Research Repository UCD

Title	Tungsten spectra recorded at the LHD and comparison with calculations
Authors(s)	Harte, Colm S., Suzuki, C., Kato, T., Sakaue, H.A., Kato, D., Sato, K., Tamura, N., Sudo, S., D'Arcy, Rebekah, Sokell, Emma, White, John K., O'Sullivan, Gerry
Publication date	2010-10
Publication information	Harte, Colm S., C. Suzuki, T. Kato, H.A. Sakaue, D. Kato, K. Sato, N. Tamura, et al. "Tungsten Spectra Recorded at the LHD and Comparison with Calculations" 43, no. 20 (October, 2010).
Publisher	IOP Science
Item record/more information	http://hdl.handle.net/10197/3567
Publisher's version (DOI)	10.1088/0953-4075/43/20/205004

Downloaded 2023-04-07T10:52:29Z

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)

© Some rights reserved. For more information

TUNGSTEN SPECTRA RECORDED AT THE LHD AND COMPARISON WITH CALCULATIONS

C S Harte¹, C Suzuki², T Kato², H A Sakaue², D Kato², K Sato², N Tamura², S Sudo²,
R D'Arcy¹, E Sokell¹, J White¹ and G O'Sullivan¹

¹ University College Dublin, Belfield, Dublin 4, Ireland

² National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

Abstract:

We have measured extreme ultraviolet (EUV) spectra from highly charged tungsten ions in low density and high temperature plasmas produced in the Large Helical Device at the National Institute for Fusion Science. The EUV spectra emitted after injection of a tungsten pellet into a hydrogen plasma were recorded at plasma temperatures of 1.5 and 3 keV and were dominated by an intense transition array in the 4.5 – 6.5 nm region, the profile and extent of which was different in both spectra. Some discrete lines present were identified by comparison with existing spectral data while atomic structure calculations showed that the dominant emission in both arose from $\Delta n = 0$, $n = 4 - n = 4$ transitions and the main differences could be attributed to the appearance of $4p - 4d$ and $4s - 4p$ transitions from W XXXIX – W XLVI in the higher temperature spectrum. Comparison with calculations showed that the dominant emission in both temperature regimes arose from stages where the $4f$ subshell was either almost or completely stripped. We also investigated if the effect of low density favours transitions to the lowest level as observed in recently reported results.

Introduction:

The next generation device for fusion research, ITER (International Thermonuclear Experimental Reactor) is planned to come on stream in 2016. The material of the plasma facing components (PFC) must be capable of tolerating extremely large thermal loads, have a low erosion rate and a low cross-section for tritium assimilation and retention. For this reason, tungsten will be used for the divertor baffles and dome and has become the standby material for use as a divertor coating as carbon generated from CFC (carbon fibre composite) tiles at the strike zones would lead to unacceptable levels of tritium capture [1]. To investigate the behavior of tungsten and tungsten coated CFC tiles in a fusion reactor studies are planned or already being undertaken at a number of major locations worldwide [2]. For example, at JET, tungsten erosion rates and the impact of an all tungsten divertor are being studied while interior regions of the ASDEX Upgrade Tokamak in Garching have been coated with tungsten and an extensive program of study has been underway for the past ten years on the effects of tungsten impurities on the plasma dynamics as well as the spectral emission from tungsten ions [3 - 6].

At the plasma temperatures typically attained in a tokamak or stellarator, tungsten ions will not be fully stripped leading to intense line emission in the EUV and x-ray spectral regions (20 eV – 10 keV). In the hot plasma core, under conditions as envisaged for ITER, one expects to have F-like W^{65+} to Cl-like W^{57+} ions and the spectra should then be dominated by L and M shell emission whereas towards the wall, one will encounter intense N and possibly O shell emission also as the average degree of ionisation decreases. A comprehensive review of the available data for tungsten spectra in all ion stages has been published by Kramida and Shirai [7], which points out the lack of any definitive spectral data for W IX – W XXVII inclusive, while reviews of data

from early fusion devices has recently been written by Reader [8] and for more recent devices and for spectra with direct relevance to ITER by Biedermann et al. [9].

From work performed in the late 1970s at ORMAK, the Oak Ridge Tokamak, it was found that radiation from tungsten ions sputtered into the plasma radiated very strongly between 4 and 7 nm where a structured quasicontinuum overlaid by a few strong lines was observed. Moreover, the radiative losses were so intense that they limited the ultimate plasma temperature attainable. The radiation was postulated to arise from overlapping transitions in W XXXI – W XXXV [10] but subsequently shown to primarily originate from $4d^{10}4f-4d^94f^2$ and $4d^{10}4f-4d^{10}5d$ transitions in Ag-like W XXVIII [11]. Subsequently Finkenthal and co-workers identified features in the 4-7 nm region resulting from groups of unresolved $4d - 4f$, $5p$ and $4f - 5d$, $5g$ transitions in W XXII through XXVI spectra from the TEXT tokamak [12]. The tungsten was introduced into the plasma discharge by laser ablation. Subsequently Sugar, Kaufman and Rowan succeeded in identifying the strongest $4d - 4f$ lines in Ag-like W XXVIII, Pd like W XXIX and Rh-like W XXX spectra from TEXT data recorded using the same injection method [13-15].

Also in the late 1970s, it was found that the emission from a laser produced plasma of tungsten emitted broad-band EUV continuum radiation overlaid with very few lines in the 3-20 nm spectral region [16]. From experimental and theoretical comparison it was known that these plasmas contained ions up to W^{15+} [17]. However the only discrete lines observed were in W VI and VII spectra [18, 19] and moreover no continuum enhancement due to unresolved lines was found in the 4.5 – 7 nm region. The absence of strong emission or absorption lines from stages

higher than W^{6+} was attributed to the near degeneracy of 5p and 4f binding energies past W^{5+} which in the most extreme cases gives rise to thousands of closely spaced lines from strongly interacting configurations based on configurations with open 5p and 4f subshells and the inherent complexity of open 4f subshell spectra [20]. The resulting extremely weak lines are then submerged in the background recombination continuum to give essentially a spectrum that appears as a line-free continuum. In their compilation of ionization potentials for tungsten, Kramida and Reader also noted the difficulty of determining the parent configuration of the lowest level because of the proximity of adjacent configurations with differing numbers of 4f and 5p electrons in W^{7+} [21]. As a result no strong lines are expected to be found in spectra from W IX to W XIII. (W^{7+} , with only two such possible configurations, $4d^{10}5s^25p^64f^{13}$ and $4d^{10}5s^25p^54f^{14}$, will have a relatively simple spectrum; however as we strip away 5p electrons the situation rapidly becomes more complex.). When the 5p subshell empties at W^{12+} , the 4f and 5s binding energies are so close that again the existence of low excited configurations with differing numbers of 4f, 5p and 5s electrons inhibits strong line emission and for example, W^{12+} has a $4d^{10}5s^24f^{14}$ ground state but transitions involving states derived from excited configurations of the same parity ($4d^{10}5s^25p4f^{13}$, $4d^{10}5s^25p^24f^{12}$, $4d^{10}5s^25p^34f^{11}$, $4d^{10}5s^25p^44f^{10}$, $4d^{10}5s^25p^54f^9$ and $4d^{10}5s^25p^64f^8$) which have a total calculated energy spread of 195.85 eV, compete to reduce the $^1S_0 - ^1P_1$ line emission expected to the lowest state. Furthermore, in both tokamak and laser produced plasmas, lines from a range of different ion stages are superimposed which makes the contribution of individual ion stages to the overall spectrum impossible to isolate and difficult to quantify.

