W7-X PLASMA DIAGNOSTICS FOR IMPURITY TRANSPORT STUDIES

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Wendelstein 7-X (W7-X) stellarator which is located in Greifswald, Germany is an experimental device for demonstration of steady-state plasma operation. It was commissioned at the end of 2015 and at the beginning, it was operated in the limiter configuration (5 poloidal uncooled graphite limiters) while started from the 2017 it has been equipped in carbon uncooled divertor. With the launch of the device, new diagnostics have been also commissioned and tested. Understanding of impurity transport in stellarator is a crucial task in optimisation process. At W7-X there are several spectroscopic systems which deliver information about plasma impurities. One of them is a pulse height analysis system (PHA) which collects soft X-ray spectra in energy range from about 300 eV up to 20 keV with 100 ms temporal resolution. There are also X-ray imaging spectrometers XICS and HR-XIS which are devoted for measurements of spatio-temporal impurity emissivity of He-like ions with high temporal resolution (5 ms). Spectra in the VUV region are measured by High-Efficiency XUV Overview Spectrometer (HEXOS).

PACS: 52.25.Vy, 52.25.Xz, 52.55.Hc, 52.25.Fi, 52.70.−m

1. INTRODUCTION

Wendelstein 7-X is a superconducting modular stellarator located in Greifswald, Germany, and its main mission is a demonstration of steady-state plasma operation which is important in fusion power plant concept [1-3]. Stellarators in comparison to tokamaks does not have a toroidal symmetry what has an impact on collisional transport. Particles could be trapped in magnetic mirrors what makes that neoclassical losses are significant especially in a high temperature. The impurities radiation has a crucial impact on a power balance of any fusion reactor. In stellarators where Greenwald limit does not apply the radiation losses are important because they defined the density limit [4]. That is the reason why the impurity transport studies are of great important in W7-X programme. In stellarators the electrons and ions are often in different collisional regimes [5]. The core radial electric field (E_r) connected with temperature and density profiles has an impact on plasma conditions. It is expected that for positive radial electric field, $E_r > 0$, electron temperature is much higher than ion temperature and plasma is in Core-Electron-Root-Confinement conditions; while for negative E_r ($E_r < 0$) electron and ion temperatures are almost equal and plasma is in Core-Ion-Root-Confinement conditions [6]. Results obtained during first W7-X experimental campaigns still cannot answer the question if the impurity transport in the core region is predominant by neoclassical transport or by turbulence.

The main components of Wendelstein 7-X stellarator are made of stainless steel (vacuum chamber) (SS) and carbon (limiter during OP1.1 or divertor during OP1.2). Thus, the impurities which are expected to be observed, beyond injected one, are carbon, oxygen and high Z-elements like iron, chromium or nickel originated from SS wall.

In order to study impurity behaviour (e.g. accumulation) diagnostics with good: - energy (wavelength) resolution to distinguish kind of impurity and ionization charge stages, - spatial resolution – to study impurity plasma profiles, - and temporal resolution – to study impurity behaviour during the discharge, are needed. Usually, collected signals correspond to line integrated along the line-of-sight information and to obtain local emissivity an inversion process is needed. Moreover, there are number of diagnostics which results must be combined to deliver reliable information. To study an impurity transport also systems for impurity injection are important. At W7-X there are pellet and TESPEL injectors, gas-puff and laser blow-off systems [7]. There are also several diagnostics which are dedicated for monitoring of impurity behaviour in W7-X plasma. Each diagnostic is dedicated for monitoring of different energy (wavelength) range. These, which are belong to so-called core plasma diagnostics are X-ray imaging spectrometers XICS (X-ray Imaging Crystal Spectrometer) and HR-XIS (High Resolution X-ray Imaging Spectrometer) [8-9], PHA (Pulse Height Analysis) system [10-11] and High-Efficiency XUV Overview Spectrometer (HEXOS) [12]. All above mentioned systems have various energy (wavelength) range and resolution. Thera are also two bolometer camera systems and soft X-ray tomography system (XMCTS) which observe wide angle of view that covers the complete plasma cross-section [13] but without energy resolution. These diagnostics are also dedicated for measurement of radiation asymmetries.

