Characterization of the W7-X Scrape-Off Layer Using the Multipurpose Manipulator

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Wendelstein 7-X (W7-X) recently concluded its first operation phase (OP1.2a) featuring an island divertor. In this concept, the heat and particle exhaust to the divertors is governed by intrinsic 3D magnetic islands at the plasma edge. In order to establish high performance plasmas with safe divertor operation, a comprehensive understanding of the island divertor physics is required, for which in turn thorough studies of the plasma properties and dynamics within the islands are essential. The multipurpose manipulator (MPM), a carrier system for probe heads mounted at the outboard midplane of W7-X, is a key diagnostic for the characterization the W7-X scrape-off layer. Being a multiuser platform, it served various scientific aspects during OP1.2a, including different electric and magnetic probes, plasma-surface interaction studies, hydrogen fuelling and impurity injection.

Characterization of the SOL by the MPM mostly relies on the use of reciprocating electric probes which can perform radial fast plunges through a magnetic island up the last closed flux surface. The fundamental quantities inferred from probe measurements (e.g., radial profiles of density, electron temperature, plasma flows, electric fields and potentials) already allow inferring conclusions on the magnitude and spatial distribution of parallel heat and particle transport to the divertor. Employing, in addition, spatially distributed arrays of probes, we obtained insight into the dynamics and propagation of turbulent fluctuations and the associated (perpendicular) fluctuation-induced transport.

Typical fundamental plasma parameters that have been obtained using the MPM are electron temperatures up to 100 eV and densities up to $1 \times 10^{19} \text{ m}^{-3}$ with a strong dependence on operation (e.g., heating power) and core plasma parameters (e.g., density). Furthermore, the complex magnetic field topology in the large configuration space of W7-X is found to play an important role for the edge plasma profiles. Hence, cross-checks with other SOL diagnostics are used for both validation of results as well as identification of local effects (e.g., due to the island structure).
CHARACTERIZATION OF THE W7-X SCRAPE-OFF LAYER USING THE MULTI-PURPOSE MANIPULATOR

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Abstract

The W7-X Scrape-Off Layer with its characteristic magnetic island chain has been probed by a reciprocating manipulator at the outboard mid-plane. Various probe heads containing electric probes have been employed to assess fundamental aspects of the SOL physics such as radial profiles of density, temperature, plasma flows, and electric fields. Profiles of plasma density and electron temperature have been taken in all major magnetic configurations and at different plasma conditions. The paper presents an excerpt of SOL plasma profiles in the most important magnetic configurations and discusses the role of plasma heating and central density for both plasma profiles as well as plasma dynamics in the edge islands.

1. INTRODUCTION

The Wendelstein 7-X (W7-X) stellarator employs the island divertor concept, where heat and particle exhaust do the divertors is controlled through large, low rational magnetic islands at the plasma edge. An island divertor has first been implemented in W7-AS[1,2] and is now employed by at W7-X [3], which (after a first campaign of limited plasmas 2015/2016 [4]) concluded its first two divertor operation phases recently (2017/2018).

Understanding the effect of the edge magnetic islands topology on the Scrape-Off Layer (SOL) profiles, dynamics and transport is fundamental for the assessment of the divertor performance and future improvement of divertor operation scenarios. The large connection length in the islands (typically a few 100m) results not only in reduced peak heat loads due to a larger wetted area on the divertors but also implicates that perpendicular transport may become more important than in tokamaks. Therefore, investigating of both parallel and perpendicular transport is required in order to address the competition of energy fuelling into the island from the confined plasma edge versus the energy loss by parallel transport to the divertors.

An established technique to address these aspects is the use of reciprocating electric probes, which can provide profiles of electron temperature, density, plasma potential, plasma flows and in addition offer the possibility to study turbulent fluctuations from which cross-field transport can be estimated, see e.g. Refs. [5] At W7-X, the Multi-Purpose Manipulator (MPM) serves as a carrier system for various interchangeable probe heads [6] It is installed at the outboard mid-plane and can perform fast reciprocating plunges through the island chain up to the last closed flux surface (LCFS) of the confined plasma.

In this contribution, an overview of results of obtained with the MPM is given. While the MPM was employed for a wide variety of applications (such as magnetic probes, material studies, impurity injection, gas fuelling and more), we here focus on electric probe measurements which provide profiles of key plasma parameters: electron temperature, density and electric field are determined from triple probes and swept Langmuir probes, while plasma dynamics are inferred from array (poloidal, radial, Mach) of pins operating in floating potential or ion saturation current mode.

