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Probing the edge ion temperature by passive Doppler spectroscopy in the TJ-II stellarator

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Abstract. We report on the measurement of the edge ion temperature in TJ-II plasmas, heated by electron cyclotron waves and neutral beam injection, using passive spectroscopy of impurity ions in low ionization stages. The measurements, which provide both temporal and some spatial resolution, offer some advantages over more intrusive or more sophisticated methods. The capabilities and limitations of this approach are illustrated by showing typical results obtained in conditions of interest for fusion plasmas.

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1. Introduction

Edge parameters have a strong influence on the core of magnetically confined plasmas and on the design of plasma facing components. Heating and erosion of these components generate impurities that can migrate to the plasma core and reduce the fusion gain by diluting the fuel and cooling the plasma by radiative emission. The edge ion temperature, T_i , is relevant for the development of plasma-surface interaction models, for predictions of the power fraction transported to the walls and for estimation of wall erosion and impurity production [1].

Charge eXchange Recombination Spectroscopy (CXRS) is the usual technique used to determine T_i at the plasma core [2, 3], but only specialized systems can reach the plasma edge [4, 5, 6, 7]. The CXRS system operating in TJ-II [3] has a high aperture spectrometer, but cannot measure the plasma outside ρ (normalized radius) > 0.8 . Spectroscopic techniques based on a supersonic He beam have been able to obtain the relative radial temperature profile in the TJ-II plasma periphery, but it needs independent temperature data in the plasma interior in order to give absolute values [8]. Because of these shortcomings in these other techniques, we need to cover the peripheral part of the TJ-II ion temperature profile by means of passive spectroscopy.

Passive spectroscopy is an alternative technique for edge diagnosis; and although inversion of chord-integrated data is usually required in order to obtain local spatial resolution, this is not always necessary if the ion species emission is itself spatially well localized. In high magnetic field devices, the complications added to the line width analysis by the influence of the Zeeman effect have the advantage that some information on the spatial origin of the emission can be recovered [9] due to the variation of magnetic field along the line-of-sight. Recently, the spectral line shape and T_i fluctuations have been extensively modeled [10], at conditions relevant to the edge of a magnetic fusion device, but scarce effort on the experimental side of using passive spectroscopy can be found in the literature notwithstanding the excellent and detailed work performed in the TEXTOR tokamak [11]. That paper deals with all the critical issues of this kind of measurements, with the exception of the possible effect of ion mass on Doppler ion temperature measurements, which can be observed only when measurements are taken with thermalized ions of significantly different mass. This effect, first pointed out by the astrophysicists, and now routinely accounted for in their analysis, is required to understand the results of ion temperature measurements of central ions [12, 13]. In contrast, retarding field analyzers have been used to monitor the edge ion temperature (see [14] for a set

of references), but that is a method that is very difficult to extrapolate to thermonuclear plasmas such as ITER. Since all magnetic confinement fusion devices have high spectral resolution devices in the visible range in order to monitor the types of impurities, their concentration and their influx, it seems natural to explore the potential and difficulty of using these instruments to also deduce the edge ion temperature.

Although it is generally believed that passive spectroscopy is a standard technique for monitoring the plasma edge ion temperature, this must not be the case since it is not often used in practice. We believe that the reason why it is not standard is that the relationship between the spectral line shape and its width (FWHM), from which the ion temperature must be deduced, is complicated. It can be altered by any of several different effects, each of which has a distinct influence on different lines belonging to different ions (for instance velocity fluctuations, Zeeman effect, spatial averaging effects) that must be considered in order to understand the raw experimental data.

Taking into account all these complications, the scope of this work is to investigate which ions and particular emission lines can be used most confidently for this purpose, with the final goal of developing an experimental set-up for routinely monitoring the edge temperature with increased spectral and spatial resolution. For this purpose, measurements of T_i in the edge of the TJ-II plasma taken using passive spectroscopy are reported and some of the limitations in the experimental approach and the data analysis are discussed. Spectral lines belonging to low ionization stages of C, He and Li impurities have been used for this purpose. Measurements of the ion temperature with time and chord resolution have been performed in TJ-II plasmas heated by Electron Cyclotron Resonance Heating (ECRH) alone and in discharges with Neutral Beam Injection (NBI). Typical illustrative results in all of these different scenarios will be presented. A discussion of the different problems encountered in both the experimental approach and the data analysis is also presented.

