Soft x-ray tomography measurements in the Wendelstein 7-X stellarator

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Abstract
The soft x-ray tomography diagnostic in the stellarator Wendelstein 7-X consists of twenty pinhole cameras, up–down symmetrically arranged in a poloidal, triangular cross-section of the plasma vessel. The x-ray emissivity is measured with 16 bit amplitude resolution at 2 MHz sampling rate along 360 lines-of-sight by silicon photodiode arrays. In the recent operation campaign data acquisition (DAQ) has been working reliable for the conducted plasma pulse lengths < 1 min, however the DAQ system are ready for the foreseen 30 min plasma pulse lengths of upcoming campaigns. The bandwidth of the preamplifiers is ≈ 200 kHz and the sensitive energy range is approximately 1–12 keV. The measurements indicate the up–down symmetric emissivity distribution in the triangular poloidal cross-section. First tomographic reconstructions of different magnetic field configurations are consistent with the theoretically calculated flux surface topology.

Keywords: x-ray, tomography, XMCTS, stellarator, Wendelstein, W7-X

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

1. Introduction

At the reactor-relevant optimized stellarator experiment Wendelstein 7-X (W7-X) the first plasma operation phases (OP) OP1.1, OP1.2a and OP1.2b have been completed. Between the OP the set of basic diagnostics has been extended [1]. An important and powerful diagnostic for a fusion plasma is the soft x-ray (SXR) tomography. SXR tomography systems have demonstrated successful operation in various fusion devices, see [2–4]. The power of this type of diagnostic is in its ability to noninvasively measure the two-dimensional x-ray emissivity with high spatial and high temporal resolution. Information about the cross-sectional shape of the plasma can be obtained without prior knowledge of the magnetic flux surface topology. At W7-X a SXR tomography system consisting of twenty cameras, the so-called SXR multi-camera tomography system (XMCTS), has been commissioned in OP1.2a and OP1.2b. The XMCTS is one of the key diagnostics capable of investigating the level of stellarator optimization in W7-X, i.e. the reduction of the Pfirsch–Schlüter currents and in turn the reduction of the radial outward shift of the magnetic axis and flux surfaces with increasing plasma pressure. This so-called Shafranov shift [5, 6] can be deduced from SXR tomograms with the assumption of constant SXR radiation on flux surfaces. Due to its high spatial resolution and high sample rate, the XMCTS can resolve occurrences of magnetohydrodynamics instabilities. These instabilities, characterized by poloidal mode number and frequency, can be compared to theoretical...
predictions. The XMCTS measures x-ray radiation in the energy range of approximately 1–12 keV. The energy window of SXR tomography diagnostics is determined by the transmittance of a metal filter (lower energy limit) in front of the detector and by the photoabsorption of the detector material (upper energy limit). The spectral emission of fusion plasmas in the SXR range consists of continuum radiation and line radiation [7–10]. The most relevant contributions originate from free-free emission (bremsstrahlung, continuum radiation), free-bound emission (recombination, continuum radiation) and from bound-bound emission (line radiation). Line radiation is emitted by radiative decay of excited states of ions or atoms created by electron-impact excitation or photo-excitation. For bremsstrahlung the decay of excited states of ions or atoms created by electron-impact excitation or photo-excitation. For bremsstrahlung the total radiated power is proportional to $Z_{\text{eff}} n_e^2 T_e^{1/2} \tilde{g}_g(T_e)$ [7] with $Z_{\text{eff}}$ being the effective charge, $n_e$ the electron density, $T_e$ the electron temperature, and $\tilde{g}_g$ the weighted averaged Gaunt factor. Since x-ray emission strongly increases with ion mass, the XMCTS enables access to the spatiotemporal dynamics of impurity atoms and impurity transport.

The setup of the XMCTS, its main mechanical parts and the assembly inside the vacuum vessel of W7-X in 2016 have been reported in [11]. The periphery components, i.e. cooling water components, compressed air components, cables, electronics, the electric racks and the data acquisition (DAQ) systems were completed in the mid of OP1.2a. In November 2017 the XMCTS started commissioning.

In section 2 the final setup of the XMCTS is summarized and main design features are discussed concerning engineering, line-of-sight geometry and electronics. First experimental results from commissioning are presented in section 3 followed by a discussion in section 4. The summary and conclusions are given in section 5.

2. Experimental setup of the XMCTS

The SXR tomography diagnostic XMCTS at W7-X measures the two-dimensional x-ray radiation profile of a poloidal cross-section. The heart of the XMCTS are SXR pinhole cameras that contain the components of the pinhole optics, the detectors and the preamplifier electronics. Together these components determine the line-of-sight geometry, the sensitivity and the spectral range. Some design features of the XMCTS cameras have been chosen to be similar to the tomography system MiniSox that was developed and successfully operated at the predecessor stellarator experiment Wendelstein 7-AS [4]. For the conditions in Wendelstein 7-X, especially the long pulse plasma operation of 30 min, a set of additional requirements had to be met [12]. In particular necessary water cooling of the cameras is required [13, 14]. After the installation in the vacuum vessel, the frame segments (five cameras are grouped in one frame segment) were measured to an accuracy of \( \pm 1.5 \) mm by metrology (see section 2). The as-built design of the XMCTS and the procedure of its in-vessel assembly in W7-X from have been reported in [11]. The following paragraphs present details of the diagnostic setup, the electronics and important for the tomography, the geometry of the lines-of-sight.

