Mid - High Z Impurities as Diagnostic Tools in Tokamak Plasmas

D. Pacella 1), M. Leigheb 1), L. Gabellieri 1), L. Panaccione 1), M. Zerbini 1),
M. Mattioli 4), M.May 3), M. Finkenthal 3), K.B. Fournier 2), W.H. Goldstein 2)

1) Associazione EURATOM - ENEA sulla Fusione , C.P. 65, 00044 Frascati, Rome (Italy)
2) Lawrence Livermore National Laboratories, PO Box 808, L-41, Livermore, CA (USA)
3) Johns Hopkins University , Baltimore MD (USA)
4) ENEA Guest

e-mail contact of main author : pacella@frascati.enea.it

Abstract. Impurity transport and temperature effects have been studied in FTU high temperature ECRH heated plasmas, by means of X-VUV emissions from mid – high Z elements (Fe, Ge, Mo, W). Experiments have been performed in collaboration with the Johns Hopkins University (JHU) and the Lawrence Livermore National Laboratory (LLNL). Medium-high Z elements have the advantage to not be fully ionized even at very high electron temperature (tens of keV) and to exhibit a large variety of soft X and VUV emissions very sensitive to the local plasma properties like temperatures, non thermal effects, turbulence, changes of transport properties and so on. For example X-ray emissions (L-shell) of intrinsic Mo in the plasma core, heated by ECRH power at about 8 keV during the current ramp up with a magnetic shear still negative or zero, revealed a negligible impurity transport and a central impurity peaking. Impurity transport in ECRH heated plasmas have been also studied by means of Ge and W, injected by laser ablation.

1. Introduction

A few results concerning the behavior of mid - high Z impurities in a wide range of plasma scenarios will be presented. These results underline the relevancy of these impurities as diagnostic tools, in particular to study very high temperature plasmas. These experiments were carried out at Frascati Tokamak Upgrade (FTU) during last two years, in collaboration with the Johns Hopkins University (JHU) and the Lawrence Livermore National Laboratory (LLNL). In particular the results we present refer to Molybdenum (Mo), Iron (Fe), intrinsic impurities in FTU, and Tungsten (W) and Germanium (Ge), injected with the laser blow off technique. These medium-high Z elements have the advantage to not be fully ionized even at very high electron temperatures (tens keV) and to exhibit a large variety of soft X and VUV emissions very sensitive to the local plasma properties like temperature, non thermal effects, turbulence, changes of transport properties and so on. Unfortunately, the atomic physics of these emissions is very complicated and accurate fully relativistic ab initio atomic calculations have been performed with HULLAC code at LLNL to interpret the experiments at FTU. For example, three different topics are presented: very high temperature plasmas (ECRH heated core), very low temperature plasmas (periphery during current ramp-down) and sensitivity to the local plasma conditions in a defined radial region.

2. Intrinsic Molybdenum in high temperature plasmas

Lawrence Livermore National Laboratory (LLNL) and the Johns Hopkins University (JHU) developed a collisional radiative (CR) model for the L-shell transitions of Mo^{30+} to Mo^{39+} and determined the relative charge state distribution at high temperature (5-15 keV) [1,2]. With peak electron temperatures, $T_e(0)$, of about 8 keV, these ions (Mo^{30+} to Mo^{39+}) extend over a large part of the plasma's minor radius, $0 < r/a < 0.7$ where a=30 cm. The ionization equilibrium times of these ions are in the range 1-5 ms, much shorter than the time scale of the evolution of the macroscopic plasma parameters affecting these emissions. The plasma has a current, I_p, of 0.7 MA, a line averaged density, $<N_e>$, of 0.8×10^{20} m^{-3} and a magnetic field, B, of 5.4 T. Soft X ray spectra, whose time resolution is 5 ms, were analyzed in a discharge (#12658) with on axis heating (400 kW) during the current ramp up [3]. At this time the magnetic shear is still negative or zero. The brightness B, (photons/s cm^2 sr), of features in the wavelength range λ_1-λ_2 can be calculated by means of following integral along the line of sight

