SIMULATION OF THE VUV SPECTRA FROM THE REVERSE FIELD PINCH

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The goal of this work is:

a) to create a computationally 'light' spectrally resolved computer model, which will fit reasonably well to the experimentally measured spectrum of the Balmer series limit. The reason for choosing these spectra is because this allows us to observe the line radiation from neutral atoms. The completion of this model will be an integration of the line of sight intensities, such that the theoretical spectrum would fit the experimental within a factor of order unity.

b) to model the total radiated power

In this work we refer to the EXTRAP T2R plasma which is basically hydrogen (deuterium) plasma with all its non – negligible contributors. No beams are used in experiments. Different physical properties and its performances influenced by the resistive shell and the vacuum vessel protected with graphite tiles were already reported in many works. The plasma has a major radius of 1.24 m and a minor radius of 0.183 m. Active (Thomson scattering, interferometry) or passive (spectrometer, monochromators and filters) diagnostics are used to measure the basic parameters. Briefly, the electron density, n_e, is situated in the range of 0.5-1.5 10^{19} m^{-3}, the electron, T_e , and ion temperature, T_i, are between 100 – 200 eV and 50 – 300 eV respectively, and main impurities concentrations referring to oxygen and carbon were considered to output a value between 1,5 and 3,0 of the average electric charge, Z_{eff}.

In the present work we continue our theoretical investigation over other phenomena which give contributions to the experimentally measured spectrum: the statistical plasma microfields, the photo-recombination and bremsstrahlung. Including their effects is absolutely essential and could be studied observing the Balmer series into the plasma.
We use the ADAS package looking at fundamental and derived data, preparing state selective charge transfer data so that their influence on the ionization balance can be modeled. The particular data considered here are state selective charge exchange cross sections in which neutral hydrogen is a donor to partially ionized oxygen ions.

- *Atomic structure calculations and CR model for Hydrogen atoms in EXTRAP T2 RFP*
    - ADAS310 performs a full bundle-n collisional – radiative model calculations which for the present purpose are used only to obtain the emission rate coefficients for a thermal plasma; the population density distribution as a function of the principal quantum shell number for hydrogen atoms was plotted including the Boltzmann distribution' correction factor.

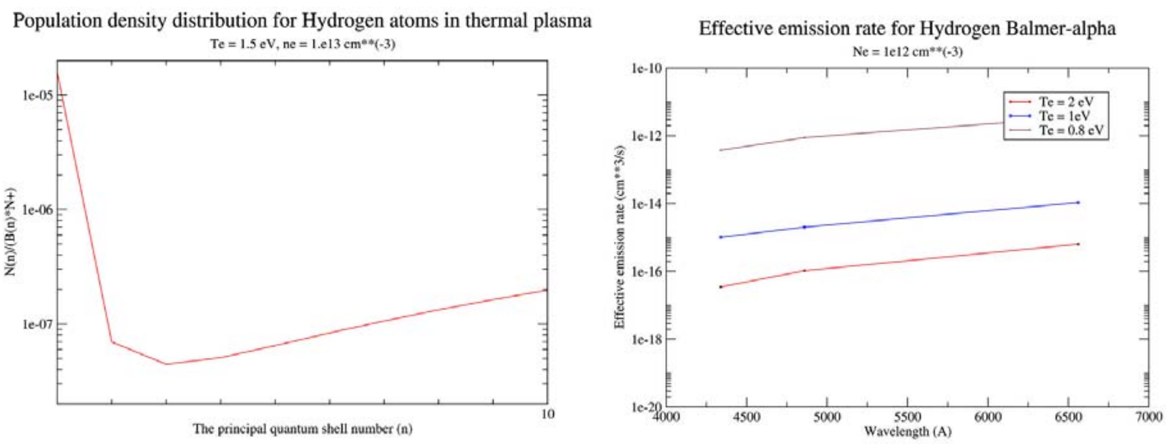

Figure 1. Population density distribution for hydrogen atoms in a thermal plasma and effective emission rate for hydrogen Balmer-alpha.

- ADAS312 has been used to output the envelope over the electron density and temperature with respect to the experimental values

These calculations have been performed under mobility during July 2003 at KTH Stockholm and VR-Euratom Association support

- *Investigation of photo-recombination contribution*

The ADAS library contains subroutines for evaluation of the usual Einstein coefficients, the stimulated emission rate, the stimulated recombination coefficients and the radiative recombination coefficients in terms of Gaunt factors. The two groups of atomic coefficients relevant for plasma modeling are the photon emission coefficients and the energy emission coefficients. The former enter the statistical balance equations (that is number conservation) and the latter the energy balance equation. Maxwell averages of the free-bound coefficients are required for thermalised electron plasma.

