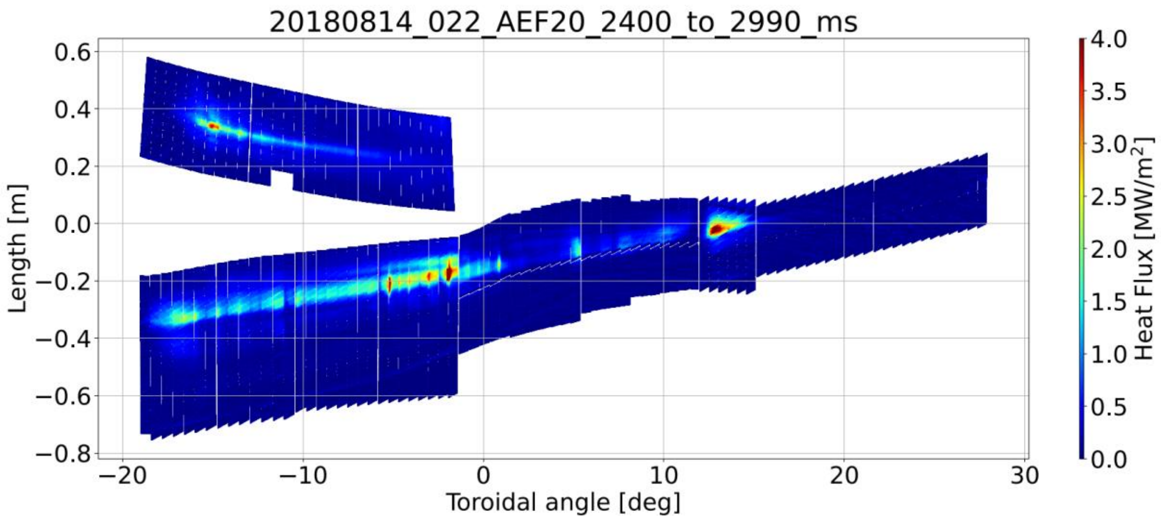


Figure 1. Heat flux distribution on the surface of divertor in module 2. Two strike-lines appear on the vertical (upper) and horizontal (lower) divertor target plates. The color scale represents the magnitude of the divertor power loads.

The resulting heat flux pattern presented in Figure 1 is therefore strongly non-axisymmetric and depends on magnetic configuration. In the standard configuration there are two strike-lines appearing on the horizontal and vertical target plates. To characterize the load pattern typically, the maximum heat flux and the wetted area are used. The first one is merely the maximum of all the profiles, while the latter is defined as

$$A_{\text{wet}} = \frac{P_{\text{div}}}{q_{\max}} = 5\sum_{j}^{\text{upper/lower}}\sum_{i=1}^{\#\text{finger}}\frac{\int_s \langle q(s)\rangle_{ij}ds}{\max(\langle q\rangle_j)}$$

In [4] it has been reported that wetted area in Wendelstein 7-X in its standard magnetic configuration (with ι = 5/5 large islands forming the exhaust channel) exceeds the values typically measured in tokamaks and reaches up to 1.5 m^2.

We have performed comprehensive analysis of the data from the previous campaigns for attached divertor plasmas and extended significantly the analysis. It has been found that in all investigated configurations the wetted area increases significantly with power entering into the scrape-off layer. The values of wetted area vary between different magnetic configurations, ranging between 1.5 m^2 and 3.5 m^2 at the maximum available SOL power (6-5 MW). For instance at the same value of P_{SOL} in standard configuration it is slightly higher than in high-mirror configuration, which also uses 5/5 islands and significantly higher than in high iota configuration (5/4 islands).

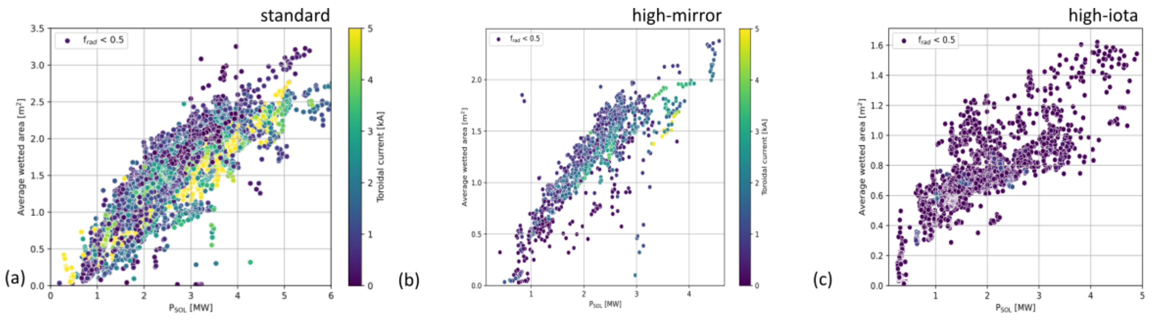


Figure 2. Wetted area vs estimated power entering the scrape-off layer (PSOL) for three different magnetic configurations. The color scale represents toroidal current flowing in the plasma.

