Prospects of the impurity transport diagnostics in Wendelstein 7-X stellarator

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The Wendelstein 7-X stellarator (W7-X, presently being in the commissioning phase in Greifswald, Germany) is designed to perform quasi-steady state operation for up to 30 minutes duration. One key issue for stationary operation is the temporal evolution of the impurity content, which could limit the pulse performance in case of strong accumulation. The thermodynamic forces predicted by standard neoclassical theory for non-axis symmetric devices are expected to cause an impurity transport towards the plasma center for the standard ion root regime in stellarators [1,2]. The magnetic confinement in stellarators does not rely on internal currents like in tokamaks, where the cooling of the plasma due to enhanced core impurity radiation leads to a disruptive end of the plasma discharge. Nevertheless, accumulation of impurity ions lead to an unfavorable dilution of the fusion plasma and associated excessive radiation might cause a significant degradation of the plasma energy. In the worst case, the pulse length would be terminated by a thermal instability.

However, favorable operational regimes have been observed in the Heliotron LHD and in the W7-AS stellarator, revealing beneficial reduction in impurity core confinement and/or impurity screening in the edge [2,3]. These regimes allow stationary discharges without radiation problems, but they are not yet thoroughly understood up to now.

An additional challenge in impurity transport is the theoretical finding (recently validated in TJ-II), that the assumption of constant density on flux surfaces might not be valid in non-axisymmetric devices [4,5] and might lead to local accumulation of impurities and radiation asymmetries. Due to the neoclassical optimization (reducing the magnitude of the effective B-field ripple), this effect is predicted to play a minor role in W7-X plasmas.

Consequently, the set of impurity diagnostics has to be capable to address a wide spectrum of tasks, ranging from the control and identification of impurity sources (by thermal overload of in-vessel components: machine safety), over investigation of the impurity transport with regard to possible radiation asymmetries, to the spectroscopic deviation of plasma parameters (e.g., grad T_i , v_{pol}), which are essential input for theoretical predictions of impurity transport.

Light impurity monitor:

A system of two Johann double-spectrometers are employed for monitoring the Lyman-α lines of the light intrinsic impurity species B (at 4.9 nm), C (at 3.4 nm), N (at 2.5 nm) and O (at 1.9 nm) [6]. These lines provide information about the Boron layer status (after machine conditioning with Boron) and possible overload of the Carbon plasma facing components. The inventory of water on the surface of the plasma vessel is reflected by the Oxygen line and qualifies the success of previous wall conditioning, e.g. by He-glow discharges. The appearance of unusually strong N-emission is a reliable signal for vacuum leakages.

In their respective wavelengths, the L_α lines are well separated from line radiation of other impurity species and therefore allow to design a system with a moderate spectral resolution, but with a high throughput (utilizing multi-layer mirrors for all but the O-line, where a cylindrically bent TlAP crystal (2d=2.59 nm) is used) in order to achieve a high temporal resolution of 1 ms. Besides the envisaged integration of the diagnostic signals for a safety interlock system during W7-X long pulse operation, the transport of the monitored light elements can be studied in connection with impurity injection experiments.

HEXOS:

The absolute calibrated High Efficiency eXtreme ultraviolet Overview Spectrometer system [7] is foreseen for transport and concentration measurements of nearly all intrinsic and injected impurity species. The spectrometer has been installed in the W7-X torus hall in 2013 and preparations for its commissioning are under way. The system consists of 4 grating spectrometers with central lines of sight through the plasma center covering the overlapping wavelength regions from 2.5-10.5 nm, 9-24 nm, 20-66 nm and 60-160 nm. Due to the splitting into 4 separate channels, this large wavelength range can be detected with a good spectral resolution (0.036 nm, 0.058 nm, 0.15 nm and 0.30 nm) and provides an excellent survey of the intermediate ionization states of all relevant intrinsic impurity species expected from the plasma wall interaction with the vessel materials. The good temporal resolution of ~1 ms offers the possibility to follow the time evolution of the successive ionization states of injected tracer impurities for impurity transport analysis. Simulations by means of the radiation and transport code STRAHL [8, 9] on the basis of profiles of plasma density and temperatures as well as neutral density measured by other diagnostic systems provide transport coefficients for the respective tracer material. The temporal rise and decay of characteristic line radiation for the different ionization states of the impurity can thereby be used for the estimation of the diffusivity and convective velocity determining the tracer transport. The highest ionization states (H- or He- like) of medium and high-Z materials cannot be detected by the Hexos system. This information, which can significantly improve the studied transport coefficients by extending the analysis region towards the plasma center, is available from the crystal spectrometers HR-XIS and XICS.