W¹³⁺ has a 4d¹⁰5s²4f¹³ ground state and Hutton et al. [22] have reported observing the 4d¹⁰4f¹⁴5s ²S_{1/2} - 4d¹⁰4f¹⁴5p ²P_{1/2} line in spectra from the Berlin EBIT. However such lines are unlikely to appear in low density fusion type plasmas which tend to be dominated by resonance transitions to the ground configuration [23, 24]. Moreover the absence of strong lines predicted to lie near 4.85 and 5.3 nm due to 4d¹⁰5s²4f¹³ - 4d⁹5s²4f¹⁴ ²F_{5/2} - ²D_{3/2} and ²F_{7/2} - ²D_{5/2} transitions in laser produced plasmas again points to competition from low lying excited configurations with open 4f subshells. Past this stage, as the 4f subshell empties the resulting line density means that once more no distinct strong lines are expected to appear, a factor greatly enhanced at the lower ionisation end of this isonuclear sequence by the presence of configurations built from variable numbers of 5s, 5p and 4f electrons lying well below the ionisation limit. However at W XXVIII, as already mentioned, strong line emission due to 4d¹⁰4f-4d⁹4f² and 4d¹⁰4f-4d¹⁰5d transitions again appears.

For spectra from ion stages possessing valence 4d subshell configurations (W XXIX through WXXXVIII), more data, both experimental and theoretical, are available. It is well known from work on rare earth spectra that for transitions of the type 4p⁶4dⁿ-4p⁵4dⁿ⁺¹+4p⁶4dⁿ⁻¹4f, final state configuration interaction causes the lines in adjacent ion stages to almost completely overlap [25-27]. Experiments at the Berlin EBIT verified that this was indeed the case and obtained almost ion stage specific information for WXXII through W XLVII [28, 29]. Again for the most part, these spectra contained strong, generally unresolved, line emission in the 4.5 – 7 nm range. However, spectra from an EBIT are usually quite different in appearance from either pinched (as in a Tokamak) or laser plasmas as they are excited by a monoenergetic electron beam at low

electron densities in an optically thin regime. In particular the width and consequently the profile of the unresolved transition arrays (UTA) resulting from ions with open 4p, 4d and 4f subshells are known to be different. Indeed, Radtke et al. [28] using detailed calculations based on a collisional-radiative (CR) model showed that the UTA observed in their experiments were narrower than predicted and also the intensity weighted mean wavelength deviated from the simple gA weighted mean of the arrays because of the low electron density.

Recently a detailed theoretical study of both EBIT and ASDEX-Upgrade spectra have been made which show that the emission spectra of the various open 4d-subshell ions, calculated by taking into account excitation from the ground state only, agree quite well with the results obtained with the CR model [30, 31]. The calculations were made using the relativistic Dirac Fock approximation [32]. Because of the low densities encountered, the plasmas are far from local thermodynamic equilibrium (LTE) and most of the ions are in the ground state. Thus the emission is essentially dominated by excitation rates from the ground level and the gA distribution of the excited ones. The influence of CI on these rates as a function of the number of 4d electrons in the lower level was explored in detail [31]. The authors also succeeded in identifying the origin of a weak unexplained feature observed in the EBIT spectra of W XXX - W XXXV as originating from 4p-5s satellite transitions [30].

The plasma temperatures obtained in the ASDEX-Upgrade are higher than in the earlier devices and consequently higher ion stages are observed and open 4p, 4s and 3d subshell spectra have been recorded in stages from W³⁸⁺ to W⁵⁰⁺ and confirmed by EBIT data. Additional data from Berlin [9], LLNL [33] and NIST [34, 35] EBITs have resulted in the identification of lines in

spectra all the way to Ne-like W LXV many of which can be potentially used for temporal and spatial diagnostics in ITER.

In the present work we report on the results of recent tungsten injection experiments at the Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS). In a previous experiment performed at the LHD [36] some 4d-5p and 4f – 5g lines from W XXII – W XXIX were identified in the 2.5 – 4 nm region but again the bulk of the emission was recorded in the 4.5 – 7 nm region and the strongest lines were found to arise from W XXVIII, W XXIX and W XXX. In this paper the effect of plasma temperature on the profile of the 4 – 4 feature are explored by comparison with previously published work and atomic structure calculations. While previous treatments have concentrated on 4d excitation in spectra from W XXVIII onwards, here the effects of these transitions in lower ion stages and their effect on profile of the 4.5 – 7 nm emission band are also investigated. From these calculations, theoretical UTA parameters are extracted and presented for the gA distributions of resonance transitions of all open 4f, 4d and 4p subshell species, i. e. for spectra from W XV to W XLIV.

Experimental:

In the present experiments, the LHD at NIFS in Toki was used. The LHD is one of the largest devices in the field of magnetically confined fusion research and plasmas are maintained under a magnetic field of 2.75 T at the center. The typical plasma density was approximately 10^{19} m^{-3} , and its spatial profile and electron temperature were measured by a Thomson scattering

diagnostic system [37]. Solid tungsten was introduced by a tracer encapsulated solid pellet (TESPEL) [38] injected into the background hydrogen plasma. Two different plasma regimes were used. In the first, the plasma core temperature was approximately 1.5 keV and the experimental conditions are summarized in figure 1 (a). In this figure the time sequences of neutral beam injection (NBI) heating power (P_{NBI}), stored energy (W_p), electron density (n_e) and radiated power (P_{rad}) are shown. The TESPEL was injected at $t = 2.3$ s and spectra were recorded in a 200 ms window centred at 2.7 and 3.5 s respectively. The actual recording intervals are shown shaded in grey. The spectra are shown in figure 2. A spectrum recorded at $t = 2.1$ sec, or before injection, is also shown to indicate the contribution from background impurities in the LHD. Note that, accompanying injection there is a pronounced drop in stored energy accompanying both a rapid increase in radiated power and a sharp decrease in NBI heating. The spectrum recorded at 2.7 s coincides with the time of lowest stored power and an enhanced radiated emission while the later spectrum is recorded under a more ‘steady-state’ regime. In figure 1(b) the conditions accompanying TESPEL injection into a plasma with a hotter core temperature of 3 keV are shown. Injection occurred here at $t = 3$ s. Spectra were again recorded with a 200 ms integration time centred at $t = 2.9$ s or just before injection, $t = 3.1$ s and $t = 3.3$ s corresponding to the times of maximum emission and recovery of the background conditions as can be seen in Fig 1 (b) where again the recording times are shown shaded in grey. The sharp lines present in the background spectra are due to Ar. Note that in this case the stored energy actually increased slightly and was less dramatically affected by the radiation losses. Overall, the tungsten injection had less impact on the parameters of the higher temperature plasma. The longer persistence of emission in the lower temperature plasma is an interesting observation that may owe its origin to the decrease of NBI and stored energy after the moment of TESPEL

injection. Indeed, there is evidence that after the second increase of NBI there is a fall off in EUV emission. The drop in energy presumably leads to lower diffusion and dispersion of the tungsten ions.