![Setup of the SXR diagnostic XMCTS:](image)

**Figure 1.** Setup of the SXR diagnostic XMCTS: (a) the soft x-ray pinhole cameras are mounted inside the vacuum vessel of the W7-X stellarator at the toroidal angle $\phi = 36^\circ$ in one of the five triangular-shaped cross-sections that are up–down symmetric with respect to the $z = 0$ axis. (b) Twenty SXR cameras grouped in five are mounted in four segments located between the wall of the vacuum vessel and the plasma facing components. The red lines indicate the fields of view of the cameras. For clarity the frame structures as well as the pipe systems for cooling water, compressed air and signal cables are omitted.

2.1. Mechanical setup of the XMCTS in W7-X

For the mechanical installation of the XMCTS cameras at the W7-X stellarator and for safe operation during high power programs a number of mechanical solutions have been developed and implemented [11, 14]. According to the required number of x-ray cameras at preferably one single toroidal position, but due to the limited number and limited access of ports in the design phase of W7-X, the whole camera system has been placed inside the vacuum vessel.

Figure 1(a) illustrates the W7-X vacuum vessel with a toroidal cut of the torus at between $\phi = -36^\circ$ and $\phi = +36^\circ$. The XMCTS is located at the toroidal angle of $\phi = +36^\circ$, i.e. at one of the five triangular shaped up–down symmetric cross-sections. In this divertor-free plane it is possible to observe the plasma from almost all poloidal directions. The diagnostic consists of 20 poloidally arranged pinhole cameras [see figure 1(b)] located in the space between the vacuum vessel and the plasma facing components. The cameras are fixed in groups of five in four stainless steel frame segments. Each of these frame segments is mounted via three bearings to M8
studs to the vacuum vessel wall. Cables for signals, control and electric power, and pipes for cooling water, compressed air and signals are guided to the camera system inside the vacuum vessel via four plugins each connected with an interface at one port. More details about the assembly and mechanical setup can be found in [11, 14].

2.2. Setup of the XMCTS x-ray cameras

The XMCTS measures the line-integrated x-ray radiation along the lines-of-sight of SXR cameras in a poloidal cross-section [15]. Figure 2 illustrates a schematic setup of an XMCTS camera. The detectors are silicon photodiode arrays of the type AXUV-22 (IRD Company). The fields of view of the cameras spanned by the fans of the lines-of-sight observe the plasma through individually shaped gaps in the plasma facing wall structure. In OP1.2 the first wall consisted of carbon tiles mounted on an actively water-cooled CuCrZr tile structure. Each photodiode array is mounted on top of an electronics box where it is enclosed in a housing that shields electron cyclotron radiation (ECR) from the ECR heating system as well as electromagnetic radiation from the plasma including the infrared, visible, ultraviolet (UV) and x-ray range. Centered above the photodiode array at the top of the housing is the slit aperture.

To allow for the detection of SXR radiation a lightproof beryllium foil of 12.5 μm thickness and 99.4 % purity mounted in the optical beam path between the slit and the photodiode array blocks all incoming electromagnetic radiation, it is only transparent for the SXR range. In addition the beryllium foils protect the photodiode arrays during plasma operation from incoming neutrals (created by charge exchange), UV and vacuum ultraviolet (VUV) radiation. UV and VUV radiation and neutron fluxes cause sensitivity degradation of the photodiodes over time [16–18].

The cameras are equipped with a shutter system [14] that is pneumatically driven by a Bourdon spring. On the one hand the shutter can cover the aperture in order to protect the beryllium foil for damages or coating during wall conditioning procedures such as baking, glow discharges and boronation. On the other hand the shutters enable in situ dark current measurements during long pulse plasma operation to check for temperature drifts of the camera electronics. The photodiode array is electrically connected via a vacuum-tight feedthrough [14] to the preamplifiers that are mounted inside the electronics box in a secondary vacuum.

The power supplies, control systems, filters and DAQ systems are located in electric cabinets outside the vacuum vessel. More details of the electronics setup can be found in section 2.3. After passing anti-alias filters the signals are digitized by analog-to-digital converter systems in the electric cabinets. The digital data is transferred via network to the W7-X database. For functional tests, and for phase and amplitude calibration, the photodiode arrays can be illuminated by intensity modulated light from calibration light sources (red light-emitting diodes) that is guided into the camera housings via optical fibers [11]. The light sources (in preparation) are located at the ports.