- In our work we refer to the ADAS211 program which calculates state –selective radiative recombination coefficients in LS coupling and in one-electron Slater type model potential adjusted to observed energies. The interactive ADAS211 program delivers the Maxwellian averaged photon emissivity coefficient. Bound-free radial integrals are required for hydrogenic and non-hydrogenic ions. The ADAS routine evaluates these integrals according to the following conditions:

a) For large *l* the radial integrals are effectively hydrogenic;

b) For small *l*, quantum defects may be large and non – hydrogenic approximations become necessary;

- *Investigation of bremsstrahlung contribution*

We calculate the bremsstrahlung contribution to the spectrum by implementing a FORTRAN routine which generates the total continuum emission (free-free and free-bound) for a hydrogen + single impurity plasma. No ionisation balance is assumed but the code requires all ion stages, so a coronal balance is used. Collisional and radiative rate coefficients are taken from the ADAS routines.

The code uses the Coulomb integrals (tables and sum rules) given by Burgess (1974) [1]. Given a photon wavelength (λ), electron temperature T_e (eV), target ion charge (z), it calculates the value of the Maxwellian –averaged free-free Gaunt factor. The code generates the total continuum emission for a hydrogen + single impurity plasma.

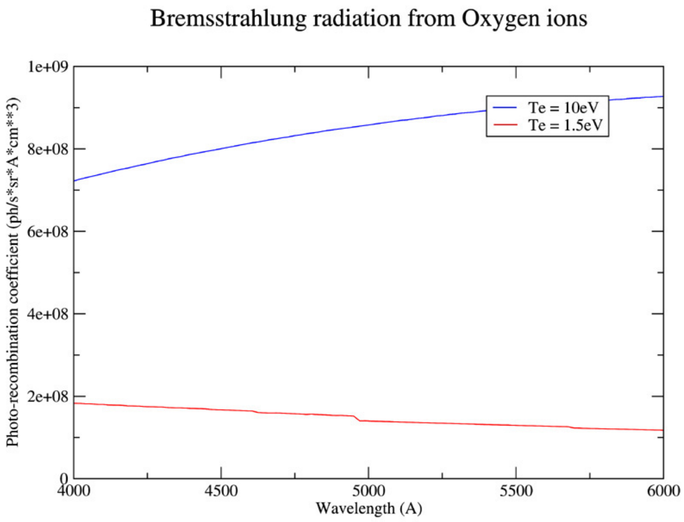

Figure 2. Bremsstrahlung radiation from Oxygen ions

- *Field's effects contribution*

Ion field and ion collision effects on bound and free electron population distributions are the main theoretical issues discussed in this section. The effect of the plasma ion field could be split into static and dynamic field contributions. When discussing the static field we take account of the fact that the atom is assumed to lie in a constant Stark electric field produced by the almost stationary ions, which splits the degenerate levels. This is then further averaged over the ion field probability distribution function to produce a broadened spectrum. Consequently, the static fields yield an ionization lifetime.

Dynamic fields are created by ions moving inside the Debye sphere around the neutral atoms. These fields fit into the framework of collisional theory and may be treated as rate coefficients in the population equations.

The program ADAS310 calculates population structure, effective ionization and recombination coefficients for hydrogen atoms or hydrogenic ions in a plasma. The calculation commences with ion/atom collision cross section data collection stored separately for each hydrogen reactant. The interactive code provides basic interrogation and display of cross sections from these collections only. The situation when both target and projectile have thermal velocity distribution functions is common. For electron impact excitation between nearby n-shells ($\Delta n \leq m \sim 2$), the impact parameter approximation of Burgess and Summers, 1976 [2] (is used. The order of the quadrature over the cross section to produce the rate coefficients may be altered but the highest precision is generally used. For $\Delta n > m$ the formulae of Percival and Richard (1970) are available or the simpler Van Regemorter approximation may be used. For impact excitation, cross sections are included for $\Delta n \leq m \sim 2$ with the expression of Lodge et al. (1976) or Vainshtein as alternatives.

ADAS 310 can compute the populations for any mixture of light impurities (hydrogen to neon) in the plasma. The mixed species effective coefficients are constructed from these pure impurity solutions by the theoretical data acquisition routines. The main population output is very complete and in principle contains all information on possible emitted spectrum lines up to very high n-shells together with both ionization and recombination collisional radiative coefficients. It is archived as ADAS data format *adf26*. The charge exchange data set is required when hydrogen nuclei can act as electron receivers from other species.

