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Spectroscopic Diagnostic of Tungsten in Fusion Plasmas

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In future fusion devices, tungsten (W) is a main candidate for being a first-wall material due to its low erosion rate and high melting point. However, when using W in a reactor, the central W-concentrations must be below 10^{-4} to avoid unduly large radiation losses. A careful plasma operation using different strategies, e.g. application of central heating power [1,2], is suited to influence the W-content of the plasma and the W-concentration profile. A pre-requisite for developing and applying such strategies is the reliable diagnostic of W, if possible radially resolved. At ASDEX Upgrade, where in the campaign 2007 all plasma facing components are made from W, the W-concentration is routinely evaluated at different electron temperatures (T_e) corresponding to different plasma radii. The diagnostic relies on spectroscopic measurements, which allow to measure several different ionization states of W between approx. Xe-like W^{20+} to Fe-like W^{48+} [3,4]. In this paper, special focus is put on the fractional abundance of ionization states of W, as this is an important ingredient to the interpretation of the spectra. In the second part of the paper, the capability of the W-diagnostic at ASDEX Upgrade is demonstrated and important issues for the W-diagnostic at ITER are emphasized.

Measurement of Fractional Abundances

For determining the electron temperature range, in which an ionization state exists, atomic data, i.e. ionization and recombination rates for all relevant ionization states, are used. Due to the fact, that it is challenging to obtain atomic data for W and since there is few experience about their accuracy, an experimental test of the available data has been performed at ASDEX Upgrade. The measurements to which the theoretical data are compared to have been performed in special discharges, which exhibit the phenomenon of impurity accumulation. During such discharge phases, the turbulent transport in the core of the plasma is small enough, such that a small neoclassical inward drift can have recognizable effects [5]. The neoclassical inward drift acts on impurities and only exists when a peaked density profile of the background ions occurs. In figure 1(a), a typical setup of the measurements during a phase with impurity accumulation is depicted. The accumulation itself can be diagnosed well by comparing two different bolometer lines of sight (LOS), one of which is central and the other slightly off-central. In figure 1(b), time traces of the respective bolometer measurements are presented. Although the central LOS is monitoring only a slightly more central part of the plasma, its signal increases to the 4-fold value of the other LOS. Following the geometry of the magnetic flux surfaces, this restricts the accumulation region to a relatively small central volume, while the impurity concentrations must be peaked by a factor of at least 20. In figure 1(a) the LOS of

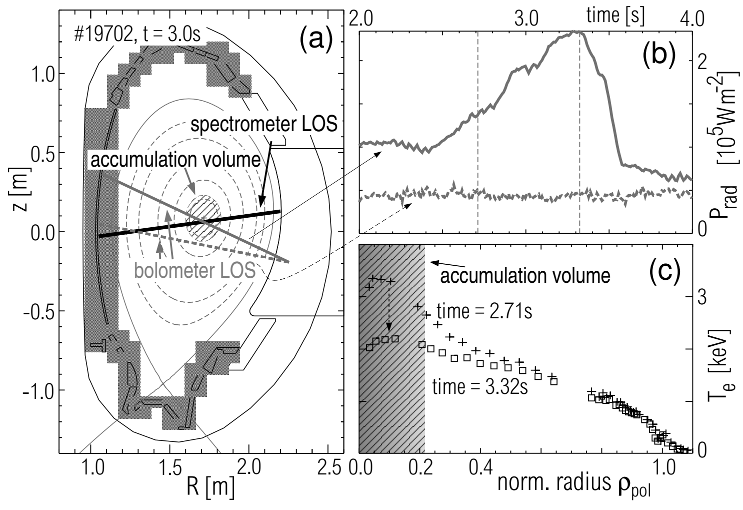

Fig. 1: *(a): Geometry of lines of sight (LOS) for measurements during impurity accumulation. (b): Bolometer measurements on depicted LOS. (c): T_e-profiles (from electron cyclotron emissions) at times marked with vertical lines in (b)*

