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Conceptual design of the multi-foil system for the stellarator W7-X

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The paper describes the conceptual design of the Multi-Foil System (MFS) for the stellarator Wendelstein 7-X (W7-X) operated at IPP-Greifswald in Germany. The proposed diagnostic is based on the well-known foil-absorption technique which is used for the estimation of the intensity of x-ray radiation and of the electron temperature.

The proposed diagnostic will be composed of up to eight detector arrays (with five Si detectors each) with beryllium filters of different thickness. The proposed detectors are silicon p-i-n diodes 380 μm thick, which assures good efficiency up to 20 keV. The main MFS vacuum chamber will be mounted on a suitable port of Wendelstein 7-X via a gate valve. At the chamber entrance are eight pinholes, covered by a beryllium foil of 10-μm thickness in order to protect the detectors from ECRH stray radiation. Additionally, inside the MFS vacuum chamber, eight beryllium filters of different thicknesses will be positioned to collect signals in eight energy ranges as defined by filters.

The paper presents the preliminary design taking into account specific W7-X requirements.

Keywords: soft x-ray diagnostic, multi-foil system, electron temperature, Silicon detectors.

1. Introduction

Measurement of soft X-ray radiation from plasmas is a standard diagnostic which is used in many different fusion devices. It can deliver various information about the plasma composition and condition. One of the main important parameters in fusion devices is the electron temperature (T_e). There are several diagnostics which deliver this information [e.g. 1-5] and one of them is a multi-foil system (MFS) which operation is based on the foil-absorption technique [6]. At the stellarator Wendelstein 7-X which passed its commissioning phase at the beginning of 2016, a set of important diagnostics [7, 8] was operated during the first experimental campaign OP1.1. The MFS is another one which is planned to be installed for the OP1.2 or OP2 experimental campaign. Assuming Maxwellian electron energy distribution, it is possible to determine T_e from the ratio of the soft X-Ray radiation registered in different energy ranges specified by application of various filters [9].

1. Purpose of the MFS system

The designed MFS diagnostic system is intended for the measurement of the X-ray emission intensity and energy spectra from five chosen areas of plasma. In this concept, the X-ray radiation is monitored by the use of 40 silicon semiconductor detectors configured in a 5×8 matrix (5 rows and 8 columns). Detectors from a row monitor five different view cones across the plasma. These view cones are defined by pinholes, delivering information about the spatial distribution of the radiation. The detectors from a column monitor the same plasma area, but each detector through a different beryllium filter (different thickness). This setup enables to obtain the spectral distribution of radiation. The shape of the spectrum cannot be obtained directly from the eight collected data sets, as spectral ranges are not standardized and they overlap. However, the shape can be obtained by applying the process of deconvolution (assuming that the shape of spectral responses of applied filters are exactly known). The resulting spectrum does not have an energy resolution high enough to reveal the line structure (as it is e.g. in the case of a PHA system [10]), but it gives the possibility of determining the slope of spectrum, which is directly related to the electron temperature of the plasma. Reconstruction of the energy spectra based on the experimental data can be realized by the deconvolution using e.g. Gilbert/Backus method [11-13].

By the use of the MFS system it is also possible to make absolute measurements of intensity of x-ray radiation, which is related to the parameters of plasma. The multi-foil system is intended for the measurement of soft X-ray (SXR) in the range of 1-20 keV.

2. Concept of the MFS for the W7-X

The design of the MFS system dedicated to W7-X has been started with the simulation of X-ray intensity for the plasma scenarios foreseen for OP.1.2 by the use of the RayX code [14]. As an input data the following parameters have been taken into account: plasma scenarios foreseen for 8MW of ECRH [15, 16], plasma-pinhole distance equal to 2.5 m (which resulted from the limitation imposed by the port dimensions) and

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pinhole-detector distance equal to 0.25 m (which resulted from the proposed detectors size and geometry (description in next chapter)). From the simulations the pinhole size has been fixed at 1 mm.

