Influence of CX-reactions on the radiation in the pedestal region at ASDEX Upgrade

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The radiation loss in the pedestal region of H-mode plasmas is an important ingredient to tune the power flux across the separatrix in a fusion reactor. The radiation critically depends on the ionisation balance of the radiating impurity in this region. The abundance of each ion stage is determined by the rates for ionisation and recombination and the radial fluxes. It can be calculated with an impurity transport code. The charge exchange (CX) reaction of neutral hydrogen with an impurity ion

$$A^{z+} + H^0 \rightarrow A^{(z-1)+} + H^+ \tag{1}$$

is a very effective recombination process in addition to the electronic channels: radiative and di-electronic recombination. The CX cross sections scale linearly with the impurity charge, are very weakly dependent on the collision energy [1] and even a low fraction of neutral hydrogen can lead to a reduction of the average charge of the radiating species. Impurities in lower charge stages can usually radiate more efficiently than higher charge stages leading to a higher radiation loss for a given impurity concentration. Fig.1 compares the radiative power parameter of noble gases with (dashed lines) and without CX-reactions (solid lines) using the ionisation equilibrium without transport. The CX rates are included using a fixed fraction of neutrals n_D/n_e=4×10^{-5}. The yellow region indicates the relevant temperature range in the H-mode pedestal. For Ne, the radiation increase is very strong. The effect becomes small for elements with high nuclear charge as can be seen for Xe. For temperatures lower than 100 eV, the increase due to CX is again small. Thus, we expect the largest effect in the pedestal region where neutral densities can still be sufficiently large. Experiments in ASDEX Upgrade have been performed to measure the ionisation balance of neon in the pedestal region of H-mode plasmas and to assess the importance of CX recombination on the radiated power emitted by neon and argon. Details about these measurement and the modelling are given in Ref.[2] and are summarised below.

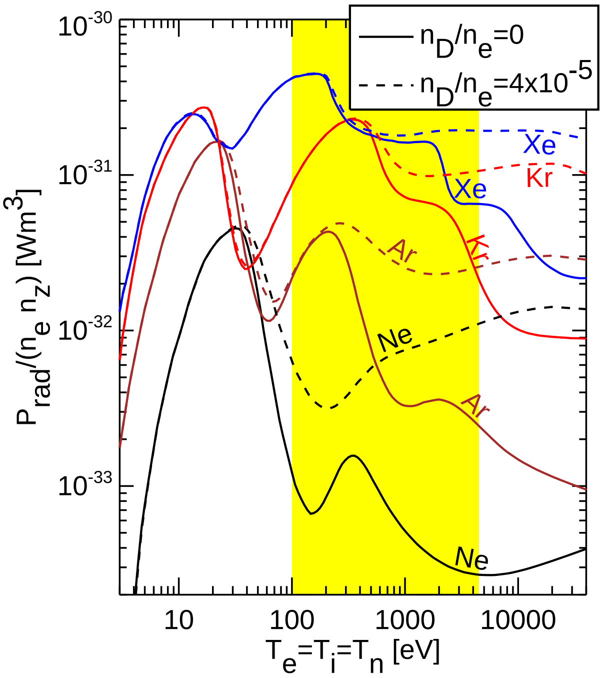

Fig.1: *Cooling factors of Ne, Ar, Kr, and Xe using the ionisation equilibrium without transport. Solid lines ar without CX-reactions and dashed line with CX for* n_D/n_e=4×10^{-5}.

Measurement and modelling of the Ne ionisation balance

A steady neon puff was applied during the flat top phase of a type-I ELMy H-mode plasma with plasma current I_p=0.8 MA, toroidal field B_t=2.5 T, heating power P= 7.7 MW, and line averaged density of $7.5\times10^{19}\,\mathrm{m}^{-3}$. The radial density profiles of Ne^{10+} and Ne^{8+} were measured from the centre up to the separatrix using the core and edge systems of the charge exchange recombination spectroscopy (CXRS). For Ne^{10+}, the n =11-10 transition of NeX at 524.9nm was used while Ne^{8+} was measured at the n =10-9 transition of NeVIII at 606.9nm, which is accompanied by the n =13-11 transition of NeVIII at 606.4nm. It is difficult to distinguish with CXRS between the He-like Ne^{8+} ion and the fully ionised oxygen O^{8+} since the emission of NeVIII and OVIII are at the same wavelength. Therefore, the discharges were performed directly after a fresh boronisation of the vessel walls in order to have as low oxygen concentration as possible. Furthermore, the neon puff was started about 0.6 s after the start of the flat top to allow for a measurement of the density profile of O^{8+}.