the grazing incidence spectrometer is depicted, as an example for a typical LOS of the spectroscopic diagnostic. The built-up of such large impurity concentrations in the core of the plasma leads to localized radiative cooling. As a result the central T_e drops on timescales between 100 ms to seconds, depending on the degree of impurity accumulation and the heating profile, while the emission from the central region always dominates the measured spectra, even if at larger radii the same ionization state exists. During the phase of decreasing T_e the radiance of a spectral line is proportional to the fractional abundance of the emitting ionization state. Deviations from proportionality due to a change in population of the upper level of the transition are relatively small as explained in [4]. As a result, the measurements in figure 2 have been obtained, while further measurements are available for Ge-like W^{42+}, As-like W^{41+}, Se-like W^{40+} and the compound abundance of the ionization states between about Sn-like W^{24+} to Y-like W^{35+}.The measured data points originate from different plasma phases, and except for Ni-like W^{46+} at least two different spectral lines per ionization state have been used. The data points have been normalized. Due to the fact, that impurity accumulation only occurs if the turbulent transport is small, transport effects are not visible in the ionization balance. It is just a function of the local T_e, as has been confirmed by numerical transport modelling. Therefore, the measurements can be compared to normalized fractional abundances obtained by different sets of theoretical ionization and recombination rates. Ionization rates from [3] (ADPAK) and [6] (CADW) have been used. The quality of the latter must be considered superior as the CADW data originate from configuration-averaged distorted-wave calculations, while the ADPAK data are calculated from the average ion model [7] with corrections for excitation-autoionization being applied. For recombination rates, the rates from the ADPAK average ion model [7] have been used. The data set labelled "adjusted ADPAK" originates also from ADPAK, but some ad-hoc corrections have been performed within this work to get better agreement with the experiments. The corrections are applied by multiplying the recombination rates of an ionization state by a factor around 1, which is independent of T_e (lowest factor for Ge-like W^{42+}: 0.25, largest factor for Sr-like W^{36+}: 2.04). These corrections are also applied to describe better the weighting of different ionization states in