$$B = \frac{1}{2\pi}\int_{0}^{a} dr N_e(r) N_{Mo}(r) \int_{\lambda_1}^{\lambda_2} d\lambda \sum_{Z} \varepsilon_Z(\lambda, T_e(r)) f_Z(r)$$

where r is the radial coordinate of the circular cross section, "a" is the plasma minor radius, f_Z is the fractional abundance of ion Z, and N_e is the electron density and N_{Mo} is the total molybdenum radial density profile. The emissivity ε_Z per unit electron and ion (charge state Z) density of at temperature T_e is calculated from the collisional-radiative model. Theoretical spectra, calculated using these emissivities, ε_Z, are shown, for three different electron temperatures in fig. 1. In fig. 2 the synthetic spectrum (blue line), calculated using the previous formula and the experimental spectrum (black line) are shown; the two red lines do not belong to the molybdenum emission. The best agreement occurs when all the ions in coronal equilibrium (no anomalous transport) and with a peaked N_{Mo} profile (N_{Mo} (r=0) / N_{Mo} (r=15 cm)=3). A negligible impurity transport and a central impurity peaking, are consistent with a neoclassical transport regime [2].

On the contrary, when ECRH heating was done at the beginning of the current flat top, with monotonic magnetic shear and sawtoothing activity, the lowest charge states (Mo^{33+} to Mo^{30+}), populated in the intermediate radial region, are affected by anomalous transport and the total molybdenum profile is found to be almost flat up to half radius.

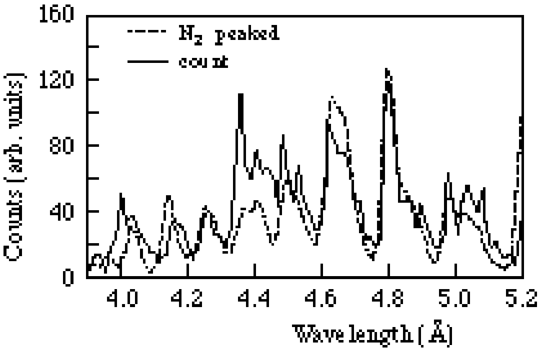

FIG. 1 - Calculated Molybdenum spectra, at low resolution, for a homogeneous plasma at electron temperature of 2.0 , 4.0 and 8.0 keV

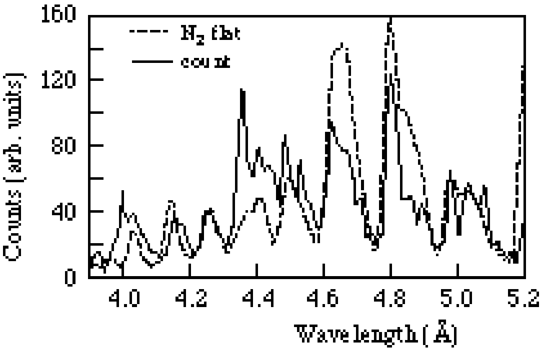

FIG. 2 - Comparison between measured soft X ray molybdenum spectrum for the shot #1265 (dashed line) and calculated

3. Injected Impurities (Ge, W) in high temperature plasmas

Using the laser blow off technique, germanium (Ge) and tungsten (W) were introduced during the current ramp up phase of ECRH heated plasmas. The goal was to use of medium – high Z elements as a probe for very high electron temperature plasmas and for the core impurity transport processes.

