

Impurity Behaviour Studies in the TJ-II Stellarator

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Introduction. An ultraviolet-visible spectroscopic survey (2000 - 6000 Å) of electron cyclotron resonance (ECR) heated plasmas created in the TJ-II stellarator is reported. For this, discharges were created in hydrogen and plasmas had central electron temperatures up to 1 keV and electron densities in the range 0.5 to $1.5 \times 10^{19} \text{ m}^{-3}$. Spectra were collected across a large number of narrow wavelength regions and were systematically analysed using tabulated spectral wavelength [2,3,4]. The purpose of the work is; to identify the principal impurities present; to identify suitable transitions for following the evolution of impurities under different operating regimes; to search for transitions from highly ionised ions; and to search for wavelength bands free from spectral lines for performing Z_{eff} measurements.

Experimental Approach. The TJ-II, a low magnetic shear stellarator of the heliac type, has an average major radius of 1.5 m and an average minor radius of ≤ 0.22 m [1]. For these experiments the device was operated with a range of magnetic field configurations and plasmas were created and heated ($\Delta t \leq 250$ ms) using either or both ECR lines ($f = 53.2$ GHz tuned to 2nd harmonic, $P_{\text{ECRH}} \leq 300$ kW). The vacuum chamber was conditioned by glow discharges in helium (> 12 hours) and argon (1/2 hour) prior to the experiments. One of the strong characteristics of TJ-II plasmas is their strong interaction with the region of the chamber (groove) surrounding the hard core coil, which acts as the main limiter for most magnetic configurations. Two mobile poloidal limiters were also used [1]. Both the vacuum vessel and mobile limiters are constructed of stainless steel SS-304-LN.

The studies were made using a 1 m focal length spectrometer (1200 lines/mm holographic grating in 1st order) and spectra were recorded using a 700 active pixel multi-channel intensified detector. Radiation from along a narrow chord was collected using a fibre optic with a focussing lens attachment that tangentially viewed plasmas through a quartz window. A cut-off filter was used above 4000 Å. In total, 250 spectra were recorded during the experimental campaign between shots #2800 and #3800 and spectral calibration was made using Hg, Ne, Ar, Kr and Xe pencil type lamps. The spectral resolution (FWHM) achieved was 0.72 Å at 4200 Å.

Results and Discussion. It has been possible to identify nearly all observed transitions using tabulated wavelengths [2,3,4]. Indeed, only a few lines or features could not be positively identified. Spectral lines from light impurities dominate. The most intense of each species are listed in Table 1. The strongest of these are C III, C V and O II. Argon line transitions were also prominent, especially above 4600 Å, at the start of each day's operation. Numerous transitions of

F II, III, IV, V and VI were observed, whose possible source may be Teflon or the acid pickling performed on vacuum chamber assemblies in a HNO₃ and HF acid solution prior to assembly.

Ion	Transition	Wavelength
C III	2s2p ¹ P ^o - 2p ² ¹ D	2296.87 Å
	2s3s ³ S ₁ - 2s3p ³ P ^o	4647.42, 4650.25 & 4651.47 Å
C V	2s ³ S - 2p ³ P ^o	2270.89, 2277.27 & 2277.92 Å
N IV	2s3s ³ S - 2s3p ³ P ^o	3478.72, 3483.0 & 3484.93 Å
O II	3p ⁴ D ^o - 3d ⁴ F	4069.63, 4069.9, 4072.2, 4075.9, 4078.9, & 4085.1 Å
	3s P - 3p ² D ^o	4414.89 & 4416.97 Å
O V	3s ³ P ^o - 3p ³ P ^o	2781.01, 2786.99 & 2789.85 Å
F III	3s ⁴ P - 3p ⁴ D ^o	3113.61, 3115.7, 3121.54, 3124.78, 3134.22 & 3142.78 Å
	3s ² P - 3p ² D ^o	3174.18, 3174.76 & 3213.97 Å
F V	3s ⁴ P ^o - 3p ⁴ D	2702.3, 2707.17, 2712.88, 2721.06, 2732.0, 2736.91 & 2756.2 Å
F VI	3s ³ S - 3p ³ P ^o	2315.39, 232335 & 2327.28 Å
Ar II	4s ⁴ P - 4p ⁴ D ^o	4266.53, 4282.9, 4331.2, 4348.064, 4379.67, 4426.0 & 4430.19 Å
	4s ⁴ P - 4p ⁴ P ^o	4735.91, 4806.02, 4847.81 & 4933.21, 4972.16, 5009.334 & 5062.04 Å
Ar III	4s' ³ D ^o - 4p' ³ F	3336.13, 3344.72, 3352.11, 3358.49 & 3361.28 Å

Table 1. Strong transitions of the principal impurities found in TJ-II plasmas.

