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Carbon charge exchange analysis in the ITER-like wall environment[a)]

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Charge exchange spectroscopy has long been a key diagnostic tool for fusion plasmas and is well developed in devices with Carbon Plasma-Facing Components. Operation with the ITER-like wall at JET has resulted in changes to the spectrum in the region of the Carbon charge exchange line at 529.06 nm and demonstrates the need to revise the core charge exchange analysis for this line. An investigation has been made of this spectral region in different plasma conditions and the revised description of the spectral lines to be included in the analysis is presented. [http://dx.doi.org/10.1063/1.4890118]

I. INTRODUCTION

Charge exchange (CX) spectroscopy is a highly developed diagnostic tool in the fusion community[1,2] and will be employed on ITER. It has become routine, for example, for ion temperature and rotation to be obtained from the Carbon CX line (CVI $n = 8 \rightarrow n = 7$) at 529.06 nm. Nearby CX lines of NeX at 524.89 nm and ArXVIII at 522.87 nm, both impurities seeded into the plasma for power load control, give the study of the CVI 8-7 spectral region a broader relevance.

Extensive experience in the interpretation of CX spectra from devices with Plasma-Facing Components of Carbon-fiber composite has been developed since the technique was first explored in the late 1970s.[2] Operation of JET with the ITER-like wall (JET-ILW)[3,4] presents new challenges for the CVI 8-7 CX analysis with a factor of ten reduction in the carbon concentrations.[5] New impurities, in particular Tungsten (W), are also introduced into the plasma leading to additional spectral lines in the CX region of interest.

This paper focuses on the analysis of the CVI 8-7 CX line measured with the JET core-CX systems. Section II introduces the diagnostic, the CX analysis, and the Carbon-wall (JET-C) spectra. Sec. III presents the development of the revised CX analysis for the JET-ILW with conclusions in Sec. IV.

II. CORE-CX DIAGNOSTIC AND CVI 8-7 ANALYSIS

The core-CX diagnostic at JET[6–8] has multi-chord views covering the low-field side edge to the plasma core from two horizontal periscopes viewing the octant 8 neutral heating beams (NBI). Spectral measurements of the collected light are made with five spectrometers; three tunable Czerny-Turner spectrometers with CCD detectors,[6] and two fixed wavelength Kaiser-Optical HoloSpec spectrometers with Roper Scientific CCDs.[8] In the initial JET-ILW operations the CX analysis was challenging as the window of one periscope was damaged with ∼10% loss of sensitivity. The XCAM cameras on the Czerny-Turner spectrometers had additional problems with sensitivity and the resolution was not high enough in the double slit Kaiser systems. The core-CX diagnostic has been upgraded replacing the XCAM with ANDOR CCDs to have better signal to noise. For the high light throughput Kaiser systems a single slit setup is now implemented, with a slit width of 75 μm and grating with ∼1.7 nm/mm also now used for the instrument viewing the CVI 8-7 line. The quality of the data that has been acquired in the recent operations is much improved.

An example from a central track in a JET-C plasma of the measured spectrum and its multi-Gaussian fit is shown in Figure 1. The CVI components are relatively strong and clear with respect to the BeII. The fit includes a high temperature active component (CVI 8-7) of the CX and a cooler, slower passive (CVIpass) component. A cool electron impact line (CVIedge) and any background spectral lines are also included. A good description of the spectrum is important to obtain the correct CVI 8-7 parameters.

III. CVI 8-7 CORE-CX ANALYSIS IN THE JET-ILW

The appearance of new spectral lines close to the CVI 8-7 in JET-ILW plasmas, in addition to the reduction in Carbon concentration, means that it is necessary to revise the CX analysis. Identifying what the background lines are helps

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[c)]See the Appendix of Romanelli *et al.*, Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA.

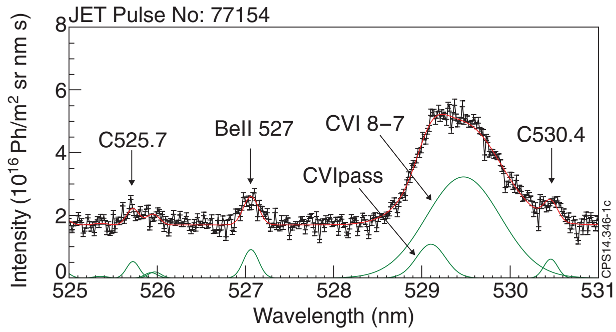

FIG. 1. (JET pulse #77154, 2 T, 1.7 MA, 21 MW of NBI) Spectrum from a JET-C central track with total fit (red) and individual lines (green).

build a better understanding of the changes to the spectrum and of the implications for CX in the JET-ILW and for ITER.