In section 2, the MPM is briefly introduced. Plasma profiles obtained with the MPM in different magnetic configurations and plasma conditions are presented in section 3. First results of plasma dynamics investigation with the MPM inside a magnetic island and the role of central plasma conditions are given in section 4, followed by a summary and discussion in section 5.

2. THE MULTI-PURPOSE MANIPULATOR (MPM) – A VERSATILE TOOL FOR SOL STUDIES

The Multi-Purpose Manipulator (MPM) serves as a versatile carrier system for a multitude of probes heads ranging from electric and magnetic probes of different kinds to plasma-wall interaction probes to plasma fuelling and impurity generation.
The MPM is mounted at the outboard mid-plane in module 4 (port AEK40) at a toroidal angle of $\phi_{\text{tor}} = 200.8^\circ$. Probe heads are mounted to the MPM in a dedicated exchange chamber outside the cryostat. Using a slow linear drive, probe heads are transported to a parking position approximately at the position of plasma vessel wall. From there, a second, fast linear drive allows fast plunges with a maximum depth of 350 mm at an acceleration of 30 m/s$^2$ [6].

2.1. MPM position the W7-X magnetic configuration space

The accessible plunge path of the MPM is indicated in the Poincare plots of the MPM’s plasma cross section in Fig. 1 for different magnetic configurations. In the magnetic standard configuration ($\iota_{\text{edge}} = 1$) the MPM crosses the 5/5 island chain slightly above the O point, see Fig. 1a).

Using the planar superconducting coils, the vacuum rotational transform $\iota$ of W7-X can be changed in a wide range between $\iota_{\text{edge}} = 5/6$ and $\iota_{\text{edge}} = 5/4$. The Poincare plots of two notable configurations at the ends of this spectrum are shown in Fig. 1b) and c). The low iota configuration with $\iota_{\text{edge}} = 5/6$ features six quite large islands and a wide SOL region of open stochastic field lines. The high iota configuration with $\iota_{\text{edge}} = 5/4$ has four smaller islands and only a very narrow region of open field lines outside the confined plasma. In contrast to the standard configuration, where the 5/5 resonance results in five individual islands, in the low and high iota configurations actually only one island exists which winds around the torus such that four (high iota) or six (low iota) instances of it appear in each poloidal plane.

Besides these basic configuration properties, also the relative position of the MPM to the island chain changes: While the MPM crosses close the O point of the elongated outer mid-plane island in the standard and high iota configuration, it crosses almost in between islands in the low iota configuration, close to the X point.

![FIG. 1. Poincare plots of the MPM cross section for different magnetic configurations. The MPM plunge path is indicated by the red line.](image)

2.2. Probe heads

An overview of all MPM probe heads used since W7-X went into operation is given in Table 1 with references where available. In this contribution, data from probe heads FZJ-COMB2 and IPP-FLUC1 has been used.

<table>
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<th>Table 1. List of MPM probe heads</th>
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<td><strong>Probe head</strong></td>
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<tr>
<td>FZJ-COMB1 [7]</td>
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<tr>
<td>FZJ-COMB2 [8,9]</td>
</tr>
<tr>
<td>Probes</td>
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<tr>
<td>IPP-FLUC1</td>
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<tr>
<td>FZJ-MACH1</td>
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<tr>
<td>FZJ-RFA1</td>
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<tr>
<td>FZJ-GAS1</td>
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<td>FZJ-GAS2</td>
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<td>FZJ-MACH2</td>
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<td>FZJ-RFA2</td>
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<td>RFX-HRP1</td>
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<td>FZJ-MAT2</td>
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<tr>
<td>IPP-LBO1</td>
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The upgraded combined probe FZJ-COMB2 depicted in Fig. 2a) is one of the MPM workhorses since it serves various purposes: Nine electric probe pins provide electron temperature and density profiles using a triple probe, radially and poloidally separated pins can be used to study spatio-temporal fluctuation dynamics, and a Mach probe provides information on plasma flow parallel to the magnetic field. Furthermore, the probe head contains an ion-sensitive probe [16], a 3D magnetic pick-up coils, a tungsten sample for PWI interaction studies, and feedthrough for gas injection.