Hydrogen Balmer series transitions H_β (2-3) at 4861.33 Å to H_ε (2-7) at 3970.07 Å have been observed. Shorter wavelength transitions of this series could not be identified with certainty as they may be blended with other lines. Of these only the H_β and H_γ transitions are suitable for diagnostic use as both are intense and clear from blending with other lines.

Ion	Transition	Wavelength
Cr I	3d 5(6S)4s - 3d 5(6S)4p	4254.35, 4274.8, 4289.72, Å
	3d 5(6S)4s - 3d4(⁵ D)s4p(³ P ^o)	3578.69, 3593.49 & 3605.33 Å
Fe I	a ⁵ D - z ⁵ F ^o	3719.94 Å
Cu I	4s ² S - 4p ² P ^o	3247.54 & 3273.96 Å

Table 2. Strong transitions observed from the metal impurities

Numerous Cr I, II, III and Fe I, II, III transitions were present in the spectra, the strongest being the Cr-I transitions about 4274.8 Å, see Table 2. Other Cr I transitions were generally weak or blended with other lines, except for those centred about 3593.49 Å. Numerous Fe I transitions were observed between 3500 and 3900 Å but most were weak. The strongest occur about

3719.94 Å. Below ~2500 Å, weak Cr II, III, and Fe II, III lines are clearly observed. Several weak nickel (which accounts for 8.0-10.5 % of the stainless steel composition) lines were observed, but no manganese (a constituent of stainless steel) transitions were identified. Copper, which is used in several diagnostics, was the only other metal impurity identified. No tungsten transitions were observed although the Langmuir probes used in TJ-II are of this material.

Ion	Transitions	Wavelength
C VI	5 - 6	2070.25 Å *
	6 - 8	2082.16 Å
	7 - 9	3138.64 Å
	6 - 7	3433.66 Å
	8 - 10	4498.81 Å
	7 - 8	5290.53 Å *
N VII	6 - 7	2522.55 Å *
	9 - 12	3442.11 Å *
	7 - 8	3886.78 Å
	10 - 13	4553.68 Å
	9 - 11	4555.45 Å
	8 - 9	5669.34 Å
O VIII	8 - 10	2530.4 Å *
	7 - 8	2975.69 Å *
	9 - 11	3487.67 Å *
	8 - 9	4340.45 Å *
F IX	8 - 9	3429.38 Å *
	11 - 13	4791.32 Å *
	9 - 10	4794.5 Å *
Fe XV	3s 3d - 3s 5f	2739. Å
	3s 3d - 3s 5f	2749. Å
	3s 3d - 3s 5f	2769. Å

Table 3. Transitions observed from highly ionized ions. (*may be blended)

Although transitions have been observed from several H-like light impurities, they are generally weak and many are crowded blended with other lines. See Table 3. The most intense and clearest is the N VII (8-9) transition. The N VII (7-8) transition is also strong although it is crowded with He (3888.65 Å) and H (3889.05 Å) transitions. The C VI (7-8) transition is observed but it may be blended with O VI transitions about 5291 Å. The C VI (8 -10) transition is also observed. The lines observed at 2739, 2749, and 2769 Å, and at 3429.4, 4791.3, and 4794.5 are tentatively attributed to Fe XV and F IX respectively. A line observed at 5302.9 Å may be a Fe XIV *green line* transition but several F VI lines are also seen near to 5300 Å thereby making a positive identification difficult. See Fig. 3.

It is generally assumed that narrow spectral bands with negligible line radiation exist between 5200 and 5400 Å for performing Z_{eff} measurements. A generally used band is 5235 ± 15 Å. However, several lines are seen in this band in TJ-II plasmas so it is necessary to select a range at longer wavelengths, 5360 ± 10 Å, to avoid spectral lines.

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References

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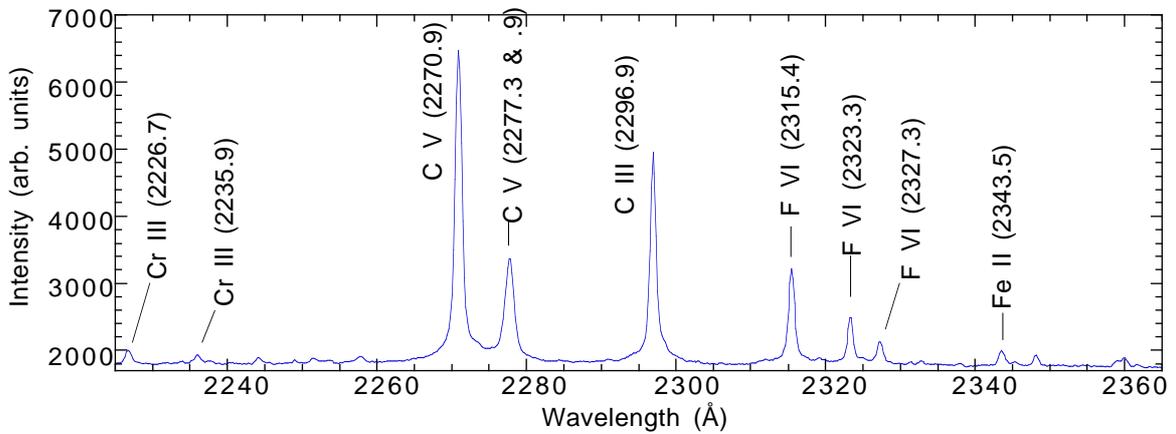


