

Impurity concentrations and their contribution to Z_{eff} in ASDEX

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Introduction:

We report on a new method to obtain immediately after the discharge time dependent central impurity concentrations of the four most important impurity species (C, O, Fe, Cu) found in ASDEX, from VUV spectroscopy (SPRED). Up to now impurity densities have been obtained at the earliest, one day after machine operation from the comparison of absolutely measured line intensities (Cu XIX, Fe XVI, O VI, C IV) (Fig. 1) with the corresponding intensities calculated by a time dependent transport code (ZEDIFF)/1/. Besides the time delay, this method suffered from the fact, that only a few discharges could be looked at due to the complexity of the input data file and the time consuming calculations performed on the CRAY computer. Following a procedure developed at JET/2/ to obtain concentrations of metallic impurities directly by a fit-function, which connects measured line intensities with the corresponding central impurity densities, using measured ne and Te profiles, we introduced a similar method on ASDEX. This enables us to obtain the time dependent central concentrations of the four dominating impurities as well as Z_{eff} (VUV) immediately after each discharge.

Parameterization procedure:

In order to calculate the dependence of line intensities of various ion species on electron temperature and density an extended scan over the accessible parameter range at ASDEX was performed with our impurity transport code ZEDIFF. This scan was made for 2 different confinement scenarios:

1.) ohmic confinement where the electron density and temperature profiles were taken from an ohmic standard discharge ($n_e = 2.8 \cdot 10^{13} \text{ cm}^{-3}$) and the impurity transport was defined by an anomalous diffusion coefficient of $D(r) = \text{constant} = 5000 \text{ cm}^2 \text{ s}^{-1}$ for C and O, $D(r) = 4000 \text{ cm}^2 \text{ s}^{-1}$ for Fe and Cu, and an inward drift velocity $v_{in} = 230 \text{ cm s}^{-1}$ at the plasma edge (with a linear decay towards the plasma center).

2.) NBI heated L-mode confinement where the density and temperature profiles are obtained from a standard L-plasma (1.5 MW NBI-heating, $n_e = 3.5 \cdot 10^{13} \text{ cm}^{-3}$) and the impurity transport is defined by $D(r) = \text{constant} = 9000 \text{ cm}^2 \text{ s}^{-1}$ and $v_{in} = 230 \text{ cm s}^{-1}$ at the plasma edge. As described in /1/ the changed ionisation equilibrium due to charge exchange recombination from beam neutrals is also taken into account by the code.

The electron density and temperature profiles are obtained from the ASDEX Thomson scattering diagnostic time dependently.

In our parameter scan the central density was changed from $1 \cdot 10^{13} \text{ cm}^{-3}$ to $8 \cdot 10^{13} \text{ cm}^{-3}$ in steps of $1 \cdot 10^{13} \text{ cm}^{-3}$ by keeping the shape of the profile constant. For each density the central electron temperature was varied from 500 eV to 2500

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eV in steps of 500 eV, again keeping the temperature profile shape constant. These calculations were performed for the above mentioned four main impurity species Cu, Fe, O, C. For each species the most prominent line intensities between 10 nm and 110 nm (Cu XIX _ 27.4 nm, Fe XVI _ 33.6 nm, O VI _ 103.2 nm, C III 31.2 nm, C IV _ 38.4 nm) were calculated considering a central impurity density of $n_z(0) = 10^{10} \text{ cm}^{-3}$. We thus obtain the line intensities I^Z as a function of $n_e(0)$ and $T_e(0)$. By applying an exponential fit- ansatz this dependence can be written as:

$$I^Z = a0 \cdot n_e(0)^\alpha \cdot T_e(0)^\beta \quad (1)$$

taking the logarithm of equation (1) we obtain a system of linear equations, which allows us to calculate the coefficients $a0$, α and β by using a linear regression fit. In fig. 1a the O VI line intensity (103.2 nm) calculated by the impurity transport code for various electron- densities and temperatures (triangles) is compared with the O VI intensity obtained from the fit formula (solid line). Fig. 1b displays the same comparison for the Cu XIX line intensity (27.3 nm). As to be seen the agreement between the fit formula and the transport code is quite satisfactory.

