4 Wendelstein 7-X

Polish contribution in the Wendelstein 7-X programme is considered to play a very important role in the integration of all Polish parties, that form our Association. Polish involvement in the W7-X programme is quite extended, ranging from cooperation on device assembly and development of NBI system through development of several diagnostics (X-ray PHA, C/O monitor, neutron and microwave diagnostics) to structural mechanical calculations and neutron MCNP calculations.

- The IPPLM contribution to the project W7-X comprises two tasks:
    - Spectrometry of soft X-ray emission from W7-X stellarator with the use of PHA and MFS diagnostics
    - Development and application of neutron diagnostics based on activation method for magnetic confinement devices (W7-X)

4.1 Contribution to the W7-X project

Spectrometry of soft X-ray emission from W7-X stellarator with the use of PHA and MFS diagnostics

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The investigation of the X-ray emission from fusion plasmas has become a standard diagnostic tool used on many different fusion experiments. The measurements of X–ray intensities by using Si–detectors, which are sensitive to the total radiation above a threshold energy determined by thin absorber foils in front of the diodes, yield an excellent spatial and temporal resolution. The determination of the X-ray energy spectrum using pulse height analysis (PHA) systems requires sufficiently long acquisition times resulting in a poor temporal resolution. However, this method is particularly suited for long pulse operation envisaged for W7–X. The multi-foil temperature analysis system (MFS) is the method destined to obtain the shape of the X-ray spectrum from data recorded by the use of different semiconductor detectors. This method is characterized by lower spectral resolution but much faster response in comparison with the PHA system.

Described two spectroscopic systems, PHA and MFS are being designed by IPPLM for measurement of soft X-ray emission from W7-X stellarator, which is now under construction in Greifswald, Germany. The project is carried out within Agreement on Cooperation between Institute of Plasma Physics and Laser Microfusion, Association EURATOM and Max-Planck-Institut für Plasmaphysik – Greifswald, Association EURATOM.

Computer simulations of soft X-ray emission from a tokamak plasma played important role in designing of both diagnostic systems. As a tool for checking the performance of a spectrometry system and optimizing filters and detectors, a special numerical code, named RayX has been developed. Number of simulations have been done and the results allowed to determined the position of the diagnostics components.

The super conducting stellarator W7-X will run pulse of up to 30 min duration with full heating power. Electron Cyclotron Resonance Heating (ECRH) is the main heating method for steady-state operation of the Wendelstein 7-X stellarator in the reactor relevant plasma parameters. A heating power of 10 MW is required to meet the envisaged plasma parameters. A wide spectrum of requirements has to be considered during design and realization of the new X-ray diagnostics. Since ECRH auxiliary heating will be applied in W7-X, different heating scenarios, characterised by widely different electron temperature and density profiles have been taken into account. The RayX code allowed to investigate the influence of a geometrical configuration of the diagnostic systems on the spectra intensity and shape. It also calculated the radiation from plasmas with the use of different pinhole sizes, types of detectors, filters' material and thickness.

Performed simulations and evaluation of the magnetic field effect on the individual elements of the system (e.g. turbomolecular pump) showed that the changeable slits must be placed at a distance of 6.5 m from the plasma center and detectors further 1 m behind them. A preliminary mechanical design of PHA system is presented in figure 1. Details of the chamber (box) which contains three sets of movable slits with piezo drives and pinholes, and three interchangeable filter systems with vacuum manipulator is presented in figure 1b. To collimate and cut off a part of the radiation a plate with three fixed holes has been located in front of the chamber. The proposed PHA diagnostic is intended to provide the spectral energy distribution with energy resolution not worse than 180 eV along a central line of sight. The system will consist of 3 single Silicon Drift Detectors (SDDs). The measurements will be taken along sightlines through the center of the plasma. In the diagnostic all detectors, operated with different filters will be installed on the horizontal port AEK50 on W7-X. Each detector will record an X-ray spectrum in three different energy ranges (energy channels) from 400 eV to 20 keV. This will allow to enhance the sensitivity for particular impurity species and for the investigation of superthermal tails in the spectra. First channel will be equipped with SD3 detector containing polymer window and aluminum light protection, to cover energy range between 250eV-20keV. Second and third channel will be equipped with standard SDD detector with 8µm of Be window, however in the third channel additional thick filter will be used. This will allow to record spectra in the range of 1-20 keV and 7-20keV, respectively. All detectors will be accompanied by an individual control of pinholes size and 3 additional replaceable filters for adjusting the energy range in each system.

