C V Line Ratio Variations Across the TJ-II Stellarator

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Introduction

We have previously reported observations of variations in the intensity ratio, $I^3P_2/(I^3P_1+I^3P_0)$, of the helium-like carbon lines $1s2s^3S_1-1s2p^3P_2$ (227.09 nm) and $1s2s^3S_1-1s2p^3P_{0,1}$ (227.7 nm) in line of sight measurements across ohmically heated plasmas in the TJ-I tokamak [1] and ECR heated plasmas in the TJ-IU torsatron device [2]. In both cases, we attributed the observed variations from the expected ratio value, $R = 1.67$, as predicted when the triplet levels are statistically populated for electron densities up to 10^{20} m^{-3}, to the selective populating of 2^3P_2 by charge exchange involving hydrogen-like carbon and neutral hydrogen. Recently, changes in the relative intensities of these C V lines have been reported for polarization spectroscopy measurements made along a line of sight close to the plasma centre of the Japanese WT-3 tokamak [3]. The WT-3 plasmas were created by ohmic heating and later sustained by additional lower hybrid and ECR heating. The variations observed were attributed to spatially anisotropic collision excitation by electrons with anisotropic velocity distributions. In contrast, measurements made on the RFX (a Reversed Field Pinch device) found this ratio to be always equal to 1.67 for plasmas with electron temperatures and densities in the ranges 300-400 eV and $2\text{-}8 \times 10^{19}$ m^{-3} respectively [4]. Here, we report on line of sight measurements of this line ratio made across ECR heated plasmas in the TJ-II stellarator [5]. In addition, we describe the experimental set-ups used for these measurements and we discuss and compare these results with regard to those obtained in the machines with similar electron densities and temperatures.

Experimental Approach

The TJ-II is a low magnetic shear stellarator of the heliac type with an average major radius of 1.5 m and an average minor radius of ≤ 0.22 m. For these experiments the device was operated with a magnetic field ($B_0 \leq 0.95$ T), magnetic field configurations 100_50_65 (first experiment) and 100_40_63 (second experiment) [5], (Fig. 1), and average electron densities $n_e \approx 0.5 \times 10^{19}$ m^{-3} and central electron cyclotron emission (ECE) temperatures $T_e \approx 0.6$ keV along the plasma flat-top. Plasmas were created in hydrogen using the QTL-1 ECR line ($f = 53.2$ GHz tuned to 2nd harmonic, $P_{ECRH} \approx 250$ kW) with perpendicular injection for the first experiment and using the QTL-2 ECR line (similar gyrotron but with higher power densities) for the second experiment (one set of data were taken with this system during the QTL-1 campaign). In both cases, the pulse duration length was $\Delta t \leq 250$ ms and the vacuum chamber was conditioned by helium glow discharge prior to the experiments.
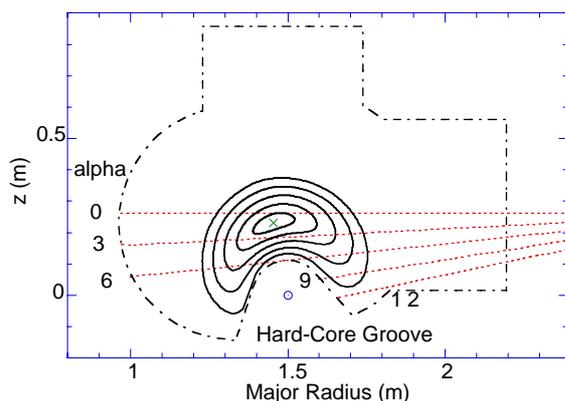
Fig. 1: Cross-section through the TJ-II vacuum chamber showing the observation geometry through the 100-50-65 magnetic field configuration (1st experimental set-up).