Figure 1: Time sequences of neutral beam injection (NBI, heating power (P_{NBI}), stored energy (W_P), line averaged electron density ($\langle n_e \rangle$) and total radiated power (P_{rad}). The shaded areas correspond to the detector integration times during which spectra were recorded. TESPEL injection occurred at $t = 2.3 \text{ s}$ in (a) and at $t = 3 \text{ s}$ in (b) which corresponds to the dotted vertical line. Tungsten emission was observed during the two (separated) integration periods of (a) but only during the central integration window of (b). See text.

The EUV spectra were recorded by a grazing incidence spectrometer SOXMOS [39] whose groove density and focal length were 600 mm^{-1} and 1 m , respectively. The spectrometer contained two microchannel plates coupled via a phosphor to silicon photodiode detectors thus

permitting the simultaneous recording of spectra from two different spectral regions. The wavelength bands simultaneously covered were 4.1 – 6.8 and 16.4 – 21.3 nm at a lower plasma core temperature of approximately 1.5 keV while simultaneous settings of 2.0 – 4.1 and 12.7 – 17.1 nm and 4.1 – 6.8 and 25.4 – 31.3 nm were investigated under identical higher temperature conditions (core temperature approximately 3 keV). Over the limited range covered at each detector setting, the spectral response of the SOXMOS is essentially constant. The overall spectral resolution was about 0.02 nm. The optical axis of the spectrometer could be slightly tilted to permit viewing either directly through the plasma core or through a line approximately halfway between the core and the wall. No differences in spectral emission were noted as the line of view was varied, though, interestingly in the case of the lower temperature emission a central accumulation was observed essentially as seen in the PLT Tokamak [40] where the core plasma cooling also led to an emission dominated by W XXVIII – XXX. In the previous tungsten TESPEL injection at NIFS with a 2.2 keV plasma temperature it was found that the central electron temperature rapidly decreased to 0.75 keV due to ionization and radiation losses and then recovered up to 1.2 keV [36]. It should be noted also that in LHD experiments with Xe and Sn injection, such strong emission from open 4d subshell ions always accompanied plasma collapse [24, 41, 42]. The spectrometer was carefully calibrated by observing carbon, boron and neon lines whose wavelengths are well known following neon injection (carbon and boron lines are always present as impurities in the LHD). When these wavelengths were fitted to the dispersion relation of the SOXMOS spectrometer the absolute wavelength could be determined within an accuracy of ± 0.01 nm.

Experimental Results:

Spectra recorded in the 4.1 – 6.8 nm region are presented in figure 2. No discrete structure was evident in the other wavelength ranges investigated so these spectra are not reproduced here. The top spectra were recorded at a lower core temperature and is expected to contain lower stages. The strong discrete lines evident between 4.9 and 5.1 nm can be attributed to the previously identified 4d – 4f resonance lines of Ag- to Rh-like W XXVIII, W XXIX and W XXX [13 - 15]. The strong line at 4.8948 nm is the $4d^{10} \ ^1S_0 - 4d^9 4f \ ^1P_1$ of W XXIX. This is the strongest line in both spectra in the upper figure and appears particularly pronounced in the spectrum recorded 3.5 s after injection. Interestingly, it appears as an isolated line in the bottom figure where the core electron temperature is 3 keV. Emission from Ag- like W XXVIII to Rh – like W XXX is strong in all three spectra though their relative contributions are difficult to assess because they are superimposed on a quasicontinuous background resulting from unresolved transitions from a range of ion stages. However while the Ag-like $^2F_{7/2} - ^2G_{9/2}$ line observed at 5.0895 nm [13] is intense in both spectra the $^2F_{5/2} - ^2G_{7/2}$ line observed at 5.1457 nm appears to be relatively weaker in the spectrum recorded at 1.5 keV. In comparing the low and high temperature spectra some major differences are apparent, most noticeably the short wavelength structure evident in the 4.5 – 4.8 nm region is absent at lower temperatures while the structure appearing in the 5.5 – 6.5 nm region is quite different in both cases. From earlier data it should be possible to associate the mean peak lying between 4.9 and 5.5 nm with transitions from open 4d subshell ions, i. e. W XXIX – XXXVIII [28 - 31]. Interestingly, the 4p - 4d and 4d - 4f lines of Rb-like W^{37+} , expected to be strong because of the $4p^6 4d$ ground configuration, are clearly present in the 3 keV spectrum but essentially absent in the lower temperature one. Spectra of ions with valence 4p subshells, W XXXIX - WXLIV, are known to give rise to two line groups

centered near 4.6 and 6.4 nm respectively [4, 5] and are responsible for the structure at these wavelengths in the higher temperature spectra as can be seen in Fig. 2. Resonance 4s - 4p transitions in W XLV and W XLVI were also found in the 3 keV spectrum.

Figure 2: Spectra recorded from the LHD at different times after TESPEL injection. Top: core electron temperature approx. 1.5 keV, bottom: core electron temperature approximately 3 keV. Prominent transitions are labeled by charge state

In lower stages, open 4f subshell ions can give rise to 4d – 4f transitions at wavelengths below 5 nm [12, 28], 4f – 5d transitions that move towards shorter wavelength with increasing charge eventually ending with a Ag-like 4f – 5d doublet near 4.4 nm [11] and these have been shown to contribute to the structure appearing in the 5.5 – 7.0 nm region which has already been identified as resulting from 4f – 5d excitation in W XXII – XXIV [12]. In addition, 4d – 5p and 4f – 5g transitions also move towards shorter wavelengths with increasing charge and should give rise to well defined UTAs in the 2.5 – 4 nm region. These latter features were found to be absent under the conditions for recording the higher energy spectrum which therefore imply that it must contain little or no contribution from stages lower than W^{27+} . So in summary, from comparison with existing results, we know that the 1.5 keV spectrum contains no contribution from ion stages above W^{36+} while the 3 keV one is essentially dominated by stages from W^{27+} to W^{45+} .

Theoretical Results:

