Investigation of turbulence rotation in limiter plasmas at W7-X with newly installed poloidal correlation reflectometer

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Abstract
For the first operation phase of the optimized stellarator W7-X, a heterodyne poloidal correlation reflectometry diagnostic is installed and put into operation. The system is intended to measure the perpendicular (with respect to the magnetic field) turbulence rotation and turbulence properties, such as the decorrelation time and correlation length at the plasma edge. Furthermore, it can give information on the magnetic field \( \ell / i \) turbulence rotation and to measure the perpendicular (with respect to the magnetic field \( \ell / i \)) correlation re

The obtained data cover various experimental programs and are partly presented in the paper.

Keywords: microwave diagnostic, plasma rotation, radial electric field, stellarator

(Some figures may appear in colour only in the online journal)

1. Introduction

For many questions on transport in fusion plasmas, knowledge of the plasma velocity \( v_\perp \) perpendicular to the magnetic field \( B \) and within a flux surface is of outstanding importance. From the velocity profile along the radius, regions of strong velocity shear can be detected. Furthermore, velocity oscillations on the plasma edge yield information on zonal flows and geodesic acoustic modes. Both phenomena are believed to interact with small-scale turbulence and hamper radial transport. An overview on both phenomena and related experiments can be found in [1]. In addition, these phenomena play an important role in the transition from low-confinement to high-confinement (L–H) regimes. A lot of studies on the transitional phase have already been conducted to understand the impact of the velocity shear on turbulence and the role of mesoscale structures [2] in the transition from the L-mode to the H-mode in stellarators [3]. These studies are based on knowledge of the mean perpendicular velocity and its fluctuations.

Under the assumption that the turbulence velocity measured by the poloidal correlation reflectometry (PCR) system has a negligible phase velocity with respect to the plasma rotation, the perpendicular velocity \( v_\perp \) and the radial electric field \( E_r \) as well as their temporal fluctuations are obtainable. These quantities are of high importance for validating theoretical
models on neoclassical transport in plasmas. But studies of the turbulent structure itself are also of interest. With information on turbulent structures in the frequency domain and their dependence on global plasma parameters, the measured turbulent structures can be attributed to certain plasma instabilities, such as ion temperature gradients (ITGs) or trapped electron modes. These issues will be addressed in the next campaign at W7-X. Here, the installed PCR system yields information on the spectral properties of turbulent structures as well as on fluctuating quantities.

The paper discusses the design of a PCR diagnostic on W7-X and its commissioning in section 2. After a short introduction on the applied methodology to calculate \( v_\perp \) in section 3, an overview of the first \( v_\perp \) and \( E_r \) measurements is given in section 4. The main achievements are summarized in section 5.

2. Design issues of the PCR system at W7-X

The PCR system at W7-X is thought to be operated at the interface between plasma core and plasma edge physics [4]. It is installed on the highly elongated bean-shaped plane at \( \phi = 72^\circ \) (AEA21 port). This port hosts a Doppler reflectometer and the PCR system. The PCR system is located slightly below the equatorial plane. The coordinates of the flange centre are \( R = 8.102 \) m, \( \phi = 71.09^\circ \) and \( z = -0.16 \) m. The system is mounted from the outside and constructed in such a way that the whole plug can be installed from DN 150CF. The flange hosts five microwave feed-throughs, followed by a 1.5 m long fundamental \( K_\perp \)-band waveguide connected to the antennas (see figure 1). The antennas labelled with the letters B, C, D, and E are the receiving horns, and the middle antenna in the first row is the launching horn (A). All five horns aim at the same focal point at \( R = 6.0 \) m, \( \phi = 71.05^\circ \) and \( z = -0.104 \) m. Each horn has a length of \( l = 61 \) mm and the antenna opening is \( 44.1 \times 34.8 \) mm. The antenna pattern has a 3 dB width of 14° on the H-plane. The whole antenna array is aiming upwards and has a certain angle with respect to the normal vector of the flux surface. The flux surface geometry is obtained from VMEC equilibrium calculations. In the case of geometrical optics, neglecting diffraction and variations in the refraction index, the condition for reflection of each launcher–receiver combination is calculated on a fine grid centred around the intersection point of the line of sight (LoS) from the launcher with each flux surface. Due to the broad antenna pattern the grid size is \( 120 \times 0.6 \) rad in the \( z \) and \( \phi \) directions. The incident beam from the launcher to each grid point is calculated and mirrored with respect to the normal vector of the flux surface at that point (the condition of reflection). The angle (\( \gamma \)) between the constructed reflected beam and the connecting line from this grid point to each receiver is calculated. In the case of \( \gamma = 0^\circ \) the reflected beam and the line between the receiver and the grid point are parallel and the grid point is taken as the point of reflection (see figure 2 for the case of antenna AB). This condition defines the geometrical point of reflection for every launcher–receiver combination. Note the position fulfilling the reflection condition does not necessarily coincide with the LoS of the antenna, due to the tilted flux surface. In all cases the reflection point is found at slightly larger toroidal positions and slightly above the LoS of the antenna combination. Therefore, a broad radiation pattern of the antenna is necessary. A cross-check with

