Cl XV AND CL XVI IN THE JET AND COMPASS-D TOKAMAKS

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Abstract

Studies of the soft X-ray emission spectrum of He-like Cl XVI and its associated Li-like Cl XV satellites from the JET (Joint European Torus) and COMPASS-D tokamaks are reported. Observations are made of the emission from this intrinsic impurity species using the same high resolution ($\lambda/\delta\lambda \simeq 3000$) curved crystal spectrometer (CCS) with a CCD detector [1], enabling a comparison to be made of the effect of widely differing plasma conditions between the two devices. A range of diagnostic measurements are made from the observed spectral region: T_e and n_e and ionisation balance information from line ratio techniques, T_i and V_ϕ (toroidal plasma rotation) from doppler line width and wavelength shift measurements respectively and heat transport studies by simultaneous observation of T_e and T_i, in particular the electron-ion heat transfer rate.

1. Introduction

Spectroscopic measurements of He-like systems are often used for plasma diagnostics. In this report observations of the intrinsic He-like Cl XVI impurity spectrum from the JET and COMPASS-D tokamaks are compared, reflecting the widely differing plasma conditions between the two devices (see table 1) and showing the range of diagnostic capability appropriate to each device. Sample spectra from JET and COMPASS-D are shown in fig.1. In addition to the resonance line w, ($1s2p\,^1P_1 \rightarrow 1s^2\,^1S_0$) the intercombination lines x and y ($1s2p\,^3P_{2,1} \rightarrow 1s^2\,^1S_0$) and the forbidden line z ($1s2s\,^3S_1 \rightarrow 1s^2\,^1S_0$), four satellite lines are visible: the dielectronic lines d_{13} ($1s2p3p\,^2D_{5/2} \rightarrow 1s^23p\,^2P_{3/2}$) and k ($1s2p^2\,^2D_{3/2} \rightarrow 1s^22p\,^2P_{1/2}$) and the inner-shell excitation q and r lines ($1s2s2p\,^2P_{3/2,1/2} \rightarrow 1s^22s\,^2S_{1/2}$). Also labelled is the j ($1s2p^2\,^2D_{5/2} \rightarrow 1s^22p\,^2P_{3/2}$)

line which is blended with the z line and the $n \geq 3$ satellites on the long wavelength side of the resonance line.

Since there is a tendancy for the ion shells to radiate from the same region of the temperature profile irrespective of small changes in the temperature gradient and ion transport, the JET spectrum as illustrated is representative of most discharges. The relatively high satellite intensities are a feature of the lower temperature COMPASS-D plasmas (the highest temperature COMPASS-D spectra are similar to the JET spectrum shown). Of particular note is the appearance of a shoulder on the long wavelength side of the y line corresponding the nuclear spin allowed $1s2p\,^3P_0 \rightarrow 1s^2\,^1S_0$ transition. The wavelengths for this line are measured at 4.4688$\mathring{A}$ and 4.4697$\mathring{A}$ from COMPASS-D and JET respectively. These compare well with the calculated value of 4.4688$\mathring{A}$ [2]. Due to the lower T_e in COMPASS-D the CL XVI spectra all emanate from the core region, a situation more conducive to spectroscopic plasma diagnostics.