Because in the MFS, the detectors run in current mode, it was decided that expected current should be at level of 100-130nA which was satisfactory when evaluating the signal to noise ratio. Based on the simulation results the concept described below of the MFS for W7-X has been proposed.

2.1 Proposed detectors for the MFS system

Silicon p-i-n diodes, type FLM, from the Institute of Electron Technology, Warsaw are proposed to be used for the MFS system for W7-X. Originally, these diodes were designed for the detection of ionising nuclear radiation. The space charge region (I-layer which is sensitive to radiation) in the diode is 380 μm thick. Such large thickness (compared to common photodiodes) assures a high efficiency of the X-ray detection in the interesting energy range up to 20 keV. The space charge region is fully depleted (i.e. becomes sensitive) at a bias about 100 V. Due to quality imperfections of the silicon base material, full collection of the charge carriers cannot be achieved at this bias and neither at higher bias up to 400 V. For this reason, the charge collection efficiency should be measured at the operating bias voltage and an appropriate correction to the measured current from X-ray interaction needs to be introduced.

The dead layer on the surface of the diode (specified by the depth of diffusion p+ layer) is about 150 nm. Its effect on X-ray efficiency above 2 keV is marginal.

The dimensions of the active layer, which is defined by the front electrode, are 4.6×4.6 mm^2. The capacitance of the diode at full depletion is 10 pF. The rise time of the diode response, when operating on 50 Ω load and at full depletion, is 5 ns enabling high frequency signal registration.

The front electrode is surrounded by another, narrow, electrode, called ring. When properly biased, it can be used to intercept the harmful current flowing to the central electrode along the surface of the diode. This way, the dark current of the diode can be lowered and the measurement of the current induced by X-rays can be made more precise. An example of one detector array as proposed for the MFS system for W7-X is presented in Fig.1.

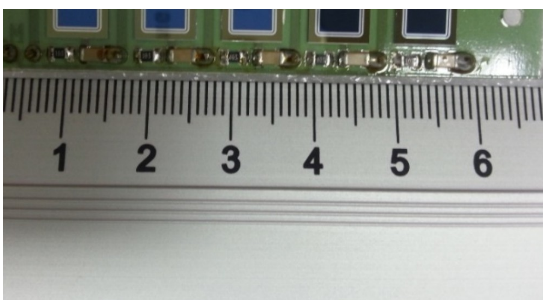

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Fig. 1. A single detector array as proposed for the MFS system for W7-X.

The detectors are mounted on a feedthrough flange. Current-signal and bias-supply connections will be provided by four DB25 connectors installed on the feedthrough flange.

2.2. Geometry and dimensions of the proposed MFS system

The main MFS vacuum chamber will be mounted on a suitable port (AEN20) of Wendelstein 7-X via a gate valve. The port is tilted to the horizontal position by an angle of 53.5° as presented in Fig.2.

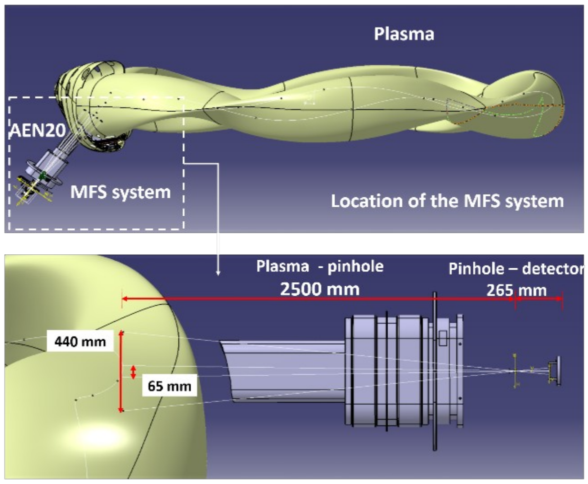

Fig. 2. Localisation (upper figure) and geometry (lower figure) of the MFS system design for W7-X.