HR-XIS:

The High Resolution X-ray Imaging Spectrometer [10] of the Johann-type with spherical crystals provides profile measurements of selectable impurity species along 6 lines-of sight across 2/3rd of the lower half of the flux surfaces in the bean shaped poloidal plane.

It contains a rotatable mount for up to 6 different spherically bent crystals, which can be selected depending on the impurity species of interest (Ar, Fe, S, etc.). It has been optimized for the narrow spectral range of H- and He-like ions around the resonance lines (e.g., Ar: 3.949 Å) and their dielectronic and inner-shell satellite spectrum nearby (e.g., Ar: 3.956 Å). This spectral range additionally offers the possibility to derive the ion temperature from Doppler broadening, the poloidal rotation (and thereby the radial electric field) from the spectral line shift as well as information about the density and electron temperature profiles from line intensity ratios of satellites to resonance line. For impurity transport analysis the measurement of the highest ionization states is especially important, since the impurity confinement time can be deduced directly from the slope of the decay of the concentration evolution.

XICS:

The X-ray Imaging Crystal Spectrometer [11] will routinely provide ion temperature and poloidal rotation velocity profiles, which are essential for the numerical modeling of the impurity transport behavior and the comparison with neoclassical theory predictions. The Johann-type spectrometer uses a spherically bent Quartz crystal and is fixed for the observation of He-like Argon (characteristic line structure between 3.9 and 4 Å), which is chosen for its high fractional abundance for the ion temperature range between a few hundred and 3 keV. The measurement requires an Argon background of $n_{AR}/n_e{\sim}10^{-5}$. The lines-of-sight cover a half-profile of the plasma cross-section. A second crystal for the detection of He-like Iron is foreseen for the higher temperature range of 2-8 keV.

In order to identify possible asymmetries of the impurity density distribution, the two crystal imaging spectrometers can measure the ion temperature and impurity concentration profiles for He-like Argon at two different toroidal locations.

XMCTS and bolometers:

The soft-X ray Multi-Camera Tomography System will measure in the SX-range along 360 lines-of-sight covering a poloidal plasma cross-section by means of 20 pin-hole cameras located inside the plasma vessel [12]. The radiation is detected with AXUV silicon diodes, filtered with a 13 µm Beryllium foil, blocking radiation with $\lambda>1.6$ nm. From the line-of-sight integrated measurements, a tomographic inversion of the radiation distribution in the poloidal plane is possible. The time resolution of the XMCTS will be ~5 µs, thus enabling the study of fast MHD activities and valuable insight into the impurity transport in 2 spatial dimensions on the flux surfaces. Following the injection of a suitable tracer impurity with a broad fractional abundance throughout the plasma, the increament in radiation level (with respect to pre-injection) can be studied with energy-integrating detectors. Similar experiments have been performed in W7-AS using two SX-cameras. Supported by radiation and transport modeling, the diffusivity and convection of the impurity was estimated [13]. Utilizing the XMCTS, the temporal evolution of the 2d impurity distribution (by means of tomographic inversion) can be estimated and transport properties be deduced.

Several bolometer cameras are planned for the measurement of the total radiation distribution [9]. Soon, a horizontal bolometer camera (HBC) and a vertical one (VBC) will be installed for monitoring the plasma at the triangular cross section. They are equipped with arrays of both blank and optically filtered gold-foil detectors (in HBC: 32 channels each; in VBC: 40 blank- and 8 filtered ones) in order to obtain more information about the spectral distribution of the whole impurity radiation content. The filtered channels are covered with 10µm-Be-foils and only sensitive to soft X-rays (>750eV) [9]. They can be used to distinguish between the contribution of different energy ranges of impurity radiation to the total radiation or even radiation asymmetries by comparing the intensities with and without Be-filters to results from XMCTS (using the same filters) at a different toroidal location. Moreover, the local radiation losses are important for the local power balance.

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