Implementation of fast line ratio spectroscopy on helium as plasma edge diagnostic at ASDEX Upgrade

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Introduction and diagnostic principle In magnetically confined fusion devices large power fluxes cross the last closed flux surface. The local power deposited on the first wall depends strongly on the transport perpendicular to the magnetic field lines driven by filamentary turbulence. To investigate steady-state as well as fast transport processes, a thermal helium beam has been implemented as plasma edge diagnostic at ASDEX Upgrade (AUG).

For this diagnostic purpose, neutral helium is injected into the plasma by a piezo valve [1]. The injected helium gets excited mainly by collisions with the plasma electrons and therefore emits light. The line specific emission intensity changes dependent on the electron temperature T_e and the electron density n_e. The light is captured with an in vessel optical head and transferred into the lab by means of optical fibers. This enables the measurement of the line resolved emission intensities of various He I lines, either with a spectrometer or with a filter based system. Helium emission intensity ratios of two singlet lines combined with a collisional radiative model (CRM) enable the reconstruction of electron density values, whereas singlet-triplet ratios provide the electron temperature.

CRM and line ratio selection In the established approach, the triple of red helium lines is used for this diagnostic. The 667/728 singlet/singlet (s/s) ratio is used for evaluating the electron density, whereas the 706/728 triplet/singlet (t/s) ratio shows a strong temperature dependence [2, 3, 4]. In general the helium line ratio technique is not limited to these three lines. Therefore a comprehensive investigation of possible ratios may expand the field of application of this powerful tool to higher intensity lines, which can improve the temporal resolution of the diagnostic, as well as lines with the best n_e and T_e dependency in the measured parameter range. For this purpose, the radial emission intensity profiles of seven He I lines were measured with a spectrometer for five plasma scenarios in AUG. The scenarios cover an L-mode as well as H-modes at different fuelling powers and densities. This leads to a density range of $1\times10^{18}\,\mathrm{m}^{-3} < n_\mathrm{e} < 4\times10^{19}\,\mathrm{m}^{-3}$ and a temperature range of $5\,\mathrm{eV} < T_\mathrm{e} < 250\,\mathrm{eV}$, which are typical parameters for the SOL and pedestal region of AUG. Within this parameter range different ratios are tested to figure out the ones with the most specific dependencies and highest emission intensities. Ratios which show a strong dependence on the plasma radius and thus on density and temperature gradients were used together with different CRMs to check their diagnostic applicability for n_e and T_e reconstruction. One of the best suitable new combinations was the 501/504 s/s ratio together with the 501/587 s/t. Combined with the CRM grid, plotted in Figure 1 based on ADAS data, this ratio is well suitable for n_e and T_e reconstruction in the given parameter range.

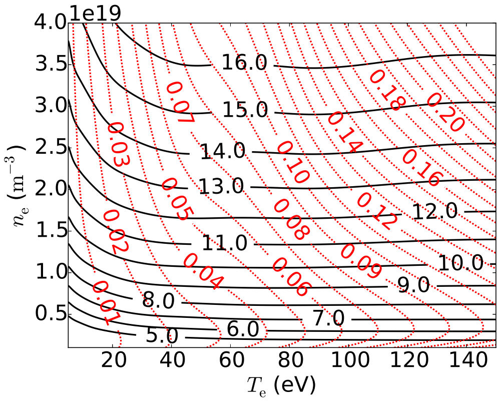

Figure 1: *Temperature and density dependence of the s/t line ratio 501/587 (red, dashed) and the s/s line ratio 501/504 (black, solid). The data are based on the ADAS data set 'pec96#he_pju#he0.dat' [5].*

