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Installation of the soft X-ray multi camera tomography system (XMCTS) in the Wendelstein 7-X stellarator

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Abstract

The soft X-ray multi camera tomography system (XMCTS) was installed inside the plasma vessel and is currently prepared for commissioning and first operation in the next experimental campaign of the Wendelstein 7-X stellarator. The diagnostic consists of a set of 20 X-ray cameras installed inside the plasma vessel. For design, engineering and manufacturing of the mechanic and electronic components extensive requirements had to be met, which are specific for operation in a long pulse plasma device. This includes for instance compatibility with high levels of microwave stray radiation, the need for active cooling and the handling of sputtering of wall material. This paper describes the final preassembly and provides a summary of major technical issues. The key work packages are the welding of the pipe systems (water cooling, compressed air, signal) and the integration of the electronic components including signal and supply cables.

Keywords: MHD modes, tomography, x-ray diagnostic, W7-X
PACS: 52.25Xz, 52.35.-g, 52.35Mw,

1. Introduction

After the first operation phase (OP) with helium and hydrogen plasmas in the Wendelstein 7-X (W7-X) stellarator between December 2015 and March 2016, the set of plasma diagnostics will be extended during the shutdown phase until OP1.2 [1]. One of these additional diagnostics is the soft X-ray multi camera tomography system (XMCTS) serving for the detection of spatiotemporally resolved high-frequency instabilities, MHD-mode dynamics and Shafranov shift of the flux surfaces with plasma beta. Together with other diagnostics [2] as the bolometer, the pulse height analysis system (PHA), the high efficiency extreme ultraviolet overview spectrometer (HEXOS) and the laser-blow system (LBO) it also provides supportive information about the transport dynamics of impurities in the plasma. The concept of the XMCTS [3, 4] is based on the tomography system MiniSoX that worked successfully in the stellarator W7-AS [5]. In the first half of 2016 the final preassembly has been accomplished and the installation of the XMCTS in the W7-X stellarator has been completed in August 2016.

After a short summary of the requirements and the setup of the XMCTS in Sec. 2, the remaining part of the paper describes the key procedures and tests during preassembly (Sec. 3) and finishes in Sec. 4 with the conclusions.

2. The soft X-ray multi camera tomography system

The XMCTS is located inside the W7-X plasma vessel in a poloidal plane at a toroidal position where the flux surfaces have a triangular shape. In this plane, there are no island diver-

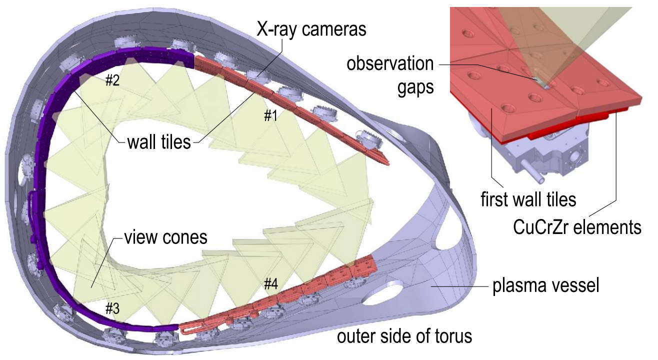

Figure 1: (Color online) Arranged in a poloidal array twenty pinhole cameras inside the plasma vessel mounted between the vessel wall and the first wall observe the plasma through individually shaped gaps in the wall element structure.

tor modules installed. A simplified schematic of the XMCTS illustrating the cameras, the plasma vessel and the wall elements is shown in Fig. 1. Twenty pinhole cameras are aligned on a poloidal circumference and mounted on four segments of stainless steel support structures. The four segments consist of two pairs with each two identical segment types: a straight and a bent type segment, each type positioning five X-ray cameras. The XMCTS segments are mounted between the plasma facing wall tiles and the vessel wall. Thereby the cameras are protected against heat and power loads from the plasma that are expected to reach values of 0.5 $\mathrm{MW/m^2}$. The graphite tiles of the first wall are mounted on actively water cooled CuCrZr wall

