Reconstruction Accuracy of the Soft X-Ray Tomography System on MHD Modes in Wendelstein 7-X Stellarator

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Introduction

The soft-X ray multi camera tomography system (XMCTS) is presently assembled in Greifswald. It consists of 20 pinhole cameras, each with a silicon diode detector array with 22 channels. The cameras are grouped in 4 segments with 5 cameras each, which will be installed inside the plasma vessel of Wendelstein 7-X (W7-X). The small current signals (order of µA) from the detector (AXUV-type by IRD-Inc, USA) are amplified in a two-stage amplifier, which is localized within a short distance to the detector in order to achieve a high bandwidth. Since the preamplifier electronic components are not UHV compatible (i.e., they would outgas and spoil the vacuum) and the Teflon-insulated cables do not withstand microwave stray radiation, a secondary vacuum system is prepared to separate the diagnostic electronics from the W7-X vacuum. The electronic boxes (E-box) containing the preamplifiers constitute the most important part of this system. Due to the in-vessel space restrictions, the height of the E-box is limited to 40 mm (including the lid, which is sealed by a CF-gasket). The E-boxes are water-cooled and contain custom-made vacuum feedthroughs (welded into the E-Boxes) for transferring the detector signals. The pins of the feedthroughs and those of the detector are connected by custom-made adapters made from peek (Socket Factory, Germany). The electrical contact is realized by gold-coated beryllium-copper springs. On the inner side of the E-Box, another adapter is used, which is brazed to a flexible printed board. This solution was chosen in order to avoid mechanical stress on the pins of the delicate vacuum feedthroughs and to compensate the tolerances of the pin locations.

The design is optimized to reduce the necessary height of the electrical adapters by lateral contacts to the pins. From the flexible printed board the signal currents are routed, via miniature plugs, to a stack of two printed boards with the multi-channel two stage pre-amplifiers. The preamplifier consists of a trans-impedance converter with a gain of 200,000 V/A followed by a differential cable driver as second stage. The receivers will be located at a distance of ~50 m, where the cubicles containing the analog-digital converters are positioned.

Preamplifier bandwidth measurements

Measurements were performed on a pre-series prototype to assess the bandwidth of the system. The main tool is a gain-phase meter (HP4194A), which records the response to a frequency sweep in the range from DC to 10 MHz. The probing signal is either electrically (via the adaptors without the diode array installed) or optically fed into the preamplifier. In the latter case, a LED emitting in the visible range is used to illuminate the AXUV-detector. A DC offset is added to the output of the gain-phase meter, so that the modulation of the light intensity is in the linear range of the LED characteristics. The results are compared to a commercially available photodetector with integrated preamplifier (Thorlabs). It was observed, that the bandwidths show a variation between the channels in the range of 400 kHz to 550 kHz. Possible reasons are the tolerances of the SMD resistance and capacitance in the feedback circuit, stray capacitances in the signal paths and capacitance variations between the diodes of the detector array. Moreover, some channels showed an increase in signal gain in this frequency range, indicating an unstable feedback situation. It was therefore decided to limit the 3dB bandwidth to f_{3dB} =170 kHz by a capacitor in the feedback circuit with C=4.7 pF for the series preamplifiers (pre-series: C=1.5 pF).

Signal simulation

In order to assess the effect of bandwidth variation (or tolerance) on the accuracy of the tomographic inversion, we consider a rotating mode (m=6) at a frequency close to the cut-off frequency. The data is simulated using the magnetic flux surfaces from a VMEC equilibrium calculation and assumed plasma density and temperature profiles to generate a radiation distribution profile using the IONEQ code. For a subset of flux surfaces in a radial range, the flux surfaces are perturbed – similar to the effect caused by a MHD mode – by an oscillation along the poloidal circumference with the excursion amplitude in radial direction. The 2D radiation distribution is calculated by mapping the 1D radiation profile onto the perturbed flux surfaces assuming constant emissivity on each (perturbed) flux surface, cf. Fig. 2. A time sequence of a rotating mode structure can be created by increasing the spatial phase of the mode between two calculated frames. The singular value decomposition (SVD) of the simulated mode is shown in Fig. 3a. The line-of sight integrated signals are calculated by ray tracing considering the étendues of the detectors. A Gaussian noise distribution is added to these signals, assuming a relative error of 2 % for all channels and additionally an absolute noise level of 1 % of the maximum signal. We note here, that the signal-to-noise ratio for certain channels is only 50 % with respect to the mode amplitude (but 400 % with respect to the DC signal).