![Figure 1. Plugin of the PCR diagnostic with the notation (capital letters) of the horns.](image1)

![Figure 2. Colour-coded angle between the reflected beam and LoS of the receiver for all grid points. The point of reflection is marked by a white circle. The intersection of the launcher (×) and the receiver (+) with the flux surface is also shown.](image2)
the ray-tracing code TRAVIS [5] yields similar results for the investigated discharges.

The reflectometer itself consists of two programmable microwave wave synthesizers coupled with a PLL. After passing a frequency multiplier (×2), the frequencies of the two synthesizers are off by 60 MHz, which is the intermediate frequency of the system. The system operates in O-mode polarization, which allows one to cover local densities ranging from 0.6 × 10^{19} \text{ m}^{-3} to 2.0 × 10^{19} \text{ m}^{-3}. Phase fluctuations from the reflection layer of each receiving antenna are measured by a quadrature detector and sampled at 4 MHz.

3. Methodology

After the frequency range of interest is determined from cross-phase and/or coherence spectra and the raw data are adequately filtered, the cross-correlation function (CCF) for all six receiver combinations is calculated. The maximum of the cross-correlation is determined to be

\[ \Delta t = \arg \max_t (|Y_i \ast Y_j|(t)) \]  

where \( Y_i, Y_j \) denote the time series of fluctuations from receivers \( i \) and \( j \). The delay time (\( \Delta t \)) is the time it takes for a structure to propagate across the flux surface on the reflection layer from one receiver to another. In figure 3 the CCF is shown for all six combinations. With increasing delay time, \( \Delta t \), the cross-correlation decreases as expected. Two facets are of interest: (i) the difference in \( \Delta t \) for combinations with equal distance—e.g. BD, EC in figure 1—and (ii) the exponential decay of the maximum of the cross-correlation as a function of \( \Delta t \). The latter allows one to estimate the decorrelation time (\( \tau_{dk} \)) of the structure from the exponential decay of the CCF with increasing distance (the dashed line in figure 3), where the decorrelation time is defined as half the width at the 1/e level of the exponential decay.

In figure 4 \( \Delta z \) distances are shown for all combinations as a function of \( r_{\text{eff}} = \theta_{\text{LCFS}} / \sqrt{2} \), where \( \theta_{\text{LCFS}} = 0.49 \text{ m} \) and \( \psi \) is the toroidal flux enclosed by the surface normalized by its value in the last closed-flux surface. The different \( \Delta t \) and its associated cross-correlation coefficient for equal distances along the \( z \)-axis (\( \Delta z \)) but different signs in the toroidal distance (\( \Delta \phi \)) result from the inclination of the magnetic field lines in front of the antenna and allow one to estimate the magnetic field line pitch angle [6, 7], as shown below for any two-antenna combination \( i, j \in \{\text{BD, BE, BC, DE, DC, EC}\} \):

