

Variation in Lyman- α fine structure components for Cl XVII during a tokamak plasma shot

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In this Brief Report we study the measured and modeled Lyman- α intensity ratios for hydrogenlike Cl XVII in a deuterium base plasma in the Joint European Torus tokamak and examine the agreement between experiment and theory for a particular plasma shot. A collisional-radiative model is used to calculate the values of the intensity ratios using measured plasma parameters for comparison with line-of-sight values. When variations in the electron parameters during the discharge are taken into account, the variations in the modeled values are seen to follow the experimental data. The difference between the values of observed and modeled intensity ratios is discussed.

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I. INTRODUCTION

A very useful plasma diagnostic in tokamak plasmas is the measurement of x-ray emission from highly ionized ions in order to determine parameters such as the impurity density or temperature. Despite comparisons between experimental Lyman- α intensity ratios and theoretically modeled values for the ratios (see Ref. [1] and references therein), there is still no consistent agreement. However, accurate theoretical results for the Lyman- α intensity ratios are important for many diagnostic analyses which require the use of the fine structure components. Hydrogenlike emission spectra can be used for the identification and monitoring of impurity species in tokamak plasmas.

This Brief Report is a followup to the study on the variation of the Lyman- α intensity ratios in the COMPASS-D tokamak for Al XIII [2], but this time using measurements from the larger JET (Joint European Torus) tokamak and theoretically modeling the intensity ratios for the hydrogenlike Cl XVII (ionization potential=3932 eV) intrinsic impurity ion in the plasma. The results confirm a similar discrepancy in the absolute magnitude of the intensity ratios to that noted for the COMPASS-D results [2]. Given that the same experimental limitations with line-of-sight effects and changing plasma pressure profiles exist, this might again be expected.

II. JET TOKAMAK

The JET tokamak is currently the world's leading magnetic confinement experiment, designed amongst other things to study heating and confinement in reactor plasma conditions, plasma-wall interactions, and α -particle production. It differs from the COMPASS-D tokamak in that it is approxi-

mately six to seven times larger in both its major and minor radii. However, its shape is the same as that of COMPASS-D, i.e., a D-shaped torus. Due to its much higher plasma current, the JET electron temperatures are much higher than those in COMPASS-D, up to about a factor of 10 larger. The electron densities, however, are similar in both the JET and COMPASS-D tokamaks.

III. EXPERIMENTAL DETAILS**A. Plasma source and the spectrometer**

Spectra were measured from a plasma formed in the large JET tokamak which was designed to produce plasma conditions approaching those in a fusion power plant [3]. It has major and minor radii of 2.96 and 1.25 m, respectively, a maximum toroidal field of 3.45 T and maximum toroidal current of 7 MA. Typical central electron densities and temperatures are $n_e \approx (1-7) \times 10^{19} \text{ m}^{-3}$ and T_e up to ~ 7 keV.

Plasma parameters for the Ohmic L -mode (low confinement) plasma discharge considered here (shot no. 23269) are shown in Fig. 1. Spatially resolved n_e and T_e measurements were made by multichannel far infrared interferometry [4] and by analysis of electron cyclotron emission [5], respectively. During the Ohmic phase, the central electron temperature is ≈ 2 keV, rising to ≈ 6 keV during additional heating from a combination of the injection of highly accelerated neutral deuterium beams, known as neutral beam injection (NBI), and the resonant coupling of radio frequency waves with the gyration frequency of plasma ions, known as ion cyclotron resonance heating (ICRH). The plasma disrupts at ≈ 14 s due to an excess of radiated power. X-ray line emission from Cl XVII ions in the plasma was measured by a double x-ray monochromator [6].

B. Fitting process and errors

Individual lines of the spectra were reduced using a pseudo-Voigt function fitting routine. The wavelengths of the Lyman- α components, 4.1841 and 4.1895 Å, and the $n \geq 3$

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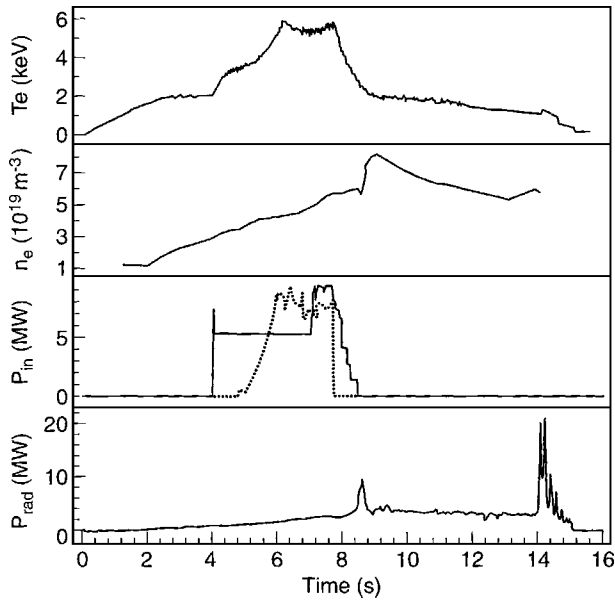