High resolution spectroscopic studies were performed between 225 and 230 nm using two independent spectrometer systems. In the first experiment, the plasma radiation was observed through a quartz window on the machine and rotated through 90° by a set of three MgF_2 coated aluminium steering mirrors that directed it onto the entrance slit of a 1 m focal length spectrometer (2400 mm^{-1} holographic grating, 2nd order) with spatial and temporal resolution capabilities. The resultant spatial resolution was about 1.5 cm at the plasma centre (Fig. 1). Spectra were recorded using a 700 active pixel multichannel intensified detector that repeatedly integrated for ~50 ms along the peak of the discharge. The line of sight through the plasma was varied on a shot-to-shot basis but experimental considerations limited access to the lower part of the plasma.

In the second experiment, measurements were made using a recently developed 8-channel system employing fibre optic cables to couple the light from parallel chords (2.5 cm separation) through the plasma onto the entrance slit of a 1 m image corrected spectrometer (3600 mm^{-1} grating). An UV sensitized CCD detector mounted at the exit focal plane was used to collect the 8 spectra simultaneously. In this experiment, the spectra were integrated along the plateau of the discharge. The relative sensitivity of each channel was calibrated using an extended Hg lamp and He line emissions from cleaning glow discharges.

Results

In Fig. 2a, we show the C V spectral line data measured close to the TJ-II plasma centre with the first experimental set-up. In the same figure, for illustrative purposes, we show ideal gaussian line ratios for $R = 1.67$. Here, the closely spaced 2^3P_0 and 2^3P_1 emission lines are not resolved. The spectra have been check for contamination lines and have been found to be free of such. In Fig. 2b, we show the temporal evolution of the global 227.09 nm line radiation for the same discharge as Fig 2a, the time integrated C V signal as measured with the first 1 m spectrometer system, and the temporal evolution of R along the discharge. (Note: the ratio R was also seen to vary along the TJ-IU discharge [2]). R is also seen to vary along the discharge for other lines of sight. Finally, in Fig 2c, the flat-top averaged R value varies significantly across the TJ-II plasma and is at all times greater than 1.67. This figure was created using data from a sequence of similar discharges that were free of X-rays.
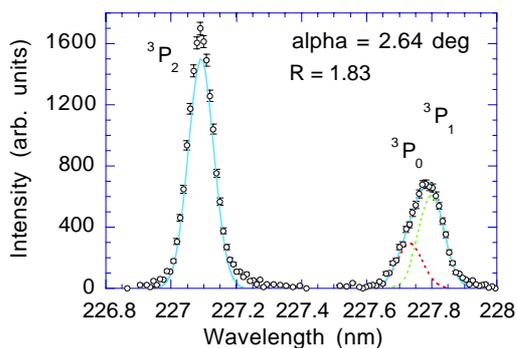
Fig. 2a: Helium-like carbon triplet line intensities (circles) as measured in TJ-II using the 1st experimental set-up. Also shown are curves for R = 1.67.
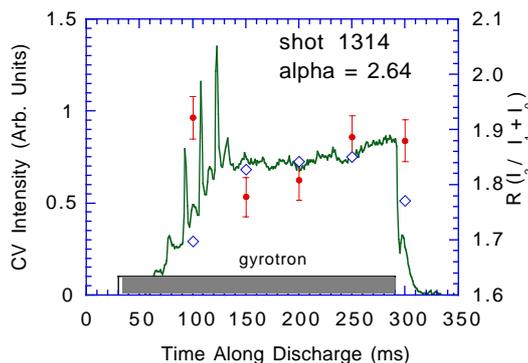

Fig. 2b: Temporal evolution of global (—) and integrated line-of sight (◊) 227.09 nm line radiation, and the C V triplet line ratio (•).
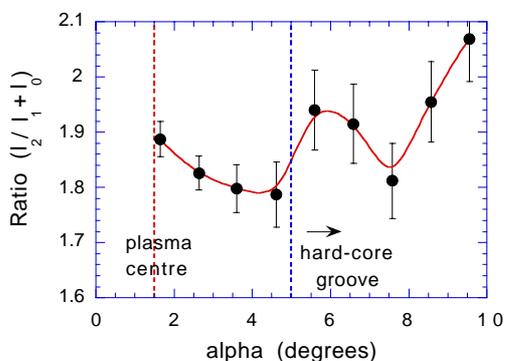

Fig. 2c: Measured line of sight triplet ratio (•) across the TJ-II plasma. Also indicated are the plasma centre and hard-core groove positions. The solid line is to guide the eye.