\[ \tan(\alpha_i) = \frac{\Delta t_i \cdot \Delta z_j - \Delta t_j \cdot \Delta z_i}{\Delta t_i \cdot \Delta \phi_i + \Delta t_j \cdot \Delta \phi_j}, \]  

where \( \Delta \phi_t, \Delta z_t \) denote the toroidal distance and the separation in the \( z \) direction for a given antenna combination. The propagation velocity of the turbulence perpendicular to the magnetic field can be calculated when \( \Delta \phi \) and \( \Delta z \) are projected along the propagation direction:

\[ \Delta v_t = R \cdot \Delta \phi_i \cdot \tan(\alpha) \cdot \cos(\alpha). \]  

The distances \( \Delta s_i \) for all receiver combinations are obtained from the point of reflection of all launcher–receiver combinations. With regression analysis the propagation velocity of the turbulence can be expressed as

\[ v_{\text{turb}} = \frac{\sum \Delta s_i \Delta t_i - N \cdot \overline{\Delta s} \cdot \overline{\Delta t}}{\sum \Delta s_i^2 - N \cdot \overline{\Delta s}^2}. \]  

where \( \overline{\Delta s}, \overline{\Delta t} \) are the mean values. Because information on the relation between the turbulence velocity and \( E \times B \) velocity is missing, the turbulence and \( E \times B \) velocities are assumed to be equal \( v_{\text{turb}} = v_{\perp} \approx v_{E\times B} \). This is justified because in the case of mainly ITG turbulence the phase velocity is low compared to the \( E \times B \) velocity and can be neglected. The effect of turbulence on \( \Delta t \) estimation for the mean velocity is also small (≈100%) and is neglected here. With these assumptions estimation of the local radial electric field of the plasma yields
\[ E_i(r_e) = v_\perp(r_e) \cdot B(r_e). \] (5)

4. First velocity measurements

The system was operated during the whole OP1.1 campaign. In December 2015 and January 2016 the duration of the plasma discharge was short and was used for the commissioning of the diagnostic. However, in February and March the discharge duration improved considerably and first systematic studies became possible. First, the direction of the rotation is investigated. When viewed from the outboard low-field side and with respect to the antenna array, the plasma rotates from bottom to top, counterclockwise, within the last closed-flux surface. The propagation is in the electron diamagnetic direction. In the following the rotation profiles for different plasma scenarios are described. Unless otherwise mentioned, the raw data of each receiver are filtered in the range 5 kHz \( \leq f \leq 350 \) kHz for the calculation of the velocity. More than 90% of the amplitude spectral power is located in this range.

4.1. Velocity profile measurements

A series of ten plasma discharges each with a total heating power of \( P_{\text{ECRH}} = 3.3 \) MW for a duration of \( t = 450 \) ms is investigated. The frequency of the reflectometer is varied on a shot-to-shot basis. The line-averaged density from interferometric measurements (see figure 5(a)) is similar for all plasmas. In OP1.1 there is no density control available; therefore, the density is slightly rising, reaching, at the end of the ECRH pulse, \( n_e = 2.5 \times 10^{19} \) m\(^{-2}\). Therefore, the reflection layer moves during the discharge towards the plasma edge as the frequency of the reflectometer is kept constant. With the density profile data from Thomson scattering [8], the position of the reflection layer is determined. The profile itself is approximated by \( n_e(r) = n_0 \cdot (1 - (r/a)^2)^\theta \), where \( n_0 \) denotes the central plasma density. The calculated \( v_\perp \) is shown in figure 5(b). The rotation profile is flat and increases slightly towards the plasma centre. At the plasma edge (the last closed-flux surface) a transition towards positive \( v_\perp \) is observed. The related \( E_r \) (see figure 5(c)) yields values in the range of \(-12 \text{ kV m}^{-1}\) to \(-17 \text{ kV m}^{-1}\) and due to the transition to positive \( v_\perp \) at \( r_{\text{eff}} \approx 0.4 \) m a transition to positive \( E_r \) is observed. The overlap between regions of positive and negative \( v_\perp \) and \( E_r \) is mainly attributed to the changes in the density profile at the plasma edge.