- *Modelling population density distribution*

Since the line intensities depend on the instantaneous population density of the ground level (Bates and Kingston 1963), the variation of the line intensities with time requires the calculation of the variation of the ground level population density. This involves the collisional radiative recombination and ionisation coefficients (Bates, Kingston and McWhirter 1962) using atomic model including all inelastic electron collisions involving bound and free electrons and all radiative processes that do not involve the absorption of photons. It is assumed that the free electrons have a Maxwellian distribution. From the instantaneous population densities, the power loss by radiation is calculated as a function of electron density and temperature

- *Total Radiated Power*

During the last T2R experimental campaigns, medium current (~85kA) with long flat top conditions (up to 7ms) plasma discharges have been successfully obtained with the full diagnostic setting requirement. The OSCR model that computes the concentration and radiation of carbon and oxygen impurities has been used to calculate the total radiated power. Since the charge exchange process with neutral hydrogen is important for the T2R plasma conditions, an adapted version of the recycling code EDCOLL is used to compute the neutral density distribution. The resulting OSCR and EDCOL calculations are directly compared with the total radiated power deduced from the 8-cord bolometer data and with the C^{3+} and O^{5+} impurity densities deduced from the VUV spectrometer measurements. To achieve a more complete analysis, a 1D time dependent Collisional-Radiative Impurity Diffusion model (CRID) has been used with the same input plasma conditions to deduce transport properties in T2R.

The Bremsstrahlung emission [3] is mainly localized at the edge and estimated to be P_{brem}~0.03MW, roughly 5% of the total radiated power. In what concerns the lower magnitude of radiation simulated by OSCR, it may be explained by neutral particle impact onto the detectors, radiation from hydrogen or other impurities and/or a higher impurity concentration in the plasma core (impurity transport or accumulation). These processes are not taken into account in the model. Considering those additional contributions and the experimental uncertainties, this simulation is presently sufficient to evaluate the radiation profile and estimate the impurity concentrations. The corresponding effective charge Z_{eff} of the plasma due to oxygen and carbon impurities are computed separately as follows:

$$Z_{eff} = \sum \frac{Z_i^2 n_i}{Z_i n_i}$$

The bremsstrahlung contribution has been included into the total radiated power modeling using the OSCR model during 2003 mobility at KTH Stockholm and VR-Euratom Association support

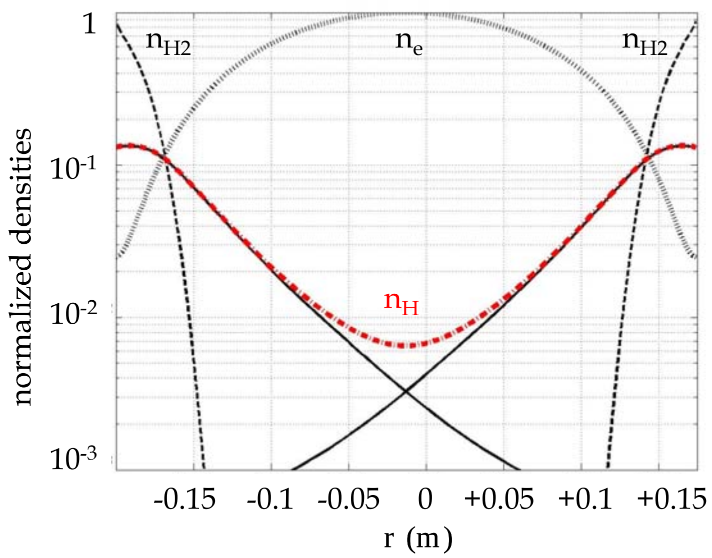

Figure 3: Normalized molecular and neutral density distributions computed by the version of EDCOLL adapted for Extrap T2R. The neutral density is estimated to be about a factor of 50 lower in the core than at the edge.