Effects of limited bandwidth on the tomographic inversion

Since the tomographic inversion routines generally only consider data from a single time point (spatial domain), but the band width limitation applies to the temporal evolution (frequency domain), any prior knowledge cannot be used to compensate these effects. For a first assessment of this effect, a time sequence (with 10000 frames) of a rotating m=6 mode was generated and the noise was applied. The bandwidth limitation is imposed by a 1st order Fourier filter and the 45° phase shift at the 3dB frequency, as expected for a RC low pass filter, was added. We arbitrarily chose a filter pattern of every 2nd channel having the 3dB bandwidth at the mode frequency.

The utilized tomographic inversion is regularized by maximum entropy. The software is running as a service on a remote linux server and the data is transferred by means of the SOAP-protocol. A rectangular grid with 40x30 pixels was chosen for the inversion, resulting in a spatial resolution of 45 mm. The tomographic reconstruction is shown in Fig. 3b, from which the m=6 mode can be identified (although some artifacts inside the actual mode location are visible).

Beryllium foil qualification

The accuracy of the tomographic reconstruction is also affected by the quality (thickness homogeneity) of the used beryllium foils for filtering the low energetic light. Rutherford backscattering measurements of 5 Be-foils using 2 MeV protons were performed at the Tandem accelerator (IPP Garching). The measured mean thickness in the foil set was 13760 ± 490 nm (i.e., with a small variation), and the observed surface roughness was 1100 ± 170 nm (on a lateral scale below the beam spot width of 1 mm, estimated by forward modeling of the measured energy spectrum). It is expected, that the roughness of the Be-foils leads to a relative signal amplitude increase in the plasma edge region with respect to the central regions (with higher plasma temperatures).

Conclusion

The XMCTS diagnostics is in the assembly phase. The setup and bandwidth of the system will allow the tomographic reconstruction of MHD modes in the plasma of W7-X in the expected mode number and frequency range (demonstrated for an m=6 mode near the system bandwidth of 180 kHz). The reconstruction is robust against electronics bandwidth variations for a subset of channels. An in-situ calibration of the detectors with a fiber optics illumination is foreseen to identify possible failures of detectors and bandwidth limitations. In contrast to other sources of error, e.g. by sightline misalignment (Thomsen et al, EPS2012), it is yet unclear how to make use of prior knowledge about the bandwidth variations between different channels to improve the quality of the tomographic inversion. A challenge remains the large data amounts to be analyzed (1.4 GB/s) [Dong Li, this conference].

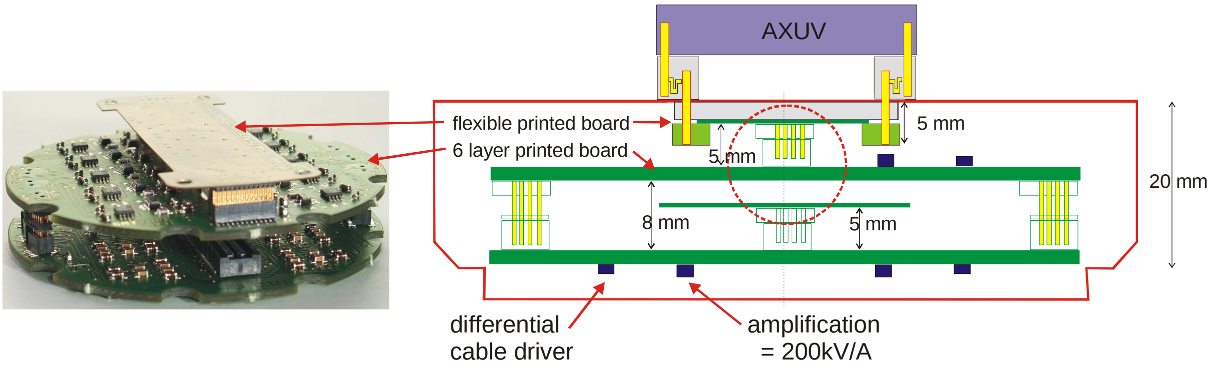

Fig 1: Photograph of the multi-channel preamplifier board and sketch of the space restrictions inside the electronic box (red outline).

