Sensitivity study of the SX tomography system on Wendelstein 7-X

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The steady state operation foreseen for the Wendelstein 7-X stellarator (W7-X) under construction in Greifswald, Germany, poses several additional challenges to the diagnostics design as compared to short pulse machines. For instance, the soft-X ray tomography system, for which the major part of in-vessel components is being manufactured now, needs water cooling for the silicon detectors and electronics. An in situ fast pneumatic shutter system will be used to recover the signal baselines during long discharges. It also can mitigate coatings of the beryllium foils during cleaning or long discharges which can sputter material comparable to a month of operations in pulsed fusion devices. Furthermore, a robust and accurate tomographic inversion of the SX radiation distribution relies on an exact knowledge of the sight line geometry. The soft-X-ray Multi Camera Tomography System (XMCTS) consists of 20 cameras, mechanically grouped in 4 segments, which are located in a poloidal plane inside the W7-X plasma vessel. A symmetry plane was chosen, where no divertor structure is present (free lines of sight). Each camera consists of a silicon array detector (AXUV-PIN with 22 diodes, manufactured by IRD), a beryllium filter to suppress visible light and soft X-radiation from the plasma edge, and a directly attached pre-amplifier inside a secondary vacuum stainless steel box. It is foreseen to achieve a bandwidth of 500 kHz in order to monitor fast MHD mode activity.

Assembly and sources for geometric misalignments For the assembly in the W7-X plasma vessel, the four pre-assembled XMCTS segments will be attached to bearings welded to the plasma vessel. For each segment one fixed (sphere) and one friction bearing is foreseen. Together with the mounting of the segment, the electrical and media supplies will be attached (sealed by conflat flanges) to the supplies from the port plug-ins. The required appropriate sealing of the flanges will constrain the freedom in the positioning of the XMCTS, so that an optimal alignment with respect to the magnetic field as reference is not feasible. The heat-protection (water-cooled CuCrZr-structures with graphite tiles, for a heat load of up to 500kW/m²) will be adjusted with respect to the neighboring plasma facing components and fastened by screws to the XMCTS support frames (cf. Fig. 1). Since the heat protection is attached to the segments (pre-adjusted in the laboratory), a vignetting of sight lines passing through the dedicated openings in the graphite tiles can be avoided. The alignment accuracy of the camera sight lines is on the one hand determined by the individual camera positioning deviations inside each of the 4 segments (manufacturing tolerances) and on the other hand by the positioning of the segments with the contained cameras during in-vessel assembly. The latter will cause a more correlated misalignment imprint on the sight lines, since a set of 5 cameras is moved together with its segment. Metrological measurements inside the plasma vessel have an absolute accuracy of <1.5 mm. In contrast, the aforementioned inaccuracies in manufacturing (in the order of ±1 mm / ±0.5°) can be accounted for by measuring the individual cameras within the segments in the laboratory. Therefore, the geometry of the cameras within one segment is known to a high precision (<0.5 mm). A further source of misalignment is caused by the expected deformation of the plasma vessel by magnetic and vacuum forces. In Fig. 2 the results from a finite element model (FEM) are presented, which show maximal deformations of ±1.6 mm in the poloidal plane of the XMCT System. The deformation causes a misalignment of the XMCTS cameras via the bearings of the segments to the plasma vessel. Since metrological measurements in the evacuated plasma vessel with the magnetic field coils in operation will not be possible, the FEM calculations are yet the only available information. We note here, that the error bars for the details of the predictions might be large, but the order of magnitude should be correct. The deformation depends on the magnetic configuration (e.g. standard case with respect to high iota case), since the magnetic forces on the vessel are different. Thus, the positioning deviation caused by deformation of the vessel adds a dynamic component on top of the less well known installation situation inside the vessel. The resulting movement of the support frame segments is constrained, since each segment has one sphere bearing and one friction (fork-shaped) bearing, thus avoiding a deformation of the individual segment. A deformation of the segment is possible by the temperature expansion. For the maximum temperature of 150 °C within the support frame, the expansion of one segment is less than 2 mm.