FIG. 1. Plasma parameters for JET *L*-mode (from top): central T_e (keV); central n_e (10^{19} m^{-3}); auxiliary input heating power in the form of NBI (solid line) and ICRH (dotted line) power (MW) and total radiated power (MW).

satellite system centered on 4.1940 \AA in the long wavelength wing of the $j=\frac{1}{2}$ component, were input as fixed parameters—all wavelengths were taken from Vainstein and Safronova [7]. All linewidths and shapes were assumed equal and fixed to the resonance line parameters. For each line, a linear convolution of a Doppler (Gaussian) profile and an instrument profile (approximated to a Lorentzian) was formed and iterated to give the best least-squares fit to the measured spectra. The free parameters used in the fit were line intensities, resonance linewidth and shape (the degree of influence of the competing Lorentzian and Gaussian line shapes), central wavelengths and background intensity. The background intensity was mainly due to continuum emission but also included a component due to noise from the electronics in the x-ray detector. An example of a measured Cl XVII spectrum and deconvolved lines from JET is shown in Fig. 2.

The main source of error in the measured line intensities derived in this way was due to blending of the main Lyman- α components with heliumlike dielectronic satellite lines. Transitions of the type $1snl-2pnl$ ($n \geq 3$) in doubly excited heliumlike ions form two series of lines, one to the long wavelength side of each hydrogenlike component. In order to demonstrate the influence of satellite lines on the measured intensity ratio, synthetic spectra are presented in Fig. 3, having been synthesized using a code described in detail in Ref. [8]. For each point on the plasma radius, the satellite line emissivities were calculated relative to a modeled resonance line emissivity and the spectra were formed by giving each line a Voigt profile (dependent on the radial ion temperature and the instrument function) at each radial point and then summing over wavelength and radius—the ion densities used were obtained from the transport code SANC0 [9] (described extensively in Ref. [10]). The radial position and hence the

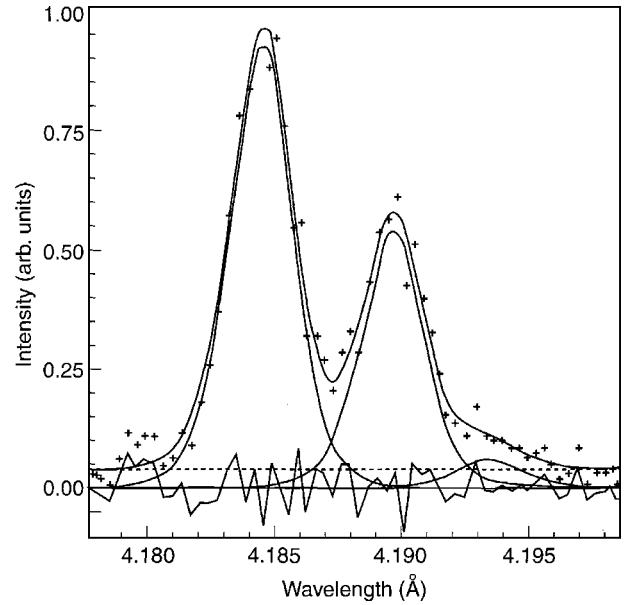


FIG. 2. Cl XVII Ly- α spectrum measured with a double crystal monochromator. The individual line fits and the residue of fit are also shown.

temperature of the maximum hydrogenlike Cl ion density profile for inclusion in the collisional-radiative code COLRAD were found using SANC0. Emission profiles of each Cl XVII line were formed from which the synthetic spectra were produced. In Fig. 3, two synthetic spectra are shown, one of which includes satellite line intensities and the other which does not; the total satellite intensity is also displayed. The intensity of any one of these satellite lines is normally rela-