This paper is organized as follows: the experimental set-up and a brief description of the analysis methods are presented in section 2. The experimental results obtained in typical TJ-II discharges are included in section 3. Finally, conclusions are drawn in section 4.

2. Experimental

The spectral line shapes of intrinsically edge ions have been recorded in TJ-II plasmas using high spectral resolution spectrometers that view the plasma perpendicular to the main magnetic field through fiber guides. One of the spectrometers has spatial resolution capabilities by means of 9 equal-spaced channels, which integrate the emission along different plasma chords. The other one monitors the impurity emission lines, with higher time resolution, along a fixed chord collinear to any one of the nine spatial channels. The experimental systems and data analysis methods are described in some detail in [15] and [16]. The information provided by both spectrometers is complementary, providing an understanding of the data obtained in a complicated geometry such as that of TJ-II plasmas. The geometry of the TJ-II plasma observation is illustrated in figures 1 (a) and (b); the first one shows the toroidal position of the two spectrometers with respect to the location of the main heating sources and key diagnostics, whereas the second one gives the details of how the nine channels (1 bottom to 9 top) of the multichannel spectrometer are distributed along different plasma chords in order to cover most of the plasma cross-section; the diameter of the collection light cone is not better than 1 cm.

We must add a few comments regarding the spatial resolution that can be achieved with this approach. The spatial resolution that can be achieved in practice depends on the intensity of emission lines available, which is typically limited by the cleanliness requirements of the plasma device, the limited physical access to the plasma and the use of spectrometers with large focal length and low f-number ($f/10$ or $f/12$) to achieve the maximum spectral resolution needed for edge ion temperature measurement. The former conditions constrain the spectral system to the use of long fibers that must be 1 mm thick if you want to collect the maximum signals. A multichannel system with compact focusing optics, and with good contrast to avoid channel crosstalk, give us an optical spot not better than 1 cm at the plasma center for every channel. Better spatial resolution could be achieved if an observation geometry where the input slit and consequently the individual pixels of the CCD array were directly focused with a single optical lens onto the plasma periphery, but this is uncommon due to space constraints.

This work has been focused on the measurement of the edge ion temperature in discharges heated by only ECRH (up to 600 kW at the second harmonic) and with additional heating of two neutral beam injectors: NBI_1 and NBI_2, parallel and anti-parallel to the magnetic field (up to 400 kW from each injector).

The impurity ions selected for this work are present in TJ-II plasmas in concentrations high enough to make these measurements possible. The Li lines are very prominent because the

plasma wall is covered by Li to reduce the influx of high Z (atomic number) metals from the plasma-wall interaction. The carbon lines are present because the NBI neutrals that shine through the plasma are dumped into graphite tile protection. Finally, He is present because it is used everyday during glow discharge cleaning, because it is used also to run the supersonic helium beam that diagnoses T_e at the edge [17], and also because it is injected after the TJ-II discharges for Heavy-Ion Beam Probe (HIBP) calibration. Other lines of contaminants are present in much smaller proportion and it would be difficult to use them for edge ion temperature measurements with good time resolution and good statistics. In table 1, we show the ionization potential of the ions whose emission lines have been used in this work.

The main assumptions implicit in Doppler broadening measurements of ion temperature are that the impurity ions are thermalized with protons and that the Zeeman effect is negligible or can be corrected. The thermalization time between protons and other ions (C and Li) has been estimated, assuming solely Coulomb collisions, using the well-known Spitzer formula [18]. For typical edge densities of 10^{18} m^{-3} and a proton temperature of 50 eV, the thermalization time is about 50 μs with C^+ and 100 μs for Li^+ . On the other hand, the ionization rate by electronic collisions is strongly influenced by the electron density and temperature. If we assume the same values as before, the ionization times of C^+ and C^{2+} , estimated using the analytical expressions for the rate coefficients given by Suno and Kato [19], are comparable to the thermalization time between C^+ and protons. The ionization time for Li^+ is about 1 ms [20], so this is the most probable ion, among those herein chosen, to reach thermal equilibrium with protons. These time estimations are shown in the figure 2(a). These times should also be compared with the global particle confinement time, which has been estimated to be about 5-6 ms for lithium-coated walls in TJ-II [21]. Similar results have been obtained for impurity confinement time in TJ-II as determined by measuring the time relaxation of global radiation signals after injecting a small amount of either a light impurity such as Boron (B) or a heavy impurity like Iron (Fe) by laser blow-off technique. These measurements have been performed for pure H plasma and with freshly Li wall deposition [22]. We must emphasize that other processes, such as fluctuations, could enhance the thermalization times but it is difficult to estimate their contribution to this problem. Regarding the spectral line shape, under some considerations of thermodynamic equilibrium for the ions, it has been shown that Doppler line width for the edge conditions, apart from mass motion, is not influenced by temperature fluctuations, although these variations might theoretically affect the spectral line wings [23].