In order to obtain further information and to simulate the emission from the contributing ions, calculations were performed with the Hartree Fock with Configuration Interaction suite of codes written by Cowan [43]. For transitions from stages with an open 4d subshell CI effects have

already been shown to be very important [25-31] because of the proximity of 4p – 4d and 4d – 4f excitation energies. Thus in the calculations for W XXX to W XXXVIII excited state CI of the form $4p^5 4d^{m+1} + 4p^6 4d^{m-1} 4f$ ($1 \leq m \leq 9$) was included. From these data the corresponding line distributions were parameterized in terms of their various moments according to the UTA model [44-48]. The general nth moment between configurations a and b is given by:

$$\mu_n (a \rightarrow b) = \sum_{m, m'} [\langle m' | H | m' \rangle - \langle m | H | m \rangle]^n \langle m | D | m' \rangle^2 / \sum_{m, m'} | \langle m | D | m' \rangle |^2$$

where D is the electric dipole operator and the sum runs over all states m and m' of configurations a and b respectively. The first moment μ_1 gives the intensity weighted mean energy of the UTA. The weighting is particularly important in the case of $\Delta n = 0$ transitions where the most intense lines are displaced well away from the difference in configuration average energies because of the large exchange interaction in the upper configuration. The variance v , or centered second order moment, $\mu_2^c = \mu_2 - \mu_1^2$ is related to the width of the array. For a normal distribution the full width at half maximum is $\sqrt{2 \ln 2} \sigma$, where $\sigma^2 = v$. The skewness, or asymmetry of the distribution, can be described by the skewness coefficient $\alpha_3 = \mu_3^c / v^{3/2}$, where $\mu_3^c = \mu_3 - 3 \mu_2^c \mu_1^2 - \mu_1^3$. The sign of the skewness describes the asymmetry and is positive when biased towards lower energy, negative when the bias is towards higher energy. For $\Delta n = 0$ transitions the skewness is generally negative as the most intense lines are observed on the high energy side of the array. Finally the coefficient of kurtosis, μ_4 / μ_2^2 gives the closeness of the fit to Gaussian, for which it has the value of 3. These parameters have been used successfully to describe line group contributions in plasma modeling for elements other than tungsten in situations where a detailed line by line calculation is too extensive or time consuming [49, 50].

Because of the large number of levels arising from the open 4f subshell it was necessary to make some adjustments to the code to permit the handling of large matrices. Note that in performing these calculations the contribution from the lowest configuration only was considered in each case. For higher ion stages this is not a problem but for lower stages one expects strong CI between low lying configurations of similar parity. However attempts to include large numbers of configurations based on open 4f subshells presented memory, array size and convergence problems. The results of the calculations for 4d – 4f (from W XIV onwards), 4f – 5d and 4f – 5g transitions are summarized in figures 3 - 5. In these plots we present distributions of gA values with wavelength as well as the result of convoluting each line with a Gaussian of width of 0.02 nm to replicate the effects of the instrumental broadening present in our experiment. It is seen from figure 3 that the most intense 4d-4f transitions are concentrated in the 4.7 – 5.5 nm region and there is a gradual shift to shorter wavelength with increasing charge. Moreover, past W XIX, they essentially give rise to two pronounced peaks in the convolved spectra with a lower energy tail that eventually evolves to become a third peak with increasing ionization.

Figure 3: Calculated transition (line by line) data for $4d^{10}4f^n - 4d^94f^{n+1}$ transitions in W XV – XXIX, i. e. $0 \leq n \leq 12$ and convoluted with a Gaussian instrumental function of width 0.02 nm to replicate the experimental conditions.

From these data, depending on the population mechanism, one might expect a significant contribution to the observed feature extending from 4.7 - 5.5 nm from these transitions. In this regard, it is interesting to note the relative positions of the $4d - 4f$, $4f - 5d$ and $4f - 5g$ lines. From comparison of the figures it is seen that the $4f-5d$ excitation requires less energy than the $4d - 4f$ up to W XXVI, while the $4f - 5g$ requires less energy than the $4d-4f$ up to W XVIII. For a collisionally dominated plasma this would imply that the $4f - 5d$ transitions would dominate in lower ionization stages and be intense in spectra up to W XXVI as population of the $4f^{n-1}5d$ configurations would be favoured over the $4d^{-1}4f^{n+1}$. In low density non-equilibrium plasmas the situation regarding the relative strength of different transition families is less clear. From figures 4 and 5 it is obvious that both $4f - 5d$ and $4f - 5g$ transitions move to shorter wavelengths with increasing ionic charge. The predicted positions of the $4f-5g$ transitions in W XXII to XXVI are in very good agreement with both the earlier calculations [12] and measurement of the associated spectral bands [12, 36]. From our calculations we can associate the unidentified peak at 2.832 nm recorded in [36] as arising from $4f - 5g$ transitions in W XXVIII, while the peak at 2.951 nm previously assigned to WXXIX $4d^{10} - 4d^9 5p^1 P_1$ is seen to possess a significant WXXVII $4f - 5g$ component.

Since the $4d^{10}4f^n - 4d^9 4f^{n+1}$ and $4d^{10}4f^n - 4d^{10}4f^{n-1}5d$ transitions overlap in energy between W XXII and W XXVIII, we investigated the effects of CI. We were especially interested to check if these transitions gained oscillator strength from the interaction in order to account for the intensity peak near 6 nm in the low energy LHD spectra. As already pointed out, the structure appearing in the 5.5 - 7.0 nm region has been identified as resulting from $4f - 5d$ excitation in W

XXII – XXIV [12] and the present calculations lend further support. From EBIT data strong line emission was also recorded in the spectra of W XXII and XXIII in the 5.5 - 6 nm region and from Fig. 3 we can infer that it is unlikely that this emission results from 4d – 4f transitions. In W XXII – W XXV we found that there is no noticeable effect due to configuration mixing between the $4d^9 4f^{n+1}$ and $4d^{10} 4f^{n-1} 5d$ and the CI spectra are essentially the same as those from summed single configuration runs. In W XXVI, the calculations predict a slight modification to the UTA near 5 nm, while in the higher two stages after the 4f – 5d transition has moved to the high energy side of the main 4 – 4 UTA array, it has negligible intensity compared to the 4d-4f so again CI effects are minimal. Because of the limited effects of CI the transitions can be essentially treated as independent and the UTA parameters given in Table 1 for these (and 4f-5g) transitions are those for non-interacting, single configurations. From figure 4, we can expect a contribution to the 5.6 – 6.5 nm peak from W XXIII – WXXIV. The higher stages blend into the main peak. The absence of lines from lower stages may be due to the presence of low lying configurations containing 5s electrons which would cause 5s – 5p transitions to contribute significantly at longer wavelengths or the absence of a significant population of ions below W^{21+} . This is also borne out by the fact that stages lower than W^{21+} do not contribute to the 4f – 5g emission recorded in the earlier LHD experiments [36]. With increasing ionization the 4f binding energy increases more rapidly than the 5s and the effects of these configurations will be reduced causing the 4f – 5d to grow in intensity. With increasing ionization therefore, there is a gradual shift from transitions involving 5s and 5p ‘valence’ electrons to 4f excitation and finally to 4d around W XXV.

Figure 4: Calculated transition (line by line) data for $4d^{10}4f^n - 4d^{10}4f^{n-1}5d$ transitions in W XV – XXVIII, i. e. $1 \leq n \leq 12$ and convoluted with a Gaussian instrumental function of width 0.02 nm to replicate the experimental conditions.

Table 1: UTA Statistics for the 4d -4f, 4f – 5d, 4f – 5g and 4d -5p transitions in a range of tungsten spectra from W XVI to W XXXVIII.