Figure 3 illustrates the detailed setup of an XMCTS camera in an isometric drawing [figure 3(a)] and a sectional view
from the plasma which are used for the measurement of x-ray radiation direction. The detector consists of 22 silicon photodiodes are 1mm in the poloidal direction and 4mm in the toroidal slit aperture, both of which contribute to the detailed shape of line-of-sight forms an individual pyramidal cone. According to the geometry of the diodes and the slit, each photodiodes are covered and can be used for dark measurements. The movement of the diamond coated shutter arm. The beryllium foil is circularly curved so that the effective thickness and in turn the line-of-sight geometry, wedge-shaped edges of the slit are manufactured with a precision of 50μm. The view cones of the central lines-of-sight span a poloidal angle of 3.7° and a toroidal angle of 14.8°. On the magnetic axis this corresponds to a toroidal section of approximately $\phi \in [35°, 37°]$. Since the poloidal width of the slit and the distance between neighboring photodiodes are equal, the line-of-sight fan does not exhibit observation gaps in the poloidal cross-section. Closely behind the slit the view cones overlap, whilst far away from the camera (>20cm, i.e. usually within the last closed magnetic flux surface (LCFS)) the fraction of overlap goes to zero for neighboring lines-of-sight of one camera. Consequently there is negligible redundant information of the plasma in signals of neighboring photodiodes within one camera.

The lower part of figure 4 presents the relative detector response of the system beryllium filter and silicon photodiode. The beryllium foil acts as a high pass filter that becomes transparent for high energy photons. The lower energy limit increases with foil thickness. The silicon photodiode acts as a low pass filter, since the photoabsorption coefficient of silicon decreases with higher energies. The higher energy limit increases with thickness of the silicon diode. The $e^{-1}$ response window corresponds to the energy range of $\approx 1.1–12$ keV (i.e. $\approx 0.10–1.13$ nm). The relative detector response is estimated as $\Gamma_{\text{Be, Si}} = T_{\text{Be}} \cdot A_{\text{Si}}$, where $\Gamma_{\text{Be, Si}}$ is the absorbed photon flux in the silicon diode, $T_{\text{Be}}$ the incident photon flux from the plasma, $T_{\text{Be}}(\varepsilon_{TB})$ the transmitted ratio through the beryllium filter, and $A_{\text{Si}}(\varepsilon_{TB})$ the absorbed ratio in the photodiode. The transmittance can be calculated by $T(\varepsilon_{TB}) = \exp(-\rho d \mu(\varepsilon_{TB}))$ with $\rho$ being the mass density, $d$ the thickness of the material layer and $\mu(\varepsilon_{TB})$ the energy dependent photoabsorption coefficient, that can be found in [20, 21]. Since specular reflectivity $R_{\text{Si}}(\varepsilon_{TB})$ is negligible in the x-ray range for small incident angles (to the surface normal) [21] the absorption in the silicon photodiode can be estimated as $A_{\text{Si}} = (1 - R_{\text{Si}} - T_{\text{Si}}) \approx (1 - T_{\text{Si}})$. The XMCTS is thus sensitive to bremsstrahlung and to impurity ion emission lines, especially for the expected impurities at W7-X, i.e. Cu (at 8.67 keV), Fe (at 6.95 keV), Cr (at 5.92 keV), Ar (at 3.32 keV) [9]. Prominent lines from carbon and oxygen are outside the energy range of the XMCTS (O at 0.65 keV, C (at 0.37 keV)).

2.3. Setup of electronics

The main electronics components of the XMCTS are the preamplifiers, the anti-alias filters and the DAQ systems (see [11, 19]). The small photodiode currents (μA range) are amplified by two-stage preamplifiers consisting of a transimpedance stage and a line driver stage. Figure 5(a) shows the two-stage preamplifier circuit for one photodiode. The AD8067 amplifies the small photodiode currents (in the order of nA) in an inverted operational amplifier circuit by a 200 kΩ feedback resistor with a feedback conversion ratio of 5 μA/1 V. The LT6350 drives the signal against the cable impedance. Inside the electronics box of one camera all twenty photodiode signals are amplified by two similar circuit boards both joined with micro pin connectors. The
feedthrough design described in [14] uses special adapters on the fragile glassed feedthrough pins to reduce forces and secure the vacuum tightness. The lower preamplifier board is illustrated in figure 5(b). Figure 5(c) shows both preamplifier boards in an open camera.

From the second board the cables for signals, power supply and control leave the camera via a 100-pin connector. In the final assembly state the connected preamplifier boards are covered with a thermal gap pad (BERGQUIST® [22]) connected to the water-cooled camera body via a copper heat conducting plate.

Safe electronics operation is possible up to 70 °C. In order to monitor the temperature especially during high energy plasma operation and baking (usually at 150 °C) each preamplifier board is equipped with two PT1000 sensors. Using a multiplexer unit the cables for the four temperature signals were reduced to two cables (select and data). Amplitude and phase responses of all photodiodes were measured in the laboratory before the camera system was installed in the vacuum vessel [11]. The photodiodes are operated with reversed bias (−5V) applied to the common anode in current mode to increase the depletion layer in the p–n junction. The amplitude response, as measured in laboratory before in-vessel assembly and without long cables, is flat and has an edge frequency of 200 kHz [11]. Successive development of dense routing of the circuits has been crucial to minimize crosstalk and to obtain flat amplitude responses.

