Investigation of higher harmonics of electron cyclotron emission using Fourier transform spectroscopy in Wendelstein 7-X

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ABSTRACT: Wendelstein 7-X stellarator has a high aspect ratio which makes the electron cyclotron harmonics spectrally well separated and more straightforward to interpret compared to a tokamak with a low aspect ratio. For fusion reactor relevant plasma operations, Wendelstein 7-X is planned to operate at high plasma densities. For these plasma conditions, the classical electron cyclotron emission fails as a diagnostic tool for electron temperature because optically thick O1 and X2 mode are in cut-off. In this paper, we report on the radiation temperatures of X-mode electron cyclotron emission measured with Fourier transform spectrometer from the high-density plasmas. The radiation temperatures of X2 and X3 mode are compared to electron temperature measured with Thomson scattering diagnostic. This comparison suggests that X3-mode can be used as a diagnostic tool to provide electron temperature for high-density plasmas beyond the cut-off of X2-mode.

KEYWORDS: Plasma diagnostics - interferometry, spectroscopy and imaging; Interferometry; Attenuators, Filters; Data analysis

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1 Introduction

In Wendelstein 7-X (W7-X) [1], for a magnetic field of 2.5 T, the classical electron cyclotron emission (ECE) [2–5] radiometer diagnostic scans the optically thick X2-mode covering the spectral range of 120-160 GHz along a line of sight in the plasma vessel where the applied magnetic field is increasing. Because of this, the cyclotron frequency of the emission line is mapped to a spatial location in the plasma, and the electron temperature profile can be inferred from ECE. The main focus of this work is the broadband ECE diagnostic which is a Fourier transform spectrometer [6] covering a spectral range of 50-500 GHz. The diagnostic is subjected to investigate the optical depth of higher harmonics as a step towards their diagnostic potential for electron temperature measurement in high-density plasmas beyond the cut-off of X2-mode. Fourier transform spectroscopy (FTS) is being used at Joint European Torus (JET) [7–9] to measure electron temperature and will also be used for the same purpose at the International Thermonuclear Experimental Reactor (ITER) [10].

W7-X has a high aspect ratio of ≈ 10, resulting in a moderate magnetic field gradient along the ECE line of sight [11]. Because of this geometry, the different ECE harmonics are spectrally well-resolved and this advantage is one of the motivations for this work. However, it is not the
case for magnetic confinement devices with low aspect ratios such as ASDEX Upgrade or JET tokamak. For these devices, the high field side (HFS) of optically thick X2-mode overlaps with the low field side (LFS) of X3-mode [12], which makes the inference of electron temperature profiles nontrivial. Stellarators can operate at high plasma density because of the absence of a current related Greenwald density limit [13]. For improved plasma confinement, W7-X is planned to work at high plasma densities up-to $2.0 \times 10^{20} \text{ m}^{-3}$ with the detached divertor operation [1]. The optically thick X2-mode has a cut-off, which for the magnetic field on plasma axis ($2.5 \text{T}$) occurs above a plasma density of $1.2 \times 10^{20} \text{ m}^{-3}$ and there is no direct access to electron temperature profiles from the classical ECE diagnostic. High-densities, exceeding the X2-mode cut-off, have been demonstrated in W7-X with plasmas heated by the O2 electron cyclotron resonance heating (ECRH) [14] and neutral beam injection (NBI). The emission from other electron cyclotron harmonics, X3, O2, O3 covering a broad spectral range of 50-500 GHz, is present at high-density operation. A Martin Puplett interferometer (MPI) [6, 15] was used with an Indium Antimonide detector cooled to liquid He temperatures to scan the broadband ECE harmonics. During the W7-X operational campaign OP1, plasmas were heated by electron cyclotron resonance at a frequency of 140 GHz with a maximum input power of 7 MW or with NBI with a maximum input power of 3.5 MW. ECE measurements are affected by the stray radiation [16] from non-absorbed microwave launched at 140 GHz which lies in the spectral range of 2$^{nd}$ harmonic. It is necessary to filter the stray radiation frequency for a clean measurement of the broadband ECE spectral features. A multi-mode notch filter [17] based on a multiple dielectric disk structure [18] was designed and used to attenuate the stray radiation.

