SIMULATION OF THE VUV SPECTRA FROM THE REVERSE FIELD PINCH

V. Stancalie, R. Cernat, A. Puiu

National Institute for Lasers, Plasma and Radiation Physics, Bucharest, Romania

We have investigated the influence of opacity on hydrogen (H-α and Ly-β and Li-like oxygen) emission lines from the EXTRAP T2R reversed field pinch (RFP). We used the Atomic Data Analysis System (ADAS) based on the escape factor approximation for radiative transfer, to calculate metastable and excited population densities via a collisional-radiative (CR) model. The population escape factor, the emergent escape factor and the modified line profiles were plotted vs. optical depth. The simulated emission line ratios in the density/temperature plane were in good agreement with experimental data for electron density and temperature measurements.

The EXTRAP T2 RFP was the subject for many works whose experimental results confirmed that most of the radiation occurred in the resonance lines of the Li-like oxygen ion. Consequently these line intensities and ratios are frequently used for the determination of plasma temperature. We investigated this impurity which has been considered with only ground and metastable states having their Boltzmann population densities, with the rest being under-populated.

The main objectives of the subtask have been:

- Atomic structure calculations and CR model for the EXTRAP T2 RFP
  - Determination of the cross-section and rates for the elementary atomic processes into the plasma
  - CR calculations of the relative metastable and excited state population densities for the main impurities on the plasma surface (carbon and oxygen)
  - Calculation of the total radiated power and comparison with the experimental data

- Investigation of the plasma thickness on the line emissivities at the EXTRAP T2 RFP

  This work has been performed under mobility support at KTH Stockholm and VR-Euratom Association support
  - Determination of the opacity effects on line emissivities belonging to Hydrogen H - α and Ly - β;
  - Determination of the opacity effects on the resonance line emissivities belonging to the Li-like oxygen ion
  - Spectra simulation (including opacity effect) in the density/temperature plane

- Activities carried out in participating in the exploitation of the JET Facilities.

During the previous period, focus has been on modeling the radiation from the reversed field pinch experiment, T2R, at the Alfvén laboratory, KTH, Stockholm. The KTH group of Atomic and Molecular Physics is a member of the ADAS (Atomic Data Analysis Structure) consortium that has the purpose to develop analysis and modeling programmes with the best available atomic and molecular data for diagnostics of hot fusion plasmas such as those of JET and ITER.

The ADAS codes with new models adjusted to the specific conditions of the T2R plasma have been used for plasma modeling. In a first study, the radiative transfer problem has been addressed for both the hydrogen and the oxygen emission from the plasma. After ensuring that no actions had to be taken for optical thickness, the programme proceeded with modeling the total radiative power from the T2R plasma. The main impurity was oxygen and the plasma working gas was hydrogen. No traces of metal impurities, e.g. from the molybdenum mushroom limiters, have yet been identified. The experimental tools available are a single chord VUV spectrometer and an 8-chord bolometer (on loan from RFX, Padova, Italy). In the first preliminary results from this study and modeling using the ADAS tools, the predicted radiation from the VUV spectrometer was found to be somewhat lower than that observed by the bolometer.

To enable fast calculations, we have adopted the escape factor technique to model the opacity effect of photo-excitation on population densities and on radiation transfer. Using escape factors in modeling the radiative transfer processes is fast and can give reasonably accurate results provided the model plasma conditions used in evaluating the escape factor are near the actual plasma conditions.

Escape factors have two uses in modeling the radiative transfer of the spectral lines (Irons, F.E., *JQRST*, **22** (1979) 1-20, *JQRST*, **45**(1991) 217-223). They are correction factors, so called ”net radiative brackets”, to the radiative transition probabilities to allow for the radiation trapping photo-excitation on quantum state densities. They can also be used as factors, so called escape probabilities, which multiply the emission expected from an optically thin plasma to allow for the effect of opacity on the emitted lines.

Atomic structure calculations and CR model for EXTRAP T2 RFP

The plasma under consideration has an electron temperature between 10 – 150 eV and density range of 10^{11} – 5.10^{13} cm^{-3}. We adopted the Doppler mechanism for the line width, and the density was assumed to be parabolic through the plasma. The geometry was assumed to be a cylinder with an effective length 0.183 m and an “aspect ratio” 30.5 (defined as cylinder length/cylinder radius). Starting with experimental values for the electronic temperature and the corona equation for fractional ionisation, we determined on the basis of macroscopic neutrality condition the abundance of He –like and Li-like oxygen ions as being 1.64% and 0.43 %, respectively. Background theory and codes in ADAS are based on the R-matrix calculation with exchange. The orbitals are generated from a single-configuration Hartree-Fock (SCHF) calculation while the pseudo states are generated from a non-orthogonal Laguerre basis. These states are then orthogonalised with respect to the Hartree-Fock orbitals and with respect to each other. These are the bases of the CIV3 and AUTOSTRUCTURE codes. We used the above-mentioned codes to output atomic parameters (level energy, line strength, oscillator strengths, etc) of different metastable and excited state of a given ion.

Various collisional and radiative processes have been included in the generalized collisional-radiative model to output relative metastable and excited state population densities for each ion with respect to the density and temperature plasma parameters. The final outcome of the codes is the PEC (radiated power coefficient) for transitions of interest. The PEC’s have been evaluated for Li-like C and O ions. The total radiated power has been compared and well fitted with experimental data measurements at EXTRAP T2R.