In [figure 2\(b\)](#) we depict the typical electron temperature profiles in the TJ-II periphery at three selected times during an ECRH+NBI discharge, obtained from the line ratio method by means of the periodic supersonic He beam [\[17\]](#). Edge electron temperature decreases as the chord-averaged density increases ($n_e = 0.6, 1$ and $3 \times 10^{19} \text{ m}^{-3}$). The lines correspond to exponential fits of the data and guide the reader through the experimental points.

This approach achieves its moderate spatial resolution by assuming that in the ideal case the plasma edge should be symmetric: the electron density and temperature would be solely a function of the flux surface. Under that assumption, impurity ions with different ionization potentials are located in distinct radial shells. The lower the ionization potential, the more external the layer from which its line emission comes from. Therefore, the ion temperature obtained in a plasma with a sufficiently large electron temperature gradient should be distinctive of the charge state and type of ion whose emission line is selected by the Doppler spectrometer.

The influence of the Zeeman effect on the two carbon ions used in this work has been estimated by a synthetic method previously described in [\[24\]](#). The method consists of a simulation of the line width, as a function of the magnetic field. This process has been performed and illustrated with the results shown in [figure 2\(c\)](#), where we have estimated the influence of the Zeeman effect on the temperature estimated from the line width of the carbon lines in the lowest ionization stage considered in this work. For the transition of the Li^+ line selected the Zeeman effect is zero in the approximation of low magnetic field, which is valid in TJ-II. We have considered the transition of the He^+ line in old calculations [\[25\]](#).

In [figure 3](#), we display traces of a typical TJ-II discharge. [Figure 3\(a\)](#) depicts the traces of the chord-averaged density, diamagnetic energy and the time evolution of C^{4+} emission. [Figure 3\(b\)](#) shows typical Thomson scattering profiles of electron temperature and density.

3. Results and discussion

In order to illustrate both the power and the limitations of using passive spectroscopy to monitor the ion temperature of peripheral ions, we will focus on a selected set of results relevant to several important physical issues. We will consider the behavior of edge ion temperature in low frequency ECRH modulation experiments. We will also perform a comparison between the behavior of edge ion temperatures monitored with different impurity ions, in low density ECRH discharges and high density NBI shots in both spatial and temporal evolution. Finally, we will compare results provided by different impurity ions with different ionization potentials since

they provide information about different radial portions of the plasma periphery even if it can be extremely complex to determine those position and extents with high accuracy. The influence of Ion Cyclotron Resonance Heating (ICRH) on edge ion temperatures has been studied in great detail [26-28]. Although these plasma heating methods are theoretically well tuned to the plasma center, some unexpected mechanism might allow some power coupling to the plasma edge and these effects can be assessed by measuring ion kinetic properties at the plasma periphery.