Fig. 1: Spectrum centred about 2300 Å.

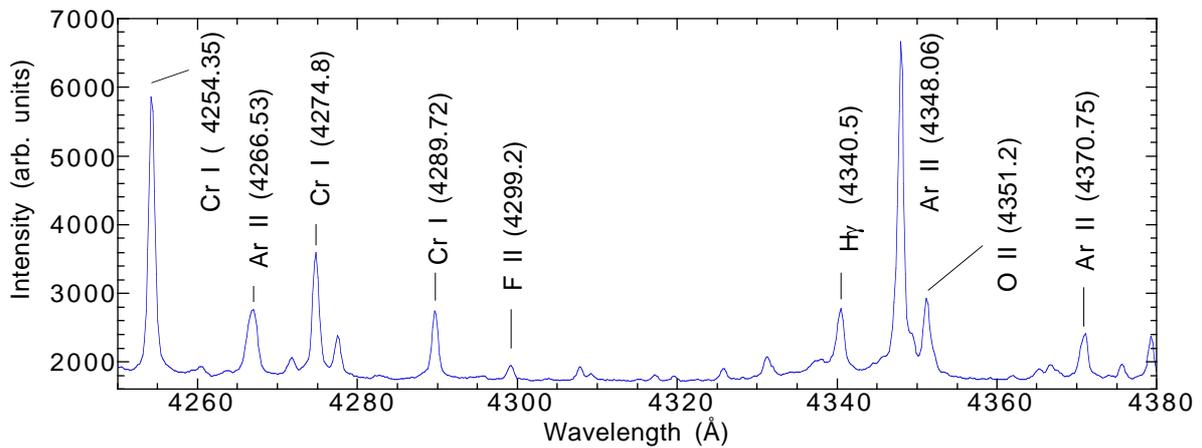


Fig. 2: Spectrum centred about 4320 Å showing the H γ line. Reduced O II line intensity is due to wall conditioning with helium and argon.

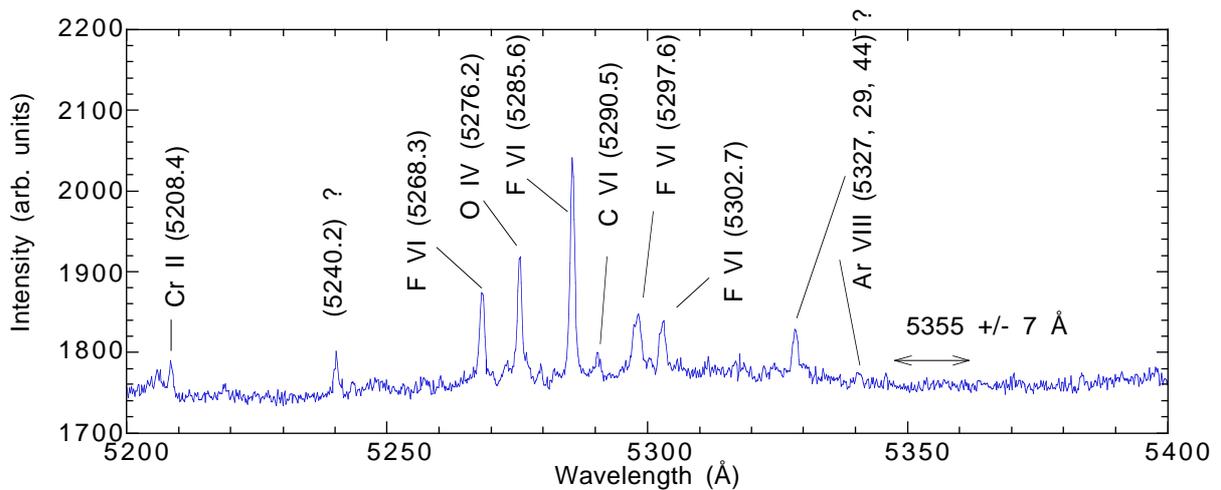


Fig. 3: Spectrum centred about 5300 Å showing the region selected for continuum measurements.