The preamplifier output signals are sent down from the cameras to the electrical cabinets via long (up to 60 m) triple shielded twisted pair cables. For stabilizing the power, bias and control signals and in order to reduce electric pickup along the cables in the torus hall, voltage regulators are used. These regulators are installed in electronics units in front of each XMCTS port. The usage of voltage regulators is also reported for the SXR diagnostic at DIII-D [23].

Before entering the DAQ system, the signals pass through 5th-order anti-alias low pass filters with an edge frequency of 700 kHz. For DAQ a 384 channel system from D-TACQ [24] is used. The system consists of four clusters, each recording 96 channels with 16 bit resolution and 2 MHz sampling rate. Three-hundred sixty input channels measure the lines-of-sight data. Twenty input channels are used to measure data of blind diodes for dark measurements, and 4 input channels record W7-X triggers for synchronization of the DAQ clusters. The maximum possible output signal of the preamplifiers is ±5 V. The input voltage range can be varied between ±1 V, ±2 V, ±5 V and ±10 V. According to calculations using the SXR radiation code IONEQ [8] photocurrents in the order of 10 μA are expected for the used silicon photodiode setup for W7-X high performance plasmas. With the 16 bit resolution the fluctuations of a 1% mode in a plasma creating a DC (direct current) photocurrent of 2 μA can be resolved with 7 bit. The noise level is expected to be in the range of the dark current (∼5 nA), i.e. in the mV range.

The total data rate of the XMCTS is 1.536 GB s⁻¹, i.e. per cluster 384 MB s⁻¹. In OP1.2 the full data sets of up to 50 s long discharges have been recorded with full time resolution.

![Figure 5](image_url)
2.4. Special aspects of the XMCTS in OP1.2 and reliability

Synchronization of the 384 input channels in the four separate DAQ clusters and separate electric cabinets is achieved via post processing of the same digitized master trigger signal in each of the clusters. The timing of the recorded data for one W7-X program identifier (W7X-PID) is corrected by software using the data of the recorded trigger signals. The obtained synchronization within the XMCTS diagnostic is accurate to 1 µs.

Small misalignments of the shutter arm positions (±0.5 mm) resulted in partly limited fields of view of some cameras and in turn in partial shadowing of some photodiodes. Work on improving this mechanical issue for the next operational phases is in progress. Shadowing effects of the photodiodes by the shutter systems have been incorporated in the tomography algorithms.

Eighteen shutters have been worked reliably during OP1.2. One shutter did not move correctly, it was mechanically blocked. This shutter (camera 3C) has been permanently opened in OP1.2b and camera 3C recorded useful data.

Camera 4B has been out of function in OP1.2. During installation of the XMCTS inside the W7-X vessel a cable of camera 4B has been damaged. A repair has not been possible at that time, it is planned for a next OP.

During high performance discharges some XMCTS signals have been in saturation. To avoid signal saturation in the next W7-X campaigns the slit size will be decreased to reduce the x-ray intensity at the photodiodes.

After OP1.2 thin coating of some beryllium filters has been found. The investigation of the reason for the coating and the analysis of its composition and thickness are in progress. The beryllium filters will be replaced until the next OP.

2.5. Geometry of lines-of-sight

Figure 6(a) shows the 360 lines-of-sight of the XMCTS in up–down symmetric coloring of the cameras. Representatively plotted are flux surfaces of the standard magnetic field configuration in the edge, the gradient and the core region. The flux surfaces are calculated by the Variational Equilibrium Code (VMEC) [25]. The cameras are aligned in a way that the area within the LCFS is homogeneously covered by lines-of-sight. In a tomographic inversion, the radiation distribution \( g(z, R) \) is reconstructed from the knowledge of the radiation contribution from each volume element along the respective line-of-sight \( l \) and the integral power \( f_l \) measured by the respective photodiode. In the following the coordinates \( z_i \) and \( R \) represent the emitting region as a 2D grid of pixels with elements \( (i, j) \). The forward model is typically formulated as a matrix product \( f = M \cdot g \), with \( M \) being the contribution matrix containing the line-of-sight geometry information [3]. More precisely \( M(i, j) \) is the fraction of emission (‘contribution’) of pixel \( (i, j) \) measured by line-of-sight \( l \) and the respective photodiode. The density of lines-of-sight is depicted in figure 6(b). The plot takes into account the shapes of the view cones of each line-of-sight and their contribution to the signals at the photodiodes. The density of the lines-of-sight corresponds to the sum of the contribution matrix values over the lines-of-sight, i.e. \( S(i, j) = \Sigma_j M(i, j) \).