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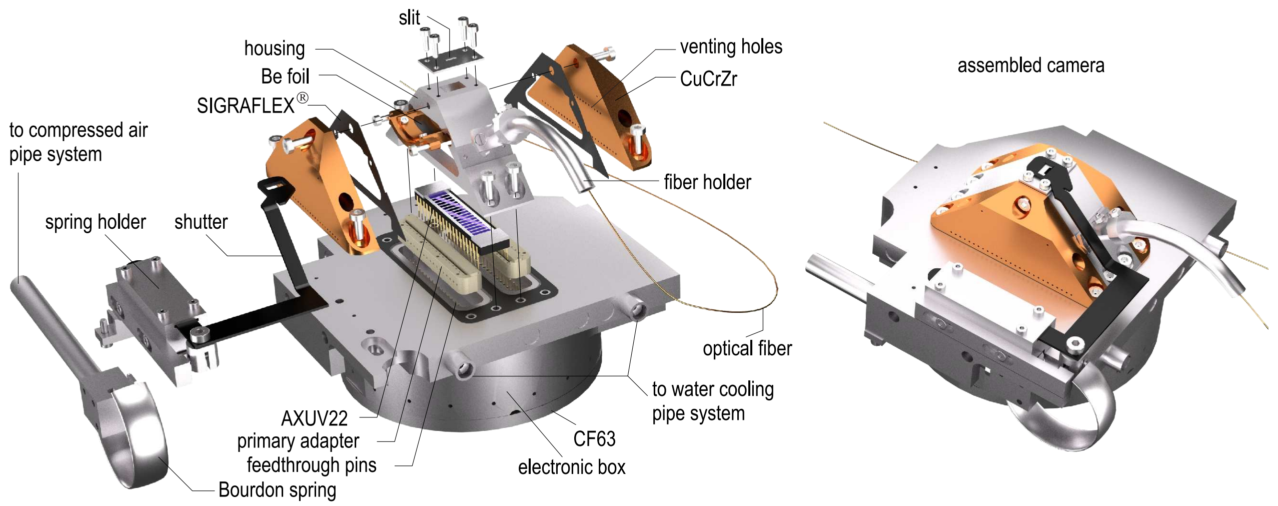

Figure 2: (Color online) Artists view of the XMCTS camera setup on the vacuum side in a blow up drawing.

elements. The XMCTS cameras observe the plasma through individually shaped gaps in the tiles as illustrated in Fig. 1. The view cones of the cameras are indicated and partly plotted only, actually they cover the complete poloidal cross section. Figure 2 shows a blow up drawing of one camera visualizing important components located on the vacuum side. Each camera is equipped with a silicon diode array (AXUV22, IRD-Inc, USA [6]). The silicon diode array is sensitive to radiation from the visible to the X-ray range. For detecting the X-ray radiation only the cameras are fitted with a curved beryllium filter of a thickness of 12.5 μm (transparent for photon energies $\gtrsim$ 1 keV). The AXUV array needs to be shielded from any radiation that is not supposed to be measured. This is achieved by encapsulation using the housing and the side plates. To ensure an effective evacuation while avoiding virtual leaks and protecting the AXUV array against microwave stray radiation from the 140 GHz electron cyclotron resonance heating (ECRH), lateral venting holes are drilled into the side plates. The holes need to have a diameter of $\approx$ 1 mm ($\lambda_{ECRH} = 2.14$ mm, openings should be $< \lambda_{ECRH}/2$) [7].

One array consists of 22 photodiodes, the 1st and the 22nd photodiode are covered by a metal shield to measure the offset relevant for detecting temperature drifts. The currents from the photodiodes are converted into voltages by transimpedance amplifiers (the half-shadowed diodes #2 and #21 are not used). In total 360 lines of sight directly observing the plasma are eventually used for tomographic reconstruction. A more detailed description of the camera setup, especially the electric multipin feedthrough, the camera cooling principle, the pneumatic shutter and the fiber illumination system can be found in Ref. [8].

In order to keep the noise level as low as possible the preamplifiers are located at closest distance inside the electronic box. To prevent any outgassing and damage due to microwave stray radiation of the preamplifiers inside the electronic box, these components including signal and supply cables are vacuum tightly sealed from the W7-X vacuum. In case of leakage, a secondary vacuum can be drawn in this volume via a vacuum pump in the torus hall. The signals of the preamplifier outputs are electrically connected with ADCs located in distant racks in the torus hall via vacuum feedthroughs. The signals are guided by teflon insulated shielded twisted pair cables. The strict vacuum requirements (maximum allowed leak rate 1.0×10^{-9} mbar L s^{-1}), the boundary conditions in space limiting the size of all parts, the active water cooling system, the shutter system, the support frame structure and the electronic demands of the photodiodes combined with the preamplifier layout required to find a working compromise for the whole design of the XMCTS. The final preassembly was started in January 2016. All steps and work packages during preassembly and in-vessel-assembly were conducted following strict quality assured assembly procedures (QAAPs). These include tests and certificates of all used materials, vacuum connections, mechanical and electrical components and functionality. Especially the demanded magnetic permeability $\mu_r < 1.01$ and the low Cobalt concentration ($<$ 500 ppm) were strictly controlled and documented.