In order to illustrate the results provided by this passive spectroscopy technique, we have selected a TJ-II discharge heated solely by ECRH where one of the gyrotrons was modulated in its full power (300 kW) at a rather low frequency (30/60 Hz). The ion temperature evolution of Li^+ , as determined from passive spectroscopy, is shown in figure 4(a), while its line intensity is shown in figure 4(b). The very prominent line at 548.4 nm emitted by this ion has been crucial for measuring the temperature with good time resolution. It is difficult to achieve such results in TJ-II with other, weaker, peripheral ion emission lines. We must emphasise that when TJ-II walls are coated with Li, oxygen lines are too weak for performing this type of measurement and we must wait for several weeks after a deposition before we can use carbon lines. In addition, NBI operation is needed for providing enough carbon for these measurements. The modulation timing provided by one central Electron Cyclotron Emission (ECE) trace is also displayed in both plots. As can be seen, the modulation is echoed in the line intensity evolution (figure 4(b)), but with a slower edge rate than ECE, which is proportional to the electron temperature. The effect on the ion temperature is delayed and less pronounced. Figure 4(c) shows the effect of ECRH modulation on Li^+ intensity and temperature when the spectral line detector was run at its highest sampling rate, and where the modulation is seen reasonably well in the temperature and line intensity traces. A peak-to-peak modulation of 15 eV is easily seen in some time cycles. The two selected discharges with ECRH modulation correspond to two different density cases (#21108, $n_e=0.6 \times 10^{19} \text{ m}^{-3}$) and (#22361, $n_e=0.3 \times 10^{19} \text{ m}^{-3}$). Notice that in the first discharge the ECRH power was modulated at a lower rate than the second one. The delay between changes in ECRH power, Li^+ density and temperature is longer for the lower electron density case (approximately a cycle), which is the behaviour expected for an electron-collision heating mechanism in which the collision rate scales with density. This delay between the microwave modulation and the ion temperature and density response at the edge shows that the ion temperature modulation is not a direct consequence of the radiofrequency source as it crosses the edge, but rather is a consequence of the central T_e modulating in response to the heating source and the subsequent ion heating modulation due to

electron-ion heat transfer, which propagates towards the edge due to transport. The electron-ion heating time, as estimated for typical TJ-II edge plasma conditions ($T_e = 50 - 100$ eV and $n_e = 1 - 2 \times 10^{18} \text{ m}^{-3}$), predicts values (3-6 ms) compatible with the delays measured in the temporal traces depicted in [figure 4](#). This data rules out the need for any anomalous effect to explain the observed behavior of Li^+ temperature modulation at the edge. As can be easily seen, in [figure 4\(a\)](#) and [4\(c\)](#), the oscillations in ion temperature from the Li^+ measurement are almost as large (~ 20 eV) as those during the ECRH modulation, but Li^+ intensity is a clearer indication of the modulation timing. Therefore, to obtain the maximum information in dedicated ECRH modulation experiments, we should choose discharges with minimum temperature fluctuations and perform the modulation at a lower frequency. In any case, a time correlation between both modulations would help to disentangle variations associated to natural fluctuations from forced modulations due to ECRH source modulation.

The plots of [figure 5\(a\)](#) and [\(b\)](#) show the time evolution of ion temperature and intensity deduced from the emission lines of other two ions used in this work, He^+ and C^{2+} . They correspond to discharges with NBI. The combination of temperature and line intensity temporal evolution allows us to understand the effect of the NBI, or the rise of density and decrease of temperature due to them, on different ions. In [figure 5\(c\)](#) and [\(d\)](#) we display only the temperature evolution of representative peripheral ions (Li^+ , He^+ , C^{2+} and C^+); [figure 5\(d\)](#) for discharges heated solely by ECRH, and [figure 5\(c\)](#) for NBI discharges. Notice the different behavior of the line intensity time evolution of impurities He and C shown in [figures 5\(a\)](#) and [\(b\)](#). Whereas the intensity of He emission decreases, with the entrance of NBI, presumably because the edge electron temperature is reduced and the density is augmented. The carbon intensity increases because the part of the beam not absorbed by the plasma hits the graphite tiles that protect the stainless steel and prevent the production of heavy impurities. The discharge #21733, where a low modulation in the Li^+ ion temperature is observed, correspond to a TJ-II experiment where an electrode inserted into the plasma edge, was dynamically polarized with a higher frequency than the modulation seen in the temperature.

The lowest density discharge taken while viewing the He^+ line (#20077) is a measurement in the ECRH phase of the discharge. In the intermediate density discharge (#20076), only the NBI1 injector was operating, while in the highest density case (#20072) both injectors were used to heat the discharge. For the selected Li^+ data, similar operating modes were used, (#21176) is a measurement in the ECRH phase of the discharge, (#20041) with one injector and (#20044) was heated by two NBI injectors. Therefore, for similar operation modes

the Li^+ and He^+ ion temperatures behave differently because of the different penetration of both ions. Radial line intensity measurements, discussed when commenting figures 7 and 8, show that in discharges heated by NBI, a significant He^+ population exist at the plasma centre, whereas Li^+ is confined at the edge. In addition, Li^+ is more probably thermalized with the protons at all densities, because of its higher ionization potential. This may explain why the Li^+ temperatures are higher than the He^+ , even for the peripheral channel (1, 2).