Additionally, the flux surfaces of the low iota and high iota configuration are plotted overlayed. In the low iota configuration the flux surfaces are completely covered by all lines-of-sight. With increasing rotational transform the horizontal elongation increases. In case of the high iota configuration the flux surface region at the outboard side, i.e. beyond \( R = 590 \) cm, is covered by few lines-of-sight only resulting in a low line-of-sight density. For interpretation of the radial outer parts of XMCTS tomograms, this needs to be kept in mind.

Due to the toroidal slit opening the XMCTS measures 2D x-ray profiles integrated over a certain toroidal range. Figure 7 shows the variation of the flux surface topology exemplarily for the high iota B-field configuration. In the toroidal direction the fields of view of the cameras have an opening angle of...
approximately 14.8° [see figure 4(a)]. Depending on the distance from the camera, each line-of-sight integrates over a certain toroidal range. The distances from the cameras to the core vary between 60 cm and 80 cm. For an approximate illustration of the flux surface variation in the core a line-of-sight with a length of 70 cm is assumed, which corresponds to a toroidal range of ±1° around the center poloidal plane of the XMCTS. The cameras 2B, 2C, 2D, 2E, 3A, 3B, 3C and 3D integrate along lines-of-sight with lengths larger than 100 cm. For an approximate illustration of the flux surface variation for these long lines-of-sight a length of 140 cm is chosen, that corresponds to a toroidal range of ±2° integrated in each photodiode. According to the averaging effect along the toroidal width of the fields of view of the cameras the tomograms can tend to decrease in vertical accuracy. This fact needs to be kept in mind when interpreting results from SXR measurements in W7-X using XMCTS.

2.6. Method of tomographic inversion used in this paper

There are various methods for the tomographic inversion of SXR camera tomography data in plasma physics. Here, we use the minimum Fisher regularized inversion as presented in [2]. The calculation of the contribution matrix is performed for a rectangular grid. Each detector and the corresponding aperture are subdivided into sub-pixels (taking into account both dimensions of the rectangular detector and rectangular aperture), which define a set of lines-of-sight for each detector. The contributions are calculated from the integration over line segments in the individual grid cells, weighted by the solid angle of the lines-of-sight launched from the detector sub-pixels. The grid cells are 3D volumes for the calculations of the line segment lengths, but the information stored in the contribution matrix only considers the grid in the poloidal plane.

Figure 7. Variation of the flux surface topology for the approximated toroidal observation range of the XMCTS exemplarily shown for a high iota B-field configuration. Flux surfaces are plotted for the effective radii $r_{eff} = \{3.2, 17.5, 31.8\}$ cm (i.e. $s = \{0.01, 0.30, 1.00\}$). The red short dashed lines indicate the flux surfaces at $\phi = 34^\circ$ and $\phi = 35^\circ$, the black solid line at $\phi = 36^\circ$, and the blue long dashed lines at $\phi = 37^\circ$ and $\phi = 38^\circ$.

Figure 8. Parameters of the reference discharge W7X-PID 20180801.024: (a) ECR heating power, (b) line-integrated density from interferometer and core electron temperature from Thomson scattering, (c) diamagnetic energy [27], and (d) the soft x-ray signal of the central line-of-sight of XMCTS camera 2C. In (d) the black line is the average data, the gray area is the maximum and minimum data of 1 ms intervals.

3. Results from first XMCTS operation in OP1.2a/b

In order to enable comparisons between different program days and different experimental configurations, a reference discharge has been conducted every plasma operation day at W7-X. The main operation and plasma parameters, namely ECR heating power, line-integrated electron density, electron temperature and diamagnetic energy of a hydrogen reference discharge from OP1.2b are shown in figure 8. The ECR heating is active for 7.5 s and has three power steps from 2 MW, 3 MW to 4 MW. With increasing heating power, both the line-integrated density and diamagnetic energy increase. After $\approx 0.2$ s the core electron temperature increases by $\approx 5$–10 keV. Figure 8(d) depicts the raw signal of one XMCTS photodiode, i.e. the central line-of-sight of camera 2C, which runs through the core (see figure 6). The SXR signal follows the heating power steps similar to the electron density and the diamagnetic energy. An overproportional increase of the SXR radiation amplitude is visible for the power step at $t = 5.0$ s from 3 to 4 MW. When ECR heating stops at $t = 7.5$ s the electron temperature and the SXR signal drop simultaneously, while the density is sustained due to a long particle confinement in W7-X [26]. In order to retain information about the fluctuation and noise level the local minima and maxima have been extracted from time intervals of 1 ms length. Both the extracted minima and maxima are plotted as gray area around the averaged signal. The fluctuation level increases during the discharge from $\approx 2$ mV at $t = 0.1$ s to $\approx 10$ mV amplitude. The noise measured before plasma operation at $t = -0.1$s can be estimated to $\leq 2$ mV amplitude.
Figure 9. (a) XMCTS raw data of camera 1A for W7X-PID 20180801.024. The colored lines show the moving average of 4.2 ms long time windows, the gray areas show the overlaid minimum and maximum values in each time interval, the inset depicts the lines-of-sight of camera 1A and the VMEC flux surfaces of the standard magnetic field configuration. (b) XMCTS signals of the plasma start up phase plotted for the central line-of-sight and the two edge lines-of-sight of camera 1A; for clear presentation only every 100th sample is shown. (c) The probability distribution function (PDF) calculated for the three signals shown in (b) for the time interval of 0.1 s before start of plasma heating at $t = 0.0$ s. The voltage difference between neighboring bits is $\Delta V/16\text{bit} = 2V/2^{16} = 30.518 \text{μV}$.