To highlight the more prominent lines we initially looked at cases with strong influxes of different impurities into the plasma. The type of influx – which included W, Ni, Fe, and Cu – and hence what spectral lines might be expected was obtained for example using VUV spectra. The influx effects could vary but in Figure 2 for an example of (a) a W influx and (b) an influx from Nickel (Ni) laser blow-off, the strongest changes are indicated. With the fitted wavelengths and intensity time histories, the NIST atomic spectra database[9] was utilized to get possible identifications. For the CVI 8-7 spectral region and its analysis, W lines looked to be of most concern.

Analyzing more standard CX cases without large influx events and with different experimental conditions, a few additional lines were added to improve the fit. As the database of analyzed pulses grew, confidence was gained in the location and identification of the lines important to the CVI 8-7 analysis. The spectral lines that are now included in the core-CX analysis for the JET-ILW plasmas are given in Table I.

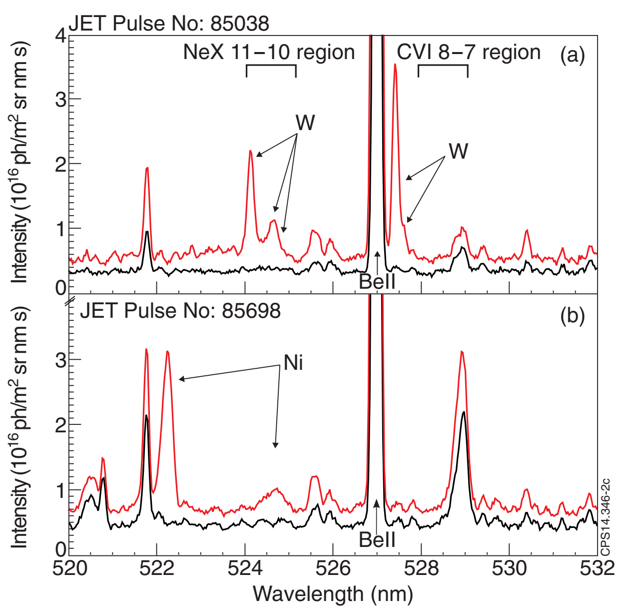

FIG. 2. (JET pulse #85038 and #85698) Examples of spectra measured before (black) and during (red) an influx of (a) W and (b) Ni. The 527 nm BeII and approximate regions of interest for the CVI 8-7 and NeX 11-10 CX analysis are indicated.

TABLE I. Spectral lines included in the JET-ILW core-CX CVI 8-7 analysis. The lines added to the JET-C recipe are in bold and italic (where wavelength is not NIST). Intensities relative to the 529.5 nm WI in the Figure 3 example are given.

Wavelength (nm)	Description	Fig. 3 relative intensities
525.586	**BeII**	**2.6**
525.724	CII	1.0
525.966	CII	0.7
526.153	**BeI**	**0.3**
527.063	BeII	(Not fitted)
527.478	**WI**	**0.4**
alt. 527.553	**WI**	
527.645	*?W (no W in NIST here)*	*0.8*
527.858	**WI**	**0.3**
527.981	**WI**	**…**
528.229	*WI (528.265 in NIST)*	*0.6*
528.408	**WI**	**0.4**
528.552	**WI**	**1.8**
528.712	**WI**	**2.4**
528.83	*WI (528.850 in NIST)*	…
529.059 (free)	CVI 8-7 (the CX line)	236
529.059 (free)	CVI passive	…
529.059 (fixed)	CVI edge	3.9
529.249	**WI**	**0.4**
529.525	**WI**	**1.0 (ref.)**
529.79	*WI (529.858 in NIST)*	*0.6*
530.238	**WI**	**…**
530.462	CIII	1.0

The spectral fitting for the CX analysis uses the BeII at 527.063 nm as a reference wavelength; its position is fixed after it is fitted early in the discharge and it is then assumed not to move in the core-CX measurements. The wavelengths of the included spectral lines relative to the BeII are well described by the NIST values except for a few lines indicated where a small shift of <0.1 nm gave consistently better fits. Although no W is listed in NIST at 527.645 nm, the time evolution and reaction to a W-influx as in Figure 2 suggests that it is W; the wavelength is derived from the spectral fit. For the WI at 527.5 nm an alternative line and wavelength is listed but both options are not included at the same time in the fitting.

Figure 3 shows the fit on an edge track where many of the lines closest to the CVI 8-7 are clear. The shaded region over

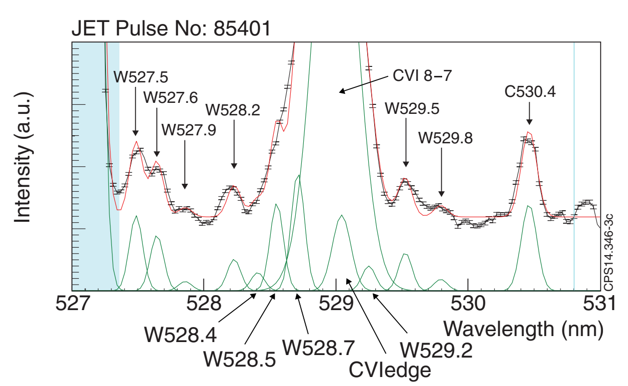

FIG. 3. (JET pulse #85401) An edge track example of the fit (red) and individual lines (green) close to the CVI 8-7.

