The effects of magnetic topology on the SOL island structure and turbulence transport in the first divertor plasma operation of W7-X


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Abstract

Wendelstein 7-X (W7-X) was operated successfully with the first divertor plasma in the operation phase 1.2a (OP1.2a). A new combined probe head, which consists of Langmuir probe pins, Mach probe, ion sensitive probe (ISP), differential coil and a tri-axial pick-up coil, is developed and installed on the multiple purposes manipulator in OP1.2a. With this new combined probe head, it is able to measure the edge plasma profiles \( (T_e, n_e, \Phi, M_\parallel) \), variation of magnetic field, poloidal and radial turbulence structures. During OP1.2a, the plasma parameters in three magnetic configurations (KJM, EJM, FTM) are measured by the new combined probe head, and the plasma parameters across the magnetic island are in good agreement with the magnetic island structure calculated by the field line tracer. In configuration of EJM+252, the floating potential has a negative value around the island center along the path of probe. Within this region, the electron pressure reveals a platform, and the parallel Mach number exhibits a symmetric profile, and the radial particle flux driven by turbulence reduces to a relatively low level. However, outside this region the particle flux is extremely high on both sides. The high particle flux is dominated by the broadband turbulence between 40 to 120 kHz, while the inner radial region with lower particle flux is driven by the turbulence below 25 kHz. It should be noticed that the high turbulent particle flux is located in the region with large gradient of electron density, indicating that the transport could be driven by the instability caused by the density gradient.

1. INTRODUCTION

The edge radial transport in fusion devices is considered to be driven by turbulence, such as anomalous transport which is much larger than neoclassic transport [1]. In stellarator, the edge transport is largely determined by the three-dimensional magnetic topology, such as in LHD, TJ-II and W7-AS [2-5]. In Wendelstein 7-X (W7-X), the turbulence characteristics also exhibit strong dependence on magnetic topologies, as measured by a combined probe head in operation phase 1.1 [6, 7]. In the island divertor configuration of operation phase 1.2a (OP1.2a), the edge magnetic island structure and the radial transport property have been obtained by a new combined probe designed to measure edge profiles and turbulence structures. In this paper, the experiment setup will be introduced in section 2; the magnetic island structures is presented in section 3; the radial transport induced by turbulence is in section 4; summary is given in section 5.

2. EXPERIMENTAL SETUP

W7-X is a new optimized stellarator to accommodate a variety of 3D magnetic configurations, with major radius of 5.5 m and minor radius about 0.5 m [8]. A multiple-purpose manipulator (MPM) has been developed and installed on W7-X in 2015, which located under the outer midplane with \( Z = -167 \) mm [9, 10]. The manipulator has a maximum plunge length of 35 cm for the fast movement, maximum acceleration of 30 m s\(^{-2}\), and a maximum speed of 2.5 m s\(^{-1}\). A new combined probe head, which consists of Langmuir probe pins, Mach probe, ion sensitive probe (ISP), differential coil and a tri-axial pick-up coil, is developed and installed on the MPM in OP1.2a. With this new combined probe head, it is able to measure the edge plasma profiles \( (T_e, n_e, \Phi, M_\parallel) \), variation of magnetic field, poloidal and radial turbulence structures. The sketch of the new combined probe is shown in Figure 1. A typical Poincaré plot of island divertor configuration in vacuum case is shown in Figure 1 (a), with the red solid line signifying the probe path which passes through the magnetic island in the SOL. As shown in Figure 1 (b), the
probe front surface is shaped to align on the local flux surface, consequently the probe pins are able to measure the plasma information on the same flux surface. Figure 1 (a) shows the arrangement of probe pins, with pin 1, 4, 5, 6, and 7 measuring the floating potentials \( \phi_1, \phi_2, \phi_3, \phi_4 \) and \( \phi_5 \). Pin 2 and pin 3 are connected with a biasing voltage of 280 eV, forming a double probe and measuring the electron density and temperature together with Pin 1 and 4. The Mach probe consists of pin 8 and 9, giving the parallel flow velocity. There are two ion sensitive probes (ISP) on both sides of the central stage, with pin 10 (12) as a guard and pin 11 (13) as an ion current collector. When both the guard and collector are biased with sweeping voltage, it is able to measure the ion temperature [11-13]. The height and voltage difference between the guard and collector are two key parameters for the ISP which is still in commissioning now. Besides the probe pins on the front surface, there are a tri-axial pick-up coil and a differential coil, while the magnetic variation along three directions \( (B_5, B_6, B_7) \) can be obtained by the former coil and the local poloidal magnetic flux (i.e., local plasma current) is measured by the latter coil. Note that the distance between the center of differential coil and the front probe tip is 43 mm, and this distance for the 3D coil is 39 mm. This new combined probe head is designed to study the edge turbulence structure and transport. The turbulence poloidal structure can be derived from the combination of two pins among the pins 1, 4, and 7 (or the pins 5 and 6), and different poloidal distance for each combination. The radial structure is calculated by pin 4 and 5 (or pin 6 and 7). It is also benefit from this probe arrangement that we can measure the radial particle flux and the Reynold stress at the same time, and characterize the SOL turbulence structure and transport.

