Spectroscopic studies of TCV divertor plasma with the DSS upgrade

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Introduction

To safely operate the next-generation fusion power plants, a *detached* regime is thought mandatory. The process of divertor detachment corresponds to a simultaneous decrease in heat and particle flux at the divertor strike points, thus alleviating target loads and erosion. A successful control of the detached regime is essential to understand the atomic/molecular processes that govern it. Here, we investigate the evolution of ion temperature, T_i, and its distribution in the divertor plasma in trasition to detachment, employing high-resolution visible spectroscopy of light impurity (He, C) lines.

Experimental setup

A high-resolution spectroscopic system was recently implemented within the Diveror Spectroscopy System (DSS) on TCV. Similarly to the previous lower resolution system [1], emission from the divertor plasma is collected by fiber arrays providing 32 radial chords crossing the divertor leg at different z-positions (see fig. 4a). The fiber array is then coupled to a 0.75 m imaging spectrometer (SPEX) equipped with a 2400 groove/mm blazed grating. The diffraction image is recorded by an Andor EMCCD camera mounted at the spectrometer output plane. The main specifications of the employed setup are given in table 1.

Spatial resolution	<1 cm
Temporal resolution	6-30 ms
Spectral resolution	~ 0.20 Å
Dispersion	~ 0.05 Å/pix
Spectral coverage	70 Å

Table 1: DSS specifications

Diagnostic principles

For T_i determination, we measure Doppler broadening of several emission lines: CIII at $\lambda = 4647$ Å, C II at $\lambda = 6578$ Å, He II at $\lambda = 4686$ Å, and He I at $\lambda = 6678$ Å. To isolate the Doppler broadening component from the observed line-shapes, we have to model and/or measure other contributing broadening mechanisms. For impurity species such as He or C, only the broadening due to Zeeman effect and the instrumental profile have to be considered (Fig. 1). The instrumental profile is defined by the spectrometer and detector specifications, and was measured for each line-of-sight (LOS) and each transition using calibration pen-lamps. The Zeeman effect was, instead, modeled using the values of toroidal magnetic field (perpendicular to the LOS) at the emission location. The line-shape resulting from the convolution of instrumental and Zeeman profiles (dashed blue lines in figures 2 and 3) is fed to the fitting algorithm [2] as a fixed parameter, where it is itself convolved with a Gaussian distribution representing Doppler broadening. The Gaussian's full width at half maximum ($\Delta\lambda_{FWHM}$) is thus the only free fit parameter for ionised species such as He II, C III, and C II. However, for neutrals transitions (He I, D), the assumption of emission only coming from radiators with two distinct T_i resulted in satisfactory line fits. Therefore, neutral ion emission was modeled as a sum of two Gaussians centered at the same central wavelength λ_0 (since LOS$\perp$ B_{tor}) with different $\Delta\lambda_{FWHM}$ parameters (Fig. 3). Finally, $\Delta\lambda_{FWHM}$ is translated to T_i using the relation:

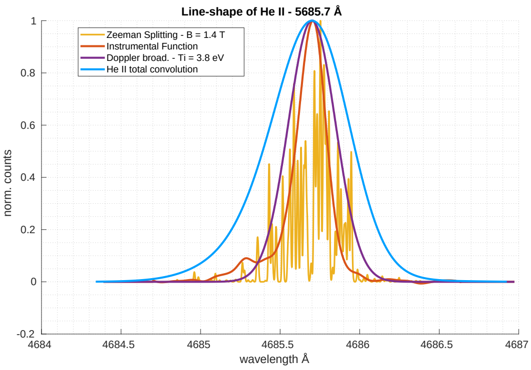

Figure 1: Convolution of Zeeman, Instrumental and Doppler broadening for He II transition at 4685.7 Å.

$$T_i = \frac{M_{ion}c^2}{8k_B \ln(2)} \frac{\Delta\lambda_{FWHM}^2}{\lambda_0^2} \tag{1}$$

Results

To study the T_i evolution prior to, and during, detachment, density-ramp discharges were conducted in TCV. To compare T_i and T_e during these discharges, outer divertor leg was set to overlap with the divertor volume observed by Thomson Scattering diagnostic (TS) for T_e and n_e measurements (Figs. 4a). In addition, Helium was injected at constant rate to enhance its emissivity (Carbon is an abundant and intrinsic impurity in TCV due its graphite walls). Figure 4 summarizes the main results of the present study. Figure 4b shows the T_i evolution of four different ions at $z = -0.62$ m (chord 12). While n_e increases with time (Fig. 4d), T_i of all ions decreases, showing the same trend as T_e that was measured previously [1]. Furthermore, we observe two phases of T_i evolution, at early times of the discharge all ions have different T_i that tend to equalize as the main plasma, and local plasma, densities increase. This interesting phenomenon requires further investigation and will be discussed in detail in future publications. Additionally, Fig. 4d shows remarkable agreement between T_i(He II) and T_e (measured by TS) in the divertor leg at $z = -0.62$ m. From now on we consider only times when the T_i of different ions equalize and $T_i \approx T_e$. Another important result inferred from Fig. 4b is the determination of $T_i(\approx T_e)$ at C III radiation front showing the extinction of C III emission for $T_e \lesssim 5$ eV. Figure 4c shows the normalized intensity evolution of the same ions at the same z-position. We see that towards the end of the discharge, emission from C ions extinguishes while the emission from He ions significantly increases. This opposite trend in the intensity evolution might be explained by a two order of magnitude difference in the recombination rate coefficient between the studied C and He ions [3]. Furthermore, initiation of the fast intensity rise of He ions (red dashed line in Fig. 4c) agrees with the start of the roll-over in ion saturation current measured by wall Langmuir probes that is used on TCV to signal the detachment onset. This suggests that the evolution of He ions emission intensity *could* be used for determination of the detachment front position along the divertor leg, but further modelling and analysis are required.