XMCTS sensitivity on geometric misalignments The sensitivity analysis is based on theoretical plasma profiles, radiation distributions and the considered geometry, neglecting effects associated with the conversion of the radiation into digitized data. The linear forward model containing the sight line geometry is described with a contribution matrix. A misalignment of the sight line geometry, i.e. the positioning deviations of the cameras, leads to a slightly different contribution matrix with respect to the unperturbed reference matrix. Using the same local emissivity distribution for the misaligned and the reference case, the line of sight integrated signals are different (c.f. Fig. 3). Following this procedure, the sensitivity of the LOS- data on misalignments in the sight line geometry can be estimated independent from a tomographic inversion. A set of realistic emission distributions is considered in the analysis in order to assess the effect of the misalignments on the detector signals. The foundation of the theoretical emission patterns are VMEC-calculations of expected flux surfaces for various coil current combinations (comprising different plasma shapes, i.e., standard, high-iota, etc.). The temperature and density profiles are taken from transport calculations (10 MW ECRH heating [1]) and SX radiation profiles considering a carbon impurity distribution are used to calculate the corresponding spatial radiation distribution (the phantom data) following the flux surface contours [2]. The relative deviation ε is defined by the normalized minimum distance between the reference and the perturbed simulated signals. A number of misalignment geometries were analyzed in which the angle around the rotation points of the segments (the sphere bearings) was set at $\alpha = \pm 1°$ and the angle direction was permutated. The relative deviation estimated over the set of phantoms with various configurations was below $\varepsilon = 4$ %, relatively independent of the concrete misalignment in the geometry. Thus, the sensitivity on angle misalignment of the support frame segment is s= 4%/°. We note, that the expected angle misalignments of the segments are a factor of 10 lower ($\alpha = \pm 0.1°$). For vertical and horizontal shifts of the segments towards the plasma vessel, we observe a sensitivity of s= 1.7%/cm to s= 3.4%/cm depending on the direction of the shifts. The expected misalignment of the segments by shift displacements is below 2 mm. Taking into account both contributions we expect relative deviations in the order of $\varepsilon < 1\%$. For the deformations predicted by the FEM calculations (Fig. 2), the displacements of $d \sim 1.6$ mm were transformed into misalignment angles for the segments ($\alpha \sim \pm 0.1°$). Additionally, the changes in the individual camera positions due to the thermal expansion were included by an increasing displacement of $d=0.5$ mm for each camera along the segment. The observed relative deviation in the line integrated signals is less than $\varepsilon \sim 0.5$ %

Conclusion The XMCT System is mounted inside the W7-X plasma vessel underneath the KiP heat shield. The assembly concept has been optimized in order to minimize in-vessel assembly time and to avoid vignetting caused by movements between XMCTS and KiP. Misalignments can be documented with metrology measurements in laboratory, using the respective support frame segment as reference. After installation inside the W7-X plasma vessel, the XMCTS segments will be measured by metrology with respect to the magnetic field (accuracy < 1.5 mm). Additional uncertainties are expected from the dynamic changes of the plasma vessel contour for different magnetic configurations. The impact on the signals detected by the XMCTS system was modeled utilizing forward functions. According to this analysis the relative deviation should be below 1%. The misalignment deviations are expected to be moderate in comparison to the uncertainties due to the electronics circuits (cross-talk, imperfect shielding, thermal noise).

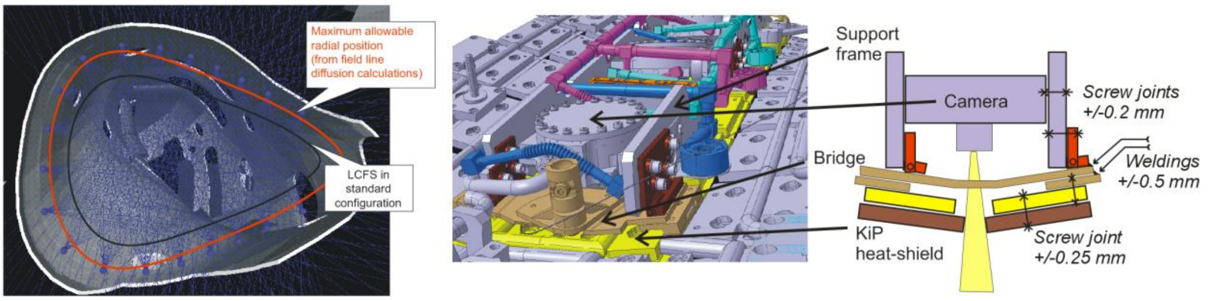

Fig 1: (a) Location of the XMCTS cameras inside the plasma vessel. (b) CAD view between plasma vessel (top, not shown) and part of an XMCTS segment with surrounding plasma facing components. (c) Schematic drawing indicating the components and fixations.