Figure 9(a) shows all photodiode signals of camera 1A for one W7-X program. The lines-of-sight of this camera cover the gradient region of the plasma from the LCFS to the core. The SXR signals increase with decreasing distance to the core. Firstly the x-ray emission rises simultaneously with the plasma pressure. Secondly the relevant integration volume of the lines-of-sight increases, since the length of the lines-of-sight within the LCFS becomes larger. To analyze the signal-to-noise ratio (SNR) the time interval of recorded data before plasma operation is included in figure 9(b) exemplarily for lines-of-sight from the edge, the gradient region and the core. The probability distribution functions (PDFs) of those signals indicate a full width at half maximum of approximately $1.0 \text{ mV}$ at $t = 0.0$ s. This means for the maximum practical input range of $\pm 5 \text{ V}$ the maximum SNR can be $\text{SNR}_{\text{max}} \approx 5000$.

Simultaneously measured XMCTS signals in an up-down symmetric plot arrangement are presented in figure 10. The ECR heating power steps are clearly visible for all camera signals. A comparison of opposite camera pairs demonstrates the up-down symmetry, according to the up-down symmetric camera arrangement at the triangular cross-section where the magnetic flux surfaces are up-down symmetric. A representation of the complete spatiotemporal XMCTS dataset for the same program is shown in figure 11. In this diagram the data is plotted in the up-down symmetric arrangement of the cameras. By comparing the profiles of opposite camera pairs the up-down symmetry in the SXR signals can be clearly recognized. Since the plot shows uncalibrated raw data the intrinsic deviations of camera profiles are not eliminated. Deviations of the measured camera profiles have various reasons. The largest impact on the deviations have the mentioned misalignments of the camera shutters. Some cameras are more affected by the shadowing of photodiodes by the shutters, resulting in a decrease of the measured intensity (up to $-30\%$). Even though the mechanical and electronic setup of all cameras are equal, differences in the camera sensitivity exist due to the tolerances of the electronic components. The raw data profiles of the four cameras 1E, 2E, 3B, and 3E show the largest deviations. For better illustration of the intended visualization of the symmetry, the camera profiles of these cameras are
each scaled with an individual correction factor ($\in [1.0, 1.3]$), that has been obtained from the ratio of the integral profile to the opposite cameras as a proxy for a well-determined calibration factor. In this way only the absolute amplitude of the camera profiles is changed but not the relative profile. Other contributions that lead to deviations from the up-down symmetry result from the limited mechanical accuracy of the installed camera system. The camera directions of up-down symmetric camera pairs deviate about $\pm 0.5^\circ$, resulting in shifted camera profiles along the photodiode array. This effect is weakly seen for the camera pairs 1B/4D and 2C/3C. Another source for deviations of the camera amplitude profiles are the beryllium filters, that have thickness tolerances in the order of $\sim 4\%$. In addition the purity level is high with 99.4% however even small amounts of impurities in the filter can lead to integral differences of the total spectral response in orders of $\sim 10\%$ [28].

The identified coating of some beryllium filters after OP1.2b is another source for deviations of the transmittance of the beryllium filters. Further analysis and calibration work is in progress to disentangle the geometric, filter and electronic effects.

For amplitude calibration the beryllium foils have been temporarily removed and the photodiode arrays have been irradiated with visible light by a fluorescence tube. From the simultaneously acquired XMCTS data for various positions of the light source in the poloidal cross-section it is envisaged to obtain a DC amplitude calibration for all photodiodes. Furthermore for accurate analysis of waves in the plasma, in particular investigations about cross-correlation and wave coupling, the knowledge of the frequency dependent phase and amplitude responses is mandatory. It is envisaged to measure the response curves of the fully installed XMCTS diagnostic (in addition to the laboratory calibration, see electronics paragraph in section 2) in the W7-X stellarator including the long cables and the anti-alias-filters. It is foreseen to use a system of light calibration sources that illuminates the photodiode arrays with intensity modulated light (see figure 3). From frequency sweeps the response curves will be measured.