As discussed in [3] difference in A_{wet} correlates quite well with the connection length of the field lines forming the SOL, which reflects the fact that strike line width is defined to large degree by ration of $q_{||}/q_{\perp}$. Increasing wetted area is associated with poloidally wider strike lines with more heat transported into the so-called island SOL, topological region of SOL formed inside the island chain, and the private flux region [5]. This is presented in Figure 3,

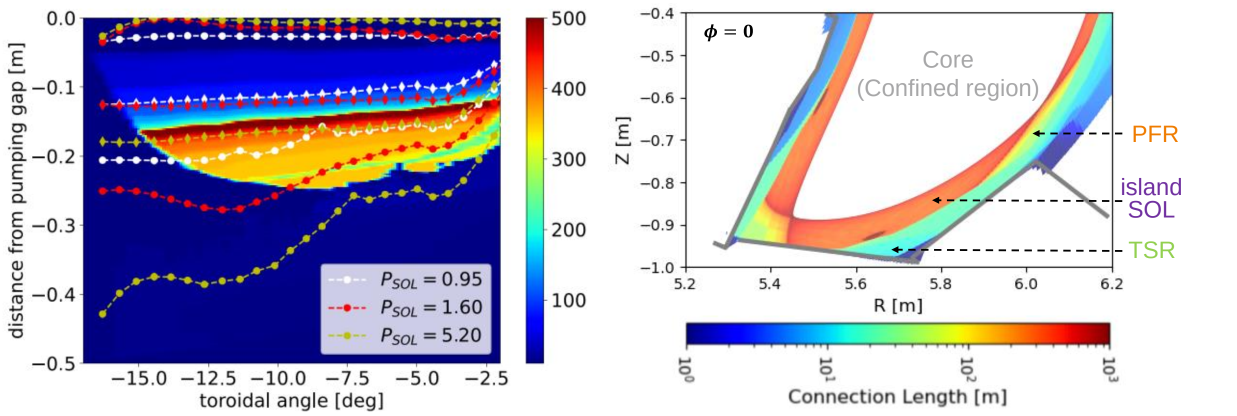
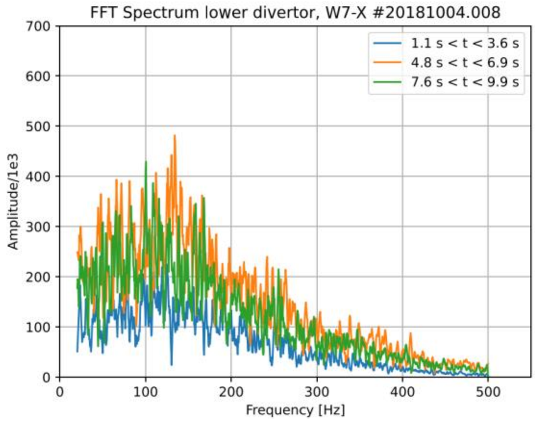


Figure 3. (left) Magnetic footprints of the divertor (Lc are expressed as a colour map) overlaid with the contours of the strike-line as measured by the infrared camera for three different values of the estimated power entering the scrape-off layer – P_{SOL} [MW]. ● -- indicates outer edge of strike line (< 0.1 q_{max}), ◆ -- indicates location of q_{max}. (right) structure of the connection lengths in the SOL: PFR – private flux region, TSR – target shadowed region [5]

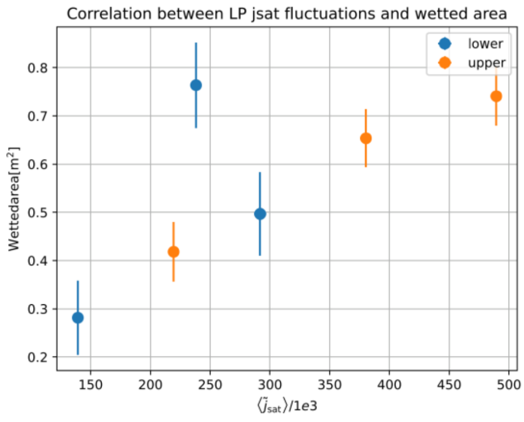
where contours of the strike line on the horizontal target plate for three different levels of P_{SOL}. The strike line maximum lies more or less at the same location (with slight shift in the direction of island SOL, whereas the outer boundary shifts significantly towards island SOL and even target shadowed region. The minimal change of the inner boundary results from the fact that the target plates end at the pumping gap, so no further extension is possible. As the effect the strike line width at the toroidal angle $\Phi = -15$ [deg] is almost two times larger for PSOL = 5.2 MW as compared to PSOL = 0.95 MW.

Our hypothesis is that with increased heating power (which leads to higher P_{SOL}) the anomalous transport is increasing, which leads to stronger transport also across the separatrix, i.e. larger values of SOL width λ_q. The indication of enhanced turbulences in the SOL is observed in the measured ion saturation current fluctuations by the Langmuir probes embedded into the divertor. Also here in many cases increasing wetted area is associated with the increasing fluctuations on the ion saturation current. The analysis for a discharge in the low iota configuration (edge $\iota = 5/6$) is presented in Figure 4. In Figure 4(a) FFT analysis of ion saturation current measured by the Langmuir probe at the strike line is performed for for three different time steps of #20181004.008. Each time step corresponds to input power of 1.5 MW, 2.5 MW and 3.5 MW correspondingly. At each level of input power, which leads to higher P_{SOL} the fluctuations increase in the whole measured range, in particular at frequencies close to 100 Hz. The average amplitude of the ion saturation current fluctuations in the frequency range of 100-200 Hz increases by a factor of two for the same increase in the wetted area (see Figure

4(b)). The changes in the amplitude of the fluctuations is observed mostly near the separatrix, but also probes measuring the far scrape-off layer detect enhancement in the fluctuations.



(a)



(b)

Figure 4. (a) FFT of jsat fluctuations measured by the Lanmguir probes near the strike line. (b) Wetted area in DBM configuration vs averaged (over the frequency range 100 – 200 Hz) amplitude of j_{sat} *fluctuations from (a).*

These are most likely some broadband turbulences appearing in the scrape-off layer, but their origin is still under investigation. These findings suggests that the wetted area increase with power entering into the SOL comes from the enhanced perpendicular anomalous transport, which spreads the width of the heat flux exhaust channel into adjacent regions, mainly the island SOL, but also the private flux region of the island divertor.

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.