The paper investigates radiation temperatures of X-mode ECE harmonics. Section 2 describes the diagnostic setup in depth, including the transmission from the plasma vessel, the polarization separation of ECE modes and the stray radiation notch filter design. Section 3 explains the analytical tools used to extract the Fourier transform of the measured interferograms and the calibration of the diagnostic using a black-body source. Section 4 presents the radiation temperatures of ECE harmonics measured during the plasma experiments.

2 Diagnostic description

Figure 1 shows the schematic of the diagnostic. Starting from the bean-shaped magnetic flux surfaces in the plasma vessel of W7-X, the ECE beam from the line of sight is focused with Gaussian optics consisting of four mirrors and a horn antenna, optimized for broadband application, collecting the radiation. The beam focusing is crucial for the precise collection of the emission from the core of the plasma, avoiding unwanted radiation entering the transmission line. The focused beam is relayed in two transmission lines, including many microwave components, such as miter bends, polarization tuners, etc., to adapt to the input of interferometer and radiometer. The torus hall of W7-X is closed during the operational phase, and the plasma vessel cannot be accessed. This lead to the development of a separate calibration unit, replicating the original Gaussian optics, antenna, and transmission lines, as shown in figure 1. Successful calibration using this setup was demonstrated with radiometer [19] and the interferometer was also calibrated with this unit. The following sections include a detailed description of the line of sight properties, mode separation, interferometer design, and the signal processing of the measurement.
Figure 1. The overall diagnostic setup of Martin-Puplett Interferometer at W7-X is shown starting from left hand side with the bean shaped magnetic configuration of plasma indicating the ECE line of sight. A low field side Gaussian optics consisting of four mirrors is used to focus the radiation from the plasma to the diagnostic and a wire-grid beam splitter separates the X and O mode polarization of the ECE. These modes then propagate through transmission line and are finally focused on stray radiation multi-mode notch filter by a spherical mirror before entering the interferometer. An In-Sb bolometer type detector is used to detect the interferograms from the ECE.

2.1 ECE line of sight

A number of selection criteria for sight-line have to be fulfilled to achieve clear signals of ECE. The first criterion is that along the sight-line magnetic field should increase monotonically to gain localized information from ECE. In a stellarator, the magnetic field can vary non-monotonically along a given sight-line, but there are tokamak like sight-lines available, which have a monotonically varying magnetic field. In W7-X, the vertically elongated bean-shaped plane, as shown in figure 1, and its surroundings are used for this purpose. The relevant parameter diagnosed by ECE measurements is the core electron temperature profile, and as a consequence, the sight-line should be able to access the plasma center. The plasma heating with electron cyclotron resonance gives rise to stray radiation [16] because a fraction of the heating power is not absorbed by the plasma. Hence another criterion requires that sight-line should be away from the ECRH ports to minimize the effect of stray radiation. As a result, the emission from the central frequencies are not hampered by stray radiation. The Doppler and relativistic effects are the main mechanisms responsible for the line broadening of ECE. The Doppler broadening can be reduced significantly by the selection of a sight-line, which is perpendicular to the applied magnetic field and ideally also to magnetic flux surfaces.

In W7-X, a sight-line [11] fulfilling the aforementioned criteria was chosen. In W7-X, due to its helical axis, the magnetic field in the center varies toroidally and hence its possible to select a sight-line where ECE from the plasma center is not at 140 GHz. Thus ECE from plasma center is shielded from non-absorbed stray radiation at 140 GHz. The applied magnetic field is almost perpendicular with an angle of $\sim 84^\circ$. The magnetic field is monotonically decreasing from the inside to the outside side of plasma vessel. The Gaussian optics and antenna are situated at the LFS of sight-line (in port AEE41 of W7-X). The advantage of focusing the beam with Gaussian optics is the narrow beam waist, resulting in enhanced spatial localization of the ECE and minimizing the
Doppler broadening resulting from a wide angular range. The focused beam passes through a 100 µm thick mica vacuum window with a broad transmission characteristic in the microwave range. An electric break in the transmission line is used for the electrical isolation of the diagnostic from plasma vessel. ECE at this stage consists of both X and O mode, hence it is essential to separate the polarization to access the pure X or O mode.