The IPP-FLUC1 probe head is made of boron nitride and is 3D shaped to adapt to the magnetic field geometry in the MPM region, see Fig. 2B. It features a poloidal array of 22 electric probe pins which can be used in different modes: floating potential, ion saturation current, swept Langmuir probe, triple probe. From this set of pins, both temperature and density profiles can be obtained as well as poloidal fluctuation dynamics and therefore radial electric fields. In addition, a 4-electrode Mach probe provides parallel and poloidal Mach numbers [17].

**FIG. 2. A) probe head FZJ-COMB2 B) probe head IPP-FLUC1.**

### 3. TEMPERATURE AND DENSITY PROFILES IN DIFFERENT CONFIGURATIONS

Temperature and density profiles are fundamental quantities for SOL characterisation. To maximize their availability, most probe heads for the MPM contain triple probes or swept Langmuir probes. Typical profiles from three major magnetic configurations (see Fig. 1) are presented in Figs. 3-6.

#### 3.1. Standard configuration, 5/5 islands

In the magnetic standard configuration with 5/5 independent islands (see Fig. 1a)) the MPM crosses the outboard mid-plane island about 15 cm above the O point. In program 20180814.34, the line integrated plasma density was aimed to be kept constant at $4.5 \times 10^{19} \text{ m}^{-2}$ while the ECRH power was stepwise increased from 2MW to 3.5MW to 5MW with each step lasting 3s, see the overview plot in Fig. 3B. During each power level, the MPM performed a fast plunge into the edge island as indicated in the fourth panel in Fig. 3B. The electron temperature and plasma density profiles determined by a triple probe are presented in Fig. 3A along with a Poincare plot of the edge island. The temperature profiles reveal a distinct local maximum in the region of $R=6.07 \text{m}$ to $R=6.08 \text{m}$, which corresponds to the center of the island as seen in the bottom panel. The profiles show a small dependence on the heating power: $T_e$ slightly increases with heating power, while the profile shape remains similar. Only in the 5MW case, $T_e$ decreases inside the island ($R<6.07 \text{m}$) with respect to the lower power cases. This is probably a local
cooling effect caused by the hot boron nitride body of the probe head releasing impurities, see the outboard radiation trace in the fourth panel of Fig. 3B.

The density profile in the middle panel of Fig. 3A reveals a significant flattening throughout the island width, i.e. for R<6.08m. In this region, the density scales approximately linearly with the heating power, indicating a much stronger dependence on the heating power compared to the Te profile. While the central (line integrated) plasma density also slightly increased with heating power (see density trace in Fig. 3B and legend in Fig. 3A), this effect alone cannot explain the density increase observed in the SOL, indicating that heating power is an important player for fuelling the SOL.

![FIG. 3. A) Temperature and density profiles obtained by triple probes on the probe head FZJ-COMB2 in the magnetic Standard configuration for different ECRH power levels at approximately (attempted) constant density. B) Overview plot of major W7-X parameters](image)

### 3.2. High iota configuration, 5/4 island

In the high iota configuration, the island has a similar poloidal position at the outboard mid-plane compared to the standard configuration (see Fig. 1a and Fig. 1c) with the MPM crossing about 15 cm above the O point. However, the island is much more compressed and narrower in the high iota configuration compared to the standard configuration.

In program 20180912.28, a power scan from 5MW to 3.5MW to 2MW was conducted while the plasma density was not actively controlled after plasma startup, see Fig. 4B. At each power level, the MPM performed a fast plunge through the SOL approximately up to the LCFS at the time instances indicated in the fourth panel of Fig. 4B. The temperature and density profiles obtained during this experiment are presented in Fig. 4A. The profiles are much smoother compared to the standard configuration and do not feature distinct peaks or flattening related to the magnetic topology. Only in the 5MW case, a small bump might be present at the island center (R=6.03m), which will be subject to a future more thorough and systematic investigation. Both the short SOL width (~2 cm) and the smooth profiles in this configuration fit well to the island being very narrow as also indicated in the bottom panel of Fig. 4A.

Comparing the different heating power levels in program 20180912.28, no effect on the SOL Te profiles is observed. The density profiles, in contrast, show a decrease of density with decreasing heating power. Again, as in section 3.1, the SOL density dependence on heating power is larger than the central (line integrated) plasma density, see the density time trace in Fig. 4B and the legend labels in Fig. 4A.
FIG. 4. A) Temperature and density profiles obtained by triple probes on the probe head IPP-FLUC1 in the high iota configuration for different ECRH power levels at approximately (attempted) constant density. B) Overview plot of major W7-X parameters.