The ionisation balance of neon has been modelled with the 1.5D-impurity transport code STRAHL. It solves the radial transport equations of all ion stages of an impurity where neighbouring ion stages are coupled via ionisation and recombination reactions. The neutral deuterium density is not constant on a flux surface in the confined plasma. However, the CX-reactions affect the ionisation balance on the whole flux surface. Thus, it is sufficient to take the flux surface averaged CX-rates into account and a 1D transport model is a good approximation. Only a large neutral density extending up to a few cm above the X-point will cause a local change of the ionisation equilibrium due to the long connection length of the field lines in this region. These neutrals are not included in our flux surface average and a calculation of the ionisation equilibrium in this area would require a 2D model.

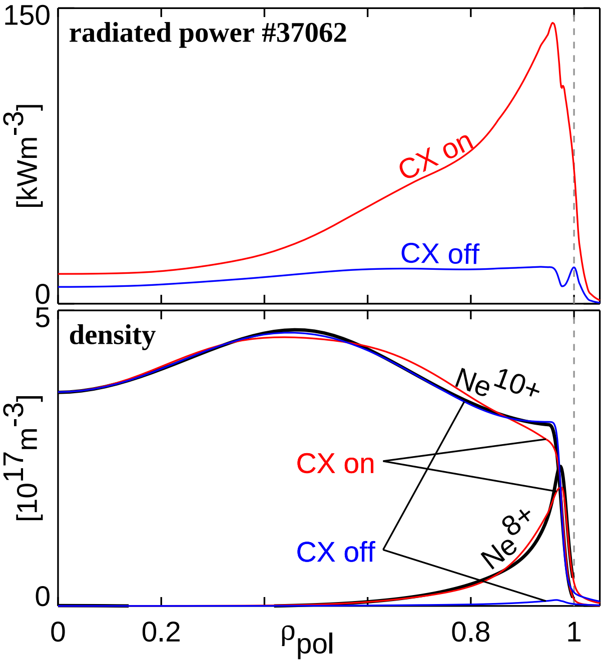

Fig.2: *Radial profiles of the Ne radiation and the densities of Ne^{8+} and Ne^{10+}. Black lines are from experiment, red/blue lines from the model with CX on/off.*

The lower graph of Fig.2 shows the experimental (black lines) and modelled density profiles of Ne^{8+} and Ne^{10+} for #37062 t=7.2-8.5 s. A simultaneous fit of both densities can not be achieved when CX-reactions are not considered. When fitting the density of Ne^{10+}, the density of Ne^{8+} is too low by a factor of 15-28 for ρ_{pol}=0.9-0.98 (blue lines). The measured profiles can only be described when adding the CX-reactions (red lines). The fit yields for the neutral density at the separatrix $n_{D,sep}=1.9\times10^{16}\ \mathrm{m}^{-3}$ and $n_D=4.1\times10^{15}\ \mathrm{m}^{-3}$ at the maximum position of the He-like neon density. These densities lead to a strong increase of the recombination rates and the neutrals cause more recombination reactions than the electrons for $\rho_{pol} > 0.85$, where $n_D/n_e = 2.8\times10^{-6}$. The ratio of the two recombination channels reaches a value of 25 at $\rho_{pol} = 0.98$ with $n_D/n_e = 2.7\times10^{-4}$ and a bit further out it has a maximum value of 50 with $n_D/n_e = 7.2\times10^{-4}$.

The much higher density of partially ionised neon inside of the pedestal top leads to an increase of the total neon radiation, which is much larger than expected without CX-reactions, since line radiation from the measured He-like stage, but also from H-like and Li-like ions can radiate much more compared to the bremsstrahlung and recombination radiation invoked by the fully ionised stage. The upper graph of Fig.2 shows the radiated power density of Ne for the two cases. In the case with CX, it is larger by up to a factor of 12 than without CX. The total radiated power emitted by neon inside the separatrix $P_{rad,sep}(\mathrm{Ne})$ increases by a factor of 5 from 220 kW to 1.1 MW. The main drivers for this increase are the line radiation from Ne^{9+} and Ne^{8+} whose contribution to $P_{rad,sep}$ is a factor of 9.6 and 16 larger than without CX. The modelled radiation with CX explains the change of the bolometric measurements with the Ne puff much better than the model without CX.

Effect of CX reactions on argon radiation in the pedestal

In the type-I ELMy H-mode discharge #36448 a strong argon puff was applied. The detected radiances by bolometers, soft X-ray cameras and by the SPRED spectrometer measuring in the vacuum ultraviolet (VUV) range are strongly dominated by argon radiation, such that this plasma is a good test case to study the effect of CX-recombination on the pedestal radiation of argon. The argon density profiles could be inferred from the soft X-ray radiation and from CXRS of Ar^{16+}, which measured the $n = 15$-14-transition of ArXVI at 541.2nm. However, without CX-recombination, the modelled radiances of the total argon radiation are about a factor of 2.2 lower than measured by the bolometer on lines-of-sights observing the main plasma. The reason for this discrepancy is that in the pedestal and in the near SOL, the He-like ion stage, which can not radiate so efficiently, has the highest fractional abundance when CX is not taken into account. This is strongly changed when CX is included. Here, the stages with $Z = 8-15$ have higher abundances than the He-like stage and can contribute to the total emission of Ar in this part of the plasma.

