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Population densities of atomic helium in the edge of high-temperature plasmas measured with laser-induced fluorescence

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1 Introduction

A method for diagnosing the edge region of high-temperature plasmas is the use of line radiation originating from atomic helium puffed radially into the plasma[1]. The measurement of intensity ratios of selected lines provides information about the electron density and temperature. In order to derive plasma parameters from intensity ratios a comparison with a model calculation of the population densities of corresponding levels is required. Therefore, the accuracy of the rate coefficients for electron collisional excitation, often only known from calculations, is crucial for a reliable data analysis. The LIF spectroscopy is used to validate the model prediction of the level populations. Both metastable levels of helium ($2^{1,3}$S) as well as the $2^{1,3}$P states are accessible with this method, complementing earlier passive visible spectroscopic investigations.[2-4]

On the tokamak TEXTOR at the Forschungszentrum Jülich in Germany an appropriate experimental set-up has been prepared allowing the measurements of helium population densities for different edge plasma parameters. Additionally, for the purpose of a reliable wavelength calibration of the laser system, a possibility for fluorescence measurements in a helium glow discharge in the laboratory has been established. This is crucial for a suitable choice of the laser wavelength scan interval during the discharge time of typically 5 seconds. Numerical simulations of the fluorescence signal response on the laser radiation predict a larger signal-to-noise ratio for the cases of triplet transitions. For this reason first measurements on TEXTOR have been carried out at the transition 2^3P $\rightarrow$ 3^3D in the triplet system at the laser wavelength of λ = 587.6 nm.

1 Experimental set-up

The laser radiation source is a two-stage system consisting of an excimer and a dye laser. The output of the laser system consists of UV-visible spectrally tuneable laser pulses of 15 ns duration, up to 60 mJ energy, repetition rate of up to 100 Hz and a spectral resolving power of better than 10^5.

The laser beam is guided from the laboratory to the top side of the tokamak by use of folding mirrors and steered onto a nozzle (*Figure 1*). Through this nozzle thermal helium atoms are radially injected into the plasma in form of a directed beam with a divergence of ~40°. The beam penetrates the plasma for some centimetres with a velocity of around 1.5 km/s and finally vanishes due to ionisation processes. The fluorescence light can be observed perpendicularly at several radial positions in the plasma simultaneously. This is equivalent to measurements at different pairs of (n_e, T_e). The observed volumes are imaged through an interference filter onto the entrance surface of fluid fibres with an inner diameter of 8 mm. The signals are detected by photomultiplier tubes and digitised by a fast acquisition device (1 GHz analogue bandwidth). A similar fluorescence set-up on a glow discharge chamber is used in the laboratory for wavelength calibration of the laser light.

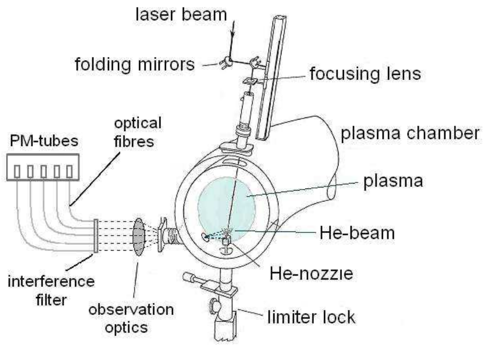

Figure 1: Experimental set-up of the LIF measurements on TEXTOR.

2 Data analysis and results

Since measurements of absolute level populations require the knowledge of the amount of helium atoms undergoing the laser excitation process, line radiation of the helium beam at λ = 501.6 nm originating from collisional excitation is recorded from a perpendicular direction with a video camera. Proper analysis of these data provides local helium density profiles for a desirable radial position.

The collisional-radiative model, being the basis for the derivation of the electron density and temperature from measured line intensity ratios, can also be used in a slightly modified form (population and depopulation contributions due to resonant laser radiation included) for the prediction of fluorescence signals which can be expected on TEXTOR and for the comparison with measured signals. Stationary population densities of 29 levels with principal quantum numbers of n = 1-5 are calculated numerically for a given set of (n_e, T_e). The result is used as starting point for investigating the laser impact on the equilibrium distribution.

Figure 2 shows one example of such a calculation and comparison with measurements for $n_e = 1.1\times10^{18}$ m^{-3} and T_e = 36 eV, for laser excitation of the transition $2^3S \rightarrow 3^3P$ at λ = 388.9 nm. The maximum fluorescence signals (during the laser pulse) measured at the laser wavelength can be directly used for derivation of the population of the pumped level. However, Zeeman splitting of the line (due to magnetic field, typically B = 2.25 T) and the impact of spectral laser width and the Doppler width of the transition must be considered additionally. Fitting of the fluorescence signal decay after the laser pulse provides a possibility to gain information on required corrections to the known rate coefficients between levels with the same principal quantum number as the upper level.