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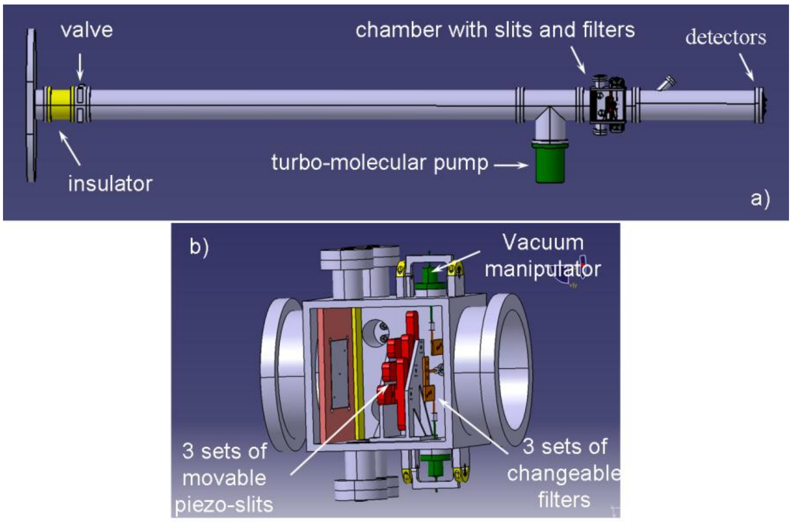

Fig. 1. Conceptual design of PHA diagnostics system for W7-X: a) main diagnostics port; b) details of the chamber contains three sets of movable slits with piezo drives and pinholes, and three interchangeable filter systems

The MFS system will be realized on port AEN20 as a part of the so-called flexible SX camera system on the AEM10-AEN10-AEO10 port combination. This diagnostic will consist of a set of semiconductor detectors using different filters, current amplifiers and a memorizing system. The temporal resolution should be high enough to allow monitoring of fast events.

A number of computer simulations using RayX code for MSF diagnostic have been performed using different geometry and plasma conditions. An analysis of a dark current and noise of the considered detectors showed that acceptable level of the detected current should be higher than 100 nA. Basing on the calculations it was established that the distance from plasma center to pinhole should be 2.5 m and the distance from pinhole to the detector - 0.20 m. Taking into account influence of magnetic field on diagnostic components, the turbo molecular pump has been placed at 6 m from the plasma center.

Tests carried out on different types of detectors showed that FLM type detectors with 380 μm of active layer, surface 5×5 mm and 10 pF of capacity, produced by Institute of Electron Technology in Warsaw are the best candidates for MFS diagnostic. Therefore, three detector arrays composed of 5 thick FLM-type detectors have been purchased. The detectors has been mounted on Alumina with a capacitor and resistor integrated to the board (SMD-technology).

A number of computer simulations have been made to obtain a conceptual design of PHA and MFS diagnostics foreseen for the Wendelstein 7-X stellarator. In the case of PHA diagnostics a conceptual designs have been developed, based on the use of the detectors in one main port (with all components inside). It was established that this diagnostics will be based on 3 detectors covering different ranges of spectrum, all viewing the central plasma. In the case of

MFS system the conceptual design has been made and proposed detector arrays have been purchased.

Development and application of neutron diagnostics based on activation method for magnetic confinement devices (W7-X)

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MCF fusion experiments that involve deuterium or deuterium tritium plasmas can generate more than 10^{12} neutrons per second. At these emission levels, it is possible to obtain information about the plasma using various techniques that measure the neutron fluxes and energy distributions. The neutron emission rates and energy spectra of neutrons for plasmas with Maxwellian energy distributions can provide information about ion temperature and fuel density, and the generated fusion power can be determined. For discharges with significant additional heating, the ion distribution functions and ratios of thermal and non-thermal reaction rates can also be evaluated.

