Identification of a Li III line relevant for TJ-II plasma diagnostics by passive spectroscopy

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Abstract. The purpose of this work was to identify the Li III spectral line located at 4498 Å. First, the wavelength of an intense line lying close to 4498 Å was examined and compared with the information provided by different atomic databases. Some theoretical predictions were performed in order to simulate the behaviour of this line under different heating conditions. Afterwards, the spatial behaviour of this line was analysed and compared with other well-isolated spectral lines belonging to already-identified elements. Finally, an analysis of the temperature and intensity evolution from this line was performed. The results show a complex behaviour of the line, which is mainly dominated by Li.

1. Introduction
Spectroscopy is one of the most powerful techniques used to measure different plasma parameters. Passive spectroscopic methods rely on the line emission by impurities present in plasma. Most of these impurities come from the plasma facing components (PFC) of the reactor. In the TJ-II stellarator, the PFC have changed over the years. The stainless steel wall has been coated with a boron layer followed by a lithium one [1]. Shortly, the carbon tiles will be removed so there is an urgent need to identify new spectral lines in order to continue performing spectral diagnostics into the TJ-II plasma core. Spectral measurements show a prominent line close to 4498.4 Å whose identification is the main purpose of this work. This line could be from Li III located at 4498 Å [2,3] formed by charge exchange (CX) recombination with either cold neutrals whose population is maximum at the edge, or fast neutrals from the neutral beam injection (NBI) system, which penetrate into the plasma core [4]. This line is formed as follows: Li$^{3+} + H^0 \rightarrow (Li^{2+})^* + H^+ \rightarrow Li^{2+} + H^+ + h\nu$, where $(Li^{2+})^*$ is an excited state (n,l).

The main focus of this paper is to identify the line located at 4498.4 Å. To do this a wavelength analysis of the line was performed, as well as a space-time resolved study of its intensity and its intensity and temperature evolution over time.

TJ-II is a four period low magnetic shear medium size heliac type stellarator with a major radius of 1.5 m and an average minor radius of $\leq 0.22$ m. A more detailed description can be found in [4]. To perform the wavelength analysis high-resolution mono and multi-channel spectrometers, described in [5,6], were used. The spectrometer explained in [7] was used for spatially resolved line emission. Finally, the system explained in [8,9] was used to perform the temporal evolution measurements.
2. Experimental Results

2.1. Wavelength analysis with spatial resolution

The first step followed in this work was to examine the wavelength of the line by performing a proper calibration and comparing its wavelength with the information found on different databases [2,3]. The atomic elements investigated were those that are most likely to be present in TJ-II plasmas. Elements with low relative line intensity, or whose strongest line is not present in TJ-II spectra, were not taken into account. The spectral line located at 4487.05 Å was successfully identified as B III. However, the line at 4498.4 Å could either be B III (4497.73 Å), C VI (4498.90 Å) or Li III (several wavelengths close to 4498 Å and one at 4500 Å due to excitation and recombination).

![Figure 1: Spectrum obtained on a TJ-II plasma heated by NBI.](image)

The next step consisted in doing a theoretical prediction of the behaviour of the Li line of interest during a NBI or ECRH plasma. We assumed solely a Doppler broadening with a Maxwellian velocity distribution as described in [10]. The intensity for all CX transitions with high-energy neutrals was assumed to be higher than for the excitation and recombination transitions, as detailed in [11].

2.1.1. NBI case

In this scenario there are fast energetic neutrals being injected into the plasma, which provoke CX reactions between stripped ions and fast energetic neutrals. Therefore, the CX processes mostly take place in the plasma core while the excitation and recombination processes should take place in the plasma periphery. The values of the temperatures are based on typical TJ-II parameters. The transitions for CX were summed and plotted along with one obtained for excitation and recombination (see Fig. 2). If all the transitions of Li III are occurring at an equal rate, the two peaks will not be easily distinguished in a NBI heated plasma.