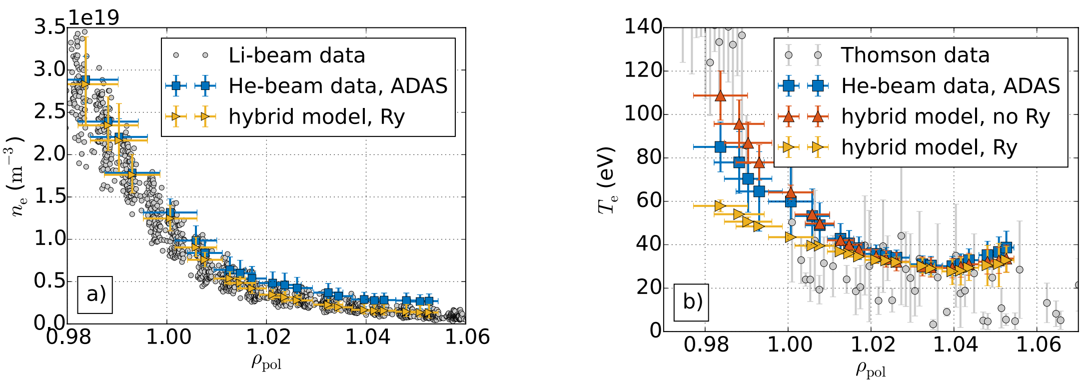

Figure 2: *L-mode profiles in AUG discharge* #32030, $t = (2.14-2.37)\,\mathrm{s}$. *a) Density reconstruction with the hybrid model with Rydberg (Ry) and the ADAS code with the 501/504 ratio, compared to Li-beam data. b) Comparison of the reconstructed temperature profile from the 501/587 ratio, with three CRMs. The hybrid model with and without high Ry and the ADAS CRM.*

The reconstructed density profile is plotted in Figure 2 a) for two CRMs leading to consistent results. One is based on ADAS data as in Figure 1, the other is called the hybrid code (cf. [4]) as it models the time dependent population density of the two spin systems. The results are in excellent agreement with the lithium beam diagnostics. Furthermore, the 504/667 ratio leads to the same profile. This shows that especially the 504.8 nm transition is well suited to replace the 728.1 nm line. Both transitions change the azimuthal quantum number by $\Delta l = +1$ and both corresponding upper states are mainly depopulated by electron collisions. Nevertheless, other possible density dependent line ratios do not lead to consistent results regarding the reconstructed profiles, with none of the tested CRMs. This points out that either some cross sections are systematically wrong or that some important processes are still missing or not correctly handled in the CRMs. This is especially critical for the temperature evaluation, where line ratios between the two spin species are formed. To the non-consistent results between different line ratios, the discrepancy between different CRMs adds up as illustrated in Figure 2 b), which shows the evaluated T_e with the ADAS and the hybrid code. It is remarkable that here the treatment of the highly excited Rydberg states (cf. [4]) leads to significantly different results in the region of high n_e and T_e. Furthermore additional processes which are not jet included may influence the s/t mixture. One candidate is the charge-exchange process between He^+ and hydrogen isotopes (cf. [6]) which may contribute as additional population channel favoring triplet state population. This process as well as a revised treatment of the Rydberg states will be implemented in the new version of the hybrid code.

The comprehensive investigation of possible He I lines for the line ratio technique in the edge of fusion plasmas shows that although several other suitable combinations were found, the classical approach with the triple of red lines seems to be the most promising one. Also the 728.1 nm line is the weakest of this triple and thus often limits the temporal resolution, the best alternative line is the 504.8 nm line, which is the weakest of all investigated lines. For the temperature, the strong 587.6 nm line can in principle be combined with one of the red singlet lines.

Hardware for helium line ratio measurements In consideration of the achieved results, a new hardware setup was installed at AUG. The newly developed multichromator system (cf. Figure 3) allows the measurement of four He I emission lines simultaneously. The device provides 32 channels. It is based on dichroic mirrors to separate the wavelengths, band interference filters with FWHM < 1.5 nm for the line selection and linear array photomultiplier tubes. The maximum data acquisition rate is 900 kHz. This allows the resolution of single edge-localised-modes, filaments and other turbulent structures, which enables the analysis of their influence on n_e and T_e in the AUG scrape-off layer.