Neutron activation is one of the technique that is used in many MCF devices to determine the neutron fluence or energy spectrum at specific locations around the machine [1]. Neutron activation is well-suited for accurately and precisely monitoring the fusion power by measuring the neutron yield. This technique gives stable and linear responses to the fusion power level. This method is based on recovering information about neutrons by registering the products of induced reactions. Samples of selected materials are used as detectors. During the irradiation of the samples, reactions that create radioactive nuclei are induced. The chosen materials have relatively high reaction cross-sections with neutrons in the specified energy ranges. The reactions are selected so that their products decay with gamma-ray emission and can thus be detected using gamma spectrometry. Exceptionally, reactions leading to beta-radiation are also used. The sample materials can be chosen such that neutrons with energies of 14- and 2.5-MeV and scattered neutrons are measured separately.

The uncertainty in measurements performed with activation techniques depends mainly on the accuracy of the cross-section data and on the geometry factor. It is generally accepted that the total yield of the 2.5-MeV neutrons from large tokamaks can be determined with an accuracy of better than 10%.

The measured neutron fluence at the irradiation point is related to the total neutron production by applying a calibration factor that is determined using neutron transport calculations (e.g., MCNP code), taking into account the geometry of the detector and the geometry and composition of the samples. Benchmark experiments, using suitable calibration neutron sources, must be performed to check the reliability of the calculations.

The reactions needed to perform useful measurements on a fusion device must meet several requirements. The isotopes naturally occurring in the activation materials must have sufficiently high reaction cross-sections in the relevant neutron energy range. At the same time, the products of these reactions should decay with appropriate half-lives and emit suitable gamma photons.

The neutrons at JET during deuterium operation come from d-d fusion and in small percentages from tritium burn-up; the neutrons are originally of 2.5- and 14-MeV energies, respectively, which are broadened due to the plasma temperature and the applied heating systems. The typical plasma pulse at JET takes usually about 30 – 60 s. The main neutron emission, on the other hand, occurs only during the additional heating phase, mainly with neutral beam injection (NBI), which only lasts for a few seconds.

The chosen reactions should lead to decay products with proper half-lives. Because of properties of the applied gamma spectrometer, the reaction products must emit gamma lines with energies between about 100 keV and 2000 keV. It was assumed that the most useful cross-sections are at least of the order of hundreds of millibarns.

An additional, very important issue is the accuracy of the available cross-sections. We strive to use only verified and current nuclear data libraries like ENDF/B-VII.0 or IRDF-2002.

The reactions considered for measuring 2.5- and 14-MeV neutrons are presented in Tab. 1 and 2, respectively. Threshold-less reactions, like radiative capture, are used for slowed (scattered) neutron measurements. We also registered this reaction type during the described experiments.

Table 1
Selected reactions for 2.5-MeV neutrons

No	Reaction	Threshold [MeV]	Product half-live
1	Ti-47 (n,p) Sc-47	1.8	3.3 d
2	Fe-54 (n,p) Mn-54	1.8	312 d
3	Ni-58 (n,p) Co-58	1.6	71 d
4	Se-77 (n,n’) Se-77m	0.2	17 s
5	Br-79 (n,n’) Br-79m	0.2	5 s
6	Sr-87 (n,n’) Sr-87m	0.4	2.8 h
7	Y-89 (n,n’) Y-89m	1.2	15.7 s
8	Zr-90 (n,n’) Zr-90m	2.3	0.8 s
9	Cd-111 (n,n’) Cd-111m	0.5	49 m
10	In-115 (n,n’) In-115m	0.6	4.5 h
11	Er-167 (n,n’) Er-167m	0.3	2.2 s
12	Hf-177 (n,n’) Hf-177m	1.3	51 m
13	Au-197 (n,n’) Au-197m	0.5	7.7 s
14	Pb-207 (n,n’) Pb-207m	1.6	0.8 s

Table 2
Selected reactions for 14-MeV neutrons

No	Reaction	Threshold [MeV]	Product half-live
1	Al-27 (n,p) Mg-27	4.3	9.5 m
2	Al-27 (n,α) Na-24	6.8	15 h
3	Ti-46 (n,p) Sc-46	3.8	84 d
4	Ti-48 (n,p) Sc-48	7.4	44 h
5	Fe-56 (n,p) Mn-56	7.0	2.6 h
6	Co-59 (n,α) Mn-56	8.5	2.6 h
7	Co-59 (n,2n) Co-58	10.8	71 d
8	Zn-64 (n,2n) Zn-63	12.6	38.5 m
9	Zr-90 (n,p) Y-90	7.6	3.2 h
10	Zr-90 (n,2n) Zr-89	12.2	4.2 m
11	Nb-93 (n,2n) Nb-92	9.1	10.1 d
12	Mo-92 (n,2n) Mo-91	12.8	15.5 m
13	Au-197 (n,2n) Au-196	8.8	9.6 h
14	Pb-204(n,n’)Pb-204m	2.7	67 m