Figure 1. The sketch of the new combined probe used in OP1.2a. (a) A typical island divertor configuration, and the red solid line denotes the probe path. (b) The projection of probe head viewed along the toroidal direction. (c) The arrangement of all probe pins.

3. TURBULENCE STRUCTURES IN THE SOL WITH MAGNETIC ISLAND

Three magnetic configurations, EJM001, KJM001 and FTM001, have been used for most experimental programs in OP1.2a, where EJM001 is a standard configuration, KJM001 is a high mirror configuration, and FTM001 is a high iota configuration [14, 15]. Three discharges with reasonable measurement of the new combined probe have
been selected to illustrate the SOL structures and turbulence behaviours in the three configurations, as presented in Table 1, including the current setting of non-planar coil, planar coil and trim coil, as well as the toroidal plasma current during the plunge of MPM. Figure 2 gives the plasma parameters of the three discharges. The heating power of electron cyclotron resonance heating (ECRH) is about 1-2 MW, for the sake of making a deep plunge of MPM and measuring the profiles of the whole SOL magnetic island in a lower heat load environment. The plasma density is measured by a central channel of the Thomson scattering due to the lack of interferometer data in KJM+252 configuration, around 1.3×10^{19}m^{-3}. The electron temperature from the Thomson scattering is about 3-4 keV, and the plasma energy is almost constant during the plunge of the probe, with the radial position of probe shown in Figure 2 (e). Compared with the high performance discharges, all the three shots here have lower heating power and line averaged density and stable plasma parameters during the plunge, which is beneficial to the characterization of the SOL properties.

Table 1. The parameters of three configurations.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Shot No.</th>
<th>Non-planar coil</th>
<th>Planar coil</th>
<th>Trim coil</th>
<th>Toroidal current</th>
</tr>
</thead>
<tbody>
<tr>
<td>EJM+252</td>
<td>20171026.38</td>
<td>13067, 13066, 13067, 13066, 13067</td>
<td>-699, -699</td>
<td>-84, 17, 96, 41, -67</td>
<td>1200</td>
</tr>
<tr>
<td>KJM+252</td>
<td>20171017.56</td>
<td>12960, 13213, 13994, 12048, 10920</td>
<td>-749, -749</td>
<td>-95, 1, 95, 59, -60</td>
<td>700</td>
</tr>
<tr>
<td>FTM+252</td>
<td>20171025.35</td>
<td>14187, 14186, 14187, 14187, 14187</td>
<td>-9789, -9789</td>
<td>-131, -43, 107, 112, -44</td>
<td>-300</td>
</tr>
</tbody>
</table>