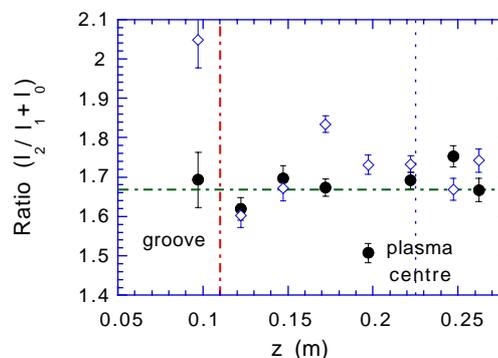Fig.3 : Triplet line ratios measured along parallel lines of sight through the TJ-II plasma using the 8-channel fibre-optic system. The (◊) and the (•) are from the QTL-1 and the QTL-2 campaigns respectively. Also indicated are R=1.67 (horizontal line) and the z positions of the hard-core groove and plasma centre (vertical lines).

In Fig. 3, we show the variation in *R* across the TJ-II plasma as measured by the 8-channel spectrometer system for one discharge during the QTL-1 campaign (100-50-65 configuration) and for a typical discharge of the 100_40_63 configuration. Again the discharges were x-ray free. For this, the spectra obtained in each channel was analysed in the same manner as before and the results were corrected for the variation in the system response across the exit slit (as calibrated using a Hg lamp).

Discussion

As in TJ-I and TJ-IU, we have also observed anomalies in the ratio *R* of the C V triplet line intensities across the TJ-II plasma when using the variable chord spectrometer system. In this case, we have viewed the lower half of the plasma from near the plasma centre to the lower tip of the bean-shaped plasma and *R* is seen to have values that are always > 1.67 and to have a range of values that are similar to those seen in the TJ-I. In addition, the value of *R* is also seen to vary along the discharge (Fig. 2b) as occured in the TJ-IU[2]. In contrast, the range of *R* values from the plasma centre to the hard-core groove is much less when measured with the second experimental set-up. It should be noted that this system has only been set up recently so the results are somewhat preliminary. For this reason, the low *R* value seen at ~0.2 m in Fig. 3 has still to be accounted for. On the otherhand, values of *R* up to 1.84 were seen during the QTL-1 campaign with this set-up. As the two sets of data presented in Fig. 3 were obtained during two campaigns using ECR heating lines with different power densities, as well as for two different magnetic configurations, it is difficult to make a direct comparison as the influence of the heating lines is not fully understood as yet. The results obtained with the fisrt experimental set-up in Fig. 2 could be explained by linear polarization effects as this set-up should be sensitive to polarization of light [3] but the anomalous *R* measurements made with the second experimental set-up loose any polarization information in the fibre optic light guides. Therefore, it is thought that the anomalous *R* measurements cannot be fully accounted for by linear polarization effects. However, during the campaign when the plasma was heated with higher power densities (QTL-2 line) significant line asymmetries were often seen in both the 227.7 and 227.1 nm lines. The cause of these asymmetries and their influence on *R* have still to be determined.

A calcite plate placed in our first experimental set-up might aid the separation of the *e* and *o*-ray contributions and hence determine if electrons with anisotropic velocity distributions are at play here while further fine tuning of the second experimental set-up should help to to confirm the measurements presented here in Fig. 3. Thus, we conclude that anomalies are present in *R* but they cannot be fully attributed to one or other explaination as yet.

References

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