Data measured for the two different magnetic field topologies of the low iota and the high iota configuration shall serve as a benchmark for SXR tomography using XMCTS. The calculated tomograms for both magnetic configurations are presented in figure 12. For each tomogram time-averaged data of a 5 $\mu$s interval is used from certain times during the chosen programs. According to the rather small variation of the amplitude responses for most cameras reported in [11] a constant sensitivity for all cameras is assumed. As a realistic proxy for the relative deviation between the sensitivities of the photodiodes a relative error variable is included in the tomography code, that has been set
to 3% [29]. Furthermore the shutter shadowing effects are included for the calculation of the contribution matrix. Note that the reconstructions are calculated without applying any information about the flux surface topology.

Figure 12(a) shows the two-dimensional x-ray emissivity distribution for the low iota configuration program 20180829.004. Superimposed are the flux surfaces calculated by VMEC equilibrium calculations [25, 30] for a plasma $\beta = 1.02\%$ approximately present at $t = 6.2$ s of the discharge. The general shape of the SXR emissivity agrees quite well with the VMEC flux surfaces. However there are some smaller deviations regarding the centering and the poloidal symmetry relative to the VMEC flux surfaces. The SXR emissivity seems shifted upwards by approximately $+5$ cm and to the HFS by $\sim 5$ cm. A weak poloidal asymmetry is visible, indicated by the variation of the emissivity contour levels relative to the flux surfaces, especially for the cyan colored levels. For the high iota case [figure 12(b)] the shape of the x-ray emissivity changes as expected according to the change of the magnetic field topology. Compared to the low iota configuration it can be clearly seen that the two-dimensional x-ray emissivity distribution decreases in size, i.e. it becomes more compressed towards the center and exhibits a more horizontally elongated shape similar to the respective VMEC flux surfaces. In both tomograms of figure 12 the emissivity seems slightly stretched in vertical direction, however the general shape of the emissivity is reasonable nested within the VMEC flux surfaces. The lower order deviations are here the same as stated for the low iota case.

In the following the time resolution of the tomography system and the bandwidth is investigated by means of data of a W7-X high performance discharge of OP1.2b. Figure 13 illustrates the main plasma parameters. The discharge is heated by ECRH in the 4 MW range. A considerable increase of the electron density is achieved by hydrogen pellet injection [31] between 1.4 and 2.5 s. Each hydrogen pellet leads to a stepwise increase of the electron density. In this way the line-integrated density is increased from $4 \times 10^{19}$ to $1.2 \times 10^{20}$ m$^{-2}$ between 2.6 and 3.2 s of the discharge. These density steps are well resolved in the SXR signals of the XMCTS camera [figure 13(d)]. During the high power plasma phase at $\sim 2.9$ s the diamagnetic energy increases above 1 MJ. The electron temperature during this phase stays below 5 keV. As already seen in figure 8 the relative shape of the SXR signals is again relatively similar to the trace of the diamagnetic energy. Especially the peak of the highest diamagnetic energy agrees with the peak of the measured SXR radiation [figures 13(c), (d)].

In the following the SXR fluctuations in the high power plasma phase between 2.2 and 3.3 s are studied. Here the ECR heating power ramps up from 4 to 4.7 MW at $t = 2.7$ s. At the begin of the time interval the hydrogen pellet injection phase ends. The electron temperature increases from $\sim 2$ to $\sim 3.5$ keV. Simultaneously the diamagnetic energy increases from 0.7 to 1.1 MJ within 0.4 s. The high power plasma phase is sustained in the time interval $\sim 2.8$–3.1 s. Within this phase the fluctuations in the SXR range increase. Figure 14 shows a frequency spectrogram calculated by wavelet analysis [32] of a SXR time trace of a line-of-sight crossing the density gradient region.

At the end of the hydrogen pellet injection phase, between 2.2 and 2.5 s, the largest fluctuation amplitudes can be associated to quasi coherent fluctuations within a low frequency band in the range of $\approx 1$–3 kHz. In the SXR frequency spectrograms hydrogen pellet injections can be usually recognized by strong, damped fluctuations in the frequency range $< 5$ kHz. Figure 14 shows three of these events at the times 2.23, 2.3 and 2.4 s. During the high power plasma phase more energy is available in the plasma that can drive instabilities. Despite the small fluctuation amplitudes in

![Figure 13](https://example.com/figure13.png)

**Figure 13.** Parameters of high performance discharge W7X-PID 20180911.033: (a) ECR heating power, (b) line-integrated density and core electron temperature, (c) diamagnetic energy, and (d) the soft x-ray signal of the central line-of-sight of XMCTS camera 2C. In (d) the purple and violet lines are the averaged data, the gray areas are the maximum and minimum data of 1 ms intervals (small fluctuation level).

![Figure 14](https://example.com/figure14.png)

**Figure 14.** Typical wavelet frequency spectrogram of a high power plasma phase of the high performance discharge W7X-PID 20180911.033 calculated from XMCTS raw data time trace of camera 1A LOS #17.
the SXR signals, the rise of the fluctuation level and the broadening in the frequency space can be clearly observed. Particularly strong fluctuations appear in the 0–50 kHz range.