In the paper main W7-X core diagnostics will be presented with some exemplary results obtained from recent experiments.

2. W7-X PLASMA DIAGNOSTICS FOR IMPURITY MONITORING

Figure 1 presents energy ranges observed by described W7-X impurity diagnostics. It is clearly seen that there is an overlap energy region of PHA and HEXOS while in the case of HEXOS and PHA there is only very small common energy range.

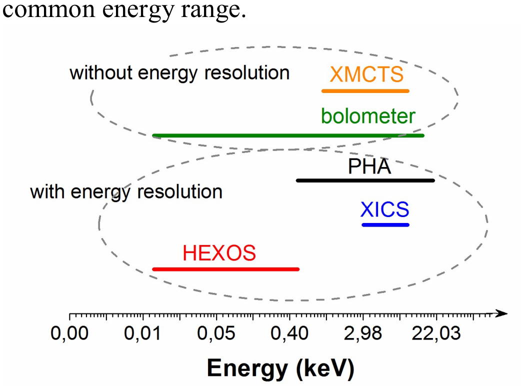

Fig.1. Energy ranges observed by chosen W7-X diagnostics.

Figure 2 illustrates location of individual diagnostics on W7-X chamber. Due to a specific stellarator magnetic field configuration, each system is related to different shape of plasma cross section, e.g. HEXOS spectrometer location correspond to triangular plasma shape while PHA system corresponds to 'bean' plasma shape.

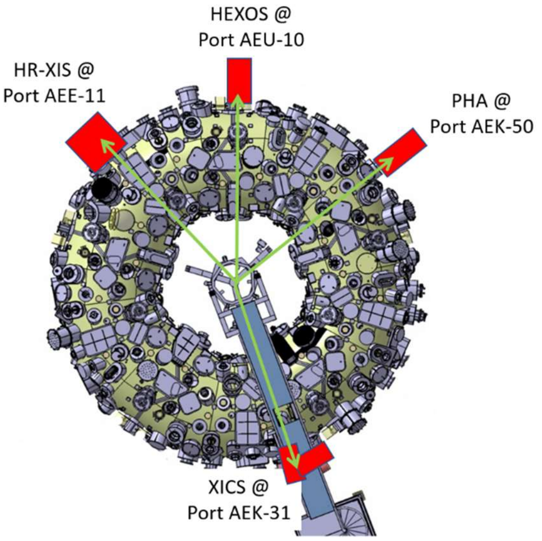

Fig.2. Location of chosen diagnostics at W7-X.

Taking into account that lines-of sight described diagnostics correspond to different geometry to compare experimental results obtained by these system, transformation to effective radius must be done.

2.1. PULSE HEIGHT ANALYSIS SYSTEM

The pulse height analysis system (PHA) is a diagnostic dedicated for spectra observation in very broad energy range [11, 14]. It is divided into 3 channels, each focus on observation light (e.g. carbon and oxygen), mid-Z (e.g. argon) and high-Z impurities (e.g. iron, cupper), respectively. First two PHA channels are equipped with Silicon Drift Detectors (SSD) (active volume: 10mm^2×450μm, internal collimator ∅ 3.2 mm) covered by 8 μm of Beryllium foil. Application of additional thicker Be foils (25, 50, 100, 500 or 1000 μm) makes possible to focus measurements on chosen energy range. Third PHA channel is equipped also with SSD but covered by thin polymer window for optimisation of low energy performance (active volume: 10mm^2×450μm, internal collimator ∅ 3.1 mm). Application of such detectors give an energy range of PHA observation starting from about 350 eV (3rd channel) up to 20 keV. Figure 3 presents detector response curve for each PHA channel during OP1.2b experimental campaign at W7-X. Through appropriate PHA settings, the energy resolution is about 150 eV FWHM at 5.9 keV what is quite good to separate spectral lines and identify plasma impurities. A temporal resolution of the PHA system is 100 ms. During this time collected spectra are of good quality taking into account the statistics.