Conclusions

i) Here, we demonstrate the ability of the high-resolution DSS to provide an accurate measurement of T_i along the divertor leg down to ~ 0.5 eV (for He II ion). Comparison of T_i(He II) and TS measurements of T_e shows that $T_i \approx T_e$ when T_i(He II)$\lesssim$12 eV. This property should allow for T_e determination in many TCV divertor configurations where TS data is not available, as for those studied in [4]. ii) Detailed analysis of the line-shapes of neutral species shows that their emission originates from two populations having distinct temperatures: a *cold emission* due to transient excited neutrals (either recycled from the walls or injected by TCV valves), and

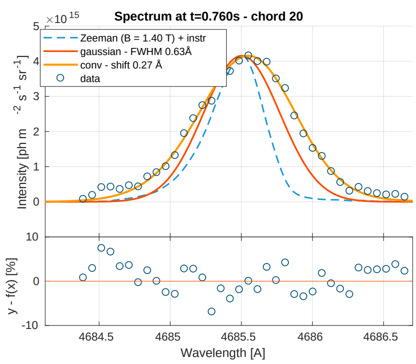

Figure 2: Fit of He II line-shape with a single Doppler broadening component, represented by the red Gaussian. The orange line is obtained with the convolutions illustrated in fig. 1.

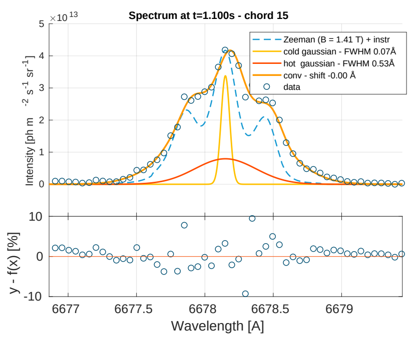

Figure 3: Fit of He I line-shape with two Doppler broadening components: the yellow Gaussian represents a cold temperature emission, while the red one is given by a hotter temperature emission.

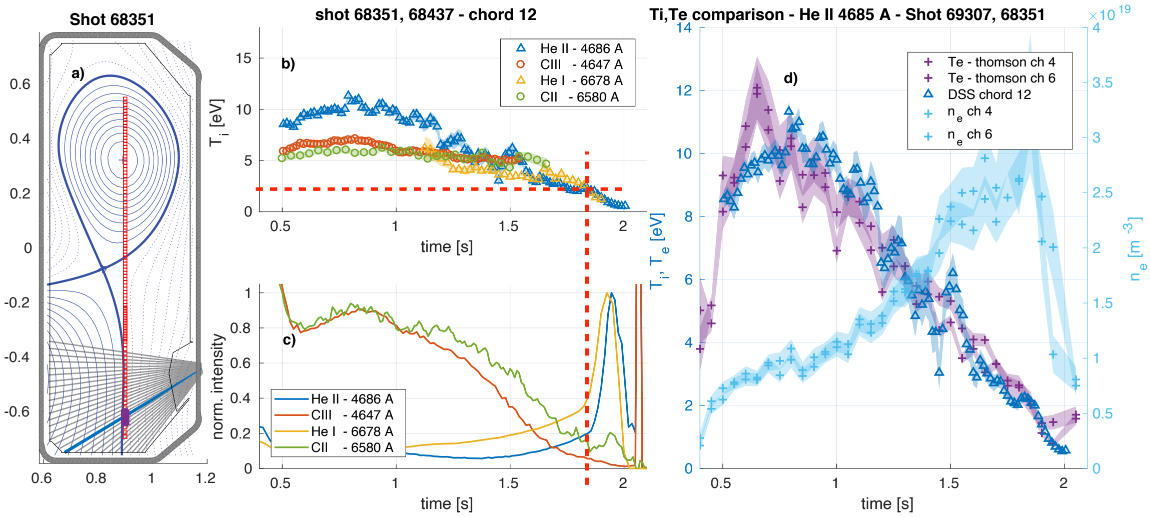

Figure 4: a) TCV poloidal cross section illustrating the equilibrium reconstruction, together with the DSS LOS (gray - blue for chord 12) and TS measurement locations (red); b) T_i evolution for the selected LOS (blue chord of fig 4a)); c) Normalised emission intensity evolution for the same impurity species and LOS as in (b); d) Comparison between the measured T_i(He II) of the selected LOS with the T_e measured by TS (TS channels used for comparison are purple squares in (a)). n_e measured by the same TS channels is plotted as reference.

a *hot emission* due to recombining singly ionized ions. This is important in analysis techniques that employ collisional-radiative models and measurements of line intensities to infer plasma parameters, and to estimate the contribution of volumetric recombination in detachment-related experiments. iii) An experimental ion temperature range of T_i(C III)$\sim$4.5-5.5 eV was assigned to the *C III radiation front* (50% intensity drop), a feature observed in C-wall machines often used as a proxy for the *low* T_e plasma regime onset that often precedes TCV's detachment [5].

Acknowledgments

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References

[1] Verhaegh K. et al, Nuclear Materials and Energy **12**, Apr 2017

[2] P. R. Bevington - Data reduction and Error Analysis for the Physical Science, pp.235-240

[3] Sultana N. Nahar, Atoms 8, issue 4, 68 (2020)

[4] Theiler C. et al, Nuclear Fusion **57**, Jul 2017

[5] Ravensbergen T. et al, Nature Communications, 17 Feb 2021,DOI 10.1038/s41467-021-21268-3