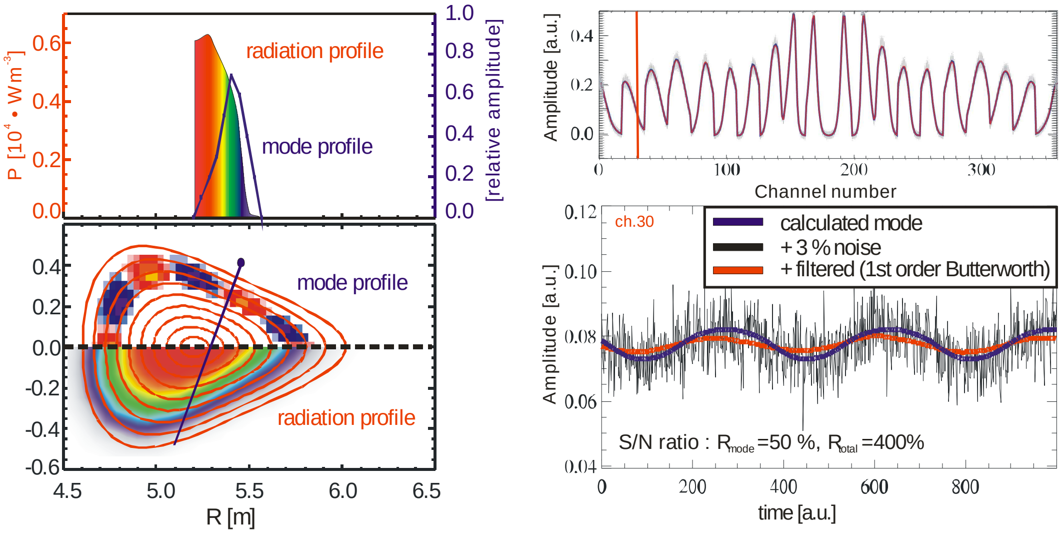

Fig 2:m=6 mode perturbs the magnetic flux-surfaces (VMEC output). The calculated signal distribution of all channels and a selected channel with the additional noise is shown in the right column.

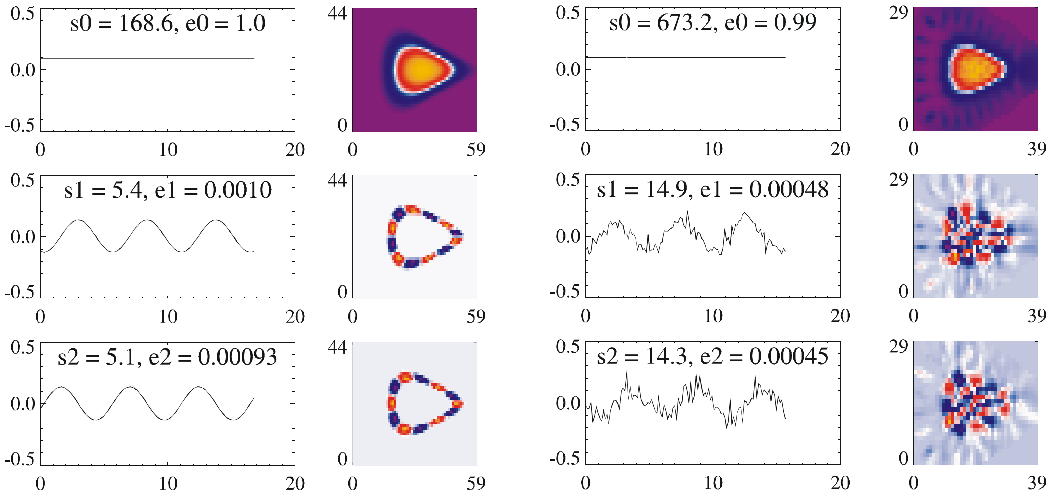

Fig 3: SVD decomposition with chronos and topos for the 3 most significant eigenvalues are shown. Left: calculated M=6 mode structure in the triangular plane of W7-X. The rotation is visible by the phase shift in the chromos of s1 and s2. Right: Tomographic reconstruction.