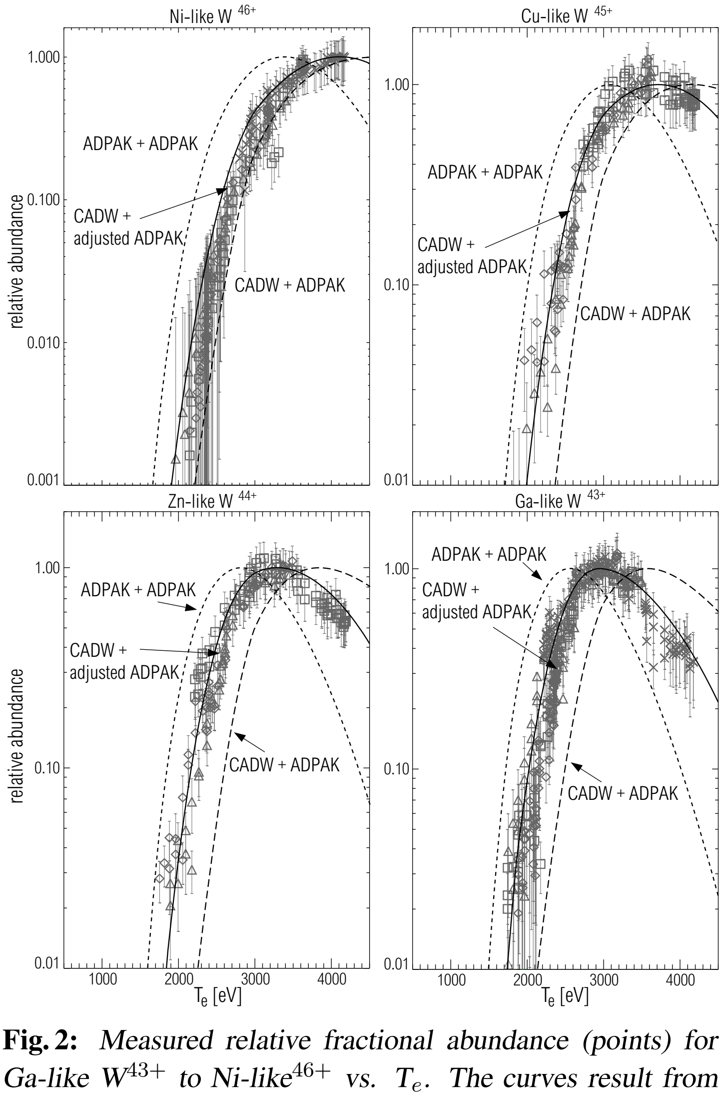

Fig. 2: *Measured relative fractional abundance (points) for Ga-like W^{43+} to Ni-like^{46+} vs. T_e. The curves result from different combinations of theoretical ionization and recombination rates.*

spectra that contain spectral lines of many ionization states, which is omitted here. It involves also predictions for spectral line intensities originating from calculations of the Cowan code [8] using plane-wave Born approximation and the baseline collisional-radiative modelling from ADAS [9]. The data presented in figure 2 demonstrate, that both the combination of ADPAK ionization and ADPAK recombination rates as well as the CADW ionization rates combined with the ADPAK recombination rates fail to describe the measurements within the error bars. (The uncertainties of the measurements in T_e are less than 200 eV, which is the maximal variation of temperature in the accumulation volume for the used plasma phases.) After correcting the ADPAK recombination rates, the resulting curves using the CADW ionization rates describe well the experimental data points.

Diagnostic of W in AUG

The knowledge of the fractional abundance of each ionization state of W allows to determine the W-concentration for any plasma discharge even if each spectral line cannot be predicted exactly by theory. To do so, it is necessary to perform a calibration during a plasma discharge with a W-injection (e.g. by laser ablation). In the phase in which the W-concentration is decaying following the injection, the additional radiative power allows to determine the additional W-concentration using the cooling factor of W, e.g. [7,10]. The spectrometers detect an additional intensity of W-lines, which can be related to the additional W-concentration. In following discharges, the radiance of these spectral lines can be used to determine the W-concentration, if their emitting ionization state is known. Depending on plasma parameters, corrections must be applied due to differences (w.r.t. the calibration discharge) in fractional abundances of the considered ionization states and electron density (for details see [3]). For the ionization states Se-like W^{40+} to Ni-like W^{46+} as well as for the ionization states Sn-like W^{24+} to Sr-like W^{35+} such interpretation of line intensities is performed routinely resulting in the availability of W-profiles. Depending on T_e 1 up to 3 radially separated measurements are routinely available. The measurement of the quasicontinuous structure at 5 nm allows for determining the W-concentration in a T_e range between approx 0.5 – 1.7 keV. Spectral lines in the range 4 – 7 nm, emitted by Se-like W^{40+} to Cu-like W^{45+} are used to determine the W-concentration in a T_e range of 1.9 – 4.5 keV. The spectral line at 0.793 nm emitted by Ni-like W^{46+} is used to determine the W-concentration in a T_e range of 2.1 – 5.5 keV. The measurements in the lower two T_e-ranges are performed using an ensemble of lines, which gives enough signal to perform the measurements also at low W-concentrations and at T_e values for which the fractional abundance of the actual ionization states is relatively small. For special cases an evaluation of single spectral lines can be performed, for the emissions of Se-like W^{40+} to Cu-like W^{45+}. However, this analysis gives larger uncertainties due to the low line strengths and therefore, is omitted in this work. In figure 3, the evaluation with these