A well-documented transition from negative to positive \( v_\perp \) is observed in 20160308.8, where the reflectometer hops with steps of 2 GHz. The contour lines of the density profile are shown in figure 6(a) together with a dashed line, which denotes the reflection radius of the reflectometer. The numbers denote
the time stamps of the measurement. From (1) to (2) the frequency jumps from 40 GHz to 22 GHz, corresponding to a step in $r_{\text{eff}}$ from 0.40 m to 0.49 m, thereby crossing the position of the last closed-flux surface ($r_{\text{LCFS}}$) and as a consequence $\vec{v}_\perp$ becomes positive at (2) (figure 6(b)). The rotation direction changes from the electron diamagnetic direction to the ion diamagnetic direction. Measurements (2) and (3) are outside $r_{\text{LCFS}}$. From (3) to (4) ($0.47 \text{ m to } 0.46 \text{ m}$) $r_{\text{LCFS}}$ is crossed once more and the plasma rotates in the electron diamagnetic direction again (5). In the narrow-transition region strong shear decreases the turbulence decorrelation time and a measurement of $\vec{v}_\perp$ from all combinations is no longer possible. From (3) and (4) the transition is estimated to happen at $r_{\text{LCFS}} = 0.466 \text{ m}$, which is close to the $r_{\text{LCFS}} = 0.49 \text{ m}$ calculated from the VMEC configuration. The deviation in the position of $r_{\text{LCFS}}$ could be partly due to a decrease in the resolution of the Thomson scattering diagnostic on the plasma edge. An increase in local plasma density at the edge in the order of 50% could explain the deviation. The transition itself happens in a narrow region $\Delta r_{\text{eff}} \lesssim 0.02 \text{ m}$. However, the performed frequency scan has a step width of 2 GHz but the instrumental properties allow only frequency steps in the order of 100 MHz and less, which could have further decreased the uncertainty in the exp. estimation of $r_{\text{LCFS}}$. The achieved results show that the PCR system can be a useful tool in the estimation of $r_{\text{LCFS}}$.

At the plasma edge around the last closed-flux surface the estimated $v_\perp$ and $E_r$ can be compared with those of a fast manipulator [9]. However, even if in the performed experiments no radial overlay between both diagnostics is achieved, both systems measure a positive $E_r$ outside $r_{\text{LCFS}}$.

4.2. Rotation in CERC plasmas

One of the main tasks within OP1.1 with its restricted set of diagnostics was the search for a core electron root confinement (CERC) regime at W7-X. This regime is characterized by peak electron temperature profiles and a strong positive radial electric field in the plasma centre [10]. For plasmas with low electron density the PCR system is capable of measuring deep in the plasma and should find evidence for a transition into the CERC regime. The analysed CERC discharges [11] exhibit certain densities and heating power scenarios. A contour plot of the electron density, which is typically observed of CERC plasmas, together with the heating timeline is shown in figure 7. The ECRH power varies from 1.9 MW ($0 \text{ s } \leq t \leq 0.4 \text{ s}$) to 0.6 MW ($0.4 \text{ s } \leq t \leq 0.7 \text{ s}$) and back to 1.3 MW for $0.7 \text{ s } \leq t \leq 1.0 \text{ s}$. The PCR system is operated in frequency scanning and fixed frequency modes. For all CERC plasmas from March 9, the reflectometer has been operated inside the last closed-flux surface and $v_\perp$ and $E_r$ are calculated, as shown in figures 8(a) and (b). For these plasmas the
configuration and $\iota$ profile are changed on a shot-to-shot basis. Weak evidence for a minor change in $v_L$ of $\lesssim 10\%$ is found after comparing the maximum and minimum $\iota$ configurations. According to neoclassical analysis, a positive $E_i$ is expected only in the core region ($r_{\text{eff}} \lesssim 0.2$ m) of the analysed discharge. A reliable analysis of PCR data in these plasmas accesses an $r_{\text{eff}} \gtrsim 0.25$ m. Deeper in the plasma the density profile becomes flat and the density scale length increases. Therefore, the radial resolution of the PCR decreases and the density scale length increases. Therefore, the reflection layer moves deeper into the plasma. This will be discussed in the following section.

