# W7-X PLASMA DIAGNOSTICS FOR IMPURITY TRANSPORT STUDIES

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The 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 starting from 2017 it has been equipped with a carbon uncooled divertor. With the launch of the device, new diagnostics have also been commissioned and tested. Understanding of impurity transport in stellarators is a crucial task in the 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 the 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 highly ionized ions with high temporal resolution (5 ms). Spectra in the VUV region are measured by the High-Efficiency XUV Overview Spectrometer (HEXOS).

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## 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 do not have a toroidal symmetry having impact on collisional transport. Particles could be trapped in magnetic mirrors leading to significant neoclassical losses especially in high temperature regimes. The impurities radiation has a crucial impact on a power balance of any fusion reactor. In stellarators where the Greenwald limit does not apply the radiation losses are important because they defined the density limit [4-5]. That is the reason why the impurity transport studies are of great importance in the W7-X programme. In stellarators the electrons and ions are often in different collisional regimes [6]. 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, $E_r > 0$, the electron temperature is much higher than the 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 the plasma is in Core-Ion-Root-Confinement conditions [7]. Results obtained during first W7-X experimental campaigns are still under analysis and discussion but first hints suggest for turbulent transport in the plasma centre [8].

The main components of the 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 ones, are carbon, oxygen and high Z-elements like iron, chromium or nickel originating from the SS wall.

In order to study impurity behaviour (e.g. accumulation) diagnostics with good:

– energy (wavelength) resolution to distinguish impurity species and ionization charge stages;
– spatial resolution – to study impurity plasma profiles;
– and temporal resolution – to study impurity confinement, are needed. Usually, collected signals correspond to line integrated data, measured along the line-of-sight of the diagnostics. To obtain the local emissivity, an inversion process is needed. Moreover, there are number of diagnostics which results must be combined to deliver reliable information. To study impurity transport, also systems for impurity injection are important. At W7-X there are pellet and tracer encapsulated solid-state pellets (TESPEL) injectors, gas-puff and a laser blow-off system [9]. There are also several diagnostics which are dedicated to monitor the impurity behaviour in W7-X plasmas. Each diagnostic observes different energy (wavelength) range. These, which 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) [10-11], PHA (Pulse Height Analysis) system [12-13] and High-Efficiency XUV Overview Spectrometer (HEXOS) [14]. All of the above mentioned systems have various energy (wavelength) range and resolution. There are also two bolometer camera systems and a soft X-ray tomography system (XMCTS) which observes a wide angle of view and covers the complete plasma cross-section [15] but without energy resolution. These diagnostics are also dedicated for measurement of radiation asymmetries.

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

## 1. W7-X PLASMA DIAGNOSTICS FOR IMPURITY MONITORING

Fig. 1 presents energy ranges observed by the above described W7-X impurity diagnostics. As evident from Fig. 1, there is an overlap energy region of PHA and

XICS while in the case of HEXOS and PHA there is only very small common energy range.

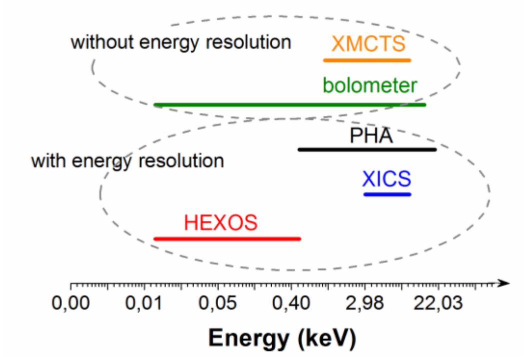

*Fig. 1. Energy ranges observed by chosen W7-X diagnostics*

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

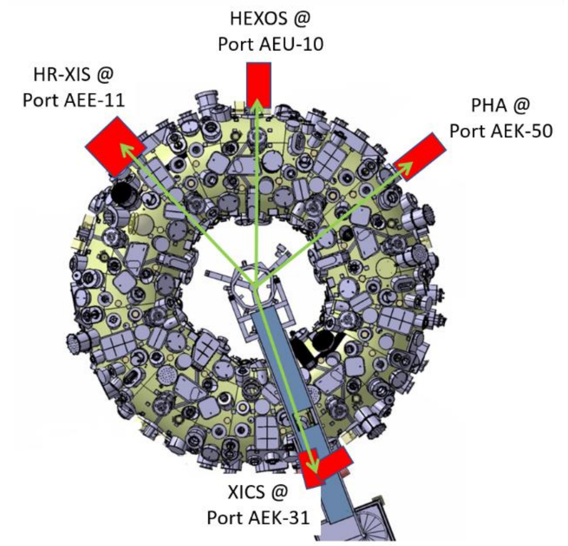

*Fig. 2. Location of chosen diagnostics at W7-X*

Given the different plasma cross sections and line of sight geometries of the individual diagnostics, a mapping of the actual line of sight positions to the effective plasma radius is required for a direct comparison of experimental results obtained from different diagnostics.