3.3. Low iota configuration, 5/6 island

The low iota configuration features a wide SOL and a large 5/6 island with especially long connection lengths. The location of the island in the MPM plane is such that the probes scan through the SOL very close to (only slightly above) the X point, see Fig. 1b) and the bottom panels in Fig. 5.

FIG. 5. Temperature and density profiles obtained by triple probes on the probe head IPP-FLUC1 in the low iota configuration as a function of ECRH power at constant density (left) and central density at constant ECRH power (right).
In this configuration, a density and power scan was conducted by performing many short discharges at one particular power and density setting each. A comparison of different heating powers at a moderate line integrated density of $4 \times 10^{19}$ $\text{m}^{-2}$ is presented in the left part of Fig. 5. The temperature profiles feature a flattened part in the far SOL at $6.12 \text{m} < R < 6.13 \text{m}$ which grows into a small local peak for the 5MW case. Both SOL temperature and density react similarly to variations of the heating power: for higher power, the magnitude of $T_e$ and $n$ increases slightly but the general profile shape remains similar.

The central density variation at the highest heating power of 5MW presented in the right part of Fig. 5 reveals a wider variety of features in the SOL profiles. For the smallest line integrated density of $2 \times 10^{19}$ $\text{m}^{-2}$, the temperature profile is slightly higher than the cases with higher densities and features local peaks at different positions. Between $4 \times 10^{19}$ $\text{m}^{-2}$ and $6 \times 10^{19}$ $\text{m}^{-2}$, no significant difference in the $T_e$ profiles is observed except for a feature at $R = 6.105 \text{m}$ which is present in some, but not all measurements performed at exactly these conditions (5MW, $6 \times 10^{19}$ $\text{m}^{-2}$). The SOL density profiles in the middle panel show a positive dependence on the line integrated plasma density but do not quite scale linearly: Comparing the highest and lowest line integrated densities which differ by a factor of 3, only a factor of 1.5-2 is observed on the SOL density. For a complete understanding of the SOL profiles’ dependence on power and central density, these results from Fig. 5 will be compared with Thomson scattering profiles of temperature and density once these are available.

### 3.4. Limiter configurations

If the edge rotational transform profile of W7-X does not contain low order rational resonances, limited plasmas are created with the divertor acting as a limiter. Various such limiter configurations have been addressed experimentally both in the iota range between low iota (5/6 island) and standard (5/5 islands) as well as between standard and high iota (5/4 island).

The SOL profiles presented in Fig. 6 have been taken in a limited configuration corresponding to the magnetic configuration in the first operation phase of W7-X (OP1.1), when inboard limiters instead of the now present divertors have been employed [4,7]. In this configuration, the 5/6 island chain from the low iota configuration has moved inwards and is now located inside the confined plasma, while the magnetic topology outside the plasma does not contain resonant islands.

Both the temperature and density profiles observed in this configuration are relatively smooth and show no extraordinary features. While the densities are comparable to those found in the low iota configuration (see Fig. 5), the electron temperatures are larger by a factor of two. It is interesting to note that the temperatures are also much larger than the values measured at the same position by the MPM in a similar magnetic configuration in OP1.1 [7]. This effect can probably be attributed to different connection lengths in the cases of inboard limiters and modular divertors and will be addressed soon.

Another interesting behaviour in this experiment concerns the SOL density profiles as a function of the line integrated plasma density. In the two programs compared in Fig. 6, the density difference between both shots very well matches that of the line integrated densities, while this was not the case in the low iota configuration, see section 3.3.

Finally, the time dependence of the SOL profiles has been investigated in this experiment. Since MPM plunges were performed at approximately 2s and 8s after plasma startup, the time evolution over 6s can be compared. Although the bootstrap current increases from 2kA to 7kA (in XP51) and 2kA to 5kA (XP52) respectively.
(corresponding to an edge iota increases of up to 0.05), no major shift of the profiles is observed. This behaviour is in contrast to island divertor configurations, where comparable iota changes caused by the bootstrap current significantly affect the edge islands and therefore the plasma profiles measured with the MPM. A dedicated publication on this topic is currently under preparation.