These two impurities were injected during the currrent ramp up phase at t = 80 ms (current plateau at t = 120 ms) with ECRH central heating from t = 50 to 350 ms. For both Ge and W, the spatial distribution of the soft X emissions are compared before the injection and when impurity reached the core (maximum of soft X emissions and line transitions of central charge states). At these two times the electron temperature and density radial profiles are roughly the same. In these two similar shots the electron temperature, as measured by ECE diagnostic, is very peaked with a central maximum value of 9 keV. The difference of the spatial profiles before and after the injection is due to the injected impurity in both the two cases (figs. 3, 4). It is moreover evident the strong radiative effect of W in high temperature plasmas. Soft X emissions confirm that the impurities reach the core with the peaked electron temperature and the negative or flat magnetic shear. The X-VUV spectroscopy of these injected elements can be very useful to study the temperature and transport processes as done for the intrinsic molybdenum. The VUV transitions of Ge were recorded with a grazing incident high resolution spectrometer ($\Delta\lambda$= 0.7Å). The resonant lines of Li-I (λ = 22.8 Å) and Be-I (λ = 92.8 Å) like germanium were detected [4]. These two charge states exist in a wide temperature range (3-10 keV) and are sensitive to the local electron temperature and transport processes. In shot 18760 the ratio between these two lines is consistent with an electron temperature of approximately 5-6 keV; it represents an estimation of the temperature averaged over the inner 5-6 cm. A more detailed analysis will be done to compare these results with the ECE measurements. The spectroscopic emissions of W are much more complicated and quite unknown for temperatures greater than 4 keV. Consequently it is not possible, at present, to derive information from the acquired W spectra in these high temperature plasmas.

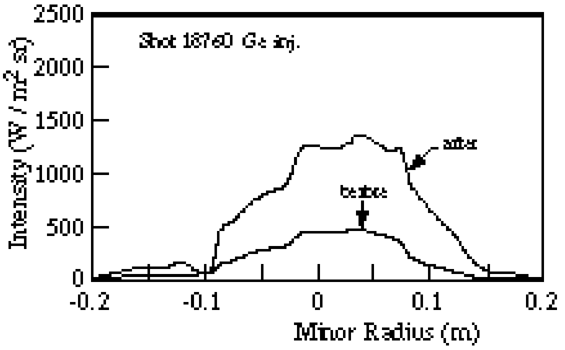

FIG. 3 - Soft X intensity vs impact parameter before (t=70 ms) Ge injection and after (t=110 ms)

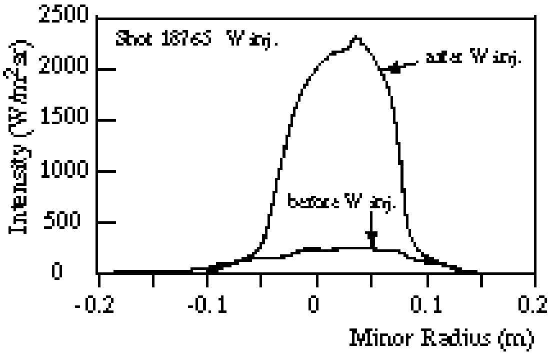

FIG. 4 - Soft X intensity vs impact parameter before (t=70 ms) W injection and after (t=110 ms)

4. Very low temperature plasmas.

We have measured the _n=0 (n=3 – n=3) XUV spectra, in the wavelength range 160-210 Å, of M-shell iron ions from a nearly single temperature tokamak plasma obtained during the “ramp-down” phase of the discharge. Temperature measurements obtained with Electron Cyclotron Emissions and Thomson Scattering indicate a broad, nearly single temperature region (in the range 50- 150 eV) in the outermost third of the plasma. This outer plateau lasts hundred ms and enhances strongly these emissions, which are difficult to observe except in a

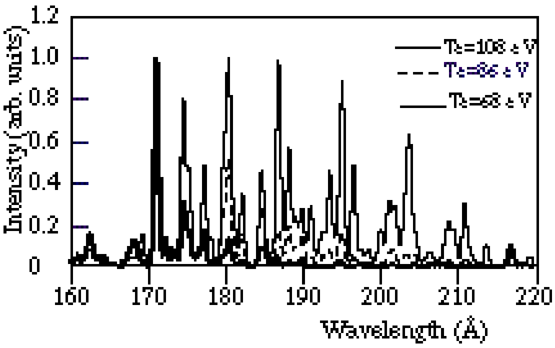

FIG. 5 - Three iron M-shell Collisional-Radiative models calculated with 3 temperature *values: a) 68 eV (dotted line) b) 86 eV (dashed line) c) 108 eV (continuous line)*