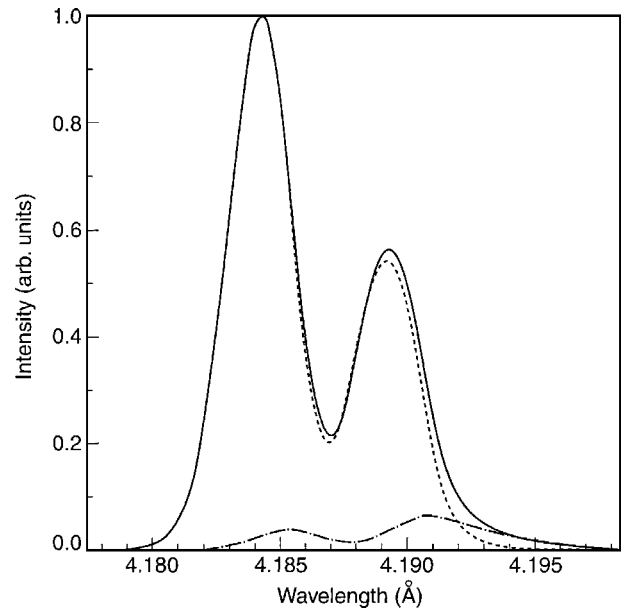


FIG. 3. Synthetic Cl XVII Ly- α spectra, calculated for central $T_e=1782 \text{ eV}$ and $n_e=7.18 \times 10^{19} \text{ m}^{-3}$. The dashed line indicates a spectrum calculated neglecting the effects of heliumlike dielectronic satellite lines. The spectrum indicated by the solid line includes satellite effects. The total satellite line intensity is also shown (broken line).

tively weak but they are numerous such that their cumulative influence can become significant. It is clear that the inclusion of satellite lines raises the unresolved Lyman- α intensity ratio, in this case by 4%. At the later times during the pulse, the central electron temperature is relatively low compared to that earlier in the pulse during additional heating. Satellite line intensities increase with decreasing electron temperature and hence this will be a significant factor on the influence of unresolved satellite lines on the intensity ratio during the pulse.

IV. THEORETICAL MODELING OF LINE INTENSITY RATIOS

As already described in our earlier paper for the COMPASS-D tokamak [2], the collisional-radiative code, COLRAD [11,12], was used to calculate the Lyman- α intensity ratios for hydrogenlike Cl XVII for the Ohmic L -mode discharge shot no. 23269. The experimental parameters used as input for the code were the electron temperature and density, and the ion temperature. COLRAD does not include the contribution from dielectronic satellite lines to the intensity ratio.

Figure 4 shows a plot of both the measured intensity ratios and the modeled values for the L -mode pulse considered. The values of all the experimental input parameters were available for each measured time step. The calculated Ly- α ratios increase from 0.509 at 43.35 s to 0.511 at 52.63 s. This overall increase of 0.4% is due to an increase in the line-average density from 2×10^{19} to $5 \times 10^{19} \text{ m}^{-3}$ over this period as shown in Fig. 1. The calculated ratio peaks at a value of 0.5116 over a time interval of ≈ 0.4 s from 48.41 to 48.82 s when the onset of the additional heating produces a strong increase in the density (and also in the temperature) up to a value of $8 \times 10^{19} \text{ m}^{-3}$ (as seen in Fig. 1) which increases the collisional coupling between the $2S_{1/2}, 2P_{1/2}$ and $2P_{3/2}$ levels, hence enhancing the intensity ratio [2]. However, from 48.55 s onwards, the ratios decrease as this is when the measured electron density also decreases steadily after the additional heating has been switched off. The measured ratios mostly lie between 0.53 and 0.58 with some data points outside this range, in particular the peak values which again occur over the time interval when the electron density is strongly increased for about 0.4 s. Experimental uncertainties are typically $\pm 10\%$. The measured ratios tend to be consistently higher than the calculated values by $\approx 10\%$ with the best agreement between the experimental and modeled values occurring during the time period of 46–50 s. The calculated ratios are generally within the experimental error bars. Measured ratios smaller than 0.5 are likely to be in error as processes such as heavy ion collisions which influence the intensity ratios tend to cause the ratios to exceed this value due to redistribution of populations from their statistically weighted values. As seen in Ref. [2], the intensity ratios are primarily affected by the electron density and this correlation can be seen from the theoretical graph. When a χ^2 analysis is done for this discharge as a measure of the “goodness of fit,” the normalized value of χ^2 (over 49 data points) is found to be 1.52, which means that the model is a good fit to the data.