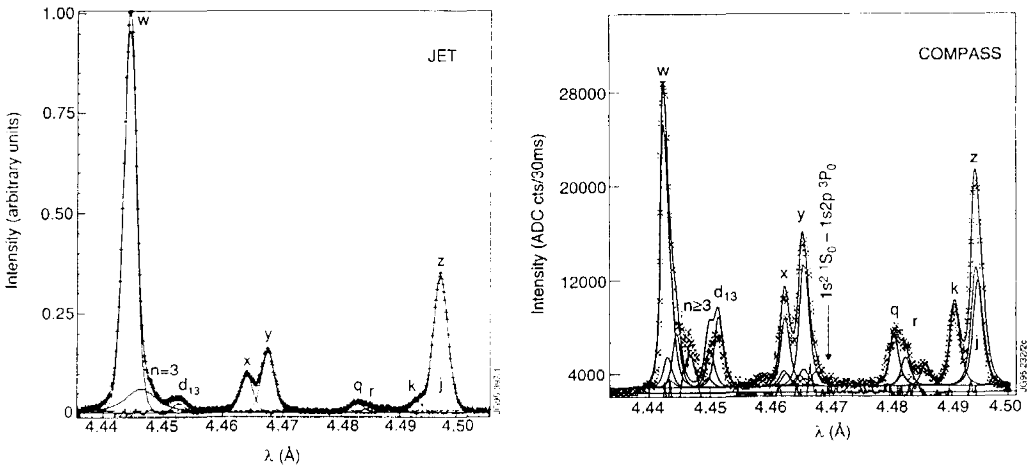

Fig. 1. *Curved Crystal Spectrum of Cl XVI from JET (left) and COMPASS-D (right).*

Table 1. Comparison of main parameters for the JET and COMPASS-D tokamaks

Parameter	**JET**	**COMPASS-D**
Major radius R (m)	2.96	0.557
Minor radius a (m)	1.25	0.232
Vertical radius b (m)	2.10	0.385
Toroidal magnetic field B_ϕ (T)	3.45	2.1
Plasma current I_P (MA)	7.0(max)	0.28
Electron Temperature $\overline{T_e}$ (KeV)	3.5 – 10.0	0.50 – 1.0
Electron Density $\overline{n_e}$ ($\times 10^{13}$cm^{-3})	0.8 – 12	0.8 – 12
Pulse Duration (s)	25	0.4
NBI Power (MW)	20	–
ICRH power (MW)	20	–
ECRH power (MW)	–	2
LHCD power (MW)	3	0.6

2. Line Ratio Measurements

The main lines in the He-like isoelectronic sequence w, x, y and z may be used to infer the electron temperature sensitive ratio: $G = (x+y+z)/w$ which is density independent for JET and COMPASS-D conditions. (the electron density sensitive ratio $R = z/(x+y)$ is in its low density limit for both JET and COMPASS-D, ie. it only shows variation above $n_e \simeq 10^{14}\mathrm{cm}^{-3}$). The Li-like satellite lines can be used in conjunction with the w line to produce the diagnostic ratios: k/w and d_{13}/w which vary as $1/T_e$ and q/w which is dependent on the ionisation balance N(Li)/N(He).

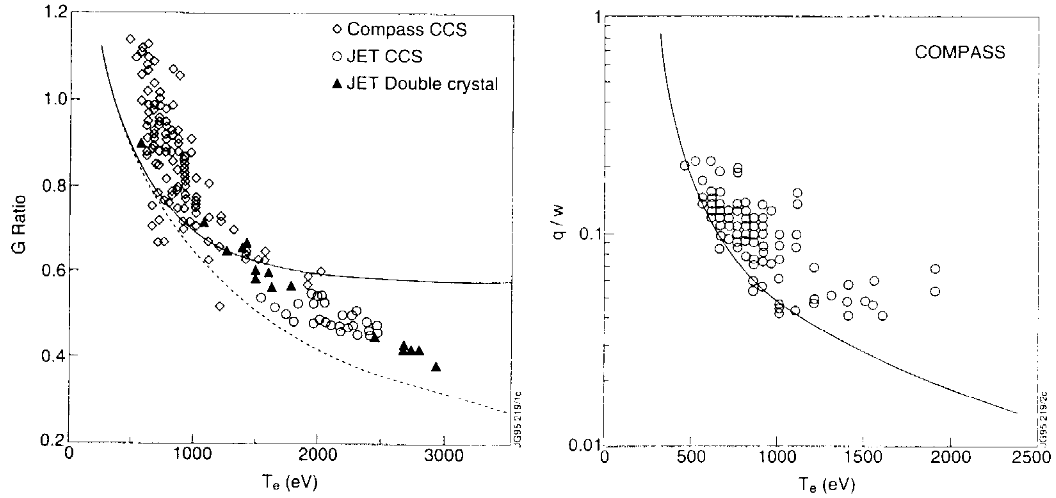

Fig. 2. *The theoretical emission ratio G (left) plotted as a function of T_e at an electron density of $n_e = 3.2 \times 10^{13} cm^{-3}$, with dielectronic recombination included in (solid line) or excluded from (dashed line) the calculations. Experimental points from the JET (circles) and COMPASS-D (diamonds) tokamaks are shown and in addition JET results from a double crystal spectrometer (triangles)[3] are displayed to extend the T_e range. On the right the ratio q/w is plotted as a function of T_e. Equilibriun values for N(Li)/N(He) have been used in the calculations. Experimental points from COMPASS-D are shown (circles.)*