## 2. PULSE HEIGHT ANALYSIS SYSTEM

The pulse height analysis system (PHA) is a diagnostic dedicated for spectra observation in a very broad energy range [13, 16]. It is divided into 3 channels, each focus on observation of light (e.g. carbon and oxygen), mid-Z (e.g. argon) and high-Z impurities (e.g. iron, copper), respectively. The first two PHA channels are equipped with Silicon Drift Detectors (SSD) (active volume: 10 mm$^2$×450 µm, internal collimator ∅ 3.2 mm) covered by 8 µm of Beryllium foil. The application of additional thicker Be foils (25, 50, 100, 500 or 1000 µm) enables to focus measurements on the chosen energy range. The third PHA channel is equipped also with a SSD but covered by a thin polymer window for optimisation of the low energy performance (active volume: 10 mm$^2$×450 µm, internal collimator ∅ 3.1 mm). The application of such detectors gives an energy range of the PHA observation starting from about 350 eV (3-rd channel) up to 20 keV. Fig. 3 presents the detector response curve for each PHA channel during the 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 sufficient to separate spectral lines and identify plasma impurities. A typical temporal resolution of the PHA system is 100 ms. During this time collected spectra are of good quality taking into account the statistics.

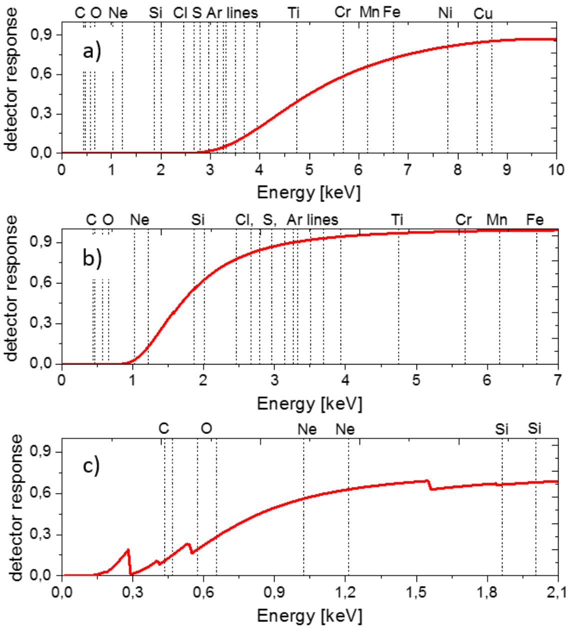

*Fig. 3. Calculated detector response curves for the 1$^{st}$ (with the application of 1000 µm-thick of additional Be foils) (a), 2$^{nd}$ (with the application of 25 µm-thick of additional Be foils) (b) and 3$^{rd}$ (c) PHA channels with the indication of selected impurity lines*

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

## 3. 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 [14, 17, 18]. It is divided into 4 sub-spectrometers which collect 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 varies from 0.013 to 0.26 nm. The HEXOS spectrometer has two lines-of-sight through the plasma core. Its temporal resolution is equal to 1ms what enables it to measure the evolution of individual impurity lines on a much faster time scale than the PHA system.

## 4. 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 the radial electric field [19] while the second one is used for monitoring lines of injected impurities ($Ar^{16+}$, $Si^{12+}$, $Fe^{24+}$, $Ti^{20+}$, $Ni^{26+}$ spectral lines) [11]. Both spectrometers are equipped with spherical bent crystals and 2D X-ray detectors (water cooled Pilatus 300kW). 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 mounted on a rotating holder and only one detector. The choice 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 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). The radial electric field, $E_r$, can be inferred from measurements of the velocity $v_p$.