The rates of the atomic processes have been included into the collisional radiative model calculations to output population density of metastable and excited states for oxygen and carbon ions. The excited state and metastable state populations of a selected ion in the EXTRAP T2 plasma have been calculated for specified temperatures and densities. Drawing on the fundamental energy level, a specific ion file ADF04 represented the rate coefficient data. Moreover, these calculations were included into another ADAS code to evaluate and display line emissivities and their ratios for specific ions: O^{VI}, C^{IV}, O^{V}.

Investigation of the plasma thickness on the line emissivities at the EXTRAP T2 RFP

We used ADAS and the collisional radiative model to output values of population density as a function of electron density and temperature.

This work has been performed under mobility support during 2002 and VR-Euratom association agreement.

The Atomic Data Analysis System (ADAS) has been used to compute opacities of low to medium Z-elements and collisional radiative calculations.

Atomic data for the $1s^2nl(^2L_j)$ levels, with $n \leq 4$ were calculated using AUTOSTRUCTURE in the ADAS package. These atomic calculations and associated derived atomic data were performed for a simple estimation of impurity fluxes from observed line-of-sight intensities using ionization per photon coefficients as well as for the examination of spectral line ratios diagnostic of local plasma conditions in the absence of opacity effects. Results are to be considered for the radiative power loss from the plasma.

Li – like O ion has resonance at ^2S – ^2P with three lines:

Ion	transition	λ(A)	A (s^{-1})	*f*	g_l	g_u
O^{5+}	2S – 2P	1033.8160	$4.14\ 10^{08}$	$1.9901 \cdot 10^{-01}$	2	6
		1037.6160	$4.0946\ 10^{08}$	$6.6091 \cdot 10^{-02}$	2	2
		1031.9261	$4.1628\ 10^{08}$	$1.3291 \cdot 10^{-01}$	2	4

The transport of photons through a plasma volume has been described by the so-called escape factor approximations. For different plasma geometry and parameters we investigated the influence of opacity on line emissivity belonging to resonance absorption lines of Li-like O ion and Hydrogen atoms. The restrictive conditions used by the ADAS codes do not affect our investigation. This conclusion is reached for 2 reasons . Firstly, from experimental measurements, the absorber density is approximately constant in the plasma along the line of sight and the absorption coefficient could be considered independent of *x* and given by an average value. Secondly, the thermal motion of neutral particles or charge exchange reactions determine the line profile. The possibility of charge transfer from thermal neutral hydrogen contributing to the observed spectral line emission has been ignored. This process can modify emission of the Lyman series of He-like C, which however is not present in the investigated plasma volume.

ADAS calculates the normalised escape factor for all transitions in the *jj* coupling scheme using as an input file ADF04 based on the data of Zhang *et al*., 1990. This file has been amended for the effect of resonances to calculate line width with close-coupling. The ADAS collisional-radiative code yields the dependence on both ground and metastable populations and provides corrections for the predefined escape factor of resonance lines. We investigated the thickness of the plasma and spectral radiance for the multiplet $1s^22s\ ^2S - 1s^22p\ ^2P^0$ with three lines from which we considered λ = 1037.6160 Å to be more sensitive to the opacity. In this case the lines have different optical thickness for density and temperature in the T2R plasma.
A normalised escape factor has been calculated with respect to $g_l = 2 \rightarrow g_u = 6$ (λ = 1033.8160 Å) and $g_l = 2 \rightarrow g_u = 2$ (λ = 1037.616 Å) transitions, respectively. In the calculation the ion temperature was set to be 10 eV. Graphs obtained as output from the code show that all these lines are insensitive to opacity.

Spectrum line ratio intensities as provided from the output of our calculations are in a very good agreement with the data resulting from experimental measurements. Data obtained in the density-temperature plane represented a good test for our plasma diagnostics.

The second investigation was Hydrogen H -α and L - β lines and their emissivities in the EXTRAP T2 RFP. In this case spectral line profiles corresponding to the $3 \rightarrow 2$ and $3 \rightarrow 1$ transitions were determined by Doppler broadening. We used ADAS central data to output values of electron-impact excitation and recombination rates with respect to our plasma parameters. The ADAS214 program for the analysis of opacity effects shows that the L - β line is more sensitive to increasing density. The input file ADF04 was chosen to be generated by compression of a *J*-resolved file. The first level was assumed to be at its Boltzmann value and the rest assumed to be under-populated. The ion temperature was set to 0.25 eV and the Boltzmann equilibrium temperature at 10 eV.
Hydrogen Balmer H - α and Lyman Ly - β were investigated by looking for their sensitivity to plasma thickness. It is well known that with increasing density the ratio of the two lines changes due to optical thickness. In all our calculations we considered the density range of $10^{11} - 10^{13}$ cm^{-3} as given by experiments. These lines were considered for CR calculations with respect to plasma geometry and density-temperature parameters.
We concluded that the lines under investigations for both O^{5+} and Hydrogen were insensitive to opacity. Plasma thickness does not affect the emission lines and consequently the population density or intensity output.
These are the first calculations on the opacity influence on plasma emissivity
for the EXTRAP T2R [1].

Publications:

[1] **Stancalie V., Rachlew E.**, *"Study of opacity effect on emission line at EXTRAP T2R RFP"*, Physica Scripta 66, (2002), 444.