![Figure 2: Gaussian calculated from the sum of all possible transitions \((n=5 \rightarrow n=4)\) for the Li III line formed by CX located around 4498.4 Å (red) and the one formed by the transition \((n=5 \rightarrow n=4)\) for excitation and recombination located at 4500 Å (blue). Theoretical temperatures are shown in the graph.](image)
2.1.2 ECRH case
In this case the density of neutrals in the plasma core is negligible and the CX processes are assumed to be occurring mainly with the cold neutrals in the plasma periphery. Two cases are assumed: the first one consists on the excitation and recombination processes occurring closer to the plasma centre and the second one where they are assumed to take place in the plasma periphery. As in the previous case, the values of the temperatures are based on typical TJ-II parameters. The two cases are plotted in Fig. 3 (a) and 3 (b), respectively. If the excitation and recombination processes are taking place closer to the plasma centre, the line at 4500 Å can be easily distinguished from the 4498.4 Å one, whereas the lines blend if both processes are occurring in the plasma periphery.

![Figure 3: Gaussian calculated from the sum of all possible transitions \((n=5 \rightarrow n=4)\) for the Li III line formed by CX located around 4498.4 Å (red) and the one formed by the transition \((n=5 \rightarrow n=4)\) for excitation and recombination located at 4500 Å (blue). Theoretical temperatures are shown in the graph.](image)

2.2. Spatial resolved study of the line intensity

2.2.1 ECRH case

Measurements were taken for two previously identified lines He I and B III and they were compared with the line of interest at three different phases of the discharge as shown in Fig. 4. The trace of B III shows a similar behaviour to He I; nevertheless its trace is narrower than the He I trace giving the clue that this element is peaking inner than neutral He I. To fully understand these traces, one has to keep in mind that the system maps the plasma from the "upper" edge of the plasma to the "lower" edge going through the plasma centre. In the He I case, the intensity valley in the central chords corresponds to a negligible concentration of this element in the plasma core. This is the typical shape for an ion that lies in the periphery. Fig. 4 (a) and (b) show how the emission corresponding to 4498.4 Å lies a bit closer to the plasma core than He I. In this case, the ion is not in the outermost part of the plasma periphery, but is not in the plasma core either. This fact also suggests that electron excitation and recombination rather than CX might be the working mechanisms in this case. This is consistent with the behaviour of a Li III peak formed by charged exchange with cold neutrals since these reactions should not take place in the plasma core.
Figure 4: Spatial resolved study of He I (5486 Å) (red), B III (4487 Å) (blue) and the 4498.4 Å (green) spectral line at approximately (a) 1100 ms (b) 1150 ms (c) 1200 ms.

2.2.2 NBI case

Measurements were taken for two previously identified lines C VI, B III and its behaviour was compared with the line of interest at three different phases of the discharge: before, during and after the NBI injection. It is seen in Fig. 5 (a) that C VI does not emit entirely in the plasma core. After the NBI is injected, its emission mostly comes from the plasma centre as can be seen in Fig. 5 (c), which shows a typical shape for an ion emitting from the plasma centre. On the other hand, the B III intensity profile shows an irregular behaviour. Fig. 5 (a) also shows that at first the 4498.4 Å line emissions do not peak at the plasma core and after the NBI is injected (Fig. 5 (b) and (c)) it emits closer to the plasma core. This behaviour is expected for a Li III ion undergoing CX recombination with highly energetic neutrals.

Figure 5: Spatial resolved study of C VI (5292 Å) (red), B III (4487 Å) (blue) and the 4498.4 Å spectral line (green) at approximately: (a) 1080 ms (b) 1102 ms (c) 1182 ms.

2.3. Measurement of the spatial evolution of ion temperatures

This section presents the analysis of the temperature and intensity evolution over time of the 4498.4 Å line. To perform this analysis the line was assumed to be either pure Li III, or a blend of different elements. The temperature and intensity evolution over time were calculated as explained in [7].