Ion	Transition	Lines	Σgf	Mean λ (nm)	σ (nm)	Skewness	Kurtosis
4d-4f							
W XVI	$4d^{10}4f^{13} - 4d^94f^{14}$	3	8.05	5.54	0.12	-0.34	1.15
W XVII	$4d^{10}4f^{12} - 4d^94f^{13}$	108	103.48	5.47	0.18	0.28	1.86
W XVIII	$4d^{10}4f^{11} - 4d^94f^{12}$	1728	612.72	5.40	0.21	0.46	2.24
W XIX	$4d^{10}4f^{10} - 4d^94f^{11}$	14084	2211.41	5.34	0.23	0.59	2.55
W XX	$4d^{10}4f^9 - 4d^94f^{10}$	64003	5447.60	5.28	0.24	0.70	2.87
W XXI	$4d^{10}4f^8 - 4d^94f^9$	171124	9636.79	5.22	0.25	0.81	3.21
W XXII	$4d^{10}4f^7 - 4d^94f^8$	277823	12629.39	5.17	0.25	0.93	3.64
W XXIII	$4d^{10}4f^6 - 4d^94f^7$	277823	12393.93	5.13	0.25	1.07	4.20
W XXIV	$4d^{10}4f^5 - 4d^94f^6$	171128	9111.54	5.09	0.25	1.24	4.98
W XXV	$4d^{10}4f^4 - 4d^94f^5$	64004	4960.45	5.05	0.24	1.48	6.16
W XXVI	$4d^{10}4f^3 - 4d^94f^4$	14086	1941.48	5.02	0.22	1.84	8.14
W XXVII	$4d^{10}4f^2 - 4d^94f^3$	1728	518.12	4.99	0.20	2.45	11.95
W XXVIII	$4d^{10}4f^1 - 4d^{10}4f^2$	108	84.39	4.96	0.17	3.71	21.46
W XXIX	$4p^64d^{10} - 4p^64d^94f$	3	6.38	4.91	0.12	9.04	83.02
W XXX	$4p^64d^9 - 4p^54d^{10} + 4p^64d^84f$	84	60.24	4.95	0.22	4.45	38.24
W XXXI	$4p^64d^8 - 4p^54d^9 + 4p^64d^74f$	781	256.22	4.99	0.29	3.05	21.44

W XXXII	$4p^6 4d^7 - 4p^5 4d^8 + 4p^6 4d^6 4f$	3291	646.90	5.03	0.36	2.29	13.73
W XXXIII	$4p^6 4d^6 - 4p^5 4d^7 + 4p^6 4d^5 4f$	7188	1073.97	5.08	0.42	1.80	9.43
W XXX IV	$4p^6 4d^5 - 4p^5 4d^6 + 4p^6 4d^4 4f$	8715	1224.78	5.12	0.48	1.45	6.75
W XXXV	$4p^6 4d^4 - 4p^5 4d^5 + 4p^6 4d^3 4f$	6069	971.21	5.16	0.54	1.20	4.97
W XXXVI	$4p^6 4d^3 - 4p^5 4d^4 + 4p^6 4d^2 4f$	2439	530.41	5.19	0.60	1.01	3.71
W XXXVII	$4p^6 4d^2 - 4p^5 4d^3 + 4p^6 4d^1 4f$	547	190.39	5.23	0.66	0.88	2.82
W XXXVIII	$4p^6 4d^1 - 4p^5 4d^2 + 4p^6 4d^0 4f$	63	40.60	5.25	0.72	0.79	2.16

4f – 5d

W XV	$4d^{10} 4f^{14} - 4d^{10} 4f^{13} 5d$	3	1.22	14.56	0.07	2.78	12.63
W XVI	$4d^{10} 4f^{13} - 4d^{10} 4f^{12} 5d$	108	15.93	12.72	0.23	-0.28	7.38
W XVII	$4d^{10} 4f^{12} - 4d^{10} 4f^{11} 5d$	1728	95.05	11.23	0.24	-0.08	5.79
W XVIII	$4d^{10} 4f^{11} - 4d^{10} 4f^{10} 5d$	14086	343.63	10.02	0.23	0.05	5.33
W XIX	$4d^{10} 4f^{10} - 4d^{10} 4f^9 5d$	64005	848.26	9.00	0.21	0.15	5.12
W XX	$4d^{10} 4f^9 - 4d^{10} 4f^8 5d$	171133	1497.79	8.15	0.18	0.24	5.06
W XXI	$4d^{10} 4f^8 - 4d^{10} 4f^7 5d$	277827	1953.20	7.43	0.16	0.32	5.08
W XXII	$4d^{10} 4f^7 - 4d^{10} 4f^6 5d$	277827	1905.54	6.80	0.14	0.41	5.15
W XXIII	$4d^{10} 4f^6 - 4d^{10} 4f^5 5d$	171133	1390.97	6.26	0.11	0.50	5.29
W XXIV	$4d^{10} 4f^5 - 4d^{10} 4f^4 5d$	64005	751.01	5.79	0.10	0.60	5.51
W XXV	$4d^{10} 4f^4 - 4d^{10} 4f^3 5d$	14087	291.46	5.37	0.08	0.73	5.88
W XXVI	$4d^{10} 4f^3 - 4d^{10} 4f^2 5d$	1728	77.00	5.00	0.06	0.89	6.54

W XXVII	$4d^{10}4f^2 - 4d^{10}4f^15d$	108	12.42	4.67	0.04	1.09	8.03
W XXVIII	$4d^{10}4f^1 - 4d^{10}4f^05d$	3	0.92	4.38	0.02	1.27	6.67
4f-5g							
WXV	$4d^{10}4f^{14} - 4d^{10}4f^{13}5g$	3	3.64	6.62	0.04	2.47	7.16
W XVI	$4d^{10}4f^{13} - 4d^{10}4f^{12}5g$	129	54.84	6.00	0.07	0.41	4.39
W XVII	$4d^{10}4f^{12} - 4d^{10}4f^{11}5g$	2303	376.26	5.49	0.08	0.49	4.16
W XVIII	$4d^{10}4f^{11} - 4d^{10}4f^{10}5g$	19835	1557.47	5.06	0.07	0.61	4.19
W XIX	$4d^{10}4f^{10} - 4d^{10}4f^95g$	92842	4349.94	4.68	0.07	0.72	4.28
W XX	$4d^{10}4f^9 - 4d^{10}4f^85g$	252284	8655.27	4.36	0.06	0.81	4.38
W XXI	$4d^{10}4f^8 - 4d^{10}4f^75g$	412549	12638.84	4.08	0.06	0.88	4.46
W XXII	$4d^{10}4f^7 - 4d^{10}4f^65g$	412551	13723.19	3.84	0.05	0.94	4.53
W XXIII	$4d^{10}4f^6 - 4d^{10}4f^55g$	252286	11085.34	3.62	0.05	0.97	4.56
W XXIV	$4d^{10}4f^5 - 4d^{10}4f^45g$	92843	6586.15	3.43	0.04	0.99	4.57
W XXV	$4d^{10}4f^4 - 4d^{10}4f^35g$	19835	2798.50	3.26	0.03	1.00	4.55
W XXVI	$4d^{10}4f^3 - 4d^{10}4f^25g$	2303	806.50	3.11	0.03	0.99	4.51
W XXVII	$4d^{10}4f^2 - 4d^{10}4f^15g$	129	141.23	2.97	0.02	0.94	4.38
W XXVIII	$4d^{10}4f^1 - 4d^{10}4f^05g$	3	11.36	2.85	0.01	-0.28	1.08
4d-5p							
W XXV	$4d^{10}4f^4 - 4d^94f^45p$	198892	1105.79	3.36	0.12	-1.22	5.21