In fig.2 the experimental G ratios from JET and COMPASS-D are plotted against T_e in conjunction with theoretical ratios [3]. The k/w is used as a temperature measurement for the COMPASS-D ratios as the line components are well resolved and independent of ionisation balance. Non spectroscopic diagnostics provide T_e(R) values for the JET data (in general the satellite lines from the higher temperature JET spectra are relatively too small to provide accurate T_e measurements).

Between approximately 800eV and 1500eV the ratio agrees with the coronal prediction. Below this temperature the triplet levels of the COMPASS-D ratios appear to have enhanced intensity above the coronal prediction. Possible explanations include: recombination (which is unlikely as it is not a cooling plasma and the N(H)/N(He) ratio would be too low at these temperatures to have a significant effect) and inner-shell ionisation of the Li-like stage. A large proportion of the Li-like ions will be in the excited $1s^2 2p\,^2P_{1/2,3/2}$ state [4], so both the ionising transitions $1s^2 2s\,^2S_{1/2} \rightarrow 1s2s\,^3S_1$ and $1s^2 2p\,^2S_{3/2,1/2} \rightarrow 1s2p\,^3P_{2,1}$ are possible. This would require an enhanced N(Li)/N(He) ratio which would naturally occur with transport. Above 1500eV the measured ratios (predominately JET) fall below the coronal prediction. At these higher temperatures where, the Cl XVI emission shell will be off-axis, diffusion effects tend to lead to a reduction in N(H)/N(He) from the equilibrium value with a corresponding lowering of the measured ratio as a result of reduced recombination into the triplet states.

Fig.2 also shows the experimental q/w ratio from COMPASS-D. Again the k/w ratio is used to provide T_e values. This ratio is in general higher than the coronal model due to transport effects causing a higher N(Li)/N(He) ratio. This effect is larger at lower densities [5], thus at higher T_e where the n_e is lower (a COMPASS-D characteristic) there is a definite trend away from the coronal balance due to radial ion diffusion.

3. Doppler Measurements of T_i and V_ϕ

The ability to simultaneously measure core values T_e (from the k/w ratio) and T_i (from the linewidth) on a 10 – 15ms timescale allows an investigation of features of the heat transport, in particular the electron-ion heat transfer rate. Fig.4 shows the measured values of T_i against the corresponding T_e. The T_i measurements are compared with Artsimovich scaling [6]:

$$T_i = \frac{2.8\times10^{-6}}{A_i^{\frac{1}{2}}}(I_p B_\phi R^2 \overline{n_e})^{\frac{1}{3}}$$

where A_i is the deuterium (plasma fuel ion) mass. The measured values are generally lower but they do increase with the Artsimovich parameters. The electron temperatures for the equivalent shots have been added. At low n_e, T_e is high and T_i is low, as n_e increases, T_e decreases and T_i increases. This can be understood from power balance considerations. At low n_e the electron conduction is anomalous and fast. As n_e increases less power is lost through conduction and more is transferred to the ions. Coulomb collisions with the electrons are the only ion heating mechanism on COMPASS-D

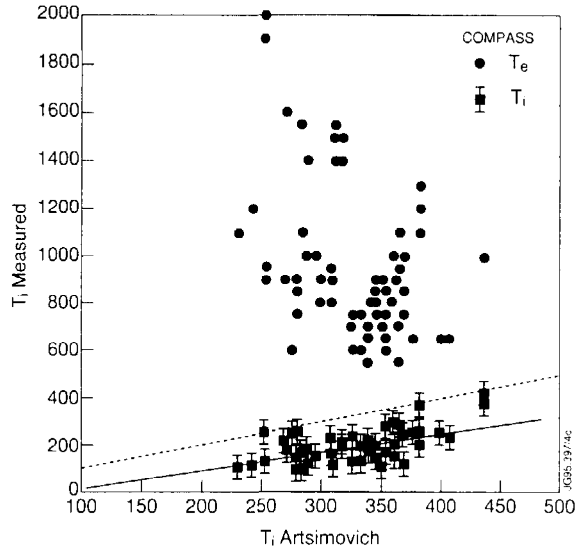

Fig. 3. *Electron and ion temperatures derived from the COMPASS-D Cl spectrum. The k/w ratio was used for T_e while line shapes of z were used for T_i. The lower group of points ($<$ 450eV) refer to T_i while the upper group ($>$ 400eV) refer to T_e. T_i scaling due to Artsimovich is shown broken, while the solid line is the best fit to the T_i data.*