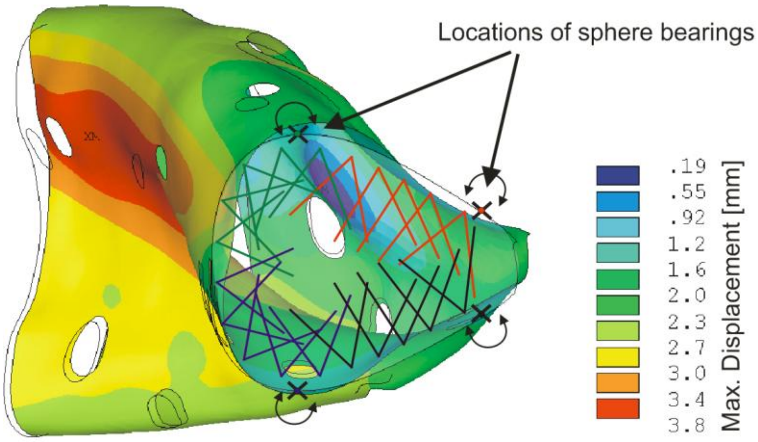

Fig 2: Results from FEM calculation showing the deformation of the plasma vessel (exaggerated) and the view lines. The location of the sphere bearings is indicated by a colored point.

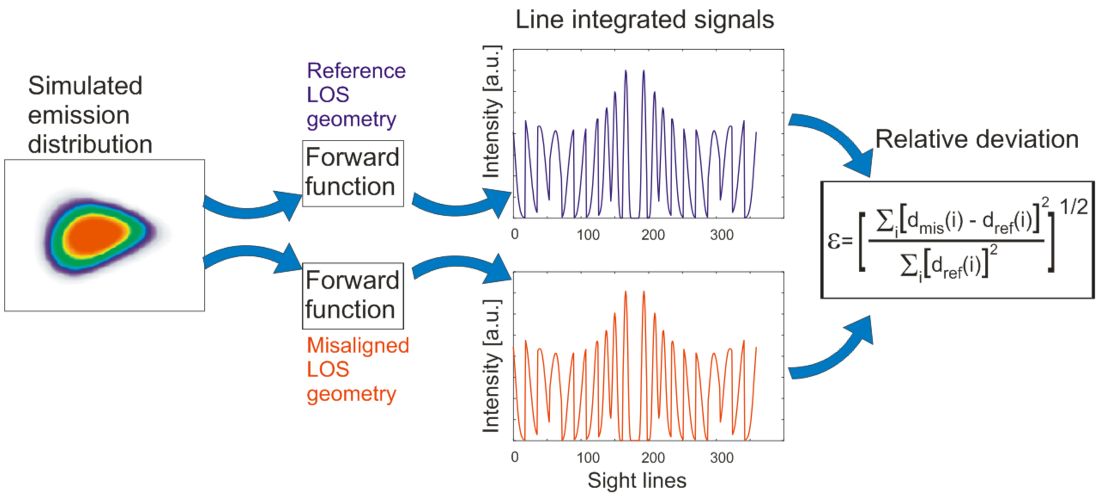

Fig 3: Schematic of the procedure to estimate the effect of misalignments in the line of sight geometry (LOS) on the line integrated signals. A set of different emission distributions was used, yielding a better error estimate.

[1] Yu. Turkin, H. Maassberg, C. D. Beidler, et al. Fusion Sci. Technol. **50**, 387 (2006).

[2] H. Thomsen, P.J. Carvalho et al, 35th EPS Conference on Plasma Physics ECA **32D**, P1.065 (2008).