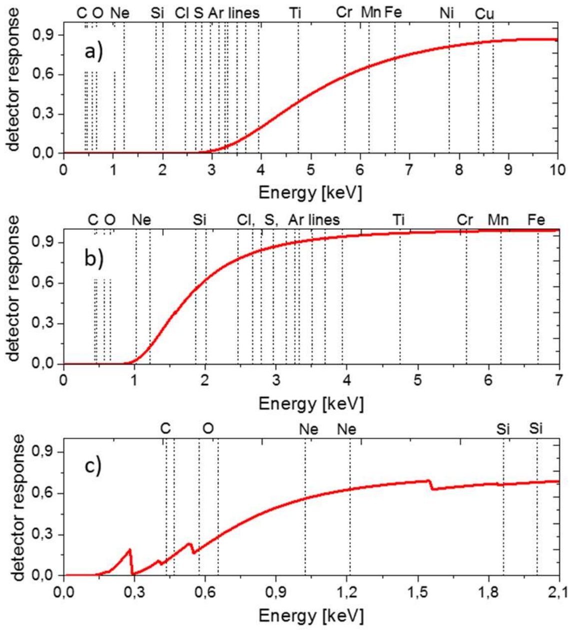

Fig.3.Detector response curves for the 1st (with the application of 1000 μm-thick of additional Be foils) (a), 2nd (with the application of 25 μm-thick of additional Be foils) (b) and 3rd (c) PHA channels with the indication of selected impurity lines.

The PHA system has 3 lines-of-sight which are more or less parallel and observe almost plasma centre. The size of observed plasma volume, defined by the slits which have changeable widths (piezo-slits), is not larger than 35 mm in the plasma centre for maximum slits width equal to 1.2 mm.

2.2. HIGH-EFFICIENCY VUV/XUV OVERVIEW SPECTROMETER

The High Efficiency Extreme Ultraviolet Overview Spectrometer, HEXOS, is a system for monitoring plasma impurities in very broad wavelength range [12, 15-16]. It is divided into 4 sub-spectrometers which collected spectra in the range between 2.5 and 160 nm. The spectrometer consists of two vacuum chambers, each equipped with two dispersive elements – holographic reflective diffraction gratings. As detectors, an open Cesium Iodide-coated multichannel-plate (MCP) with light amplifier and camera head (a linear photodiode array with 1024 pixels) are used. The wavelength resolution depends on observation range and it vary from 0.013 nm to 0.26 nm. The HEXOS spectrometer has two lines-of-sight through the plasma core. Its temporal resolution is equal to 1ms what is much higher in comparison with the PHA system.

2.3. X-RAY IMAGING CRYSTAL SPECTROMETERS

At W7-X there are two X-ray imaging crystal spectrometers: XICS (X-ray Imaging Crystal Spectrometer) and HR-XIS (High Resolution X-ray Imaging Spectrometer). The first one is used for routine measurements of electron and ion temperature, and radial electric field [17] while the second one is used for monitoring of lines of injected chosen impurities (Ar^{16+}, Si^{12+}, Fe^{24+}, Ti^{20+}, Ni^{26+} spectral lines). Spectrometers consist of spherical bent crystal and 2D X-ray detector (water cooled Pilatus). The XICS has two dispersive elements and two detectors which are dedicated for observation of Ar^{16+}/Ar^{17+} and Fe^{24+}/Mo^{32+} spectral lines, respectively. The HR-XIS is equipped with 8 crystals located at the rotating holder and only one detector. The choose of the crystal depends on the experimental conditions. Both X-ray imaging spectrometers have about 20 lines-of sight and deliver data with 2 cm of spatial resolution and 5 ms of temporal resolution. Based on the XICS spectra it is possible to deliver time resolved profiles of electron (T_e, from line intensity ratio) and ion (T_i, from Doppler broadening) temperature, perpendicular flow velocity (v_p, from line shift) and impurity concentration (n_z, from absolute line intensity). Radial electric field, E_r, can be inferred from measurements of the velocity v_p.