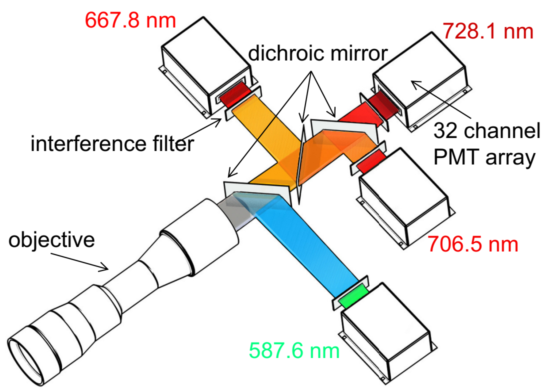

Figure 3: *Four color 32 channel multichromator system.*

The measured light is collected by a two lens optical head, placed at the low-field side of the vacuum chamber of AUG. It enables a radial resolution of the measurements up to 3 mm with in total 53 lines of sight. They are aligned with the magnetic field lines in the observation region which covers a radial as well as poloidal distance of 8.5 cm as shown in Figure 4. The same gas puff region can be observed with a fast camera, which is supplied by an image fiber providing a full 2D view of the puff. An example result of this gas puff imaging technique with the 587.6 nm helium line is represented in Figure 5. It shows probably a density blob which is translating radially outwards. This nicely demonstrates that in dependence of the conditions, the whole scrape-off layer is covered by the diagnostic.

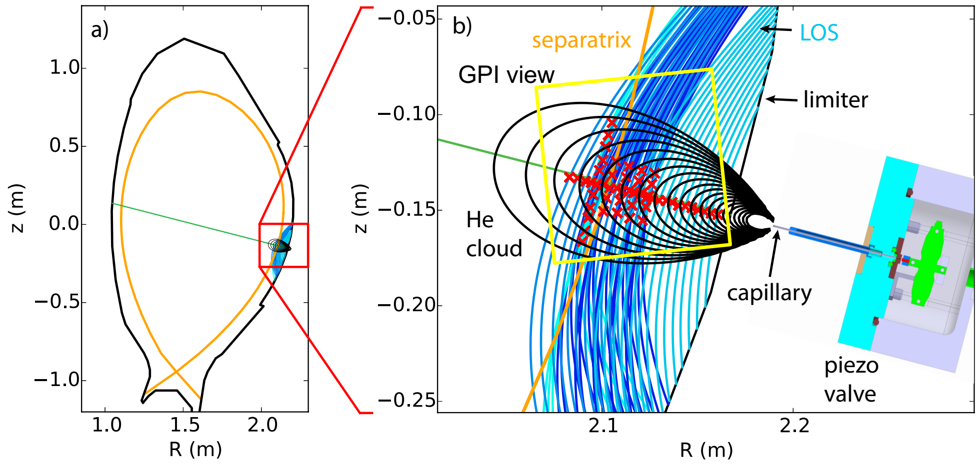

Figure 4: *Poloidal cross section of AUG. The LOS (blue), the piezo valve and a contour plot of the helium density (black) as well as the separatrix (orange) and limiter position (black) are illustrated. The green line shows the central axis of the helium cloud which lies perpendicular to the flux surfaces and the LOS at the measurement region. The red crosses mark the points of highest emission along the LOS.*

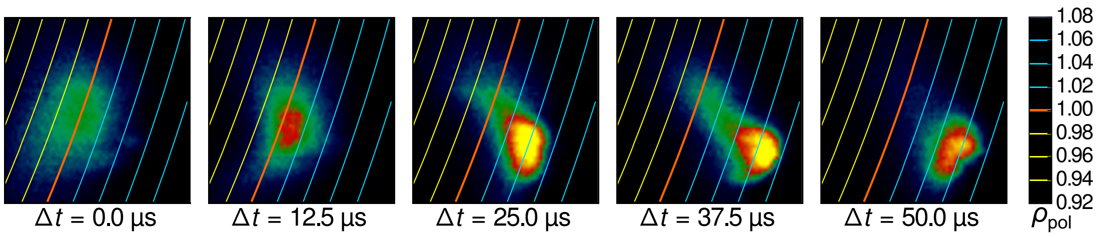

Figure 5: *Total emission intensity of the He I* 587.6 nm *line, measured with the GPI technique at AUG* #34 266, $t_0 = 6.907\,78$ s *and a frame rate of the fast camera "Phantom v711" of* 400 kfps.

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