The MFS system construction consists of a vacuum chamber equipped with a detector flange, collimating system, filters holder, shutter and entrance pinholes. The conceptual design of the main MFS vacuum chamber is presented in Fig. 3. At the entrance of the chamber, 8 pinholes with a 1 mm of diameter covered by a 10 μm Be foil to avoid ECRH stray radiation in the region of the detectors, are located. Additional filters, which define the energy ranges for each array, are mounted on a separated filter holder. Inside the MFS vacuum chamber, a shutter is also located. A wobble stick will be used as a rotary motion vacuum feedthrough to drive this shutter. A pneumatic actuator for the stick with position sensor will be located on the top of the MFS chamber which is presented in Fig.3.

The total observable area for an array of 5 detectors (due to the port size limitation) will be 440 mm while for separate single detector it is 65 mm in the plasma center (Fig.2). The proposed chamber dimensions are 447 × 200 × 210 mm and the estimated MFS chamber weight is about 50 kg (made of 316(L) stainless steel).

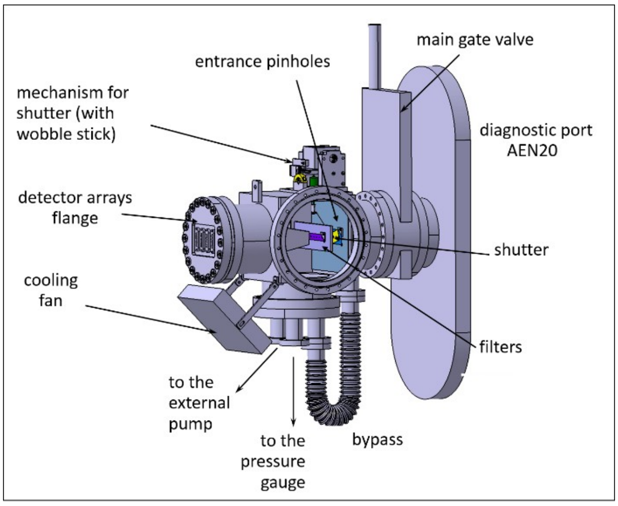

Fig.3. CAD model of the main MFS vacuum chamber.

Inside the MFS chamber a plate with additional Be filters of different thicknesses will be mounted to define the energy range of registration. Taking into account 10μm Be at the entrance window, the efficiency of each detector array (including Be and Si transmission) is presented in Fig. 4.

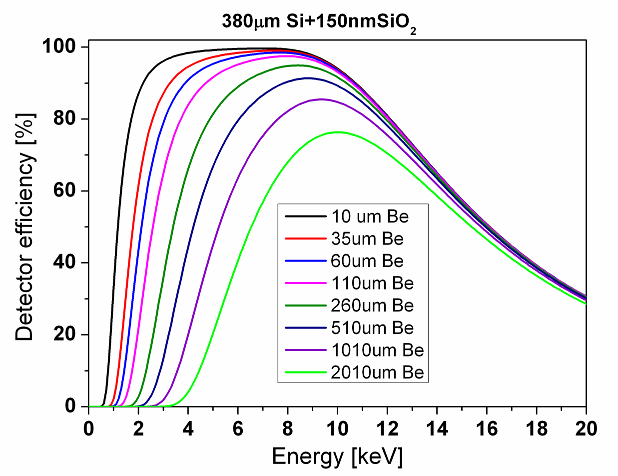

Fig.4. Detector efficiency for 8 MFS detector arrays proposed for MFS dedicated to W7-X.

2.3. Proposed vacuum systems

A turbomolecular pump is necessary for the evacuation of the MFS vacuum chamber. Due to the sensitivity of the pump with respect to the external magnetic field strength, its location must be appropriately chosen. The distribution of the magnetic field around the diagnostic port is shown in Fig. 5. During the design process, three concepts for the vacuum system have been proposed.