2.2 X and O mode separation

The focused ECE beam exiting the plasma vessel through Gaussian optics and entering a 4 mm circular wave-guide via a horn antenna which limits the number of modes before transitioning to a broader 28 mm circular wave-guide as shown in figure 1. The window was optimized for the radiometer, however not with respect to the number of modes for the broadband range 50-500 GHz measured by the interferometer. The horn acts as a mode converter from the Gaussian to the TE11 mode defined by the 4 mm circular output. In the focused beam both polarization components, X and O mode, are present. The optimized stellarator, W7-X has a low shear resulting in well-defined separation of X and O mode when radiation leaves the plasma towards the optics. The plane of polarization of the applied magnetic field $\vec{B}$ has a small deviation of $\sim 6^\circ$ from perpendicular direction $\vec{B}$ along ECE sight-line. This was taken care of with a wire-grid [20] that was used as a polarization splitter to match the direction of the applied magnetic field. The X-mode polarization is transmitted through the wire-grid with maximum intensity, while the O-mode polarization is reflected. Two identical circular waveguides with a diameter of 28 mm were used with several miter bends for the propagation of X and O mode to the input of interferometer. The total length of transmission line from the plasma vessel to the diagnostic input is approximately 23.7 m. Intentionally, the separation of modes is done closer to the plasma vessel to reduce the risk of spurious mode conversion along the transmission line. The plasma is heated with electron cyclotron resonance at a frequency of 140 GHz, which lies nearly in the middle of 2\textsuperscript{nd} harmonic ECE. As the non-absorbed incident electron cyclotron power at 140 GHz is very large compared to the ECE, it will saturate the detector signal resulting in the obstruction of the measurement of the ECE harmonics by a reduced or overshadowed response in the interferogram. Therefore, the attenuation of this non-absorbed stray radiation is prerequisite to detect the broadband ECE from the ECRH plasmas. A commercial notch filter is not available with broad transmission characteristics for a range of 50-500 GHz. Hence, a multi-mode notch filter was designed for this specific application with a notch at 140 GHz.

2.3 Multi-mode stray radiation notch filter

The design chosen for a multi-mode stray radiation [17] filter is based on a multi-layer dielectric structure [18, 21]. The theoretical transmission, reflection and absorption of a multi-layer structure was determined by solving the Fresnel’s equations [22], using the transmission-matrix-method and determining the poynting vector for each dielectric plate. The resonance condition for the transmission characteristics of such a structure can be optimized by the variation of the refractive indices and the width of the layers. Here, a dielectric structure made up of multiple layers of $\lambda/2$ thickness with each $\lambda/2$ stack consisting of two $\lambda/4$ layers was considered. The transmission of this structure vanishes at odd multiples of frequency $f$ corresponding to design wavelength $\lambda$. In practice, the filter was constructed with $3\lambda/2$ stacks instead of $\lambda/2$ because of manufacturing
tolerance limitations of the width of each dielectric layer, corresponding to wavelengths in the microwave range (≈ mm). The transmission of multi-layer 3λ/2 stack structure vanishes [17] at odd multiples of the frequency of f/3 such as f/3, f, 5f/3, 7f/3. The spectral width and attenuation depth of the notch at a frequency of f/3 is a function of refractive indices of the dielectric layers and the number of stacks assembled. As a result of theoretical studies of the filter design, the spectral width of the notch is directly proportional to the difference of refractive indices of two dielectric layers in the stack as shown in the following equation [18].

\[
\frac{\Delta f}{f} = \frac{1}{45} \sin^{-1} \left( \frac{n_1 - n_2}{n_1 + n_2} \right)
\]  

(2.1)

Where \( f \) and \( \Delta f \) are the notch frequency and spectral width, \( n_1 \) and \( n_2 \) are the refractive indices of the dielectric layers in the stack. The optical path difference between two reflecting beams from a single dielectric plate is a multiple of the cosine of the angle of refraction inside the plate. Consequently, the increase in the angle of incidence would lead to a decreased optical path difference and hence a higher notch frequency. This advantage of the filter design can be used to fine-tune the filter near the design frequency. The angle of incidence affects the transverse electric and magnetic polarization of incident radiation differently. However the incident radiation at the input of the diagnostic was only transverse electric.

A single stack in the filter is made up of two layers of PTFE and air with refractive indices [23] 1.466 and 1, respectively. The eq. (2.1) shows that a small difference in refractive indices of the layers in a stack leads to a narrow notch width. In total 19 such dielectric stacks of 3λ/2 thickness were used to assemble the final filter.