3. SUMMARY

All three described in the paper W7-X systems belong to W7-X core plasma diagnostics which have energy/wavelength resolution. The PHA and XEXOS spectrometers measure spectra in very broad energy ranges while XICS because it is a crystal spectrometer, deliver spectra in very narrow energy ranges but with higher energy resolution (it observes resonant line with satellites). The HEXOS observation wavelength range gives the possibility to measure simultaneously radiation emitted from various ionisation stages of impurity ions. This makes the spectrometer one of the most important system in impurity transport studies. Kind of impurities is provided by lines identification from PHA and HEXOS spectra while time evolution is study by all three spectrometers but with different temporal resolution. In HEXOS spectra there is possible to measure Fe lines belong to ions from 6+ up to 22+. Complementary to these results are PHA and XICS data which deliver information about He-like ions. Study of impurity confinement time depending on atomic number based on He-like lines is only possible by these systems and XICS has much better time resolution in comparison with the PHA. The VUV spectrometer has also very good time resolution to observe impurity behaviour during the W7-X discharges and determine decay time of injected impurities. Despite the fact that all these spectrometers are focus on different energy region and have different temporal and spatial resolution, all are needed to confirm observation and make cross calibration if needed. An example results obtained by HR-XIS and PHA are presented in fig. 4. This figure presents time evolution of injected elements in chosen W7-X discharge [11].

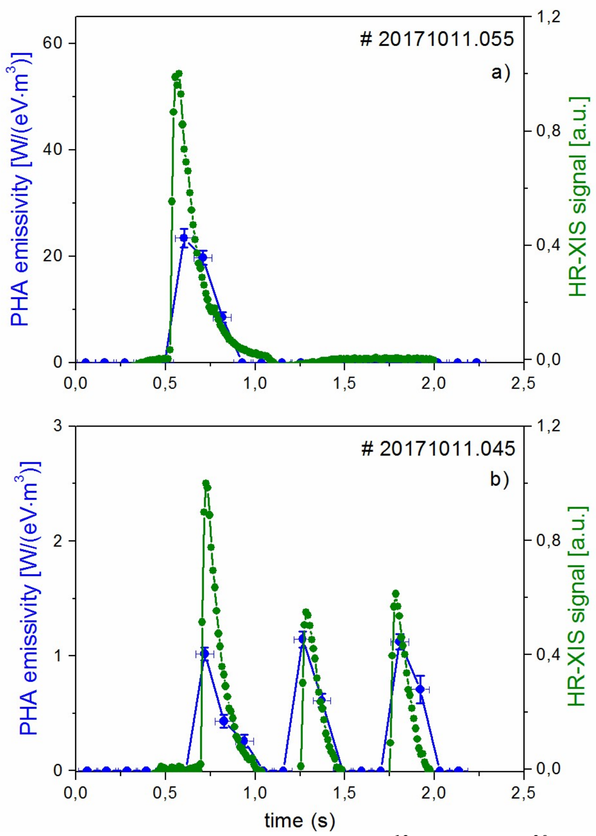

Fig.4. An example of time traces of Si^{12+} (a) and Ti^{20+} (b) lines during the laser blow-off injection, —•— corresponds to PHA signal and —•— corresponds to HR-XIS signal.

The radial electric field profile calculated based on XICS spectra defines the transport regime. Obtained impurity confinement time with combination of simulations deliver information about transport coefficients like diffusive *D* and convective *v* parameters.

Table 1 presents a summary of described diagnostics together with their application.

Summarising, study of impurity transport is possible thanks to appropriate spectroscopic diagnostic systems which deliver spectra in broad energy range and with good temporal resolution. Additionally, diagnostics with spatial resolution are needed to deliver profiles of main plasma parameters (T_e, n_e, T_i). It is also worth to add, that information about the impurity content in the plasma and its accumulation is also important from the safety point of view of the device.