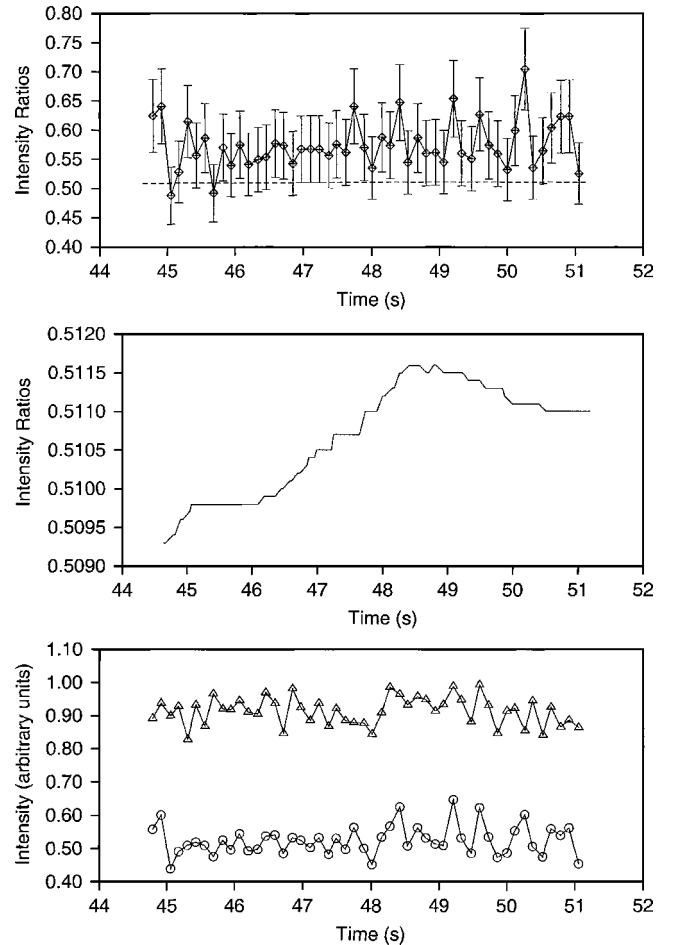


FIG. 4. The top graph shows the variation in the values of both the measured (solid curve with diamonds) and modeled (dashed curve) values of the intensity ratio for JET L -mode plasma. The middle graph shows the modeled intensity ratios on an expanded scale in order to illustrate the resolved structure of the curve which correlates to variations in experimental parameters such as the electron density. The bottom graph shows the intensities of the components of the measured doublet, Ly- α_1 (top curve with triangles) and Ly- α_2 (bottom curve with circles).

The fit would be even better if the data points which are below the statistical value of 0.5 were disregarded (as discussed above).

There are atomic processes not included in the model such as state-selective charge exchange collisions which might have a small influence in neutral beam-heated plasmas. The satellite intensity is more significant for medium Z impurity ions such as Cl XVII than for those with lower Z [13]. Hence an obvious complication in the intensity ratio analysis are line blends which could be adding to the Ly- α_2 intensity and hence increasing the intensity ratio since they are not accounted for in the line fitting.

V. CONCLUSIONS

The theoretical results show a clear dependence on the measured electron density for the variations in the Ly- α intensity ratios. Given the spiky nature of the measured experi-

mental intensity ratio data, this correlation in the case of the JET tokamak is harder to observe, though on a smaller scale the general trend for the early part of the graph can be seen to be an increase in the ratios. The measured values of the ratios tend to be systematically higher than those calculated using the COLRAD collisional-radiative model by $\approx 10\%$. Although the density correlation with the calculated values is seen as a general trend, a more detailed comparison of the temporal behavior is not possible due to the insufficient accuracy of the measurements which is due to a combination of statistical measurement uncertainties and systematic effects (e.g., unknown line blends). It is apparent that the question of the difference between the measured and the theoretical intensity ratios continues to be an unresolved one, and one which might be partially explained by the difficulty in deducing an accurate experimental ratio from the observed spectral curves. In this paper the Cl XVII spectral emission lines are not very intense since Cl is an intrinsic impurity in JET and hence the levels of Cl present in the plasma are relatively low compared to those of ions which are introduced by gas puffing or laser ablation (e.g., Al in Ref. [2]). This means that the signal to noise ratio for the shot considered is low and hence produces the spiky experimental data graph in Fig. 4 rather than a smooth curve, which makes a detailed comparison with the profile of the modeled intensity difficult. The fit to the spectral data does not take account of any satellite lines which may be unresolved from the Lyman

doublet. The synthetic spectrum shows some satellite lines which contribute mostly to the Ly- α_2 component and alter the line shape to some extent, which will also reduce the “goodness of fit.” As in Ref. [2], there are a number of reasons why the discrepancy between the two sets of data exists, the main ones being plasma transport and variances in the profiles for the plasma pressure. Line of sight effects could also play a part as well as possible residual asymmetric vignetting of the line profile that might cause a systematic underestimate or overestimate of the ratios which are very sensitive to the contour base level assumed. Given the experimental uncertainties, the modeled Ly- α ratios do reproduce the magnitude of the measured ratios and also the general temporal trends adequately, and hence the model does replicate well the variation in the measured ratios with time.

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