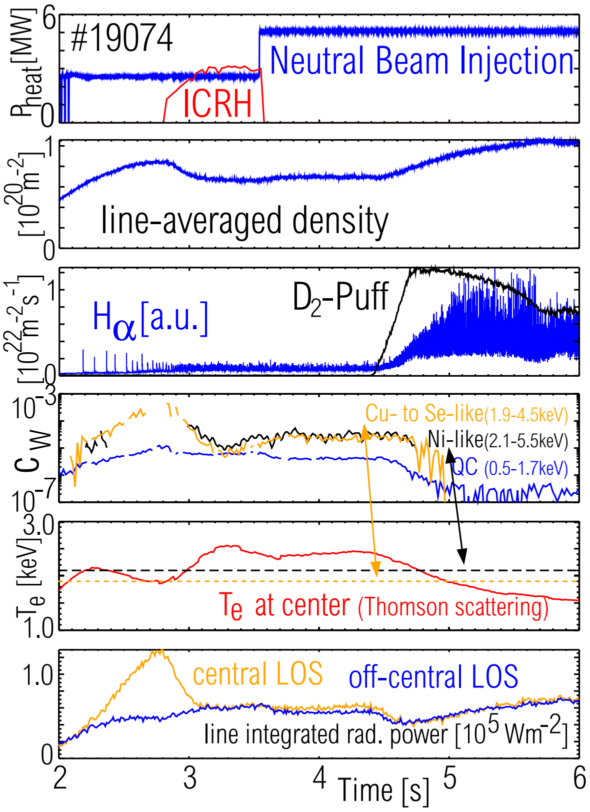

Fig. 3: *W-diagnostic at ASDEX Upgrade for different temperatures*

groups of lines is presented for discharge #19074. During the presented discharge phase the T_e-profile stays monotonic and therefore, the blue, orange and black lines in figure 3 represent the W-concentration at decreasing plasma radius, respectively. As an additional information, the heating scheme, electron density, central T_e, gas puffs, H_α-emissions in the divertor and the radiated power on two bolometer LOS are presented. In #19074 impurity accumulation is provoked by low central heating at 2 s, resulting in a W-concentration which is about a factor of 40 higher in the center (orange, black) than between about mid-radius and the pedestal top (blue). The radiated power measured on the central and off-central LOS of the bolometer differs by a factor of 3. After switch-on of ICRH heating at 2.8 s, the impurity accumulation is reduced as seen by the W-diagnostic and the bolometer. Later at 3.4 s, a phase of moderate peaking (factor of about 2 –4) starts. At 3.55 s the ICRH is switched-off, while a beam source heating the plasma center is switched-on at the same time. This leads to a reduction of the W-concentration at pedestal region of the plasma, while the central tungsten values are unchanged resulting in a peaking factor of about 8. Starting at 4.5 s, a deuterium gas puff is applied by the density feedback control. This immediately reduces the W-concentration at the pedestal-top and also in the plasma center. As the central T_e-values drop below 2.1 keV and 1.9 keV the central W-measurement are not possible anymore and the W-measurement at lowest T_e is giving now an average value for nearly the total radial range of the plasma. The W-concentration is close to the detection limit (10^{-7}) during the high density phase. It may be noted, that the impurity accumulation is also visible by comparing a central and off-central LOS of the bolometer, however, as a large part of the radiation in the bulk plasma outside the core is emitted by low-Z ions and atoms, it is difficult to determine the peaking factor of tungsten. During the phase between 3.4 –4.5 s it is difficult to even recognize the W-peaking in the bolometer measurements, demonstrating that in this phase W is not dominating the radiation losses.

Diagnostic of W in ITER and JET

In ITER, there will be a central T_e of 15 keV and above. Therefore, higher charged ionization states up to possibly He-like W^{72+} will be abundant. These ionization states emit spectral lines, that have not been observed until today in fusion plasmas. A similar issue will arise for hot discharges (central T_e above 6 keV) in the JET tokamak during the ITER-like wall project starting in 2009. An effort to modell these emissions using the Cowan code [8] and the collisional radiative modelling of ADAS [9] has been undertaken, and important spectral regions have been identified. Especially, the spectral region from 0.1 –0.15 nm is very promising for a W-diagnostic in ITER, as strong spectral lines for all ionization states between Ti-like W^{47+} to C-like W^{68+} have been predicted in this region [10]. Experiments are planned to confirm their use as a W-diagnostics in fusion plasmas. Another spectral region of interest is situated at 1.8 – 3.5 nm, where also relatively strong lines have been predicted for Co-like W^{47+} to C-like W^{68+}.

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