## 5. EXEMPLARY RESULTS

All three impurity monitoring systems described in the paper belong to the W7-X core plasma diagnostics which have energy and wavelength resolution. The PHA and HEXOS spectrometers measure spectra in very broad energy ranges while XICS being an imaging crystal spectrometer, delivers 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 various impurity ions. This makes the spectrometer one of the most important system in impurity transport studies. Impurity species are provided by line identification in PHA and HEXOS spectra while the time evolution is studied by all three spectrometers but with different temporal resolution. In HEXOS spectra it is possible to measure Fe lines of charge states from 6+ up to 23+. Complementary to these results are PHA and XICS data which deliver information about He-like ions. The study of impurity confinement times depending on atomic numbers 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 a very good time resolution to observe impurity behaviour during the W7-X discharges and determine decay times of injected impurities. Despite the fact that all these spectrometers are focused on different energy regions and have different temporal and spatial resolution, a direct comparison of measured signals allows for cross calibration and also for an absolute intensity calibration of all three diagnostics. Exemplary results obtained by HR-XIS and PHA are presented in Fig. 4 presenting time evolution of injected elements in chosen W7-X discharges [13].

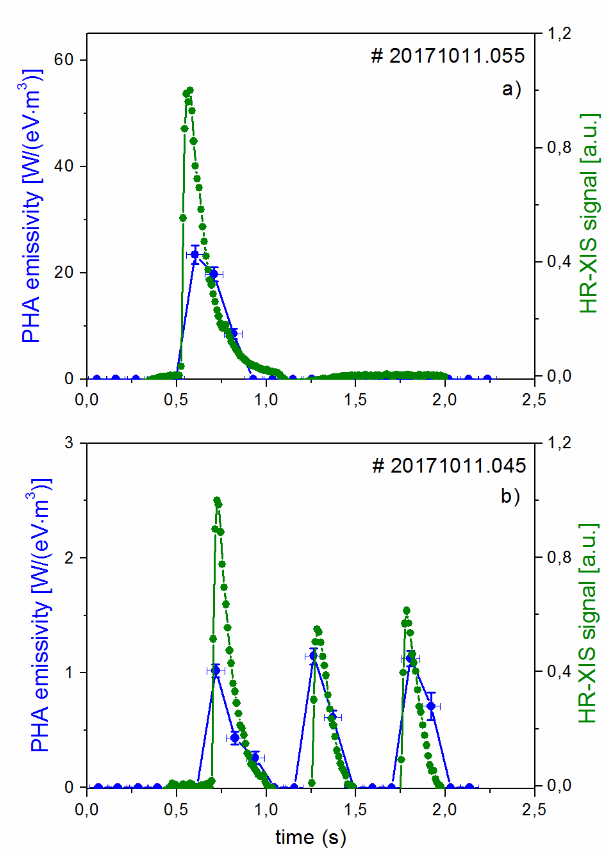

*Fig. 4. An example of time traces of $Si^{12+}$ (a) and $Ti^{20+}$ (b) lines during the laser blow-off injection. —•— corresponds to the PHA signal and —•— corresponds to the HR-XIS signal*

The radial electric field profile calculated based on XICS spectra defines the transport regime (ion or electron root confinement). Impurity confinement times obtained from a combination of measurements with simulations deliver information about transport coefficients like diffusive *D* and convective *v* parameters [8].

## CONCLUSIONS

Summarising, the 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 (electron temperature, $T_e$, electron density, $n_e$, ion temperature, $T_i$). Table presents a summary of here described diagnostics together with their applications. 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.

*A comparison of the described in this paper W7-X core plasma diagnostic systems*

| | **HEXOS** | **XICS/HR-XIS** | **PHA** |
|---|---|---|---|
| **Wavelength /energy range** | (2.5...160) nm<br>(8...496) eV | (1.8...6.7)keV<br>(0.18...69 )nm dependant on crystal choice | (0.06...3.5) nm<br>(0.35...20) keV |
| **Wavelength /energy resolution** | (0.013...0.26) nm | 0.0001… 4 Å | (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<br>impurity decay time<br>$n_z$ if calibration is performed | $T_e$,$T_i$, $v_p$, $n_z$, $E_r$<br>impurity decay time | Impurities identification<br>$n_z$ $T_e$ – average along line of sight impurity decay time |

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

***M. Kubkowska, B. Buttenschön, A. Langenberg and the W7-X team***

Стелларатор 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).

## ЕКСПЕРИМЕНТАЛЬНА СИСТЕМА ДІАГНОСТИКИ ПЛАЗМИ НА СТЕЛАРАТОРІ W7-X ДЛЯ ТРАНСПОРТНИХ ДОСЛІДЖЕНЬ ДОМІШОК У ПЛАЗМІ

***M. Kubkowska, B. Buttenschön, A. Langenberg 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 було введено в експлуатацію в 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 у 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, гелієподібних іонів з високою часовою роздільною здатністю (5 мс). Спектри в області VUV вимірюють за допомогою високоефективного оглядового спектроаналізатора (HEXOS).