W XXVI	$4d^{10}4f^3 - 4d^94f^35p$	33150	401.20	3.24	0.10	-1.34	6.03
W XXVII	$4d^{10}4f^2 - 4d^94f^25p$	2976	100.05	3.12	0.09	-1.43	6.99
W XXVIII	$4d^{10}4f^1 - 4d^94f^15p$	130	15.34	3.01	0.07	-1.35	7.67
W XXIX	$4p^64d^{10} - 4p^64d^95p$	3	1.09	2.91	0.05	-0.45	3.17
W XXX	$4p^64d^9 - 4p^64d^85p$	59	8.77	2.81	0.05	-0.31	3.49
W XXXI	$4p^64d^8 - 4p^64d^75p$	465	37.89	2.72	0.05	-0.24	4.13
W XXXII	$4p^64d^7 - 4p^64d^65p$	1718	90.22	2.63	0.05	-0.11	4.27
W XXXIII	$4p^64d^6 - 4p^64d^55p$	3245	134.49	2.55	0.05	-0.04	4.24
W XXXIV	$4p^64d^5 - 4p^64d^45p$	3245	133.62	2.47	0.05	0.01	4.13
W XXXV	$4p^64d^4 - 4p^64d^35p$	1718	88.47	2.40	0.05	0.05	3.91
W XXXVI	$4p^64d^3 - 4p^64d^25p$	466	37.64	2.33	0.04	0.07	3.56
W XXXVII	$4p^64d^2 - 4p^64d^15p$	60	9.34	2.26	0.04	0.08	3.05
W XXXVIII	$4p^64d^1 - 4p^64d^05p$	3	1.03	2.19	0.04	0.07	2.30

Figure 5: Calculated transition (line by line) data for $4d^{10}4f^n - 4d^{10}4f^{n-1}5g$ transitions in $W\ XV - XXVIII$, i. e. $1 \leq n \leq 12$ and convoluted with a Gaussian instrumental function of width 0.02 nm to replicate the experimental conditions.

Figure 6: Calculated transition (line by line) data for $4p^6 4d^m - 4p^5 4d^{m+1} + 4p^6 4d^{m-1} 4f$ transitions in W XXX – XXXVIII, i. e. $1 \leq m \leq 9$ and convoluted with a Gaussian instrumental function of width 0.02 nm to replicate the experimental conditions.

Figure 7: Calculated transition (line by line) data for $4p^6 4d^{10} 4f^n - 4p^6 4d^9 4f^n 5p$ transitions in W XXV – XXVIII, i.e. $2 \leq n \leq 5$ and $4p^6 4d^m - 4p^6 4d^{m-1} 5p$ transitions in W XXIX – XXXVIII, i.e. $1 \leq m \leq 10$ convoluted with a Gaussian instrumental function of width 0.02 nm to replicate the experimental conditions.

For ions with an outermost 4d subshell, the dominant transitions in W XXIX are 4d – 4f and 4d – 5p. Once the 4d subshell opens, the dominant transitions become $4p^6 4d^m - 4p^5 4d^{m+1} + 4p^6 4d^{m-1} 4f$ and $4p^6 4d^m - 4p^6 4d^{m-1} 5p$. Figures 6 and 7 contain plots for W XXIX - XXXVIII showing the line by line data and superimposed convoluted plots where, as before in figures 3 - 5, each line is given a width of 0.02 nm and the resulting distributions are summed to illustrate the effects of instrumental broadening. Note that the spectra in the lower ion stages are dominated by intense emission near 5 nm that essentially originates from transitions to the $4d_{5/2}$ sublevel. A second peak which appears near 4.5 nm in WXXX grows rapidly in intensity with increasing ionization and is associated with transitions to the $4d_{3/2}$ sublevel and comes to dominate the spectrum past W XXXV. This feature is essentially absent from both experimental spectra.

For W XXXIX, the resonance transitions are $4s^2 4p^6 - 4s^2 4p^5 4d$ and give rise to lines observed at 4.640 and 6.398 in Berlin EBIT data [28]. Although many of the lines for the ions from W XXXIX – W XLIV have been measured and identified from both EBIT and ASDEX-Upgrade data [4-6,7], and are clearly identifiable in figure 2, for completeness, calculations were performed for resonance transitions of the type $4s^2 4p^m - 4s^2 4p^{m-1} 4d + 4s 4p^{m+1}$ ($1 \leq m \leq 5$). The results are presented in Figure 8 while the corresponding UTA statistics are again given in Table 1.

Figure 8: Calculated transition (line by line) data for $4s^n 4p^m - 4s^2 4p^{m-1} 4d + 4s^n 4p^{m+1}$ transitions in W XXXIX – XLVI, i. e. $0 \leq m \leq 6$ and $0 \leq n \leq 2$. Spectra were convoluted with a Gaussian instrumental function of width 0.02 nm to replicate the experimental conditions.

Comparison and Conclusions:

Since equilibrium is not established between the ions and the LHD plasma it is extremely difficult to calculate relative ion abundances and their spatial and temporal variations during the integration time of the detector. Nevertheless, it is instructive to explore the variation of ion stage with temperature for an equilibrium plasma. The fractional abundances were obtained using the collisional-radiative plasma model of Colombant and Tonon [51], where collisional excitation is essentially balanced by radiative decay. In performing this calculation the electron and ion densities were assumed to be 10^{19} m^{-3} , while the ionisation potentials of Kramida and Reader [21] were used. The results showed that were the plasma in equilibrium, the maximum stages we could expect would correspond to W^{45+} for a 1.5 keV plasma and W^{59+} for the 3 keV case. In our spectra we expect the limiting stages to be lower in each case because of the low collisional excitation rates. Indeed the absence of the 4d – 4f lines of W^{37+} in the 1.5 keV spectrum indicates that the maximum ion stage is lower than this.

To check for the validity of the same population mechanism as proposed for the low density plasmas in both EBIT and ASDEX-Upgrade, calculations for 4d – 4f excitation analogous to those presented in [30] and [31] were performed. In figure 9 (a) the results of a calculation based on dipole excitation from the lowest level followed by emission from the subsequent decay of the upper states, exactly analogous to the calculations in [29,30], are presented. In this plot each ion stage was assigned an equal population and the figure represents the resulting summation for all spectra from W XVI – W XXVIII. From this figure, the main contribution should be near 5.5 nm and this was found to originate primarily from spectra up to W XXIII. In figure 9 (b) we show for comparison the cumulative effect of adding all 4d-4f transitions involving the lowest

configuration, i.e. all of the transitions presented in figure 3, in these stages. Comparison shows that if excitation from the lowest level only is considered, as well as dramatically reducing the number of possible transitions, the higher energy, high intensity lines are largely removed. In figure 9 (a), the transitions near 5.5 nm are predicted to be amongst the most intense, while from the gA distribution these lines are more than a factor of three weaker ($gA \sim 5 \times 10^{13} \text{s}^{-1}$) than the group near 4.75 nm. Hence we can infer that in situations where this model is applicable, the overall contribution of 4d – 4f transitions in these ion stages will be lower than expected simply by consideration of gA distributions alone.