The calculations have been performed assuming that the overwhelming majority of the neutron emission from the JET pulse takes place only during the NBI heating period, which usually lasts not more than 10 seconds. Six different threshold reactions for 2.5-MeV neutrons were recorded: ^{47}Ti(n,p), ^{54}Fe(n,p), ^{113}In(n,n’), ^{58}Ni(n,p), ^{89}Y(n,n’) and ^{115}In(n,n’). We shall discuss more carefully the data obtained from three of them: ^{58}Ni(n,p), ^{89}Y(n,n’) and ^{115}In(n,n’).

The obtained reaction rates are presented in Fig. 1 as a function of total neutron rate. One can see that the reaction rate varies roughly linearly with the neutron emission. Some scatter in these results can be explained by the uncertainties in determining the details of the measuring procedure (the cooling and counting times were measured by a wrist watch, not automatically) and also by the uncertainties in the detector calibration and counting statistics.

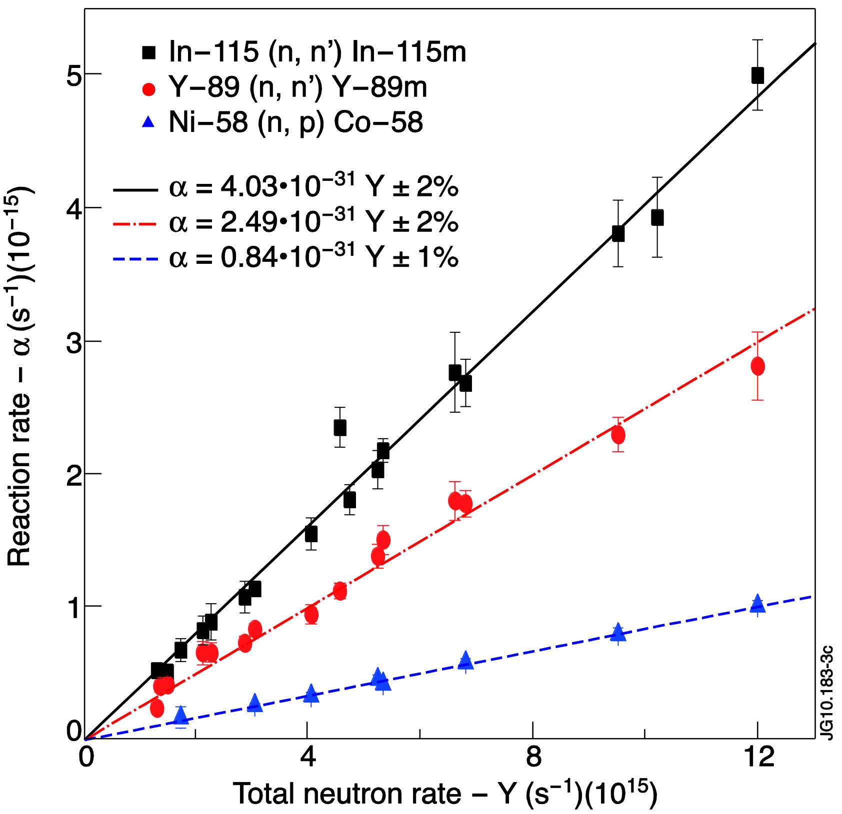
In−115 (n, n') In−115m
Y−89 (n, n') Y−89m
Ni−58 (n, p) Co−58
α = 4.03•10−31 Y ± 2%
α = 2.49•10−31 Y ± 2%
α = 0.84•10−31 Y ± 1%
Reaction rate − α (s−1)(10−15)
Total neutron rate − Y (s−1)(1015)
0
1
2
3
4
5
0
4
8
12
JG10.183-3c

Fig. 1.