Figure 2. The plasma parameters for three magnetic configurations in OP1.2a.
The Poincaré plot of the three configurations in the same poloidal projection as the MPM, and the connection length along the path of probe are calculated by the field line tracer with the real current settings in Table 1, as shown in Figure 3 [16-18]. When calculating the field line connection length, all the machine grids of W7-X in OP1.2a are included. For the standard configuration EJM+252, there is a broad magnetic island on the path of probe, with an island width of ~5 cm and the last closed flux surface (LCFS) located at $R = 6.026$ m. In the far SOL, the connection length $L_{||}$ is below 15 m but increases sharply to over 200 m at the edge of island, then shows a flat region inside the island, and finally $L_{||}$ reaches the given threshold near the LCFS. The high mirror configuration KJM+252 also exhibits similar variations for magnetic configuration and connection length, except that the island width is about 2 cm wider than EJM+252 configuration and the LCFS moves inward to about $R = 6$ m. However, the high iota configuration FTM+252 has a relatively narrow SOL island, and its connection length raises significantly quickly around the LCFS. Moreover, there is a clear stochastic region between the LCFS and SOL island in both EJM+252 and KJM+252 configurations, but it is difficult to distinguish this region in the high iota configuration.

![Figure 3](image.png)

Figure 3. The Poincaré plot of the three configurations of OP1.2a on the poloidal plane of MPM. Panels from left to right are EJM+252, KJM+252 and FTM+252.

The typical SOL profiles measured by the new combined probe for the three configurations are shown in Figure 4. The left panels display the floating potential of $\phi_{P3}$, electron temperature $T_e$, electron density $n_e$ and the connection length along the path of the new combined probe, and the right panels display the auto-correlation spectrum power density (APSD). The electron temperature and density are derived from the triple probe, with $T_e = [\phi + (\phi_{f1} + \phi_{f2})/2]/\ln 2$ and $n_e = I_e/(0.49 e A_s \sqrt{T_e/m_i})$, where $\phi_s$ and $I_e$ are measured by the double-probe pin 3 and pin 2, respectively [19]. As shown in Figure 4 (a-c), the plasma profiles have strong dependence on the magnetic topology. In KJM+252 configuration, $T_e$ and $n_e$ present synchronous increase trend with the connection length, and $n_e$ peaks around the island center along the probe path ($R \approx 6.52$ m). When the probe continues to plunge into the inner side of the island, both $T_e$ and $n_e$ decrease gradually to be saturated, but it is unable to form an out-in symmetric distribution about the island center due to a large particle outflow on the inner side. In the EJM+252 configuration, the island center along the probe path is located at $R \approx 6.069$ m. In this region, the floating potential becomes a negative valley, and $T_e$ exhibits a symmetry peak. When $R < 6.04$ m, the connection length increases quickly from 345 m to several kilometer, and both $T_e$ and $n_e$ start to rise significantly. The plasma profiles are shifted inward dramatically in FTM+252 configuration because of the narrow island and small SOL width. As a result, both $T_e$ and $n_e$ have a great increase within this ~2 cm radial region, i.e., $T_e$ from 25 eV to 80 eV and $n_e$ from 0.8 to $2 \times 10^{19}$ m$^{-3}$. The large oscillations with a frequency about 180 Hz in the signal of $\phi_{P3}$, $T_e$ and $n_e$ are induced by a global event in the high iota configuration of OP1.2a. For all the three configurations, their APSDs of floating potential are raised to a much higher level when the connection length increases. In EJM+252 configuration, there is a broadband spectrum in the frequency range of about 40-200 kHz at the radial region of $R = 6.063 - 6.075$ m, but this broadband becomes weak or even disappears at the center of island along the path of probe (i.e., $6.068 \text{ m} < R < 6.071$ m).
When entering the radial region of $R < 6.06 \text{ m}$, the turbulence is dominated by the low frequency fluctuations mainly below 30 kHz. Near the LCFS ($R < 6.038 \text{ m}$), the high frequency part of fluctuations become much larger but still smaller than the low frequency part. The KJM+252 configuration also presents similar APSD radial evolution as the standard configuration, with the island center on the probe path changing to $R = 6.052 \text{ m}$ and the broadband spectrum becoming weak around this region. But the innermost point of the probe still has a 2 cm distance away from the LCFS, the significant raise of the high frequency fluctuations near the LCFS is not seen in Figure 4 (f). In FTM+252 configuration, the APSD increases quickly with decreasing $d_{R_{sep}} = R - R_{sep}$, and the global oscillations appear in the frequency spectrum as some horizontal bands. It should be pointed out that in these three discharges a very large positive floating potential (several hundred volt) has been observed in the island divertor topology, indicating a strong imbalance of ions and electrons in the upstream plasmas. The detailed analysis about the positive potential is in progress and will be reported later.