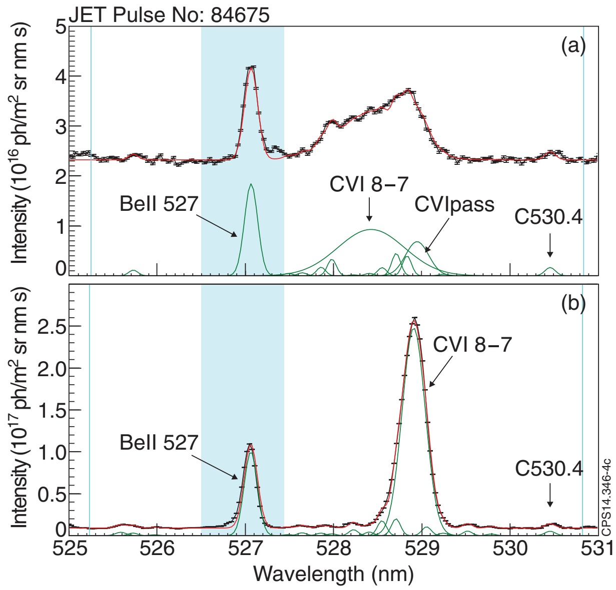

FIG. 4. (JET pulse #84675, 2 T, 2.1 MA, 20.5 MW of NBI) Example of JET-ILW core-CX analysis for a track through the plasma (a) center and (b) edge. The measured spectrum (black), total fit (red), and individual fit lines (green) are shown. The region over the BeII 527 nm excluded from the fit is shaded.

the 527 nm BeII is excluded from the main fit to avoid issues from saturation of the BeII. The relative intensities from the Figure 3 example are included in Table I as an illustration, however, the plasma conditions and which track the spectra is measured on affect the relative strengths.

The revised analysis is so far able to describe the spectra measured in most scenarios in the present JET-ILW operations. For example, Figure 4 shows the fit to a track through the plasma (a) center and (b) edge. In this pulse the underlying lines are significant for the quality of the CVI 8-7 fit. The temperature of the CVI 8-7 in Figure 4(a) is 5580 ± 650 eV and the rotation is $(4.0 \times 10^5) \pm (0.16 \times 10^5)$ m/s; omitting the background WI lines from the fit would give incorrect values of 7970 ± 520 eV and $3.6 \pm 0.1 \times 10^5$ m/s.

Having applied the JET-ILW CVI 8-7 analysis to pulses from different operating scenarios, it is apparent that the plasma conditions, the carbon concentration and the attenuation of the neutral beam affect the relative significance of the WI lines. The location on the outer wall of the ends of the lines-of-sight may also play a role, although the WI lines are seen on all tracks. Investigations are underway to build a clearer picture of the significant parameters.

The CVI 8-7 line is also measured by the edge-CX diagnostic[10,11] at JET which covers r/a of 0.75–1.0. The higher relative strength of the CVI 8-7 in the plasma edge due to the lower attenuation of the neutral beams means that the extra lines from Table I are not required as part of the standard

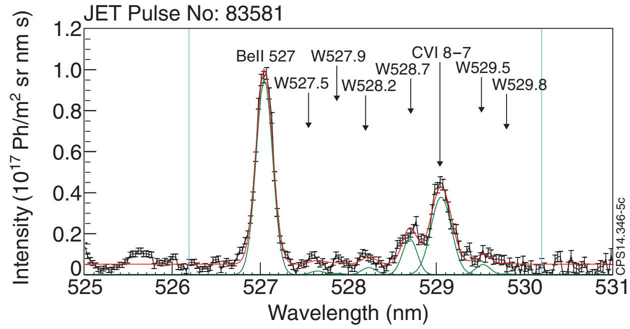

FIG. 5. (JET pulse #83581) High background example from the edge-CX diagnostic (black) with the total fit (red) and individual lines (green).

edge-CX analysis. However, there can be cases as in Figure 5 when background lines are seen in the outermost tracks. Such spectra can successfully be described by including in the fit the stronger of the WI lines identified for the core-CX analysis.

IV. CONCLUSIONS

It is essential for the analysis of the CVI 8-7 charge exchange line at 529.06 nm to have a good description of the measured spectrum. Operation with the ITER-like wall at JET has changed the spectrum with respect to JET-C requiring the inclusion of spectral lines from neutral tungsten in the CVI 8-7 core-CX analysis. Applying the revised prescription we are able to obtain a good fit of the measured spectra in a wide range of conditions. The development of the CVI 8-7 core-CX analysis in the JET-ILW environment is continuing with exploration of the critical plasma parameters which cause the background WI lines to be more significant.

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