2.3.1 ECRH case

In this case, the line was analysed as being solely Li III. The temperature and intensity were plotted against time, as shown in Fig. 6 (b). The temperature, about 25 eV, is consistent with the peripheral ion temperatures found in TJ-II. Either charge exchange with cold neutrals or electron excitation could explain this emission.
2.3.2 NBI case

In this case, the line was analysed as being solely Li III. It can be seen, on Fig. 7 (c), how the line intensity starts to increase at 1150 ms. This increase coincides with the NBI injection. Notice that the maximum temperature reaches higher values than those seen in the previous case for ECRH.

Figure 7: (a) The 4498.4 Å peak measured in first order. Assuming it was only Li III, it was analyzed using just one Gaussian. (b) Intensity (blue) and temperature (red) evolution over time when the peak is assumed to be only Li III.

It was intended to analyze these peaks using two Gaussians; however it could not be easily performed and the results obtained did not have a reasonable physical background. Therefore, the line was measured in second order with the purpose of examining the line with higher spectral resolution.

2.3.3 ECRH case in second order diffraction

These measurements show that the 4498.4 Å line is a combination of at least two peaks (Fig. 8). Hence, different assumptions were made concerning the nature of these peaks. First, it was assumed that there is a Li III peak at 4498.4 Å formed by CX and another one at 4500.2 Å due to excitation and recombination [3]. It can be seen from Fig. 9 that the temperature for the excitation and recombination processes is higher than for the CX processes, meaning that the former are occurring closer to the plasma core. Conversely, the intensity for the CX processes is higher. This result matches quite well with the results obtained with the theoretical predictions explained in section 2.1.

Figure 8: The 4498.4 Å peak measured in second order, showing two peaks. It was adjusted using two Gaussians.
The second assumption was based on the fact that there is a B III line with a theoretical intensity of about 20% of the well isolated one located at 4487.6 Å [3]. Fig. 10 shows how a higher temperature for B III. The intensity of both lines shows a similar behaviour, Li III having a higher intensity.

Finally, the presence of C VI, which occurs at 4498.9 Å was analysed [2]. Fig 11 shows a higher temperature for Li III, however its temperature is lower. This means that C VI lies closer to the plasma core than Li III.

3. Conclusions
The Gaussian fit performed for the different transitions of Li III shows how this line has a complex behaviour. This behaviour depends on the ion temperature and the location where the processes are taking place. If the excitation and recombination processes occur at a higher temperature, or closer to the plasma core than the CX processes, it would be easier to identify both lines. The results also show that the behaviour of this line is mainly dominated by Li III. However, a major source of uncertainty in
the process to accurately identify this line is caused by the CV line located at a similar wavelength as Li III. Therefore, to fully understand the different atomic processes that may influence the behaviour of this line, it is recommended to perform measurements with an adequate charge exchange system.

References
[1] Tafalla D, Tabarés F, and Ferreira J 2010 Fusion Eng. Des. 85 915
[2] http://physics.nist.gov
[3] http://open.adas.ac.uk
[4] Alejaldre C 2000 Plasma Phys. Contr. Fusion 41 232
[5] Peláez R, Zurro B and Baciero A 2010 J. Phys. B: At. Mol. Opt. Phys. 43 1440
[6] Baciero A, Zurro B and McCarthy K 2001 Rev. Sci. Instrum. 72 971 (2001)
[7] Baciero A, Zurro B, 34th Conference on Plasma Physics (ECA, Warsaw, 2007), Vol. 31, p.5.
[8] D. Rapisarda, B. Zurro, and V. Tribaldos. Plasma Phys. Control Fusion 49, 309 (2007).
[9] D. Rapisarda, B Zurro and A. Baciero. Review of Scientific Instruments 77 33506 (2006).
[10] Hutchinson I, Principles of plasma diagnostics (Cambridge University Press, United States, 2002)
[11] Zou S, Kato T, and Murakami I 2001 Nat. Inst. Fusion Sci. 69 50