The transmission characteristic of the filter was tested with a tunable microwave source in a range of 110-170 GHz, as shown in figure 2. The experimental observation shows a notch at 140 GHz. The notch width and attenuation vary with the experimental setup. The characterization done with the filter in between two 28 mm waveguides to couple and detect the power resulted in a notch width of 3 GHz and notch depth of 50 dB. It was observed that experimental notch
width is significantly less compared to theoretical predictions with this experimental setup. The possible reason could be that each PTFE layer in the filter was constructed by compiling three layers of PTFE to achieve a thickness of $3\lambda/4$, because of this construction effect, one introduces more air-gap surfaces for multiple reflections than intended, hence affecting the resonance condition for transmission of filter.

However, when the filter was tested by placing it in front of the interferometer and a bolometer detector, a notch of approximately 10 GHz width and an attenuation depth of 20 dB was observed. The input beam to the filter was focused [24] with a spherical mirror as shown in figure 1 and the output beam was not focused before entering the interferometer. As a result, the notch is wider and less deep. The experimentally measured insertion loss of the notch filter is of the order of approximately 6 dB. As a conclusion, for the use of the filter in the diagnostic setup it is essential to have well-defined optics at both input and output of such a multiple layer dielectric structure.

Interferometer is used for a broad spectral range of 50-500 GHz. For these frequencies, the filter produces four notches at 140, 234, 327 and 420 GHz in the spectrum. The filter was used at an angle of incidence of approximately 20° with respect to normal incidence during the experimental campaign of W7-X to attenuate stray radiation from both X2 and O2 ECRH experiments at a frequency of 140 GHz. It was found that a 20 dB notch depth is sufficient to suppress the stray radiation. However, the notch width at 140 GHz is more than 10 GHz wide and which makes a large fraction of the 2nd harmonic ECE inaccessible for measurements of the ECRH plasmas.

2.4 Martin-Puplett Interferometer

The MPI [6, 25, 26] is a four-port device with two input and two output ports, analyzing the spectrum of the input radiation. Figure 1 shows the interferometer integrated into the transmission lines in W7-X. A wire-grid splits the input radiation of intensity, $I_f$, into two arms with one arm ending at a fixed mirror and the second arm consisting of a mirror moving at an average speed of approximately 1 ms$^{-1}$. The reflected beams from both arms are combined at a beam splitter, interfering with each other at the detector surface. The moving mirror creates the optical path difference, $x$, between the two arms resulting in an interferogram, $V_x$, with maxima and minima at the detector surface. The whole setup is mounted on an optical bench to reduce the effect of vibrations. Input and output ports are equipped with a wire-grid to select a specific polarization that enters and exits the system. Interferometer can access both X and O mode transmission lines with a mechanical switch. This way many harmonics of both X and O mode are accessible, and hence different parts of the phase space of the electron’s motion in plasma can be studied.

The MPI instrument [27] was used at the ASDEX [28] Upgrade tokamak. It was refurbished for the use at W7-X. Because of the strong impact of stray radiation and the overlapped harmonics due to a higher magnetic field gradient, the operation at ASDEX upgrade was limited.

An In-Sb detector cooled to liquid helium temperatures is used for detection of the interferogram. The I-V curve characterization of the In-Sb detector was measured at room and liquid helium temperatures. It was verified that the detector operating point was set in the linear regime of the I-V response. A preamplification stage with a voltage gain, $G_p$, of 60 dB was applied to the detection signal $V_x$. Additionally, a video amplifier was used at a gain setting, $G_v$, varying with plasma heating power. The stray radiation at the start of plasma may lead to the damage of the In-Sb detector or can cause the saturation of the signal. Thus, for the first 100 ms of a plasma,
Figure 3. (a) Sinusoidal and phase signals corresponding to a full mirror sweep of 44 ms, combining both directions of scanning the maximum optical path difference of 30 mm. (b) Zoomed in view of (a) showing the sinusoidal, phase, and marker signals at the location of mirror turning point.

an automatic shutter was used for shielding the diagnostic. During the experimental campaign of W7-X, data acquisition was done with a FPGA at a sampling rate of 2 MSs⁻¹. For the interpretation of the measured ECE in terms of the radiation temperature, $T_{rad}$, it is important to calibrate the diagnostic to know its sensitivity, $C_f$ (Vm/keV). The diagnostic was calibrated with a black-body source emitting broadband radiation at different temperatures.