Central impurity concentrations and Z_{eff} :

In order to determine the central impurity densities for a special discharge, we have to compare the intensities calculated by the fit formula with the absolutely measured ones obtained from the VUV SPRED spectrometer.

$$n_z(0) = (I^{\text{SPRED}} / I^{\text{calc.}}) \cdot 10^{10} \text{ cm}^{-3} \quad (2)$$

These calculations are made for all four main impurity species time dependently on a regular basis immediately after each discharge. In addition their contributions to the central Z_{eff} resulting in the total $Z_{\text{eff}}(0,t)$ can be calculated by introducing an average charge state (in the plasma center) for each ion species:

$$Z_{\text{eff}}(0) = \sum n_z(0) \cdot Z^2 / n_e(0); \quad \text{where: } (Z_C = 6; Z_O = 8; Z_{Fe} = 22; Z_{Cu} = 24) \quad (3)$$

This simple approach for the average charge state in the plasma center is justified by the fact that in the main part of our parameter space these numbers are correct, while at the two extreme ends the situation is as follows: At high density and low temperature the metallic concentration is very low and does practically not contribute to Z_{eff} . The light impurities, which then solely define Z_{eff} , are also under these conditions totally stripped in the central plasma. On the other hand, in low density, high temperature discharges the metallic contribution to Z_{eff} is more important, which is also true for additional heating. In these cases the above listed charge states again agree rather well with the experimental ones. Moreover, small deviations (+2) in the charge states of the metallic impurities do not have a significant effect on Z_{eff} which is largely dominated by the two light impurities.

Experimental results:

The above described method has been applied to all discharges of the last experimental campaign. However, the results obtained are only correct for the two parameterized confinement regimes (OH, L), thus we are not able to assess impurity concentrations for the high confinement plasmas (H-mode, pellet, counter N) observed in ASDEX. Due to the limited space we can only present the impurity concentrations and their contribution to Z_{eff} for a few representative discharges under carbonized wall condition.

- During **ohmic heating** several density scans have been performed covering almost the whole parameterized density and temperature range. The dependence of the central concentration of O and C on $n_e(0)$ is displayed in Fig.2a. In this case we observe an almost inverse linear dependence of the light impurity

concentration on the electron density. This dependence is more pronounced for carbon than for oxygen, resulting in twice as much carbon (4%) compared to oxygen (2%) at low densities ($2 \cdot 10^{13} \text{cm}^{-3}$). The metallic impurity concentration on the other hand (Fig. 2b), shows almost no dependence on $n_e(0)$ above $3.5 \cdot 10^{13} \text{cm}^{-3}$ but increase nearly exponentially towards lower densities. This behaviour reflects the retention capability of the ASDEX divertor for target plate produced materials /3/. We have to point out that practically 100% of the Cu influx and approximately 30 to 50% of the Fe influx is produced in the non carbonized divertor chambers/4/. Thus the Cu contribution to Z_{eff} at low densities ($2 \cdot 10^{13} \text{cm}^{-3}$) becomes as important as the contribution of oxygen or carbon.

Fig. 2c shows the n_e -dependence of the contribution of the different impurity species to Z_{eff} and the dilution of deuterons. Further, the spectroscopic- Z_{eff} is compared with the bremsstrahlung- Z_{eff} . The overall agreement between these two quantities is rather good, except for low densities where the spectroscopic Z_{eff} is always higher than the bremsstrahlung- Z_{eff} . This systematic deviation can be partly explained by the worse fit quality in this range (Fig. 1). In addition however, the uncertainty in determining n_e at the position of the radiating shells of C IV and O VI is increasing when these shells are shifted outwards towards stronger density gradients due to the higher temperatures at low n_e .

- During neutral **beam heating** with two different beam species (H^0 , D^0) and during combined **beam- (1.2 MW) and ICRF- heating (2 MW)** the above described method proved to be a powerful tool for automatic impurity evaluation also under **L- mode** conditions. Fig. 3a shows the time dependence of the Z_{eff} contributions and the D^+ dilution for a beam heated (1.2 MW) L- mode discharge. There is a first heating period (0.8 - 1.7 sec) of 1.0 MW with H^0 beams and a second one (2.0 - 2.9 sec) of 1.2 MW with D^0 beams. During the first period the moderate increase of Z_{eff} (1.7 to 2.2) is mainly caused by an increase of carbon as well as Cu and Fe. This behaviour corroborates the observed enhancement of wall erosion during neutral beam heating. In the D^0 heating period Z_{eff} increases to a value higher than 3, with a contribution of all four impurities (Fig. 3a). In agreement with previous results/3/ the D^0 beams seem to cause much higher wall erosion especially in the divertor region compared to the H^0 beams. The dilution of D^+ in the second heating period turns out to be already 35%, mainly due to the relatively high concentration of light impurities (C+O=2.9%).