Before the high power plasma phase the bandwidth can be roughly estimated from the width of the frequency range to be up to ~100 kHz where the noise level is reached. During the high power plasma phase broadband activity can be seen up to ~200 kHz. According to a higher SNR the high frequency components become also visible in the 100–200 kHz range.

4. Discussion

For the tomographic inversion the most serious problem for OP1.2 turned out to be small misalignments of some camera shutters. Fifteen camera shutters did not open as accurately as planned with deviations in the order of ±0.5 mm resulting in partly blocked lines-of-sight. Depending on the magnetic field configuration (and thus on the flux surface topology) in the order of 100 lines-of-sight are affected by partly shadowing of the photodiodes by the camera shutters. To include data from the affected photodiodes for tomographic inversion, the shadowing effects due to the shutters have been incorporated in the tomographic inversion. In particular the shutter positions are estimated and included in the calculation of the contribution matrix. In this way most of the affected lines-of-sight could be used for tomography. Under the assumption of constant SXR emissivity on flux surfaces a similarity of contour lines in the tomograms and flux surfaces is expected. The experimentally obtained x-ray emissivity distributions in figure 12 obtained from tomography are reasonably nested within the flux surface topology. We note that for the low iota case the x-ray emissivity seems to be slightly shifted towards the HFS. Deviations from the flux surface symmetry especially for \( \phi > 0.2 \) can be recognized for which two main effects can be accounted for. According to the toroidal averaging effect along the toroidal width of the view cones the tomograms seem stretched in vertical direction (see figure 7). For the W7-X setup this means the tomograms can be stretched up to 10% in vertical direction compared to the flux surface topology in the poloidal cross-section at exactly \( \phi = 36^\circ \). In future improved versions of tomography codes this effect could be avoided by including the toroidal variation of the magnetic field lines in the calculation of the contribution matrix. The second main reason for the observed deviations from the flux surfaces are the mentioned variation of photodiode sensitivity as well as (small) differences in the electronics. Those deviations will be compensated by accurate amplitude calibration measurements. An inspection of the beryllium filters after OP1.2 exhibited thin coating on some of the filters. Investigations of its influence on the spectral transmittance of the filters are in process. The filters will be renewed until the upcoming OP. The bandwidth of 200 kHz of the XMCTS cameras has been measured in the laboratory from amplitude phase responses. The frequency spectrograms of the SXR traces of the high performance discharge in figure 14 indicate that the cameras are sensitive enough to detect fluctuations up to ~200 kHz. A calibration of the complete system including the long signal cables and the anti-alias-filter modules is scheduled for OP2.

5. Summary and conclusions

The SXR tomography diagnostic (XMCTS) at the stellarator W7-X has been commissioned in the recent OP OP1.2a/b. Twenty pinhole cameras are installed inside the vacuum vessel in a poloidal circumference in one of the five up–down symmetric triangular cross-sections. Being actively water-cooled the cameras with its onboard preamplifiers performed reliable within the planned temperature range and can now be expected to withstand the heat fluxes in the forseen 30 min long high power plasmas in the upcoming OP. The XMCTS uses AXUV silicon photodiode arrays to measure SXR radiation along 360 lines-of-sight. The lower limit of the spectral range is set by a beryllium filter of 12.5 \( \mu \)m thickness to approximately 1 keV (transmittance reduced to \( e^{-1} \)). The upper part of the spectral range is limited by the responsivity of the silicon photodiodes to approximately 12 keV (\( e^{-1} \) responsivity). The setup and line-of-sight geometry finally used during the commissioning of the XMCTS at the W7-X stellarator have been presented. Nineteen of the twenty cameras have regularly acquired data in OP1.2a/b. One camera is scheduled for repair after upcoming OP2. It turned out that several shutters did not open completely, resulting in partial shadowing of lines-of-sight. As proof of principle the XMCTS raw data basically reflect the up–down symmetry of the x-ray emissivity distribution. Deviations from this symmetry are observed in terms of varying signal amplitudes of some opposite camera pairs (up to the order of 30%). The line-of-sight shadowing by the misaligned shutters is one reason for these deviations. Furthermore the variation of the beryllium foils in the cameras and the coating of the beryllium foils can be accounted for camera profile deviations. For more clarification of these deviations amplitude calibrations are envisaged in the upcoming OPs, especially as soon as the \( \text{in situ} \) calibration system operates reliably. First results from tomographic reconstructions indicate two-dimensional x-ray radiation distributions being in reasonable agreement with the flux surface geometry obtained from VMEC calculations. Reasonable tomographic inversions need to incorporate the individual line-of-sight shadowing by the shutters in the tomography code. For high performance discharges the measured XMCTS signals occasionally saturate. In order to compensate for the shutter misalignment and to avoid saturation the entry slits of the cameras will be adapted in the upcoming OP. Comparisons of obtained tomograms from XMCTS measurements with the magnetic field topology calculated by VMEC show reasonable agreement. A frequency analysis of SXR data of a high power plasma show activity in a wide frequency range. Depending on the SNR the bandwidth is approximately in the 0–200 kHz range.
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