For ions with an open 4d subshell we also present in figure 9 (c) the results allowing for ground state excitation only, again summed assuming an equal population from each stage. In preparing these plots the results for each stage were seen to be very similar to the theoretical spectra shown in the works of Jonsaukas *et al.* and Kucas *et al.* [30, 31]. Any differences could be attributed to the different atomic structure codes used. Moreover similarities between excitation and decay spectra were found due to the fact that the upper terms preferentially recombine with the lowest level which is also in agreement with the earlier results. In figure (d) the superposition of gA distributions for the same group of ions is given. The main difference encountered when considering excitation from the lowest level only, apart from the reduced number of lines, is the near elimination of structure at wavelengths lower than 5 nm, which could explain the absence of the structure predicted in the 4.5 – 5 nm region (Fig. 8) in the observed spectra though the more likely cause is the weakness of these lines compared to those of Ag- and Pd-like W due to the distribution of a greater number of excited level amongst a similar or lower population. In Figs.

9 (e) and (f) we sum in the contribution from 4s-4p and 4p – 4d transitions for W XXXIX – XLVI, again assuming equal populations. However when we compare these various distributions to the experimental results of Fig. 2 it would appear that the summed gA distributions provide a better overall approximation for both sets of experimental data. Further evidence comes from the fact that the Ag-like $^2F_{7/2} - ^2G_{9/2}$ line observed at 5.0895 nm is stronger in the observed spectra than the $^2F_{5/2} - ^2G_{7/2}$ despite the fact that the upper $4d^9 4f^2 \ ^2G_{9/2}$ level is not directly accessible from the ground, $^2F_{5/2}$, state.

Figure 9 (a): Calculated emission data for $4d^{l0}4f^n - 4d^9 4f^{n+1}$ transitions in W XVI – XXVIII, assuming excitation from only the ground level of each ion and an equal contribution from each ion stage. (b) same as in (a) but allowing for all possible transitions. (c) Calculated emission data for $4p^6 4d^m - 4p^5 4d^{m+1} + 4p^6 4d^{m-1} 4f$ transitions in W XXIX – XXXVIII, assuming excitation from the ground level of each ion (d) Same as (c) but including all possible transitions. (e) Calculated emission data for $4s^2 4p^m - 4s^2 4p^{m-1} 4d + 4s 4p^{m+1}$ transitions in W XXXIX – XLVI, assuming excitation from the ground level of each ion + contribution from (a) and (c) assuming all ions contribute equally. (f) Same as (e) but with contributions from all levels.

In figure 10 we show a scatter plot for the 4d-4f transitions where each line is represented as a point with a specific energy and gA value. From these plots the enormous line density resulting from the presence of the open 4f subshell is immediately obvious as is the fact that the vast majority of lines have almost negligible transition probability. The UTA parameters derived from these are listed in Table 1. Because of the configuration mixing between $4p^5 4d^{m+1}$ and $4p^6 4d^{m-1} 4f$ it is meaningless to treat these as separate arrays and the UTA data refer to the mixed configuration. Note that because of the spin-orbit splitting of the resulting array, the fit to a single curve results in the UTA having a considerable width. The values of the different parameters for each of the open 4d subshell ions are also given in Table 1. In figure 11, the

UTA results are summarized graphically for all of the spectra from W XV to W XXXVIII. Also from figure 11 it is possible to identify the unidentified peaks measured in the earlier LHD experiment [36] at 2.687 and 2.536 nm as arising from 4d -5p transitions in W XXXI, XXXII and W XXXIII.

Figure 10: Calculated transition gA vs wavelength data for $4d^{10}4f^n - 4d^94f^{n+1}$ transitions in W XVII – XXVIII, i. e. $1 \leq n \leq 11$ and $4p^64d^m - 4p^54d^{m+1} + 4p^64d^{m-1}4f$ transitions in W XXIX – XXXVI, i. e. $3 \leq m \leq 10$ presented in the form of a scatter plot, where each point corresponds to an individual transition.

Figure 11: Mean position and array widths for $4d-4f$, $4d-5p$, $4f-5g$ and $4f-5d$ transitions in a range of tungsten spectra.

In figure 12, comparison is made of the theoretical data with the experimental results. We can infer that the 1.5 keV plasma contains emission from open 4f and 4d subshell ions. The strong lines in the 4.8 – 5.2 nm region in both spectra result from 4d- 4f transitions in W XXVIII – XXX, while the bulk of the underlying UTA results from W XXX – W XXXV, as past this stage transitions will contribute mainly in the 4.5 nm region and are not evident from the experimental spectrum. Although this structure is effectively removed by consideration of excitation from the ground level (or lowest spin orbit split configuration only) this mechanism does not tally with the observation of excited to excited state lines clearly evident in figure 2. Thus we can infer that consideration of dipole excitation from the ground state only does not provide a good fit to the experimental data in the present case.

In figure 12 (a) the contribution of ions from W^{21+} – W^{34+} is presented and is seen to reproduce the essential features of the shorter wavelength end of the lower temperature rather well. From comparison with Fig. 4, the structure lying between 5.6 and 6.5 nm in the experimental spectrum and absent from figure 12 (a) is associated with 4f – 5d transitions in W XXIII – XXIV as well as some 4d – 4f and 4p – 4d transitions in W XXXV – XXXVIII. The absence of 4f – 5d transitions at longer wavelengths is most likely associated with the presence of configurations containing one or two 5s electrons or low populations of stages lower than W^{21+} or both.

In the hotter 3 keV plasma, the increased emission in the 4.5 – 4.8 and 6 – 7 nm regions is mainly due to additional contributions from 4p - 4d transitions from species with an open 4p subshell. Indeed many of the individual peaks can be associated with lines from W XXXVIII –

XLIV from a comparison with tabulated data [7]. In figure 12 (b) the contribution of all spectra up to W XXXVIII are summed in equal measure while the contribution from W XXXVIII is weighted by 33% to reduce the peak at 4.5 nm and give better agreement with observation. Thus it appears that the population of ions with 4p or 4s valence subshells is significantly less than those with valence 4d.

Figure 12: (a) Superimposed W XV – W XXXIII 4d-4f theoretical spectra to replicate the 1.5 keV experimental spectra

(b) Superimposed W XV- WXLVI resonance transitions with 100% weighting for XV- XXXVIII and 33% for WXLVI to replicate the 3 keV experimental spectra.

Acknowledgement:

This work was supported by NIFS, by Science Foundation Ireland under Research Grant Number 08/RFP/PHY1100. ES acknowledges support from the Japan Society for the Promotion of Science.