3. Preassembly of the XMCTS

The main work packages of preassembly in the laboratory could be parallelized into two areas of work: (1) the assembly of mechanics of cameras and frame structures and (2) the assembly of the electronic components. In the following the work packages are briefly described and summarized.

Assembly of mechanical components. Figure 3 shows the two types of segments in CAD drawings representing the planned geometry and the components in photographs after preassembly. The setup and the mounting concept of both types of segments the same, only their weight is slightly different. Fully equipped without water cooling a bent segment has a weight of $m \approx 26.6$ kg and a straight segment has a weight of $m \approx 23.3$ kg. The support frame structures were prepared for starting the iterative work of aligning and welding the three pipe systems, i.e., the pipe systems for cooling water, compressed air and signal cables. With more than 350 orbital welding seams this work

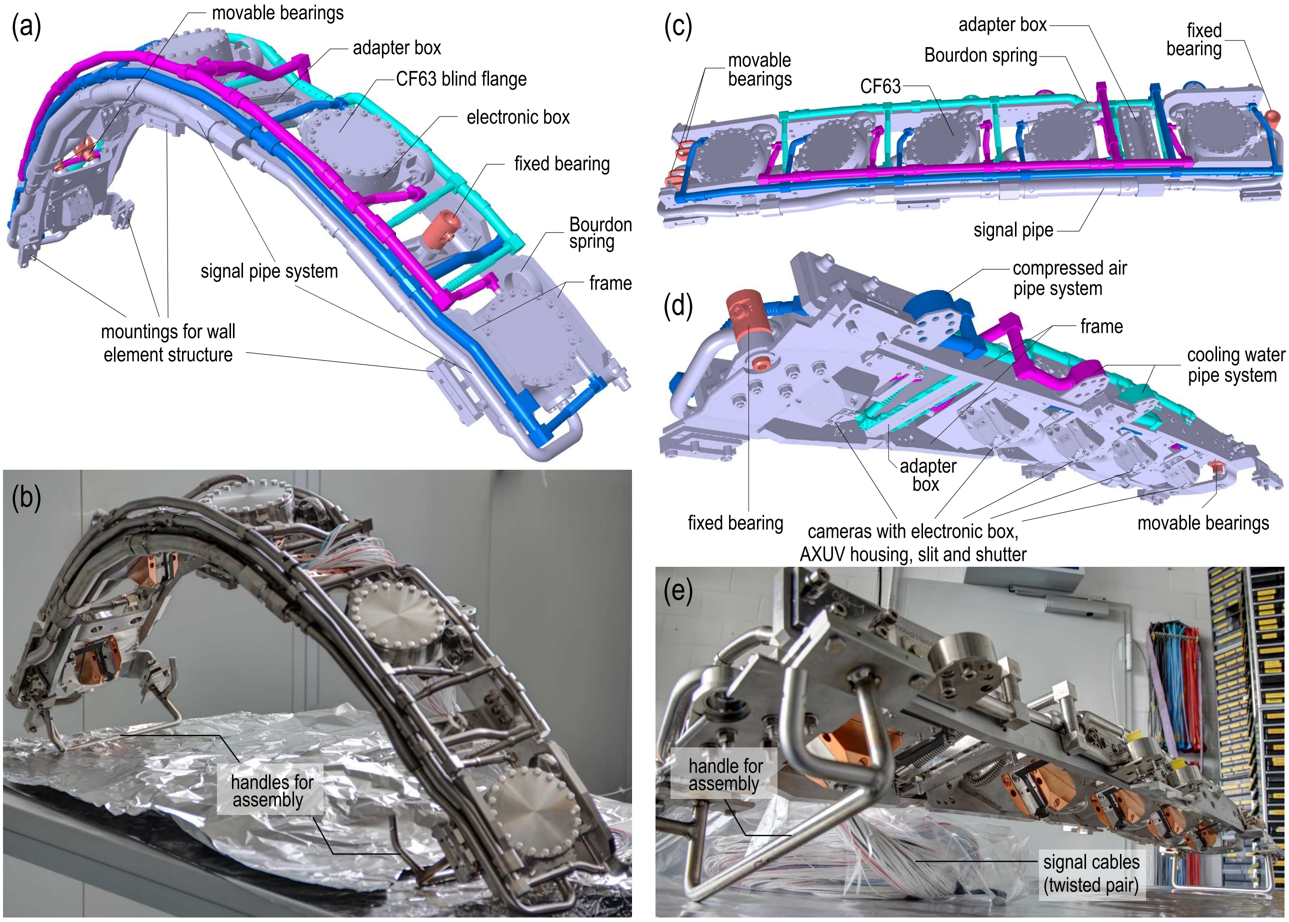

Figure 3: (Color online) The two types of segments: the bent segment (a) as planned in CAD and (b) after preassembly; the straight segment (c,d) as planned in CAD and (e) after preassembly. (At the time of the photographs taken the bearings have not been delivered yet, and are thus missing.)

package was most critical. With a specially manufactured support structure for mounting and keeping the alignment of the cameras (which is essential in order to avoid shadowing of view cones), all welding seams could be set correctly. In the framework of the QAAPs all welding seems were visually inspected, 15 % were X-rayed and helium leak-tested. Simultaneously, the cameras were completely assembled before mounting on the frame structures. After inserting the primary adapters on the vacuum side and soldering the electronic adapters in the electronic boxes, helium leak tests were repeated to confirm that the delicate custom-made electric feedthroughs remained leakproof. Prior to installation all AXUV arrays were