2.5 Signal processing

The experimental data measured during the plasma experiments in W7-X consisted of three signals. One signal is corresponding to the interferograms, $V_x$, the other two signals named sine and cosine, as shown in figure 3a are corresponding to the mirror movement. Figure 3b shows the phase and markers generated from sine and cosine signals. The phase signal keeps track of mirror movement direction and the temporal location where mirror turns. The half period of the phase signal is also the temporal resolution of the diagnostic. The marker signals represent the temporal locations of a 20 µm mirror step. The resultant optical path difference, $x$, between the two arms is twice of the mirror step. This is required for providing the spectral resolution, $f_{min}$, and the frequency grid, $f$, to overlay the fast Fourier transform (FFT) of the measured intensity, $I_f$, of interferograms.

3 Analysis

ECE is used since many decades to provide electron temperatures in magnetically confined plasma devices. Despite this, the calibration of the diagnostic is still a complex process. An absolute calibration is to provide the sensitivity of the diagnostic to a change in the temperature of the input radiation. This is achieved with the hot-cold calibration technique. Two broadband sources with known emission characteristics are essentials for the implementation of this calibration technique. A black-body emitter made up of a ceramic material with a surface area of approximately 12 x 12 cm is used for the calibration. The black-body emitter can be tuned to temperatures between room
temperature and 600°C, which is measured with a thermocouple. For the black-body emission in the microwave range, the signal to noise ratio is too low to be used directly for calibration. Hence, the data integration time had to be increased to four hours per measurement, and the averaging of the interferograms was done for that temporal duration. The following quantities need to be analyzed for extracting the spectral information from the measured interferograms.

### 3.1 Spectral and temporal resolution

The spectral resolution is a direct result of the maximum optical path difference that can be achieved between the two arms. This is the key quantity that determines the degree up to which the spectral characteristics of the input radiation can be recovered. The minimum increment, \( x_{\text{min}}/2 \), of mirror is chosen to be 20 \( \mu \)m to cover the maximum mirror excursion of 15 mm. The spectral resolution, \( f_{\text{min}} \), is given by,

\[
f_{\text{min}} = \frac{c}{2 x_{\text{max}}} = \frac{c}{2 N x_{\text{min}}}
\]

where \( c \) is the speed of light, \( x_{\text{max}} \) is the maximum optical path difference achieved with \( N \) mirror steps of minimum optical path difference, \( x_{\text{min}} \). The total number of data points in the interferogram are \( N_{1} = N + N_{0} \) instead of \( N \), so that the total number of data indices is, a power of 2, fulfilling the condition for the FFT. This results in \( f_{\text{min}} \approx 3.66 \text{ GHz} \), corresponding to \( N_{1} = 2^{m} = 1024 \) data indices with \( N = 750 \) steps for the 20 \( \mu \)m increment of the mirror excursion creating a maximum optical path difference. \( N_{0} \) is the zero padded steps. The final frequency grid, \( f \), to evaluate the spectra ranging from 3.66 GHz to \( 2^{m} \times 3.66 \text{ GHz} \). The interferograms and their Fourier transform, obtaining frequency dependent calibration factors, are explained in the following sections.

The temporal resolution is a result of how fast the mirror can complete one path from zero to the maximum optical path difference. Hence, to have a high spectral resolution, one has to pay from temporal resolution and vice versa. An acceptable spectral and temporal resolutions can be achieved by optimizing the maximum mirror excursion and speed per excursion. At W7-X, the interferometer was commissioned with a maximum mirror excursion, \( x_{\text{max}}/2 \), of 15 mm with a speed of 1 ms\(^{-1}\). The mirror frequency for a full sweep, covering both scanning directions, is approximately 22 Hz. This sweeping frequency cannot be increased further as this would over-strain the mechanical coupling between motor and mirror. The temporal resolution corresponding to this frequency is approximately 22 ms.