### 4.3. Influence of position and power on $v_L$

For the CERC discharges discussed above, evaluation of $v_L$ is made for the frequency range around the carrier frequency of the system of $\pm 350$ kHz. Applying this filter to the raw data for combinations of $P_{\text{ECRH}} \gtrsim 600$ kW and $r_{\text{eff}} \lesssim 0.25$ m yields large error bars in the $\Delta \varphi$ values, which lead to large uncertainties in the analysis of $v_L$ and $E_r$. As an example, the plasma discharge 20160909.24 is analysed in detail. The reflection layer for the critical density at the probing frequency of 32 GHz is located in the plasma for the whole duration of the discharge. During ECRH the reflection layer (red dashed line in figure 7) varies between 0.39 m and 0.24 m. For two time intervals at $r_{\text{eff}} = 0.24$ m and marked by the vertical dashed boxes labelled I and 2 in figure 7, the cross-phase ($\Phi$) spectra for the antenna combination DE are analysed in detail (see figures 9(a) and (b)). Just before the jump in $P_{\text{ECRH}}$ from 0.6 MW to 1.3 MW, $\Phi$ is characterized by a single negative slope (red dashed line figure 9(a)). The slope in $\Phi$ corresponds well to the broad peak in the coherence ($\Gamma$) spectrum, as indicated by the vertical dashed lines in figure 9(c). As a consequence, turbulent structures propagate with one velocity across the flux surface and are monitored by the antenna. In the succeeding time window a drastic change in $\Phi$ and $\Gamma$ is observed (see figures 9(b) and (d)). The central peak in $\Gamma$ shrinks in width. The $\Phi$ spectrum is now characterized by three slopes. For $-80$ kHz $\leq f \leq 80$ kHz a negative slope for $\Phi$ is obtained. A positive slope in $\Phi$ is observed for $80$ kHz $\leq f \leq 190$ kHz and $-190$ kHz $\leq f \leq -80$ kHz. The negative slope in the cross-phase spectrum corresponds to the central peak in the coherence spectrum (vertical dashed lines in figures 9(b) and (d)), representing the propagation of the plasma column, and the positive slopes correspond to an additional broad peak in the coherence spectrum at $f \approx 160$ kHz, representing another propagating turbulent structure.

The origin of the observed high-frequency structure is still not clear. Two possible explanations are discussed here. The first one is that it originates from Alfvén waves, which in general are detectable by reflectometry [12]. In this case the Alfvén velocity is given as $v_A = B_l \sqrt{\mu_0 n_i m_i}$, where $n_i \cdot m_i$ denotes the ion mass density. The corresponding frequency $f_A \approx 240$ kHz is $\gtrsim 80$ kHz higher than the measured frequency. To further support the Alfvén hypothesis the density scaling of $v_A$ is investigated. The expected decrease of $v_A$ with increasing density is not observed. The absence of any mechanism generating fast energetic ions (NBI, ICRH), the missing scaling with the density and the observed increase of the slope with increasing distance in the cross-phase spectra make the interpretation of the structure as Alfvén modes doubtful.

The second interpretation assumes a reflection at the cut-off layer and takes the slope of the cross-phase as a measure for the turbulence propagation. The measured slopes correspond directly to the velocity according to
larger errors in the case of the narrow filter band are due to larger errors in $\Delta t$ estimation.

$$v_{\text{turb}}(f) = \frac{2\pi \cdot \Delta s}{\partial \Phi / \partial f},$$

where $\Delta s$ denotes the distance between the antennas. The absolute values of the slopes in figure 9(a) and those of the high-frequency structure in figure 9(b) are similar, yielding a similar propagation velocity. The central slope in figure 9(b) is smaller and therefore indicates a higher velocity.