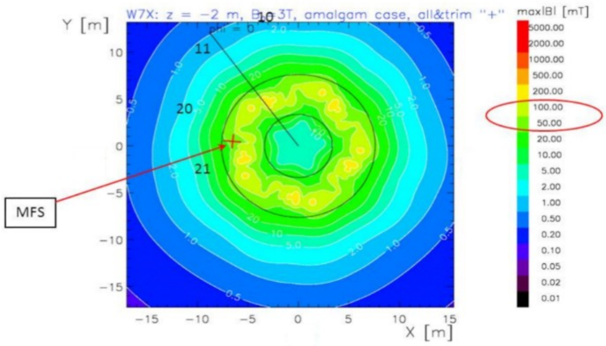

Fig. 5. Position of the MFS system at the magnetic field distribution around the W7-X.

One proposal is similar to the solution already applied in two existing diagnostics [17, 18]. A long pipe locates the turbomolecular pump at a place with suitably low magnetic field (B ~ 5mT) as presented in Fig. 6. In this case the distance between the pump and the plasma center is 4.5m. This proposal requires application of additional support structures to stay within the acceptable limits for the load on the gate valve.

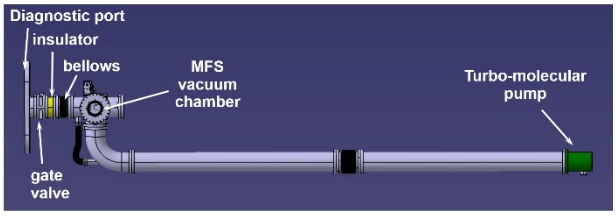

Fig.6. A CAD model of the vacuum pump located at the long distance from the plasma.

The second proposal is a movable pump which will be connected only before the operation of the diagnostic to obtain the required pressure inside the MFS chamber. After that, the pump will be disconnected and the MFS vacuum will be maintained by the W7-X vacuum pumps. This solution does not require any support structure, and thereby saves valuable space in the W7-X torus hall (in contrast to the case of the first proposal). A problem could appear when the pressure inside the MFS system is larger than that required for opening the gate valve to the W7-X vacuum. Then the gate vale must remain closed and the system cannot operate. To solve such problem, access to the torus hall, which is restricted during the experimental phase, would be needed to identify the cause.

The last concept is based on using a small turbomolecular pump located close to the main MFS system which will be only switched-on when the magnetic field is switched-off, to get the required pressure. This could be done externally by using the software applied for the MFS operation. This solution seems to be the most appropriate because it does not require a support structure like in the first proposal, and since it is compatible with the W7-X requirements related to the access to the torus hall.

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2.4. Proposed data acquisition system

The signals from the PIN diodes are passing into four preamplifier boards. Ten transimpedance amplifiers are situated on each board which gives a total number of forty channels. Each transimpedance amplifier will consist of transimpedance preamplifier and two-stages voltage amplifier. Design parameters are: transimpedance = 100 MOhm, bandwidth = 500 kHz (rise time 0.6 μs). Due to the noise sensitivity the distance between detectors and preamplifiers should be less than 10 cm. The signals from preamplifiers will be transferred via multiwire screened twisted pairs cables to A/D convertors boards. It is planned to use two PCIe boards from General Standards Company (e.g.: type 18AI32SC1M) which are equipped with 32 independent channels each. Every A/D converter has a differential input with dedicated ADC per channel (1.0MSPS SAR18-bit). The proposed solution enables simultaneous collection of output signals from all forty channels

3. Summary

The measurement of soft X-ray radiation originating from hot plasmas is a standard diagnostic used in many different fusion devices. In the work presented here, the conceptual design of a multi-foil system for the stellarator Wendelstein 7-X operated at IPP-Greifswald in Germany has been described. The proposed diagnostic is based on 8 detector arrays. Each array consists of 5 Si detectors. Three vacuum systems have been proposed considering the access constraints and the compatibility with the local magnetic field strength. The concept with a turbomolecular pump which will be operated only when the magnetic field is off is the most promising one. The described MFS system is foreseen to be installed for future experimental campaigns. The main purpose of this diagnostic will be to estimate the T_e and unfolding of filtered data to determine the X-ray radiation spectra.

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