The SPRED spectrometer, which has a radial line-of-sight at the plasma equator, measures in the VUV region from 12 to 90 nm. Many VUV-multiplets emitted by argon from charge stages between $Z = 6$ (Mg-like) and $Z = 15$ (Li-like) could be identified. The radiances of the multiplets that could be well fitted account for about half of the total line radiation emitted by these ion stages. Fortunately, new atomic data sets from Bluteau [3] exist for all ion stages of argon, which enabled the calculation of the radiances of these multiplets for the case with and without CX as shown in Fig.3. With the exception of one outlier (ArXV at $\lambda = 26.5$ nm), which is a factor of 7.4 too small, there is rather good agreement with the measurement when CX is on. Here, the mean deviation between model and measurement is 24% and the maximum deviation is -44%. When CX is off, the emission from $Z = 5$ and 6 and from $Z = 15$ are not much lower, but especially the lines from $Z = 11$ and 12, which come from the outer pedestal close to the separatrix, are much too low. The higher radiances with CX are not due to a shift of the emitting shell into a region with higher n_e and thus higher excitation and emission rates, but due to a higher fractional abundance of the emitting ion. For the Mg-like ion stage, which has its maximum in the SOL, the densities and the radiation are almost equal. Even though the CX recombination is much larger than the electronic recombination for this stage, it does not influence the density distribution much. Rather it is governed by a balance of the ionisation rate and the radial transport, i.e. ions which are transported inward get ionised to higher stages, while most ions which move outwards do not recombine to lower ion stages during their travel time towards the plasma facing components.

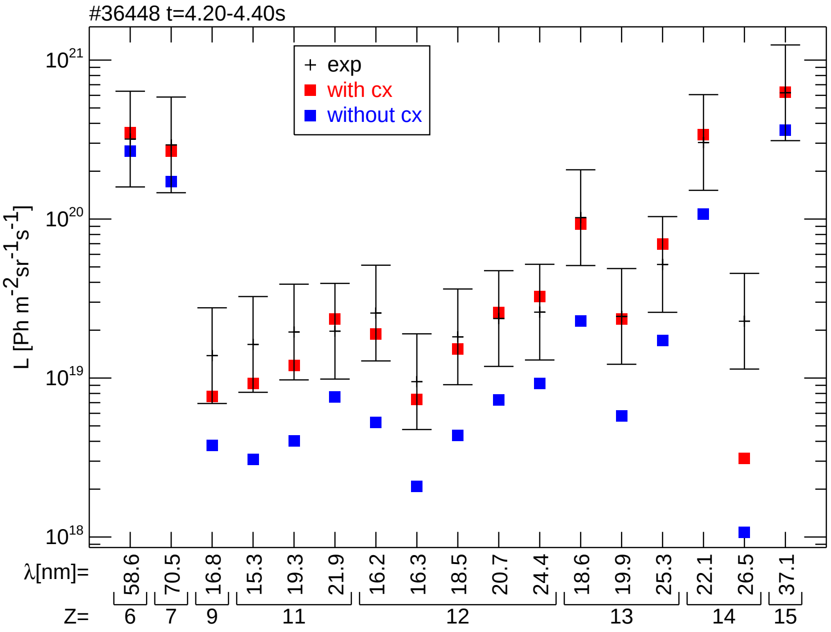

Fig.3: *The radiances of 17 multiplets emitted by argon ions with charge* $Z = 6-15$ *in the VUV range along a radial line-of-sight at the plasma equator and the corresponding model values without (blue) and with (red) CX recombination. The main difference between the models with and without CX is for lines emitted in the confined plasma close to the separatrix (Z=11-13).*

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References

[1] R.K. Janev and J.J. Smith (1993) *Atomic and Plasma Material Interaction Data for Fusion* (*Atomic and Plasma Material Interaction Data for Fusion* no 4) (Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY)

[2] R. Dux, M. Cavedon, A. Kallenbach, R.M. McDermott, G. Vogel et al, Nucl. Fus.**60** (2020) 126039.

[3] M.M Bluteau (2019) Fundamental atomic data and prototype techniques for a generalised collisional-radiative model of medium-weight elements in fusion and astrophysical plasmas, PhD thesis University of Strathclyde.