![Figure 4](image)

**Figure 4.** The plasma profiles measured by the new combined probe. (a-c) Floating potential, electron temperature, electron density; (d) Connection length; (e-g) The auto-correlation spectrum power density of $\phi_{f3}$ for the three configurations. The shaded region in (b) and (c) denotes the standard deviation of the measurements.

### 4. TURBULENCE TRANSPORT

The radial transport in the plasma edge is usually driven by turbulence, and the SOL radial heat and particle transport in OP1.2a will be presented in this section. The radial particle flux and heat flux can be derived from the four-tip triple probe, pin 1-4, as shown in Figure 1. The particle flux and heat flux driven by turbulence is calculated by the following formulas:

\[
\Gamma_e = \langle \tilde{\bar{\eta_e}} \tilde{\bar{p}} \rangle = \frac{\langle \tilde{\bar{\eta_e} \tilde{\bar{E}_\phi}} \rangle}{B_\psi} \tag{1}
\]

\[
Q_e = \frac{3}{2} \langle \tilde{\bar{\bar{P}}_r \tilde{\bar{E}_\phi}} \rangle = \frac{3\langle T_r \tilde{\bar{\eta_e} \tilde{\bar{E}_\phi}} \rangle}{2B_\psi} + \frac{3n_e \langle \tilde{\bar{\eta_e} \tilde{\bar{E}_\phi}} \rangle}{2B_\psi} \tag{2}
\]

Where the tilde on the top denotes the fluctuation of the signal, the angle bracket denotes the ensemble average, and $B_\psi$ is the toroidal magnetic field, $E_\phi = (\phi_{f2} - \phi_{f1})/d$. In addition, the heat and particle fluxes in the frequency space can be obtained by the cross-correlation power between two parameters, as shown in the following formulas:

\[
\Gamma_e = \frac{2\langle |\tilde{\bar{\eta_e} \tilde{\bar{E}_\phi}(f)}| \cos \phi \tilde{\bar{\eta_e} \tilde{\bar{E}_\phi}}(f) \rangle}{B_\psi} \tag{3}
\]