Based on a broader set of data than that presented here for illustration, the He^+ ion temperature typically responds to the NBI by approximately doubling its temperature, whereas C^{2+} temperature either does not change or even decreases during the NBI phase and little change in Li^+ temperature is observed. As we will see later, to understand the distinct behavior of He^+ under NBI we must consider how its observed penetration differs from the other ions. That rules out a simple argument based on the pure ordering of ionization potential. In addition, you can observe that the ion temperature of Li^+ is less prone to change with both density and NBI heating. In contrast, the temperature of C^{2+} exhibits high “apparent” temperature values that decrease as the density increases (see [figure 5\(c\)](#)). This might be due to the influence of plasma velocity turbulence on different ions, already reported by us for highly ionized ions [12, 13], that is more important for the higher the mass ions. In general, C^{2+} and C^+ exhibit more significant temporal temperature variations than other ions. These fluctuations have a dominant frequency of 50-100 Hz and have been observed in both NBI and ECRH discharges. We attribute this to the more external radial location of these ions where temperature fluctuations are enhanced.

Finally, in [figure 6](#) we present results of edge ion temperatures provided by the single shot multichannel system measured along different chords. In the labels displayed on each plot we show the type of ion, wavelength of the emission spectral line used, the discharge number and the mean chord-averaged density in the time window where the data collection took place. Typically, each plot includes one case corresponding to the ECRH phase, the lowest density, and two cases corresponding to the NBI phase, corresponding to densities higher than $1.5 \times 10^{19} \text{ m}^{-3}$. A few features must be highlighted from these figures. Notice that Li^+ ion temperature does not change significantly along the different parallel set of chords, see [figure 6\(a\)](#), and also note the low sensitivity to density changes. A more significant and unexpected change is observed in the spatially resolved results of He^+ temperatures, shown in [figure 6\(b\)](#), where we observe that its temperature increases significantly when the electron density decreases. It is much higher for central chords (4-7 channels) and lower for the bottom channels (1,2) than for the top edge

channels (8,9). The first effect can be qualitatively understood, because of the deeper penetration of He^+ ion, as we will see when we present and comment on the results in the next figure. The second effect might be understood because of the $\mathbf{B} \times \text{grad } B$ drifts, which tend to concentrate the hottest ions in the top part of the plasma. Therefore, as the temperature is one of the first moments of the distribution function, that effect leaves a track in this parameter.

In contrast with Li^+ and He^+ , we can see from [figures 6\(c\) and \(d\)](#) the behavior of similar data for C^{2+} and C^+ ions as a function of density. On the one hand, C^{2+} exhibits a greater temperature change with density than Li^+ , but its temperature decreases as the density increases, consistent with the density behavior of edge T_e presented in [figure 2\(b\)](#). A similar trend is also expected for plasma turbulence. This behavior can be qualitatively explained because, on the one hand, the C^+ and C^{2+} ions are more external than Li^+ , consistent with their lower ionization potential (see table 1), and they do not exhibit the same penetration as the He^+ , as we will see when we discuss next figure. In addition, due to the higher mass of carbon it is more prone to velocity turbulence influence on Doppler line width than lighter ions [\[12, 13\]](#).

Regarding to the behaviour of C^{2+} temperatures, we must point out that our data set using this ion is small because its emission is often too weak to perform these measurements meaningfully. However, we feel obligated to show its temperature behaviour, even if we do not fully understand it. In fact, the C^{2+} temperature data, shown in [figure 6 \(c\)](#), exhibits a trend with density similar to that shown by the edge electron temperature profiles selected and presented in [figure 2 \(b\)](#); it tends to decrease when the density rises and the edge electron temperature decreases. That behaviour would be very difficult to explain from a classical mechanism such as electron-ion heating through Coulomb collisions. However, it is generally observed that some types of plasma turbulence tend to decrease, when increasing the electron plasma density, see ref. [\[12\]](#). That might be a hint to look more deeply into this effect in the future, to figure out whether this behaviour of C^{2+} temperature could be caused by turbulent velocities.