checked for best quality, especially for undamaged bonding wires to the anode (since this would result in poor quality amplitude and phase responses). The photodiode arrays were mounted on the primary adapters. The housings of the AXUV arrays were completed including the beryllium filters and were attached to the electronic box. The pneumatic shutters of each camera were tested and adjusted in vacuum. The closure of the shutter is achieved by applying $\Delta p = 5\,\text{bar}$. During W7-X operation, it will be used to protect the Be foils during boronization and for electronics drift compensation during long W7-X plasmas.

Assembly of electronic components. The preamplifier electronics were installed in the electronic boxes and the signal and supply cables ($\Sigma = 135$ cables) were pulled from each electronic box to the adapter box. In the adapter box the cables from all five cameras within the individual segments are grouped and routed further to the feedthroughs via the port plugins. Both tasks needed to be done with utmost care. The correct installation of the stack of three preamplifier boards - each equipped with micro-connectors - within the electronic box were visually controlled with dental mirrors, endoscopy as well as with control measurements of chosen resistances and capacitances (between AXUV anode and supply contacts or bias contact) to avoid and the check any damage during the procedure of connection. For the functional tests of the preamplifier electronics intensity-modulated light of a LED was guided to the photodiode array using the optical fiber system [compare Fig. 2]. The amplitude and phase responses of the arrays in the frequency range 1 kHz to 1 MHz were measured using a gain phase analyzer (*HP 4194A*).

Figure 4(a,b) exemplarily shows the measured amplitude and phase responses of one camera. Two signals are shown, one is measured by a well illuminated photodiode (#12) and the other one is measured by one of the covered photodiodes (#01). The responses of the well illuminated photodiode are completely