Table 1. A comparison of described W7-X core plasma diagnostic systems

	HEXOS	XICS/HR-XIS	PHA
Wavelength /energy range	(2.5 –160) nm (8 – 496) eV	dedicated for particular impurity line observation (3 -9) keV	(0.06 - 3.5) nm (0.35 – 20) keV
Wavelength /energy resolution	(0.013 - 0.26) nm		(140-200) eV
Time resolution	1 ms	5 ms	(60 – 100) ms
Spatial resolution	two lines of sight through the plasma center (observed about 10 cm of plasma in the core (depending on pinhole size))	about 20 lines of sight 2 cm (deliver profiles)	one line of sight through the plasma center (observed about 3 cm of plasma in the core (depending on pinhole size))
Delivered information	- Impurities identification - impurity decay time - n_z if calibration is performed	T_e, T_i, v_p, n_z, E_r impurity decay time	- Impurities identification n_z - T_e – average along line of sight - impurity decay time

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This scientific work was partly supported by Polish Ministry of Science and Higher Education within the framework of the scientific financial resources in the years 2014-2018 allocated for the realization of the international co-financed project.

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ЭКСПЕРИМЕТАЛЬНАЯ СИСТЕМА ДИАГНОСТИКИ ПЛАЗМЫ НА СТЕЛЛАРАТОРЕ W7-X ДЛЯ ТРАНСПОРТНЫХ ИССЛЕДОВАНИЙ ПРИМЕСЕЙ В ПЛАЗМЕ

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Стеллараторр Wendelstein 7-X (W7-X), который расположен в Грайфсвальде, Германия, является экспериментальной установкой для демонстрации стационарного удержания плазмы. Стелларатор был введен в эксплуатацию в конце 2015 года и вначале эксплуатировался в конфигурации с ограничителем (5 полоидальных неохлаждаемых графитовых ограничителей). С 2017 года установка оснащена углеродным неохлаждаемым дивертором. С запуском стелларатора были также введены в эксплуатацию и испытаны новые диагностические системы. Понимание транспорта примесей в стеллараторе является важной задачей для оптимизации его работы. На W7-X имеется несколько спектроскопических систем, которые предоставляют информацию о примесях в плазме. Одна из них - система анализа высоты наблюдаемого импульса (PHA) - регистрирует спектры мягкого рентгеновского излучения в диапазоне энергий от около 300 эВ до 20 кэВ с временным разрешением 100 мс. Имеются также рентгенографические спектрометры XICS и HR-XIS, предназначенные для измерения пространственно-временной примесной излучательной способности гелиоподобных ионов с высоким временным разрешением (5 мс). Спектры в области VUV измеряют с помощью высокоэффективного обзорного спектроанализатора (HEXOS)..

ЕКСПЕРІМЕТАЛЬНА СИСТЕМА ДІАГНОСТИКИ ПЛАЗМИ НА СТЕЛАРАТОРІ W7-X ДЛЯ ТРАНСПОРТНИХ ДОСЛІДЖЕНЬ ДОМІШОК В ПЛАЗМІ

M. Kubkowska[1], B. Buttenschön[2], A. Langenberg[2], and the W7-X team

Стеларатор Wendelstein 7-X (W7-X), який розташований в Грайфсвальді, Німеччина, є експериментальною установкою для демонстрації стаціонарного утримання плазми. Стеларатор був введений в експлуатацію у кінці 2015 року та спочатку експлуатувався в конфігурації з обмежувачем (5 полоідальних неохолоджуваних графітових обмежувачів). З 2017 року установка була оснащена вуглецевим неохолоджуваним дивертором. Із запуском стеларатора були також введені в експлуатацію і випробувані нові діагностичні системи. Розуміння транспорту домішок в стелараторі є важливим завданням для оптимізації його роботи. На W7-X є декілька спектроскопічних систем, які надають інформацію про домішки в плазмі. Одна з них - система аналізу висоти спостережуваного імпульсу (PHA) - реєструє спектри м'якого рентгенівського випромінювання в діапазоні енергій від близько 300 еВ до 20 кеВ з часовою роздільною здатністю 100 мс. Є також рентгенографічні спектрометри XICS і HR-XIS, призначені для виміру просторово-часової випромінювальної здатності домішок, геліоподібних іонів з високою часовою роздільною здатністю (5 мс). Спектри в області VUV вимірюють за допомогою високоефективного оглядового спектроаналізатора (HEXOS).