### 3.2 Interferogram and window function

The experimentally measured interferogram, \( V_{x} \), for an input radiation of intensity, \( I_{f} \), and for the diagnostic sensitivity, \( C_{i} \), is given by the following equation

\[
V_{x} = G \text{ FFT}^{-1}(C_{i}I_{f})
\]
Figure 4. (a) Interferograms, $V_x$, from radiation emitted by the black-body source at two different temperatures ($600\,^\circ\text{C}$ and $400\,^\circ\text{C}$) and the interferogram for a temperature change of 200 K as a function of data index. (b) $w_x$, cosine window function from eq. (3.4) as a function of $x$, optical path difference and the measured black-body interferogram multiplied with the window function.

where $G = G_p \times G_v$ is the external gain applied to the interferogram signal. The spectral intensity, $I_f$, for a black-body emission at a temperature $T$ is given by the Rayleigh-Jeans law,

$$I_f = f^2 \frac{k_B T}{2\pi c^2}$$

$$dV_x = G \text{FFT}^{-1}(C_t dT)$$

(3.3)

where $f$ is the spectral frequency, $c$ is the speed of light, $k_B$ is the Boltzmann constant and $C_t = C_i I_f / dT$ is the diagnostic sensitivity. Figure 4a shows experimentally measured interferograms, $V_x$, of the black-body emission at two different temperatures of $400\,^\circ\text{C}$ and $600\,^\circ\text{C}$. The difference interferogram, $dV_x$, in the figure reflects a change of 200 K in the radiation temperature.

A window function, $w_x$, is used to increase the weight of data points around zero optical path difference. Figure 4b shows the window as a function of optical path difference. The window function used for the analysis is,

$$w_x = \cos \left( \frac{\pi x}{2 x_{\text{max}}} \right); 0 \leq i \leq \frac{x_{\text{max}}}{x_{\text{min}}}$$

(3.4)

where $i$ is the mirror movement index, $x_{\text{min}}$ and $x_{\text{max}}$ are minimum and maximum optical path difference. The interferograms $V_x$ are padded with zeros at the end to have $2^N$ data points.

3.3 Difference spectra

The whole transmission line of the diagnostic setup, including the Gaussian optics, as shown in figure 1 has a transmission loss, $A_f$, of approximately 20 dB (figure 6a). The 4 mm waveguide used to focus the fundamental mode, reduces the number of modes propagating in the system and hence reduced propagation power, which would make the calibration process difficult in the microwave range. The input power from the calibration source was not enough to overcome the attenuation
of the total transmission line, even with the increased integration time. As a consequence, a different strategy was applied, calibrating the interferometer individually and later combining these calibration factors with the separately measured attenuation, \( A_f \), of the transmission line. The spectral information, \( S_f \), is the quantity of interest, which requires a FFT of the interferogram, \( V_x \).

\[
dS_f = \text{FFT}(w_x dV_x)
\]  

The black-body source was used at temperatures of 600°C and 400°C to derive difference interferogram. Because of low emitted power from the black-body source at low temperatures, it was not possible to measure temperatures below 400°C. Figure 5a shows the difference spectra from the black-body emission measured without notch filter and figure 5b with. Hence, two sets of calibration factors were determined to analyze the experimental results. One of the common features in both spectra is the water absorption lines, which were also used to validate the observed spectra. The key feature in the spectra with notch filter is the periodic notches with one at 140 GHz as it was designed to have and this assures that the stray radiation will not dominate the ECE from other harmonics.

### 3.4 Calibration factors

The sensitivity, \( C_t \), of the diagnostic is,

\[
C_t = \frac{A_f dS_f}{G dT}
\]

where \( A_f \) (figure 6a) is frequency dependent loss of the transmission line. Depending on the plasma density at W7-X, the ECE up to the 4\(^{th}\) harmonic could be observed. Hence, the calibration factors...
are required only for frequencies below 300 GHz. In addition, as this work is targeting plasmas at high-densities where parts of the 1st harmonic will be in the cut-off. Thus, the lower frequency limit for calibration was set to 100 GHz. Figure 6b shows the calibration factors which were used to get the radiation temperature of ECE. For the spectral range of 100-300 GHz, the diagnostic sensitivity is of the order of $10^{-9}$ Vm/keV and after introducing the notch filter, the sensitivity of the diagnostic decreases by an order of magnitude.

4 Experimental results

The radiation temperature extracted from the diagnostic is given by

$$ T_{rad} = \frac{S_f}{G C_t} $$

(4.1)

where $S_f$ is the ECE spectrum including the transmission line losses.