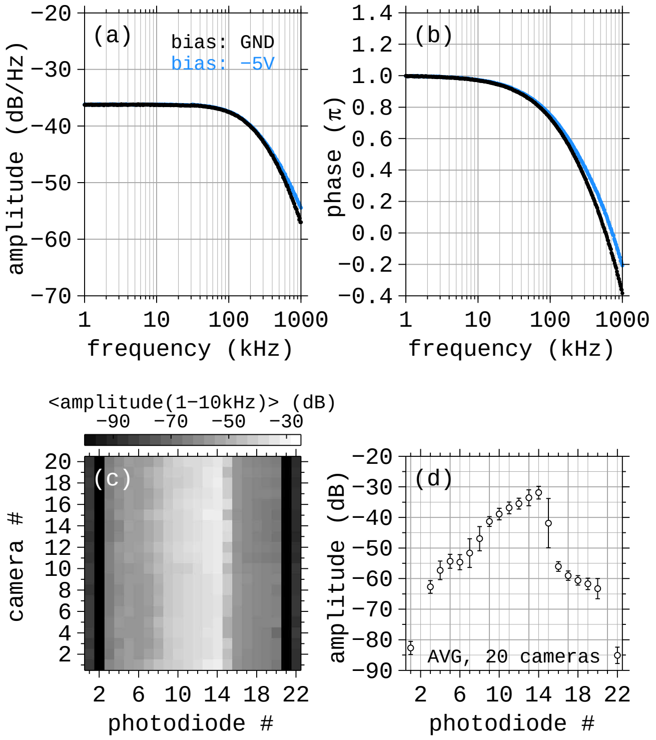

Figure 4: (Color online) (a) Amplitude and (b) phase responses of photodiode #12 of camera #3 on segment #2. The measured averaged amplitudes of the functional test between 1 – 10 kHz shown (c) for all photodiodes of the 20 cameras. The photodiodes #2 and #21 are not connected. Averaging these amplitudes over all cameras yields plot (d). The error bars are plotted as 2σ, indicating the deviation of the measured amplitudes between all cameras.

smooth until $\approx$ 100 kHz, when the amplitude response starts to decrease. The cutoff frequency is $\approx$ 200 kHz. Compared to the prototype design presented in Ref. [9] the quality of the amplitude and phase response of the preamplifier boards could be further improved by optimizing the layout of the conducting paths.

The maximum detected amplitudes averaged over the first 10 kHz for all cameras and all photodiodes are shown in Fig. 4. All photodiodes are fully functional. Figure 4(b) shows the amplitudes averaged over the 20 cameras. For all cameras the trend of the amplitudes along the array is similar. The indicated deviation has two origins, the deviation of the photodiode electronics and the deviation due to slight differences in alignment of the optical fiber system. Especially the higher value of the deviation at photodiode #17 can be attributed to the limited alignment accuracy. The small deviations for all other photodiodes indicate quite comparable electronic characteristics of all AXUV arrays.

4. Conclusions

The preassembly of the XMCTS segments was successfully finished following the strict quality assured assembly procedures. Figure 5 shows a photograph taken before handing the diagnostic over to the assembly department. In August 2016 the four XMCTS segments were mounted inside the W7-X plasma

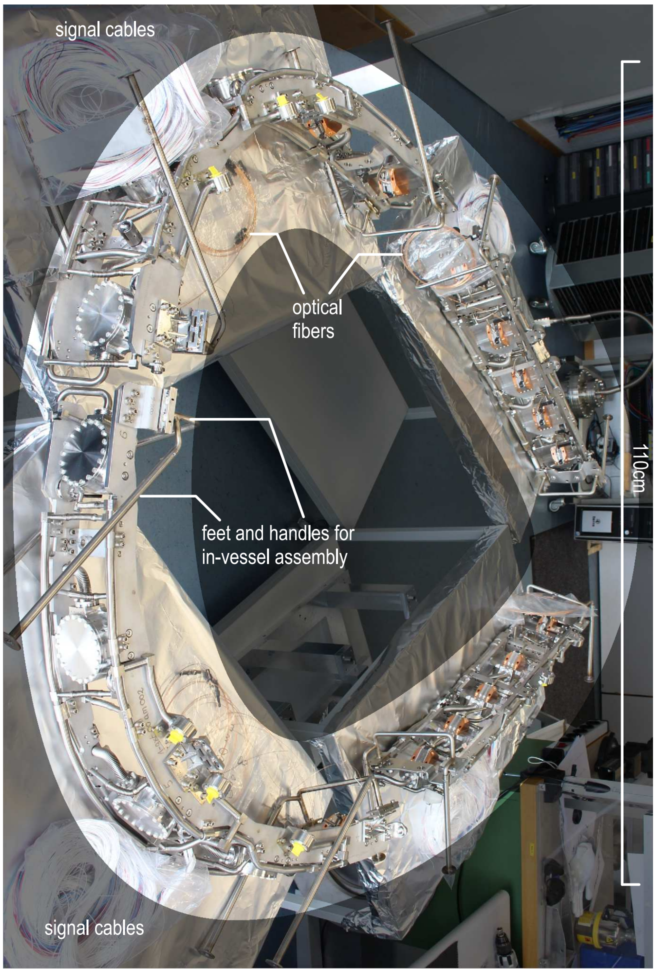

Figure 5: (Color online) All segments arranged in the laboratory after final preassembly.

vessel. Further work is ongoing to complete the ex-vessel installation of the periphery components in the torus hall.

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