References:

1. Matthews G F, Edwards P, Hirai T, Kear M, Lioure A, Lomas P, Loving A, Lungu C, Maier H, Metens P, Nielson D, Neu R, Pamela J, Philipps J, Piazza G, Riccardo V, Rubel M, Ruset C, Villedieu E and Way M on behalf of the ITER-like Wall Project Team 2007 *Phys. Scr.* **T128** 137
2. Neu R, Maier H, Gauthier E, Greuner H, Hirai T, Hopf Ch, Likonen J, Maddaluno G, Matthews G F, Mitteau R, Philipps V, Piazza G, Ruset C and JET EFDA Contributors 2007 *Phys. Scr.* **T128** 150
3. Neu R, Fournier K B, Schlög D and Rice J 1997 *J. Phys. B: Atom. Mol. Opt. Phys.* **30** 5057
4. Asmussen K, Fournier K B, Laming J M, Neu R, Seely J F, Dux R, Englehardt W, Fuchs JC and the ASDEX Upgrade Team 1998 *Nucl. Fusion* **38** 967
5. Pütterich T, Neu R, Biedermann C, Radtke R and the ASDEX Upgrade Team 2005 *J. Phys. B: Atom. Mol. Opt. Phys.* **38** 3071
6. Pütterich T, Neu R, Dux R, Whiteford A, O'Mullane M G and the ASDEX Upgrade Team 2008 *Plasma Phys. Control. Fusion* **50** 085016
7. Kramida A E and Shirai T 2009 *Atomic Data and Nuclear Data Tables* **95** 305–474
8. Reader J 2009 *Phys. Scr.* **T134** 014023
9. Biedermann C, Radtke R, Seidel R and Pütterich T 2009 *Phys. Scr.* **T134** 014026
10. Isler R C, Neidigh R V and Cowan R 1977 *Phy. Lett.* **63A** 295

11. Sugar J and Kaufman V 1980 *Phys. Rev. A* **21** 2096
12. Finkenthal M, Huang L K, Lippman S, Moos H W, Mandelbaum P, Schwob J L, Klapisch M and the TEXT Group 1988 *Phys. Lett.* **127A** 255
13. Sugar J, Kaufman V and Rowan W L 1993 *J. Opt. Soc. Am.* **B10** 1321
14. Sugar J, Kaufman V and Rowan W L 1993 *J. Opt. Soc. Am.* **B10** 799
15. Sugar J, Kaufman V and Rowan W L 1993 *J. Opt. Soc. Am.* **B10** 1977
16. Carroll P K, Kennedy E T and O'Sullivan G 1980 *Appl. Opt.* **19** 1454
17. O'Sullivan G and Carroll P K 1981 *J. Opt. Soc. Am.* **71** 227
18. Sugar J and Kaufman V 1975 *Phys. Rev. A* **12** 994
19. Sugar J and Kaufman V 1979 *J. Opt. Soc. Am.* **69** 141
20. O'Sullivan G, Carroll P K, Dunne P, Faulkner R, McGuinness C and Murphy N 1999 *J. Phys. B: At. Mol. Opt. Phys.* **32** 1893
21. Kramida A E and Reader J 2006 *At. Data Nuc. Data Tables* **92** 457
22. Hutton R, Zou Y, Reyna Almandos J, Biedermann, C, Radtke R, Greier A and Neu R 2003 *Nuc. Instrum. Method. Phys. Res B* **205** 114
23. Suzuki C, Kato T, Sato K, Tamura N, Kato D, Sudo S, Yamamoto N, Tanuma H, Ohashi H, Suda S, O'Sullivan G and Sasaki A 2009 *J. Phys. Conf. Ser.* **163** 012019

24. D'Arcy R, Ohashi H, Suda S, Tanuma H, Fujioka S, Nishimura H, Nishihara K, Suzuki C, Kato T, Koike F, White J and O'Sullivan G 2009 *Phys. Rev. A* **79** 042509
25. Koike F, Fritzsche S, Nishihara K, Sasaki A, Kagawa T, Nishikawa T, Fujima K, Kawamura T and Furukawa H 2006 *J. Plasma. Fusion. Res.* **7** 253
26. Mandelbaum P, Finkenthal M, Schwob J L, and Klapisch M 1987 *Phys. Rev. A* **35** 5051
27. Svendsen W and O'Sullivan G 1994 *Phys. Rev. A* **50** 3710
28. Radtke R, Biedermann C, Schwob J L, Mandelbaum P and Doron R 2001 *Phys. Rev. A* **64** 012720.
29. Biedermann C, Radtke R, Schwob J L, Mandelbaum P, Doron R, Fuchs T, and Fußmann G. 2001 *Phys, Scr.* **T92** 85
30. Jonauskas V, Kucas S and Karazija R 2007, *J. Phys. B: At. Mol. Opt. Phys.* **40** 2179
31. Kucas S, Karazija R, Jonauskas V and Momkauskaite A, 2009 *J. Phys. B: At. Mol. Opt. Phys.* **42** 205001
32. Grant I P, McKenzie BJ, Norrington P H, Mayers DF and Pyper N C, 1980 *Comput. Phys. Commun.* **21** 207
33. Utter S B, Beiersdorfer P, and Träbert E, 2002 *Can. J. Phys.* **80** 1503
34. Ralchenko Yu, Reader J, Pomeroy J M, Tan J N and Gillaspay J D 2007 *J. Phys. B: At. Mol. Opt. Phys.* **40** 3861
35. Ralchenko Yu, Draganic I N, Tan J N, Pomeroy J M, Reader J, Feldman U and Holland G E 2008 *J. Phys. B: At. Mol. Opt. Phys.* **41** 021003

36. Chowdhuri M B, Morita S, Goto M, Nishimura H, Nagai K and Fujioka S 2007 *Plasma and Fus. Res.* **2** S1060.
37. Narihara K, Yamada I, Hayashi H and Yamauchi K 2001 *Rev. Sci. Instrum.* **72** 1122
38. Sudo S 1993 *J. Plasma Fusion Res.* **69** 1349
39. Schwob J L, Wouters A W and Suckewer S 1987 *Rev. Sci. Instrum.* **58** 1601
40. Neu R 2006 *Phys. Scr.* **T123** 33
41. Kato T, Funaba H, Sato K, Kato D, Song M-Y, Yamamoto N, Tanuma H, Ohashi H, Sasaki A, Koike F, Nishihara K, Fahy K and O'Sullivan G 2008 *J. Phys. B: At. Mol. Opt. Phys.* **41** 035703
42. Suzuki C, Kato T, Sakaue H A, Kato D, Sato K, Tamura N, Sudo S, Yamamoto N, Tanuma H, Ohashi H, D'Arcy R and O'Sullivan G 2010 2008 *J. Phys. B: At. Mol. Opt. Phys.* **(in press)**
43. Cowan R D 1991 *The Theory of Atomic Structure and Spectra* (University of California Press, Berkeley)
44. Bauche-Arnoult C, Bauche J and Klapisch M, *J. Opt. Soc. Am.* **68**, 1136 (1978)
45. Bauche-Arnoult C, Bauche J and Klapisch M, 1979 *Phys. Rev. A* **20** 2424
46. Bauche-Arnoult C, Bauche J and Klapisch M, 1982 *Phys. Rev. A* **25** 2641
47. Bauche-Arnoult C, Bauche J and Klapisch M, 1984 *Phys. Rev. A* **30** 3026
48. Bauche-Arnoult C, Bauche J and Klapisch M, 1985 *Phys. Rev A* **31** 2248
49. White J, Dunne P, Hayden P and O'Sullivan G 2009 *J. Appl. Phys.* **106** 113303

50. Sasaki A, Nishihara K, Koike F, Kagawa T, Nishikawa T, Fujima K, Kawamura T and Furukawa H 2004 *IEEE J. Sel. Top. Quantum Electron.* **10** 1307
51. Colombant D and Tonon G F 1973 *J. Appl. Phys.* **44** 13524