4. TRANSPORT AND DYNAMICS INSIDE A MAGNETIC ISLAND

Finally, a glimpse into one of the many aspects of MPM measurements currently being analyzed and worked on is presented in this section. In a hydrogen discharge in the magnetic standard configuration featuring different heating power and density steps (XP20171121.12), the MPM has probed the edge twice: first at an ECRH power of 3MW and a line integrated density of $1.5 \times 10^{19}$ m$^{-2}$ (in the following denoted as plunge 1 – P1) and two seconds later at a higher power and density of 5MW and $3.5 \times 10^{19}$ m$^{-2}$ respectively (denoted as plunge 2 – P2).

Since the MPM was equipped with the IPP-FLUC1 probe head (introduced in section 2.2), different quantities relating to dynamics and transport have been addressed and are presented in Fig. 7. First, the floating potential profile shown in Fig. 7B is qualitatively different in both situations. In the low power, low density case (P1), it tends to increase towards the plasma, while it drops to negative values approximately in the center of the island at the second plunge P2. Although no electron temperature and density measurements are available for this shot (day) due to technical failures, the ion saturation current shown in Fig. 7C can be taken as a proxy for the plasma density and indicates that the SOL density increases along with the total line integrated plasma density. The poloidal Mach numbers deduced from the 4-electrode Mach probe also reveals an interesting feature at $d_{\text{lcfs}} < 3$ cm (just as the floating potential): While the profile is flat at P1, the poloidal Mach number significantly increases at P2. Finally, the poloidal phase velocity of fluctuation propagating along the poloidal probe array has been determined from the cross-correlation between pins of that array. Again, the profile is flat at P1 but shows a sudden increase including a change of sign at $d_{\text{lcfs}} < 3$ cm. Since fluctuations are considered to be $E \times B$ driven, we take the poloidal velocity in Fig. 7E as a measure for the radial electric field which therefore appears to change sign in the island at situation P2. This hypothesis is supported by the correlating change in $M_{\text{pol}}$ and the floating potential profile, which (assuming that the $T_e$ profile is relatively smooth) can be taken as a proxy for the plasma potential. Hence, a sign change radial electric field at P2 can also be estimated from the floating potential profile.

![FIG. 7. A) Poincare plot of edge island in standard configuration with probe path indicated. Profiles of different quantities taken at two instances in time of program 20171121.12: Floating potential (B), Ion saturation current (C), poloidal Mach number (D), poloidal phase velocity of propagating fluctuation (E). The profiles were taken at P1: $t=1.1s$, $P=3$MW, $ndl=1.5 \times 10^{19}$ m$^{-2}$, P2: $t=3.1s$, $P=5$MW, $ndl=3.5 \times 10^{19}$ m$^{-2}$](image)

5. SUMMARY AND CONCLUSION

In the first island divertor operation phase (OP1.2a/b), the MPM was continuously employed to investigate the SOL with electric probes. Surveying SOL profiles of electron temperature and plasma density, a clear role of the magnetic configuration was observed: In the standard configuration (EJM), where the MPM experiences a relatively wide island, the SOL is also quite wide (~5cm) and features local peaks or flat regions in the temperature profiles. These are related to the local magnetic topology, which is known to influence temperature profiles via the connection length [9,18]. In the high iota configuration (FTM), where the MPM crosses a narrow island, the SOL width is just ~ 2cm and the profiles do not reveal any extraordinary features, possibly since the island is too small the MPM position. In the low iota configuration (DBM), no particular features are seen in the very wide SOL profiles (SOL width ~5cm), which can be expected since the MPM here crosses in between two islands, close to the X point. Limited configurations, in contrast to diverted ones, feature narrow profiles (SOL width ~2cm) with generally higher electron temperatures of up to 100eV. As expected, the SOL width is larger than in tokamaks [19] due to the longer connection lengths.
The role of heating power and central plasma fuelling for SOL temperature and density is not consistent in all configurations and remains to be addressed by future investigations. Besides systematic MPM measurements, other edge/SOL diagnostics will help to benchmark measurements and to address the inherent three-dimensionality of the W7-X SOL. Also, the observation of changing radial electric fields and plasma dynamics in the islands due to changing intra-shot plasma conditions is an interesting first result which will be addressed in an integrated approach encompassing various diagnostics in the near future.

ACKNOWLEDGEMENTS

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