The observation is mainly triggered by the applied heating power. It is interesting to note that the occurrence of the high-frequency mode seems to be related to the ECRH power. The appearance of more than one slope in the cross-phase spectrum is in hopping operation, 150 kHz to separate the two effects. The result is shown in figure 9.

The small difference between the $r_{\text{eff}}$ values calculated from the high-frequency structure and the data set for $r_{\text{eff}} > 0.25$ m is related to the transition from the electron root to the ion root. The coherence above 100kHz drops rapidly, which explains the increased scatter in the cross-phase spectrum and ultimately results in a larger uncertainty of the $\Delta t$ values. For $r_{\text{eff}} < 0.25$ m the restriction to the high-frequency filter yields a $\Delta t$ for the high-frequency structure with small error bars.

A crucial test for the estimation of $E_r$ is comparison with neoclassical calculations. For the discharge 20160310.34 drift kinetic equation solver (DKES) [13] calculations are compared with the $E_r$ measurements from reflectometry. The calculations are based on the experimental profiles and their error bars. Since the ion temperature profile is missing, the error bar is mostly due to the assumptions in $T_i$. The input profiles are available on a 100 ms timescale. The calculations yield the flux surface averaged $E_r$ at $t = 1$ s. For comparison the experimental local $E_r$ is estimated on the flux surface average according to $E_r = E_r / \nabla r_{\text{eff}}$. The reflectometry data are analysed for $0.82 < t < 1.0$ s and averaged for each frequency step of $t_{\text{ms}} = 20$ ms. As can be seen in figure 11, the measurements and neoclassical calculations are in reasonable agreement. Also, the radial positions of the crossover from electron-root to ion-root $E_r$ coincide. This demonstrates further experimental evidence that the high-frequency structure is related to the transition from the electron root to the ion root. The small difference between the reflectometry data set for 5 kHz $f < 350$ kHz and the data set for 150 kHz $f < 350$ kHz could have resulted from the different phase velocity of the turbulence. For $r_{\text{eff}} < 0.25$ m the absolute $E_r$ is also in reasonable agreement with the measurements of an x-ray imaging crystal spectrometer [14].

5. Summary and outlook

A poloidal heterodyne correlation reflectometer is successfully installed and commissioned at W7-X. The system is capable of measuring turbulence velocities and turbulence
properties across a wide radial range in frequency hopping operation. Measurements of the turbulence velocity even outside the last closed-flux surface are possible. Turbulence velocities have been measured for nearly all plasmas in OP1.1. The measured velocities are in the range of $-7$ to $-4$ km s$^{-1}$. Neglecting any additional phase velocity, the turbulence velocity is equal to the $E \times B$ velocity and the radial electric field can be deduced from the diagnostic. At the last closed-flux surface a reversal of the velocity is observed. In the plasma centre, high-frequency structures are observed in a frequency range just below the Alfvén frequency but no indication of highly energetic ions can be found. Because evidence is found for a cut-off position, the propagation of the high-frequency structures on the flux surface is calculated. The velocity is in the ion diamagnetic drift direction. For low frequencies a negative velocity is calculated. The high-frequency structures dominate the coherence spectrum when the applied heating power is increased and/or the reflection radius is decreased. The underlying mechanism generating these high-frequency structures is not yet identified and is outside the scope of this paper. There may be a connection to the CERC regime, which expects a crossover from negative to positive velocity, and to the radial electric field in the plasma centre. With regard to the radial position of the crossover, DKES calculations of $E_r$ and the experimentally estimated $E_i$ from the high-frequency structures are in agreement.

For the next campaign the system will be upgraded with a second microwave synthesizer operating in the same range of frequencies to measure radial correlations as well.

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References