Fig. 4. shows the changes observed in V_ϕ for JET and COMPASS-D respectively. For JET Neutral Beam Injection (NBI) heating results in a change of $\simeq$ 100kms^{-1} (in this example) by direct momentum transfer to the plasma. The reduction in the H_α signal at 55s signifies the beginning of an H-mode (high confinement regime). The rotation falls off slowly after the NBI period until the end of the H-mode when a step in V_ϕ is observed, after which V_ϕ falls off rapidly. Note the increase in the radial position of

maximum emissivity of the Cl XVI emitting shell with increasing central T_e during the heating period. For COMPASS-D, where there is no NBI, changes in V_ϕ of typically 20kms^{-1} in the ion drift direction are observed in the edge ions of B IV and in the core ions of Cl XVI as the plasma enters the H-mode. The H-mode signature is shown by the reduction in the H_α signal caused by a lessening in plasma wall interactions and edge recycling during this period. This momentum change in the bulk plasma is not well understood, but could be due to a combination of enhanced diamagnetic drifts and relaxation of viscous and frictional forces in the H-mode.

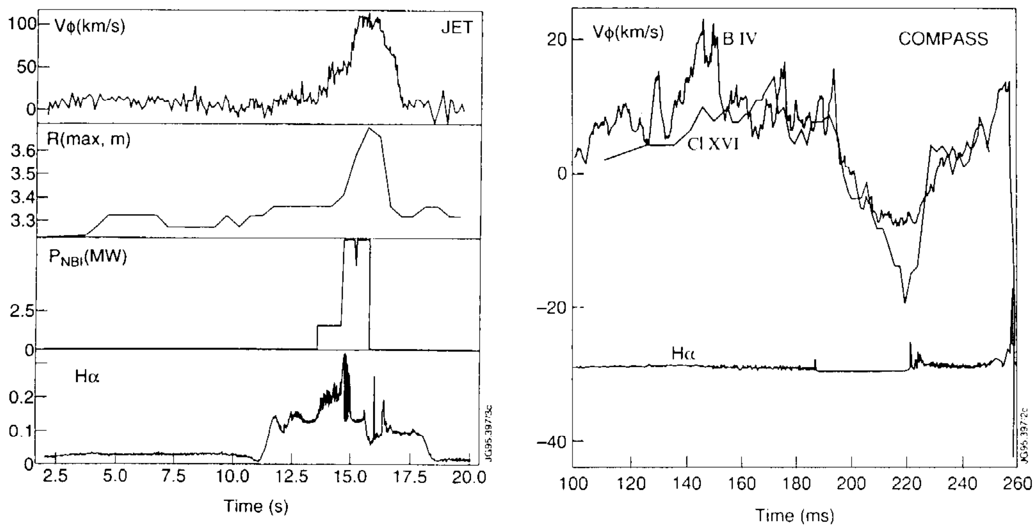

Fig. 4. *V_ϕ measurements from JET (left) shown in conjunction with the calculated radial position of maximum Cl XVI emissivity (R_{max},m), NBI injection power (MW) and the H_α emission. The V_ϕ measurements from COMPASS-D (right) are shown in conjunction with similar measurements from B IV at the plasma edge [7] and the H_α emission.*

4. Conclusions

High resolution spectroscopic studies ($\lambda/\delta\lambda \simeq 3000$) of the intrinsic ClXVI system and its associated Cl XV satellites have produced a broad range of diagnostic information from a relatively narrow spectral region. Simultaneous easurements of T_e, T_i, ionisation balance, V_ϕ and electron-ion heat transfer can been made from the observed spectra. Such methods are not routinely used on the JET device, however they provide useful diagnostic information on COMPASS-D where the operating parameters are suited to such measurements.

5. References

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