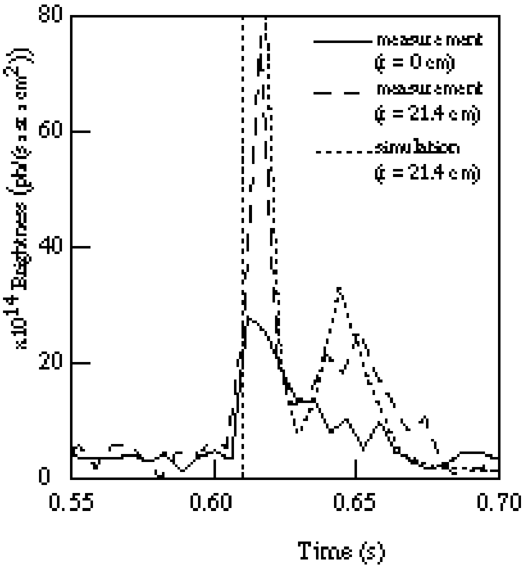

FIG. 6 - Time history of line emission of Fe^{8+}*along a central l.o.s. (continous line), along a peripheral (impact parameter 21.4 cm) l.o.s. (dashed line) and simulation (dotted line)*

very transient phase. The observed charge states span those from K-like Fe VIII to Si-like Fe XIII. Collisional-radiative simulations have been computed for the above ions, using the HULLAC suite of codes. The spectra of the multiple charge states are combined according to the relative populations of Arnaud and Raymond. The blended M-shell spectrum is strongly sensitive to temperature. In Fig. 5 the synthetic spectra for three temperature values (68, 86, 108 eV) are shown and exhibit a strong sensitivity to the temperature. Changes of only a few eV produce completely different emissions. Very good agreement with the observations is found within the limits imposed by the local electron temperature measurements.

5. Sensitivity to the local plasma conditions

Iron injection produces perturbations in both the SOL than in the confined plasma. In the unperturbed SOL, at the LCMS an average electron density Ne(LCMS) = $0.7 \cdot 10^{19}$ m^{-3} and temperature Te(LCMS) = 25 eV are measured. After the injections, a decrease of Ne and Te lasting approximately 40-80 ms is observed. The decrease is stronger at the poloidal position corresponding to the poloidal limiter, where Ne(LCMS) = $0.3 \cdot 10^{19}$ m^{-3} and Te(LCMS) 10 eV are measured. Inside the LCMS the temperature drops in the range $0.7 < r/a < 1$ which is the cause of the second bump observed in the time history of VUV line emission of a low ionization state (Fe^{8+}) along a peripheral line of sight (dotted curve in fig 6). The same line emission , observed with a a central view, does not show this effect (continuous curve) [5]. This illustrate how a charge state can be very sensitive to the local plasma conditions.

This time behaviour can be simulated by time dependent impurity transport simulations, taking into account the changes of the temperature profile induced by the injection. The atomic physics giving the best agreement with the measurements is Arnaud and Rothenflug (1992). Concerning the anomalous transport coefficients, typical values for FTU are taken, D=0.5 m^2/s , V= 3 m/s.

References

[1] Fournier, K.B., Goldstein, W.H., Pacella D. et al., Phys. Rev. E, **53**, 1, (1996)1084

[2] Pacella, D.et al. Phys. Rev. E, **61**, (2000) 4

[3] Buratti, P. et al.: Phys. Rev. Letts, **82**, (1999) 569

[4] Pacella, D. et al 26th EPS Conference CFPP June 1999 Maastricht

[5] Pacella, D. et al. 27th EPS Conference CFPP June 2000 Budapest