The ECE measurements, for different plasma parameters, were investigated with a focus on the over-dense plasmas beyond X2 emission cut-off. This work deals with the study of the X3 emission, and hence only radiation temperatures of the X-mode are shown in the following sections. The emission from O-mode can also be accessed by this diagnostic, but it is not used for further analysis, as emission from higher O-mode harmonics is optically thin. The polarization of ECE depends on the direction of magnetic field at the plasma boundary where the microwaves start to propagate in vacuum towards the optics. Hence, there will be a slight mismatch present at all times with respect to pure separation of polarization from wire-grid. This mismatch results in leakage of strong X-mode in the O-mode measurement and hence polluting O-mode. On the other hand, the X-mode is not affected much with leakage of weak O-mode, as seen by radiometer measurements.
Figure 7. (a) X-mode radiation temperature, $T_{\text{rad}}$, spectra for plasma #20181009.21, heated with pure NBI of 3.5 MW, with a linear density ramp (as shown with color bar). The two spectral peaks correspond to X2-mode, covering the spectral range from 110 to 160 GHz, and the X3-mode covering the spectral range from 190 to 230 GHz. (b) A direct comparison of the spectral shape of X2-mode measured with the radiometer and interferometer diagnostics, both attached alternatively to identical optics and sight-line, for comparable plasmas.

4.1 X-mode emission spectra

Figure 7a shows the measured spectra for X-mode emission. For the plasma taken as an example, due to the limited NBI heating power of 3.5 MW, the electron temperature was $\approx 1$ keV, which is relatively low. The X2-mode, covering the spectral range of 120-160 GHz, is optically thick and the measured radiation temperature directly corresponds to the electron temperature. The evolution of the spectral features with the change of the plasma density (measured with the dispersion interferometer [30]) shows that the X2-mode is going into cut-off at a density $\sim 1.2 \times 10^{20}$ m$^{-2}$. One of the key experimental observation is that the strong X3-mode, covering spectral range of 190-230 GHz, is also present alongside the X2 emission. The radiation temperature of X3-mode increases with density, even though $T_e$ does not vary a lot, indicating a continuous increase of its optical thickness. Also the spectral peak of X3-mode shifts towards the LFS with increase in plasma density, indicating changing absorption conditions. However, with plasma densities above X2-mode cut-off and $T_e \approx 1$ keV, the X3 emission starts to saturate despite further increasing density. This indicates that the optical thickness has reached the black-body conditions. Additionally, there are other features present in the spectra between the frequency range of X2 and X3 emission. Forward modeling of the radiation temperature taking into account radiation transport calculations [31] and wall reflections are underway to understand these extra features, which could add to a better understanding of wall reflections properties, sight-line, and mode separation. The last feature seen in figure, above 240 GHz, is a leakage from the radiometer local oscillator (second harmonic at $\approx 244$ GHz), which is reflected back in the transmission line components and at the interferometer. It is seen independent of plasma conditions. This signal was used as a marker to validate the spectral features. Since the interferometer and radiometer share the same line of sight, a direct comparison of the X2 emission is possible.
Figure 8. (a) A comparison of $T_{\text{rad}}$ at plasma center of X2 and X3 mode and $T_e$ from the Thomson scattering diagnostic for an NBI heated plasma #20181009.21 with low $T_e$ $\approx$ 1.2 keV and high plasma density and (b) for an O2-mode ECRH plasma #20181010.30, measured with stray radiation notch filter, with $T_e$ $\approx$ 2.5 keV and high plasma density (indicated in orange dashed line).