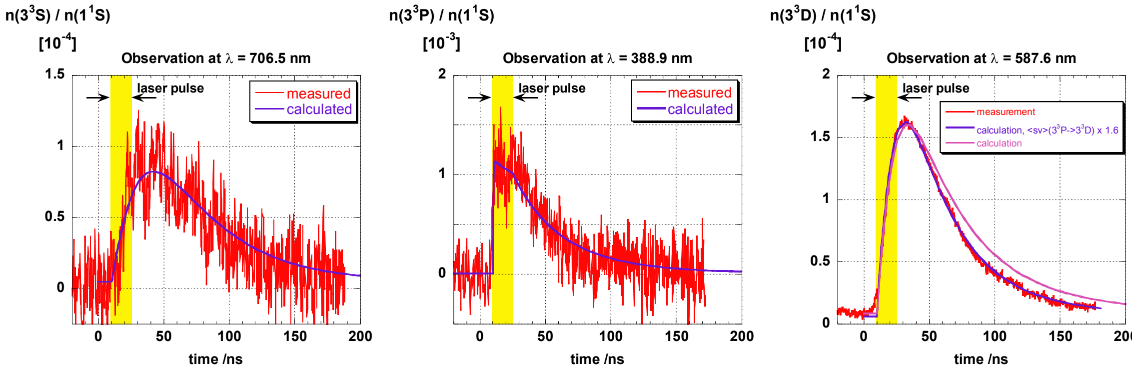

Figure 2: Simulated and measured impact of the resonant laser radiation at λ = 388.9 nm on the populations of triplet levels (relative to the ground state) with principal quantum number n = 3.

In the next step, for proper comparison of the maximum fluorescence signal from measurement and simulation, the impact of the Zeeman splitting of the pumped transition on the pumping efficiency is considered. All Zeeman components as calculated with the code Xpaschen[5] are shown with their wavelengths and transition probabilities in *Figure 3*. With this information a numerical simulation of the fluorescence signal as a function of laser wavelength (which is scanned over the Zemann components during plasma discharge) is possible. Additional input in form of the laser energy and laser spectral width or helium temperature (Doppler width of the absorption profile) is needed. As result of the fit of the calculated spectral profile to the measured one a correction factor is obtained containing the information about how effective the pumping process is. In *Figure 4* a fit of the part of the spectrum is presented where π components are dominant. For comparison also one example laser profile is included.

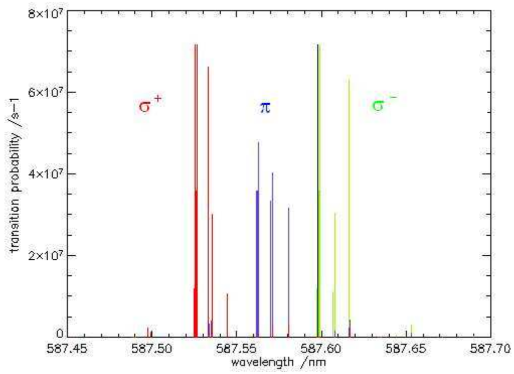

Figure 3: Calculated Zeeman components of the transition $3^3D \rightarrow 2^3P$ at λ = 587.6 nm for B = 2.25 T.

Finally, using the absolute calibration of the observation system, the relative population of the pumped level can be derived and compared with the model. *Figure 5* shows one result for the population of the 2^3P level derived from the fluorescence signal at 587.6 nm and 388.9 nm. Both measured values lie below the model prediction by a factor of 1.5-2 but within the error bars. As a last step, the rate coefficients of the collisional-radiative model can be varied in order to find a set providing a lower population of the 2^3P level matching the measured one. In first order the calculation is made each time with only one rate coefficient lowered by a factor of 5. The result is, that only three cases exhibit a significant decrease of 2^3P population (by a factor of 1.3-2). These are the rate coefficients for the following transitions: $1^1S \rightarrow 2^3S$, $1^1S \rightarrow 2^3P$ and $2^3S \rightarrow 2^3P$. In all three cases the changes in the model result in a 10-20% higher intensity ratio of the spectral lines at 728.1 nm and 706.5 nm which is proportional to the electron temperature. This is the equivalent to overestimating T_e by 10-20%. The ratio of the line intensities at 667.8 nm and 728.1 nm being proportional to the electron density remains unchanged. On the other hand increasing the rate coefficient for the transition $2^3P \rightarrow 3^3D$ by a factor of 15 reduces the 2^3P population by a factor of 2 as well. This would mean that T_e has been underestimated by 20%. To decide which case is more probable measurements of other level populations are required.

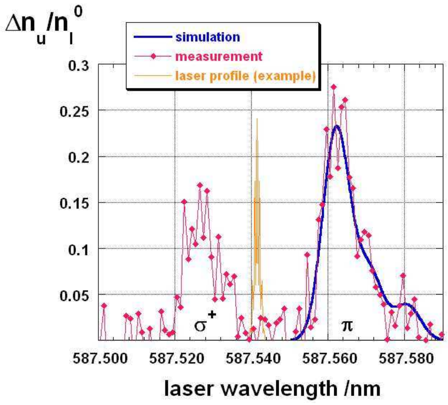

Figure 4: Numerical fit of the measured fluorescence profile as a function of the laser wavelength.

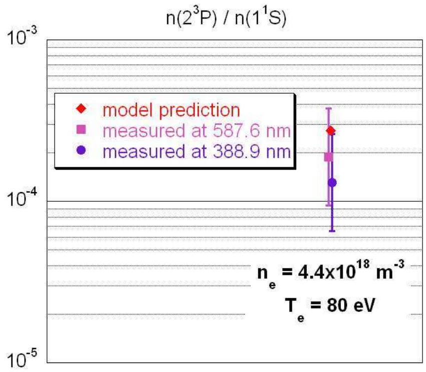

Figure 5: Relative population of the 2^3P level derived from the fluorescence signal at 587.6 nm and 388.9 nm

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