\[
Q_e(f) = \frac{3}{2} T_r \Gamma_e(f) + \frac{3n_e \langle |\tilde{\bar{\eta_e} \tilde{\bar{E}_\phi}(f)}| \cos \phi \tilde{\bar{\eta_e} \tilde{\bar{E}_\phi}}(f) \rangle}{B_\psi} \tag{4}
\]
A typical radial particle flux driven by turbulence is illustrated in Figure 5. A comparison of the radial turbulent particle flux calculated by equation (1) and (3) are shown in Figure 5 (e) and (f), with the blue solid line from equation (1) and the red dashed line denoting the integral of \( \int \Gamma_r(f, t)df \). Both turbulent particle flux exhibits very consistent evolution with each other. The electron pressure is displayed in Figure 5 (d), which has an extremely flat profile in the radial region of \( R = 6.066 - 6.07 \text{ m} \), as marked in the pink rectangle. The floating potential Figure 5 (a) is shaped as a negative valley in this region, which indicates that the ratio of the positive charges (ions) and the negative charges (electrons) is around 1/1, i.e., the plasma is almost quasi-neutrality. Besides, both \( T_e \) and \( n_e \) have slow variation, and the parallel Mach number is \( \sim 0 \) within this radial region. The radial electric field, derived from \( E_r = -d(V_f + 2.87T_e)/dR \), continues to decrease with deceasing \( R \) within the pink rectangle. The particle flux calculated by equation (1) is shown as the blue solid line in Figure 5 (f). In the whole SOL region, the particle flux driven by turbulence is directed outward, and exhibits a minimum value in the pink rectangle region, i.e., the turbulence transport is mitigated in this region. Figure 5 (e) shows the distribution of turbulent particle flux in the frequency space which is derived from equation (3). In accordance with Figure 5 (f), the particle flux from almost the whole frequency region is reduced to a relatively low level. On both sides of this region, \( \Gamma_r \) increases significantly and two peaks appear at \( R = 6.063 \text{ m} \) and \( R = 6.071 \text{ m} \). In the region of the two peaks, the turbulent particle flux is as large as \( 10^{21} \text{ m}^{-2} \text{s}^{-1} \), and is dominated by the broadband turbulence within the frequency range of 40-120 kHz. Noted that this particle flux can be up to several \( 10^{22} \text{ m}^{-2} \text{s}^{-1} \) in high heating power and plasma density discharges. Within the radial region of \( R = 6.045 - 6.057 \text{ m} \), \( \Gamma_r \) drops to \( \sim 0.3 \times 10^{21} \text{ m}^{-2} \text{s}^{-1} \). When \( R < 6.045 \text{ m} \), the base line of \( \Gamma_r \) increases gradually with decreasing \( R \). There are some spikes on the profile of particle flux in this region, which is contributed by the low frequency fluctuations with central frequency about 15 kHz. A significant change can be found near \( R = 6.06 \text{ m} \), i.e., the dominant frequency for radial transport switches from the broadband spectrum (40-120 kHz) to low frequency turbulence. As shown in Figure 4, the island centre along the probe path is about \( R = 6.069 \text{ m} \), which is roughly located in the pink rectangle in Figure 5. Inside the island center along the probe path, the radial transport is mitigated to a relatively low level. Meanwhile, there is a flat pressure profile and negative shear of electric field \( \partial E_r/\partial R \), which could contribute to suppress the turbulence intensity [20]. It is obvious that a steep density gradient exists in the radial region of \( 6.059 \leq R \leq 6.065 \text{ m} \), where the large particle flux induced by the broadband spectrum (40-120 kHz) is also located in this region, indicating that the turbulence transport in this region could be driven by drift wave turbulence.

Figure 5. The turbulent radial transport particle flux and profiles measured by the new combined probe. (a-d) floating potential, electron temperature, electron density and electron pressure. (e) the distribution of the turbulent radial particle flux
in frequency space. The pink rectangle signifies a region with flat electron pressure and low radial heat flux. Positive value means the particle flux is directed outward. (f) The radial particle flux. (g) Parallel Mach number. (h) Radial electric field.

5. SUMMARY

A new combined probe designed to measure the edge plasma profiles and turbulence structures has been developed and used in OP1.2a on W7-X. The plasma parameters in three magnetic configurations (KJM, EJM, FTM) are measured by the new combined probe head, and the plasma parameters across the magnetic island are in good agreement with the magnetic island structure calculated by the field line tracer. In configuration of EJM+252, the floating potential has a negative value around the island center along the path of probe. Within this region, the electron pressure reveals a platform, and the parallel Mach number exhibits a symmetric profile, and the radial particle flux driven by turbulence reduces to a relatively low level. However, outside this region the particle flux is extremely high on both sides. The high particle flux is dominated by the broadband turbulence between 40 to 120 kHz, while the inner radial region with low particle flux is driven by the turbulence below 25 kHz. It should be noticed that the high turbulent particle flux is located in the region with large gradient of electron density, indicating that the transport could be driven by the instability caused by the density gradient.

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