Regarding the low frequency modulation of C^{2+} ion temperature for discharge #21187, we suspect that the presence of an 8/5 resonance at the very edge, for the particular magnetic configuration of the former discharge (which is not the standard one), might explain that modulation. It is not seen in neighbouring discharges, which were performed with the standard magnetic configuration. However, in order to corroborate that theory we would need a deeper analysis involving other diagnostics, which is outside the scope of the present work. More puzzling, at first sight, is the fact that the C^{2+} temperature is higher than that of the other ions in

the data shown in figure 5 (c). We must remark that although we cannot compare data for different ions in the same discharge, and this could be the reason for some of the differences, but we do not believe that it is the only explanation. Since carbon mass is significantly higher than that of Li and He, carbon temperatures might be more influenced by the effect of turbulent velocities on the kinetic temperature deduced from line width, see our references [12, 13] for a more detailed discussion of this effect.

The decrease of ion temperature in channel 7 of discharge #21326 was correlated with a short pulse injection of gas, which was done because that discharge was part of an experiment where the T_e profile was forcibly transitioned from “bell” to “dome” shape by timed gas injection. This result illustrates how sensitive these measurements are to anything that happens at the plasma edge, even if it is observed only in one channel.

In order to quantify the influence of the finite radial extent of the emission region for each ion charge state, we have carried out an analysis using the method described in [15] and references therein. In summary, we use a simple emissivity localization function, of the type $I(\rho) = I_0 \exp(-[(\rho-\rho_0)/\lambda]^2)$, to account for the chord-integrated results, where I_0 is the maximum emissivity, ρ_0 the radius of the magnetic surface where that value occurs and λ the decay length of the selected line emission of the corresponding ion. The local ion temperature profile is simulated by this analytical expression: $T_i(\rho) = (T_{i0} - T_{\text{edge}}) (1 - \rho^\alpha)^\beta + T_{\text{edge}}$, where the central value is taken from Doppler measurements of inner ions. The TJ-II magnetic configuration, needed to choose the shell structure seen by any observational cone, is taken from the TJ-II data base.

Some results from this type of simulation are shown in figure 7 (a) and (b) for He^+ in an NBI discharge and figure 7 (c) and (d) for an ECRH discharge; in figure 8 (a) and (b) we present a similar simulation for Li^+ and figure 8 (c) and (d) for C^{2+} . Both the chord integrated intensity and temperatures are shown. The edge temperatures assumed in the simulations are 40 and 20 eV for the two He cases; one corresponds to the NBI phase (#20072), whereas the accompanying case corresponds to ECRH alone (#20077). In contrast, for the Li^+ case selected, which is representative of many cases, the edge temperature assumed to account for the multichannel system results is between 60-70 eV. Much lower values of around 25 eV are found for C^{2+} . These cases represent typical behavior of results obtained for these different ions. The edge temperature deduced from the simulation is, within the experimental uncertainties very close to the temperature provided by the more peripheral channels, although slightly higher. This fact suggests that a single channel looking at the plasma edge tangentially would be a good

ion temperature monitor. However, simulation of chord integrated values either of line emissions or of ion temperatures does not fully clarify some difficult to interpret points with local or chord integrated values. For instance, the fact that the Li^+ temperatures tend to be a factor ≤ 2 higher than that found with any other emission lines. We think that a further and deeper study of the emission mechanism of this line, such as role of electron excitation versus charge exchange recombination might help to understand better these results.