4.2 X2 emission comparison with radiometer

The heterodyne radiometer [32] measures the same physical quantity, radiation temperature of ECE, as the Fourier transform spectrometer. The spectral resolution of radiometer is 1.2 GHz. The radiometer is absolutely calibrated by the same calibration optics but using microwave absorber at room temperature and 77 K from liquid Nitrogen as references. The comparison of measurements from the two diagnostics, with the radiometer having a better spectral resolution, makes it easier to understand the instrument function of the interferometer. Hence, a direct comparison is a good test of both diagnostics. Figure 7b shows a comparison of the $T_{\text{rad}}$ of X2-mode measured with the radiometer and interferometer. Due to the diagnostic setup, X or O mode access was limited to one of the ECE diagnostic at a given time. Hence two similar NBI heated plasmas (#20181009.14 and #20181009.18), with $T_e$ of 1.2 keV and plasma density of $\approx$ 9 x $10^{19}$ m$^{-3}$, are chosen for comparison. The peak radiation temperatures from the two diagnostic are in agreement, which validates the calibration of the interferometer. The HFS of the spectra are relatively in good agreement as well. However, the spectral features are more smooth with the interferometer because of its poor spectral resolution in comparison to the radiometer. The LFS, in contrast, is not in agreement from two diagnostic. A possible reason is the high uncertainty of the interferometer calibration for lower frequencies because of less emission from black-body source (see figures 4a and 6b). Also it cannot be excluded that emission from hot core electrons at frequencies outside the limited radiometer bandwidth contributes to this feature in the interferometer spectrum.

4.3 X3 emission comparison with electron temperature

Figure 8a shows the comparison of X2 and X3 emission spectral peaks (see figure 7a) with $T_e$ measurement from Thomson scattering diagnostic [33, 34]. The radiation temperature of X2 emission represents $T_e$ before reaching the cut-off around 2.5 s. The X3 emission, for this relatively cold NBI heated plasma, is increasing during the density ramp before saturating. It can be seen
that during plasma decay (after 4 s), the X2 emission recovers from the cut-off and represents $T_e$ as displayed by Thomson Scattering, however the X3 radiation temperatures always remain below $T_e$. Hence, X3 emission is not sufficiently optically thick to reproduce $T_e$ for these plasma parameters.

Figure 8b shows a similar comparison, however for different plasma parameters with higher $T_e$, where the optical thickness is expected to be higher. The O2-ECRH plasma was measured with the stray radiation notch filter and hence a calibrated X2-emission is not available for this measurement. However, the X3 emission for these plasma parameters, coincides with $T_e$ inferred from Thomson scattering. This is a clear indication that the optical thickness of the X3 emission is high enough to use it as an electron temperature measurement.

5 Conclusions

The MPI was commissioned at W7-X for the operational phase of OP1 to scan the broadband ECE in spectral range 50-500 GHz. The diagnostic results also support the studies of multiple reflections and polarization effects for selected the radiometer diagnostic sight-line. However, the focus of the work is to investigate the diagnostic capabilities of X3 emission for over-dense plasma. For that the diagnostic was absolutely calibrated with a black-body source. Since the calibration source did not overcome the transmission line losses, a different approach of calibration by parts implemented. The interferometer was individually calibrated without the transmission line. The calibration of interferometer combined with frequency-dependent transmission line losses provides the overall diagnostic sensitivity. The transmission line losses are of the order of approximately 20 dB and the diagnostic sensitivity is of the order of nV m/keV. The first assessment of the transmission line losses is a motivation for the next experimental campaign to reduce the losses to improve calibration. The ECRH heated plasma were successfully scanned by attenuating the stray radiation approximately by 25 dB with a multi-mode notch filter. However the X2 emission was lost in the spectral range of notch width of approximately 10 GHz centered at 140 GHz. Hence only the X3 emission is available with the ECRH plasma.

High-density plasmas above the X2 cut-off are heated by, presently available, two NBI sources (power $\leq$ 3.5 MW) or O2 polarized ECRH. The X3 emission becomes optically thick only if electron temperature exceeds 2 keV as indicated by a radiation temperature which reproduces the electron temperature and has become independent of the plasma density. The X3 emission from interferometer, for these plasma parameters, can be directly used as a proxy for the electron temperature measurement, where the radiometer is unavailable. For electron temperatures below 2 keV, where the plasmas are not yet optically thick for X3 emission, the observed X3 radiation temperature increases with plasma density as expected.

This work could be extended by the improvement of the transmission line resulting in an improved absolute calibration and a notch filter with reduced spectral notch width to extract the X2 emission for the ECRH plasmas as well. As the outcome of the experimental results from this work, a direct diagnostic application of X3 emission can be implemented to track $T_e$ for over dense plasmas beyond X2 emission cut-off in the next experimental campaign of W7-X.
Acknowledgments

The authors would like to thank K. Ewert and M. Stern for the technical assistance with the setup and maintenance of the diagnostic. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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