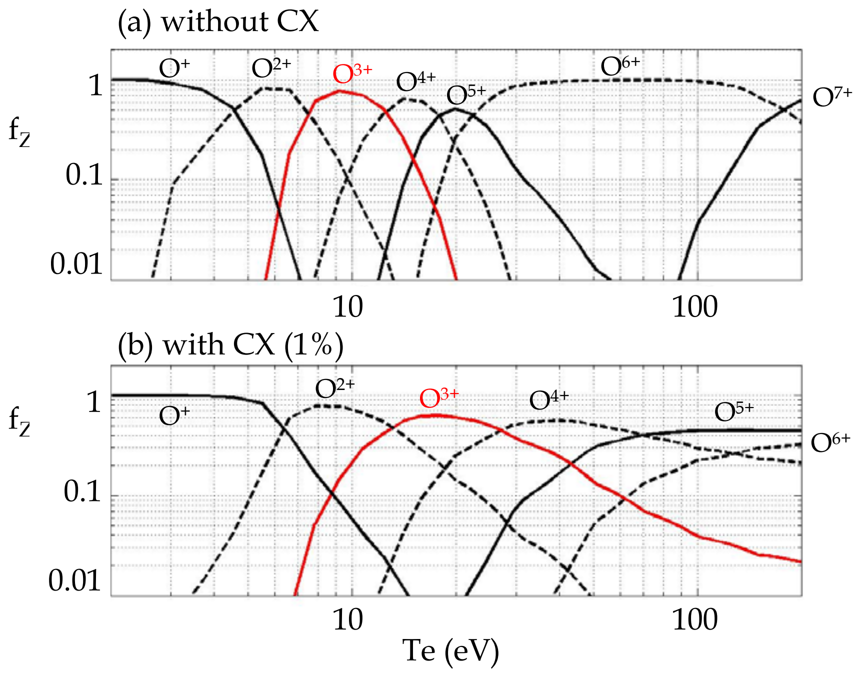

Figure 4: Fractional abundances $f_Z=n_Z/\Sigma n_Z$ of oxygen (a) without charge exchange and (b) including charge exchange where n_H=1%

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- *Simulations with and without transport calculation*

To investigate the validity of the OSCR simulation, two simulations [4, 5] with a 1-D time dependant Collisional-Radiative Impurity Diffusion (CRID) model have been processed with both *high* ($n_H{\sim}10^{-2}{\cdot}n_e$) and *low* ($n_H{\sim}10^{-3}{\cdot}n_e$) neutral density profiles; pinch velocity $V_P=10^6 cm{\cdot}s^{-1}$ at the edge and $V_P=0$ in the centre; impurity influx $\Gamma_i=7{\cdot}10^{19}$ $p{\cdot}m^{-2}{\cdot}s^{-1}$ and perpendicular diffusivity $D_\perp=10m^2{\cdot}s^{-1}$. The total radiated power computed with CRID (P_{rad}=0.6MW) matches the measured value (P_{rad}=0.55MW) in the *low* neutral density case while the OSCR simulation matches better the experimental value using the *high* neutral density profile. The experimental data are in between OSCR and CRID simulations, within a factor smaller than two. Using the CRID simulation with the *low* neutral density case as reference, the OSCR model is therefore estimated to be valid at ±50%.

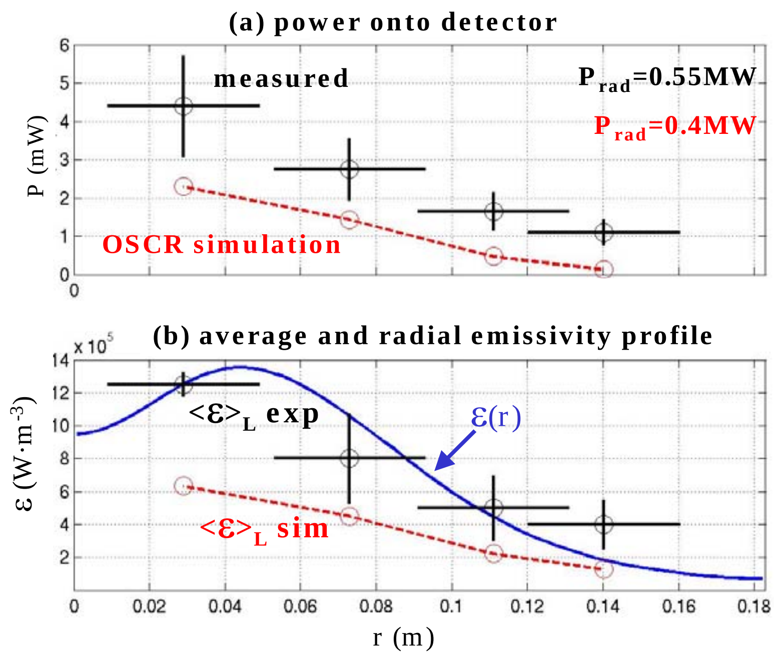

Figure 5: (a) Radiated power on the detector measured (black) and simulated (red). (b) Average emissivity along the bolometer lines of sights measured (black) and simulated (red). The blue curve shows the radial simulated emissivity profile.

Publications and references:

[1] **Burgess A., Hummer D.G. and Tully J.A.,** Phil.Trans.R.Soc. 266, (1970), 225.

[2] **Summers H.P. and McWhirter R.W.P.,** J. Phys. B:Atom.Molec.Phys. 12, (1979), 2387.

[3] **Stancalie V. and Rachlew E.**, "*Radiation from Hydrogen atoms as related to the modeling of the EXTRAP T2R plasma*", 23rd International Conference on Photonic, Electronic, and Atomic Collisions, July, 2003.

[4] **Corre Y. et *al.*** ,"*Radiated power and impurity concentrations in the EXTRAP T2R reversed-field pinch*", 30th EPS Conference on Controlled Fusion and Plasma Physics,

St. Petersbourg, July, 2003, ECA. 27A, P-3.221

[5] **Corre Y. et *al.*,** "*Radiated power and impurity concentrations in the EXTRAP T2R reversed-field pinch*"**,** (submitted to Plasma Phys. and Contr. Fusion, 2003)