4. Conclusions

Typical peripheral T_i obtained with the 548.4 nm Li^+ spectral line is in the range of 60-100 eV. Due to the prominence of this line, high temporal resolution has been achieved in these measurements, as illustrated by data obtained in an ECRH power modulation experiment. He^+ ions seems to penetrate deeper into the plasma, as indicated by its emissivity profile, which explains the higher temperature values measured in central chords in the NBI regime. The temperature of C^{2+} and C^+ ions exhibit more pronounced temporal variations in standard discharges without any input power modulation. We believe this is because they are the most external ions and so they must be sensitive to what occurs at the very plasma edge. Edge temperatures estimated by the 464.7 nm C^{2+} exhibit a behaviour that suggests that its spectral line width might be influenced, more than the other lighter ions, by the turbulence at the very plasma edge. A dedicated system monitoring the plasma edge with spatial resolution of a few millimetres would help to understand these results better, and would be worth setting up in a fusion plasma in order to compare passive spectroscopic results with other methods that are more popular nowadays. In fusion devices with much higher magnetic field it would be essential to explicitly incorporate the Zeeman effect into the analysis. However, the line of Li^+ (548.4 nm) used in this work, which is not affected by the Zeeman effect and which will be very prominent in Li coated-wall machines, would be the right choice for monitoring in the very edge of fusion plasmas. In addition, since the ionization potential of this Li^+ ion is higher than that of the other studied ions, it can reach easier the thermal equilibrium with protons at the edge.

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Table 1. Ionization potentials (eV) of the lowest three ionization stages of the intrinsic edge ions used in this work. The specific ions whose emission lines have been used are in bold and are shaded.

Element	Atomic weight	Ionization potential (eV)			
		Ion charge			
		0	+1	+2	+3
He	4.003	24.588	54.418		
Li	6.939	5.39	75.64	122.4	
C	12.011	11.26	24.384	47.89	64.49

Figure 1. Illustration of experiment geometry: (a) the location of the spectrometers with respect to the TJ-II heating systems and a key diagnostic; (b) the observation geometry of the multichannel system and the vacuum chamber showing a typical TJ-II set of contours corresponding to the magnetic configuration 100_44_64.

Figure 2. (a) Equilibration time, by Coulomb collisions, between protons and either C or Li at an edge density of 10^{18} m^{-3} (solid lines); and ionization times by electronic collisions at similar density (dashed lines); (b) Edge electron temperature profiles measured by the He line-ratio using a supersonic He beam. The lines correspond to exponential fits of the data and they guide the reader through the experimental points. The chord-averaged density increases with time and the values are, 0.6, 1 and $3 \times 10^{19} \text{ m}^{-3}$ and (c) Estimation of the Zeeman effect on ion temperature determination for C⁺, the ion with the lowest ionization potential considered in this work.

Figure 3. (a) Display of the most relevant continuous traces in a typical TJ-II discharge, and (b) typical Thomson scattering profiles in a TJ-II discharge, taken at 1106 ms.

Figure 4. Behavior of Li^+ emission in a modulated ECRH experiment: (a) Li^+ peripheral ion temperature time evolution obtained from passive spectroscopy, and its comparison with the ECE central trace (ECE10); (b) Comparison similar to (a), but for the Li^+ line intensity and (c) Comparison of Li^+ temperature and intensity with the modulated gyrotron trace in a case with a faster modulation rate.

Figure 5. Time evolution of different ion temperatures: (a) He^+ temperature and intensity in a discharge with NBI where the temperature doubles with NBI; (b) A similar case, but for C^{2+} . No significant change is observed in its temperature during the NBI phase; (c) Temperature of three different peripheral ions in NBI discharges. Only the He^+ temperature changes during the NBI phase d) Ion temperature behavior of four different ions in discharges with solely ECRH.

Figure 6. Chord-averaged temperature profiles for several peripherals ions, for different chord-averaged electron densities as indicated in the plot legends (with units of 10^{19} m^{-3}): (a) He^+ (ECRH+NBI); (b) Li^+ (ECRH+NBI); (c) C^{2+} (ECRH+NBI) and (d) C^+ (ECRH+NBI).

Figure 7. Simulations of chord integrated results by means of a local model for two cases of He^+ : (a) and (b) A case with NBI, where ρ_0 , λ and T_{edge} assumed are: 0.95, 0.6 and 40 eV, respectively and (c) and (d) A case with solely ECRH, where these parameters are: 0.7, 0.45 and 20 eV.

Figure 8. Simulations of chord integrated results by means of a local model: (a) and (b) A case of Li⁺, where ρ_0 , λ and T_{edge} assumed are: 0.7, 0.16 and 70 eV, respectively and (c) and (d) A case of C²⁺, where these parameters are: 0.75, 0.12 and 25 eV.