In addition to pure NI- heating 2.0 MW ICRH heating was applied to the above discharges during 0.9 to 2.7 seconds (Fig. 3b). Three time intervals can be distinguished: During the first one (H^0 +ICRH) Z_{eff} nearly reaches 3 due to a strong increase of C and Fe whereas O and Cu show only a slight increase compared to the pure NI case. This behaviour is consistent with previous conclusions/5/, according to which ICRF enhances the wall erosion in the main chamber due to accelerated ions in the scrape off layer. In the second interval (1.7 - 2.0 sec) of pure ICRF heating Z_{eff} is reduced to 2.4 mainly by the reduction of Cu and Fe. In the third interval (D^0 +ICRH) Z_{eff} rises up to 4 due to a pronounced increase of the metals. This enhancement of the metallic fluxes can be explained by a deteriorated absorption condition for the ICRF waves (H^+ - second harmonic heating) because of a too low H^+ concentration (< 20%) in case of D^0 beam heating of the deuterium background plasma. Such effects of impurity enhancement under bad coupling conditions have been found already in previous investigations/5/.

References:

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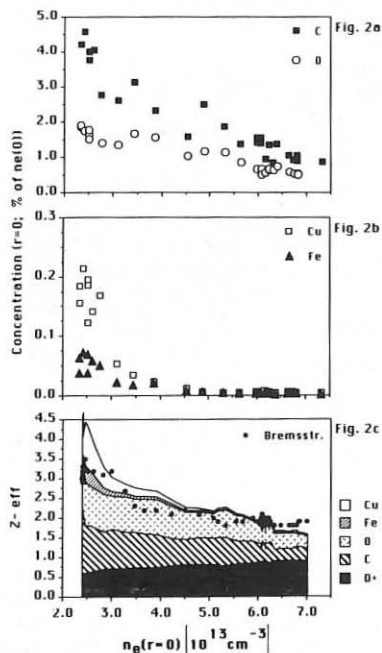


Fig. 2: Central concentrations of light impurities (2a) and metals (2b) vs. $n_e(0)$ for an ohmic ASDEX discharge. The various contributions to Z_{eff} and the comparison with bremsstrahlung- Z_{eff} is shown in (2c).

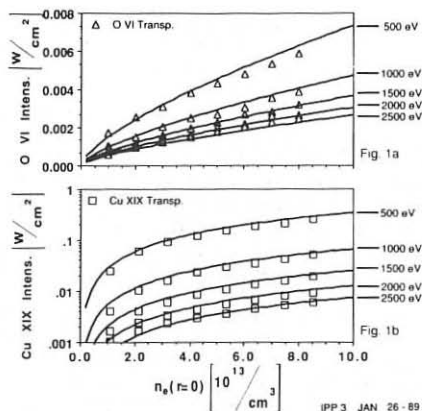


Fig. 1: Calculated line intensities (integrated along a central chord) for oxygen (1a) and copper (1b) as a function of central n_e and T_e in ASDEX. Code results are presented by Δ (O VI, 103.2 nm) and \square (Cu XIX, 27.3 nm), solid lines according to the fitting formula eq.(1).

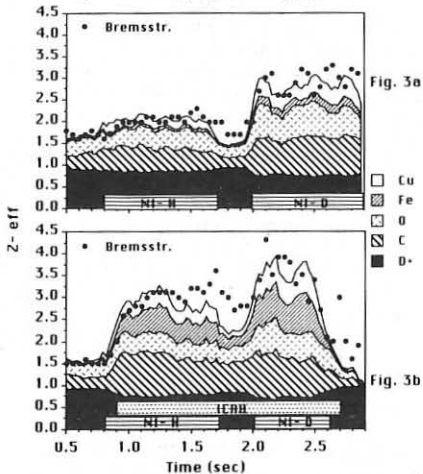


Fig. 3: Z_{eff} variations in case of auxiliary heating. (3a): H⁰ and D⁰ beams, (3b): H⁰ and D⁰ beams combined with 2MW ICRH. The contributions of the four main impurities and the deuteron dilution (D⁺) are indicated. Z_{eff} according to bremsstrahlung is also shown for comparison.